Technical Report Documentation Page

1. REPORT No.
FHWA-CA-TL-3150-77-14

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
Evaluation Of The Cox Deflection Devices

5. REPORT DATE
June 1977

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
Donald V. Roberts, Gary W. Mann and C. Alan Curtis

8. PERFORMING ORGANIZATION REPORT No.
19304-633150

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT No.

11. CONTRACT OR GRANT No.
D-5-50

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Final April 1975 to April 1977

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

An evaluation of two dynamic deflection devices developed by Cox and Sons, Inc., of Colfax, California, is reported. these devices were compared to our presently used deflection devices (Deflectometer and Dynaflect) on roadway structural sections (State Highway and City Streets). Additional testing was performed at the San Jose Municipal Airport to evaluate the equipment on heavily constructed structural sections and obtain deflection correlations with a massive deflection measuring device owned by the U.S. Army Corps of Engineers, the WES device.

17. KEYWORDS
Evaluation, deflection, deflection equipment, correlations, regression analysis

18. No. OF PAGES:
61

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1976-1977/77-14.pdf

20. FILE NAME
77-14.pdf

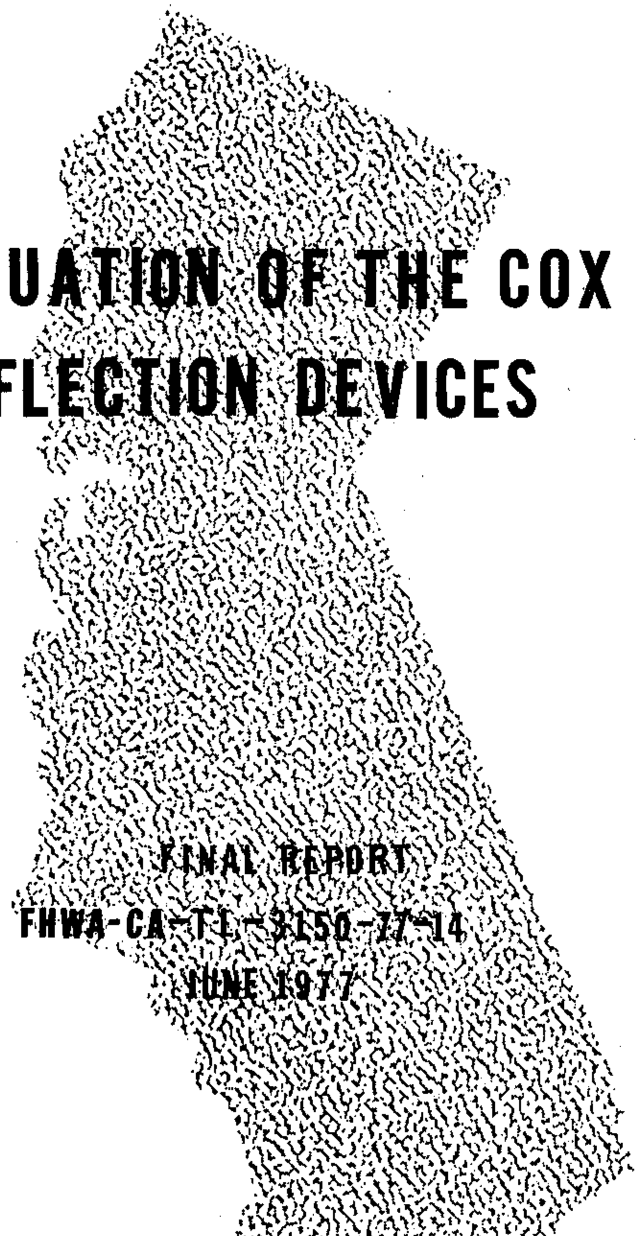
B63

DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

EVALUATION OF THE COX DEFLECTION DEVICES



FINAL REPORT

FHWA-CA-TL-3150-77-14

JUNE 1977

Prepared in Cooperation with the U.S. Department of Transportation,
Federal Highway Administration

Caltrans
CALIFORNIA DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
FHWA-CA-TL-3150-77-14

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
EVALUATION OF THE COX DEFLECTION DEVICES

5. REPORT DATE
June 1977

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Donald V. Roberts, Gary W. Mann and C. Alan Curtis

8. PERFORMING ORGANIZATION REPORT NO.
19304-633150

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
D-5-50

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Final
April 1975 to April 1977

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

An evaluation of two dynamic deflection devices developed by Cox and Sons, Inc., of Colfax, California, is reported. These devices were compared to our presently used deflection devices (Deflectometer and Dynaflect) on roadway structural sections (State Highway and City Streets). Additional testing was performed at the San Jose Municipal Airport to evaluate the equipment on heavily constructed structural sections and obtain deflection correlations with a massive deflection measuring device owned by the U. S. Army Corps of Engineers, the WES device.

17. KEY WORDS
Evaluation, deflection, deflection equipment, correlations, regression analysis.

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. SECURITY CLASSIF. (OF THIS REPORT)
Unclassified

20. SECURITY CLASSIF. (OF THIS PAGE)
Unclassified

21. NO. OF PAGES
61

22. PRICE

DS-TL-1242 (Rev.6/76)

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES AND ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

June 1977

FHWA No. D-5-50
TL No. 633150

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

EVALUATION OF THE COX DEFLECTION DEVICES

Study made by ....Roadbed and Concrete Branch

Under the Supervision of ....Donald L. Spellman
and
John B. Skog

Principal Investigator.................James A. Matthews

Co-Investigators.......................Donald V. Roberts
and
Roy W. Bushey

Report Prepared by.....................Donald V. Roberts,
Gary W. Mann, and
C. Alan Curtis

Very truly yours,

George A Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

GWM:bjs
Attachment

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to personnel from the Transportation Laboratory involved with testing, data collection and data analysis - in particular Roy Bushey and Earl Boerger. We also express appreciation to the engineers and technicians of Contra Costa County and the United States Forest Service at Pleasant Hill, California, for their efforts in this study.

A special thanks is given to the personnel from the City of San Jose and Municipal Airport who arranged for us to perform airport deflection testing and provided us with the airport deflection data obtained with the WES device, owned by the U. S. Army Corps of Engineers, Vicksburg, Mississippi.

The research for this report was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration, under Item No. D-5-50.

TABLE OF CONTENTS

INTRODUCTION

California's pavement deflection research dates back to 1938(1). Since that time a considerable amount of deflection data has been collected. In 1969, an overlay design method was developed for asphalt concrete roadways utilizing pavement deflections(2). Most of the pavement deflections measured over the years have been obtained with a deflection device developed by California called the Deflectometer. This automatic measuring device based on the Benkelman beam principle is California's current deflection standard. Other deflection measuring devices such as the Dynaflect and Road Rater have been correlated with the Deflectometer. This has allowed highway consultants and public agencies throughout the State to perform tests with these devices and draw upon California's experience with pavement deflections(1-8).

The main purpose of this research effort was to evaluate two dynamic deflection devices developed by James Cox and Sons, Inc. of Colfax, California, for Contra Costa County and the United States Forest Service; and obtain deflection correlations with the Cox devices and California's presently used deflection measuring devices (Deflectometer and Dynaflect). The Deflectometer and Dynaflect are both approximately 9 years old and will need replacement soon. Also, with the increased emphasis on pavement rehabilitation and the development of a "Pavement Management System" (Federally Funded Research Project F-1-6), greater use of pavement deflections may be utilized in the future. If so, additional or improved equipment will probably be needed to supplement California's currently used deflection devices.

The Benkelman beam and Deflectometer basically measure static or nearly static deflections. Deflections measured with these devices represent the net effect of the total pavement structural section.

Until the development of the Cox deflection devices the only other dynamic deflection measuring devices available were the Dynaflect and Road Rater.

It should be noted that the Cox deflection devices are similar in operation to the Road Rater in that they apply a preload as well as a superimposed vibratory load to pavement surfaces. The vibratory load and frequency (number of cycles per second) of the Cox deflection devices can both be varied, if desired, whereas the Dynaflect operates at a fixed vibratory load and fixed frequency.

An additional opportunity for comparative study presented itself when the U.S. Army Corps of Engineers brought their "WES" device to the San Jose Airport to conduct deflection tests. This is a device similar in operation to the Cox devices and Road Rater, but with much larger preload and vibratory load capabilities. Thus, the WES device was also included in this study.

CONCLUSIONS

1. Light deflection measuring devices, such as the Dynaflect and Cox devices, are adequate for measuring pavement deflections on thick structural sections as well as thin structural sections.

2. The best deflection correlation achieved on this study were between (a) the Dynaflect and the Deflectometer and (b) the Contra Costa County (Cox) device and the Dynaflect.

3. The correlation between the Dynaflect and Deflectometer did not change appreciably for thick or thin structural sections. The correlations between (a) the Contra Costa County (Cox) device and the Deflectometer and (b) the United States Forest Service (Cox) device and the Deflectometer changed significantly for different structural sections.

4. For all airport pavements tested with the WES device, maximum pavement deflections, regardless of the vibratory load, occurred between 8 and 10 cycles per second.

5. The method of operation and performance of the Contra Costa County and United States Forest Service (Cox) devices were satisfactory for use as routine testing devices or research equipment.

6. The Contra Costa County and United States Forest Service (Cox) devices should carry calibration equipment within the test vehicles so that calibration checks could be made at test sites prior to each day's work.

IMPLEMENTATION

From the results of this study the Cox deflection devices have shown merit both as a routine testing device and a research tool. They should be considered along with the other dynamic testing devices for future acquisition by Caltrans.

DESCRIPTION OF EQUIPMENT

The deflection measuring devices evaluated in this study were California's Deflectometer, Dynaflect and Benkelman beam; the United States Army Corps of Engineers device (WES device); the Contra Costa County device (built by Cox and Sons, Inc.) and the United States Forest Service device (also built by Cox and Sons, Inc.). A short description of each deflection measuring device follows:

1. California Deflectometer. This instrument (Figure 1) is an automatic deflection measuring device based upon the Benkelman beam principle. It combines a tractor-trailer unit which carries an 18,000 pound (8,200 kg) single axle test load on the rear tires [11.00 x 22.5, 12-ply and 70 psi (483 kN/m^2) pressure] and probes for measuring pavement deflection under both wheels simultaneously. The Deflectometer is an electro-mechanical instrument capable of measuring pavement deflections at approximately 20 foot (6.1 m) intervals uniformly and continuously as the vehicle moves steadily along the roadway at about one half mile (0.8 km) per hour. The deflections are measured to the nearest 0.001 inch (0.025 mm) by means of probe arms resting on the pavement surface between each set of dual tires. Inner and outer wheel track deflections are permanently recorded on chart paper within the cab of the trailer unit.

Two people are required to operate the Deflectometer - one person to drive the tractor-trailer unit and the other to operate the test equipment located in the cab of the trailer unit. A five-minute calibration check is performed on the Deflectometer at the job site prior to each day's work.

The Deflectometer's mode of operation is such that once testing commences, measurements are continuously taken at approximately 20 foot (6.1 m) intervals. The Deflectometer does not have the ability to test at locations of predetermined points. All the other devices used in this study were capable of being set-up and measuring deflections over selected test points. The Deflectometer is capable of measuring about 800 to 1000 pavement deflections at approximately 20 foot (6.1 m) intervals under each wheel path per average work day.

The testing parameters of this device are fixed. Namely, the axle load is 18,000 pounds (8,200 kg), the tire size, pressure and spacing between the duals are fixed and, due to the constant creep speed of the vehicle during operation, the rate of loading is nearly static.

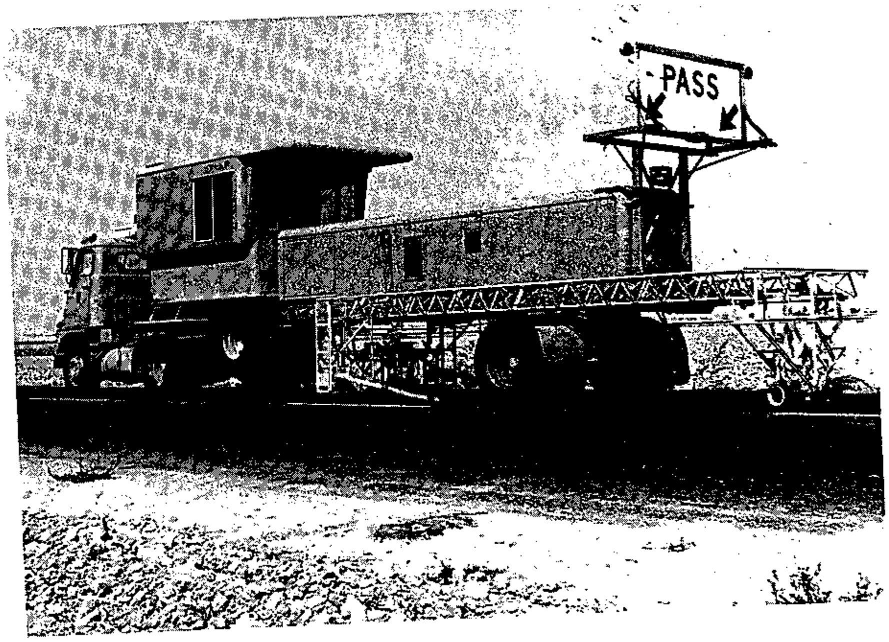


Figure 1 - California Deflectometer

2. Dynaflect. This device (Figure 2) is an electromechanical system for measuring dynamic deflections of a roadway surface. This device consists of a dynamic force generator together with a motion measuring instrument, a calibration unit and a series of five motion-sensing geophones mounted on a 1600 pound (730 kg) trailer unit. The stationary unit applies a 1100 to 2100 pound (500 to 950 kg) oscillatory load to the pavement surface through two rubber covered steel test wheels which are lowered for testing. The resulting amplitude of deflection is picked up by the geophones and converted to a deflection measurement on a meter located in the tow vehicle.

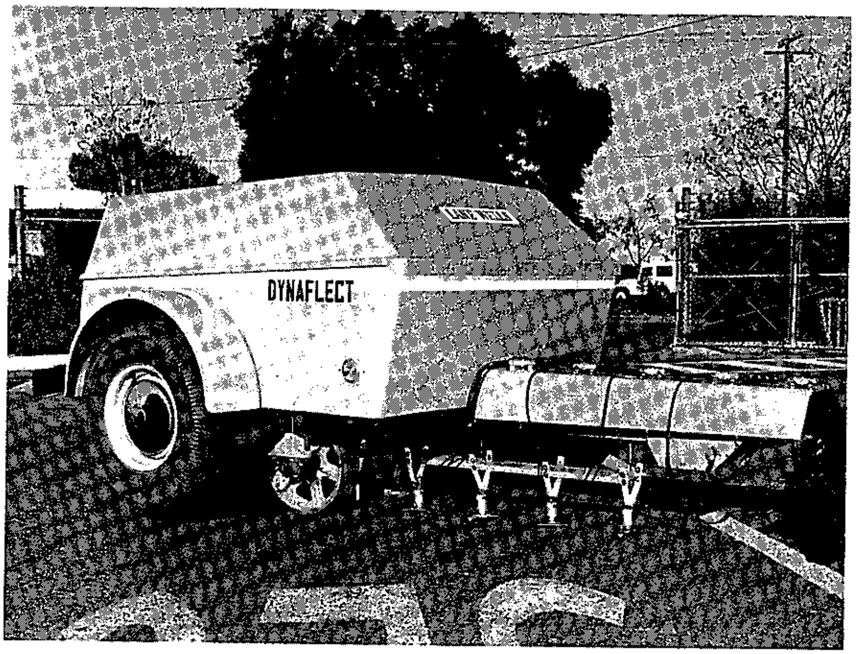


Figure 2 - Dynaflect

The Dynaflect can be operated by one person. Prior to each day's work, the unit is calibrated at the test site. This requires approximately five minutes. The Dynaflect can be used to measure maximum deflections or deflection basins of pavement surfaces. Maximum pavement deflections are determined by using the sensor located directly between the test wheels and deflection basins are determined by using all five sensors spaced outwardly at one foot (0.3 m) intervals. These pavement deflections must now be recorded manually. When using one sensor, the time required to read and record a single deflection measurement is about 15 to 20 seconds; when using all five sensors the time needed is 30 to 40 seconds per test. The Dynaflect must be in a stopped position to make deflection measurements but can safely travel up to five miles (8 km) per hour between test points on the test wheels.

The testing parameters of this device are fixed. The dynamic load, 1100 to 2100 pounds (500 to 950 kg), generated by rotating weights is applied to pavement surfaces at a constant frequency of 8 cycles per second.

3. Benkelman Beam. This instrument (Figure 3) operates on a simple lever arm principle. The 8-foot-long (2.4 m) probe is inserted between the dual tires [11.00 x 22.5, 12-ply and 70 psi (483 kN/m^2) pressure] of a test vehicle which carries an 18,000 pound (8,200 kg) single axle load. As the pavement is depressed, the beam pivots around a point of rotation on the reference beam which rests on the pavement outside the area of influence, so that the back four-foot (1.2-m) extension of the beam depresses an Ames dial which registers the deflections to within 0.001 inch (0.025 mm).

Two people are needed to obtain pavement deflections using this device - one to drive the test vehicle and the other to measure and record Benkelman beam deflections. A five minute calibration check can be made prior to each day's testing. This device is used only to measure maximum pavement deflections. Various test methods have been written using this device(2,5); however, the

WASHTO test procedure was utilized on this study, and the test vehicle had an 18,000 pound (8,200 kg) rear axle load. Approximately 300 to 400 individual deflection measurements can be made in an average work day with this device.

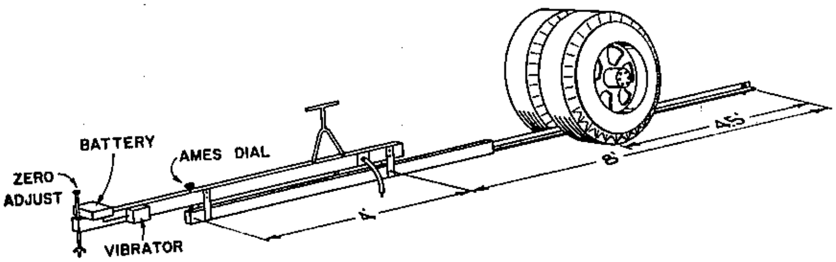


Figure 3 - Benkelman Beam

4. <u>United States Army Corps of Engineers device (WES device)</u>. The WES device (Figure 4) is a electrohydraulic system mounted in a 36 foot (11 m) long van unit, and is primarily used to determine pavement responses of thick structural sections. This device is generally used as a research tool with principal application in airport design. The WES device applies a 16,000 pound (7,300 kg) preload to pavement surfaces plus a vibratory load which can be varied from 0 to 15,000 pounds (0 to 6,800 kg). Vibratory loads can be applied at any frequency from 5 to 72 cycles per second. Loads are applied to pavement surfaces through an 18-inch (0.46 m) diameter steel plate.

Two people are required to operate the WES device, one to drive the tractor unit and the other to operate the test equipment within the van. This equipment can be used to measure maximum deflections or define deflection basins. With the WES device, it takes about 3 minutes to perform a load sweep (a series of vibratory loads of different magnitudes). An additional minute is required to determine a deflection basin. A frequency sweep can be made in about 12 minutes. The WES device is equipped with an automatic deflection printout and plotter. It also has a portable calibration unit to check calibration prior to each day's work. The calibration check takes approximately 20 to 30 minutes to perform.

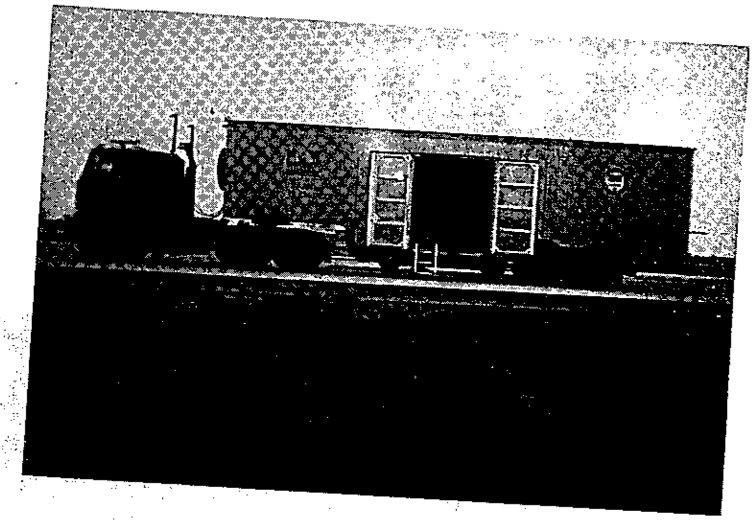


Figure 4 - Wes Device

5. Contra Costa County device/United States Forest Service device. These devices (Figures 5 and 6) are electrohydraulic systems that measure dynamic deflections of roadway surfaces. In operation, these devices can exert a 500 to 2,000 pound (230 to 900 kg) preload to the pavement surface followed by a variable dynamic load from 0 to

1200 pounds (0 to 540 kg). The effective frequency range for these devices is 25 to 50 cycles per second.

The Contra Costa County device and United States Forest Service device were both built by the same manufacturer, Cox and Sons, Inc., of Colfax, California. They are identical in design, method of operation and capabilities. Slight variations in the deflection devices are only due to differences in the van units used to mount the deflection equipment.

Only one person is needed to operate each device. During operation, loads are applied to the pavement surface through a 9-inch (23 cm) diameter steel plate. Only maximum deflections are measured with these devices. Deflections can be recorded manually or on punched paper tape. Generally pavement deflections can be measured in about 45 seconds for a designated preload, vibratory load and frequency. An additional 10 seconds in operating time is required to measure deflections at additional frequencies. Calibration units for these devices are available from the manufacturer. Presently calibration checks and adjustments are made by the manufacturer.

Figure 5 - Contra Costa County Device

Figure 6 - United States Forest Service Device

TESTING PROGRAM

Roadway Testing

The first phase of our testing program consisted of measuring pavement deflections with the California Deflectometer, Dynaflect, Contra Costa County device and the United States Forest Service device on various roadway structural sections in the San Jose area. A full range of pavement deflections was obtained to correlate the various deflection measuring devices. The test sections chosen were as follows:

High Deflections - Residential subdivision roads were selected for this category. On the roadways tested Deflectometer deflections averaged 0.038 inch (1.0 mm) and ranged from 0.009 to 0.092 inch (0.2 to 2.3 mm). All roadways investigated appeared to be in good condition with very few visible surface cracks. The structural section for most of these test sections consisted of 0.15 foot (4.6 cm) AC* over 0.45 foot (13.7 cm) AB*.

Medium and Low Deflections - The various devices were used to measure pavement deflections on portions of Route 4 in Contra Costa County (P.M. 6.6 to P.M. 7.4) and Interstate 680 in Alameda County (P.M. 18.9 to P.M. 19.3). Deflectometer deflections ranged from 0.001 to 0.036 inch (0.03 to 0.90 mm) on the two roadways tested. Test sections were selected to include both good and poor roadway conditions by visual observation. On the Route 4 project, the structural section of the roadway consisted of 0.58 foot (17.7 cm) AC, 0.67 foot (20.4 cm) AB, and 1.50 foot (0.46 m) AS*. The structural section of the tested portion on Interstate 680 was 0.50 foot (15.2 cm) AC, 0.67 foot (20.4 cm) CTB* and 1.00 foot (0.3 m) AS.

*AC - Asphaltic Concrete
AB - Aggregate Base
AS - Aggregate Subbase
CTB - Cement Treated Base

Deflection measurements were also obtained on a thick AC section on Concord Boulevard in Concord, California, between East Street and 5th Street. Deflection values obtained with the Deflectometer averaged 0.002 inch (0.05 mm) and ranged from 0 to 0.028 inch (0 to 0.7 mm). The structural section of Concord Boulevard consisted of 2 inches (5 cm) of asphalt concrete and 2 to 4 inches (5 to 10 cm) of asphalt concrete base.

The Deflectometer was selected as the first device to make deflection measurements for this study due to its lack of maneuverability and fixed pattern of taking deflection measurements.

The individual test locations of the Deflectometer were painted on the pavement surfaces and deflection measurements were then taken with each of the devices at these locations. The deflection measuring devices were lined up in a train-like fashion and measurements were taken in sequence. All deflection measurements at each test location were taken within a time span of a few minutes. A total of over 500 individual test points at 18 test sections were measured in this manner.

For the roadway testing, the Contra Costa County and the United States Forest Service devices applied a preload of 2000 pounds (910 kg) plus a vibratory load of 750 pounds (340 kg) at 33 cycles per second. Thus the pavement load varied from 1250 pounds to 2750 pounds (570 to 1200 kg). The operation of the Deflectometer and Dynaflect was as described in the description of equipment.

Airport Testing

Work planned by the City of San Jose at their municipal airport made it possible to compare deflections measured with the United States Army Corps of Engineers device (WES device) with that of the Benkelman beam, Dynaflect, Contra Costa County device and the

United States Forest Service device. To our knowledge, this was the first time the WES device was available for comparative deflection studies within the State of California. Questions have been raised as to the validity of the deflection values obtained on heavily constructed structural sections with relatively light dynamic testing devices such as the Dynaflect and Cox devices. One of the main objectives of the airport testing was to investigate this concept. Because of mechanical breakdown, the California Deflectometer was not available for the airport testing.

Due to airport traffic scheduling, the WES device could only be used during the early morning hours (midnight to 6:00 a.m.). From September 9 through September 24, 1975, deflection measurements were obtained at approximately 160 locations on various airport pavements using the WES device.

On October 1, 1975, from midnight to 6:00 a.m., the Benkelman beam, Dynaflect, Contra Costa County device and United States Forest Service device were used to measure deflections at 30 test locations on the airport pavements in a train-like manner as described earlier. Of the 30 locations tested, only 20 coincided with locations tested with the WES device.

The test parameters for the dynamic devices used in this phase of the study are shown in Table 1.

The structural sections of the airport pavements that were tested varied considerably. Asphalt concrete thicknesses ranged from 2 to 16 inches (5 to 41 cm) and base material ranged from 4 to 47 inches (10 to 120 cm). Therefore, no attempt will be made to describe the entire structural section at each test site.

Table 1

Test Parameters (Dynamic Test Equipment)
San Jose Municipal Airport

Test Equipment	Frequency (Cycles/Sec.)	Preload (Pounds)	Vibratory Load (Pounds)	Load Range (Pounds)
WES Device	Varied from 5 to 72	16,000	± 2000 ± 4000 ± 5000 ± 6000	14,000 to 18,000 12,000 to 20,000 11,000 to 21,000 10,000 to 22,000
Contra Costa County Device	33 45 60	2,000 2,000 2,000	± 750 ± 750 ± 750	2,700 to 1,250 2,750 to 1,250 2,750 to 1,250
United States Forest Service Device	33 45 60	1,800 1,800 1,800	± 600 ± 600 ± 600	2,400 to 1,200 2,400 to 1,200 2,400 to 1,200
Dynaflect	8	1,600	± 500	2,100 to 1,100

Note: 1 pound = 0.45 kg

In addition to the nondestructive deflection testing that was performed at the airport, plate bearing tests were also made at five locations by personnel from the City of San Jose. Three of the tests were on asphalt concrete pavements, one test was on PCC pavement and one test was on ground not covered with pavement. These tests were performed in accordance with ASTM Method D1195 with the following modifications:

1. The plate was 24 inches (0.6 m) in diameter.

2. The total load applied was 50,000 pounds (23,000 kg) in 5,000 pound (2300 kg) increments.

3. There were three reference points at 120° on the top edge of the plate.

4. Deflection readings were taken at intervals of 1, 4, and 15 minutes; 1 and 2 hours. Readings were also taken at 4, 8, and 16 hours when possible.

5. Rebound readings were taken during the unloading cycle.

Benkelman beam deflection measurements were taken at the five plate bearing test locations to determine K-values utilizing Test Method CA-TM-359. These values were then compared to K-values determined from plate bearing tests.

DATA ANALYSIS (ROADWAY TESTING)

Of the total number of deflection measurements taken on the roadway testing program, 496 test points common to all the devices studied were selected for correlation purposes. The Deflectometer, Dynaflect, Contra Costa County device and United States Forest Service device were utilized in this phase of the study and the following deflection correlations were investigated:

1. Dynaflect versus Deflectometer

2. United States Forest Service device versus Deflectometer

3. Contra Costa County device versus Deflectometer

4. United States Forest Service device versus Dynaflect

5. Contra Costa County device versus Dynaflect

6. Contra Costa County device versus United States Forest Service device.

Corresponding deflection data were plotted for each of the above combinations. The method of least squares and regression analysis were used to determine curve fits for the deflection data using the following equations:

1. $Y = A + B \cdot X$

2. $Y = A^{(B \cdot X)}$

3. $Y = AX^{B}$,

4. Y = A + B/X

5. Y = 1/(A+B·X)

6. Y = X/(A+B·X)

Dynaflect versus Deflectometer

Figure 7 shows a plot of Dynaflect versus Deflectometer deflections. As shown, a good correlation is achieved with the two devices. The straight line defined by the equation Y = -0.005 + 18.15X appears to be the best representation for the plotted points. The correlation coefficient for the straight line relationship is 0.92 and the standard error is $\pm$0.007 inch (0.02 mm).

United States Forest Service device versus Deflectometer

A plot of the deflection values for the two devices is shown on Figure 8. The scattered pattern of plotted points indicates a rather poor correlation. The correlation coefficients for the various curve fits vary from 0.55 to 0.86. Of the six equations considered, the straight line relationship Y = 0.001 + 4.09X appears to be a reasonable representation of the plotted points. The correlation coefficient for this curve fit is 0.81 and the standard error is $\pm$0.011 inch (0.3 mm).

Contra Costa County device versus Deflectometer

A deflection plot for these devices is shown in Figure 9. As shown, a fair correlation is found between the Contra Costa County device and the Deflectometer. A straight line representation Y = -0.006 + 12.24X has a correlation coefficient of 0.86 and a standard error of $\pm$0.009 inch (0.2 mm).

United States Forest Service device versus Dynaflect

Figure 10 shows the deflection plot for the United States Forest Service device and the Dynaflect. A fair correlation is shown in the low deflection range, Dynaflect deflections less than 0.0015 inch (0.04 mm) ; however, in the middle and high deflection ranges, deflection values are quite scattered. Correlation coefficients for the six curve fits vary from 0.64 to 0.89. A reasonable curve fit appears to be the straight line relationship $Y = 0.0004 + 0.206X$ with a correlation coefficient of 0.81 and a standard error of ± 0.0005 inch (0.01 mm).

Contra Costa County device versus Dynaflect

A deflection plot for these devices is shown in Figure 11. As shown, a good correlation is achieved with the Contra Costa County device and the Dynaflect. The straight line equation $Y = 0.645X$ has a correlation coefficient of 0.90 and a standard error of ± 0.0004 inch (0.01 mm).

Contra Costa County device versus United States Forest Service device

Figure 12 shows the deflection plot for the Contra Costa County device and the United States Forest Service device. As shown a fair correlation is achieved at low levels of deflection, Contra Costa County and United States Forest Service device deflections less than 0.005 inch (0.13 mm) ; and a poor correlation is found at middle and high deflections. A reasonable representation for the plotted points is a straight line, $Y = 0.0002 + 2.22X$. The correlation coefficient for this equation is 0.79 and the standard error is ± 0.0022 inch (0.06 mm).

Deflection Correlation for Thick and Thin Structural Sections

A visual inspection of the plotted points for the dynamic loading equipment (Dynaflect, United States Forest Service and Contra Costa County devices) versus the Deflectometer seems to indicate that better correlations would be obtained at lower deflection values than at higher deflection values. There has always been some concern as to whether the lighter testing device would correlate well with the heavier test equipment, especially on thick structural sections. Thus, deflection correlations were determined for the various devices separating thick and thin structural sections. The results of these correlations are shown in Figures 13 to 18. A summary of the deflection correlations separating thick, thin, and combined structural sections is presented in Table 2. The various correlation equations from Table 2 are presented graphically in Figure 19.

TABLE 2

CORRELATION SUMMARY (ROADWAY TESTING)

Equipment	Structural Section	Equation	Corr. Coeff.(R)	Standard Error
Dyna. vs. Defl.	All Sections	Y=-0.005+18.15X	0.92	±0.007 in.
"	Thick Sections	Y=-0.004+16.95X	0.85	±0.003 in.
"	Thin Sections	Y=-0.004+17.95X	0.83	±0.008 in.
U.S.F.S.vs.Defl.	All Sections	Y=0.001+4.09X	0.81	±0.011 in.
"	Thick Sections	Y=-0.002+3.49X	0.81	±0.004 in.
"	Thin Sections	Y=0.011+3.08X	0.64	±0.012 in.
C.C.C. vs. Defl.	All Sections	Y=-0.006+12.24X	0.86	±0.009 in.
"	Thick Sections	Y=-0.006+9.29X	0.84	±0.003 in.
"	Thin Sections	Y=0.002+12.17X	0.74	±0.010 in.

Note: 1 in. = 25.4 mm

As shown, the three equations for the Dynaflect versus the Deflectometer did not change appreciably for the different structural sections tested. However, the equations for the Contra Costa County device and United States Forest Service device versus the Deflectometer did change significantly for thick and thin structural sections. For these devices it would seem reasonable that different correlation curves should be used when comparing deflections on thick or thin sections (the agency using these devices would have to do further study on several pavement thicknesses to define the limits between thick and thin sections).

Summary of Road Testing

Of the various deflection devices investigated, the best correlations ($R \geq 0.90$) were achieved with: (1) the Dynaflect and Deflectometer (Figure 7) and (2) the Contra Costa County (Cox) device and Dynaflect (Figure 11). A fair correlation was achieved with the Contra Costa County device and the Deflectometer (Figure 9). The correlations of the United States Forest Service (Cox) device and Dynaflect (Figure 10), United States Forest Service device and Deflectometer (Figure 8) and Contra Costa County device and United States Forest Service device (Figure 12) were rather poor. It was found that all correlations had a substantial scatter at high deflection levels, Deflectometer deflections of about 0.030 inch (0.8 mm) or more . Conversely, all correlations had substantially less scatter at Deflectometer deflections of about 0.020 inch (0.5 mm) or less (Figures 7 to 12). This could be expected, however, as the possible variation at low deflection levels is less.

It should be noted that the deflection data obtained with the United States Forest Service device on this study was termed "questionable" by personnel from the United States Forest Service. The United States Forest Service device may or may not have been in calibration at the time of testing. Presently this device is not equipped with a built-in calibration unit to check the equipment prior to each day's testing.

Statistical data for the various deflection correlations investigated on the roadway testing is presented in Table 1-A in the Appendix.

Figure 7

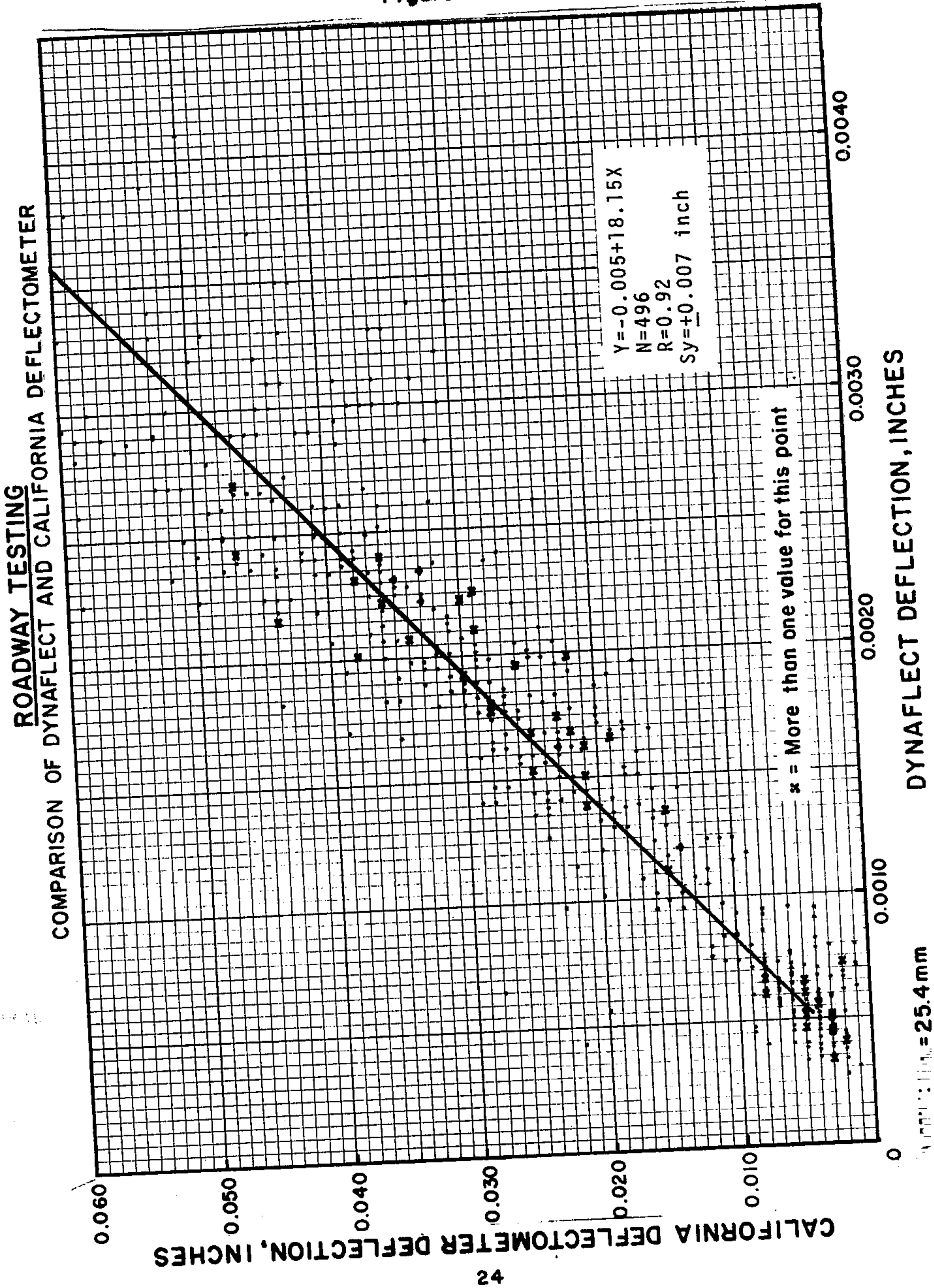
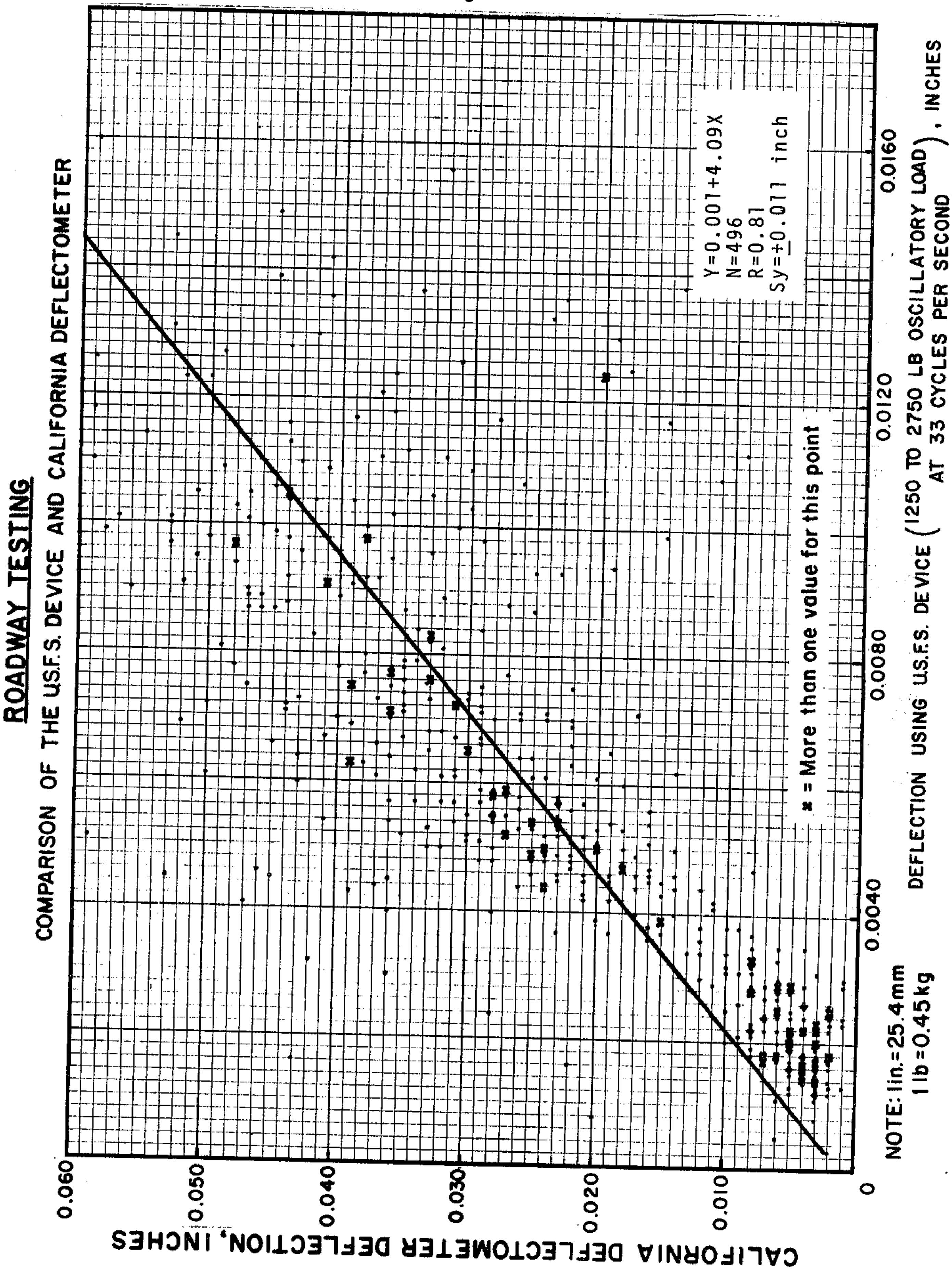

ROADWAY TESTING
COMPARISON OF DYNAFLECT AND CALIFORNIA DEFLECTOMETER
Y=-0.005+18.15X
N=496
R=0.92
Sy=±0.007 inch
x = More than one value for this point
DYNAFLECT DEFLECTION, INCHES
0
0.0010
0.0020
0.0030
0.0040
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
0.060
0.050
0.040
0.030
0.020
0.010
=25.4mm

Figure 8



ROADWAY TESTING
COMPARISON OF THE U.S.F.S. DEVICE AND CALIFORNIA DEFLECTOMETER
Y=0.001+4.09X
N=496
R=0.81
Sy=±0.011 inch
* = More than one value for this point
NOTE: 1 in.=25.4 mm
1 lb=0.45 kg
DEFLECTION USING U.S.F.S. DEVICE (1250 TO 2750 LB OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
0
0.0040
0.0080
0.0120
0.0160
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
0.010
0.020
0.030
0.040
0.050
0.060

Figure 9

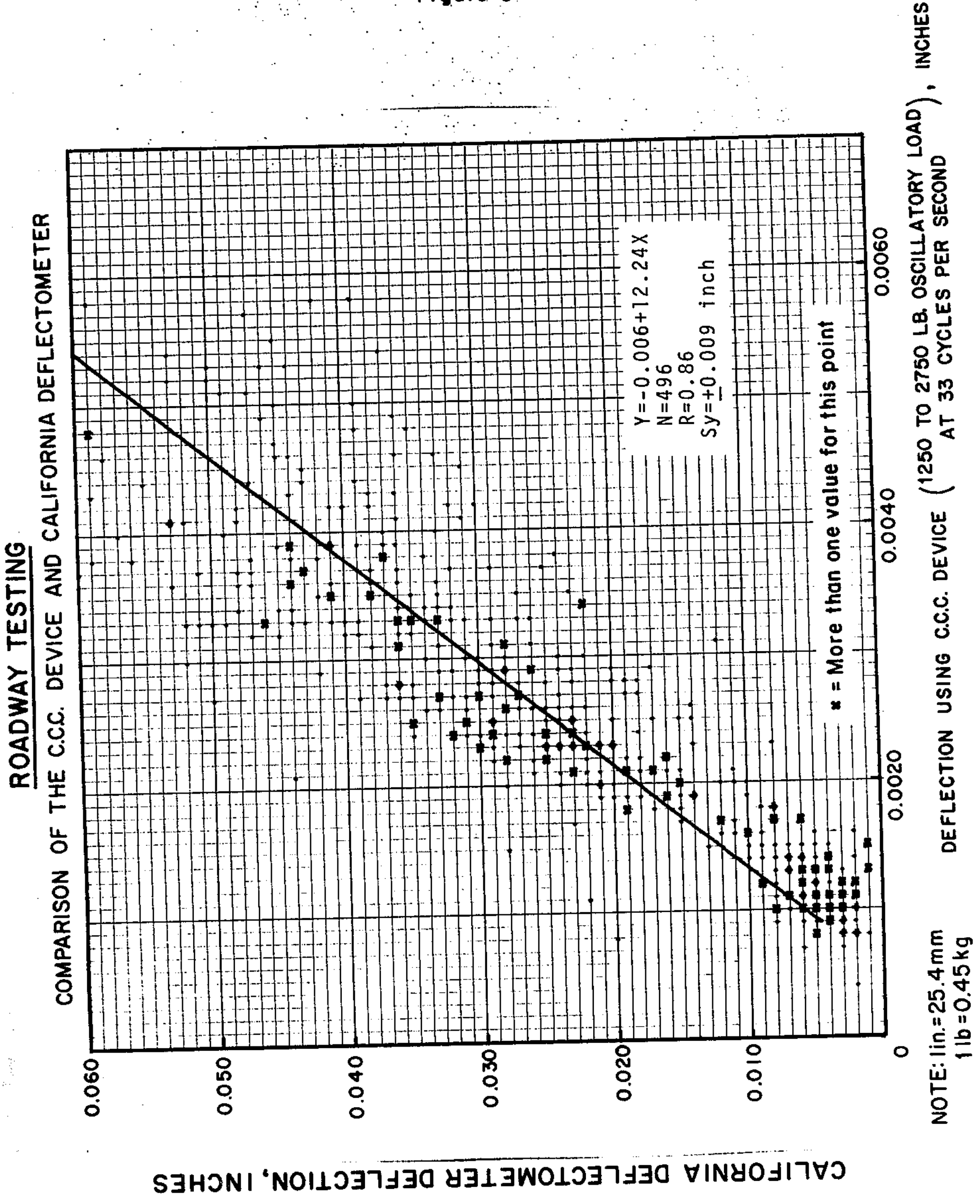

ROADWAY TESTING
COMPARISON OF THE C.C.C. DEVICE AND CALIFORNIA DEFLECTOMETER
Y=-0.006+12.24X
N=496
R=0.86
Sy=±0.009 inch
* = More than one value for this point
DEFLECTION USING C.C.C. DEVICE (1250 TO 2750 LB. OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
0.060
0.050
0.040
0.030
0.020
0.010
0
0.0020
0.0040
0.0060
NOTE: 1in.=25.4mm
1 lb=0.45 kg

Figure 10

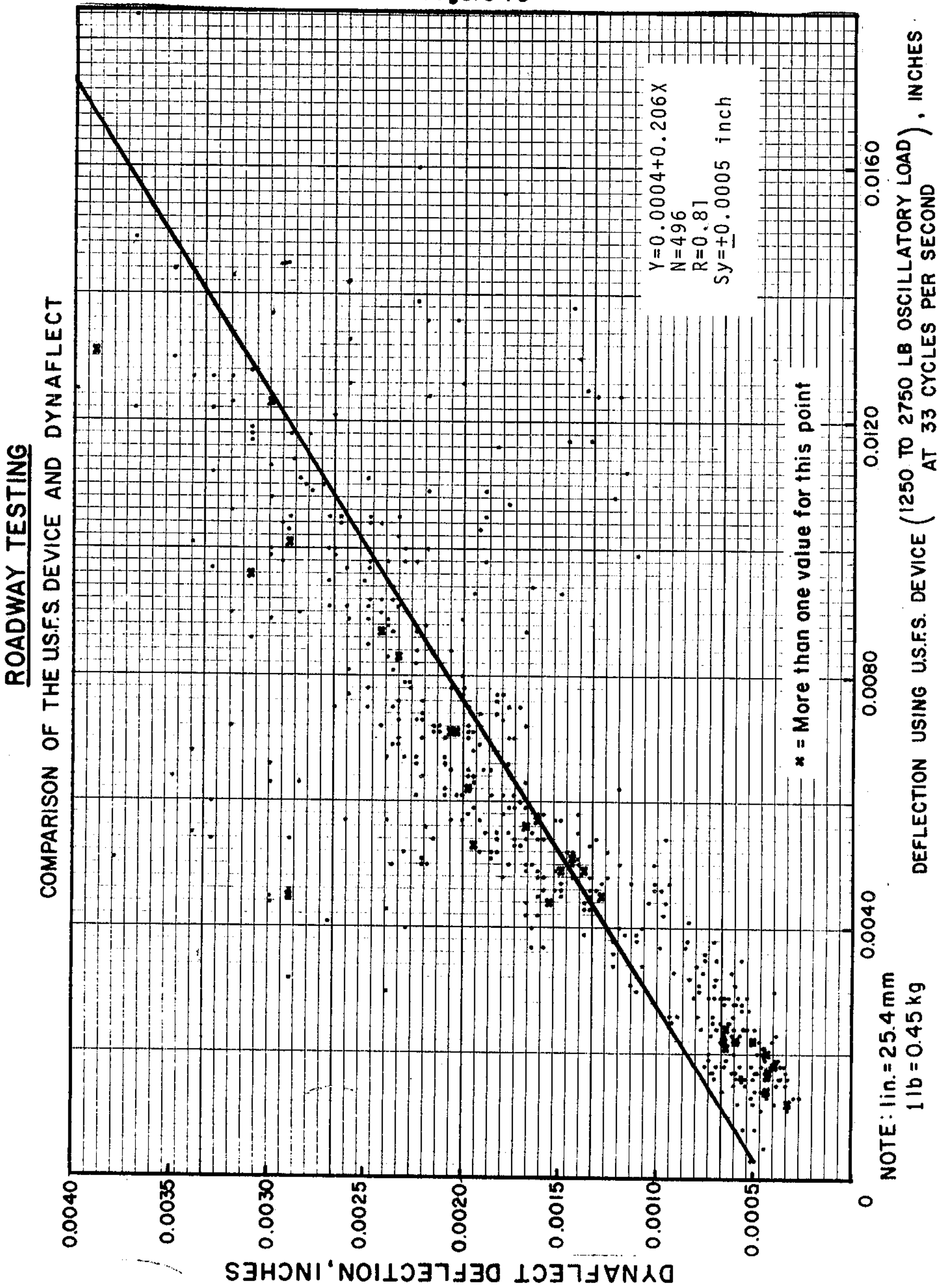
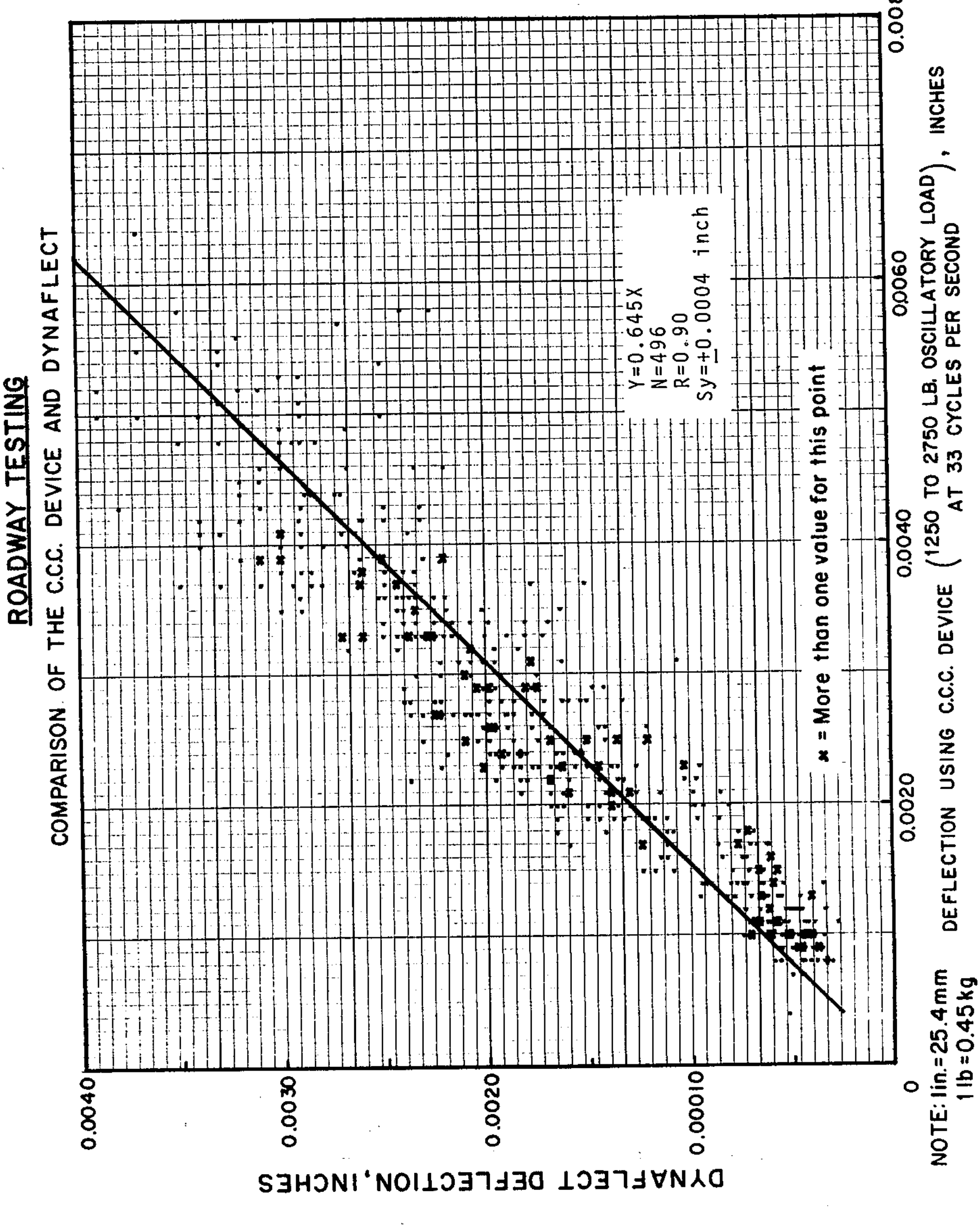

ROADWAY TESTING
COMPARISON OF THE U.S.F.S. DEVICE AND DYNAFLECT
Y=0.0004+0.206X
N=496
R=0.81
Sy=±0.0005 inch
✱ = More than one value for this point
NOTE: 1in.=25.4mm
1lb=0.45kg
DEFLECTION USING U.S.F.S. DEVICE (1250 TO 2750 LB OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
0
0.0040
0.0080
0.0120
0.0160
DYNAFLECT DEFLECTION, INCHES
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040

Figure 11



ROADWAY TESTING
COMPARISON OF THE C.C.C. DEVICE AND DYNAFLECT
Y=0.645X
N=496
R=0.90
Sy=±0.0004 inch
✱ = More than one value for this point
DYNAFLECT DEFLECTION, INCHES
0.0040
0.0030
0.0020
0.00010
0
0.0020
0.0040
0.0060
0.0080
DEFLECTION USING C.C.C. DEVICE (1250 TO 2750 LB. OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
NOTE: 1in.=25.4mm
1lb=0.45kg

Figure 12

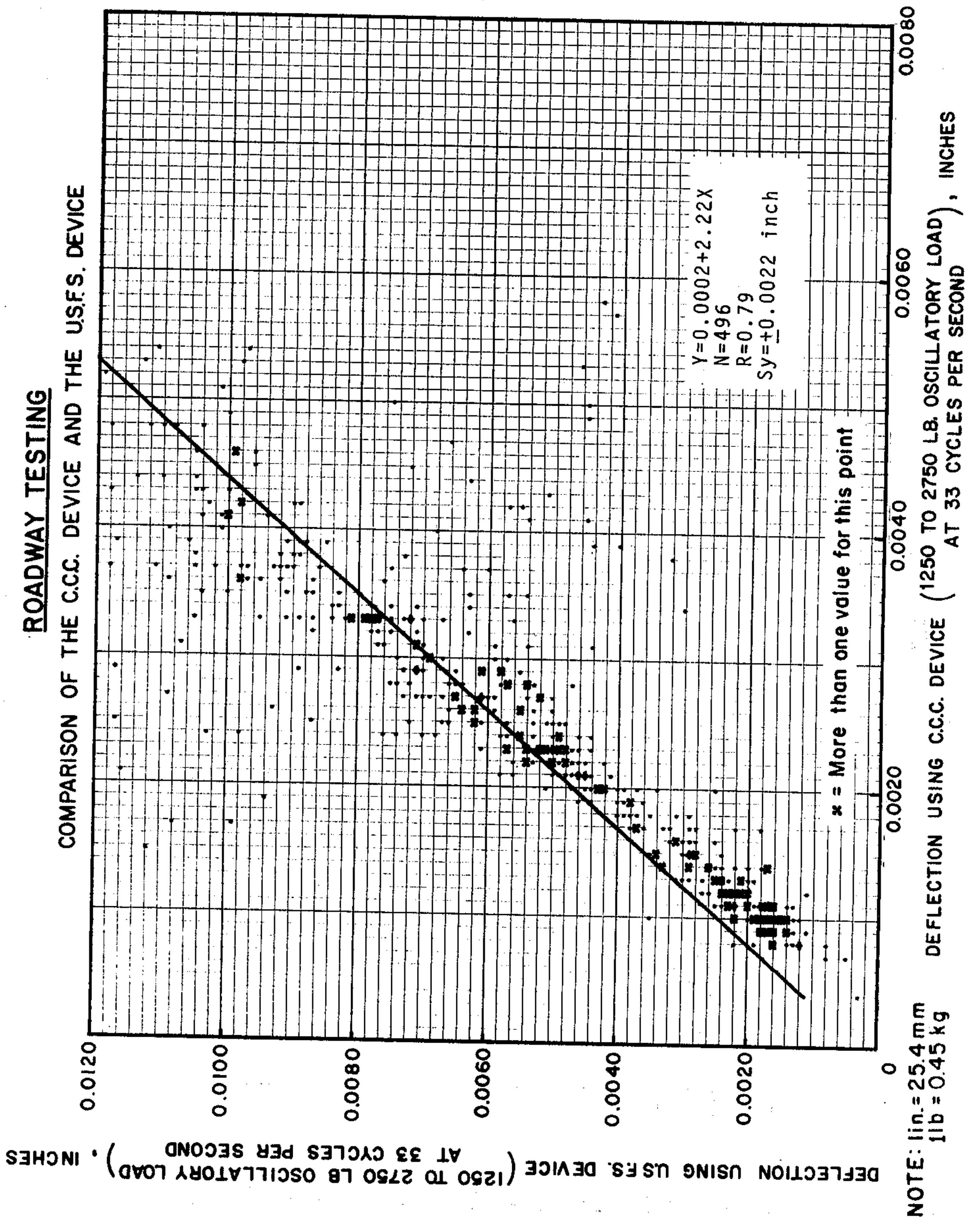

ROADWAY TESTING
COMPARISON OF THE C.C.C. DEVICE AND THE U.S.F.S. DEVICE
Y=0.0002+2.22X
N=496
R=0.79
Sy=±0.0022 inch
* = More than one value for this point
DEFLECTION USING C.C.C. DEVICE (1250 TO 2750 LB. OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
DEFLECTION USING U.S.F.S. DEVICE (1250 TO 2750 LB OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES
0
0.0020
0.0040
0.0060
0.0080
0.0100
0.0120
NOTE: 1in.= 25.4 mm
1lb = 0.45 kg

Figure 13

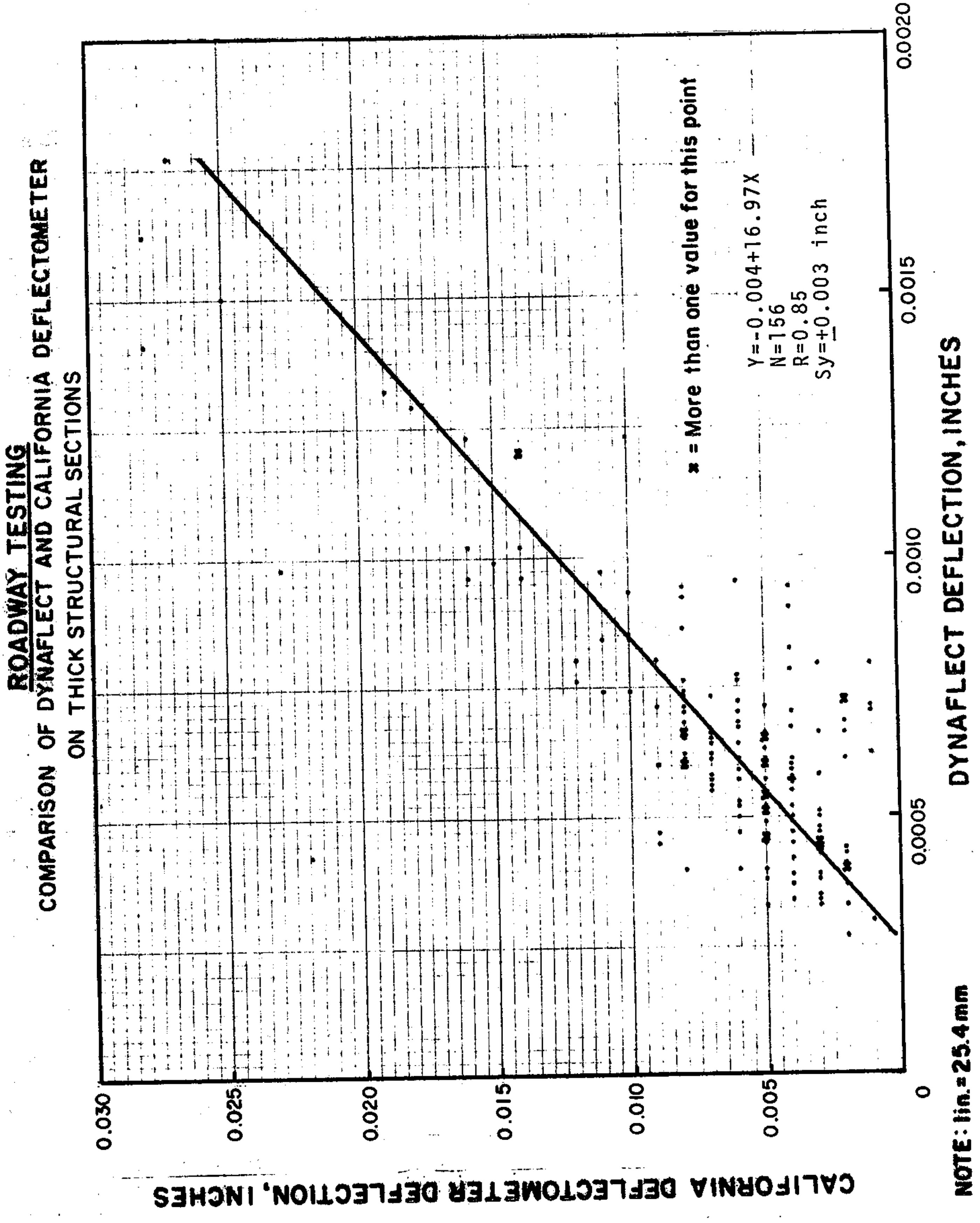
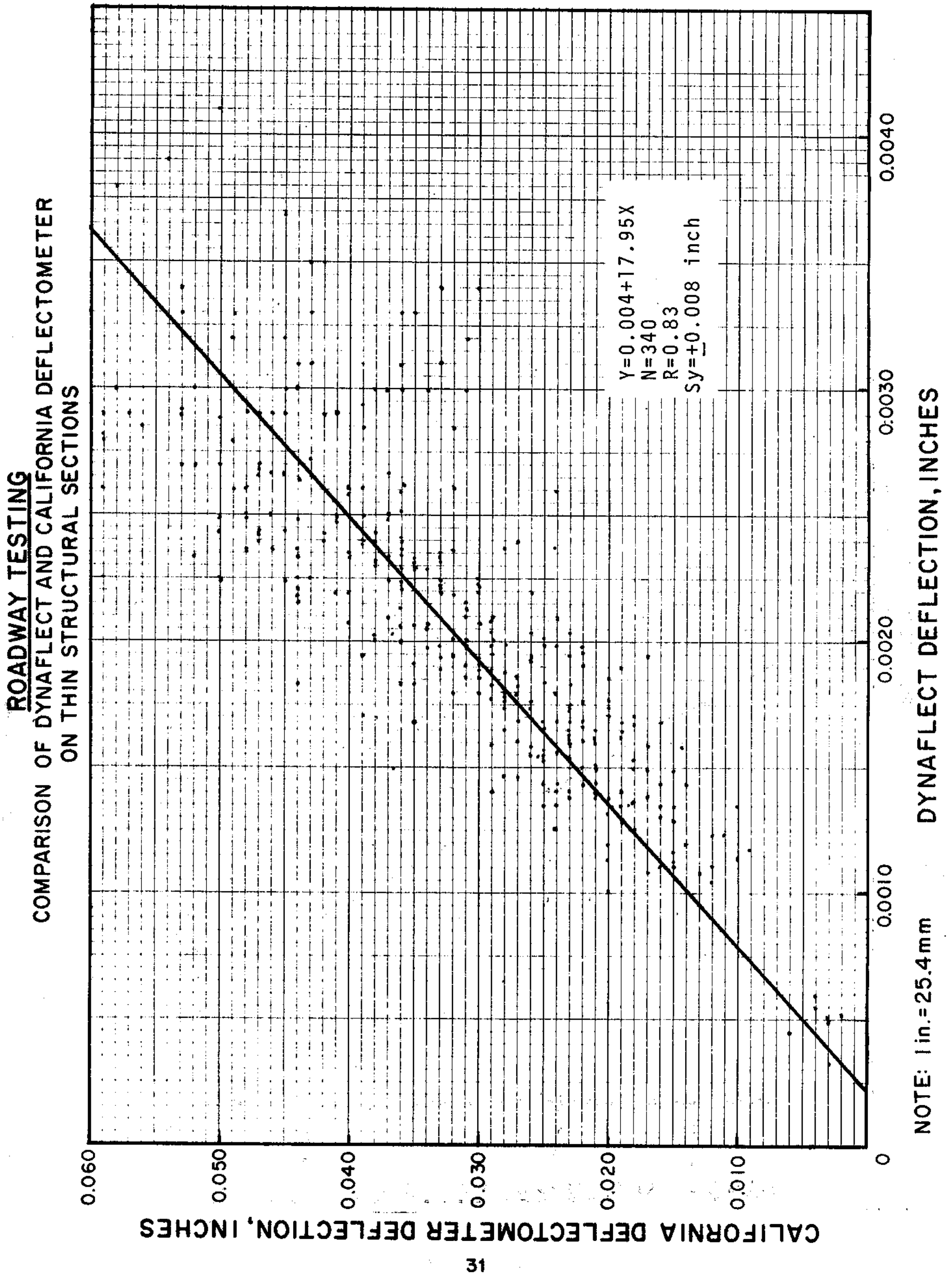

ROADWAY TESTING
COMPARISON OF DYNAFLECT AND CALIFORNIA DEFLECTOMETER
ON THICK STRUCTURAL SECTIONS
* = More than one value for this point
Y=-0.004+16.97X
N=156
R=0.85
Sy=±0.003 inch
DYNAFLECT DEFLECTION, INCHES
0
0.0005
0.0010
0.0015
0.0020
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
0.030
0.025
0.020
0.015
0.010
0.005
NOTE: 1in.=25.4mm

Figure 14



ROADWAY TESTING
COMPARISON OF DYNAFLECT AND CALIFORNIA DEFLECTOMETER
ON THIN STRUCTURAL SECTIONS
Y=0.004+17.95X
N=340
R=0.83
Sy=+0.008 inch
DYNAFLECT DEFLECTION, INCHES
0
0.0010
0.0020
0.0030
0.0040
NOTE: 1in.=25.4mm
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
0.060
0.050
0.040
0.030
0.020
0.010

Figure 15

ROADWAY TESTING

COMPARISON OF THE C.C.C. DEVICE AND CALIFORNIA DEFLECTOMETER ON THICK STRUCTURAL SECTIONS

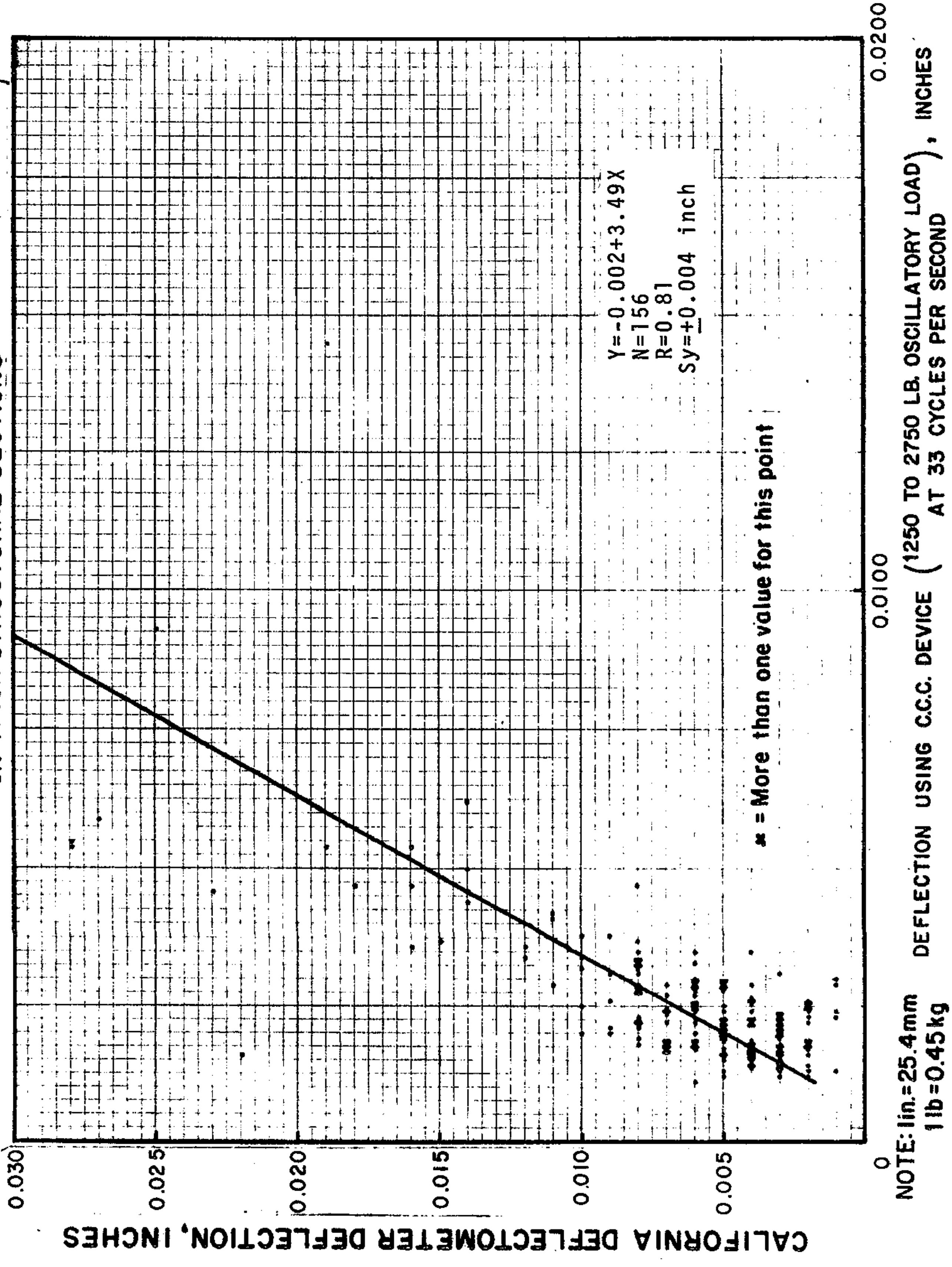


Figure 16

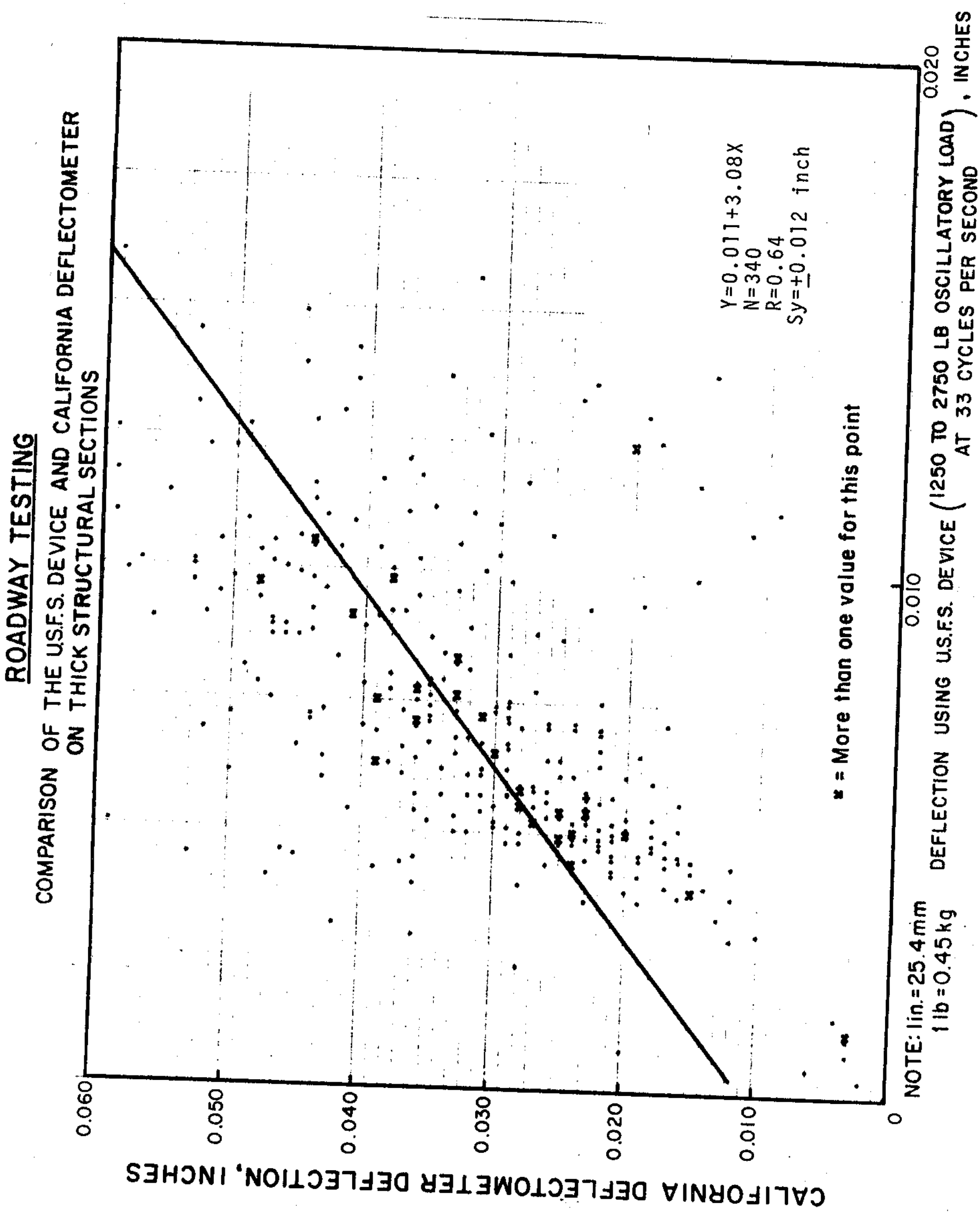

ROADWAY TESTING
COMPARISON OF THE U.S.F.S. DEVICE AND CALIFORNIA DEFLECTOMETER
ON THICK STRUCTURAL SECTIONS
Y=0.011+3.08X
N=340
R=0.64
Sy=±0.012 inch
* = More than one value for this point
NOTE: 1in.=25.4mm
1 lb=0.45kg
0
0.010
0.020
0.030
0.040
0.050
0.060
CALIFORNIA DEFLECTOMETER DEFLECTION, INCHES
DEFLECTION USING U.S.F.S. DEVICE (1250 TO 2750 LB OSCILLATORY LOAD AT 33 CYCLES PER SECOND), INCHES

Figure 17

ROADWAY TESTING

COMPARISON OF THE C.C.C. DEVICE AND CALIFORNIA DEFLECTOMETER ON THICK STRUCTURAL SECTIONS

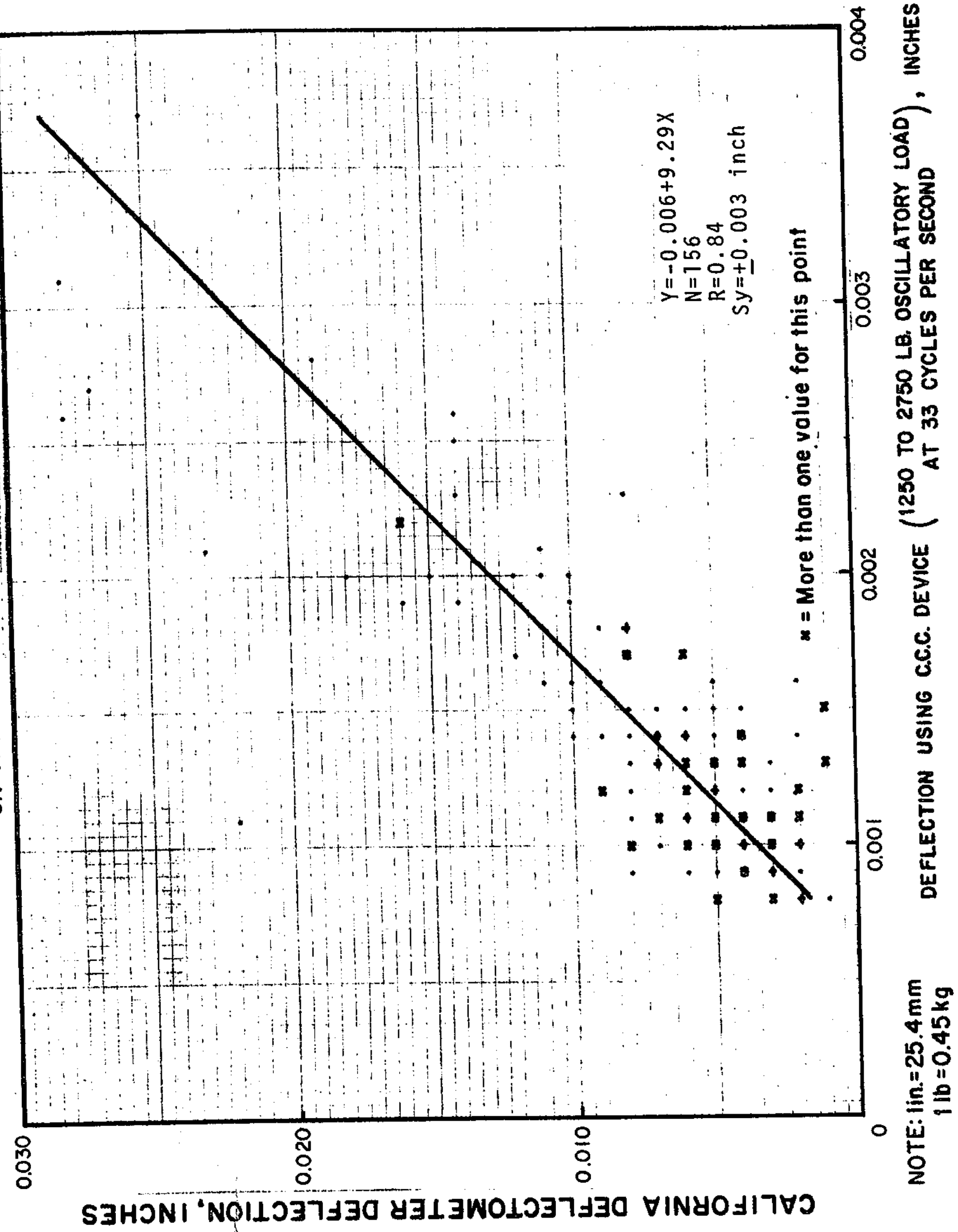


Figure 18

ROADWAY TESTING

COMPARISON OF THE C.C.C. DEVICE AND CALIFORNIA DEFLECTOMETER ON THIN STRUCTURAL SECTIONS

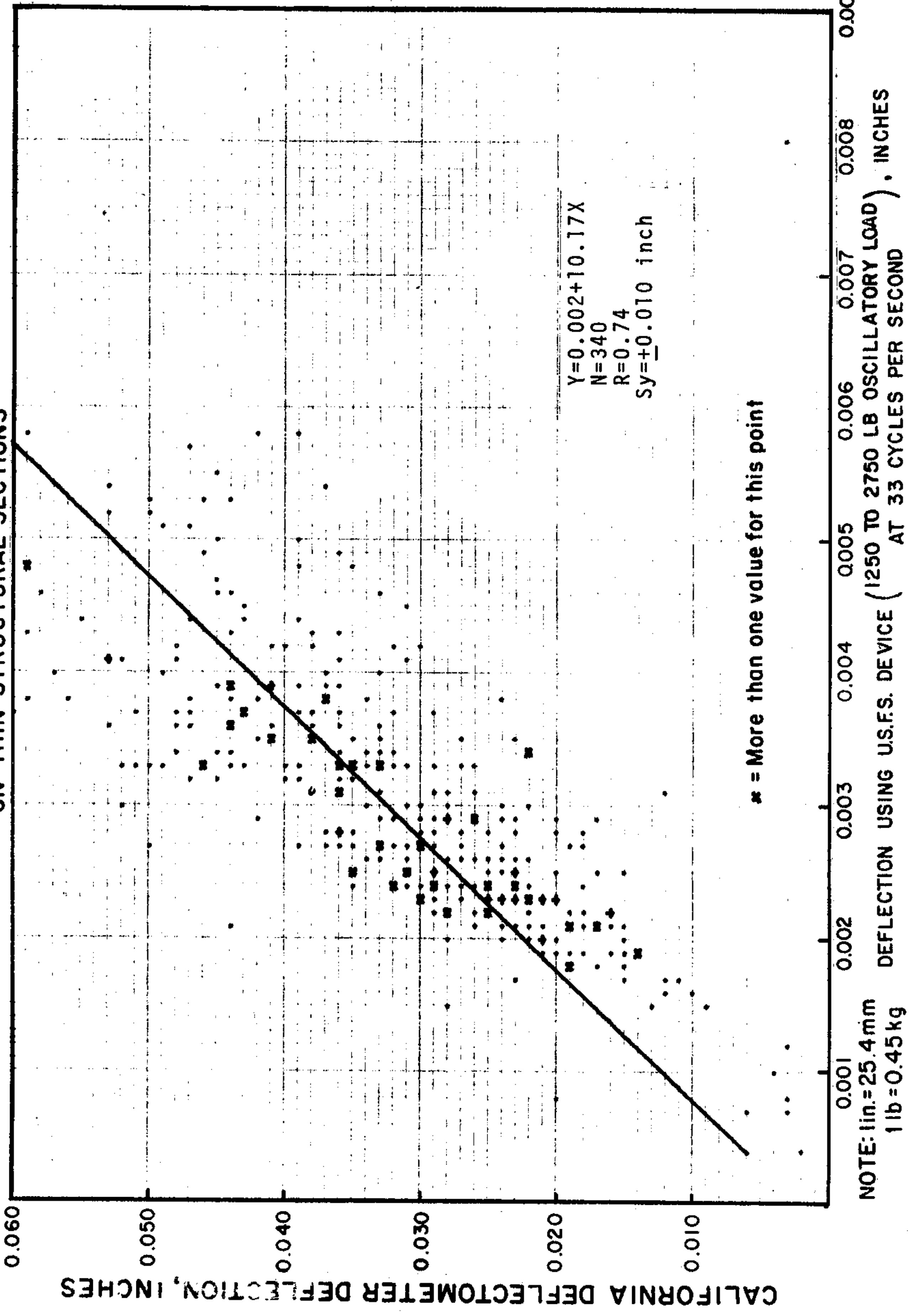
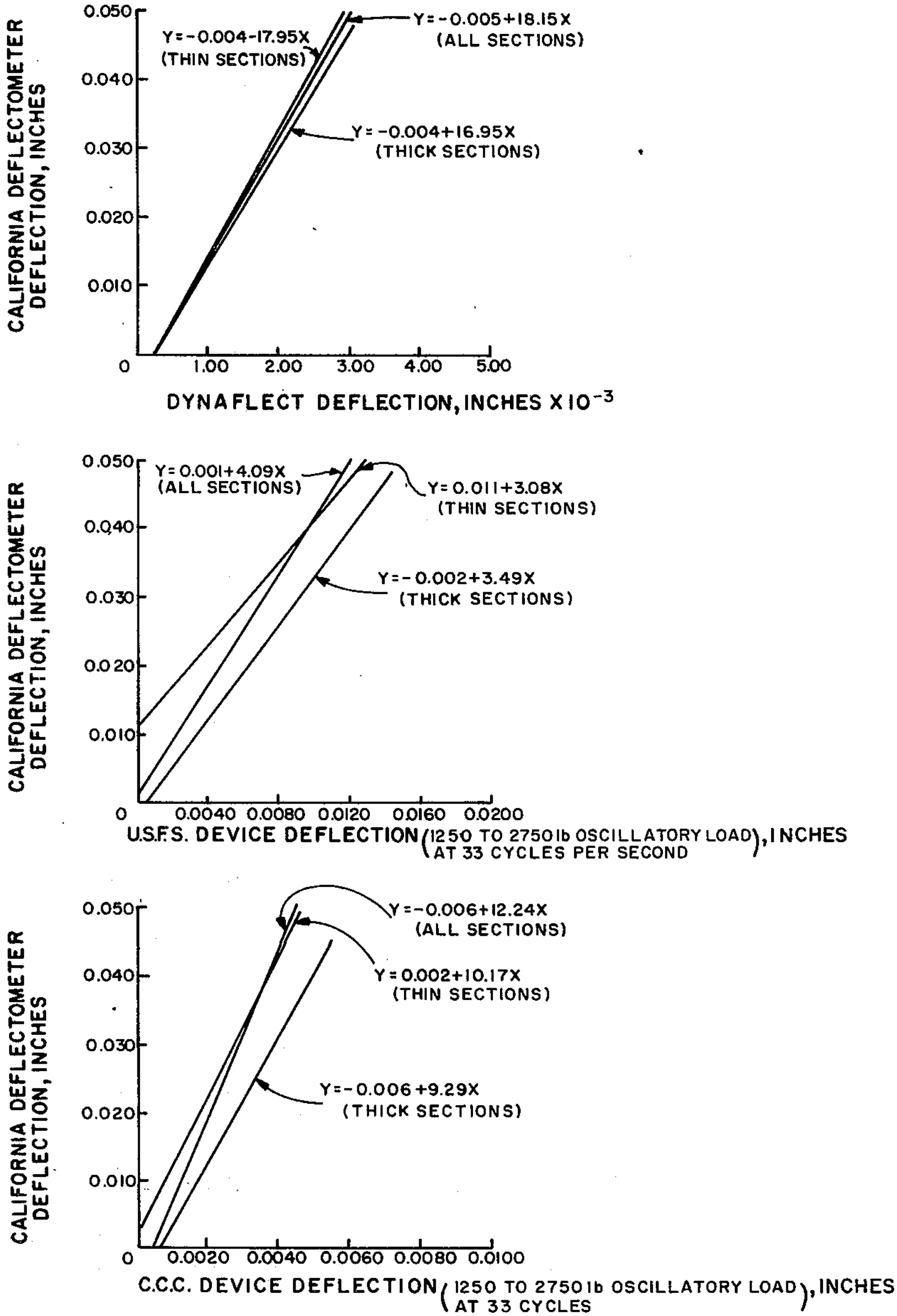


Figure 19

DEFLECTION CORRELATIONS ON THIN, THICK AND COMBINED STRUCTURAL SECTIONS



DATA ANALYSIS (AIRPORT TESTING)

Using the airport deflection data obtained with the WES device, the Dynaflect, the United States Forest Service device, the Contra Costa County device, and the Benkelman beam, various deflection correlations were investigated. Correlation equations were determined in the same manner as described in the roadway testing of this report. In the airport testing, special emphasis was placed on comparing deflection values of the various devices with those of the WES device, on the assumption that only a very heavy load could cause deflection of thick structural sections.

As shown in Table 1, the deflection measuring equipment used on the airport testing operated at different test parameters, depending on the capabilities of each device. The WES device, in particular, used a wide variety of test parameters during its testing. Unfortunately, the test parameters were randomly selected for each test location. Consequently, not all test results could be used for correlation purposes. As expected, some of the correlations for the airport testing were obtained using a limited amount of deflection data. The deflection correlations calculated for the airport testing are as follows:

Benkelman Beam [WASHTO Method - 18,000 pound (8,200 kg)Axle Load] versus WES device (Lowest Frequency - 5 cycles per second)

The reason for determining this correlation was to compare the two slowest "rate-of-loading" devices used at the airport. Benkelman beam deflections are determined from a nearly static load. Thus, they were compared to the lowest frequency measured with the WES device, approximately five cycles per second. Due to different testing parameters, only eight test points could be compared for the two devices. This data produced a correlation coefficient (R) of 0.55 and a standard error of ±0.0012 inch (0.03 mm) in terms of WES device deflection (Figure 20). Even though the small number of test points would normally be of little significance for a comparative study, the deflections did cover a range of from 0.008 to 0.018 inch (0.2 to 0.5 mm), in terms of Benkelman beam deflections. This data suggests a poor correlation between Benkelman beam and the WES device using the above-mentioned test parameters.

Benkelman Beam [WASHTO Method - 18,000 pound (8,200 kg) Axle Load] versus WES device (Maximum Measured Deflection)

Deflection measurements obtained at the 14 duplicate test points for these devices and test parameters produced a coefficient of correlation (R) of 0.73 and a standard error of ±0.0013 inch (0.03 mm), in terms of WES device deflection (Figure 21). It was noted that the maximum deflection for the WES device for the 4,000 pound (1,800 kg) vibratory load occurred between 8 and 10 cycles per second. Again, the results indicate a poor correlation for the deflection devices at the above-mentioned test parameters.

Contra Costa County device (33 cycles/second) versus WES device (33 cycles/second)

Contra Costa County device (45 cycles/second) versus WES device (45 cycles/second)

Correlation calculations were performed to compare the dynamic test equipment at different frequencies. Correlation coefficients were about the same for the two frequencies tested. At 33 cycles per second, the coefficient of correlation was 0.85 with a standard error of ±0.0003 inch (0.008 mm) in terms of WES device deflection (Figure 22). The coefficient of correlation at 45 cycles per second was 0.79 with a standard error of ±0.0004 inch (0.010 mm), in terms of WES device deflection (Figure 23). These regression analyses demonstrate a fair degree of correlation for the devices at the parameters tested.

U. S. Forest Service device (33 cycles/second) versus WES device (33 cycles/second)

U. S. Forest Service device (45 cycles/second) versus WES device (45 cycles/second)

Deflection measurements obtained at the 19 duplicate test points for these devices and test parameters produced a coefficient of correlation of 0.86 with a standard error of ±0.0003 inch (0.008 mm), in terms of WES device deflection at 33 cycles per second (Figure 24). At the 45 cycles per second frequency, the correlation coefficient was 0.83 with a standard error of ±0.0003 inch (0.008 mm), in terms of WES device deflection (Figure 25). A fair correlation was achieved with the devices tested at the above-mentioned parameters.

Dynaflect (8 cycles/second) versus WES device (Maximum Measured Deflection)

Deflection measurements obtained at the 14 duplicate test points for these devices and test parameters produced a coefficient of correlation of 0.89 with a standard error of ±0.0008 inch (0.02 mm) in terms of WES device deflection (Figure 26). As previously stated, the maximum deflection measured with the WES device occurred between 8 and 10 cycles per second.

Dynaflect (8 cycles/second) versus WES device (8 cycles/second)

The best correlation for all the comparative airport studies was produced by these dynamic testing devices operating at 8 cycles per second. The correlation coefficient was 0.91 with a standard error of ±0.0009 inch (0.02 mm) in terms of WES device deflection (Figure 27). This was slightly better than the comparison of the devices at the previously stated condition, Dynaflect (8 cycles per second) versus WES device (Maximum Measured Deflection).

The statistical data for the various deflection correlations investigated on the airport testing is presented in Table 2-A.

Comparison of K-Values Determined from Plate Bearing Tests and Benkelman Beam Deflections

Benkelman beam deflections measured at the three locations where plate bearing tests were performed on asphalt concrete surfaces were 0.008 inch (0.20 mm), 0.008 inch (0.20 mm) and 0.006 inch (0.15 mm). Using the deflection values and Figure 1 from Test Method CA-TM-359(9), K-values were extrapolated (see Table 3). As shown, K-values determined from Benkelman beam deflections compared favorably with those determined from plate bearing tests.

Table 3

K-Values (San Jose Municipal Airport)

Test Location	Structural Section	Benkelman Beam Deflection (Inches)	K-Value Determined From Plate Bearing Test* (psi/in.)	K-Value Determined From Benkelman Beam Deflection** (psi/in.)
18b	9" AC 7" Crushed Rock Base 2" AC 6" Crushed Rock Base 15" Subbase	0.008	695	860
26a	3" AC 10" Crushed Rock Base 20" Subbase	0.008	857	860
45b	5" AC 38" Bituminous Base Course	0.006	884	940

Note: 1 in. = 2.54 cm

*ASTM Method D1185
** Test Method CA-TM-359

Summary of Airport Pavement Testing

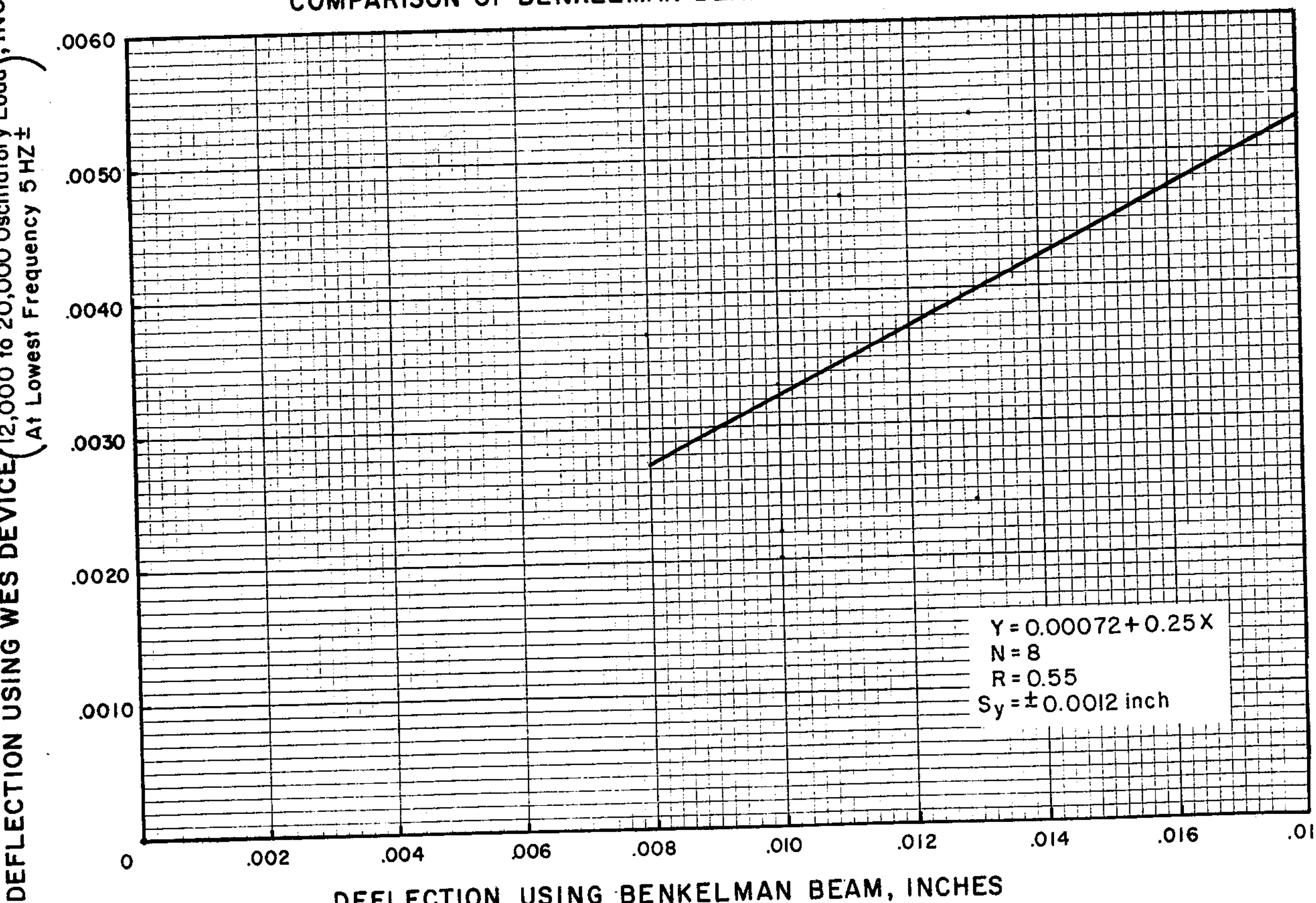
Even though the correlations for the various deflection measuring devices contained rather limited data, some indications are apparent. The lighter dynamic testing devices appear to be adequate for the evaluation of heavily constructed structural sections. The roadway testing confirmed this on several heavily constructed highway sections.

Deflection data obtained with the WES device showed that maximum pavement deflections were found at frequencies between 8 and 10 cycles per second, regardless of vibratory loads. At the airport, tests were performed with the WES device at vibratory loads from 1,000 to 6,000 pounds (450 to 2,300 kg) and at frequencies from 5 to 70 cycles per second. In all cases maximum pavement deflections occurred between 8 and 10 cycles per second (for example - see typical data sheet, Table 3-A in the Appendix).

Perhaps the better correlations achieved with the Dynaflect versus the WES device as opposed to the Cox devices is due to the fact that the Dynaflect measures deflections at a fixed frequency of 8 cycles per second; whereas, the effective frequency range for the Cox devices is from 25 to 50 cycles per second. It is also interesting to note the correlation coefficients for the Cox devices versus the WES device were slightly better when compared at 33 cycles per second than 45 cycles per second.

AIRPORT TESTING

COMPARISON OF BENKELMAN BEAM AND WES DEVICE



NOTE: 1" = 25.4mm

Figure 20

Figure 21

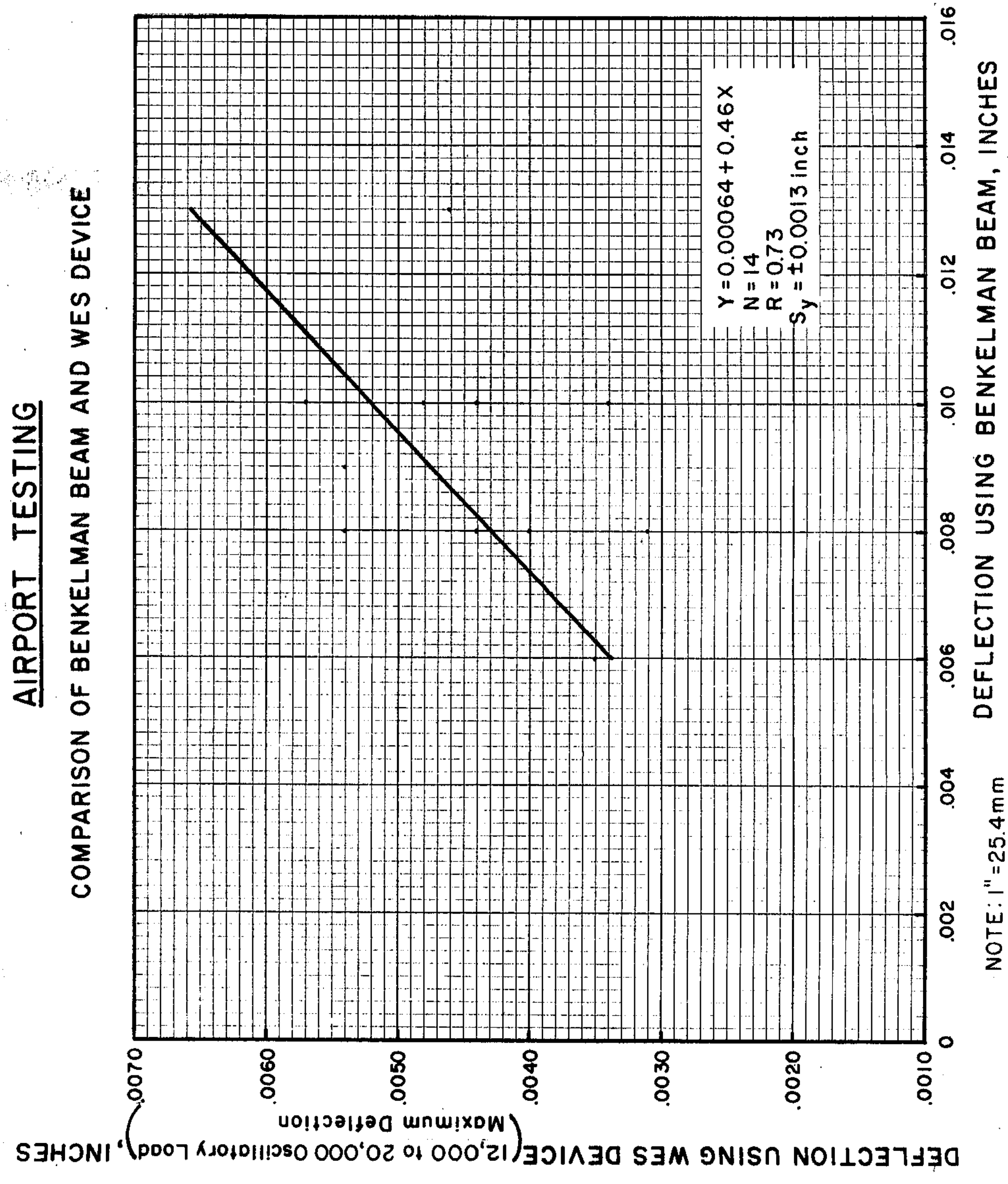

AIRPORT TESTING
COMPARISON OF BENKELMAN BEAM AND WES DEVICE
Y = 0.00064 + 0.46X
N = 14
R = 0.73
S_y = ±0.0013 inch
DEFLECTION USING BENKELMAN BEAM, INCHES
0
.002
.004
.006
.008
.010
.012
.014
.016
NOTE: 1" = 25.4mm
DEFLECTION USING WES DEVICE (12,000 to 20,000 Oscillatory Load, Maximum Deflection), INCHES
.0010
.0020
.0030
.0040
.0050
.0060
.0070

Figure 22

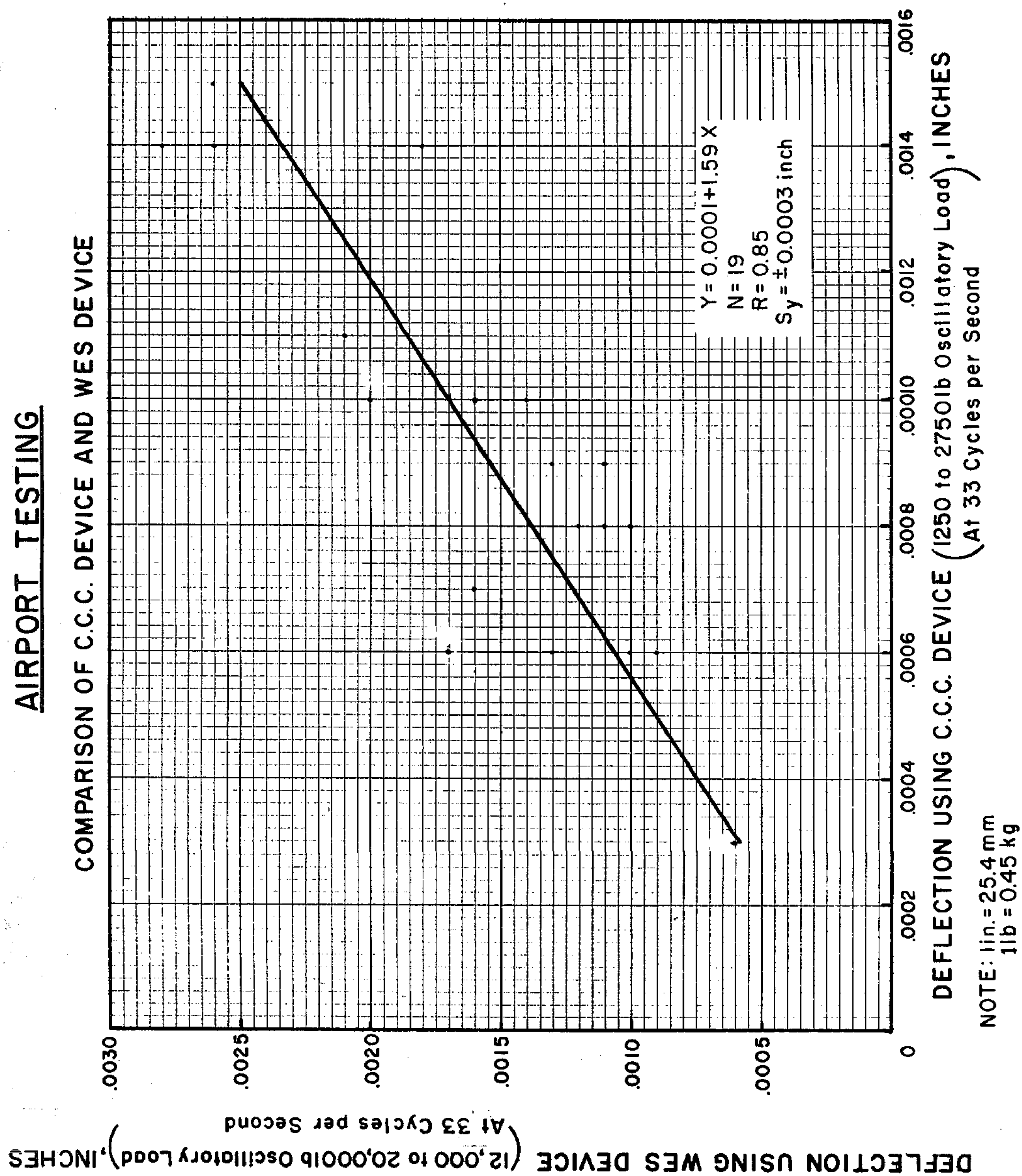

AIRPORT TESTING
COMPARISON OF C.C.C. DEVICE AND WES DEVICE
Y = 0.0001 + 1.59 X
N = 19
R = 0.85
$S_y = \pm 0.0003$ inch
DEFLECTION USING C.C.C. DEVICE (1250 to 2750 lb Oscillatory Load), INCHES
(At 33 Cycles per Second
DEFLECTION USING WES DEVICE (12,000 to 20,000 lb Oscillatory Load), INCHES
(At 33 Cycles per Second
NOTE: 1 in. = 25.4 mm
1 lb = 0.45 kg
0
.0002
.0004
.0006
.0008
.00010
.0012
.0014
.0016
.0005
.0010
.0015
.0020
.0025
.0030

Figure 23

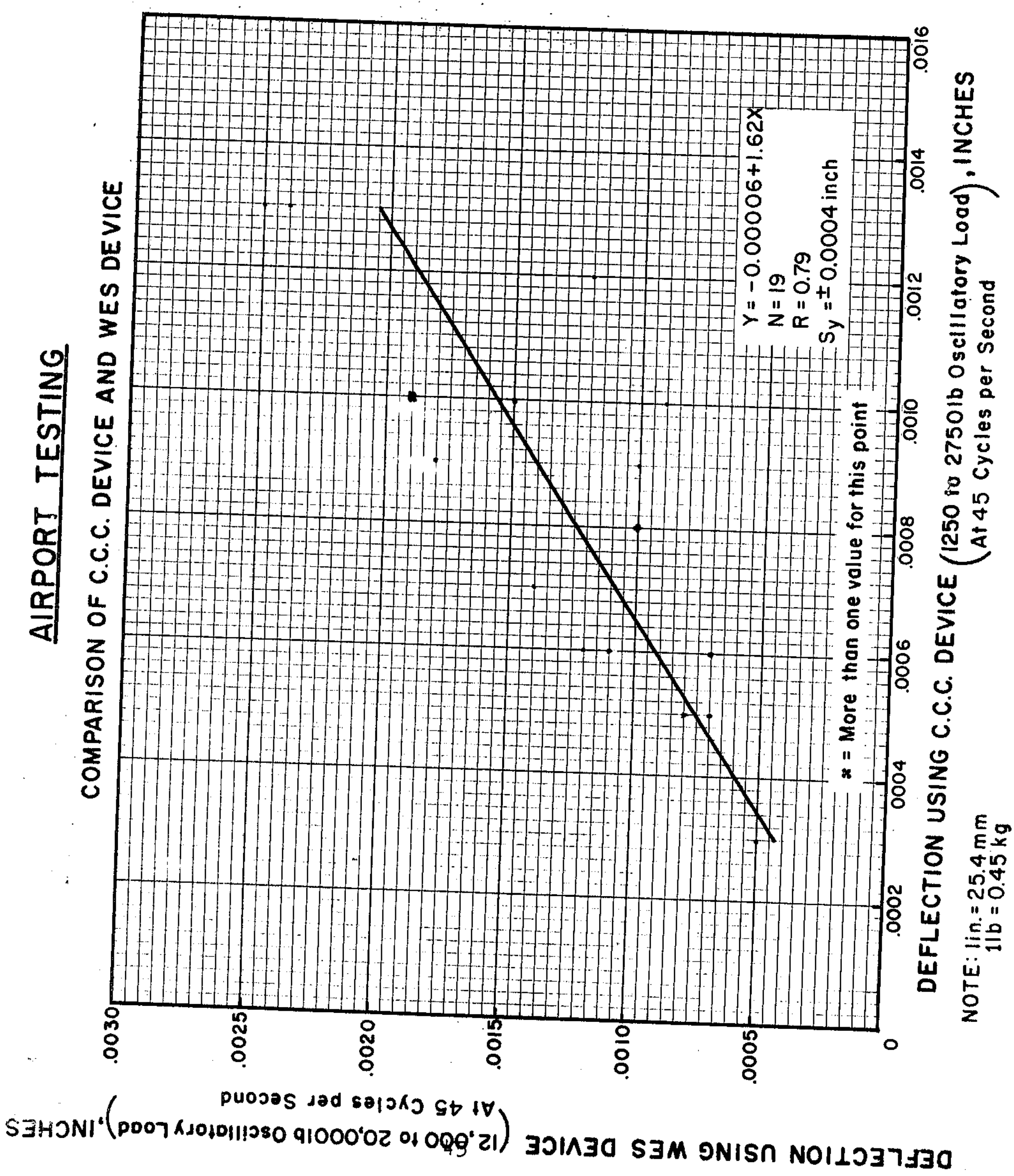
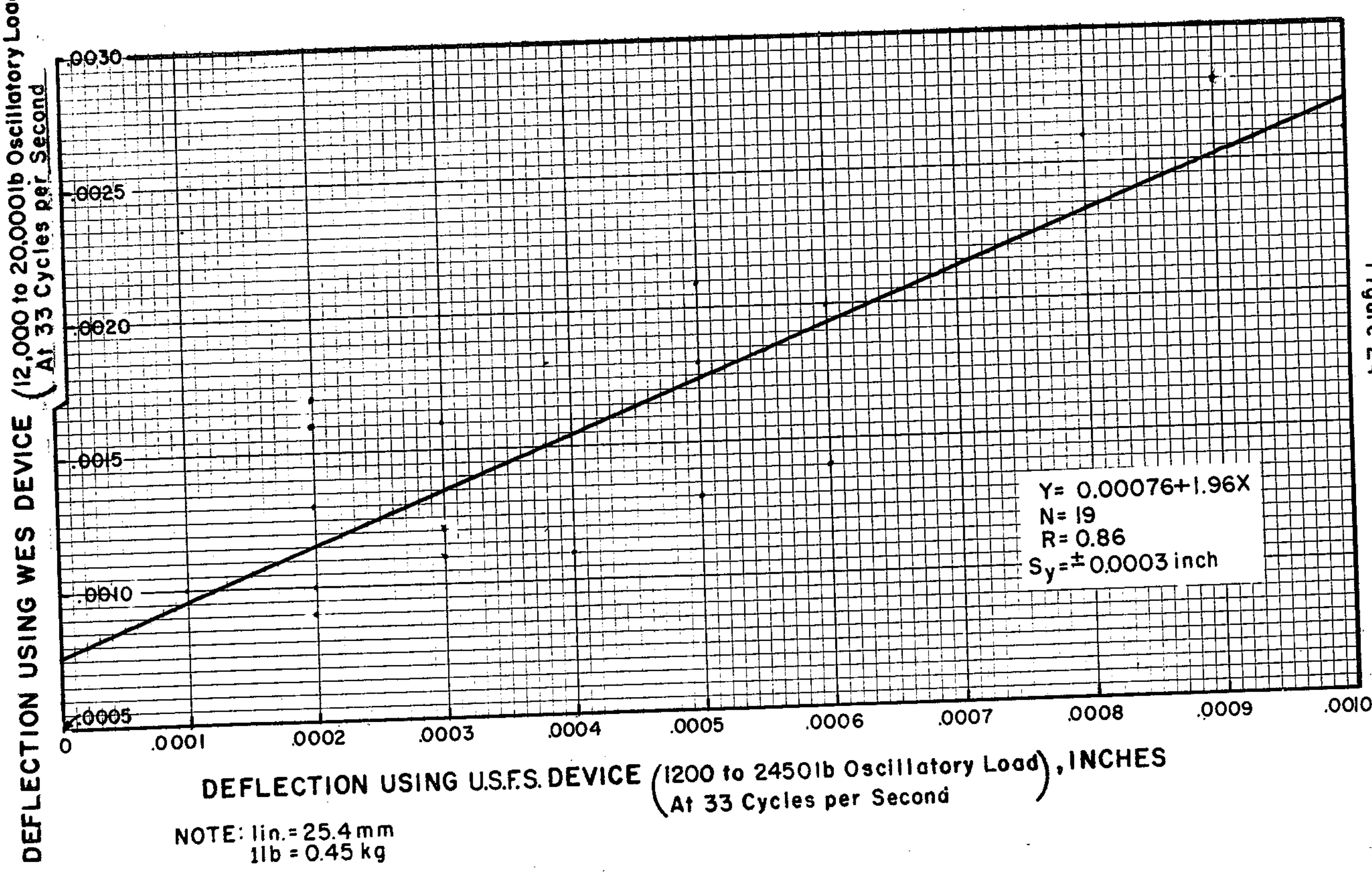

AIRPORT TESTING
COMPARISON OF C.C.C. DEVICE AND WES DEVICE
Y = -0.00006+1.62X
N = 19
R = 0.79
Sy = ± 0.0004 inch
* = More than one value for this point
DEFLECTION USING C.C.C. DEVICE (1250 to 2750 lb Oscillatory Load, At 45 Cycles per Second), INCHES
DEFLECTION USING WES DEVICE (12,000 to 20,000 lb Oscillatory Load, At 45 Cycles per Second), INCHES
NOTE: 1 in. = 25.4 mm
1 lb = 0.45 kg
0
.0002
.0004
.0006
.0008
.0010
.0012
.0014
.0016
.0005
.0010
.0015
.0020
.0025
.0030

Figure 24

AIRPORT TESTING

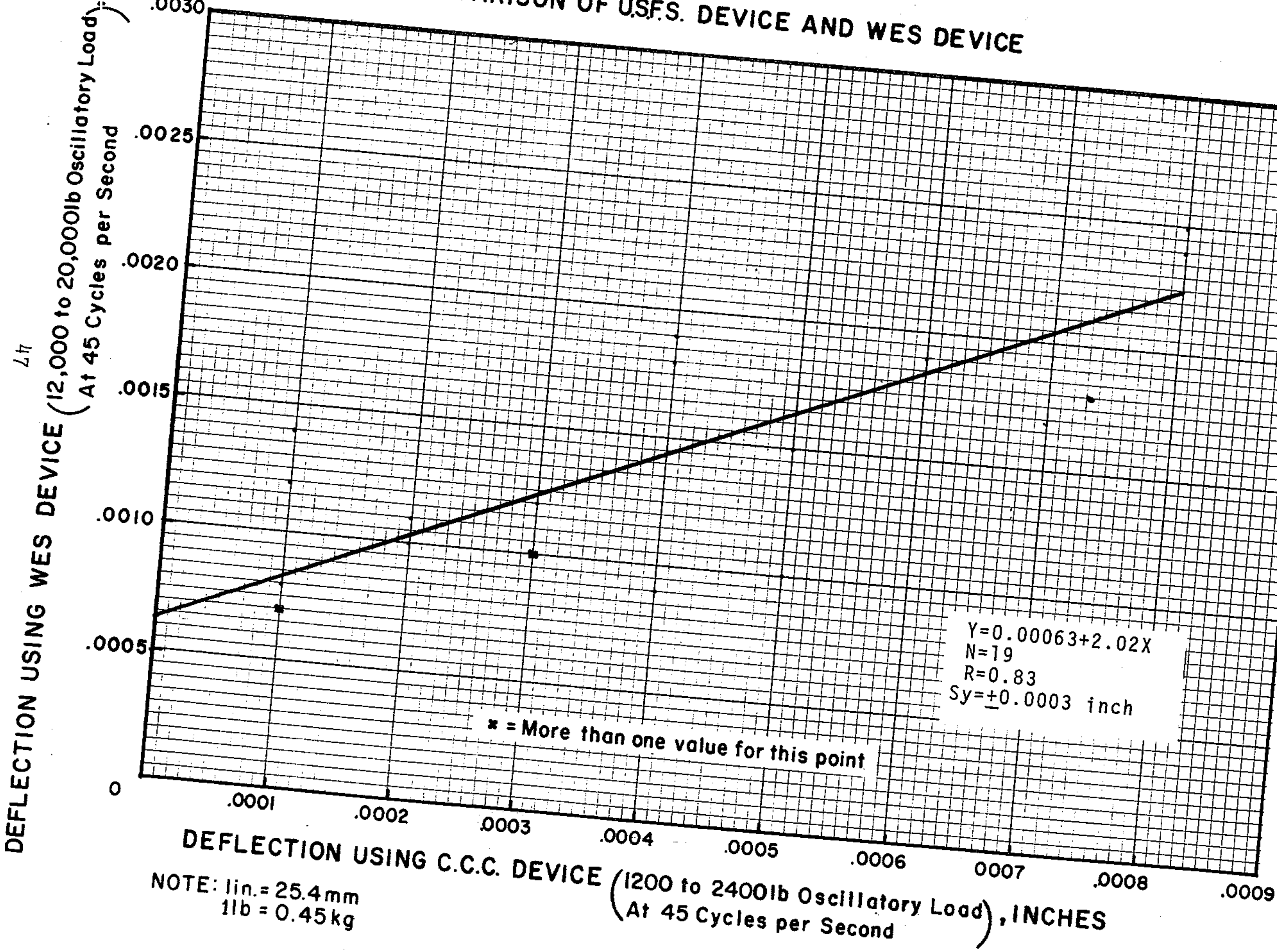
COMPARISON OF U.S.F.S. DEVICE AND WES DEVICE



NOTE: 1 in. = 25.4 mm
1 lb = 0.45 kg

Figure 25

COMPARISON OF U.S.F.S. DEVICE AND WES DEVICE



NOTE: 1in. = 25.4mm
1lb = 0.45kg

AIRPORT TESTING

COMPARISON OF DYNAFLECT AND WES DEVICE

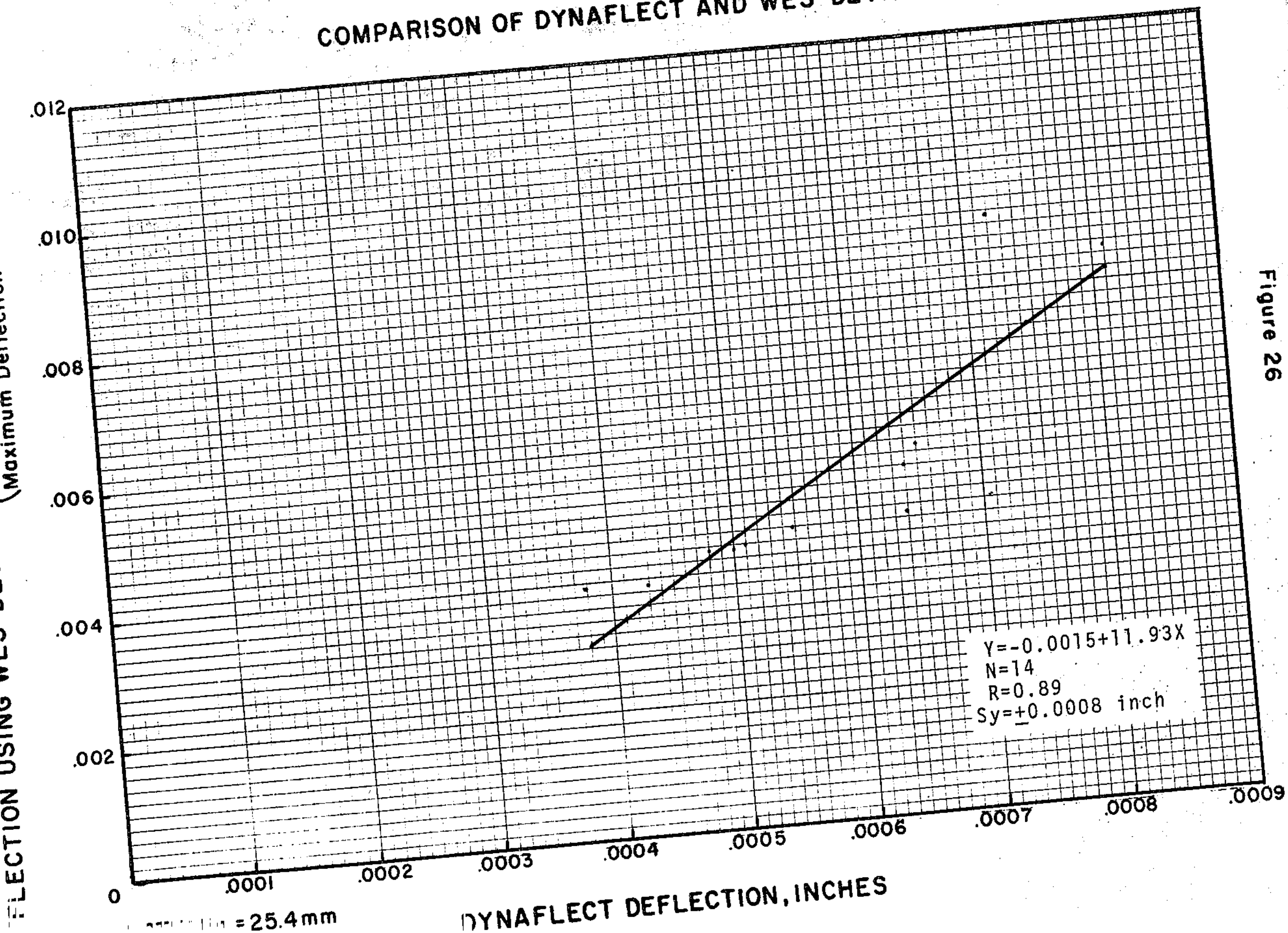
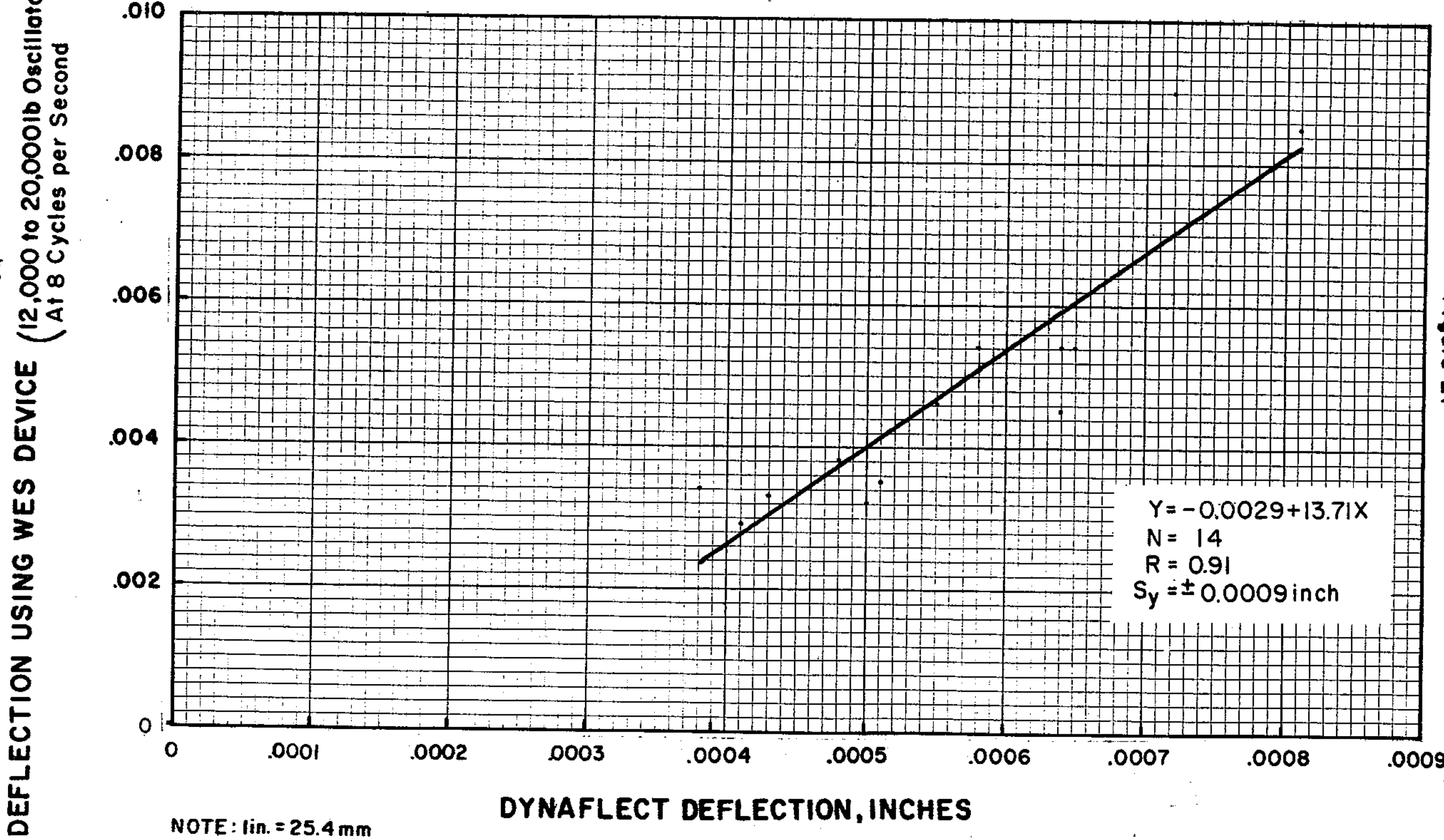


Figure 26

Figure 27

AIRPORT TESTING

COMPARISON OF DYNAFLECT AND WES DEVICE



NOTE: 1in. = 25.4 mm
1 lb = 0.45 kg

REFERENCES

1. Zube, E. and Forsyth, R. A., "Pavement Deflection Research and Operations Since 1938", California Division of Highways, Materials and Research Department, Research Report, April, 1966.

2. State of California, Division of Highways Materials Manual, Testing and Control Procedures, Vol. II, Test Method No. Calif. 356.

3. Zube, E., Tueller, D. O., Forsyth, R. A., and Hannon, J. B., "Evaluation of the Lane-Wells Dynaflect", State of California, Department of Public Works, Division of Highways, Materials and Research Department, Research Report 633297, October, 1968.

4. Hveem, F. N., "Pavement Deflection and Fatigue Failures", "HRB Bulletin 114, Highway Research Board, Washington, D. C., 1955.

5. Kingham, R. I., "San Diego Experimental Base Project: A Correlation of California and Canadian Benkelman Beam Deflection Procedures", Asphalt Institute Research Report 70-1, January 1970.

6. Zube, E. and Forsyth, R. A., "Flexible Pavement Maintenance Requirements as Determined by Deflection Measurements", Proceedings, 45th Annual Meeting of the Highway Research Board, January 1966.

7. Zube, E., Tueller, D. O. and Hannon, J. B., "K-Value Deflection Relationship for AC Pavements", State of California, Department of Public Works, Division of Highways, Materials and Research Department, Research Report 643449, November 1969.

8. Bushey, R. W., Baumeister, K. L., and Matthews, J. A., "Structural Overlays for Pavement Rehabilitation", Proceedings,

54th Annual Meeting of the Transportation Research Board, January 1975.

9. State of California, Division of Highways Materials Manual, Testing and Control Procedures, Vol. II, Test Method No. Calif. 359.

10. Majidzadeh, Dr. Kamran, "Dynamic Deflection Study for Pavement Condition Investigation", Ohio Department of Transportation, OHIO-DOT-16-74, June 1974.

11. Yang, Dr. Nai, "Design of Functional Pavements", McGraw-Hill Book Company, 1972.

12. Parl, Boris, "Basic Statistics", Doubleday and Company 1967.

13. Young, H. D., "Statistical Treatment of Experimental Data" McGraw-Hill Book Company, Inc., 1962.

APPENDIX

Table 1-A

Statistical Data (Roadway Testing)

	Curve Type	A	B	R	F	SYX
				Based on Linear Transformation		
Dynaflect vs. Deflectometer (All Sections) - See Figure 7						
1.	Y=A+B*X	-.004906	18.154933	.9168	2604.41	.007210
2.	Y=A*EXP(B*X)	.003537	959.953940	.8832	1751.46	.464918
3.	Y=A*X^B	167.266357	1.391526	.9296	3140.18	.365448
4.	Y=A+B/X	.044048	-.000020	.7662	702.42	.011604
5.	Y=1/(A+B*X)	262.288734	-96073.708631	.6175	304.48	111.595772
6.	Y=X/(A+B*X)	.151132	-36.507093	.7272	554.38	97.391555
U.S.F.S. Device vs. Deflectometer (All Sections) - See Figure 8						
1.	Y=A+B*X	.001004	4.087153	.8081	929.79	.010637
2.	Y=A*EXP(B*X)	.004876	214.667026	.7732	734.60	.628526
3.	Y=A*X^B	13.076850	1.241772	.8592	393.63	.507072
4.	Y=A+B/X	.037044	-.000043	.5956	271.58	.014506
5.	Y=1/(A+B*X)	232.069849	-21803.760278	.5487	212.79	118.613510
6.	Y=X/(A+B*X)	.331966	12.740797	.5851	257.21	115.053635
C.C.C. Device vs. Deflectometer (All Sections) - See Figure 9						
1.	Y=A+B*X	-.006343	12.235911	.8604	1408.44	.009202
2.	Y=A*EXP(B*X)	.003425	630.241542	.8074	925.14	.584812
3.	Y=A*X^B	466.851668	1.675212	.8878	1838.81	.456130
4.	Y=A+B/X	.049596	-.000048	.7712	724.81	.011497
5.	Y=1/(A+B*X)	263.344411	-62248.523137	.5571	222.36	117.819212
6.	Y=X/(A+B*X)	.337452	-68.645796	.6940	458.92	102.153453
U.S.F.S. Device vs. Dynaflect (All Sections) - See Figure 10						
1.	Y=A+B*X	.000438	.206427	.8082	930.47	.000537
2.	Y=A*EXP(B*X)	.000571	148.206872	.7992	873.19	.398012
3.	Y=A*X^B	.133330	.857880	.8886	1854.46	.303682
4.	Y=A+B/X	.002301	-.000002	.6393	341.41	.000701
5.	Y=1/(A+B*X)	1745.612988	-------------	.7273	554.69	468.538786
6.	Y=X/(A+B*X)	2.028130	370.320192	.7430	608.72	456.916839

APPENDIX

Table I-A

Statistical Data (Roadway Testing)

Based on Linear Transformation

[illegible] (All Sections) - See Figure 7

	A	B	R	F	SYX
	-.004906	18.154933	.9168	2604.41	.007210
[illegible]	.003537	959.953940	.8832	1751.46	.464918
	167.266457	1.391526	.9296	3140.18	.365448
	.040048	-.000020	.7662	702.42	.011604
[illegible]	262.288734	-96073.708631	.6175	304.48	111.595772
[illegible]	.151132	-36.507093	.7272	554.38	97.391555

[illegible] Vs. Deflectometer (All Sections) - See Figure 8

	A	B	R	F	SYX
	.001004	4.087153	.8081	929.79	.010657
[illegible]	.004876	214.667026	.7732	734.69	.628526
	13.076850	1.241772	.8592	393.63	.507072
	.53044	-.000043	.5956	271.58	.014506
[illegible]	252.069846	-21803.760278	.5487	212.79	118.613510
[illegible]	.533966	12.740797	.5851	257.21	115.058635

[illegible] Vs. Deflectometer (All Sections) - See Figure 9

	A	B	R	F	SYX
	-.006943	12.235911	.8604	1408.44	.009203
[illegible]	.003425	630.241542	.8074	925.14	.564912
	466.851668	1.675212	.8878	1898.81	.456130
	.049596	-.000048	.7712	724.81	.011497
[illegible]	263.344411	-62248.523137	.5571	222.36	117.819212
[illegible]	.337452	-68.645796	.6940	458.92	102.153154

[illegible] Vs. Dynaflect (All Sections) - See Figure 10

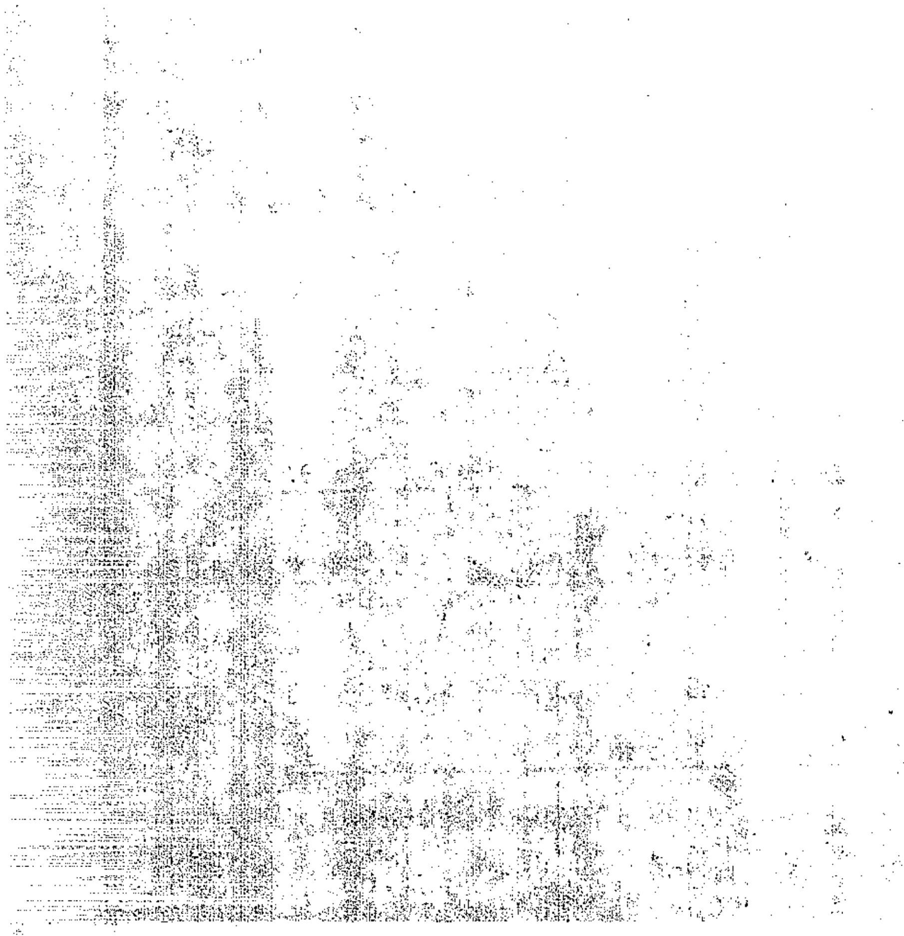
	A	B	R	F	SYX
	.000438	.206427	.8082	930.47	.000537
[illegible]	.000571	148.206872	.7992	873.19	.398012
	.133330	.857880	.8886	1854.46	.303682
	.002301	-.000002	.6393	341.41	.000701
[illegible]	175.612988	----------	.7273	554.69	468.538786
[illegible]	2.028130	370.320192	.7430	608.72	456.916839

Table 1-A (Continued)

				Based on Linear Transformati-		
	Curve Type	A	B	R	F	SYX
C.C.C. Device vs. Dynaflect (All Sections) - See Figure 11						
1.	Y=A+B*X	-.000005	.645476	.8988	2077.00	.000400
2.	Y=A*EXP(B*X)	.000436	445.140112	.8537	1327.39	.344834
3.	Y=A*X^B	1.669567	1.166805	.9257	2959.04	.250444
4.	Y=A+B/X	.002977	-.000003	.8249	1052.06	.000515
5.	Y=1/(A+B*X)	1962.725815	------------	.7510	639.06	450.757519
6.	Y=X/(A+B*X)	2.068367	-130.272851	.8840	1766.93	319.099403
C.C.C. Device vs. U.S.F.S. Device (All Sections) - See Figure 12						
1.	Y=A+B*X	.000233	2.218168	.7889	814.15	.002194
2.	Y=A*EXP(B*X)	.001613	426.444387	.7896	817.63	.420916
3.	Y=A*X^B	5.265216	1.148481	.8797	1689.75	.326212
4.	Y=A+B/X	.010572	-.000009	.7395	596.07	.002404
5.	Y=1/(A+B*X)	573.456165	------------	.6002	278.16	200.030407
6.	Y=X/(A+B*X)	.744434	-108.876357	.8685	1516.93	123.951500
Dynaflect vs. Deflectometer (Thick Sections) - See Figure 13						
1.	Y=A+B*X	-.004327	16.971006	.8535	413.19	.003288
2.	Y=A*EXP(B*X)	.001936	1543.634871	.6862	137.07	.519324
3.	Y=A*X^B	60.159401	1.260501	.6751	129.08	.526673
4.	Y=A+B/X	.018077	-.000006	.6075	90.06	.005013
5.	Y=1/(A+B*X)	383.179528	------------	.3813	26.21	171.496331
6.	Y=X/(A+B*X)	.126998	15.300691	.4111	31.32	169.114214
Dynaflect vs. Deflectometer (Thin Sections) - See Figure 14						
1.	Y=A+B*X	-.004372	17.954110	.8299	747.93	.008423
2.	Y=A*EXP(B*X)	.008109	617.576775	.8184	685.26	.302678
3.	Y=A*X^B	65.986046	1.237460	.8807	1169.10	.249404
4.	Y=A+B/X	.051710	-.000033	.6308	223.36	.011715
5.	Y=1/(A+B*X)	116.464709	-35607.199479	.5446	142.50	38.269752
6.	Y=X/(A+B*X)	.130515	-30.283214	.8368	789.70	24.980630
U.S.F.S. Device vs. Deflectometer (Thick Sections) - See Figure 15						
1.	Y=A+B*X	-.002065	3.495971	.8066	286.75	.003730
2.	Y=A*EXP(B*X)	.002346	323.281114	.6593	118.42	.536804
3.	Y=A*X^B	4.545047	1.112495	.6575	117.27	.537938
4.	Y=A+B/X	.017407	-0.00023	.5997	86.46	.005051
5.	Y=1/(A+B*X)	354.586373	-46340.403814	.3637	23.48	172.810246
6.	Y=X/(A+B*X)	.397833	52.214820	.3587	22.74	173.168588

Table 1-A (Continued)

	Curve Type	A	B	Based on Linear Transformation R	F	SYX
U.S.F.S. Device vs. Deflectometer (Thin Sections) - See Figure 16						
1.	Y=A+B*X	.010807	3.076600	.6416	236.46	.011580
2.	Y=A*EXP(B*X)	.014113	101.618570	.6075	197.68	.418332
3.	Y=A*X^B	1.325409	.756811	.7265	377.84	.361881
4.	Y=A+B/X	.038399	-.000024	.3682	53.04	.014036
5.	Y=1/(A+B*X)	86.627057	-6136.604001	.4234	73.83	41.337197
6.	Y=X/(A+B*X)	.157225	12.049147	.8074	633.05	26.920297
C.C.C. Device vs. Deflectometer (Thick Sections) - See Figure 17						
1.	Y=A+B*X	-.005769	9.287720	.8420	375.28	.003404
2.	Y=A*EXP(B*X)	.001604	885.508818	.7096	156.23	.503027
3.	Y=A*X^B	120.385032	1.505260	.7072	154.04	.504812
4.	Y=A+B/X	.021760	-.000018	.6783	131.25	.004637
5.	Y=1/(A+B*X)	414.722701	------------	.4041	30.06	169.694611
6.	Y=X/(A+B*X)	.328965	-31.853912	.4177	32.55	168.555770
C.C.C. Device vs. Deflectometer (Thin Sections) - See Figure 18						
1.	Y=A+B*X	.001832	10.174889	.7384	405.24	.010181
2.	Y=A*EXP(B*X)	.010950	322.645115	.6712	277.15	.390378
3.	Y=A*X^B	19.418296	1.110309	.7819	531.60	.328333
4.	Y=A+B/X	.050628	-.000045	.5863	177.08	.012230
5.	Y=1/(A+B*X)	89.805078	-15663.578230	.3762	55.69	42.278943
6.	Y=X/(A+B*X)	.183588	-26.588939	.7854	544.38	28.240527



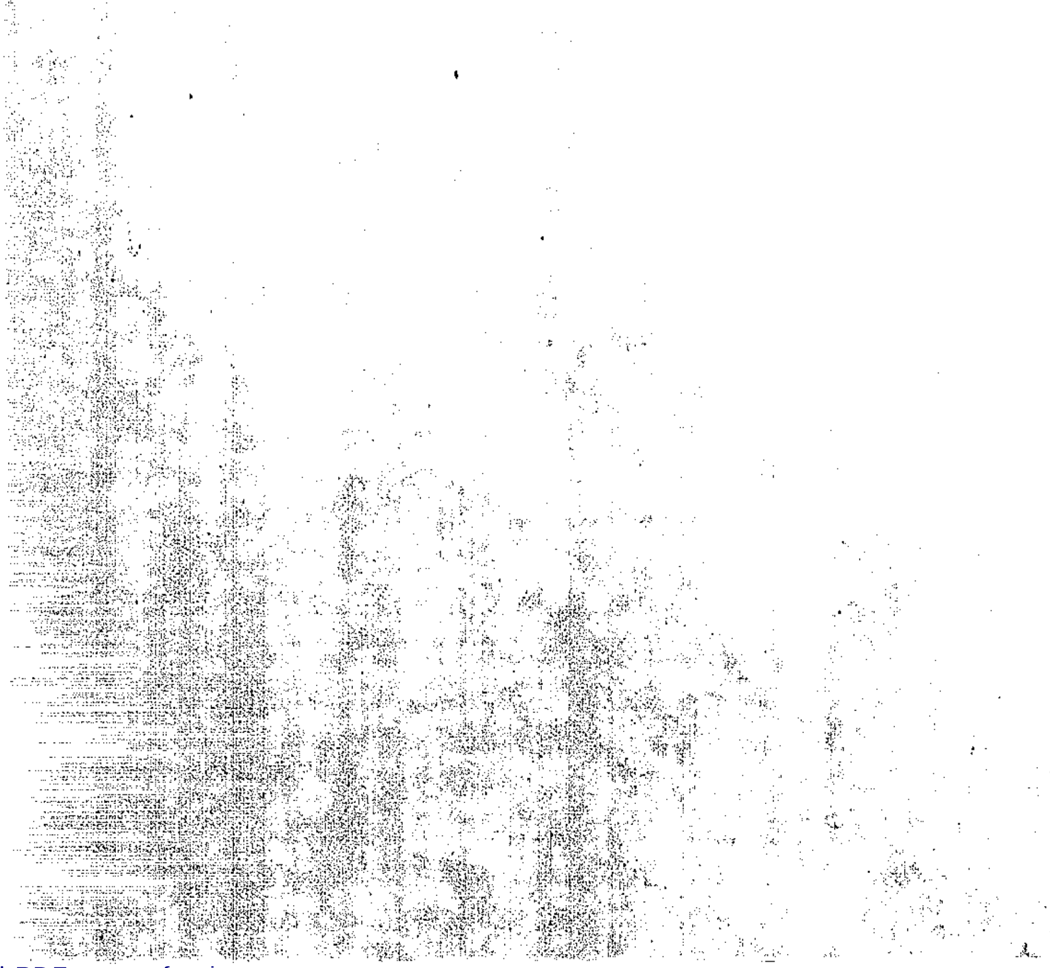


Table 2-A

Statistical Data (Airport Testing)

	Curve Type	A	B	R	F	SYX
				Based on Linear Transformati...		
Benkelman Beam vs. Wes Device (Lowest Frequency) - See Figure 20						
1.	Y=A+B*X	.000718	.250095	.5546	2.67	.001243
2.	Y=A*EXP(B*X)	.001617	63.605242	.4887	1.88	.376331
3.	Y=A*X^B	.094576	.742797	.4561	1.58	.383852
4.	Y=A+B/X	.006513	-.000032	.4807	1.80	.001310
5.	Y=1/(A+B*X)	518.162804	-17345.552178	.4259	1.33	122.187239
6.	Y=X/(A+B*X)	2.049894	130.541595	.3423	.80	126.888262
Benkelman Beam vs. Wes Device (Maximum Deflection) - See Figure 21						
1.	Y=A+B*X	.000639	.456049	.7314	13.80	.001321
2.	Y=A*EXP(B*X)	.002261	78.120807	.7056	11.90	.243625
3.	Y=A*X^B	.270910	.863161	.7090	12.13	.242457
4.	Y=A+B/X	.010204	-.000047	.6890	10.84	.001403
5.	Y=1/(A+B*X)	355.600695	-14346.801364	.6622	9.37	50.415880
6.	Y=X/(A+B*X)	1.570025	44.323445	.6654	9.53	50.226054
C.C.C. Device (33 Hz) vs. Wes Device (33 Hz) - See Figure 22						
1.	Y=A+B*X	.000104	1.593198	.8463	42.92	.000341
2.	Y=A*EXP(B*X)	.000564	1030.502320	.8421	41.46	.224366
3.	Y=A*X^B	.602772	.853644	.8386	40.28	.226664
4.	Y=A+B/X	.002462	-.000001	.6891	15.37	.000464
5.	Y=1/(A+B*X)	1447.586542	------------	.7982	29.85	196.493371
6.	Y=X/(A+B*X)	.451130	173.548055	.8619	49.11	165.424762
C.C.C. Device (45 Hz) vs. Wes Device (45 Hz) - See Figure 23						
1.	Y=A+B*X	-.000057	1.619284	.7863	27.52	.000363
2.	Y=A*EXP(B*X)	.000412	1265.834031	.8057	31.46	.265226
3.	Y=A*X^B	.959663	.936976	.8062	31.57	.264922
4.	Y=A+B/X	.002150	-.000001	.6675	13.66	.000437
5.	Y=1/(A+B*X)	1890.731668	-.1159752E+07	.7946	29.12	252.584682
6.	Y=X/(A+B*X)	.568179	145.630245	.8542	45.90	216.281252
U.S.F.S. Device (33 Hz) vs. Wes Device (33 Hz) - See Figure 24						
1.	Y=A+B*X	.000760	1.956977	.8641	50.12	.000322
2.	Y=A*EXP(B*X)	.000878	1221.936220	.8301	37.66	.232031
3.	Y=A*X^B	--------	-----------	-----	-----	--------
4.	Y=A+B/X	--------	-----------	-----	-----	--------
5.	Y=1/(A+B*X)	1104.556416	-----------	.7562	22.71	213.447348
6.	Y=X/(A+B*X)	--------	-----------	-----	-----	--------

Table 2-A (Continued)

	Curve Type	A	B	R	F	SYX
				Based on Linear Transformati		
U.S.F.S. Device (45 Hz) vs. Wes Device (45 Hz) - See Figure 25						
1.	Y=A+B*X	.000630	2.021647	.8340	38.83	.000324
2.	Y=A*EXP(B*X)	.000726	1486.231158	.8037	31.02	.266443
3.	Y=A*X^B	--------	-----------	-----	-----	--------
4.	Y=A+B/X	--------	-----------	-----	-----	--------
5.	Y=1/(A+B*X)	130.781408	-.1270166E+07	.7393	20.50	280.116242
6.	Y=X/(A+B*X)	--------	-----------	-----	-----	--------
Dynaflect vs. Wes Device (Maximum Deflection)-See Figure 26						
1.	Y=A+B*X	-.001500	11.925028	.8933	47.37	.000825
2.	Y=A*EXP(B*X)	.001535	2096.906551	.9275	73.87	.116179
3.	Y=A*X^B	30.502369	1.160980	.9066	55.42	.131109
4.	Y=A+B/X	.011535	-.000003	.8240	25.39	.001040
5.	Y=1/(A+B*X)	426.551980	------------	.9435	97.31	18.791510
6.	Y=X/(A+B*X)	.115603	-8.699657	.9124	59.62	23.214810
Dynaflect vs. Wes Device (8 Hz) - See Figure 27						
1.	Y=A+B*X	-.002864	13.713341	.9083	56.59	.000868
2.	Y=A*EXP(B*X)	.001044	2615.172392	.9328	80.39	.138887
3.	Y=A*X^B	247.895411	1.452500	.9147	61.49	.155726
4.	Y=A+B/X	.012154	-.000004	.8412	29.05	.001122
5.	Y=1/(A+B*X)	535.079172	-----------	.9325	79.96	28.635215
6.	Y=X/(A+B*X)	.160389	-67.428522	.9057	54.77	33.604424

Table 3-A

Typical Data Sheet For WES Device

San Jose Airport Frequency Sweep Data

Test Location 9
11 Sep 1975, 0113 hr

Frequency Hz	Force lb	Deflection in.
4.98	5036.4	0.002589
6.07	4949.9	0.003128
7.13	4977.4	0.003367
8.20	4979.4	0.003851
9.07	5027.0	0.004553
10.17	5075.4	0.003594
11.22	4969.9	0.002718
12.26	4962.1	0.002464
14.25	4995.1	0.002195
16.33	4985.9	0.001978
18.51	5068.7	0.001797
20.33	4985.5	0.001618
22.17	4999.6	0.001527
24.27	4965.1	0.001429
25.62	5018.4	0.001429
28.32	4970.7	0.001259
30.50	4975.8	0.001183
32.57	4988.1	0.001102
34.70	5004.2	0.001020
37.03	5072.4	0.000994
38.60	5028.8	0.000985
41.22	4990.5	0.000994
42.45	4953.0	0.000905
45.79	5002.5	0.000848
51.52	4954.5	0.000881
55.67	4938.5	0.000695
61.27	4924.4	0.000487
66.51	4993.9	0.000529

Test Location 11
11 Sep 1975, 0132 hr

Frequency Hz	Force lb	Deflection in.
4.97	4911.8	0.002407
6.12	4928.1	0.003086
7.02	5075.7	0.003173
8.02	4989.2	0.003522
9.07	4917.9	0.004290
10.17	4978.7	0.003495
11.12	4930.7	0.002753
12.10	4914.8	0.002531
14.33	4916.7	0.002230
16.13	4999.0	0.002053
18.33	5018.9	0.001872
20.33	5018.1	0.001672
22.27	4956.9	0.001545
24.47	4978.1	0.001545
26.07	5080.4	0.001380
28.15	5023.1	0.001330
30.87	4927.3	0.001173
32.53	5092.8	0.001156
34.73	5064.8	0.001025
35.92	4989.9	0.000995
39.00	4978.1	0.000970
40.91	4978.3	0.000965
42.49	4981.4	0.000837
45.27	4920.4	0.000771
50.71	4992.8	0.000851
55.53	5041.4	0.000694
61.17	5024.6	0.000485
66.27	5027.6	0.000418
71.39	4982.3	0.000848

Test Location 13
11 Sep 1975, 0149 hr

Frequency Hz	Force lb	Deflection in.
4.97	4999.2	0.003513
6.04	4973.8	0.004138
7.12	4953.3	0.004374
7.93	4975.9	0.004694
9.05	5057.4	0.005445
10.08	5085.6	0.005179
11.21	4972.6	0.003955
12.29	5003.5	0.003689
14.24	5006.8	0.003359
16.32	5058.5	0.002945
18.26	5096.4	0.002506
20.27	5015.1	0.002238
22.50	5076.4	0.002010
24.51	5082.4	0.001830
26.32	5021.4	0.001622
28.20	4964.3	0.001545
30.62	4918.2	0.001465
31.97	4935.4	0.001425
34.80	5018.3	0.001305
36.04	4971.8	0.001274
38.53	5060.3	0.001240
41.23	5006.0	0.001195
42.71	5080.3	0.001093
45.85	5022.7	0.000990
51.39	4983.9	0.000993
56.28	5074.0	0.000799
60.57	5000.2	0.000571
65.97	5047.7	0.000399
71.43	5030.9	0.000713

Test Location 16
11 Sep 1975, 0211 hr

Frequency Hz	Force lb	Deflection in.
4.97	5074.3	0.001677
6.02	4956.6	0.002201
7.07	4991.9	0.002226
8.02	4976.2	0.002553
9.05	5041.6	0.003465
9.94	5065.1	0.003229
11.32	5003.9	0.001750
12.27	4985.7	0.001613
14.27	5047.4	0.001524
16.20	4982.5	0.001434
18.32	5006.5	0.001348
20.10	4990.8	0.001259
22.27	5045.6	0.001170
24.58	4944.9	0.001086
26.90	5098.8	0.001034
26.96	4919.4	0.001009
27.93	4938.8	0.001001
30.47	4948.1	0.000947
32.73	4933.9	0.000874
34.03	5065.6	0.000851
35.20	4962.6	0.000801
38.07	4949.4	0.000788
40.84	4930.8	0.000818
42.50	4950.5	0.000745
44.84	4983.4	0.000652
51.03	5022.9	0.000672
56.42	5016.2	0.000485
60.72	5002.4	0.000355
66.73	5011.8	0.000474
71.44	5027.3	0.000769

Test Location 10
11 Sep 1975, 0125 hr

Frequency Hz	Force lb	Deflection in.
4.95	4961.9	0.002319
6.10	5000.9	0.002936
7.00	4971.7	0.002989
8.02	4946.1	0.003319
9.05	5071.4	0.004097
10.09	4964.3	0.003688
11.15	4981.5	0.002717
12.20	5069.0	0.002535
14.25	4983.6	0.002181
16.25	5017.6	0.001973
18.51	5020.1	0.001721
20.40	5048.7	0.001567
22.33	5013.4	0.001432
24.72	5017.4	0.001326
26.57	5102.7	0.001245
26.47	5064.6	0.001242
27.27	5097.0	0.001224
30.14	5008.3	0.001108
31.51	4997.5	0.001075
35.17	5034.8	0.000945
38.12	5048.8	0.000877
40.63	4944.5	0.000923
42.66	4925.4	0.000823
45.53	4984.0	0.000731
51.09	4987.9	0.000789
55.70	5091.6	0.000631
62.05	5080.3	0.000422
66.87	4950.0	0.000345
71.64	5018.4	0.000631

Test Location 12
11 Sep 1975, 0144 hr

Frequency Hz	Force lb	Deflection in.
4.97	5005.7	0.002851
5.99	4981.4	0.003440
7.07	5076.0	0.003600
8.02	4975.6	0.003929
9.07	5016.7	0.004586
10.10	5000.3	0.004158
11.22	5064.0	0.003069
12.16	4966.9	0.002902
14.26	4976.4	0.002613
16.25	4949.0	0.002363
18.27	4985.1	0.002097
20.17	4968.1	0.001897
22.33	5021.3	0.001781
24.40	5003.8	0.001588
26.33	5073.9	0.001487
27.84	5094.1	0.001429
30.00	4983.1	0.001351
32.15	4994.8	0.001269
34.47	4950.0	0.001150
36.69	5034.3	0.001099
39.37	5020.3	0.001096
40.75	5001.9	0.001071
42.58	4923.9	0.000983
45.70	5029.1	0.000885
50.55	4928.3	0.000880
56.26	5045.2	0.000717
61.08	5043.9	0.000498
66.33	4949.9	0.000376
71.48	5065.8	0.000871

Test Location 15
11 Sep 1975, 0200 hr

Frequency Hz	Force lb	Deflection in.
4.96	5035.8	0.002216
6.03	4923.9	0.002754
6.96	5005.8	0.002824
8.02	4903.0	0.003186
9.00	5029.8	0.004007
10.00	4977.1	0.003794
11.20	4956.0	0.002424
12.17	4990.5	0.002241
14.17	4942.3	0.001959
16.27	4934.0	0.001723
18.25	5082.6	0.001606
20.26	4983.6	0.001425
22.47	5024.4	0.001333
24.66	4941.1	0.001245
26.47	5028.0	0.001166
29.00	5043.9	0.001104
30.97	4928.6	0.001041
32.53	4966.4	0.001004
34.71	4993.0	0.000930
36.46	5016.3	0.000894
38.22	4907.4	0.000858
40.67	4926.8	0.000689
42.73	4958.1	0.000806
45.75	5034.1	0.000748
50.77	4991.4	0.000781
56.02	5029.9	0.000615
60.77	4964.6	0.000442
66.32	5052.5	0.000445
71.00	5046.4	0.000783

Test Location 17
11 Sep 1975, 0221 hr

Frequency Hz	Force lb	Deflection in.
4.97	4981.7	0.001956
6.11	4981.6	0.002457
6.98	5010.9	0.002472
8.02	4963.6	0.002757
9.05	4998.5	0.003591
10.02	5058.4	0.003391
11.13	4940.5	0.002302
12.01	4979.5	0.002121
14.19	4962.9	0.001864
16.17	5012.9	0.001634
18.27	5092.9	0.001469
20.32	4953.9	0.001329
22.24	4964.9	0.001252
24.47	4941.2	0.001180
26.57	4930.9	0.001162
28.13	5001.3	0.001067
30.22	5064.9	0.001037
32.23	4952.5	0.000954
33.57	5077.6	0.000937
34.71	5062.1	0.000920
36.22	5020.6	0.000880
38.55	5002.8	0.000866
40.75	4995.9	0.000699
42.99	4939.4	0.000779
45.92	5018.8	0.000764
51.02	4952.9	0.000782
55.63	5009.6	0.000599
61.32	4914.0	0.000391
66.52	4952.8	0.000509
72.33	5017.6	0.000853

TECHNICAL REPORT STANDARD TITLE PAGE

Field	Content
1. REPORT NO.	CA-TL-7254-77-24
2. GOVERNMENT ACCESSION NO.	
3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE	LEAD EMISSIONS FROM ROADWAY VEHICLES
5. REPORT DATE	August 1977
6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S)	D. M. Coats, C. R. Sundquist, E. C. Shirley
8. PERFORMING ORGANIZATION REPORT NO.	19701-657254
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Office of Transportation Laboratory California Department of Transportation Sacramento, California 95819
10. WORK UNIT NO.	
11. CONTRACT OR GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS	California Department of Transportation Sacramento, California 95807
13. TYPE OF REPORT & PERIOD COVERED	Final - 1977
14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

This report presents a synthesis of information on particulate lead in the urban-suburban community. It results from a limited review and is intended only as an aid to Transportation District Environmental Analysis. Emphasis is placed on lead emitted from vehicles using transportation systems. A method of estimating lead particulate emissions, in grams per mile, from a composite vehicle, is presented. The emission rates are calculated as a function of calendar year, vehicle type, distribution, and fraction of non-catalyst equipped vehicles.

Field	Content
17. KEY WORDS	Vehicle emission factors, air quality, air pollution, lead, Particulates, dispersion.
18. DISTRIBUTION STATEMENT	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161
19. SECURITY CLASSIF. (OF THIS REPORT)	Unclassified
20. SECURITY CLASSIF. (OF THIS PAGE)	Unclassified
21. NO. OF PAGES	43
22. PRICE	

DS-TL-1242 (Rev.6/76)

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

August 1977

TL No. 657254

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

LEAD EMISSIONS FROM ROADWAY VEHICLES

Study made by .... Enviro-Chemical Branch

Under the Supervision of .... E. C. Shirley, P. E.

Principal Investigator .... C. R. Sundquist, P. E.

Co-Principal Investigator .... D. M. Coats

Report Prepared by .... D. M. Coats

Very truly yours,

GEORGE A. HILL
Chief, Office of Transportation Laboratory

DMC:bjs
Attachment

ACKNOWLEDGEMENTS

The contents of this report reflect the views of the Transportation Laboratory, which is responsible for the interpretation of facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views of the State of California. This report does not constitute a standard, specification or regulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

The reduction schedule for lead in gasoline is as follows:

Refineries With a Gasoline Production Capacity of <u>More</u> Than 20,000 Bbls/Day

Effective Date of Limitation	Three Month Average Maximum Lead Content (Grams Per Gallon)
January 1, 1977	1.4
January 1, 1978	1.0
January 1, 1979	0.7
January 1, 1980	0.4

Refineries With a Gasoline Production Capacity of <u>Less</u> Than 20,000 Bbls/Day.

Effective Date of Limitation	Three Month Average Maximum Lead Content (Grams Per Gallon)
January 1, 1979	1.7
January 1, 1980	1.4

STATUTORY REGULATIONS FOR LEAD

There have been several statutory regulations established to control or minimize the adverse health effects of lead and lead compounds. Some of the more significant mitigating measures affecting California are:

Occupational Safety and Health Act (OSHA), 1970-71 (Title 8, Cal OSHA, October 1973), Public Law 91-596.

Lead Based Paint Poisoning Prevention Act, 1971, Public Law 91-695.

National Consumer Health Information and Health Promotion Act of 1976, Public Law 94-317 (Lead in Paint).

Clean Air Act, Amendments of 1970.
42 U.S.C. 1857c-3 [108] Air Quality Criteria & Control Techniques.
42 U.S.C. 1857c-4 [109] Nat. Ambient Air Quality Standards.
42 U.S.C. 1857c-5 [110] Implementation Plans
42 U.S.C. 1857c-6c [211] Regulation of Fuels

California Air Resources Board, Ambient Air Quality Standards for Lead, November 19, 1970 (1.5 $\mu g/m^3$ for 30 day average).

California Air Resources Board Requires Reduction of Lead in Gasoline, ARB Resolution 76-3, February 19, 1976.

SOURCES OF LEAD

The subject of health effects of lead is not new. On an average day the human body absorbs approximately 23 micrograms (µg). Of this total, approximately 65 percent is due to ingestion and the remaining 35 percent is inhaled. This is discussed in more detail later in this report.

The potential toxic effect of lead has been recognized since antiquity. Early studies identified lead-based paints and eating utensils containing lead as hazards. In spite of this, man has continued to make new and greater uses of lead. Exposure to lead has come to us in many forms; in mining, smelting, cooking and eating utensils, water pipes, lead-based paints, storage batteries, insecticides, but mostly as an antiknock additive in gasoline. Over 90% of the lead emissions into the atmosphere are derived from the combustion of leaded gasoline.

For discussion purposes, these various sources of lead in our environment will be divided into two categories, stationary and mobile. Stationary sources are those sources that can be associated with a fixed geographical location. Mobile sources are synonomus with transportation vehicles, primarily the automobile.

Mobile Sources

Lead emissions into the atmosphere are in two basic forms, organic (alkyl lead compounds) and inorganic. Alkyl lead, generally tetraethyl (TEL) and tetramethyl (TML), are the antiknock compounds added to gasoline to increase its octane rating. Inorganic lead, in its basic form, Pb, is present naturally. Inorganic lead may also be present in various lead compounds (39), $PbCl \cdot Br$, $NH_4Cl \cdot 2PbCl \cdot Br$, $2NH_4Cl \cdot PbCl \cdot Br$, $3Pb_3(PO_4)_2 \cdot PbCl \cdot Br$, that are emitted in the exhausts of automobiles using leaded gasoline as fuel.

Tetraethyl lead (TEL) compound has been used to increase the octane rating of gasoline since about 1920. Since about 1959, tetramethyl lead (TML) has been used both separately and in combination with tetraethyl lead (TEL) to increase octane ratings. Their use is presently the most inexpensive method of raising the octane rating of gasoline. Other methods of increasing the octane rating are available to industry, such as further refining or other more costly additives. Economics have dictated the use of lead. As much as 4 grams of lead compound can be used in a gallon of gasoline. Generally the range would be 0.5 grams to 2.5 grams lead compound per gallon of gasoline.

When leaded gasoline evaporates, a portion of the evaporative emissions will be organic lead. The lead concentrations of the evaporative emissions will be, generally, less than the original concentration since lead compounds are less volatile than gasoline and tend to remain behind. The organic lead that has entered the atmosphere in this manner will change rapidly and oxidize due to its high reactivity with other compounds. There is disagreement about whether organic lead in its volatile state is subject to photochemical oxidation(39). Evaporation is now partially controlled with a gas tank ventilation cannister on new autos. Some counties have controls on service station fill hose connections to restrict vapor loss during filling operations.

As leaded gasoline goes through the combustion process in an internal combustion engine, it is subjected to extreme heat and pressure. This process transforms the organic lead to inorganic lead oxides and/or carbonates. These products are many and complex. The exhausted products are mainly governed by type and amounts of gasoline additives. These also include scavengers added to limit the amount of lead deposits that remain in the combustion chamber.

About 80% of the lead added to fuel and burned is eventually exhausted into the atmosphere. On a new vehicle or new exhaust system, a portion of the lead is accumulated in the exhaust system. This accumulation stabilizes after 20,000 to 30,000 miles. Older vehicles and likewise older exhaust systems will exhaust greater amounts of the lead particulates.

The remaining portion of the burned lead goes into the engine oil, accumulates in the oil filter, remains in the combustion chamber, or is collected in the exhaust system. The disposal of these items may be a potential source of lead emissions if not handled properly (i.e., burning of used motor oil). The amount of lead emissions from an automobile at a given time, varies greatly and is directly related to the speed and mode of operation as well as the immediately preceding speed and mode. Lead in the exhaust system accumulates under light and moderate use and is exhausted under hard acceleration and high speed.

For example, a moderate acceleration-deceleration combined with moderate urban cruise speed would allow lead to build-up in the exhaust system due to reduced velocity of the exhaust gas. Then, under a hard acceleration and high speed cruise mode, such as would be experienced on entering an expressway or freeway, an increase of the exhaust gas velocity would occur causing lead particulates to dislodge from the exhaust system and be emitted into the atmosphere.

The lead particulates being emitted under "city type" driving would generally have diameters less than 5μ with only about 5% to 10% equal to or less than 1μ. Under highway cruise mode approximately 65% of the lead particulates in the immediate roadside atmosphere have diameters under 2μ and over 85% are under 4μ(10).

Measurements by various researchers indicate that the highest concentration of atmospheric lead from automobiles is found immediately adjacent to the roadway. One study(10) shows that the airborne concentration due to traffic was reduced about 50% between 10 feet and 30 feet from the edge of pavement. Additionally 50% of the 6.5μ particulates had settled out in approximately one mile. Only about 6% to 13% of the particles were greater than 3.5μ. Evidence from this study and one other(11) indicates that the lead loss rate was approximately 23% to 32% per 100 feet for each 100 feet between 100 feet and 500 feet downwind from the roadway.

Any study of lead particulate emissions is highly influenced by meteorology. Wind, weather, humidity, and precipitation play an important role in transporting and scavenging pollutants. This will be discussed further in another section.

Stationary Sources

Stationary sources may be a major contributor to a small sector or corridor. Sometimes this is not obvious. Such is the case of houses painted with lead based paint. As the paint ages and oxidizes, its dust contributes lead to the environment in the immediate vicinity of the painted surface. It can then be transported by wind and water. Lead deposited on the ground can be carried into the home on shoes. This can be very significant if the home has infants playing on the floor or on the ground in the yard. It is especially significant for children afflicted with pica, a condition that causes children to eat soil and other inorganic substances.

Effects of other stationary sources such as smelting or battery manufacture will vary greatly. Established emission controls for such facilities do exist. Consequently, their zone of influence will vary as a function of the effectiveness of their emission controls.

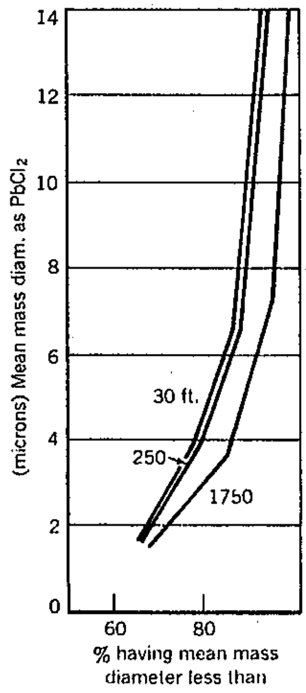


FIGURE 1. Relationship of the Diameter of the Particles (mass diameter) to Distance From the Highway. As per(10) Robert H. Daines, Harry Motto, et al.

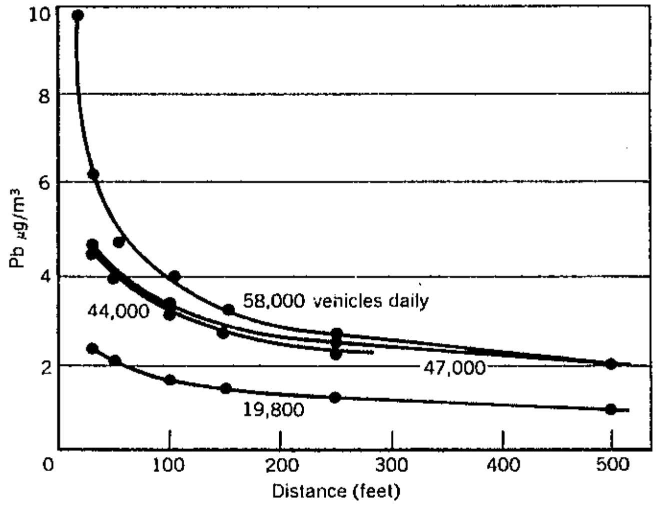


FIGURE 2. Air-Lead Values as a Function of Traffic Volume and Distance from the Highway. As per(10) Robert H. Daines, Harry Motto, et al.

Petroleum service stations are a potential source of lead emissions. Evaporation of leaded fuel results in organic lead emissions. Because the compounds are highly reactive, oxidation takes place rapidly and transformation from a vapor to a particulate occurs in a relatively short time. New controls by some counties place restrictions on the equipment used to fill tanks in autos as well as storage tanks. These controls restrict the amount of vapors that can enter the atmosphere.

Since all lead originates from the earth, the earth too, is a contributor to atmospheric lead. However, naturally occurring lead levels are very low. For comparison, the annual average lead aerosol concentration at White Mountain, California of 0.0080 $\mu g/m^3$ may be considered the baseline for lead "clean" atmospheres in the continental United States(19).

Lead finds its way to humans daily. Canned foods are a common contributor since the cans are soldered and solder contains lead. Fresh produce when unwashed may have many times the lead level that occurs on washed produce. Concern has been voiced about lead uptake by plants. Generally, lead contamination to the above ground portions occurs from settling of particulates and is reduced greatly by washing. Lead uptake in the subsurface portion of the plant can occur and is influenced by low soil pH. Lead translocation in the plant from the subsurface portion to the above ground portions is controversial. Conclusive evidence is not available on plant uptake from surface lead deposits.

DOSE-RESPONSE INFORMATION

It is valuable to know that elevated lead levels in living organisims may be unhealthy. Additionally, it is important to know that control of elevated lead exposure levels has a favorable effect on health. What is most important is the balance of exposure to lead with minimal adverse health effects.

Humans

Human response to elevated lead levels varies with the individual. It is, however, accepted that infants under five years have greater identifiable responses to comparable exposures, than do adults. Exposure to lead is primarily through eating food, drinking water, and breathing air. Children with pica may expose themselves to higher levels.

Lead generally enters the body through ingestion and inhalation. On the average, ingestion of lead accounts for about 65 percent of the body burden. The ingested contribution of lead to the body ranges from about 120 μg to 350 μg lead/day/person(3). Of this amount, about 10 percent may be absorbed. Inhaled lead accounts for about 35 percent of the body burden with an absorption rate ranging from 20 percent to 50 percent. The absorption rate for inhaled lead is very dependent on particle size. Smaller particles have the opportunity to penetrate deeper into the respiratory tract where absorption rates are higher. Hence, the smaller the particles, the higher the absorption rate. Commonly, humans inhale approximately $20m^3$ of air per day.

From the above, a conservative estimate of absorbed lead can be made. Assuming an ambient air lead level of 2 $\mu g/m^3$ and an ingested level of 150 μg lead per day:

Ingested Contribution

Assumed: 150µg/day x 10% absorbed = 15 µg/day (65%)

Inhaled Contribution

20 m^3/day x 2 µg/m^3 lead x 20% absorbed = 8 µg/day (35%)

Total lead absorbed per day is 23 µg/day (100%)

One source(4) states that the contribution of the respired lead to total blood lead is minor in comparison to other sources, 1.2 µg/100 ml lead in blood for every 1 µg/m^3 lead in air. This contribution appears small but lead can accumulate in the body. A person with an existing blood lead level of 40 µg/100 ml might be concerned. Continued exposure to elevated lead levels can increase the body burden(3). The body mechanism is very complex and all the variables associated with accumulation of lead with the body burden will not be addressed here. Different sources identify blood lead to be clinically significant at greatly differing levels. Levels generally associated with identifiable responses range from 30 to 80 µg/100 ml blood lead. California Air Resources Board (ARB) established its ambient lead levels of 1.5 µg/m^3 for 30 day average such that the mean blood lead level would be 15 µg/100 ml blood lead and that no more than 5% would exceed 30 µg/100 ml blood lead. A conservative standard, for some metropolitan areas, but, one that can be met by removing lead from gasoline.

Symptoms of mild lead intoxication include loss of appetite, irritability, drowsiness, apathy, and abdominal pain. Since these symptoms also have other causes, the contribution of lead is usually difficult to evaluate. Higher levels may cause mental retardation or hyperactivity in children.

Lead is known to interfere with enzyme systems. Delta amino levulinic acid dehydratase(ALAD), an enzyme involved in hemoglobin synthesis, is the best documented example of lead enzyme inhibition in man; however, the significance of ALAD inhibition in man is not clear at this time. Children that may be sensitive to lead ingestion are those that are anemic and calcium deficient(3).

Other health effects from elevated lead levels include impairment of mental and neurological development in children and nerve impulse transmission in adults.

Healthy adults do not normally show symptoms of lead poisoning until blood lead levels reach 80 µg/100 ml, but, in children, cases of lead poisoning have been reported at blood lead levels of 40-50 µg/100 ml.

Vegetation

The response of vegetation to elevated lead levels is not rapid and only occurs in a narrow corridor near the source. This corridor would seldom exceed 500 ft.

Lead exists in most soils naturally, but its effect in most cases is only minor and goes unnoticed. Vehicular contributions and contributions from stationary sources are somewhat greater. As lead particulates settle from the atmosphere, they come to rest on foliage, on the ground, or whatever else is present (impaction). Smooth surfaces tend to retain less of these particulates than do rough surfaces. These accumulations on surfaces are periodically washed with precipitation bringing the upper level particulates increasingly lower, eventually to ground level. This then becomes a surface deposit and will remain as such in one form or another. There is no conclusive evidence regarding contributions of surface deposits to plant uptake. The above-ground portion of the plant can be cleansed for human consumption by washing. The subsurface portion of the plant may takeup lead if it is present in the soil. This is dependent on the plant type, and is influenced by soil pH. If the plant is part of an agricultural crop, a farmer is probably tilling the soil. This relocates the surface deposited lead to the subsurface and makes it available for plant up-take.

Grazing animals would be subjected primarily to the surface deposited lead present on foliage. As shown previously, ingested lead is known to have less effect on humans than inhaled lead and it is assumed to have similar effects on other animals.

Plants growing near roadways are contaminated primarily on their above-ground surfaces. This contamination diminishes as the perpendicular distance from the roadway or source increases.

TRANSPORT AND DISTRIBUTION

The average annual concentration of lead in the air of most cities in the United States ranges from 1 to 4 μg/m^3. One study in the Los Angeles area in 1965(1) recorded a maximum single sample concentration of 11.4 μg/m^3. The continental United States baseline for "lead-clean" atmospheres occurs at White Mountain, California with an annual average concentration of 0.0080 μg/m^3.

Determining the movement of lead in the air is very complex since transport is dependent on wind, weather, and terrain. Annual high concentrations have generally been witnessed in the fall and winter months while diurnal highs occur in the morning and evening following peak traffic. Atmospheric stability appears to play an important role in diffusion of lead particulates but documentation is inconclusive as to extent. Atmospheric lead contributions from roadways will always be greatest downwind of the source.

Traffic volume of non-catalytically controlled vehicles that burn leaded gasoline will determine the source strength at the roadway.

Lead, being a heavy substance, settles more quickly than many other airborne particulates. One study(10) reports the corridor along a roadway that would be expected to have high lead concentrations would be limited to approximately 250 ft from the roadway.

Lead and other particulates are subject to settling and impaction. Receptors or barriers contacted tend to accumulate a high percentage of the particulates being moved. Any roadside trees and shrubs "filter" the air as it passes these barriers. The particulates become be resident in this "filter" until scavenged by precipitation or reentrained. The effectiveness is related to wind velocities, i.e., the lower the wind velocity the more effective the barrier.

The smaller particulates, less than 3μ, tend to stay aloft until scavenged by rainfall or until impaction occurs. Under certain climatic conditions, particulates become condensation nuclei which increases their mass causing them then to settle out.

Moisture on surfaces contacted by particulates reduces reintrainment. Conversely, dry dusty conditions promote reentrainment.

EMISSIONS

Research is currently being conducted by various groups across the nation to better understand and document the influence of parameters involved in the transport and dispersion of lead particulates. Modeling efforts have been few and limited.

To date, neither the Environmental Protection Agency (EPA) nor ARB have published formal guidelines for calculating lead emissions. EPA, however, has provided particulate emission rates, for vehicles using leaded fuel, in Supplement No. 5(14). This, and additional information in an unpublished EPA report(6) provide sufficient data for making estimates.

This section provides tables for making an approximation of the total and suspended lead particualtes from the California composite vehicle using information from the above sources and others.

From Table 1 (page 19) note that an 85% reduction in non-sulfate particulates results from the use of unleaded fuel in light duty autos (LDA).

All particulates related to leaded fuel are not lead. Vehicles burning leaded gasoline exhaust particulates containing numerous metallic salts and oxides. Among them are bromine, iron, and residual compounds used in the production of tetraethyl and tetramethyl lead additives and others such as lead scavengers.

Table 2 (page 20) indicates that exhaust particulate emissions from a "new" (less than 3 years) or "old" (equal to or greater than 3 years) vehicle burning leaded fuel contain about 46 percent lead.

Of the lead-containing particulates (46%) about 41 percent are suspended lead particulates.

The comparison here is made for the "old" ($\geq$3 year) vehicle since, with the exception of a few cars, only the Medium-Duty Trucks (MDT) and Heavy Duty Gasoline (HDG) Powered Trucks presently contain any "new" ($\leq$ 3 year) vehicles not equipped with catalyst systems. Statewide the MDT and HDG combined population is approximately 10 percent of the California fleet. Of this total, only 20 to 30 percent are "new" and non-catalytic. This population will continue to decrease as controls on these vehicles come about.

Particulate emission rates are different for each class of vehicle. The rates very as the rate of fuel consumed varies. This is accounted for in the EPA emission factors.

The calculations for a composite (average) vehicle are as follows. Input data include the inventory year and the fraction of each vehicle type in the study population. To determine the fraction of non-catalyst vehicles, assign the inventory year to, n, in the middle column of Tables 3 thru 6, and refer to Table 7. Table 7 lists those model year vehicles not equipped with catalyst systems and subject to using leaded gasoline. Once the non-catalyst vehicles are established for each vehicle type, sum the vehicle miles traveled (VMT) distribution for each non-catalyst vehicle type. Then compute, by vehicle type, the product of EPA emission factor, fraction non-catalyst (sum of VMT distribution) and fraction vehicle type. The sum of these products yields the total particulate emission rate for the composite vehicle. Multiply this total by 0.46 to get the total lead emission rate. For suspended lead particulate rate, multiply 0.41 times the total lead emission rate.

For convenience a form has been provided to simplify the calculations (Figure 3).

TABLE 1

EPA PARTICULATE EMISSION FACTORS, gm/mile

	Non-Catalyst Leaded Fuel	Non-Catalyst Unleaded Fuel	Catalyst Unleaded Fuel
LDA Exhaust Particulates (excluding sulfates and sulfuric acid)	0.34	0.05	0.05
Total LDA Exhaust Particulates	0.47	0.18	0.18
LDT-MDT Exhaust Particulates (excluding sulfates and sulfuric acid)	0.34	0.05	0.05
Total LDT-MDT Exhaust Particulates	0.52	0.23	0.23
HDG Exhaust Particulates (excluding sulfates and sulfuric acid)	0.91	----	----
Total HDG Exhaust Particulates	1.27	----	----

Note: 1 mile = 1.6093 km

Ref (14)

TABLE 2

EXHAUST PARTICULATES

gm/mile

	New (<3 yrs)	Old (≥3 yrs)
Total Exhaust Particulates	0.22	0.48
Suspended Particulates (<10μ)	0.18	0.35
Total Lead	0.10	0.22
Suspended Lead (<10μ)	0.06	0.09

Percent lead in exhaust particulates $\frac{0.22}{0.48} \times 100 = 46\%$

Percent suspended lead in exhaust particulates $\frac{0.09}{0.22} \times 100 = 41\%$

Percent lead in suspended particulates $\frac{0.09}{0.35} \times 100 = 26\%$

Note: 1 mile = 1.6093 km

Ref. (6)

TABLE 3

WEIGHTED NUMBER OF VEHICLES IN USE AND ANNUAL TRAVEL FOR LIGHT-DUTY AUTOMBILES

Nominal Age, Years		Model Year	VMT Distribution
0		n+1	0.00778
1	Inventory Year	n	0.12305
2		n-1	0.16851
3		n-2	0.14573
4		n-3	0.12364
5		n-4	0.10436
6		n-5	0.08512
7		n-6	0.06786
8		n-7	0.05195
9		n-8	0.03871
10		n-9	0.02730
11		n-10	0.01837
12		n-11	0.01140
13		n-12	0.00709
14		n-13	0.00463
15		n-14	0.00351
16		n-15	0.00263
≥17		n-16	0.00838
			1.00000

Ref.(43)

TABLE 4

WEIGHTED NUMBER OF VEHICLES IN USE AND ANNUAL TRAVEL FOR LIGHT-DUTY GASOLINE POWERED TRUCKS (≤ 6000-lb. GVW)

Nominal Age, Years		Model Year	VMT Distribution
0		n+1	0.00845
1	Inventory Year	n	0.13169
2		n-1	0.19578
3		n-2	0.15112
4		n-3	0.11567
5		n-4	0.08947
6		n-5	0.07004
7		n-6	0.05476
8		n-7	0.04209
9		n-8	0.03174
10		n-9	0.02354
11		n-10	0.01712
12		n-11	0.01225
13		n-12	0.00868
14		n-13	0.00663
15		n-14	0.00597
16		n-15	0.00530
≥17		n-16	0.02968
			1.0000

Note: 1-lb = 454 gm

Ref. (43)

TABLE 5

WEIGHTED NUMBER OF VEHICLES IN USE AND ANNUAL TRAVEL FOR MEDIUM-DUTY GASOLINE POWERED TRUCKS (6000-8500 lb. GVW)

Nominal Age, Years		Model Year	VMT Distribution
0		n+1	0.00845
1	Inventory Year	n	0.13169
2		n-1	0.19578
3		n-2	0.15112
4		n-3	0.11567
5		n-4	0.08947
6		n-5	0.07004
7		n-6	0.05476
8		n-7	0.04209
9		n-8	0.03174
10		n-9	0.02354
11		n-10	0.01712
12		n-11	0.01225
13		n-12	0.00868
14		n-13	0.00663
15		n-14	0.00597
16		n-15	0.00530
≥17		n-16	0.02968
			1.0000

Note: 1-lb. = 454 gm

Ref. (43)

TABLE 6

WEIGHTED NUMBER OF VEHICLES IN USE AND ANNUAL TRAVEL FOR HEAVY-DUTY, GASOLINE POWERED TRUCKS (>8500 lb. GVW)

Nominal Age, Years		Model Year	VMT Distribution
0		n+1	0
1	Inventory Year	n	0.08937
2		n-1	0.13791
3		n-2	0.11377
4		n-3	0.10455
5		n-4	0.08167
6		n-5	0.07671
7		n-6	0.05447
8		n-7	0.05051
9		n-8	0.04040
10		n-9	0.03704
11		n-10	0.02477
12		n-11	0.02223
13		n-12	0.01969
14		n-13	0.01757
15		n-14	0.01639
16		n-15	0.01521
≥17		n-16	0.09766
			1.0000

Note: 1-lb. = 454 gm

Ref. (43)

TABLE 7

FRACTION OF MODEL YEAR NOT EQUIPPED WITH CATALYST SYSTEMS

Model Year	LDA	LDT	MDT	HDG
Pre 1975	1.00	1.00	1.00	1.00
1975	0	0.75	1.00	1.00
1976	0	0	1.00	1.00
1977	0	0	1.00	1.00
1978	0	0	0	1.00
1979	0	0	0	1.00
1980	0	0	0	1.00
1981	0	0	0	1.00
1982	0	0	0	1.00
≥1983	0	0	0	0

Note: Motorcycles are not included due to their small contribution to total lead emissions.

Ref. (43)

FIGURE 3

CALCULATION SHEET FOR VEHICULAR LEAD EMISSIONS

Inventory Year, n, ____________

Vehicle Type	(1) EPA Emission Factor gm/mile (From Table 1)	(2) Fraction Non-Catalyst (From Table 7)	(3) Fraction Vehicle Type (From Traffic Data)	(4) Total Particulate Emission Rate, gm/mile (1)x(2)x(3) = (4)
LDA	0.47			
LDT	0.52			
MDT	0.52			
HDG	1.27			
			TOTAL	____________

(5) Total Particulate Emission Rate, gm/mile From (4)	(6) % Lead / 100	(7) Total Lead Emission Rate, gm/mile (5)x(6) = (7)	(8) % Suspended Lead / 100	(9) Suspended Lead Emission Rate, gm/mile (7)x(8) = (9)
	0.46		0.41	

Note: This approach does not include all vehicles (e.g., motorcycles, motorbikes). Those vehicles that have been excluded contribute a very small percentage of the lead particulates and have been omitted to simplify calculations.

REFERENCES

1. "Survey of Lead in the Atmosphere of Three Urban Communities", U. S. Department of Health, Education, and Welfare, Public Health Service Publication No. 999-AP-12, Washington, D. C., January, 1965.

2. "A Survey of Air and Population Lead Levels in Selected American Communities", U. S. Environmental Protection Agency, E.P.A. Publication No. EPA-R1-73-005, Washington, D. C., December, 1972.

3. "A Report to the 1976 Legislature on Health Effects of Air Pollution Pursuant to Assembly Concurrent Resolution No. 45", California, State, Health and Welfare Agency, Department of Health, 1975.

4. "Report on Reconsideration of Ambient Air Quality Standard for Lead of November 19, 1970", California State Air Resources Board, January 15, 1976.

5. State of California, Air Reosurces Board, Resolution 76-3, "ARB Requires Reduction of Lead in Gasoline", February 19, 1976.

6. Lillis, Edward J., and Dunbar, David R., Draft Report, "Impact of Automotive Particle Exhaust Emissions on Air Quality", U. S. Environmental Protection Agency, Washington, D. C., November 13, 1975.

7. Proceedings of the First Annual NSF Trace Contaminants Conference, Conference 730802, March, 1974.

8. "Automotive Lead Emissions", Part 1 and 2, Hearing before the Panel on Environmental Science and Technology of the Subcommittee on Environmental Pollution of Committee on Public Works, U. S. Senate, Ninety-Third Congress, second session, May 7 and 8, 1974, Serial Number 93-H41.

9. Ault, Wayne U., et al., "Isotopic Composition as a Natural Tracer of Lead in the Environment", Environmental Science and Technology, April, 1970.

10. Daines, Robert H., Motto, Harry, Chilko, Daniel M., "Atmospheric Lead: Its Relationship to Traffic Volume and Proximity to Highways", Environmental Science and Technology, April, 1970.

11. Schuck, E. A., Locke, J. K., "Relationship of Automotive Lead Particulates to Certain Consumer Crops", Environmental Science and Technology, April, 1970.

12. Smith, Ralph G., Szajnar, Joanne, and Hecker, Lawrence, "Study of Lead Levels in Experimental Animal", Environmental Science and Technology, April, 1970.

13. Public Law 94-317, 94th Congress, S. 1466 "National Consumer Health Information and Health Promotion Act of 1976" (Lead in Paint) June 23, 1976.

14. "Compilation of Air Pollution Emission Factors" Second Edition, Supplement No. 5, U. S. Environmental Protection Agency, Washington, D. C., December, 1975.

15. Coats, Deane M., Allen, Paul D., Loscutoff, William V., "Motor Vehicle Emission Factors for Estimates of Highway Impact on Air Quality", Publication No. CA-DOT-TL-7082-14-76-54, State of California, Caltrans, Transportation Laboratory, August, 1976.

16. Shirley, Earl C., et al., "Impact of Transportation Systems on the Air Environment", State of California, Caltrans, Transportat[illegible] Laboratory, May, 1975.

17. Ter Haar, G. L., Lenane, D. L., Hu, J. N., and Brandt, M., "Composition, Size, and Control of Automotive Exhaust Particulates", Journal of the Air Pollution Control Association, 1972.

18. Habibi, K., "Characterization of Particulate Lead in Vehicle Exhaust", Environmental Science and Technology, 1970.

19. Smith, William H., "Lead Contamination of the Roadside Ecosystem", Journal of the Air Pollution Control Association, August, 1976.

20. Solomon, Robert L., and Hartford, John A., "Lead and Cadmium in Dusts and Soils in a Small Urban Community", Environmental Science and Technology, August, 1976.

21. Liu, C. Y., Goodin, W. R., "A Two-Dimensional Model for the Transport of Pollutants in an Urban Basin", Atomospheric Environment, 1976.

22. Heichel, Gary, H. and Hankin, Lester, "Roadside Coniferous Windbreaks as Sinks for Vehicular Lead Emissions", Journal of the Air Pollution Control Association, August, 1976.

23. Public Law 91-596, "Occupational Safety and Health Act", 1970-71.

24. Public Law 91-695, "Lead Based Paint Poisoning Prevention Act", 1971.

25. Clean Air Act Amendments of 1970.

26. Altshuller, A. P., "Effects of Reduced Use of Lead in Gasoline on Vehicle Emissions and Photochemical Reactivity", U. S. Environmental Protection Agency, Research Triangle Park, N. C., February, 1972.

27. Purdue, Larry J., et al, "Determination of Organic and Total Lead in the Atmosphere by Atomic Absorption Spectometry" Analytical Chemistry, Vol. 45, No. 3, March, 1973.

28. Bullock, J. and Lewis, W. M., "The Influence of Traffic on Atmospheric Pollution", The High Street-Warwick, England, Atmospheric Environment, Vol. 2, pp 517-534, 1968.

29. Chow, Tsaihwa J., and Earl, John L., "Lead Aerosols in the Atmosphere: Increasing Concentrations", Science Vol. 169, August 7, 1970.

30. Kobayashi, Yoshitaka, Hori, Masahiro, Tsuchiya, Kenzzburo, "Distribution of Lead in the Air Near City Roads", Keio J. Med. 19:183-194, 1970.

31. Kehoe, Robert A., "Toxicological Appraisal of Lead in Relation to the Tolerable Concentration in the Ambient Air", Journal of the Air Pollution Control Association, September, 1969.

32. Laveskog, Anders, "A Method for Determination of Tetramethyl Lead (TML) and Tetraethyl Lead (TEL) in Air", Second International Clean Air Congress, International Union of Air Pollution Prevention Association, Washington, D. C., December 6-11, 1970.

33. Chisolm, J. Julian, Jr., "Lead Poisoning", Scientific American, Vol. 224, No. 2, February, 1971.

34. Page, A. L., Ganje, J. J., Joshi, M. S., "Lead Quantities in Plants, Soil, and Air near Some Major Highways in Southern California Hilgardia, Vol. 41, No. 1, July, 1971.

35. Bevan, J. G., Colwill, D. M., and Hogbin, L. E., "Measurements of Particulate Lead on the M4 Motorway at Harlington", Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Lab Report 626, 1974.

36. Colwill, D. M., and Hickman, A. J., "The Concentration of Volatile and Particulate Lead Compounds in the Atmosphere: Measurements at Four Road Sites", Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Lab. Report No. LR-545, 1973.

38. "Air Pollution Research, 1975 Annual Report", State of California, Air Resources Board, January, 1976.

39. "Lead, Airborne Lead in Perspective", National Academy of Sciences, Washington, D. C., 1972.

40. Lawrence, John H., and Landaw, Stephen A., "Heme Metabolism and Red Blood Cell Survival in Lead-Intoxicated Animals", University of California at Berkeley, California State Air Resources Board Projects: 7-078-1, 1973.

41. Zimdahl, Robert L., "Entry and Movement in Vegetation of Lead Derived From Air and Soil Sources", Journal of the Air Pollution Control Association, Vol. 26, No. 7, July, 1976.

42. Linzon, S. N., Chai, B. L., Temple, P. J., Pearson, R. G. and Smith, M. L., "Lead Contamination of Urban Soils and Vegetation by Emissions From Secondary Lead Industries", Journal of the Air Pollution Control Association, Vol. 26, No. 7, July, 1976.

43. "Data Base and Documentation for Estimating Emissions from Motor Vehicles in California", Report, State of California, Air Resources Board, May 1977.

APPENDIX A*

---

*Prepared by Meyer I. Haik and Aurora del Rosario, Air and Industrial Hygiene Laboratory, State Department of Health, Berkeley, California (December 1974)

Air and Industrial Hygiene Laboratory

ANALYSIS FOR LEAD CONTENT OF ATMOSPHERIC PARTICULATE MATTER COLLECTED ON HIGH-VOLUME GLASS FIBER FILTERS

1. Principle of the Method

   1.1 Airborne particulate matter is collected on glass fiber filters using the high-volume air sampler. (10.1)

   1.2 The filter samples are extracted with hot nitric acid to solubilize the lead.

   1.3 The lead content of the resulting solution is determined by flame atomic absorption spectroscopy.

2. Range and Sensitivity

   2.1 The lowest concentration of Pb measured in this method is 200 µg per 8" x 10" filter. For a 2000 m^3 air sample, the lowest concentration measured in this method is therefore 0.1 µg/m^3 of air.

   2.2 The atomic absorption working range is 0.5 to 20 µg Pb/ml of solution. When the sample solution exceeds this concentration range, it can be diluted accordingly to extend the upper limit of the analysis.

3. Interferences

   3.1 No serious interferences have been reported for Pb. (10.2)

Prepared by Meyer I. Haik and Aurora del Rosario, Air and Industrial Hygiene Laboratory, State Department of Health, Berkeley, California (December 1974).

3. Interferences (continued)

3.2 Extract solutions with a solids content greater than 0.5% may exhibit a matrix effect. (10.3)

4. Precision and Accuracy

4.1 Precision and accuracy of the method using actual air samples have not been determined.

4.2 The recovery obtained as described in Section 7 indicates that, for an average of 14 determinations using glass fiber filters from two different manufacturers, a value of 99.4% ± 1.7 is found, i.e., the precision of this recovery determination is within 2%. (10.4)

4.3 The analytical result obtained from the analysis of the solution as described in Section 7.3 is 2% low when compared with a standard addition technique. This difference is not statistically significant (P = .60, Wilcoxon matched pairs rank test). (10.4)

5. Apparatus

5.1 Sample collection

5.1.1 A high-volume sampler equipped with a 8" x 10" glass fiber filter is used to collect the sample. The filter blank should be investigated to establish the extent of lead contamination.

5.2 Glassware

5.2.1 Borosilicate glassware should be used throughout the analysis. This includes: 500 ml Phillips beakers with covers, 100 ml volumetric flasks, funnels, 400 ml beakers, pipets. The glassware must be cleaned with 10% HNO_3 and rinsed with deionized water.

5. Apparatus (continued)

5.3 Equipment

5.3.1 Tank of acetylene gas

5.3.2 Air supply

5.3.3 Gas regulators for the above

5.3.4 Atomic absorption spectrophotometer

5.3.5 Hot plates

6. Reagents

6.1 A.C.S. reagent grade concentrated nitric acid, HNO_3

6.2 Reagent grade lead nitrate, $Pb (NO_3)_2$

6.3 Deionized water

7. Procedure

7.1 Sample preparation

7.1.1 One quarter section of the exposed area of the glass fiber filter is cut out. This portion is cut into pieces approximately one-inch square and placed into the Phillips beaker. Fifty ml of concentrated HNO_3 are added and the cover fitted. The beaker is placed on a hot plate and gently heated to boiling. After a one-hour refluxing period, the heating is discontinued, 50 ml deionized water added and the solution is filtered through Whatman 541 paper. The filtrate is collected into a 400 ml beaker. Hot deionized water is used to rinse the glass fiber residue until the volume is approximately 300 ml. The filtrate is evaporated on a hot plate to a 5-10 ml volume. This solution is quantitatively transferred into a 100 ml volumetric flask, allowed to cool and the volume adjusted with deionized water.

7. Procedure (continued)

7.2 Blank and Recovery

A blank 1/4 sheet glass filter and a blank 1/4 sheet glass filter to which a known quantity of Pb is added are carried through the same sample preparation procedure as described in 7.1. A Pb standard solution prepared as described in Section 8 is used for addition; 5 ml of the 100 µg/ml standard is adequate.

7.3 Analysis

7.3.1 The instrument operating parameters are set as recommended by the manufacturer. The wavelength used is the 2833 Å Pb line.

7.3.2 The Pb standard (8.3), the recovery sample (7.2), the blank (7.2) and the test samples (7.1) are respectively aspirated and the absorbances recorded. Solutions showing absorbances higher than that of the 20 µg/ml standard are diluted.

8. Standards and Calibration

8.1 Standard Pb, Master Solution

8.1.1 Dissolve 1.598 g of reagent grade $Pb(NO_3)_2$ in 1 liter of 1% HNO_3. This solution which contains 1000 µg Pb/ml is commercially available.

8.2 Dilute Standard, 100 µg Pb/ml

8.2.1 The Dilute Standard is prepared by diluting 10-fold the 1000 µg/ml Master Solution using 1% HNO_3.

8.3 Working Standards

8.3.1 Working Standards covering the range of 0.5 µg/ml through 20 µg/ml are prepared by appropriate dilution in 1% HNO_3 of the 100 µg/ml Dilute Standard. It is recommended that the Working Standards be freshly prepared.

9. Calculations

9.1 Calculating the concentration of the solution.

9.1.1 The standard curve relating absorbance to concentration is linear from 0.5 to 20 μg Pb/ml. The concentration of the sample is obtained by reading out of the standard curve or calculated from the linear regression equation.

Direct concentration read-out capability is available in certain instruments and this eliminates the need for plotting a curve or calculating concentrations.

9.2 Calculating the concentration of Pb in the air.

9.2.1

$$\mu g\ Pb/m^3 = \frac{\mu g\ Pb/ml \times 100\ ml \times 4}{\text{Volume of air, } m^3}$$

9.3 The blank value, if any, should be subtracted.

10. References

10.1 Orange County Air Pollution Control District, California, November 1973, unpublished method.

10.2 Slavin, W: Atomic Absorption Spectroscopy. New York, Inter-Science Publishers, 1968.

10.3 Thompson R, Morgan GB, Purdue LJ: Atomic Absorption Newsletter 9:3, 1970.

10.4 Air and Industrial Hygiene Laboratory, California State Department of Health, unpublished report. December 1974.