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Report on Pavement Deflection Research and Operations By the California Division of Highways Since 1938

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In the evolution of the many existing pavement design procedures and formulas by highway engineers in the United States and throughout the world, primary consideration has been given to the elimation of roadway failure by shear displacement or plastic flow. It has been recognized for a number of years, however, that this is not a complete solution since another type of pavement distress, known as "fatigue cracking", may manifest itself early in the service life of the roadway. "Fatigue" cracking is the result of repeated flexure of the asphalt concrete surfacing at stresses which are not sufficient to induce permanent deformation. These cracks generally appear in an "alligator" pattern and are not associated with any type of pavement deformation. A typical "alligator crack pattern is shown by Figure 1. The report (1) which introduced the R-value method of pavement design also listed the three prime factors affecting the propensity of an AC surfacing to crack from fatigue as: (1) potential deforming affect of vehicle traffic or repetitions of wheel load, (2) resiliency or springiness of the basement soil, and (3) flexibility characteristics of the surfacing.


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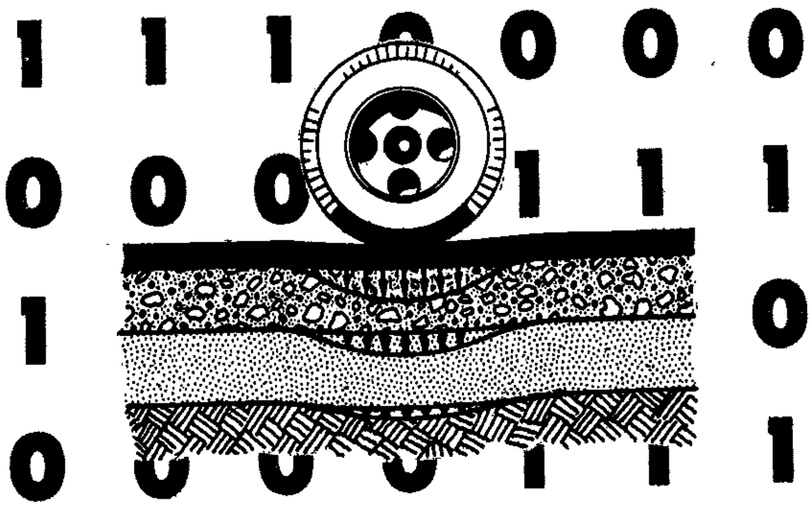
# PAVEMENT DEFLECTION RESEARCH AND OPERATIONS SINCE 1938



APRIL 1966

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MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

State of California
Department of Public Works
Division of Highways
Materials and Research Department

April 8, 1966

Mr. J. C. Womack
State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

REPORT

ON

PAVEMENT DEFLECTION RESEARCH

AND OPERATIONS BY THE

CALIFORNIA DIVISION OF HIGHWAYS

SINCE 1938

Study made by . . . . . . . . . . . . . Pavement Section
Under direction of . . . . . . . . . . Ernest Zube
Report prepared by . . . . . . . . . . R. A. Forsyth
Ernest Zube

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

Attach
cc: LRGillis
ACEstep
JFJorgensen
ELTinney
CTLedden

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## I. INTRODUCTION

In the evolution of the many existing pavement design procedures and formulas by highway engineers in the United States and throughout the world, primary consideration has been given to the elimination of roadway failure by shear displacement or plastic flow. It has been recognized for a number of years, however, that this is not a complete solution since another type of pavement distress, known as "fatigue cracking", may manifest itself early in the service life of the roadway. "Fatigue" cracking is the result of repeated flexure of the asphalt concrete surfacing at stresses which are not sufficient to induce permanent deformation. These cracks generally appear in an "alligator" pattern and are not associated with any type of pavement deformation. A typical "alligator" crack pattern is shown by Figure 1. The report(1) which introduced the R-value method of pavement design also listed the three prime factors affecting the propensity of an AC surfacing to crack from fatigue as: (1) potential deforming affect of vehicle traffic or repetitions of wheel load, (2) resiliency or springiness of the basement soil, and (3) flexibility characteristics of the surfacing.

The primary requirement for a valid assessment of AC fatigue cracking was the evolution of a method by which accurate measurements of the compression and rebound properties of a pavement under load could be obtained. The earliest device for measuring pavement deflection used by the California Division of Highways was the General Electric travel gauge. These instruments were installed on California highways as early as 1938 and on the Brighton Test Track in 1940. They were also utilized during World War II on the Stockton Test Track. A schematic illustration of a G.E. gauge is shown by Figure 2. These installations required the drilling of 5" diameter holes through the pavement surface and the insertion of rods to depths up to 18' into the pavement section. It was found early in the program, however, that the compression and rebound which occurred in the top 8' to 9' of the roadbed was, for all practical purposes, all that was required for successful correlation with pavement performance. The principal advantage of these devices was that it was possible to obtain not only the total pavement deflection which occurred through the entire length of the rod but also increments of deflection contributed individual layers of the pavement structural section. This gauge installation was time consuming and thus expensive, however, so that only very limited coverage was possible. Between 1938 and 1951 G.E. travel gauges were installed on the main highways throughout the state in order to obtain data in support of special pavement investigations which occurred during this period. In order to effectively utilize pavement deflection data it became apparent, however, that a tie between magnitude of pavement deflection and performance of various types of roadway structural section was required. The problems in establishing this relationship were different from those encountered in the establishment of the R-value design method, however, since accelerated test track data are not entirely applicable. Here many millions of equivalent wheel loads are applied to the test track within a very relatively short period of time, (usually 2 to 3 years). While it is possible to evaluate the tendency to plastic deformation within this period, a distorted picture with respect to fatigue failure of the surfacing is probable since the relatively short duration of the test does not permit the average AC surfacing to weather to the degree of hardness at which even moderate to low transient pavement deflections become critical. It was decided, therefore, that the establishment of a reasonable tie between fatigue failure of AC surfacing and magnitude of transient deflection would necessitate deflection measurements over roadways which had been in operation for several years so that the asphalt concrete surfacing would have hardened to a critical or near critical state.

## II. ESTABLISHMENT OF TOLERABLE DEFLECTION CRITERIA

In 1951 a comprehensive deflection research program was initiated by the Materials and Research Department. The primary objective of this study was the establishment of a tie between pavement deflection and pavement performance or condition. Secondary objectives included: (1) establishment of the relationship between single axle load and pavement deflection, (2) a determination of the effect on pavement deflection of wheel configuration i.e., single versus tandum axles, and (3) the examination of the relationship between pavement deflection and pavement temperature.

Approximately 400 General Electric gauge units were installed on forty-three projects throughout the State of California. These installations included rigid as well as flexible pavements. The test roadways included a wide variety of pavement structural section since it was obvious in the beginning that thickness of the asphalt concrete surfacing was a prime variable. A limited number of gauges were also installed in PCC pavements. Installations were made on both distressed and uncracked sections of the test roadways. The results and conclusions of this study were published in 1955 in Highway Research Board Bulletin #114.[2] Plots of what may be considered typical data resulting from this study are shown by Figures 3 and 4 of the present report. Examination of these and the many other plots resulting from this investigation led to the immediate conclusion that pavement deflection can be assumed to vary lineally with single axle loading. It was also noted that with few exceptions a large percentage of the deflection occurring at the 18' level occurs in the top 3'. As would normally be expected, rigid or composite pavements produced lower readings than did the flexible test sections. A composite plot of test data similar to that shown by Figures 3 and 4 in which axle loading is plotted against pavement deflection for cracked and uncracked pavements as shown by Figure 5. Here it can be seen that although there is a certain degree of overlap, a fairly well defined boundary between the cracked and uncracked sections is apparent. For the 15,000 pound single axle loading (which was later established as the standard test axle loading in subsequent deflection studies) 0.020" appears to be the maximum safe tolerable level of deflection for 3" asphalt concrete surfacings.

The results of similar analyses for other AC thicknesses, CTB and PCC pavements are presented by Table 1.

TABLE 1

| Thickness of Pavement | Type of Pavement | Max. Permissible Deflection |
|---|---|---|
| 8 in. | Portland Cement Concrete | 0.012 in. |
| 6 in. | Cement Treated Base (Surfaced with Bituminous Pavement) | 0.012 in. |
| 6 in. | Asphalt Concrete | 0.012 in. |
| 4 in. | Asphalt Concrete | 0.017 in. |
| 3 in. | Asphalt Concrete | 0.020 in. |
| 2 in. | Asphalt Concrete | 0.025 in. |
| 1 in. | Road Mixed Asphalt Surfacing | 0.036 in. |
| ½ in. | Surface Treatment | 0.050 in. |

The criteria presented by Table 1 are of fundamental importance since they provide the basis for the operational application of Pavement Deflection data to overlay design. When compared to similar criteria established by other agencies they tend to the conservative. For example, as a result of a comprehensive deflection study in the state of North Carolina by Mr. L. D. Hicks, Chief Soils Engineer of the State Highway Commission, a value of 0.030" was established as a maximum safe limiting deflection for AC pavements two, three and four inches in thickness. As a result of the WASHO Road Test, a value of 0.045" for warm weather and 0.030" for cold weather was proposed. Under traffic conditions comparable to those under which the California criteria were established, 0.030" appeared to be the tolerable limit on the AASHO Road Test. The differences in deflection criteria established by the various agencies engaged in deflection research can undoubtedly be assigned to variations in asphalt quantity, design and control of mixes, and duration of test. For this reason, limiting deflection values established by other agencies are not believed applicable to California highways.

There is every reason to believe, however, that the values established as a result of the 1951-1955 study may be low when applied to the AC surfacings being constructed today due primarily to an upgrading of asphalt durability characteristics which resulted from the 1960 specification change. In addition, as was previously mentioned, these data were accumulated over roads with a relatively high volume of traffic (plus or minus 9.0 TI). Because of this, an interim method for adjustment of tolerable deflection level according to variations in traffic volume has been developed by the Materials and Research Department. This adjustment is based upon AC surfacing fatigue tests by the Materials and Research Department. The results of this work indicated that while 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 versus deflection lines were relatively uniform when plotted as logarithmic functions. By utilizing an average AC surfacing fatigue line slope and pivoting lines through known deflection criteria at the 9.0 traffic index (TI) level, Fig. 6 was developed for the purpose of making "rule of thumb" adjustment in tolerable deflection for varying traffic volumes. Although these curves are based solely on laboratory surfacing fatigue data and have not yet been correlated with field performance, they appear quite reasonable within the ranges of 6.0 to 10.0 TI. This "rule of thumb" adjustment of the existing deflection criteria is made on lightly traveled roads until the results of a comprehensive statewide deflection study now being conducted are available. This study, which will be described in detail in a subsequent section, involves periodic deflection measurements over a wide variety of structural sections and traffic volumes. The objective of this investigation is to establish new relationships between AC surfacing, quality, traffic volume, and transient deflection. The results of the study comparing pavement deflections induced by tandem as opposed to single axle configuration is presented by Figures 7 through 9. As shown by Figure 7, flexible section consisting of asphalt concrete surfacing over untreated base resulted in an equivalence in lineal deflection of 13,000 pounds for the single axle as opposed to 24,000 pounds across the tandum axle. As shown by Figure 8 for the asphalt concrete surfacing over cement treated base sections 21,000 pounds carried by the single axle was found to be equivalent to 32,000 pounds over the tandem axle. For the portland cement concrete section 24,000 pounds over the single axles were equivalent to 32,000 pounds over the tandem axle (Figure 9). A reasonable explanation for this trend appears to be the fact that the flexible section would, of course, tend to concentrate wheel loadings to a greater extent and thus induce higher pavement deflections for the single axle grouping. This concentration would tend to become less significant as the pavement section became more rigid or distributed either type of loading over a larger area of the subgrade. This is graphically illustrated by the longitudinal deflection profile shown by Figure 10.

## III. EVOLUTION OF DEFLECTION MEASUREMENT EQUIPMENT

Referring back to the introduction, the first device with which a large amount of deflection data were accumulated was the General Electric travel gauge and an improved version of this device, the Linear Variable Differential Transformer (LVDT). The electric travel gauges permitted only a few readings per day and necessitated barricading of the roadway. During the operation of the WASHO Test Road, the tedious processes involved in the installation of the LVDT gauges and the difficulties encountered in maintaining calibration of these devices brought home the desirability of an improved method for the measurement of pavement deflection.

Consequently, a new instrument was developed by Mr. A. C. Benkelman of the Bureau of Public Roads while he was temporarily assigned to the WASHO project. This device, popularly known as the Benkelman beam, operates on a simple lever arm principle. As shown by Figure 11, the 8' long probe is inserted between the dual tires of the test vehicle. As the pavement is depressed the beam pivots around a point of rotation on the reference beam which rests on the pavement well behind the area of influence, so that the back four feet extension of the beam depresses the Ames dial which records maximum deflection to within 0.001". While this device is limited to measurements of total deflection only for test vehicles operating at creep speed, it has the very important advantages of simplicity, versatility and speed. Upwards of 200 individual deflection measurements are possible in a day with this device. Over 60,000 deflection measurements were obtained with the Benkelman beam at the WASHO Test Road.

With the development of the Benkelman beam, the volume of deflection data and the practical operational application of pavement deflection measurement to overlay design was greatly augmented.

In order to further increase the rapidity of making deflection measurements and thereby reducing the cost of this work, the Materials and Research Department developed between the years 1955 and 1960 a semi-automatic pavement deflection device based upon the Benkelman beam principle. This instrument, which is shown by Figure 12 combines a truck-trailer unit, which carries the test load on the rear wheels and probes for measuring pavement deflection under both wheels simultaneously. It is an electro-mechanical instrument capable of measuring pavement deflections at 12½' intervals uniformly and continuously as the vehicle moves steadily along the road at one-half mile per hour. The deflections are recorded to the nearest 0.001" by means of a probe arm resting on the pavement and are permanently recorded on chart paper. As many as four simultaneous measurements (two between the wheels and two outside the outer duals) at 12½' intervals are possible. The most obvious advantage of the deflectometer, therefore, is the relatively large volume of data which may be accumulated in a relatively short period of time. Between 1500 and 2000 individual deflection measurements can be made during an average working day as opposed to the 300 which was the maximum obtainable with the Benkleman beam and truck arrangement. Another significant advantage of the deflectometer was the elimination of the human variable in pavement deflection measurement due to variations in truck speed, location of probe and the time interval required to position the beam. In addition, it is possible to quickly scan random spots on long stretches of roadway or to make measurements at close intervals where desired. A typical deflectometer trace is shown by Figure 13. The Materials and Research Department has only recently begun to seriously analyze and attempt to include characteristics of wave shape into deflection analysis in addition to the lineal deflection measurement. Even now, a cursory inspection of traces from any given job can provide very useful information with regard to the overall condition of the pavement. For example, a very steep abrupt slope generally indicates the very flexible structural section which tends to concentrate the wheel load in a relatively small area of influence of a cracked pavement. Thus if a small area of influence is indicated by the deflection traces coupled with a relatively high lineal deflection we can reasonably assume that the pavement is in a state of incipient failure since steep curves indicate load concentration and high pavement strains. On the other hand, a relatively gentle slope indicates a large area of influence i.e., severe bending and the ability of the structural section being tested to transmit the load applied to a relatively large area. It is theoretically possible, therefore, that the degree of strain or severity of bending would be of a lesser consequence for a high lineal deflection coupled with a gentle sloping trace (indicating a large area of influence) than for a low lineal deflection within a small area of influence.

Final development of the traveling deflectometer was completed in 1960. Since that time it has been used almost continuously on research and operation deflection studies requiring an analysis of the cause of distress and recommendations for reconstruction. The large volume of accurate and permanently recorded deflection data obtainable in very short periods of operating time on the various roadways tested has resulted in a greatly improved operating procedure which has made the deflection method economically feasible for preliminary analyses of even lightly travelled facilities.

## IV. DEFLECTION ATTENUATION RESEARCH

With the establishment of deflection criteria for various structural sections in 1955 and development of the Benkelman beam at approximately the same time, it became possible to accumulate and evaluate relatively large amounts of pavement deflection data. Lineal pavement deflection coupled with visual observation of surface condition and in some cases physical tests of the surfacing were utilized on several distress investigations in order to determine the cause of existing distress and evaluate a probable street performance of the subject roadway. Having satisfactorily established pavement deflection as a means for the analysis of failures, the necessary next step was the utilization of this same data for determination of the required degree of corrective treatment. The necessary area of immediate concern, therefore, was a determination of the deflection attenuation which could be expected from a given thickness or type of corrective treatment. This data would, of course, provide an indication of the minimum required maintenance to restore the facility for an extended period of service life.

Accumulation of deflection attenuation data since the middle of 1950 has been accomplished by two methods. The first was the use of follow-up measurements over projects constructed according to recommendations resulting from a deflection study or distress investigation. Another very important source of attenuation data has been systematic deflection measurements over successive layers on projects selected specifically for peculiarities in structural section or unusual or widely varying thicknesses of surfacing and base. Two test projects which provided an unusually wide range of deflection attenuation data of successive layers will be subsequently discussed.

### 03-Sac-99 (El Centro Road)

Located between Sacramento and Marysville, this facility was developed initially in 1949 by Sacramento and Sutter Counties as an agricultural service road. In 1957, it was incorporated into the state highway system as the most direct route between Sacramento and Marysville. The original structural section consisted only of an armor coat over 6" of aggregate base over 10" of sand. The native soil is an unusually plastic clay which is subject to wide variations in moisture due to the intense rice cultivation on both sides of the roadway.

In 1959 and 1960 three different structural sections were utilized for the reconstruction of this facility. Because of the variation in structural design and the high initial deflection levels, the project provided an excellent opportunity to study the pavement deflection damping characteristics of gravel, CTB, and AC. The effect of successive layers of reconstruction on initial deflection levels for all three structural sections is shown by Figures 14, 15, and 16. Of particular interest is Figure 14 which very clearly reveals the seasonal variation in basement soil water content within the section that was subsequently overlain with cement treated base. Here, initial deflections ranged between 0.090" and 0.105" in May 1959 as opposed to an average deflection of 0.067" over the same section in September 1959.

After placing and compacting 8" of gravel, average deflection was reduced to 0.036". Cement treatment and a one-day cure of the 8" gravel blanket afforded a further reduction to an average of 0.023". With the placement of a 3" AC surfacing, the deflection averaged 0.013". Undoubtedly a large part of the latter reduction was due to further curing of the CTB. The second unit (thick AC) shown by Figure 15 consisted of 6½" of AC over a 6" AB, where the average initial deflection over the original roadway was 0.060". After placement of 6" of AB, average deflection was 0.045". The placement of two 2" AC surfacing lifts resulted in average deflections of 0.035" and 0.031". The third 2" AC layer did not produce a measurable reduction. However, after 18 days of curing, deflection on the 6" AC averaged 0.022". In October 1961, the average deflection was reduced further to 0.012" undoubtedly due to additional curing of the AC surfacing particle adjustment and some traffic compaction. Over the third test section (gravel base) shown by Figure 16, the average initial deflection over the existing roadway was 0.060" as of July 1960. Placement of 6" of compacted gravel lowers the deflection to 0.036". A second 6" compacted layer afforded a reduction of only 0.006" resulting in an average deflection of 0.030". Placement of 3½" of AC brought the average deflection, on September 1962, to 0.021".

## 05-Mon-101

In the summer of 1960, the reconstruction of project of 05-Mon-101 afforded an excellent opportunity to obtain deflection attenuation data through an unusually thick AC blanket. The structural section of this project included 11" of AS, 6" AB and 7" AC placed in lifts of 3" of AC base, 2" AC level course, 1½" surface course and ½" AC open graded mix. The reduction in average initial deflection (0.033" of the base course) resulting from successive layers of AC base and surface is clearly shown by Figure 17. The very significant reduction of deflection afforded by the ½" open graded mix as measured in March 1961, undoubtedly was the result of a seven month traffic compaction and curing.

The results of these and other similar projects produced a sufficient amount of tangible information on deflection attenuation of various materials to provide a reasonable basis for estimating the amount of required reconstruction over projects subject to deflection investigations. In addition, it was noted that curing of AC surfacing and CTB invariably produced very significant reductions in deflection. This is illustrated by Figure 18 which graphically illustrates the reduction in deflection on project 05-Mon-101 after seven months. It was also apparent from these studies that the reduction in deflection afforded by a given thickness of material was to a large extent dependent upon initial deflection level. Put another way, absolute reduction in deflections resulting from the placement of an AC blanket is substantially greater when the initial deflection is high as opposed to low. It was thus found more realistic to estimate reduction in deflection in terms of percent of initial deflection per inch rather than in the absolute terms of thousandths-of-an-inch per inch. In Figure 19, percent reduction is shown plotted against increase in gravel equivalence for projects which have been the subject of deflection measurements before and after reconstruction. This plot is the basic tool for planning the reconstruction of roadways based upon deflection measurements since it contains virtually the sum total of the department's deflection attenuation experience to date. It not only establishes a general trend in deflection reduction afforded by various roadway materials but also indicates the results of specific types of reconstruction on individual projects. A comprehensive report on deflection attenuation research by the Division of Highways was presented in 1962 to the International Conference on Structural Design of Asphalt Pavements.(3)

## V. THE USE OF PAVEMENT DEFLECTION MEASUREMENTS FOR OVERLAY DESIGN

Since 1960, deflection measurements have been made on about eighty different projects for the purpose of recommending corrective treatment. These projects have included not only state primary and secondary highways but also County roads and city streets. From this comparatively long and varied experience, a general procedure has evolved which though varying somewhat from project to project may be briefly described as follows:

> Prior to making deflection measurements the contract file for each project is studied for information on variations in the structural section design, TI, foundation and drainage conditions, and unusual occurrences during construction. From this and visual examination of the project, test sections considered to be representative are selected. A minimum of one thousand feet per center-line mile is tested on each project. Deflection test data is separated into the categories of fill and cut, cracked and uncracked, travel lane, passing lane, and inner and outer wheel track. Further breakdowns or divisions are established as warranted by peculiarities of the project. Examination of average deflections for each of these categories can frequently indicate the nature or cause of early pavement distress and

the practicability of utilizing more than one type of corrective treatment. In those cases where deflection is relatively uniform, an evaluated* deflection level (80 percentile) is established by recombining all outer wheel track 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.

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 carefully considered to arrive at a satisfactory design. These are:

1. Existing vertical controls (curbs and gutters)

2. Anticipated use of the roadway

3. Extent and nature of cracking

4. Anticipated traffic volume

The existence of curbs and gutters or the presence of an excellent passing lane next to a distressed travel lane often makes the utilization 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 asphalt concrete (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 value at which 80 percent of the measurements are lower and 20 percent are higher.

It should be borne in mind that the deflection method for the design of reconstruction is assumed to be valid when roadway distress is attributable to excessive compression and rebound of the structural section. Evidence of the instability of the structural section as manifested by wheel track depression or 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 upon the standard R-value procedure.

The following are brief reviews of the results of two operational deflection studies:

05-Mon-183-Salinas

In July 1961 District Materials Personnel sampled the in-place structural section of this facility at several locations. It was found that within the City limits of Salinas the asphalt surfacing varied from 0.25' to 0.50' in thickness and the aggregate base varied from 0.20' to 0.90'. Average passing and travel lane deflection measurements taken in August of 1961 are shown below.

| Location | | Lane | Mean Deflection outer wheel track |
|---|---|---|---|
| 1. | Between Lincoln and Vale Streets | Westbound Travel | 0.067" |
| 2. | Between Stone and Capitol Streets | Westbound Passing | 0.034" |
| 3. | Between New Street and West City Limits | Westbound Travel | 0.038" |
| 4. | Between Capitol and Stone Streets | Eastbound Travel | 0.058" |
| 5. | Between Riker and Capitol Streets | Eastbound Passing | 0.042" |
| 6. | Between Clark and New Streets | Eastbound Travel | 0.029" |

Based upon the above average travel lane deflection levels of 0.067" and 0.058", it was determined that an increase in gravel equivalence of 12" was required. In view of the generally lower average deflection levels and lower volume of traffic, an increase of 4" in gravel equivalence was recommended for the passing lanes. The existence of curbs and gutters and buried utility lines near the surface limited the extent of reconstruction possible for the travel lanes. As a result, the travel lanes were scarified to a depth of 0.67'. Upon removal of the existing base and surfacing, 0.67' of Class 2 aggregate base was placed and compacted, bringing the passing lanes back up to finished grade. Both the passing and the travel lanes were blanketed with 0.25' of AC surfacing.

The net result of the reconstruction of the travel lanes was the replacement of a cracked asphalt concrete surfacing with a new 0.25' AC blanket. The placement of a 0.25' 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 on one test section before and after reconstruction are shown by Figure 20. As shown by this plot, the percent reduction in deflection was significantly greater in the passing lane section than in the travel digout sections. (46% as opposed to 18%) This project illustrates what has been found to be a basic truism with regard to overlay design; that is, 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.

## 05-SLO-101

On another project in District 05, originally constructed in 1949, the structural section consisted of 4" of AC surfacing over 6" of crusher run base over 12" of imported subbase material. Because of the appearance of early surface distress, a portion of the roadway was resurfaced in 1954 with a 3" AC blanket. In 1959, District 05 materials personnel conducted an investigation in order 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 found to be 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" type cracking with some spalling in both the inner and outer wheel tracks of the outer lane. Little evidence of pavement rutting or pumping was observed however. Deflection measurements were found to be uniformly low, averaging 0.016" in the travel lane outer wheel track and 0.012" in the passing lane outer wheel track. The results of tests on AC surfacing cores, however, indicated that the asphalt binder in the 1954 surface course had hardened to a critical state in which it could not withstand even the relatively low deflections characteristic of this roadway. It was also observed that the 1954 surfacing was cracked to a greater extent than even the underlying 1949 pavement.

In view of the low deflection levels it was recommended that a 2" 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" AC blanket was placed as recommended, in 1960. To date, after nearly 5½ years 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.

Similar economies may have been realized on several other projects in which thin blankets or surface treatments have been recommended based upon a low level of deflection even though some surface distress was visible.

## VI. CURRENT DEFLECTION RESEARCH

Pavement deflection research by the California Division of Highways is at the present time concentrated into three general problem areas. The first and by far the largest program involves the establishment of a tie between tolerable deflection levels, structural section, and traffic volume or Traffic Index (TI). As was mentioned earlier, the present limiting criteria for maximum allowable deflection were established in 1955 as a result of a comprehensive study throughout the State of California. 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, since the initial investigation was conducted over heavily trafficked roads ($9.0 \pm$ TI).

Another very important reason why these values may be subject to some alteration is the improvement in AC durability and thus AC surfacing fatigue resistance which has undoubtedly been brought about by a recent upgrading of our asphalt specifications. 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, which is being financed by the Bureau of Public Roads research funds, has been under way for approximately 18 months. Twenty-five roadways throughout the state, meeting the following requirements, were selected for a five year comprehensive pretest program:

1. They are AC surfaced roadways over which reliable traffic data are available.

2. They are undistressed all new alignment which have not been in operation for more than three years.

3. They have a reasonably large variation in structural section and deflection level.

The test program which will be carried out during the spring of each year will consist of deflection measurements obtained with the traveling deflectometer over selected test sections of each roadway. These sections consist of three to five one thousand foot lengths of the roadway, depending upon 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. Four and twelve inch diameter AC cores are taken in and between the wheel tracks. These samples are subject to flexural strength, microviscosity, permeability, stability, cohesion, density, and percent voids tests. The yearly test program outlined above 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 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 of these entities to pavement performance. It would seem entirely reasonable, as many authorities contend, that pavement performance and condition is more directly relatable to severity bending or area of influence than to lineal deflection measurement alone. At the 1962 International Conference on Flexible Pavement Design[4], an ardent proponent of the "radius of curvature" concept reported on a new device for the measurement of radius of curvature. This device, called a curvature meter, is an aluminum bar approximately one foot 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 one foot in length in the deflected basin from which a radius of curvature can be calculated (Figure 21).

This device has been fabricated by us and used on several projects in conjunction with conventional deflection measurements. The data are shown graphically on Figures 22 and 23. On Figure 22, radius of curvature calculated from curvature meter measurements versus 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 little data is available, it appears that lineal deflection was the best predictor of cement treated base performance since there is a clear-cut demarcation of cracked and uncracked measurements at the 0.012" 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 feet. A similar plot for aggregate base structural sections is shown by Figure 23. 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 feet. The critical zone for lineal deflection occurs at approximately 0.020", although there is a considerable zone of overlap between 0.020" and 0.030". Based upon the limited amount of data presented by Figures 22 and 23, it would be difficult to determine whether either 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 due to the fact that the zone of critical bending is confined to a very small portion of the trace, thus reducing sensitivity.

The third area of study involves a continuing accumulation of deflection attenuation data, the bulk of which is now obtained by follow-up deflection measurements over projects subject to deflection studies prior to reconstruction.

It is anticipated that in the coming fiscal year the Materials and Research Department will begin an evaluation of an entirely new system for the measurement of pavement deflection which was recently developed by the Lane-Wells Highway Company of Houston, Texas. This device, known as "Dynaflect", is a small, trailer-mounted apparatus which is capable of making 45 deflection measurements per hour.

The results of correlation measurements with the Benkelman beam and Lane-Wells "Dynaflect" on several Texas state highways were reported(5) to the 45th Annual Meeting of the Highway Research Board in January, 1966. This work produced a correlation coefficient of 0.91 with a standard deviation of 0.007". The reproducibility of the "Dynaflect" measurements was reported to be good.

In the course of a demonstration to the California Division of Highways in the fall of 1965, "Dynaflect" data was compared to that obtained with the traveling deflectometer over several roadways. Here, also, a reasonably good correlation was found to exist although insufficient information was obtained to warrant a definite conclusion.

The "Dynaflect" system operates by the application of a relatively light vibratory or repetitive force to the pavement which produces displacements very nearly equal to the much heavier near static loads utilized in conventional deflection testing. Because of the relatively light loadings involved, it may be possible to obtain deflection measurements on unsurfaced roadbeds during the various stages of construction. This has not been possible with the deflectometer or the Benkelman beam due to distortion and up-thrust between the loaded dual wheels. This new device presents the possibility of locating weak spots on going construction projects for corrective treatment prior to completion of the structural section.

Because the "Dynaflect", as shown by Figure 24, is trailer-mounted and may be towed by a passenger vehicle, it has a far greater degree of mobility than the Benkelmen beam and truck. It may, therefore, be extremely useful in deflection studies of limited scope in outlying areas of the state.

## VII.. SUMMARY AND CONCLUSIONS

### Summary

The California Division of Highways initiated this Pavement Deflection Research program in 1938, using permanently installed General Electric travel gauges. In 1955, as a result of a comprehensive statewide deflection study, the Materials and Research Department estimated maximum tolerable deflection criteria for a variety of structural sections. These criteria provided the basis for future application of pavement deflection measurements to distress investigations on overlay design.

During the operation of the WASHO test road in 1952 and 1953, a device for rapid and accurate deflection measurement was developed. This instrument, the Benkelman beam, thus stimulated deflection research by this department and other agencies. In 1960, the Materials and Research Department put into operation the traveling deflectometer, which is a fully automatic pavement deflection device utilizing the Benkelman beam principle. With the deflectometer, the amount of extremely recordable pavement deflection data was further increased. With this instrument it is possible to obtain up to 2,000 individual deflection measurements in a single day. Its principle advantages are the elimination of human error, and its ability to scan large areas in a relatively short period of time.

From 1955 to 1960 a sufficient amount of deflection attenuation data by the Materials and Research Department permitted reasonable estimates as to the deflection damping process to various roadway materials. Using these data in the deflection criteria estimated in 1955, the Materials and Research Department has made deflection investigations and recommended overlay design on 75 projects since 1958.

Current deflection research is centered upon the establishment of new tolerable deflection criteria which may be adjusted for variations in traffic volume. Another phase of this work involves the analysis of the effect of area of influence as indicated by radius of curvature on pavement performance.

Several aspects of the Division's pavement deflection work which have not been discussed in this report include the effect of temperature and time of loading on deflection measurements and the reproducibility of deflection equipment. Detailed progress reports on these subjects are on file with the Materials and Research Department.

## The Significance of Pavement Deflection

With the steadily increasing reconstruction of existing roadways, the need for a method to determine the minimum degree of reconstruction 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 by the R-value design procedure under moisture and density conditions which are estimated to be the worst that will occur during the lifetime of the pavement. From the results of these tests, a design R-value is selected and a necessary thickness of base or subbase chosen to provide the required cover in accordance with the 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 in the structural section. In this case, the normal R-value criteria 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 to gradually increase in-place soil strength. Another factor which is difficult to evaluate is the residual strength of an AC 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.

This department recommends, therefore, that, prior to corrective treatment of a state highway for the primary purpose of strengthening the structural section, a deflection study be initiated and that the data resulting be considered in the design of the reconstruction.

# REFERENCES

(1) Hveem, F. N. and Carmany, R. M., "The Factors Underlying The Rational Design of Pavements", Proceedings, Highway Research Board, Vol. 28, 1948, p. 101.

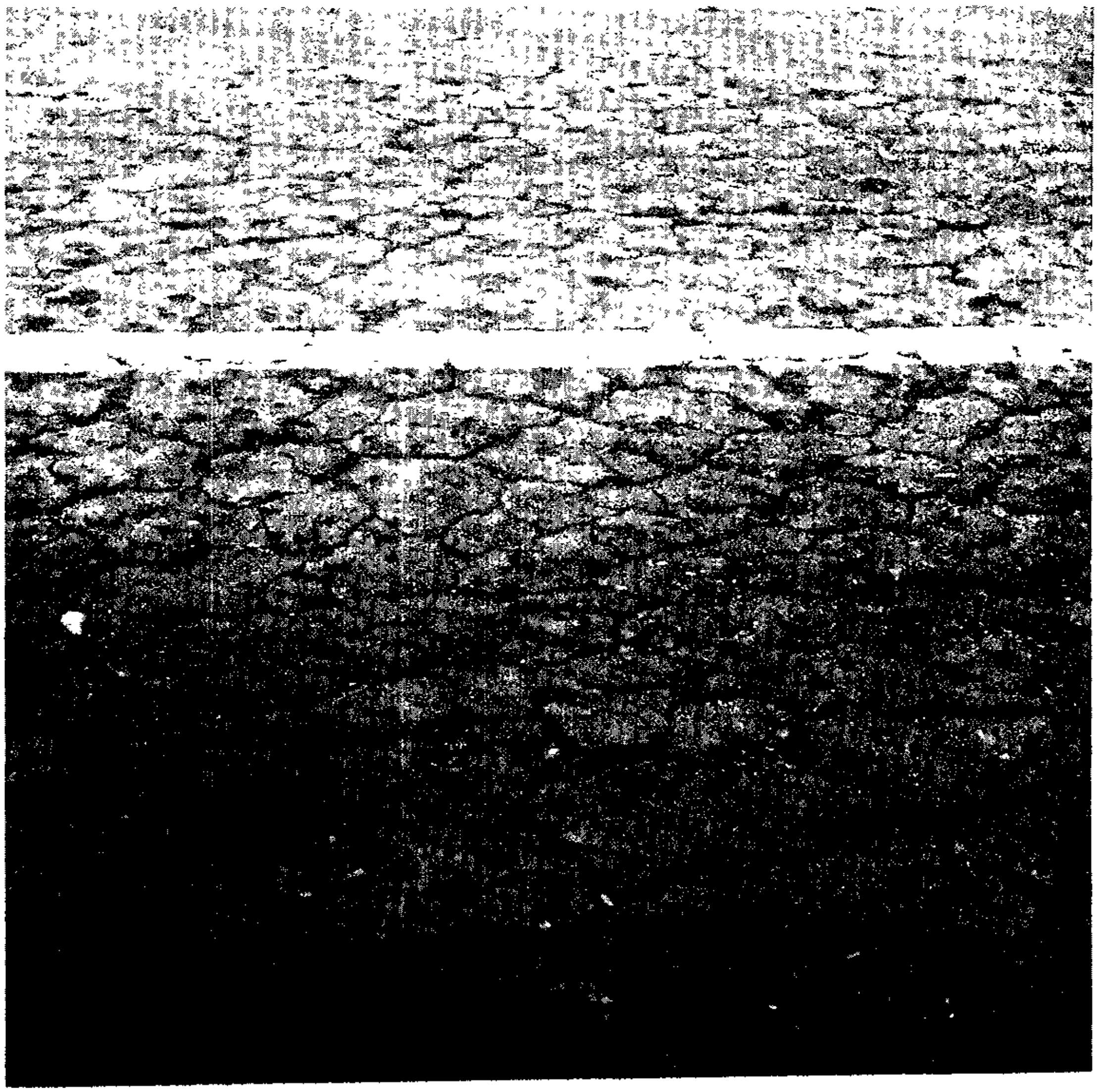
(2) Hveem, F. N., "Pavement Deflections and Fatigue Failures", Highway Research Board Bulletin 114, 1955.

(3) Zube, Ernest and Bridges, Robert, "Use of Pavement Deflections in Asphalt Pavement Overlay Design", Proceedings, International Conference on Structural Design of Asphalt Pavements, University of Michigan, August 1962.

(4) Dehlen, G. L., "An Investigation of Flexure Cracking on a Major Highway", International Conference on The Structural Design of Asphalt Pavements, p. 812, University of Michigan, August 1962.

(5) Scrivner, F. H., Swift, Gilbert and Moore, W. M., "A New Research Tool For Measuring Deflection of Pavements", presented to the 45th Annual Meeting of the Highway Research Board, Washington, D. C., January 1966.

FIGURE 1



"Alligator" Cracking

FIGURE 2

## SCHEMATIC DIAGRAM OF APPARATUS FOR DEFLECTION MEASUREMENTS

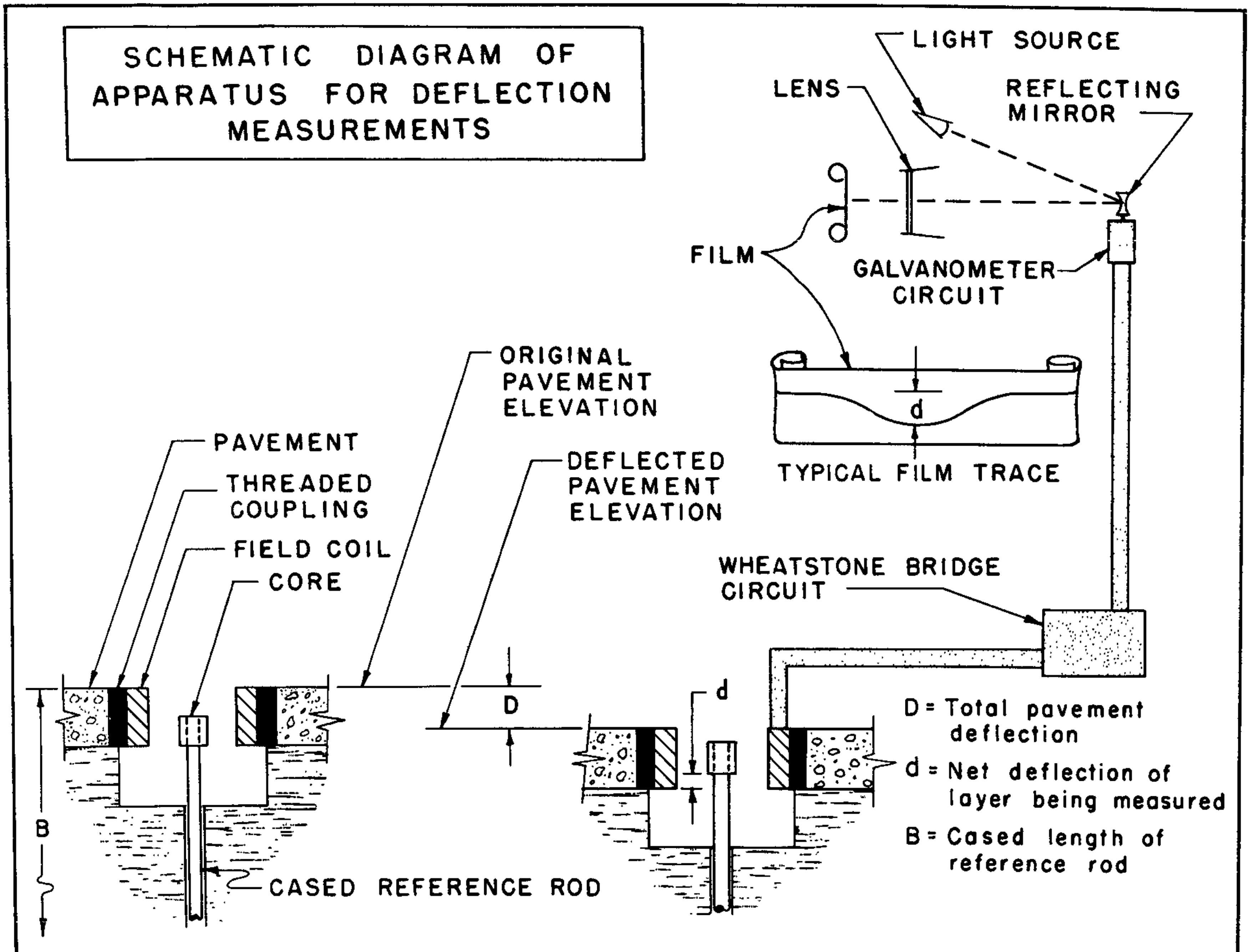
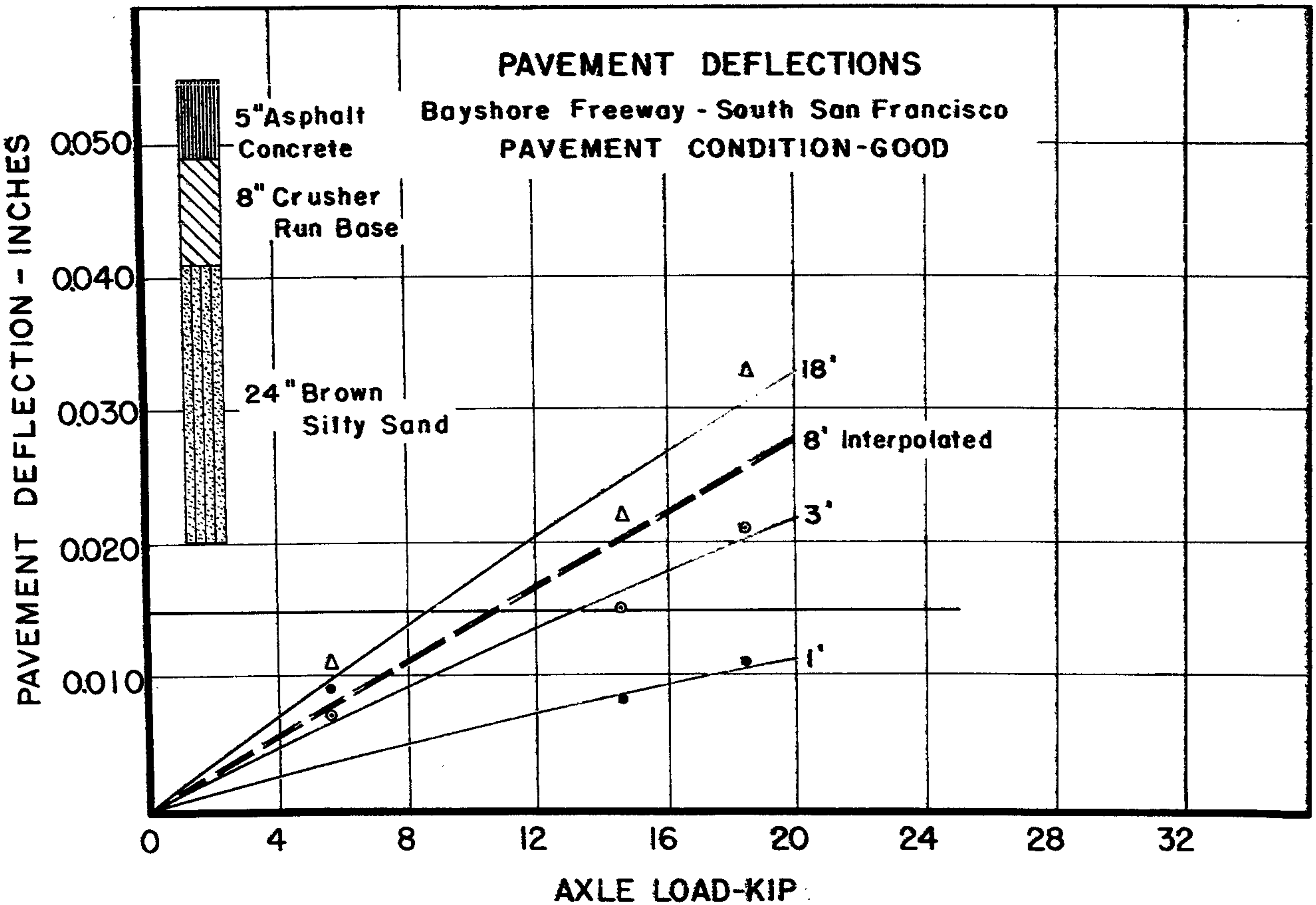


FIGURE 3



PAVEMENT DEFLECTIONS
Bayshore Freeway - South San Francisco
PAVEMENT CONDITION-GOOD
5" Asphalt Concrete
8" Crusher Run Base
24" Brown Silty Sand
18'
8' Interpolated
3'
1'
PAVEMENT DEFLECTION - INCHES
0.050
0.040
0.030
0.020
0.010
0
4
8
12
16
20
24
28
32
AXLE LOAD-KIP

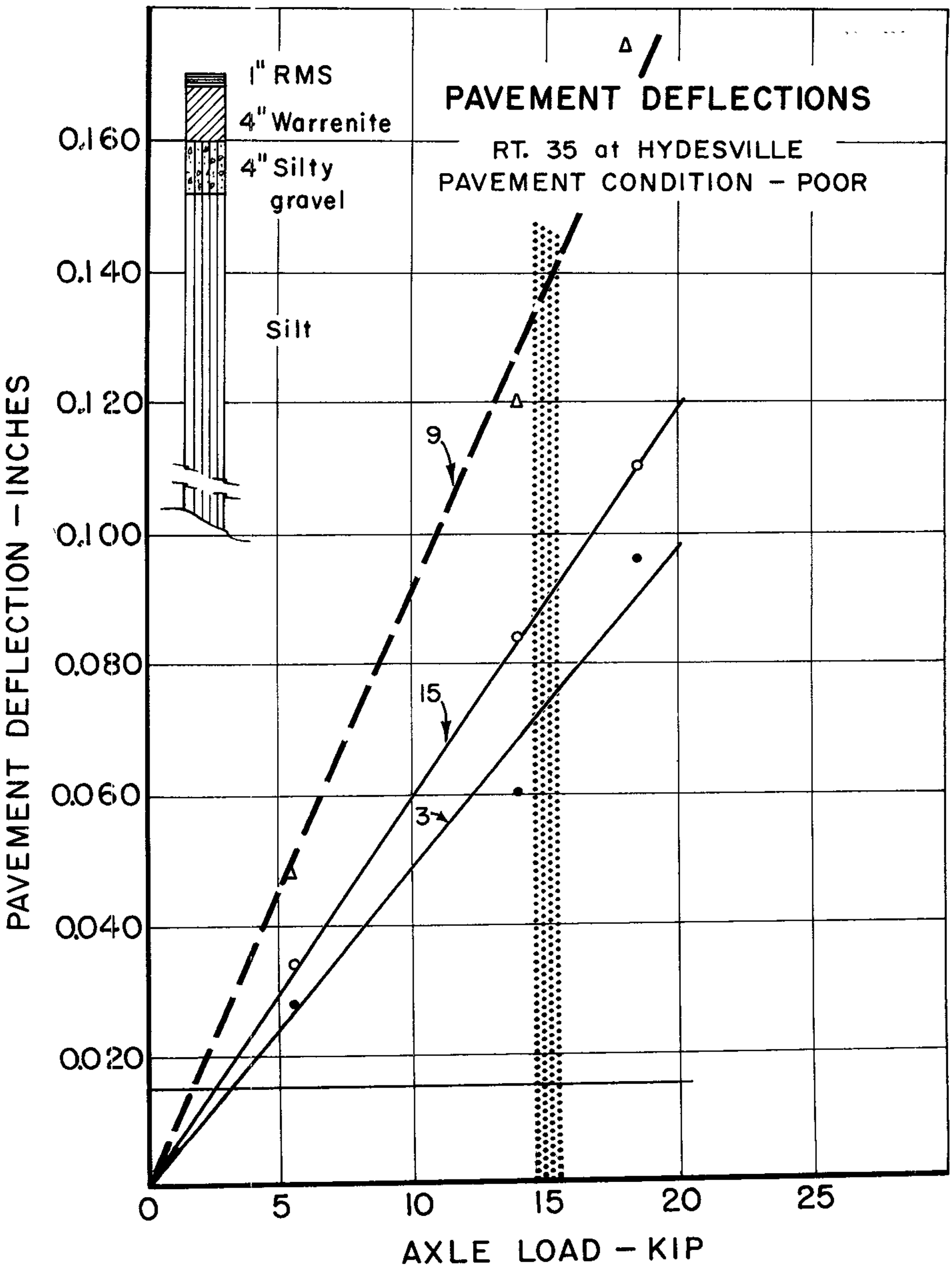

PAVEMENT DEFLECTIONS
RT. 35 at HYDESVILLE
PAVEMENT CONDITION - POOR
1" RMS
4" Warrenite
4" Silty gravel
Silt
9
15
3
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0
5
10
15
20
25
PAVEMENT DEFLECTION - INCHES
AXLE LOAD - KIP

FIGURE 5

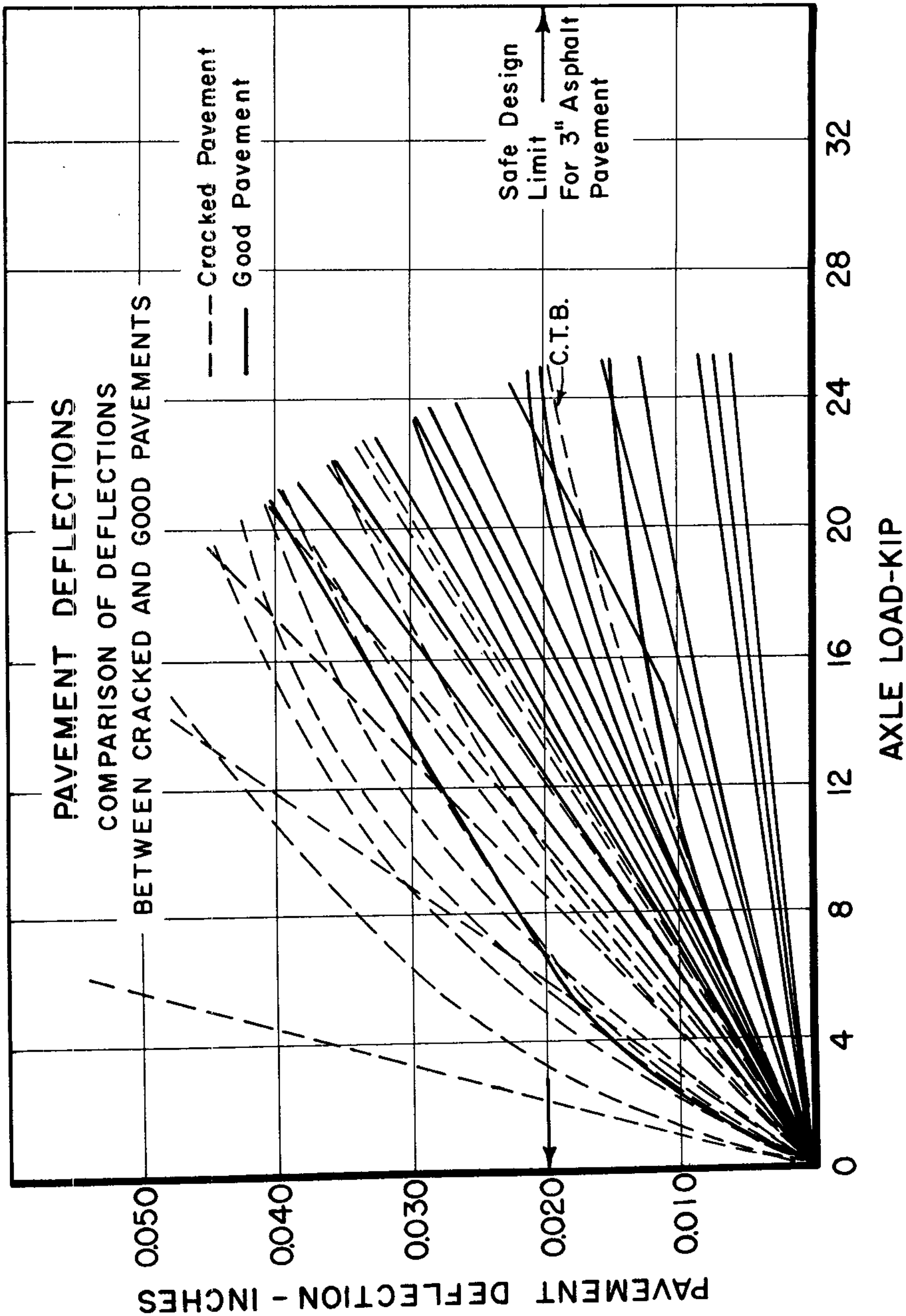

PAVEMENT DEFLECTIONS
COMPARISON OF DEFLECTIONS
BETWEEN CRACKED AND GOOD PAVEMENTS
Cracked Pavement
Good Pavement
Safe Design Limit For 3" Asphalt Pavement
C.T.B.
0
4
8
12
16
20
24
28
32
AXLE LOAD-KIP
0.010
0.020
0.030
0.040
0.050
PAVEMENT DEFLECTION - INCHES

FIGURE 6

# VARIATION IN TOLERABLE DEFLECTION BASED ON A.C. FATIGUE TESTS

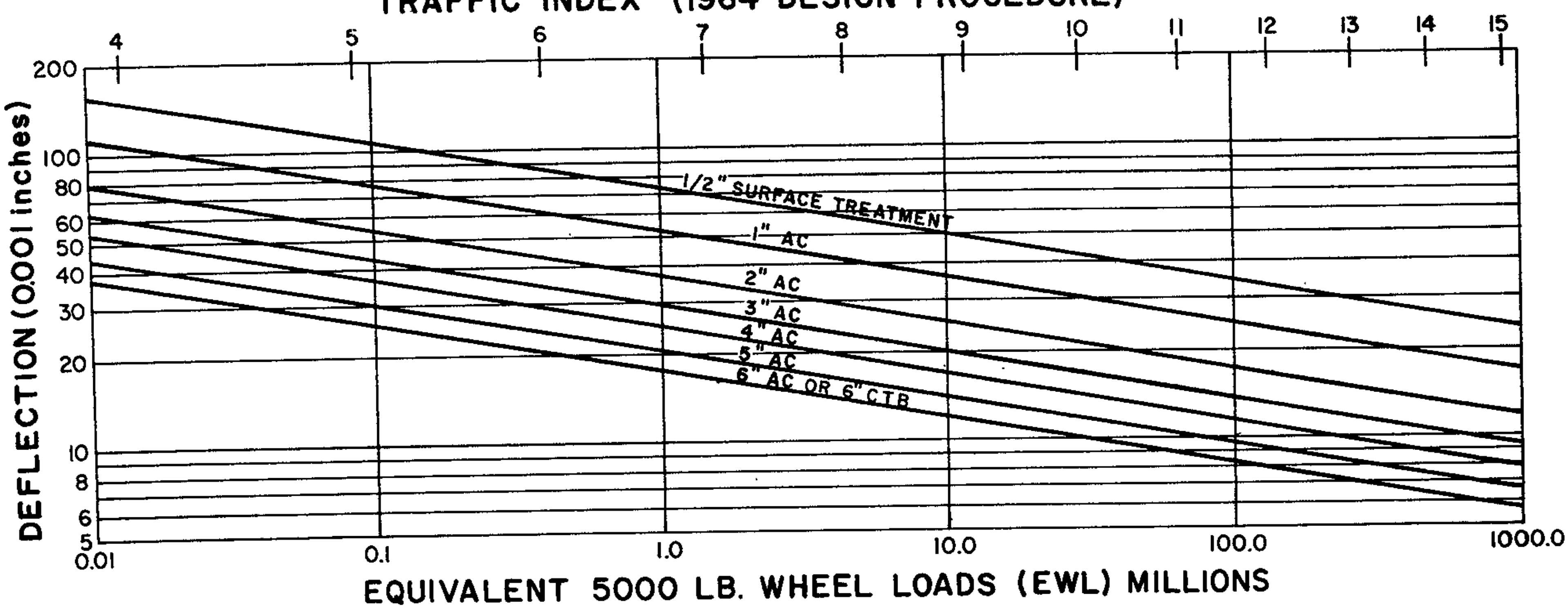


FIGURE 7

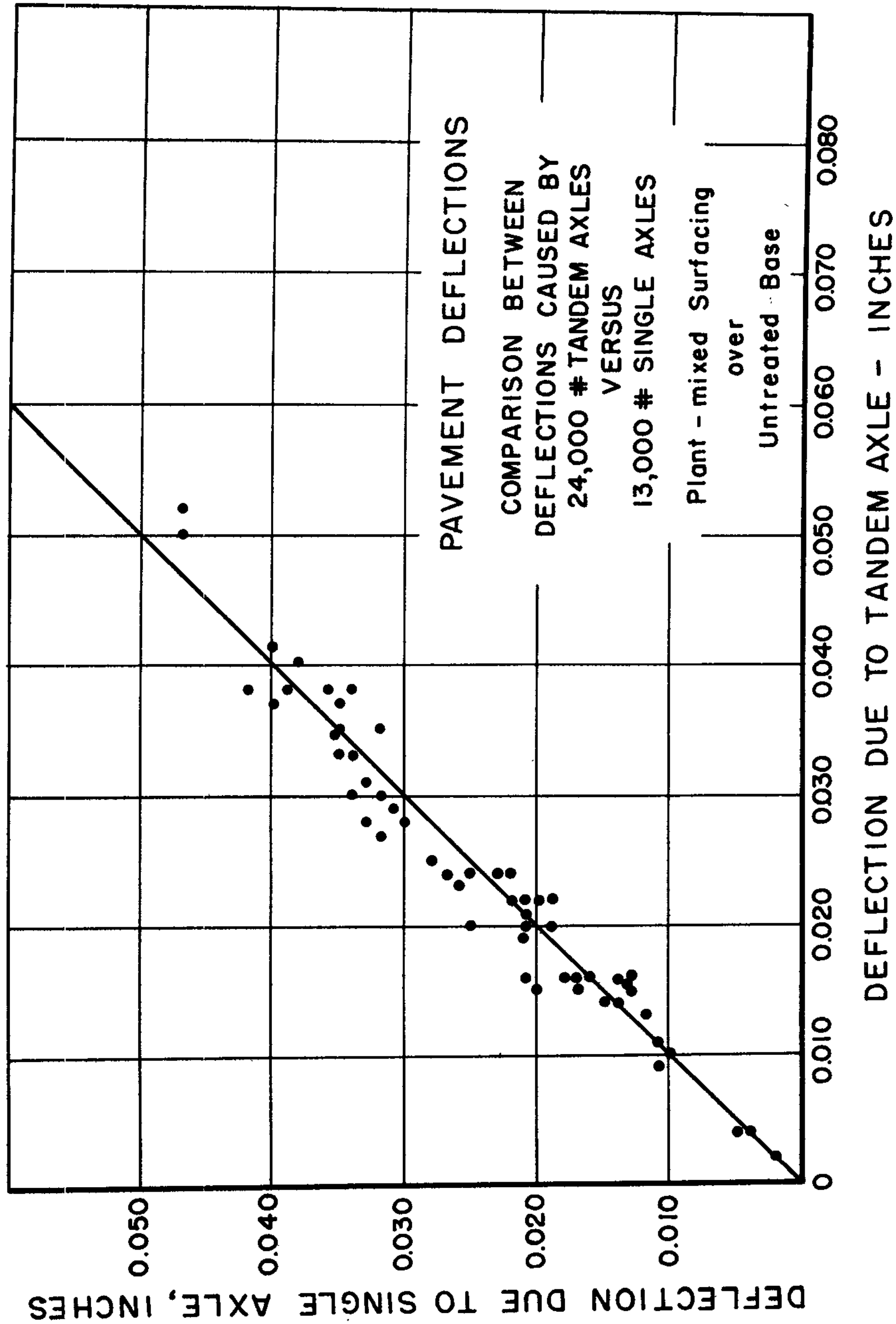

PAVEMENT DEFLECTIONS
COMPARISON BETWEEN
DEFLECTIONS CAUSED BY
24,000 # TANDEM AXLES
VERSUS
13,000 # SINGLE AXLES
Plant - mixed Surfacing
over
Untreated Base
DEFLECTION DUE TO TANDEM AXLE - INCHES
DEFLECTION DUE TO SINGLE AXLE, INCHES
0
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080

FIGURE 8

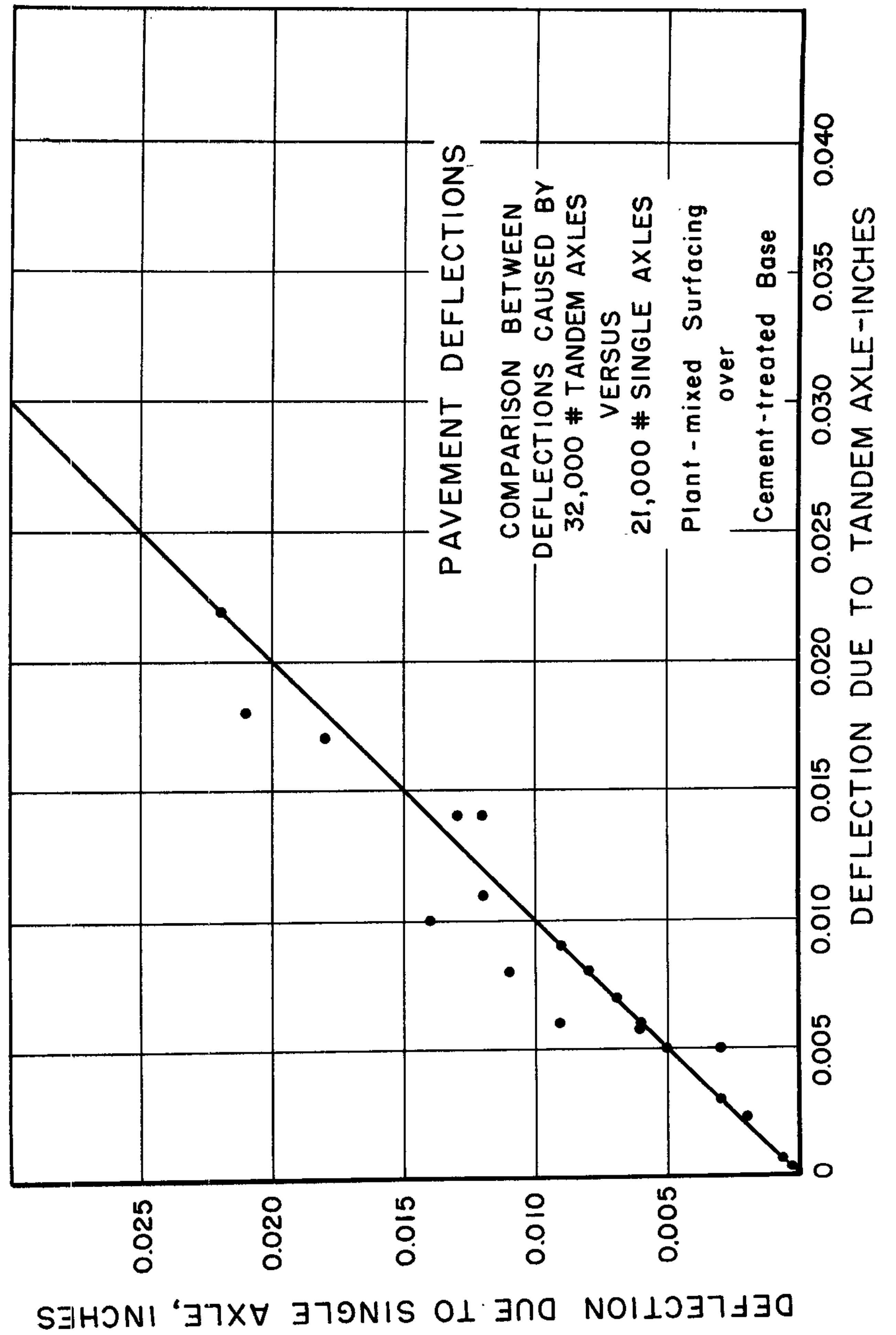
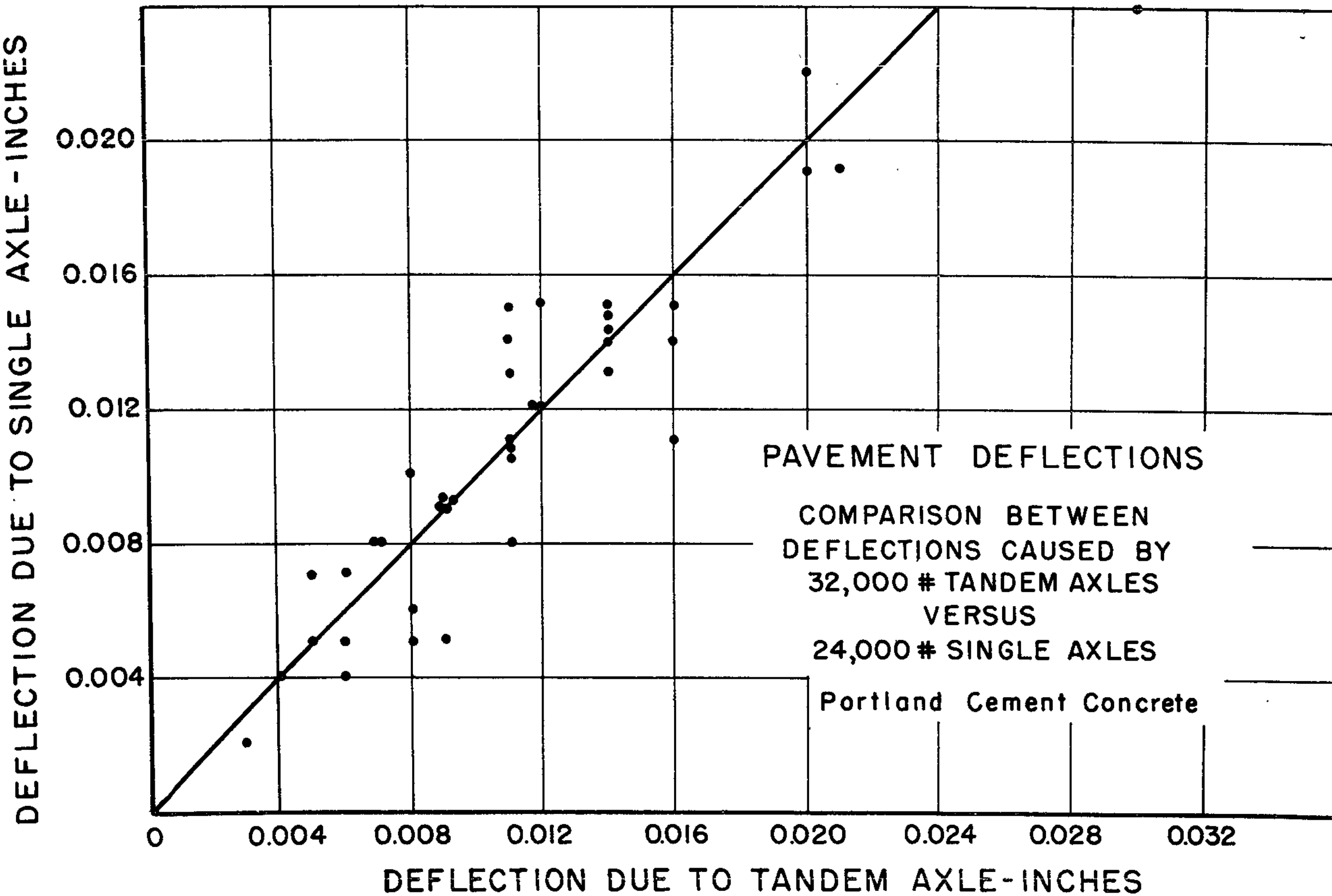
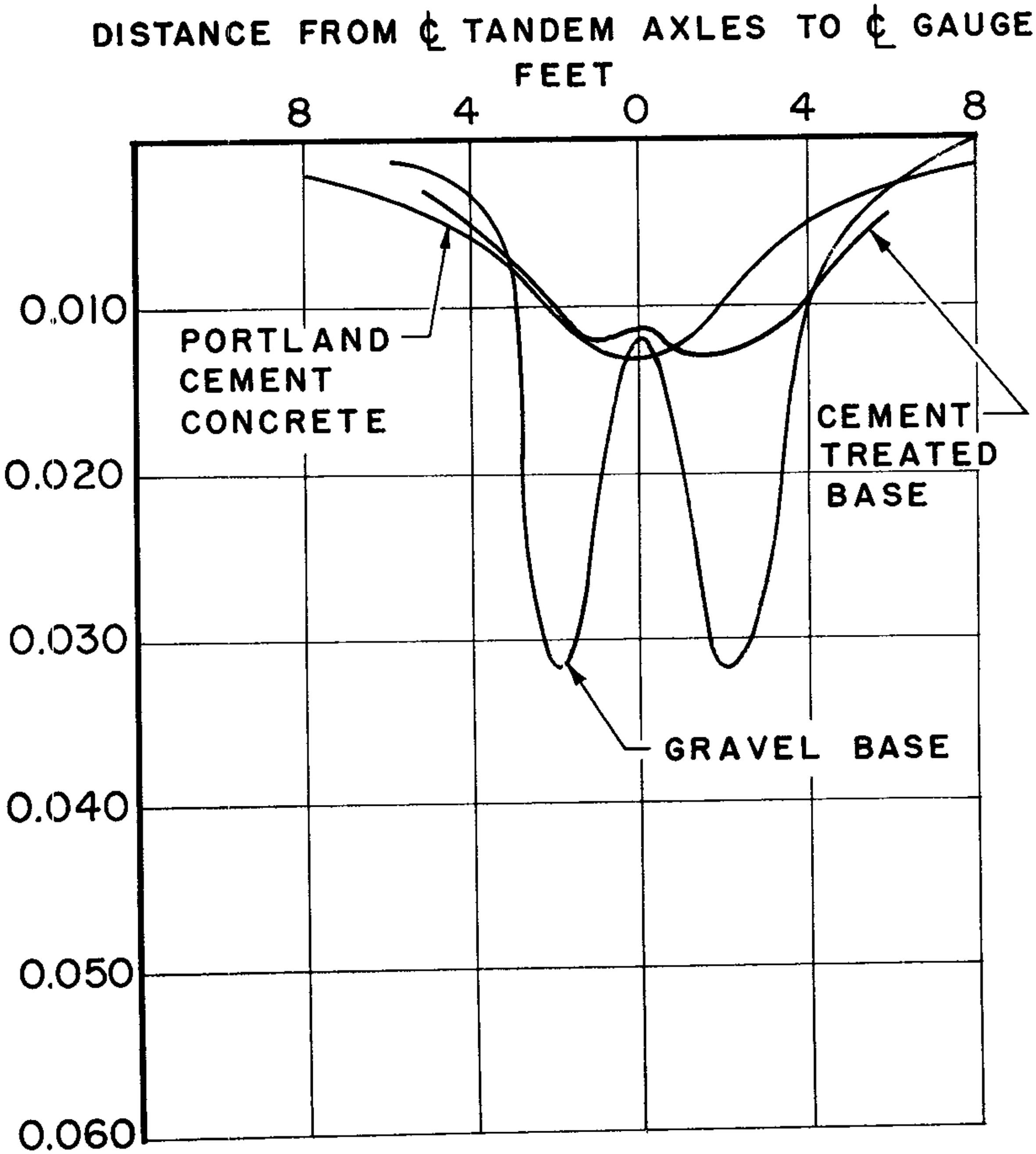

PAVEMENT DEFLECTIONS
COMPARISON BETWEEN
DEFLECTIONS CAUSED BY
32,000 # TANDEM AXLES
VERSUS
21,000 # SINGLE AXLES
Plant - mixed Surfacing
over
Cement - treated Base
DEFLECTION DUE TO TANDEM AXLE - INCHES
0
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
DEFLECTION DUE TO SINGLE AXLE, INCHES
0.005
0.010
0.015
0.020
0.025

FIGURE 9

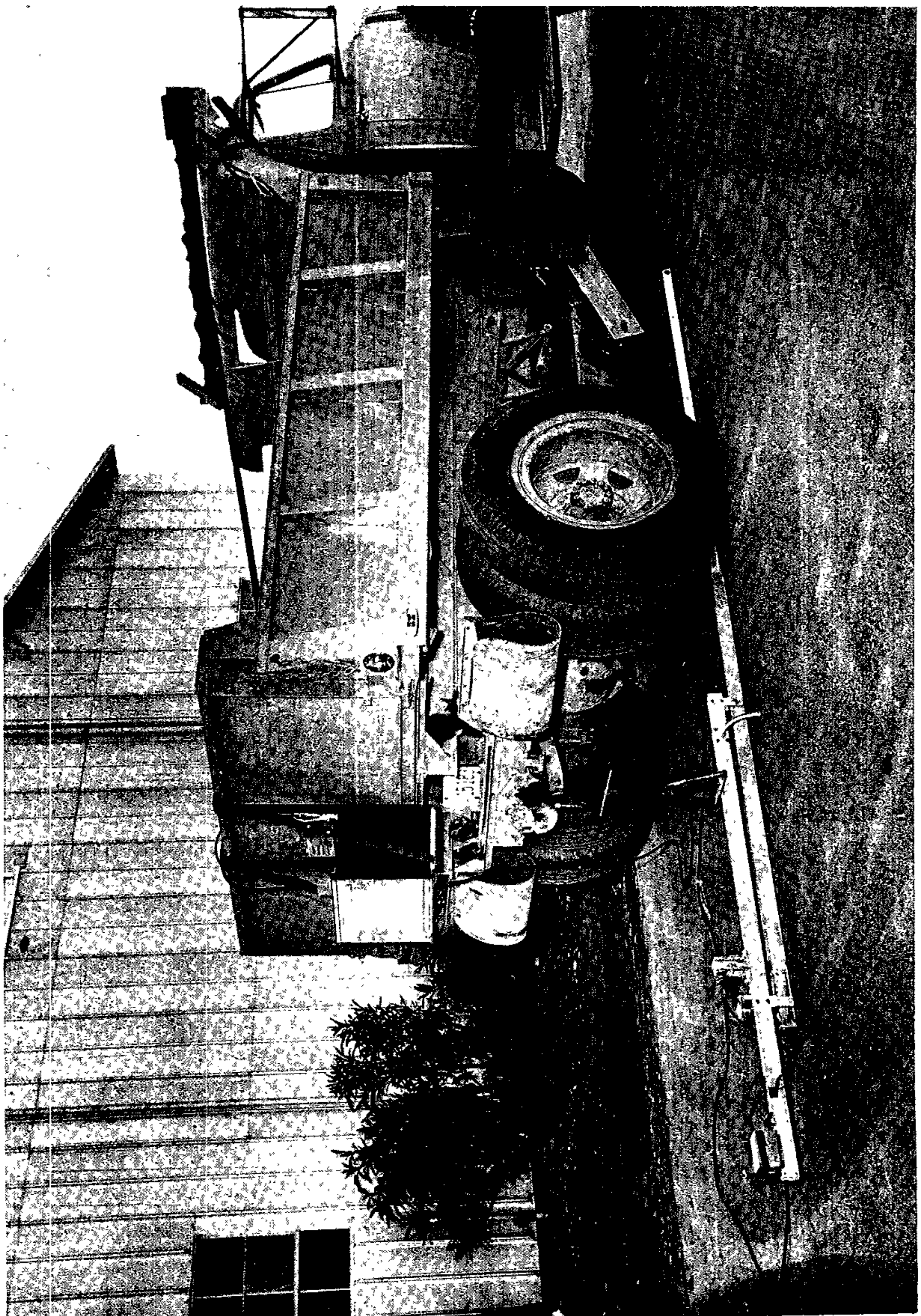


PAVEMENT DEFLECTIONS
COMPARISON BETWEEN
DEFLECTIONS CAUSED BY
32,000 # TANDEM AXLES
VERSUS
24,000 # SINGLE AXLES
Portland Cement Concrete
DEFLECTION DUE TO SINGLE AXLE - INCHES
0.020
0.016
0.012
0.008
0.004
0
0.004
0.008
0.012
0.016
0.020
0.024
0.028
0.032
DEFLECTION DUE TO TANDEM AXLE - INCHES




COMPARISON OF TANDEM AXLE DEFLECTION CURVES ON VARIOUS TYPES OF PAVEMENTS

FIGURE 11

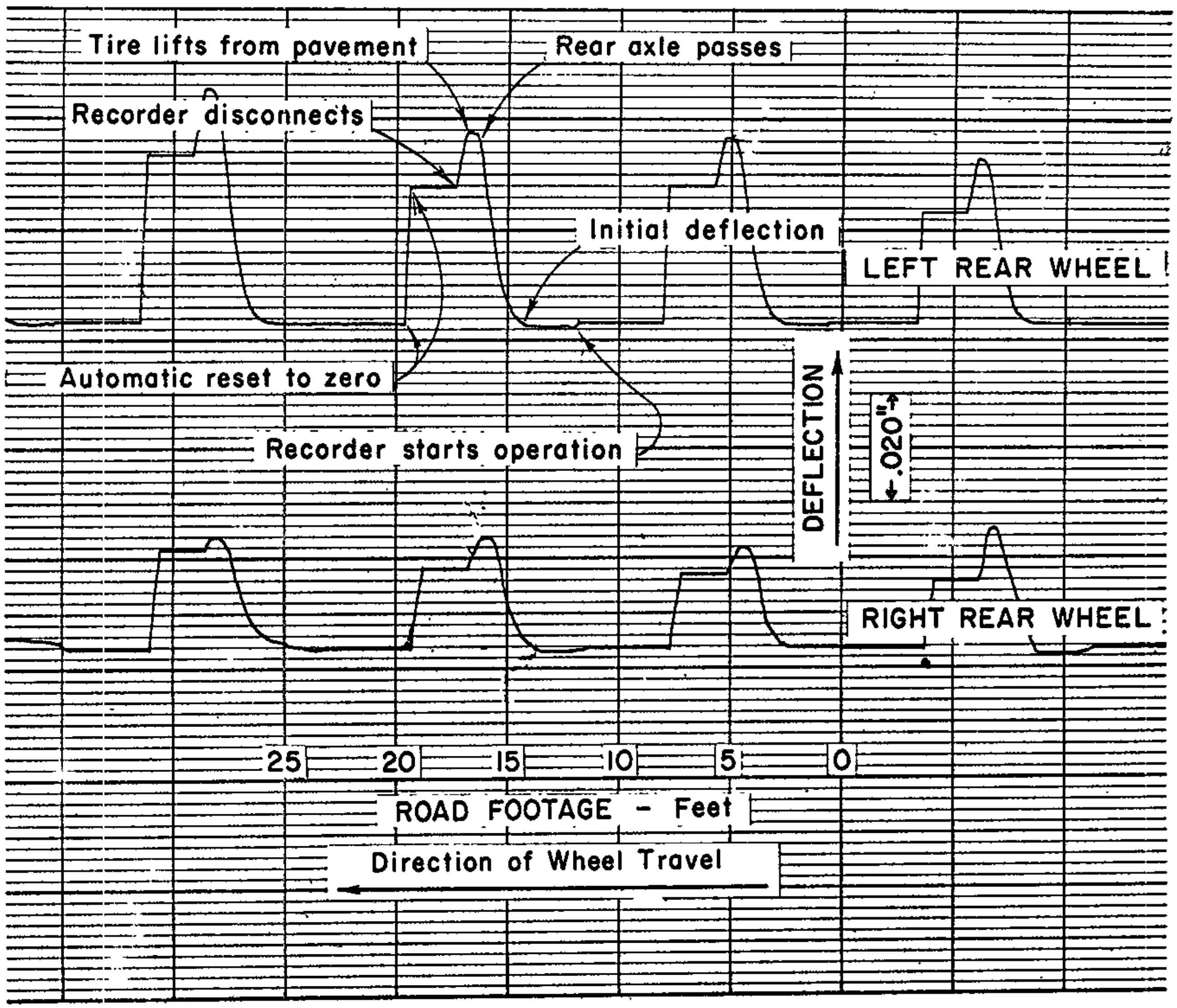


Arrangement for deflection measurements with the Benkelman Beam.

FIGURE 12


Traveling Deflectometer

FIGURE 13




Deflectometer Traces

# DEFLECTIONS - ROAD III - SAC - 232-A
## NORTHBOUND LANE - OUTER WHEEL TRACK

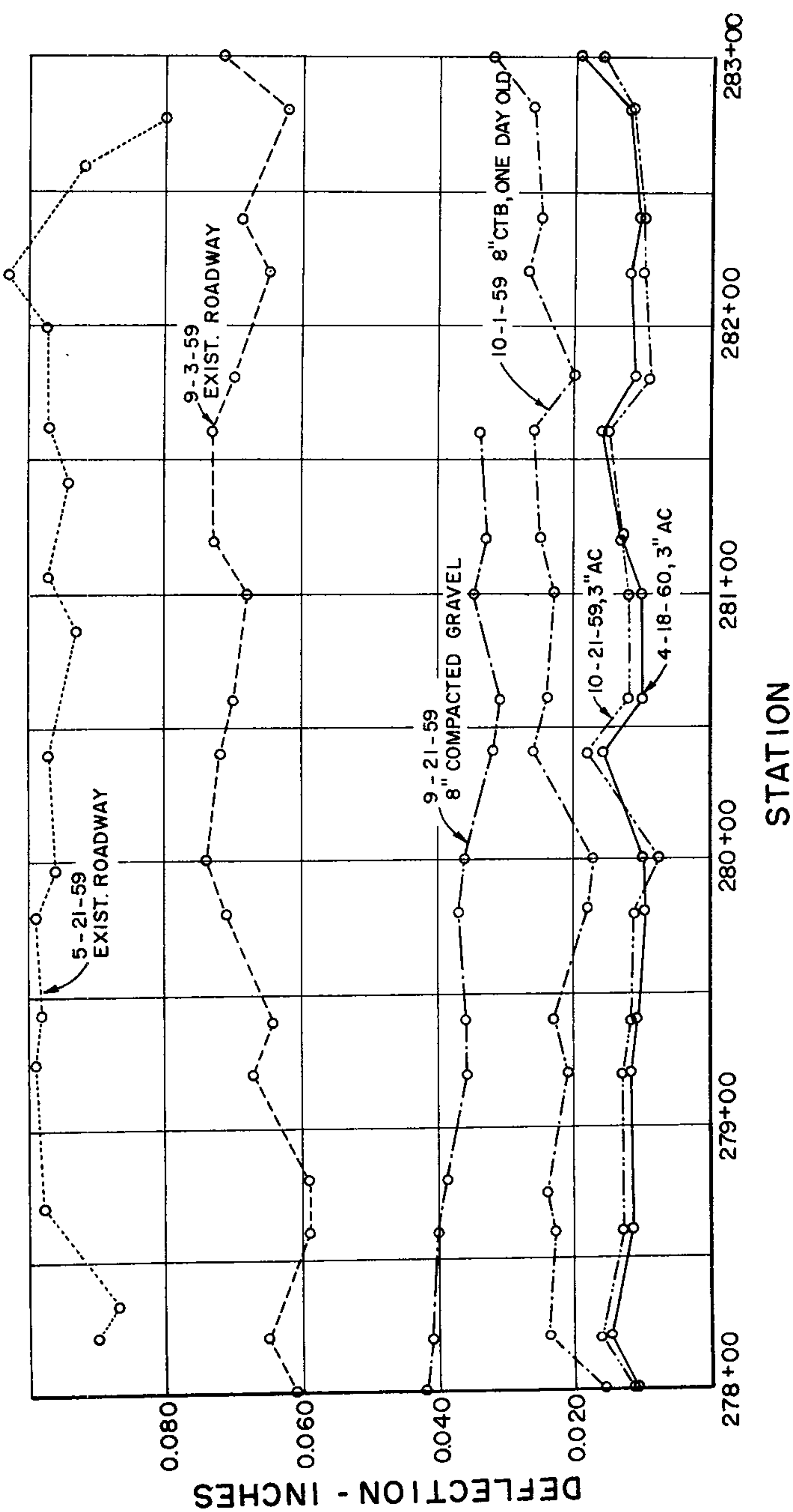
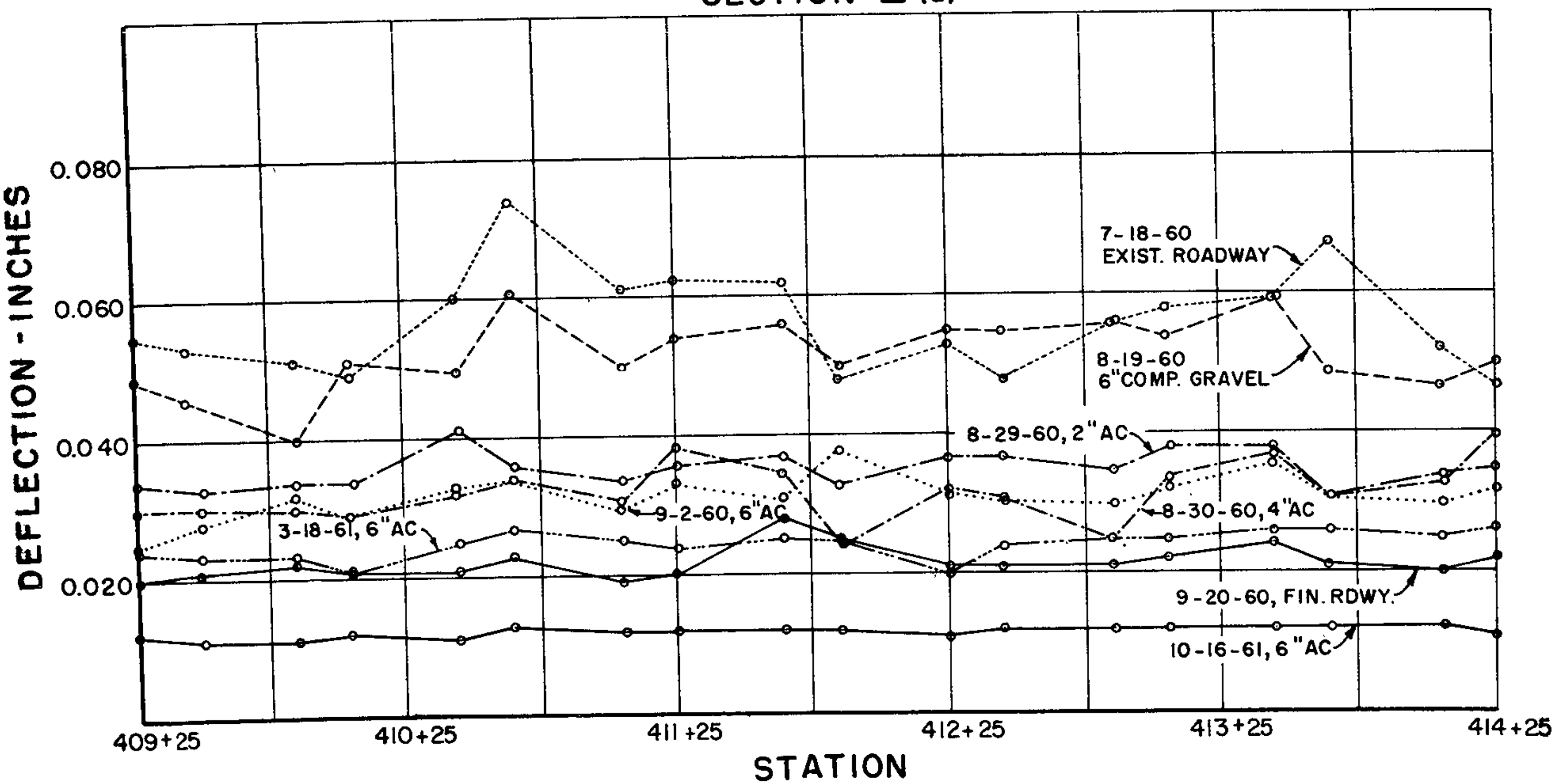
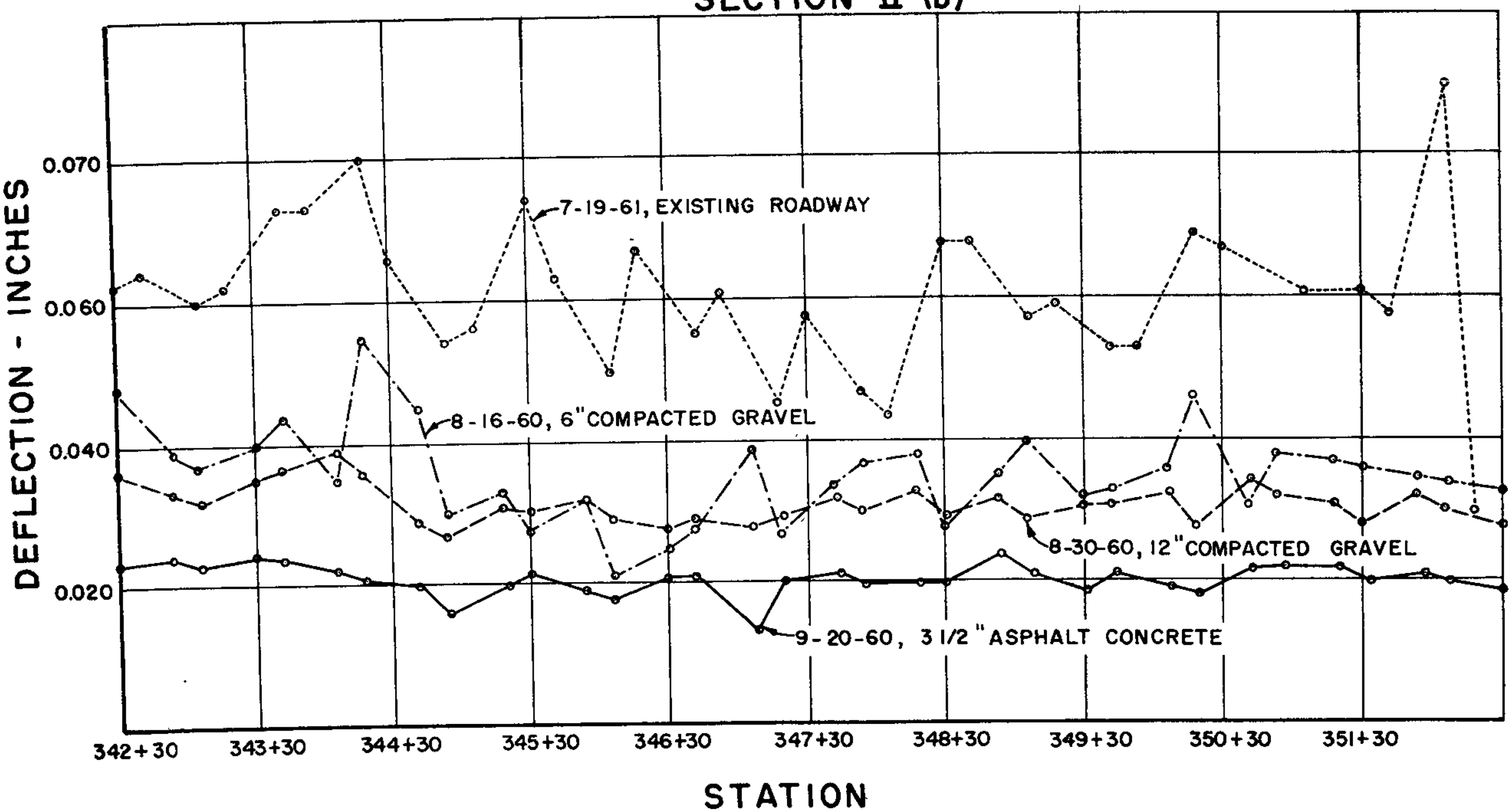


FIGURE 15

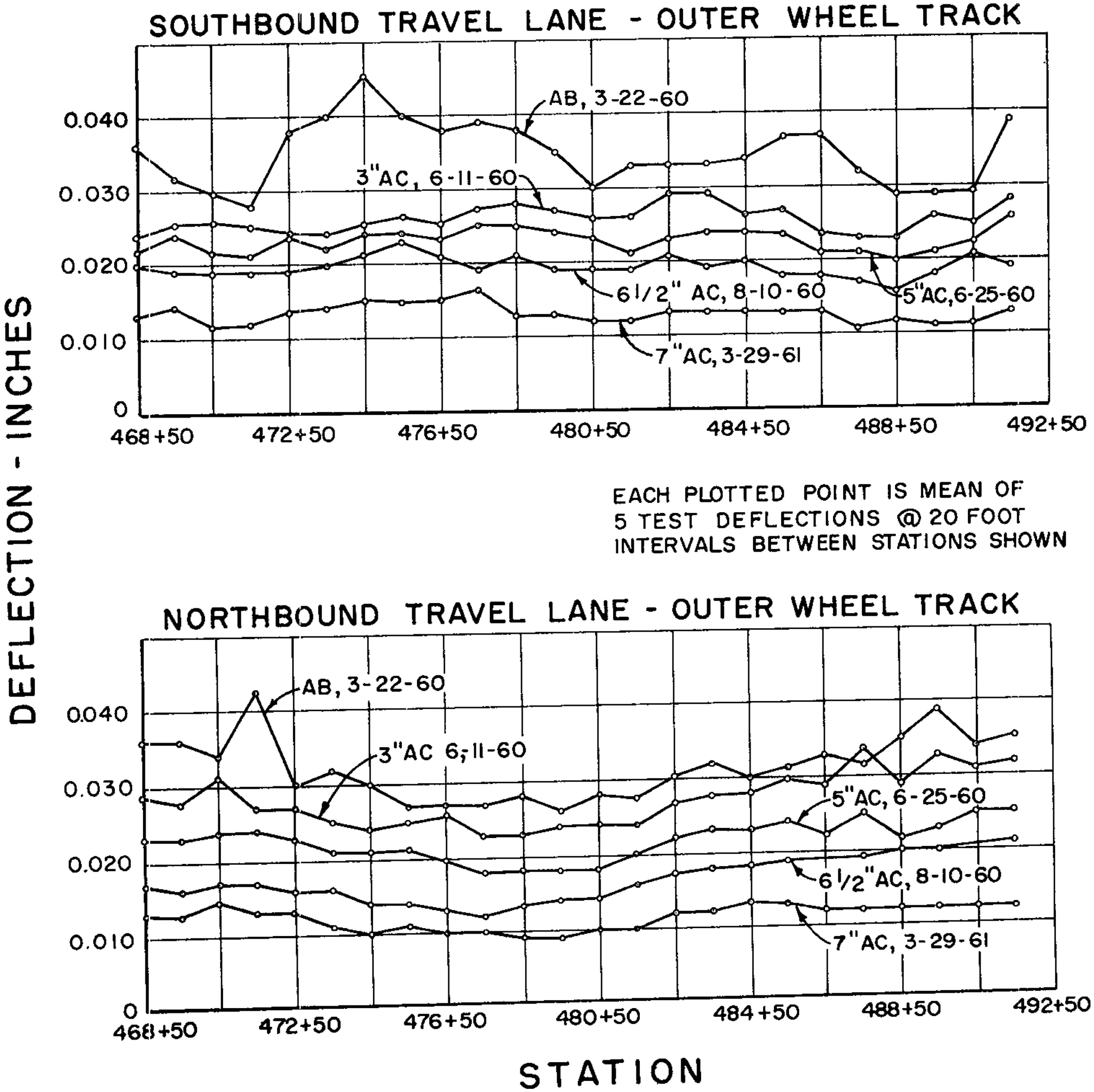
# DEFLECTIONS - ROAD III-SAC-232-A
## SOUTHBOUND LANE - OUTER WHEEL TRACK
### SECTION II (a)



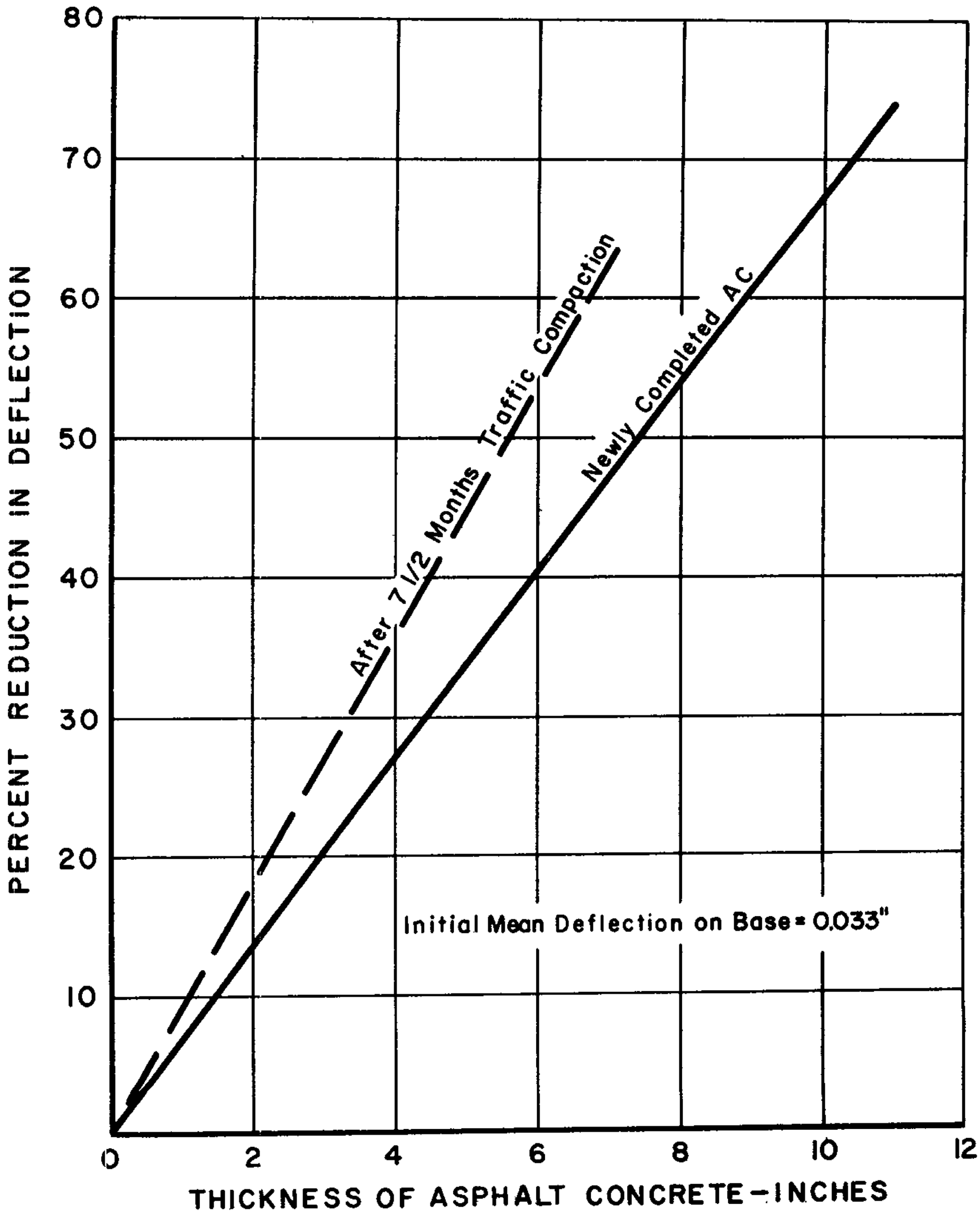
# DEFLECTIONS - ROAD III-SAC-232-A
## SOUTHBOUND LANE - OUTER WHEEL TRACK
### SECTION II (b)



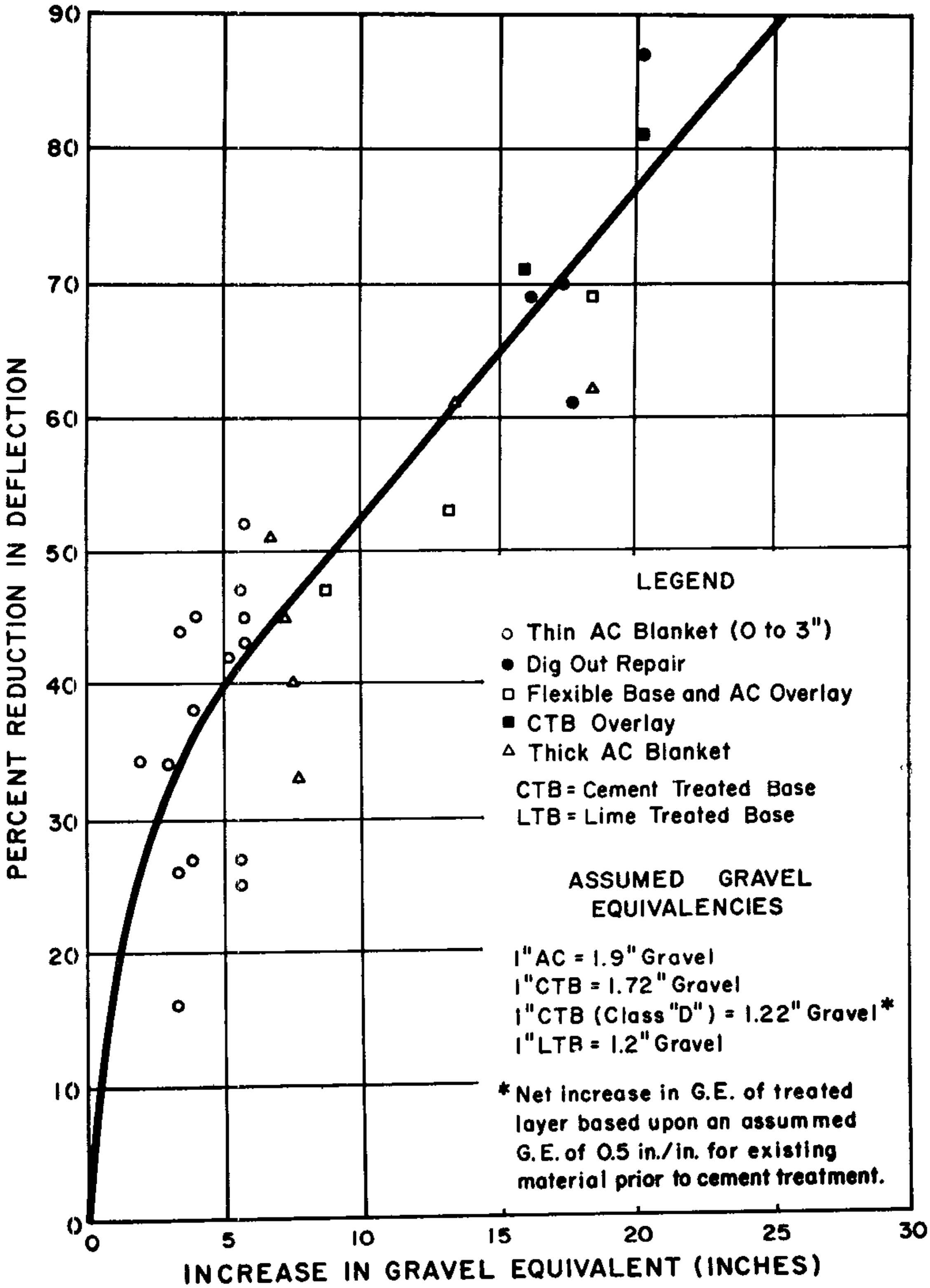
# DEFLECTION STUDY
# V-MON-2-D



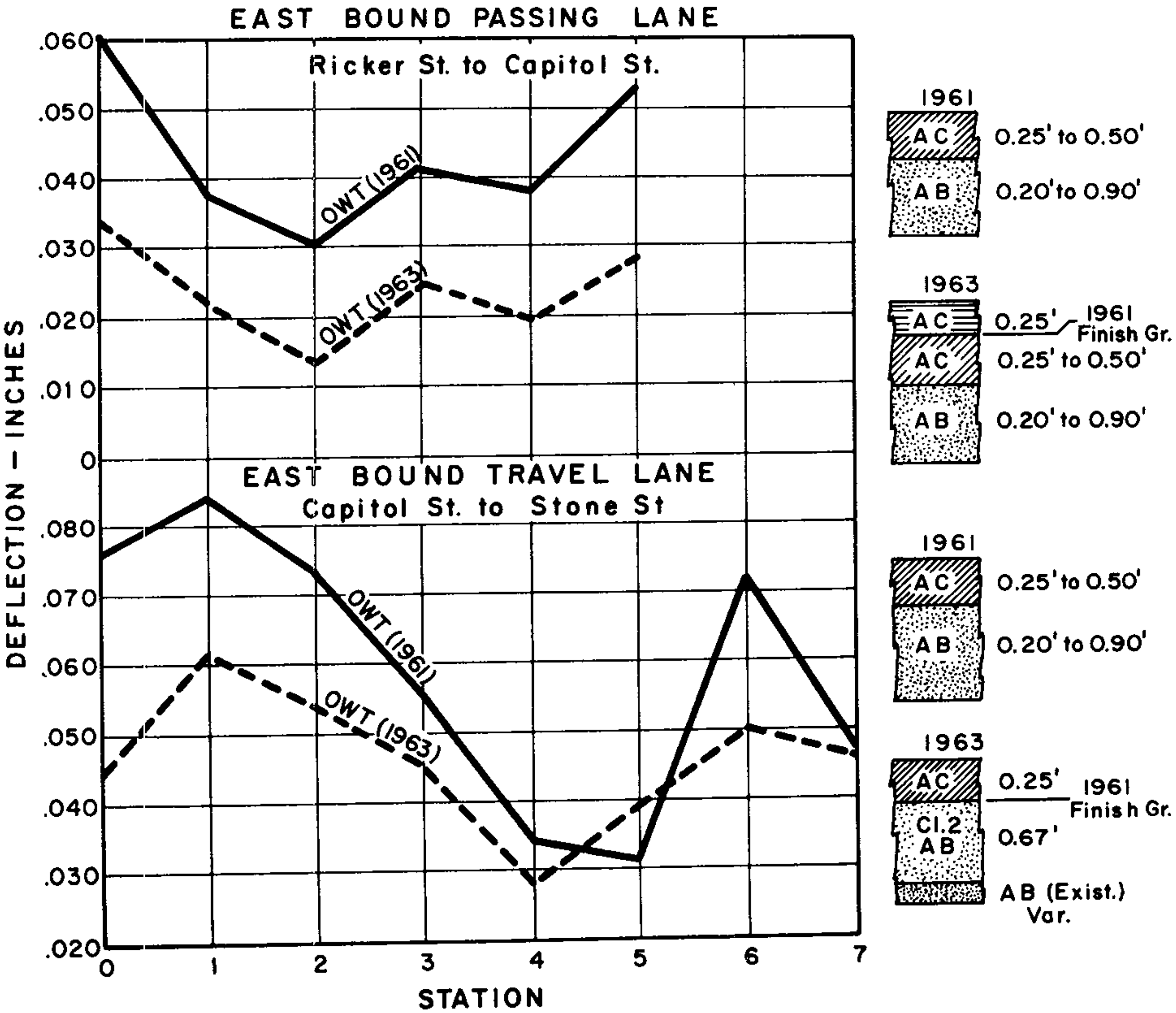
# DAMPING EFFECT OF ADDITIONAL THICKNESS OF ASPHALT CONCRETE ON BASE DEFLECTION V-MON-2-D

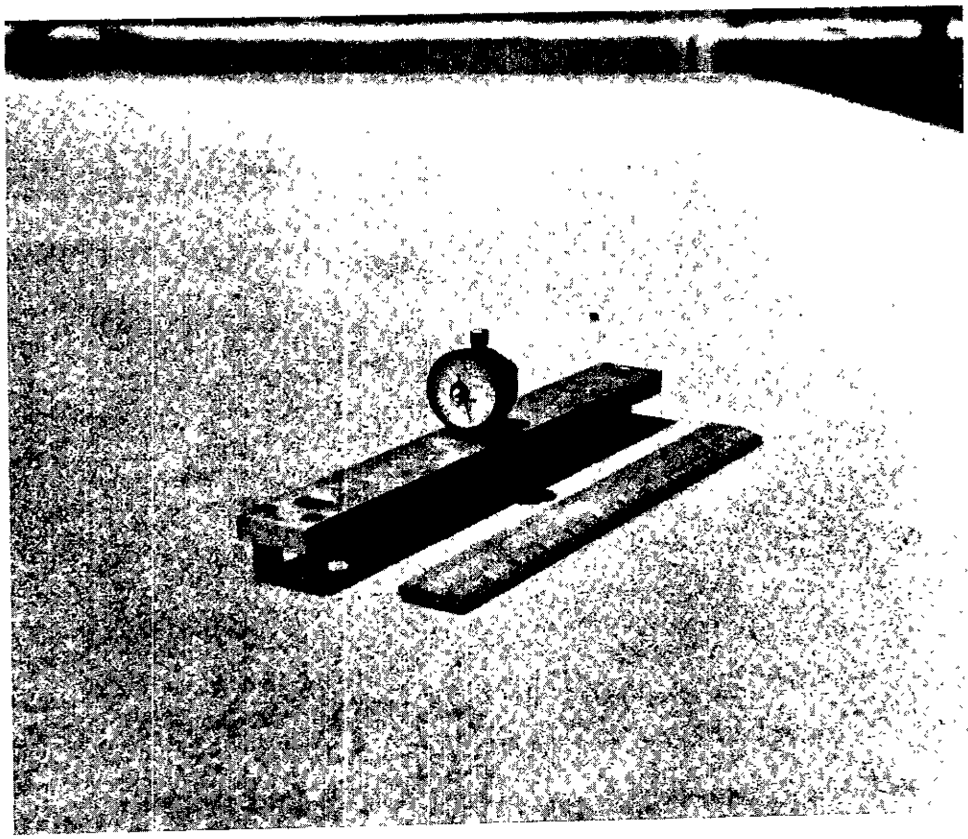


# REDUCTION IN DEFLECTION RESULTING FROM PAVEMENT RECONSTRUCTION

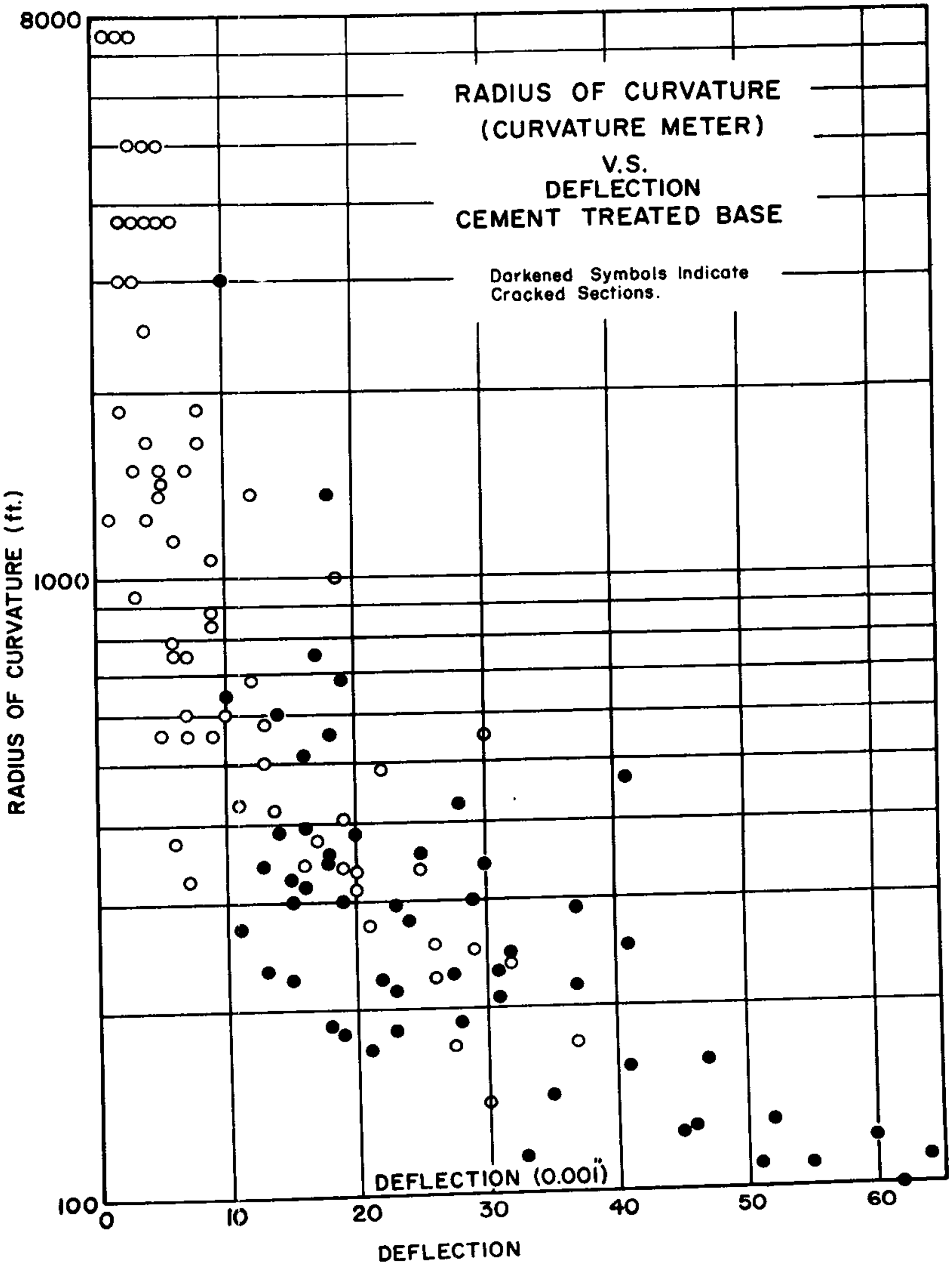


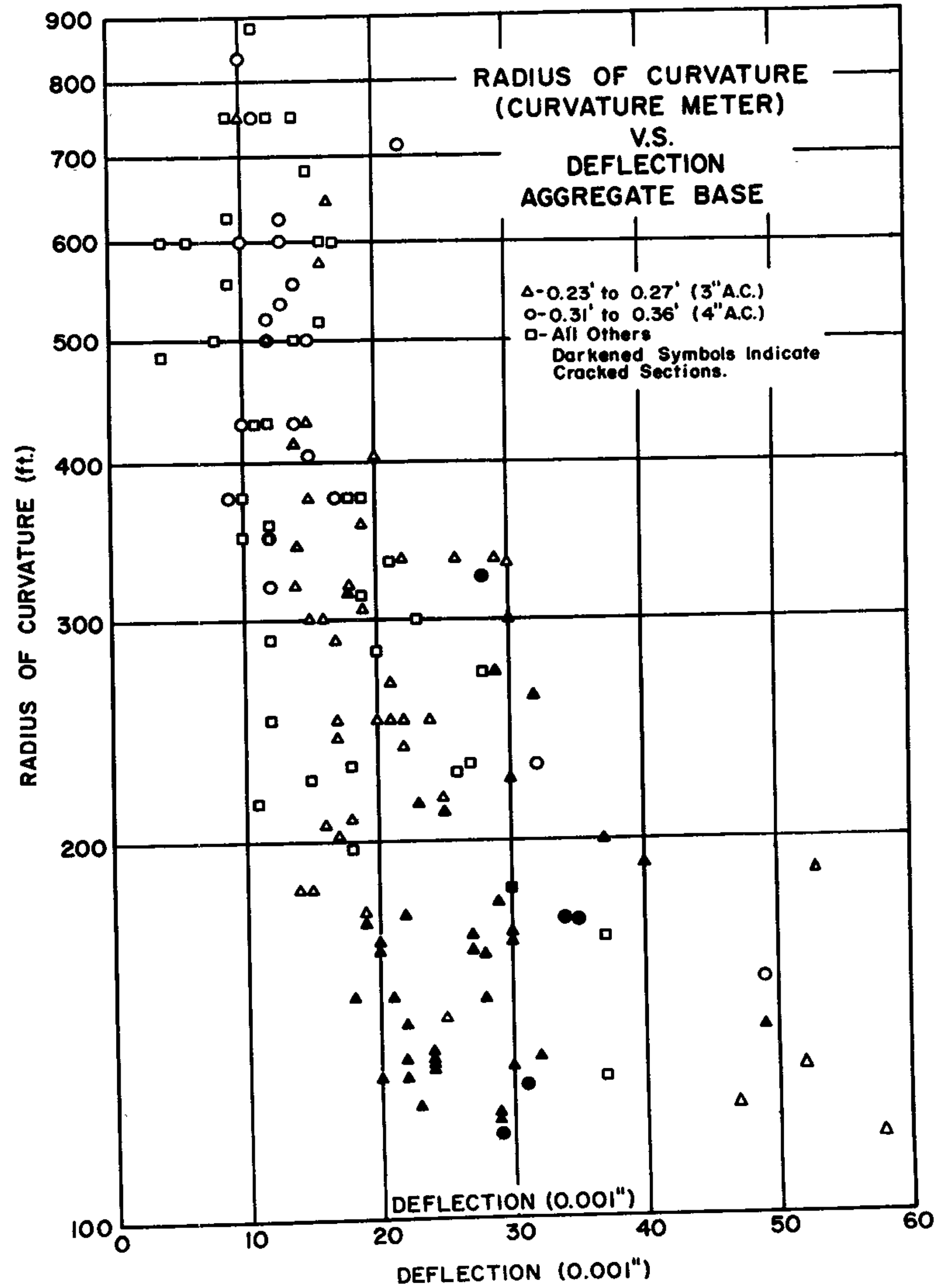
## ROAD V - Mon - 118 - SALINAS

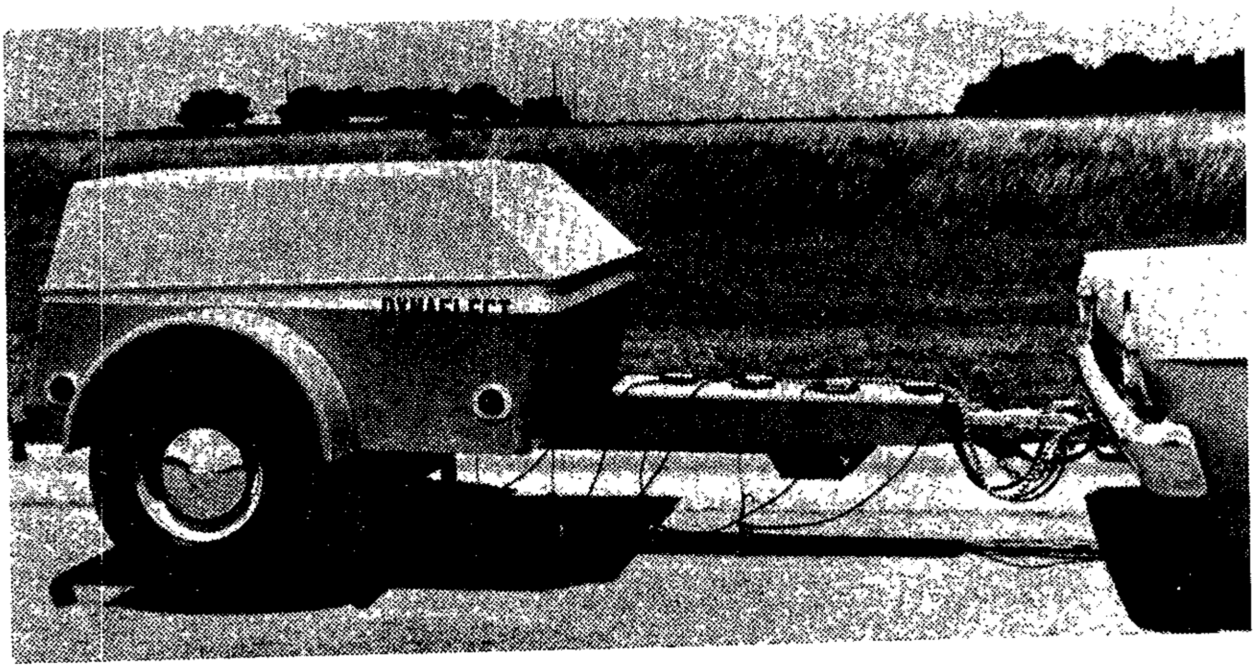




Dehlen "Curvature Meter"


RADIUS OF CURVATURE
(CURVATURE METER)
V.S.
DEFLECTION
CEMENT TREATED BASE
Darkened Symbols Indicate Cracked Sections.
8000
1000
100
RADIUS OF CURVATURE (ft.)
0
10
20
30
40
50
60
DEFLECTION (0.001")
DEFLECTION


RADIUS OF CURVATURE
(CURVATURE METER)
V.S.
DEFLECTION
AGGREGATE BASE
△-0.23' to 0.27' (3"A.C.)
○-0.31' to 0.36' (4"A.C.)
□-All Others
Darkened Symbols Indicate Cracked Sections.
RADIUS OF CURVATURE (ft.)
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
DEFLECTION (0.001")
DEFLECTION (0.001")




Lane-Wells "Dynaflect"