TECHNICAL REPORT NO. 3-666

PERFORMANCE OF SOILS UNDER TIRE LOADS

Report 4

ANALYSIS OF TESTS IN SAND FROM SEPTEMBER 1962 THROUGH NOVEMBER 1963

by

G. W. Turnage
A. J. Green, Jr.

February 1966

Sponsored by

U. S. Army Materiel Command

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U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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Task 03

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ARMY-MRC VICKSBURG, MISS.

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FOREWORD

This report concerns tests conducted at the U. S. Army Engineer Waterways Experiment Station (WES) as a part of the vehicle mobility research program under DA Project No. 1-V-0-21701-A-046, "Trafficability and Mobility Research," Task 1-V-0-21701-A-046-03, "Mobility Fundamentals and Model Studies," under the sponsorship and guidance of the Directorate of Research and Development, U. S. Army Materiel Command.

The tests were performed by personnel of the Mobility Section, Army Mobility Research Branch (AMRB), Mobility and Environmental Division, WES, during the period from April 1960 to November 1963 under the general supervision of Messrs. W. J. Turnbull, W. G. Shockley, and S. J Knight, and under the direct supervision of Dr. D. R. Freitag. Actively engaged in the study were Messrs. J. L. McRae, C. J. Powell, A. B. Thompson, R. D. Wismer, G. T. Easley, J. L. Smith, A. J. Green, G. W. Turnage, and N. R. Murphy. The data analysis was conducted by Messrs. Powell, Turnage, and Green. This report was prepared by Messrs. Turnage and Green, and Appendix A was prepared by Mr. Smith.

Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE, were Directors of the WES during this study, and Mr. J. B. Tiffany was Technical Director.

CONTENTS

SUMMARY

This report examines the effects of tire deflection, tread, carcass stiffness, construction, speed, and slip on tire performance in a dry sand. Laboratory tests results indicate that for best performance in a dry sand a tire should be highly deflected, smooth, and of diagonal-ply construction. Variations in carcass stiffness have negligible effects on tire performance when comparisons are made at equal loads and deflections. It was concluded that the performance of pneumatic tires in sand is affected by speed; however, the extent of this influence was not wholly determined. Logical, orderly relations are shown between slip and several independent and dependent variables--wheel load, soil strength, pull, and sinkage--both at the towed and the maximum pull points.

A direct relation is shown between the pull developed by a full-scale 4x4 vehicle and that developed by a single wheel in multiple passes. Good agreement was attained in this relation for both Yuma (desert) and mortar sand.

Significant differences in tire performance registered in Yuma and mortar sands at corresponding levels of soil strength (as measured by cone index) prompted a study of the physical characteristics of the two soils. This study revealed notable differences in the strength characteristics of Yuma and mortar sands that explain a portion of the differences in tire performance in the two sands.

PERFORMANCE OF SOILS UNDER TIRE LOADS

ANALYSIS OF TESTS IN SAND FROM SEPTEMBER 1962 THROUGH NOVEMBER 1963

PART I: INTRODUCTION

Background

1. In March 1960 the Chief of Research and Development, Department of the Army, directed the Office, Chief of Engineers,* to have the U. S. Army Engineer Waterways Experiment Station (WES) proceed with the investigation outlined in the document entitled Plan of Tests, "Performance of Soils Under Tire Loads," dated February 1960. The study was initiated immediately, using a system composed principally of a single-wheel dynamometer system and a series of movable soil bins. Test techniques were developed to vary the wheel slip during a run so as to allow the towed, self-propelled, and maximum pull conditions to be attained within the usable length of the soil bins. A desert sand and an alluvial clay were selected as principal test soils, and a third soil, river-deposited mortar sand, was used for auxiliary tests. A series of tires having different widths, diameters, cross sections, and structural characteristics was tested.

2. This investigation is described in a series of reports under the general title Performance of Soils Under Tire Loads (WES Technical Report No. 3-666).[9-11**] Report 1 of this series describes the techniques and equipment used in the WES mobility test program and presents details of the test plan. Report 2 presents results of the analysis of first-pass performance of a number of tires in Yuma sand based on test data procured through August 1962. Report 3 describes the preliminary analysis of the tire performance data from tests in fat clay. This report is the fourth in the series and continues the analysis of tire performance in sand that was begun in Report 2. Included are results from both single-wheel and

* Responsibility for ground mobility research was assigned to the U. S. Army Materiel Command in August 1962.

** Raised numbers refer to similarly numbered items in the Selected Bibliography following the main text of this report.

4x4 vehicle tests conducted in two sands. The test techniques employed for single-wheel tests are given in Report 1. The 4x4 vehicle and testing techniques used are described in the appropriate part of this report.

Purpose and Scope

3. The tests upon which this report is based are part of a comprehensive study of the interrelation of sand and moving pneumatic tires. The broad purpose of this study is to develop a basis for the selection of the appropriate tire size and inflation pressure to achieve the desired mobility for a given vehicle, load, and soil condition or range of soil conditions. The specific objectives of the study reported herein were to:

- a. Examine in detail the effects of several variables on tire performance in sand that were not thoroughly analyzed in Report 2.
- b. Demonstrate that the performance data obtained with the single wheel provide a valid basis for predicting performance of a multiwheel vehicle.
- c. Compare the physical characteristics and the behavior of the Yuma and mortar sands under moving pneumatic tires.

4. Two soils were used in this study. One, a desert sand taken from dunes near Yuma, Arizona, has been described in Report 2. The other was a stream-deposited mortar sand taken from a site near the Big Black River south of Vicksburg, Mississippi. Both Yuma and mortar sands were air-dry for all tests, with actual moisture content ranging from 0.2 to 0.5 percent.

5. Tests were run using several different loads and deflections, and with tires ranging in size from 1.75 to 15.2 in. in width and from 14.9 to 41.3 in. in diameter.

Definitions

6. Certain terms used in this series of reports are unique to this study, while others are considered unique to this field of research. To

facilitate the analysis of the data and the communication of the test results, these terms were rigidly defined in Report 1 of this series.

PART II: ANALYSIS OF THE EFFECTS OF SEVERAL VARIABLES ON TIRE PERFORMANCE

Data Used

7. The effects of most variables on the performance of a pneumatic tire operating in soil can be determined from an analysis of the results of programed-slip tests using various loads and deflections and a constant rotational speed. Report 2 of this series describes the influence of some of the variables associated with these programed-slip tests. This report continues the study by analyzing the influence of several important variables that were not thoroughly studied in the earlier report. Although data available at this time do not permit a complete analysis of all variables, they do reveal important trends that warrant further investigation.

8. Portions of this analysis are based on data from tests reported in Report 2, and pertinent data from those tests can be found in the tables in that report. Other data, originally used in Report 2, have been modified and reanalyzed for this report, and these, as well as data from tests unique to the study reported herein, are listed in tables 1-14.

Effect of Deflection

9. Performance data from tests with a 6.00-16 solid rubber tire and corresponding performance data obtained with a two-ply pneumatic tire of the same nominal size are plotted in plates 1 and 2 and show the effect of a tire's deflection on its performance in sand. Overall dimensions of the two tires were similar, with the diameters approximately 28 in. and the diameter/width ratios approximately 4.2. The pneumatic tire was tested at deflections of 15, 25, and 35 percent, but the deflection of the solid tire did not exceed 3 percent, even for the heaviest load tested.

Performance parameters

10. The test data demonstrate that, within the range tested, as the tire deflection is increased, sinkage is decreased, towed force is

decreased, and maximum pull is increased as long as soil strength and horizontal velocity are reasonably constant.

Towed coefficient

11. For the towed condition, the curves of the towed coefficient $\frac{P_T}{W}$ (P_T = pull at towed point; W = load) versus soil strength tend to converge and approach a horizontal asymptote at a high soil strength (plate 1). The towed coefficient at that point is comparable to the average hard-surface rolling resistance for the range of deflections considered. The curves representing sinkage at the towed point versus soil strength exhibit trends similar to those of the towed coefficient versus soil strength for the same group of tests and, in doing so, suggest that these two dependent variables are related.

Maximum pull coefficient

12. For the maximum pull condition, the curves of the maximum pull coefficient $\frac{P_M}{W}$ (P_M = pull at maximum pull point) versus soil strength tend to converge as they approach the immobilization point at low soil strengths (plate 2). This is attributed, in part at least, to the fact that differences in the in-soil tire deflections (δ_{MS}) were considerably less than differences in the hard-surface deflections (δ_{MH}) that were used in constructing the plots. At the higher soil strengths, the in-soil and hard-surface deflections are of the same order of magnitude. The trends exhibited by the sinkage at the maximum pull point versus soil strength curves are somewhat ill-defined by these data but generally agree with data collected during the latter phase of this program which suggest that the maximum pull coefficient and sinkage are also related.

Effect of Tread

13. Data from tests with two 6.00-16 radial ply tires, one with a directional-bar tread and the other buffed free of tread, were used to determine the effect of tread on performance. Basic performance curves for the two tires are shown in plates 3 and 4. Though only five tests were conducted using the tire with tread and performance curves are based on not more than three points, the test data appear consistent. For the limited range of test conditions studied, the smooth, radial-ply tire consistently

outperformed its bar-tread counterpart, and while the advantage is slight in each case, it is well defined. This superiority in performance was maintained although the tire with tread was tested at slightly greater deflections than the smooth tire in each case. Early in the test program, deflections were computed on the basis of carcass section height plus tread height. To be consistent with the method by which deflections are expressed for smooth tires, it was necessary to recalculate these deflection values on the basis of carcass section height without tread. Computed in this way, hard-surface deflection values for the tire with tread were 16.5 and 39.3 percent as shown in plates 3 and 4. Since it has been shown that an increase in tire deflection results in increased tire performance, the superiority of the smooth tire is probably greater than the margin indicated.

Effect of Speed

Inertial forces

14. Normal (6 fps) tests. In a normal programed-slip test, wheel angular velocity is held constant while test carriage speed is increased at a uniform rate to some predetermined value and then decreased to zero (see fig. 1). The deceleration required introduces an inertial force into the system which can be calculated from the equation $F_d = ma$, if the mass decelerated (m) and the change in wheel velocity (a) at the point in question are known. For example:

$$m = \frac{\text{(total static weight of carriage components acting against horizontal load cells, lb)}}{\text{acceleration of gravity}} = \frac{517 \text{ lb}}{32.2 \text{ ft/sec}^2}$$

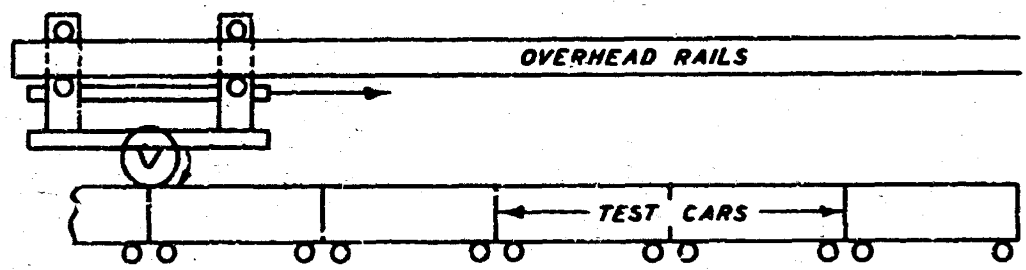
$$a = \frac{\Delta v}{\Delta t}$$

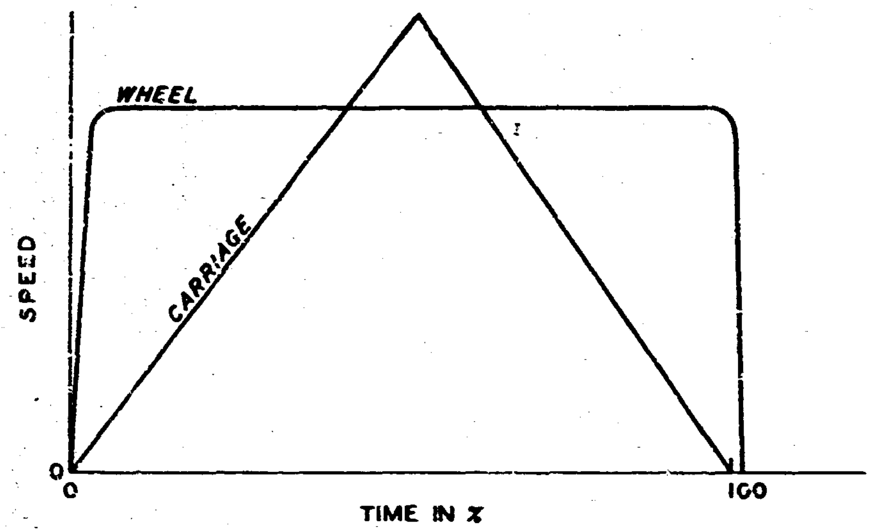
$$\Delta t = \frac{\text{test car length traversed during deceleration}}{\text{average speed during deceleration}} = \frac{40 \text{ ft}}{6 \text{ fps}/2} = 13.3 \text{ sec}$$

$$a = \frac{6 \text{ fps}}{13.3 \text{ sec}} = 0.45 \text{ ft/sec}^2$$

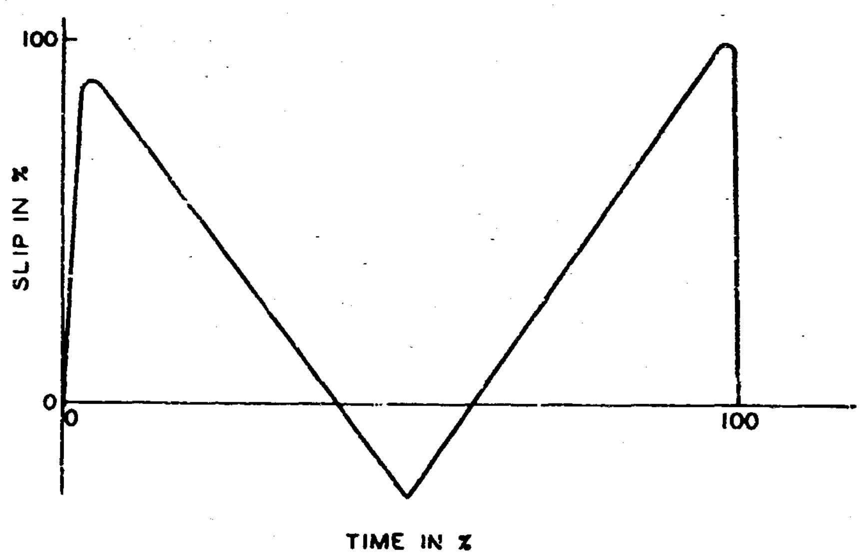
$$F_d = ma = \frac{517 \text{ lb}}{32.2 \text{ ft/sec}^2} \times 0.45 \text{ ft/sec}^2 = 7.2 \text{ lb}$$

This sample calculation uses typical values from a 6-fps test and assumes a constant rate of velocity decrease and also assumes that the vertical center





SPEED VS TIME



SLIP VS TIME

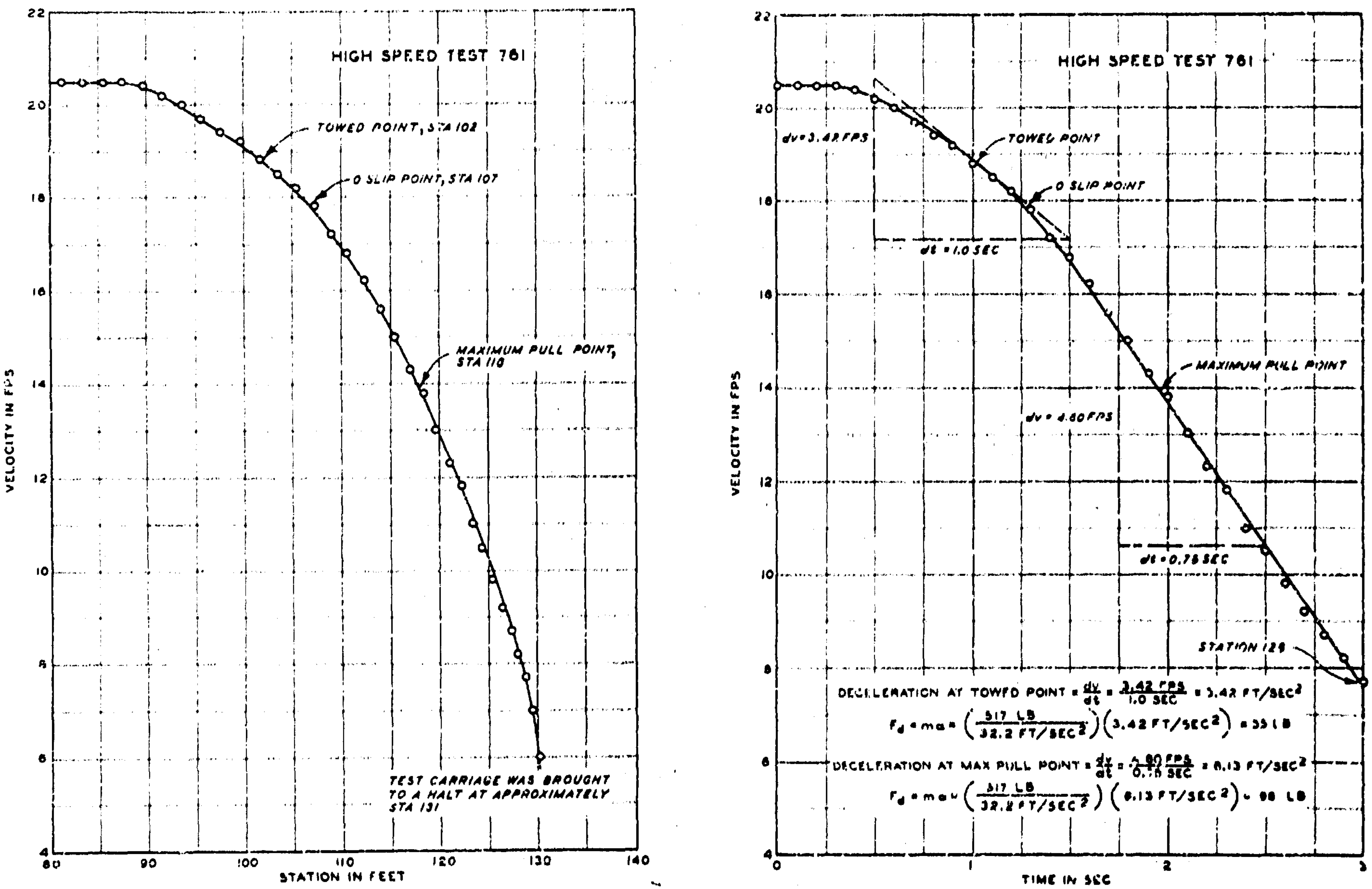
Fig. 1. Speed and slip diagrams for a typical programed-slip test

of gravity is in the same horizontal plane as the line of action of the horizontal load cell. In all low-speed tests (6 fps or less) the inertial force due to deceleration is of the order of 5 lb, so that for practical purposes it can be neglected.

15. High-speed (18 fps) tests. To study the influence of speed on tire performance, a series of 18 special tests were conducted with a 4.50-18, 4-PR tire at speeds (at zero slip) of 0.5 and 18 fps. Results of these tests are listed in tables 1 and 2. In high-speed tests (18 fps), it was found that the force caused by deceleration had to be considered to accurately determine the pull developed by the wheel. The testing technique used in the high-speed tests is somewhat different from that used in the regular tests (fig. 1). At the beginning of the high-speed tests, the test carriage is accelerated very rapidly so that maximum carriage speed is reached a considerable distance ahead of the first test car. This speed is maintained at a nearly constant level until shortly after the carriage enters the first test car, when deceleration is begun. This procedure is followed to prevent the buffeting of the test carriage which the buildup to and sudden drop from high speed would cause if the normal speed versus time testing relation were maintained.

16. The velocity-location pattern of a typical high-speed test is shown in fig. 2a. When velocity is plotted versus time (fig. 2b), these same data show that a nearly constant deceleration was achieved over a large portion of the test car length after a brief transition from nearly constant high speed. Fig. 2b also illustrates that the deceleration at a given point is easily determined from the slope of the velocity versus time curve at that point. Noteworthy here are the relative magnitudes of the two deceleration forces, with the force at the towed point (in the curved portion of the curve) nearly 50 percent smaller than that at the maximum pull point. This is explained by the fact that the towed point in this test was reached during the transition from constant speed to constant deceleration and the value of the slope of the velocity-time curve, $\frac{dv}{dt}$ (deceleration), is smaller in the transition zone. Therefore, the force due to deceleration was less at the towed point than it was in the constant deceleration portion of the test. It is evident that the magnitude of the inertial force, F_d, at both the towed point and the maximum pull point, was significant in the high-speed, programed-slip tests.

17. The inertial force that acts on the load cells that measure



a. Velocity versus station

b. Velocity versus time

Fig. 2. Typical high-speed test: 4.50, 4-PR tire; 455-lb load; first pass; Yuma sand

horizontal forces is in the direction of travel, which is the same direction as that of a positive pull, so that inertial forces are recorded as an additional positive force. Thus, the absolute magnitude of the true maximum pull when the wheel was assumed to be traveling at a constant speed was less than that registered by the load cells, and the absolute magnitude of the towed force was greater than that registered by the load cells. Since pull at the towed point is known to be negative, the actual pull developed by the wheel was determined by the following equation:

Actual wheel pull = (recorded force) - (inertial force)

All data developed in the high-speed (18 fps), programed-slip tests have been adjusted using this formula.

Effect of speed on pull

18. Plate 5 shows plots of pull versus slip using data from four tests conducted with a 4.50-18, 4-PR tire under nearly equal conditions of load, deflection, and soil strength, but at three different wheel speeds. Data shown are from a towed test run at 0.5 fps, a programed-slip test at 18 fps, and both a towed and a programed-slip test run at 6 fps. It is interesting to note that the pull-slip values developed during the 6-fps towed test link the 0.5-fps towed test with the programed-slip tests. The curves representing the 18-fps test and the 6-fps programed-slip test (plate 5) converge at about -2.5 percent slip. Up to the maximum pull point, the curve representing the 18-fps test rises more sharply than the one representing the 6-fps programed-slip test. The maximum pull produced was considerably larger in the 18-fps test and occurred at a slightly lower value of slip than in the 6-fps test. Beyond the maximum pull point of the 6-fps programed-slip test the two curves generally parallel one another, and the pull values appear to vary in proportion to velocity over this slip range (+22 to +55 percent).

19. Plate 6 shows a second group of tests with the same size tire, conducted under the same conditions as those shown in plate 5. However, before-traffic 0- to 6-in. cone index values in these tests were 22 or 23, while those in the tests shown in plate 5 ranged from 44 to 46. Generally, the pull-slip curves presented in the two plates follow the same pattern.

In plate 6, the curves representing data from the 6-fps and the 18-fps programed-slip tests appear to converge, or perhaps cross, at about 0 slip, and the curve for the 0.5 fps towed data appears to fall on an extension of the curve representing the 6-fps test. The curve shown for the 18-fps test rises more sharply and again indicates a larger maximum pull value at a lower value of slip than was attained during the 6-fps test. The pull values appear to vary in proportion to speed once both have reached the maximum pull point.

Effect of speed on other parameters

20. To further examine the influence of speed on tire performance in air-dry sand, sinkage at the towed point and the towed coefficient have each been plotted versus cone index in plate 7. For a tire deflected 15 percent, three curves are required to describe the sinkages for 0.5-, 6-, and 18-fps tests at equal cone index values; however, a single curve can be used to represent the relation of towed coefficient to cone index at all speeds. Conversely, at 35 percent deflection, the relation of towed coefficient to cone index appears to vary with speed, while a single curve can be used to represent the relation of sinkage to cone index for tests at both speeds.

21. The sinkage at the maximum pull point and the maximum pull coefficient are each plotted versus cone index in plate 8. The 15 percent deflection data indicate that the pull coefficient and the sinkage vary with speed, i.e. the pull coefficient increases as speed increases, while sinkage decreases as speed increases. Although the pull coefficient increased as speed increased in tests conducted at 35 percent deflection, the sinkages for this same group of tests did not appear to vary with speed.

22. When the maximum pull and towed force data shown in plates 7 and 8 are examined with respect to sinkage rather than soil strength, it can be seen that the towed and pull coefficients increase as speed increases at any given value of sinkage. This suggests that the resistance to displacement of sand increases as the rate of displacement increases. At the towed point, the increase in resistance apparently results in a greater rolling resistance, and at the maximum pull point, it apparently results in greater available traction.

23. From the data in plates 5-8 it is concluded that the performance

of pneumatic tires operating in air-dry sand is affected by changes in speed. However, the extent to which speed influences performance has not been wholly determined, and it is apparent that additional tests are needed.

Effect of Carcass Stiffness

24. Performance data from tests with two 9.00-14 tires with widely different carcass stiffnesses (2- and 8-PR) are compared in plates 9 and 10 to determine the effect of carcass stiffness on performance. The tires were tested with an 890-lb load at 15 and 35 percent deflection. When not inflated, the 2-PR tire is relatively flexible, but even at zero inflation the 8-PR tire has considerable carcass stiffness; therefore, significantly different inflation pressures were required to develop the same percentage hard-surface deflection. To obtain a deflection of 15 percent, 39.6 psi was required for the 2-PR tire as opposed to only 33.4 psi for the 8-PR tire. For 35 percent deflection, the 2-PR tire required 11.9 psi compared to 7.8 psi for the 8-PR tire.

25. The towed coefficient and sinkage at the towed point for both tires are plotted versus soil strength in plate 9, and the maximum pull data and related sinkage versus soil strength in plate 10. At 15 percent deflection, the test performance of the 2-PR tire was slightly better, i.e. it developed more pull and less force was required to tow it. For tests at 35 percent deflection, no difference in performance was noted.

26. Based on these observations, it is concluded that wide differences in tire carcass stiffness result in very little difference in tire performance on dry desert sand when the tires are of equal size and are operating at the same deflection. It is further concluded that for a given load-soil strength combination, deflection is a more useful criterion of tire performance than is inflation pressure.

Effect of Tire Construction

Diagonal ply

27. The primary difference between the radial-ply tire and the diagonal-ply tire most commonly used is in the arrangement of the cord

fabric. Diagonal-ply construction places an even number of layers (or plies) of cord fabric one atop the other. The cords in each layer are parallel and make an angle of approximately 45 deg with the tire sidewall. The tire is constructed so that the cords of each successive ply are approximately opposite to those of the previous ply. In this manner, a crisscross or diagonal pattern of cords is developed with an angle of approximately 90 deg between cords in adjacent plies.

Radial ply

28. In radial-ply construction the inner (or body) cords are placed radially so as to make an angle of approximately 90 deg with the tire sidewall. Layers of cord fabric are then placed nearly circumferentially atop the radial plies in the crown area. The only direct contact between the two separate series of plies is between the outermost radial ply and the innermost circumferential ply. Because of the slight angle at which the circumferential ply cords are set, the angle between these layers is somewhat less than 90 deg. The radial direction of the body plies provides a very flexible sidewall, and the circumferential layers provide a stiff hoop or belt that resists circumferential compression or extension.

Comparison

29. In plates 11 and 12, performance data for the 6.00-16, 4-PR radial-ply tire are compared with corresponding data obtained with the 6.00-16, 2-PR diagonal-ply tire. The dimensions of the two tires are similar, with diameters of approximately 27 in. and diameter-to-width ratios of approximately 4.3. Data discussed in paragraphs 25 and 26 indicated that large variations in carcass stiffness produced very minor differences in tire performance. Differences in construction, compared in plates 11 and 12, show that for all comparisons, either a single line or generally parallel lines describe the performance of both tires, with the diagonal-ply tire performing as well as, or slightly better than the radial-ply tire in each instance. These differences in performance may be due in part to the difference in tire construction and the associated differences in hard-surface contact pressure. The average contact pressures measured for the two tires at comparable load-deflection conditions are:

Tire Type	Load lb	Deflection, %	Average Contact Pressure psi
Radial ply	890	15	50.9
Diagonal ply	890	15	46.2
Radial ply	890	35	20.3
Diagonal ply	890	35	15.5

For a given load-deflection condition, the diagonal-ply tire has a lower hard-surface contact pressure. Investigations described in Report 2 of this series indicate that for a given tire the pull/load ratio $\left(\frac{P_M}{W}\right)$ developed in sand is increased as hard-surface contact pressure is decreased. Thus, the trends shown here generally agree with those described in Report 2.

Correlation of Wheel Slip with Other Test Variables

30. It is important that any relations which may exist between performance parameters be established because such knowledge will enhance the development of design criteria and performance prediction equations. Since wheel slip is an indicator of the interaction that takes place at the tire-soil interface, it follows that orderly relations should exist between this variable and others in the tire-soil system. Therefore, investigations were made to determine the relations between slip and each of several variables, including both static (wheel load, soil strength) and dynamic (pull, sinkage) measurements, so that slip might be used as a common denominator in studying the interrelations of performance parameters for a wide variety of tire sizes and shapes. Data from these investigations are plotted in plates 13-20.

Slip at the towed point versus soil strength

31. The slip at the towed point for each of the test tires under a variety of test conditions is plotted against cone index in plates 13-18. The plates show that for each tire operating at a given deflection, the plotted data separate by load. Individual curves tend to become asymptotic at low negative slip values in the high soil strength range (55 cone index

and above). At various lower soil strength levels (the exact value depending on the test conditions), these curves reach a point at which negative wheel slips increase rapidly with very small changes in soil strength. A decrease in slip with soil strength is observed in each instance, and although the specific effects of changes in load, tire size, and tire deflection have not been delineated, it can be seen that each of these has an effect on the relation of slip to soil strength.

Slip versus towed force and versus sinkage

32. Definite correlations have been established between slip and towed force and between slip and sinkage at the towed point (see plates 19 and 20, respectively). The data represent tests conducted with 16 tires (including two dual configurations). It should be noted that the 11.00-20, 12-PR tire data diverge considerably from the performance curves established for the remaining tires. Curves representing $\frac{P_T}{W}$ and $\frac{z_T}{d}$ (z_T = sinkage at the towed point; d = carcass diameter) values for this tire are significantly lower than those drawn to represent the average of the other tire data. The reason for these differences is not fully understood. It is also interesting to note that more slip was required for duals than for corresponding single tires to produce equal sinkage. The scatter in the data for the various smaller single tires obscures any size influences that may exist. The combined plots shown simply present the general trends of the slip-performance relations. In general, data plotted in plates 19 and 20 indicate that the sinkage and rolling resistance of a towed wheel are related to slip and that at any given slip, these two parameters are functions of tire geometry. Discussions in Report 2 and in paragraph 31 herein indicate that they are functions of soil strength, wheel load, and deflection, as well.

Relations between slip, sinkage, and pull at the towed point

33. To illustrate the orderly relations that exist between the dependent variables (slip, sinkage, and pull) at the towed point, as well as their relation to soil strength, a group of tests were chosen in which tire geometry, tire deflection, and wheel load could be considered constant. In plate 21, four coordinated curves depict the relation of the four variables

in different combinations. The average curves shown were drawn from visual examination and are considered to fit the plotted data well. Any particular point on the average curves can be projected from one curve to the next until it is returned to its original position. While the plotted points in plate 21 represent tests conducted at a single tire-load-deflection combination, similar relations can be shown for other combinations.

Slip at the maximum pull point

34. The slip versus performance relations investigated up to this point have been based on towed point data. Development of corresponding plots at the maximum pull point was not feasible because the first-pass maximum pull was attained within a relatively narrow slip range (approximately 15 to 25 percent) for all of the various test conditions. Since slip of the wheel and the strain occurring in the underlying soil are related to some degree, the fact that the maximum pull occurs over a relatively narrow slip range is of some physical significance. However, it must be recognized that the effective rolling radius of a pneumatic tire is partially dependent on soil strength; therefore, the calculated slip can be considered no more than an approximation, and the differences in the slip at the maximum pull point may actually be less than indicated. These observations illustrate the need to conduct tests with wheels of a known radius (i.e. rigid wheels) in order to ascertain relations among wheel slip, soil strain, and soil strength.

Major Performance Coefficients at the Towed and Maximum Pull Points Versus Sinkage

35. In Report 2 of this series the towed and pull coefficients $\left(\frac{P_T}{W} \text{ and } \frac{P_M}{W}\right)$ were plotted versus cone index and it was found that the relation developed for each tire operating at a given deflection separated by load. Slip at the towed point is related to cone index (paragraph 31); therefore, it was of interest to study the relation between sinkage and pull at the towed point and at the maximum pull point. A correlation between the dimensionless ratios $\frac{z_T}{d}$ and $\frac{P_T}{W}$ is shown in plate 22, and between $\frac{z_M}{d}$ and $\frac{P_M}{W}$ in plate 23, using test data which included 16 tire configurations, all loads, all deflections, and all soil strengths tested in Yuma sand. Test results for all tires except the 11.00-20, 12-PR appear

in tables included in Report 2. Results of the 11.00-20, 12-PR tire tests are in tables 3 and 4 of this report.

36. The correlations shown in plates 22 and 23 are important because they indicate that any system that can be used to predict either of the major performance coefficients, $\frac{P}{W}$ or $\frac{z}{d}$, at the towed or maximum pull point can also be used to predict the other performance coefficient at the same point. This indicates that both the forces on the wheel and the sinkage are related to the same independent variables, i.e. tire geometry, tire deflection, wheel load, and soil strength. The scatter in the data shown in plates 22 and 23 has not been fully explained, but to some extent it may be due to differences in slip. For instance, at 15 percent deflection the negative slip of the 11.00-20 tire at the towed point was higher than that of the other tires at a given cone index value, and data for this tire separate from the other data in plate 22. However, the slips associated with the maximum pull data for the 11.00-20 tire generally fall within the 15 to 25 percent range previously mentioned, and in plate 23 the maximum pull data for this tire fall within the scatter band established by the other tire data. The need for a detailed study of the slip phenomena is also apparent in this comparison.

37. A statistical analysis of the data in plates 22 and 23 was considered. It was decided that the results of such an analysis would not be particularly revealing because the differences in slip values appear to have affected the correlation.

PART III: CORRELATION OF SINGLE-WHEEL AND 4x4 VEHICLE DATA

38. Single-wheel tests provide a convenient means for studying the basic relations that govern the movement of a pneumatic tire in soft soils. A wide variety of tires, loads, and soil strengths can be studied quickly and at relatively small expense. However, it must be shown that the single-wheel test results are related to the performance of actual wheeled vehicles.

Method of Correlation

39. To verify this relation, results of single-wheel tests were compared with performance data for a 4x4 vehicle. The first pass of the single-wheel tests was assumed to represent the passage of the front wheels of a vehicle and the second the passage of the rear wheels. The pull values developed in the first and second passes were added and the sum multiplied by two (to represent both sides of the vehicle) to produce a value comparable to the pull developed by a 4x4 vehicle under similar test conditions. One complicating factor which had to be considered was that maximum pull usually occurs at different percentages of slip for the first and second passes of a single wheel, while slip experienced by the front and rear axles of a 4x4 vehicle normally is about the same. Hence it was necessary to select a common value of slip at which to read the pull for both passes of the single wheel.

Selection of slip values

40. As a matter of utility, the constant slip value at which the 4x4 vehicle data and single-wheel data were compared was selected to correspond to a significant level of tire performance. Examination of a large block of tabulated tire test results and the pull versus slip curves for a number of tests in both Yuma and mortar sands showed that 20 percent slip was the value most frequently associated with the maximum pull point. All of the following test data are compared at 20 percent slip. In the 4x4 vehicle tests, slip was maintained at a constant level for at least two lengths of the test vehicle. Performance data were taken for the

second length so that the rear wheels would be developing pull in a rut that had been generated by the front wheels operating at the test slip.

4x4 test vehicle

41. Forty tests were performed with a 4x4 vehicle in Yuma and mortar sands to provide vehicle performance data for comparisons with single-wheel results. The 4x4 test vehicle was a jeep station wagon (see fig. 3) which was modified by eliminating the differential action so that all wheels would rotate at the same speed. Also, the suspension springs were blocked off by welding to reduce the vertical load oscillations caused by the vehicle's own suspension system. Weights were so placed on the vehicle that each wheel was equally loaded, and a hand-operated gas feed arrangement was installed to improve control of wheel speed. The test vehicle was connected to the dynamometer carriage by means of a linear ball bushing and swivel joint to eliminate eccentric loading that might otherwise have taken place. Instrumentation for this test system was arranged so that a continuous record was made of horizontal pull, wheel distance (revolutions) traveled, and horizontal ground distance traveled. The last two items of information were recorded so that the wheel slip could be calculated at any point.

Load transfer between axles

42. In order to estimate the extent of load transfer between the front and rear axles of the 4x4 test vehicle when pull is developed, the vehicle was loaded to 3560 lb gross weight and placed on a set of heavy-duty truck scales. These scales are arranged so that front and rear axle loads can be measured separately. The brakes were set and horizontal pulls applied at the drawbar pin. For each change of pull, the resulting load transfer between axles was measured. When load transfer was plotted against pull (plate 24), it was found that the load transfer on a firm, level surface amounted to about 9 percent of the pull. These data (plate 24) are in general agreement with the solutions obtained from a previously developed theoretical weight transfer equation. The equation and its development are given in Appendix A. If the pull developed by a wheel varies directly with the load applied, the loss of pull by one axle usually will be partially compensated for by an equal gain in pull by the other axle because of the load transfer. Therefore, no attempt was made to correct for load transfer in this analysis.

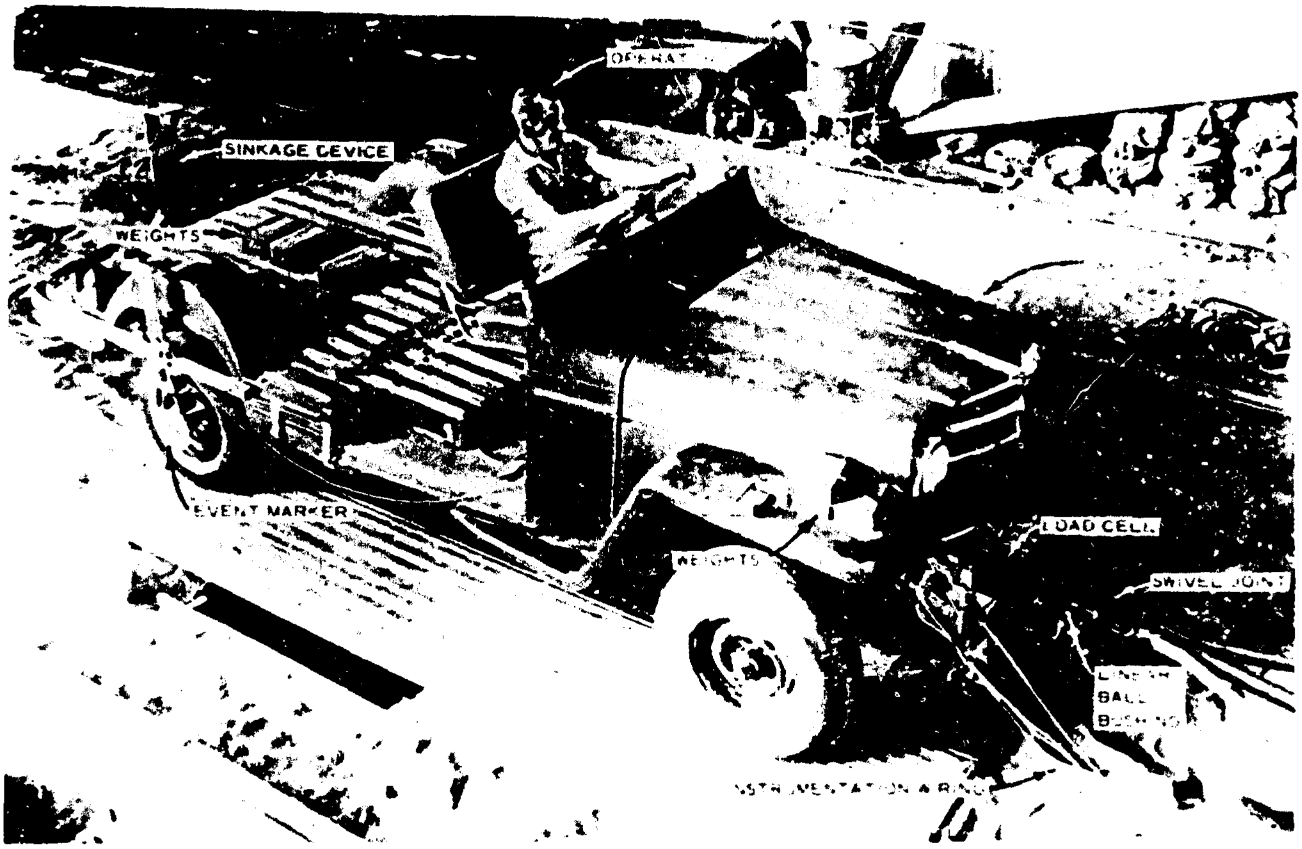


Fig. 3. Modified 4x4 jeep vehicle used in constant 20 percent slip tests

Relation of Single-Wheel to 4x4 Vehicle Data

43. The data that were used to compare single-wheel and 4x4 vehicle performance are listed in tables 5-11. The relations of adjusted single-wheel and 4x4 performance data to soil strength are illustrated in plates 25-27. For a constant level of soil strength, the formula for adjusted single-wheel data, $2[P_{20}$ (first pass) + P_{20} (second pass)], should indicate better performance than a four-wheel drive vehicle equipped with the same tires since four factors were known to detract from the 4x4 vehicle's performance during these tests: it experienced dynamic load transfer; its inherent friction was greater than that of the single wheel; the rotational speed of its wheels are approximately 30 percent less than that of the single wheel, even though the slips were equal; and observations made during the test indicated that the rear wheels did not perfectly track the front wheels.

44. Data obtained from tests with the 4.50-18 tires operating in Yuma sand are plotted in plate 25 and display the expected pattern. Data shown in plates 26 and 27 were taken from tests with the 9.00-14 tires operating in Yuma and mortar sands, respectively. For the 9.00-14 tires at 35 percent deflection, a reverse of the expected trend is seen, i.e. the 4x4 vehicle performance exceeds the adjusted data by a noticeable margin in both sands. Although inertial forces have not been considered in the adjusted single-wheel data shown in plates 25-27, the total correction from this source would not increase the adjusted pull by more than 20 to 30 lb. One possible explanation of the reversals may lie in the assessment of soil strength. The tires were of about equal diameters but of different widths. It may be that cone index averaged over the 0- to 6-in. depth may be adequate for the narrow tire (4.50-18), but inadequate for the wider tire (9.00-14). This suggests that cone index should be averaged over a depth proportional to tire width. A review of the cone index versus depth curves revealed that the 4x4 tests were conducted on test sections where the slopes of penetration curves were fairly constant to a depth of at least 9 in. For the single-wheel tests, the slopes of the penetration resistance curves were fairly constant to a depth of about 6 in. and then

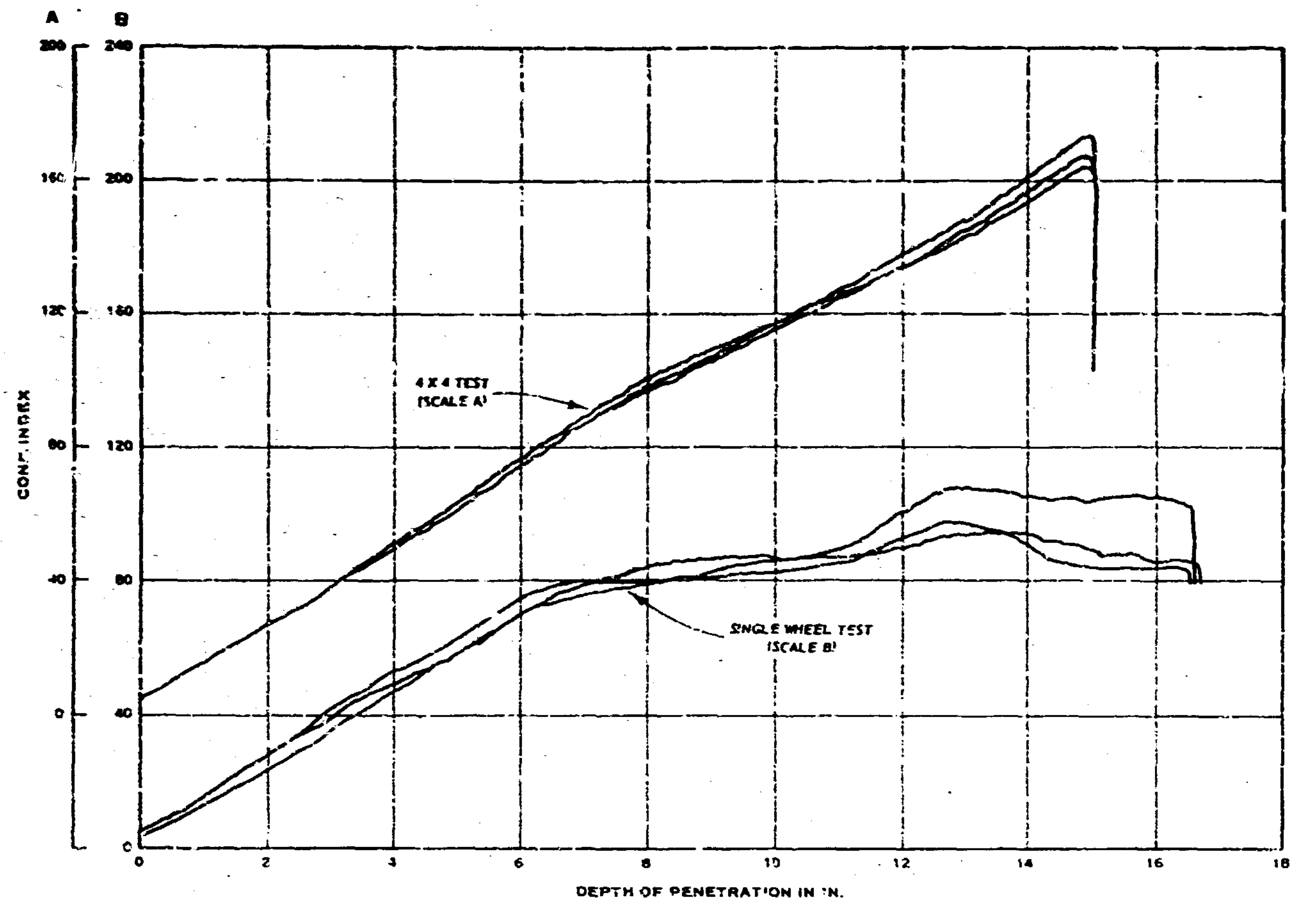


Fig. 4. Typical penetration resistance curves, mortar sand

began to decrease. Typical penetration resistance curves are shown in fig. 4.

45. The relation between single-wheel and 4x4 vehicle test data is examined in a different manner in plates 28 and 29, by using the smooth curves from plates 25-27 to compare performances directly at different values of cone index. Using the average cone index of the 0- to 6-in. layer, the points on each curve progress by an interval of 5 cone index, with the first and last points identified. As explained in the preceding paragraph, the adjusted single-wheel pull data were expected to exceed the 4x4 vehicle's pull for a constant soil strength. In both plates, the plotted curves are generally parallel to a 1:1 line and follow the expected trends, with the exception of the curves representing data from tests with the 9.00-14 tires at 35 percent deflection. While these results suggest that the performance of a 4x4 vehicle can be estimated from single-wheel tests with reasonable accuracy, the need for further study is also indicated.

PART IV: DIFFERENCES BETWEEN YUMA AND MORTAR SANDS

46. For a system of predicting vehicle performance to be effective, the technique for measuring soil strength must account for minor differences in generally similar soils. Comparisons of 4x4-vehicle and single-wheel performance data developed in Yuma and mortar sands provide a basis for such an evaluation of the 0- to 6-in. cone index measurement.

Comparisons of Tire Performance in Yuma and Mortar Sands

Maximum pull

47. Pulls produced in Yuma and mortar sands are compared in plates 30-32. These plates show that in both sands the pull versus cone index curves are similar in shape for each individual combination of wheel load, tire size, and deflection. (In plate 32, this is true for 15 percent deflection only if the 14 CI mortar sand data point is ignored.) Pulls developed by the 4.50-18, 4-PR tire in Yuma sand were greater than those developed in mortar sand by the nearly constant amounts of 300 lb at 15 percent deflection and about 230 lb at 35 percent deflection (plate 30). Pulls developed by the 9.00-14, 2-PR tire at 15 percent deflection were also greater in Yuma sand. Data indicate that vehicle tests with this tire deflected 15 percent produced about 200 lb more pull in Yuma sand than in mortar sand, and that adjusted single-wheel pull was about 200 to 300 lb more (plates 31 and 32). Pulls developed by the same tire at 35 percent deflection were about the same in Yuma and mortar sands of the same cone index.

48. In examining these differences in pull for the four tire size-deflection conditions in the two sands, it was noted that the magnitude of the differences varied approximately in proportion to the hard-surface tire contact pressure. Hard-surface contact pressures for the 4.50-18, 4-PR tire at 15 and 35 percent deflections under 890-lb wheel load are 70.4 and 25.0 psi, respectively, while corresponding measurements for the 9.00-14, 2-PR tire are 37.0 and 12.5 psi, respectively.

Pull-slip relations

49. The pull-slip relations for eight tests with the 9.00-14, 2-PR

tire are shown in plates 33 and 34. Except for the type of sand, test conditions were practically identical in every respect; a difference of 1 cone index (0- to 6-in. average) was the largest variation in a controlled test variable for each set of curves shown. For comparable sets of data, the pull-slip relation for Yuma sand is generally parallel to the relation for mortar sand but displaces toward the larger values of pull. Differences between pull values are somewhat more pronounced at 15 percent deflection than at 35 percent. These results follow the general trends observed in plates 30-32, i.e. the pulls developed in Yuma sand were usually higher than those in mortar sand and the magnitude of these differences was related to the hard-surface contact pressure. Plates 33 and 34 also show that the differences in the pull developed are not unique to the maximum pull condition.

Comparison of Physical Characteristics of Yuma and Mortar Sands

Classification data

50. A general description of the origin of the Yuma and mortar sands used in the WES mobility test program is given in paragraph 4 of this report. Gradation and classification data are given in plate 35 and show that both sands are poorly graded to approximately the same degree, but mortar sand is coarser. Based upon the mechanical analysis indicated in plate 35 and other analyses made in the field for the two sands, Yuma sand was classified as SP-SM and mortar sand as SP under the Unified Soil Classification System. Average specific gravities for the two sands were determined and are almost identical at 2.67. An examination of samples under a microscope revealed that the Yuma sand particles are slightly more rounded than those of mortar sand. Minimum density values for the two sands are approximately equal, but the maximum density of the mortar sand is 106.1 lb/cu ft, while that of Yuma sand is 104.0 lb/cu ft.

Relation of c_r to cone index

51. The data in plate 36 show the relation of c_r to 0- to 6-in. cone index for Yuma and mortar sands. Basically, c_r is a measure of relative effective soil strength as determined from penetration tests with circular, flat plates.[3] All the data in plate 36 fall within a restricted

scatter band about a single line, indicating that the soil properties described by c_r and 0- to 6-in. cone index are approximately the same for Yuma and mortar sands.

Dry density versus cone index

52. Dry density versus 0- to 6-in. cone index are compared for Yuma and mortar sands in plate 37. The Yuma sand data are from a special series of tests conducted in carefully prepared test sections.[7] Mortar sand data are from soil sections for routine tire performance tests 548 through 558 and from some special soil test sections. There is more scatter about the curve for mortar sand data, but curves for both sands are fairly well defined. At density values in excess of about 97 lb/cu ft, the cone index of mortar sand is slightly less than that of Yuma sand. These data lead to the tentative conclusion that the cone index-density relation is not the same for the two soils.

53. However, the in situ density measurements* used to construct the plot shown in plate 37 represent an average of the top 2 in. of soil, while the cone index is an average of the top 6 in. Plate 38 shows a plot of the 0- to 2-in. cone index measurements versus density for the same group of tests as shown in plate 37. A single line now delineates the cone index-density relation for both sands, although considerable scatter is evidenced. This scatter may be attributed to one or more of several factors; namely, disturbance created by placing the density device (particularly at very low or very high relative densities), the method of evaluating the shallow cone index-depth profiles, and the changes in strength that result from small changes (even a fraction of a percent) in moisture content of the sand. Thus, the comparison shown in plate 38, in which the relative strength and the density were measured for approximately** the same layer of soil, leads to the conclusion that cone index and density are related in the same proportion in both sands.

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* These should not be confused with the density measurements connected with triaxial and direct shear tests (see table 12).

** The height of the cone is 1.5 in., and therefore, the 0- to 2-in. average reflects an average strength over a depth in excess of 2 in.

Direct shear and tri-
axial shear test results

54. Carefully controlled direct shear and triaxial shear tests were made in the laboratory with representative samples of Yuma and mortar sands. Test results for both are listed in order of increasing values of dry density, γ_d , in tables 13 and 14. In each table, the Yuma and mortar sand test results are grouped opposite one another by generally corresponding dry densities.

55. Direct shear tests. Data from direct shear tests are used in plate 39 to plot the relation of friction angle to dry density for each of the test sands. The relation reveals that values for Yuma sand are consistently larger than those for mortar sand of the same density. Friction angle values for mortar sand increase with dry density faster than do those for Yuma sand, so that the difference between friction angle values for the two soils decreases from about 9 deg at a dry density of 92 lb/cu ft to only 4 deg at 105 lb/cu ft.

56. In plate 40, the two sands are compared by plotting the maximum frictional shear stress against dry density, again using results of the direct shear tests. For the three normal stresses--σ_3 = 7, 21, and 42 psi--the maximum frictional shear stress for Yuma sand remains practically constant (5, 15, and 30 psi, respectively) for all values of density. For the normal stresses, values of maximum frictional shear stress for mortar sand are smaller than for Yuma sand. The difference in the shear strength of the two soils increases as the normal stress increases when the densities are equal.

57. Triaxial shear tests. The internal friction angle and dry density data from the triaxial shear tests for both Yuma and mortar sand are used in plate 41 to show that the friction angle, ϕ_t , increases steadily as dry density increases. The rate of this change is approximately the same for both sands, and internal friction angle values for Yuma sand are consistently about 7 deg larger than those of mortar sand. Similarly, the triaxial shear test data used in plate 42 show that maximum frictional shear stress values for both Yuma and mortar sand increase steadily as dry density increases. Maximum frictional shear stress is defined as one half of the maximum principal stress difference less the indicated cohesion.

For the three different minor principal stresses--σ_3 = 7, 21, and 42 psi--plate 42 shows that the maximum frictional shear strength of Yuma sand is larger than that of mortar sand by nearly constant amounts throughout the range of dry densities tested, and that shear strength increases as the normal stress increases.

Shear stress versus contact pressure

58. Plate 43, which includes direct shear test data and tire contact pressure data, is included at this point to offer a possible explanation for the observed differences in the performance data obtained in the two sands (paragraph 49). If contact pressure is considered as a normal pressure applied to the sand, the data (plate 43) show that the difference in shear stress in the two sands is small for the 9.00-14, 2-PR at 35 percent deflection. Reference to plates 30-32 reveals that the difference in the pulls developed is negligibly small for this test condition. Conversely, the largest difference in pulls is associated with the 4.50-18, 4-PR tire operating at 15 percent deflection. This corresponds to the condition (plate 43) where the largest difference in shear stress for the two sands is noted.

59. Information gained by measuring the magnitude and distribution of stresses at the tire-soil interface tends to support this observation.[5,6] Data presented in references 5 and 6 suggest that the contact pressures beneath the 9.00-14, 2-PR tire were relatively uniformly distributed. These contact pressures probably were approximately equal to the inflation pressure when the deflection was relatively large (25 to 35 percent) and greater than the inflation pressure when deflection was small (15 percent). Pressures beneath the more rigid 4.50-18, 4-PR tire probably were less uniformly distributed, with peak interface pressures exceeding both the inflation pressure and the hard-surface contact pressure.

60. Based on the results of triaxial and direct shear tests and the relation between cone index and density, the conclusion is drawn that when cone indexes are equal, a constant difference exists between the strength of Yuma and mortar sand for a given normal pressure and that this difference in strength increases as the normal stress increases. This was reflected by the difference in pulls which increased as the tire-soil interface pressures increased during tests in the two soils (plate 43). If

laboratory tests, such as the triaxial and direct shear tests, are to be used to predict the relative ability of coarse-grained soils to provide support and traction for pneumatic tires, more accurate in situ density data, measured to depths of 6 in. or more, must accompany the tests.

PART V: CONCLUSION

Summary of Results and Conclusions

61. Based on the analysis of test results reported herein, the following conclusions are drawn:

- a. The performance in a dry sand of a tire of given dimensions improves significantly when tire deflection is increased or when the tread is buffed off (paragraphs 10 and 13).
- b. Pull developed in the positive slip range is increased by an increase in wheel speed, other conditions being equal. The effect of speed on pull in the negative slip range is less well defined, but there appears to be a tendency for towed force to increase as speed increases. At equal sinkages, pull at both the towed and maximum pull point is of larger magnitude as wheel speed increases, suggesting that the sand's resistance to displacement increases as wheel speed increases (paragraphs 20-23).
- c. Large variations in tire carcass stiffness appear to introduce only negligible differences in tire performance when comparisons are made at equal tire deflections (paragraph 26).
- d. A slightly better performance is realized with a diagonal-ply 6.00-16 tire than with a radial ply 6.00-16 tire (paragraph 29).
- e. Logical, orderly relations exist between slip and each of several independent and dependent test variables at both the towed and maximum pull points (paragraphs 33 and 34).
- f. Comparisons of 4x4 vehicle performance with the results of single-wheel tests show that good correlation can be attained between these two sets of data (paragraph 45).
- g. At the same cone index, Yuma sand has a higher angle of internal friction and permits a given tire to develop a higher pull than does mortar sand (paragraphs 55 and 60).

Recommendations

62. The following recommendations are made based on the experience gained in this study:

- a. Additional tests should be conducted in Yuma sand to provide data that can be used to describe quantitatively the effects on tire performance of (1) tire deflection, (2) tread, and (3) wheel speed. Towed tests and constant-slip tests run at both high and low speeds are needed so that the influence of speed can be studied more directly.

b. A program of fundamental studies should be continued to explain the influence on tire performance of all the important variables.

c. Additional tests should be conducted with full-scale wheeled vehicles both in the laboratory and in the field to demonstrate the relation to single-wheel, multiple-pass data, and a correlation should be made of single-wheel, multiple-pass data with existing full-scale vehicle performance data.

d. The application of laboratory tests, such as the triaxial and direct shear tests, in predicting the ability of coarse-grained soils to support and provide traction for pneumatic tires should be further investigated and an effort made to develop more precise correlations between laboratory test data and in situ strength-density relations.

SELECTED BIBLIOGRAPHY

1. Forrest, P. J., Reed, I. F., and Constantakis, G. V., "Tractive characteristics of radial-ply tires." Transactions of the ASAE, vol 5, No. 2 (1962), p 108.

2. Nuttall, C. J., and McGowan, R. P., Scale Models of Vehicles in Soils and Snows. Technical Report No. 61-50, U. S. Army Transportation Research and Engineering Command, Fort Eustis, Va., June 1961.

3. Nuttall, C. J., and Wilson, C. W., Scale-Model Vehicles in Snow. Technical Report No. 29-3, U. S. Army Transportation Research and Engineering Command, Fort Eustis, Va., January 1959.

4. Thaden, T. J., "Operating characteristics of radial-ply tractor tires." Transactions of the ASAE, vol 5, No. 2 (1962), p 109.

5. U. S. Army Engineer Waterways Experiment Station, CE, Stresses Under Moving Vehicles; Distribution of Stresses on an Unyielding Surface Beneath Stationary and Towed Pneumatic Tires, by J. L. McRae, and N. R. Murphy, Jr. Technical Report No. 3-545, Report 4, Vicksburg, Miss., July 1964.

6. ________, Stresses Under Moving Vehicles; Distribution of Stresses Beneath a Towed Pneumatic Tire in Air-Dry Sand, by A. J. Green, Jr., and N. R. Murphy, Jr. Technical Report No. 3-545, Report 5, Vicksburg, Miss., July 1964.

7. ________, Measuring Soil Properties in Vehicle Mobility Research; Strength-Density Relations of an Air-Dry Sand, by A. J. Green, J. L. Smith, and N. R. Murphy, Jr. Technical Report No. 3-652, Report 1, Vicksburg, Miss., August 1964.

8. ________, Wheels on Soft Soils, an Analysis of Existing Data, by Dean R. Freitag. Technical Report No. 3-670, Vicksburg, Miss., January 1965.

9. ________, Performance of Soils Under Tire Loads; Test Facilities and Techniques, by J. L. McRae, C. J. Powell, and R. D. Wismer. Technical Report No. 3-666, Report 1, Vicksburg, Miss., January 1965.

10. ________, Performance of Soils Under Tire Loads; Analysis of Tests in Yuma Sand Through August 1962, by C. J. Powell and A. J. Green. Technical Report No. 3-666, Report 2, Vicksburg, Miss., August 1965.

11. ________, Performance of Soils Under Tire Loads; Preliminary Analysis, Tests in Clay, by R. D. Wismer. Technical Report No. 3-666, Report 3, Vicksburg, Miss. (In preparation.)

Table 1

Summary of Low-Speed (0.5 fps) Test Results

Yuma Sand, Pass 1, Towed Point

4.50-14, 4-PR Tire

Test No.	Station	Deflection %	Load (W) lb	Towed Force (P_T) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_T}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
746A	125	15	458	-165	0	4.15	-31.6	-0.360	0.153	22
748A	99	15	465	-137	0	1.97	-19.0	-0.295	0.073	45
749A	95	15	880	-341	0	3.95	-25.0	-0.388	0.146	49
750A	121	15	888	-413	0	6.04	-33.3	-0.466	0.223	23
747A	116	35	465	-135	0	2.54	-22.7	-0.290	0.094	23
751A	96	35	875	-300	0	3.46	-30.7	-0.343	0.128	24

* d is carcass diameter.

Table 2

Summary of High-Speed (18 fps) Test Results

Yuma Sand, Pass 1

4.50-18, 4-PR Tire

Test No.	Station	Deflection %	Load (W) lb	Towed Force (P_T) lb	Pull (P_{sp}) lb	Max Pull (P_M) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_T}{W}$	$\frac{P_{sp}}{W}$	$\frac{P_M}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
							Towed Point							
752A	100	15	421	-189			0	2.50	-28.2	-0.449			0.092	22
754A	116	15	452	-76			0	0.62	-6.8	-0.168			0.023	54
758A	99	15	455	-28			0	0.49	-5.3	-0.062			0.018	53
762A	105	15	457	-61			0	0.47	-4.2	-0.133			0.017	53
757A	105	15	461	-71			0	0.89	-4.7	-0.158			0.033	45
761A	102	15	461	-70			0	0.47	-2.0	-0.152			0.017	53
756A	108	35	442	-142			0	1.79	-20.5	-0.322			0.066	23
763A	110	35	467	-49			0	0.24	-1.0	-0.105			0.009	52
760A	102	35	474	-61			0	0.17	-3.1	-0.129			0.006	57
							Self-Propelled Point							
753A	107	15	423		0		150	2.85	6.1		0		0.105	23
761A	107	15	443		0		91	0.47	6.5		0		0.017	53
757A	111	15	450		0		88	0.76	4.3		0		0.028	45
758A	103	15	450		0		22	0.48	-2.6		0		0.018	53
755A	109	35	450		0		119	1.46	1.0		0		0.054	22
760A	105	35	476		0		70	0.31	0.0		0		0.011	57
							Maximum Pull Point							
753A	112	15	417			35	190	3.20	18.7			0.084	0.118	23
757A	117	15	442			119	129	0.84	16.3			0.278	0.031	45
761A	118	15	444			117	182	0.97	20.2			0.264	0.036	53
758A	111	15	446			120	200	0.76	9.1			0.269	0.028	53
755A	116	35	438			91	167	2.32	21.2			0.208	0.086	22
759A	97	35	448			232	234	0.22	13.4			0.518	0.008	45
760A	114	35	450			185	209	0.27	17.6			0.411	0.010	57

* d is carcass diameter.

Table 3

Summary of Test Results

Yuma Sand, Pass 1, Towed Point

11.00-20, 12-PR Tire

Test No.	Station	Deflection %	Load (W) lb	Pull (P_T) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_T}{W}$	$\frac{z}{d*}$	0- to 6-in. Avg Cone Index
2-63-0001A	36	15	3000	-1028	0	5.18	-36.9	-0.343	0.126	31
2-63-0002A	65	15	3000	-1137	0	6.19	-41.5	-0.379	0.151	21
2-63-0003A	39	15	3000	-888	0	4.68	-33.0	-0.296	0.114	47
2-63-0004A	53	15	3000	-981	0	5.13	-37.0	-0.327	0.125	37
2-63-0005A	34	15	3000	-788	0	2.78	-20.8	-0.263	0.068	70
2-63-0006A	60	15	3000	-914	0	3.88	-29.2	-0.305	0.094	56
2-63-0013A	35	15	4500	-1380	0	6.02	-36.9	-0.307	0.146	66
2-63-0014A	56	15	4500	-1489	0	6.89	-41.7	-0.331	0.168	58
2-63-0015A	42	15	4500	-1505	0	7.40	-46.7	-0.334	0.180	48
2-63-0016A	52	15	4500	-1572	0	7.69	-58.3	-0.349	0.187	39
2-63-0017A	43	15	4500	-1591	0	8.54	-52.5	-0.354	0.208	32
2-63-0018A	45	15	4500	-1619	0	9.06	-57.7	-0.360	0.220	23
2-63-0007A	37	35	3000	-401	0	2.46	-8.0	-0.137	0.060	31
2-63-0008A	58	35	3000	-484	0	3.22	-10.8	-0.161	0.078	22
2-63-0009A	36	35	3000	-225	0	0.98	-2.9	-0.075	0.024	67
2-63-0010A	56	35	3000	-246	0	1.39	-3.5	-0.082	0.034	56
2-63-0011A	36	35	3000	-316	0	1.57	-5.7	-0.105	0.038	45
2-63-0012A	57	35	3000	-353	0	2.04	-6.9	-0.118	0.050	36
2-63-0019A	33	35	4500	-546	0	1.43	-6.2	-0.121	0.035	65
2-63-0020A	53	35	4500	-681	0	2.46	-8.5	-0.151	0.060	56
2-63-0021A	32	35	4500	-681	0	2.20	-8.5	-0.151	0.054	49
2-63-0022A	65	35	4500	-898	0	3.51	-15.3	-0.200	0.085	40
2-63-0023A	33	35	4500	-847	0	3.32	-15.1	-0.188	0.081	33
2-63-0024A	33	35	4500	-1095	0	5.14	-26.9	-0.243	0.125	25

* Average carcass diameter = 41.3 in.

Table 4

Summary of Test Results

Yuma Sand, Pass 1, Maximum Pull Point

11.00-20, 12-PR Tire

Test No.	Station	Deflection %	Load (W) lb	Pull (F_M) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{F_M}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
2-63-0025A	43	15	3060	233	--**	3.16	18.9	0.076	0.076	63
2-63-0026A	66	15	3080	169	--	3.37	20.0	0.055	0.082	57
2-63-0027A	56	15	3100	116	--	4.26	20.0	0.037	0.103	44
2-63-0028A	56	15	3050	107	--	4.57	20.0	0.035	0.111	36
2-63-0029A	54	15	3025	13	--	5.12	20.0	0.004	0.124	22
2-63-0041A	56	15	3028	295	1876	3.35	20.2	0.097	0.081	69
2-63-0042A	54	15	3000	123	1777	4.00	20.0	0.041	0.097	41
2-63-0043A	55	15	3068	12	1855	5.40	20.0	0.004	0.131	22
2-63-0044A	57	15	4520	-117	2761	4.96	21.0	-0.026	0.120	69
2-63-0045A	55	15	4478	25	2866	5.03	20.0	0.006	0.122	56
2-63-0046A	61	15	4460	-114	2699	5.08	21.4	-0.026	0.123	49
2-63-0047A	60	15	4500	-241	2735	6.05	20.0	-0.054	0.146	39
2-63-0048A	50	15	4540	-345	2855	6.33	17.7	-0.076	0.153	26
2-63-0030A	55	23	3085	728	--	2.35	20.0	0.236	0.057	62
2-63-0031A	58	23	3030	480	--	2.66	18.7	0.158	0.064	52
2-63-0032A	57	23	3050	526	--	3.16	20.0	0.172	0.076	46
2-63-0033A	55	23	3019	513	--	3.35	19.2	0.170	0.081	39
2-63-0034A	58	23	3040	387	--	3.63	20.0	0.127	0.088	34
2-63-0035A	56	23	3070	183	--	4.02	20.0	0.060	0.097	22
2-63-0036A	57	35	3020	998	--	2.06	21.2	0.330	0.050	62
2-63-0037A	58	35	3000	884	--	1.82	20.0	0.295	0.044	[illegible]6
2-63-0038A	56	35	3080	954	1928	2.26	19.3	0.310	0.055	47
2-63-0039A	56	35	3030	906	1928	2.07	20.0	0.299	0.050	38
2-63-0040A	55	35	3050	676	1901	3.86	20.5	0.222	0.093	25
2-63-0049A	55	35	4508	1077	2740	2.23	21.4	0.239	0.054	67
2-63-0050A	56	35	4500	915	2552	2.77	21.0	0.203	0.067	55
2-63-0051A	54	35	4500	888	26[illegible]	3.58	20.0	0.197	0.087	45
2-63-0052A	55	35	4449	753	2553	4.25	20.6	0.169	0.103	36
2-63-0053A	55	35	4629	534	2506	5.50	20.0	0.115	0.133	25

* Average carcass diameter = 41.3 in.

** Dashes denote data not valid.

Table 5

Summary of Test Results

Yuma Sand, Single Wheel, Constant 20% Slip Tests

4.50-18, 4-PR Tire

Test No.	Pass No.	Station	Deflection %	Load (W) lb	Pull (P_{20}) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_{20}}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
150A	1	112	15	878	-23	361	3.88	20	-0.026	0.143	31
	2	113	15	900	-9	352	5.29	20	-0.010	0.195	
140A	1	114	15	908	62	304	1.61	20	0.068	0.059	59
	2	114	15	916	40	350	2.79	20	0.044	0.103	
363A	1	112	15	910	36	[illegible]	2.47	20	0.040	0.091	46
	2	112	15	893	6	309	3.79	20	0.007	0.140	
142A	1	111	15	910	58	349	1.77	20	0.064	0.065	60
	2	111	15	947	35	366	2.96	20	0.037	0.109	
139A	1	111	15	916	52	314	1.98	20	0.057	0.073	54
	2	111	15	910	43	310	3.08	20	0.047	0.114	
146A	1	113	35	895	-70	[illegible]	4.90	20	-0.078	0.181	24
	2	113	35	907	21	289	4.90	20	0.023	0.181	
129A	1	111	35	888	258	359	0.30	20	0.291	0.011	58
	2	111	35	880	188	322	1.17	20	0.214	0.043	
121A	1	114	35	896	246	354	0.76	20	0.274	0.028	54
	2	113	35	891	201	330	1.25	20	0.225	0.046	
115A	1	110	35	892	257	368	0.24	20	0.288	0.009	55
	2	110	35	876	147	307	1.[illegible]	20	0.193	0.045	
128A	1	110	35	896	268	364	0.69	20	0.299	0.025	62
	2	110	35	894	186	323	1.42	20	0.208	0.052	
152A	1	111	35	896	76	330	1.17	20	0.085	0.043	40
	2	110	35	900	43	301	2.43	20	0.048	0.090	
110A	1	110	35	903	152	316	1.08	20	0.168	0.040	38
	2	110	35	870	94	290	2.27	20	0.108	0.084	
92A	1	114	35	905	94	288	1.80	20	0.104	0.066	33
	2	115	35	897	90	[illegible]	3.01	20	0.100	0.111	
127A	1	111	35	905	240	356	0.54	20	0.265	0.020	59
	2	110	35	898	164	319	1.66	20	0.183	0.061	
96A	1	110	35	906	118	303	1.47	20	0.130	0.054	40
	2	109	35	893	84	296	2.61	20	0.094	0.096	
357A	1	109	35	906	58	313	2.89	20	0.064	0.107	30
	2	109	35	886	58	293	3.96	20	0.065	0.146	
105A	1	110	35	911	156	323	1.46	20	0.171	0.054	37
	2	110	35	890	109	301	2.33	20	0.122	0.086	
120A	1	111	35	912	248	352	0.71	20	0.272	0.026	58
	2	111	35	879	180	322	1.47	20	0.205	0.054	
95A	1	109	35	915	76	317	2.28	20	0.083	0.084	32
	2	109	35	864	54	294	3.40	20	0.061	0.125	
104A	1	111	35	916	94	317	2.23	20	0.103	0.082	36
	2	110	35	898	85	289	2.97	20	0.095	0.110	
108A	1	111	35	917	177	[illegible]	1.41	20	0.193	0.052	38
	2	110	35	878	120	294	2.08	20	0.137	0.077	
153A	1	112	35	920	76	313	2.33	20	0.083	0.086	31
	2	111	35	882	48	302	3.45	20	0.054	0.127	
109A	1	111	35	922	178	335	1.44	20	0.193	0.053	36
	2	111	35	897	112	294	2.15	20	0.125	0.079	
155A	1	112	35	932	83	332	2.35	20	0.089	0.087	39
	2	113	35	896	45	305	3.51	20	0.050	0.130	
102A	1	111	35	925	180	328	1.48	20	0.195	0.055	44
	2	109	35	902	120	290	1.89	20	0.133	0.070	

* d is carcass diameter.

Table 6

Summary of Test Results

Yuma Sand, Single Wheel, Constant 20% Slip Tests

9.00-14, 2-PR Tire

Test No.	Pass No.	Station	Deflection %	Load (W) lb	Pull (P_{20}) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_{20}}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
539A	1	105	15	845	185	362	1.37	20	0.219	0.051	48
	2	105	15	864	112	336	2.08	20	0.130	0.077	
540A	1	108	15	853	25	347	3.47	20	0.029	0.128	25
	2	109	15	832	31	300	4.33	20	0.037	0.160	
742A	1	108	15	864	108	353	2.28	20	0.125	0.084	32
	2	108	15	862	79	320	3.11	20	0.092	0.115	
737A	1	108	15	871	225	395	1.20	20	0.258	0.044	57
	2	108	15	875	136	351	1.82	20	0.155	0.067	
741A	1	109	15	872	136	377	1.87	20	0.156	0.069	36
	2	107	15	870	84	323	2.70	20	0.097	0.100	
744A	1	107	15	873	229	405	1.05	20	0.262	0.039	48
	2	107	15	877	126	349	1.83	20	0.144	0.068	
254A	1	107	15	874	166	343	1.43	20	0.190	0.053	45
	2	107	15	873	80	316	2.11	20	0.092	0.078	
246A	1	107	15	876	8	331	3.20	20	0.009	0.118	23
	2	106	15	861	21	299	3.92	20	0.024	0.145	
743A	1	108	15	880	225	407	1.17	20	0.256	0.043	51
	2	108	15	852	130	353	2.03	20	0.153	0.075	
579A	1	108	15	881	115	385	2.43	20	0.131	0.090	29
	2	108	15	900	65	342	4.43	20	0.072	0.163	
570A	1	110	15	885	209	397	1.84	20	0.236	0.068	45
	2	110	15	897	115	360	2.84	20	0.128	0.105	
568A	1	105	15	888	285	430	0.85	20	0.321	0.031	81
	2	104	15	876	179	345	1.41	20	0.204	0.052	
574A	1	108	15	888	221	424	1.39	20	0.249	0.051	50
	2	108	15	876	110	370	2.27	20	0.126	0.084	
738A	1	107	15	889	241	412	1.10	20	0.271	0.041	47
	2	107	15	880	133	346	1.93	20	0.151	0.071	
571A	1	112	15	891	167	413	1.89	20	0.187	0.070	39
	2	110	15	878	98	358	2.65	20	0.112	0.098	
576A	1	110	15	898	270	416	1.24	20	0.301	0.046	66
	2	110	15	868	165	370	1.65	20	0.186	0.061	
580A	1	109	15	899	185	393	1.79	20	0.206	0.066	40
	2	108	15	890	119	355	2.61	20	0.134	0.096	
581A	1	107	15	903	206	450	1.46	20	0.228	0.054	45
	2	106	15	897	119	351	2.27	20	0.133	0.084	
537A	1	103	15	904	223	406	0.45	20	0.246	0.017	54
	2	103	15	844	121	326	1.17	20	0.143	0.043	

(Continued)

* d is carcass diameter.

Table 6 (Concluded)

Test No.	Pass No.	Sta-tion	Deflection %	Load (W) lb	Pull (P_{20}) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_{20}}{W}$	$\frac{z}{l}$	0- to 6-in. Avg Cone Index
582A	1	110	15	904	113	392	2.71	20	0.125	0.100	27
	2	110	15	905	70	354	3.79	20	0.077	0.140	
583A	1	108	15	904	223	409	1.27	20	0.247	0.047	48
	2	107	15	898	130	357	1.78	20	0.144	0.066	
577A	1	112	15	905	41	393	3.05	20	0.045	0.113	25
	2	111	15	912	44	353	4.35	20	0.048	0.161	
572A	1	109	15	906	93	384	1.38	20	0.103	0.051	26
	2	109	15	904	59	365	2.18	20	0.065	0.080	
573A	1	111	15	906	106	383	2.26	20	0.117	0.083	35
	2	110	15	888	80	358	3.21	20	0.090	0.118	
568A	1	110	15	901	78	374	2.94	20	0.087	0.108	35
	2	110	15	890	66	337	3.55	20	0.074	0.131	
575A	1	107	15	909	248	406	1.07	20	0.273	0.039	57
	2	108	15	901	155	361	1.12	20	0.172	0.041	
740A	1	108	15	914	133	390	2.15	20	0.146	0.079	32
	2	108	15	914	91	348	3.10	20	0.100	0.114	
536A	1	107	35	861	371	456	0.49	20	0.431	0.018	60
	2	107	35	862	264	379	0.75	20	0.306	0.028	
282A	1	108	35	864	178	339	2.00	20	0.206	0.074	27
	2	107	35	868	131	304	2.03	20	0.151	0.075	
538A	1	106	35	869	313	422	0.81	20	0.360	0.030	47
	2	106	35	873	214	365	1.33	20	0.245	0.049	
293A	1	105	35	872	306	414	0.69	20	0.351	0.025	39
	2	104	35	877	211	359	1.16	20	0.241	0.043	
299A	1	104	35	885	386	434	0.38	20	0.436	0.014	66
	2	105	35	876	284	380	0.57	20	0.324	0.021	
563A	1	108	35	880	241	369	1.57	20	0.274	0.058	29
	2	108	35	872	167	334	2.24	20	0.191	0.083	
562A	1	105	35	884	338	435	0.93	20	0.382	0.034	54
	2	103	35	880	231	361	1.32	20	0.263	0.049	

Table 7

Summary of Test Results

Mortar Sand, Single Wheel, 20% Slip Point

9.00-14, 2-PR Tire

Test No.	Pass No.	Station	Deflection %	Load (W) lb	Pull (P_{20}) lb	Torque ft-lb	Sinkage (z) in.	Slip %	$\frac{P_{20}}{W}$	$\frac{z}{d^*}$	0- to 6-in. Avg Cone Index
553	1	116	15	870	14	314	2.66	20	0.016	0.098	33
	2	117	15	868	34	308	3.60	20	0.039	0.133	
551	1	116	15	872	-36	322	3.67	20	-0.041	0.135	26
	2	116	15	864	22	298	4.26	20	0.025	0.157	
557	1	106	15	876	130	314	1.32	20	0.148	0.049	52
	2	105	15	876	78	310	1.91	20	0.089	0.070	
549	1	116	15	876	-42	324	4.60	20	-0.048	0.170	14
	2	116	15	880	24	304	4.57	20	0.027	0.169	
556	1	107	15	879	83	320	1.75	20	0.094	0.065	41
	2	106	15	874	56	307	2.55	20	0.064	0.094	
554	1	108	35	852	212	332	1.42	20	0.249	0.052	33
	2	107	35	856	178	312	1.95	20	0.208	0.072	
548	1	118	35	854	-22	299	3.21	20	-0.026	0.118	11
	2	116	35	850	107	300	4.29	20	0.126	0.158	
558	1	104	35	883	305	408	0.44	20	0.345	0.016	54
	2	105	35	890	198	351	0.93	20	0.222	0.034	
550	1	116	35	886	51	293	2.93	20	0.058	0.108	23
	2	117	35	872	112	315	3.34	20	0.128	0.123	
555	1	106	35	889	257	380	1.10	20	0.289	0.041	38
	2	106	35	875	167	332	1.45	20	0.191	0.054	

* d is carcass diameter.

Table 8

Summary of Test Results

Yuma Sand, 4x4 Vehicle, Constant 20% Slip Tests

7.50-18, 4-PR Tire

Test No.	Deflection %	Load (W) lb	Pull (P_{20}) lb	Slip %	$\frac{P_{20}}{W}$	0- to 6-in. Avg Cone Index
32-4	15	890	110	20	0.124	53
33-4	15	890	-60	20	-0.067	41
36-4	15	890	-90	20	-0.101	36
38-4	15	890	130	20	0.146	63
34-4	35	890	510	20	0.573	41
37-4	35	890	400	20	0.449	37
40-4	35	890	780	20	0.876	61
41-4	35	890	610	20	0.685	49

Table 9

Summary of Test Results

Yuma Sand, 4x4 Vehicle, Constant 20% Slip Tests

9.00-14, 2-PR Tire

Test No.	Deflection %	Load (W) lb	Pull (P_{20}) lb	Slip %	$\frac{P_{20}}{W}$	0- to 6-in. Avg Cone Index
46-4	15	890	720	20	0.809	63
47-4	15	890	225	20	0.253	30
48-4	15	890	490	20	0.551	47
49-4	15	890	65	20	0.073	17
43-4	35	890	1170	20	1.315	50
44-4	35	890	900	20	1.011	34
45-4	35	890	1290	20	1.449	59
51-4	35	890	725	20	0.815	23

Table 10

<u>Summary of Test Results</u>

<u>Mortar Sand, 4x4 Vehicle, Constant 20% Slip Tests</u>

4.50-18, 4-PR Tire

Test No.	Deflection %	Load (W) lb	Pull (P_{20}) lb	Slip %	$\frac{P_{20}}{W}$	0- to 6-in. Avg Cone Index
21-4	15	890	-253	20	-0.284	51
22-4	15	890	-262	20	-0.294	44
24-4	15	890	-320	20	-0.360	37
30-4	15	890	-225	20	-0.253	58
31-4	15	890	-340	20	-0.382	26
20-4	35	890	420	20	0.472	51
23-4	[illegible]	890	255	20	0.287	43
26-4	35	890	65	20	0.073	37
27-4	35	890	500	20	0.562	59
28-4	35	890	-100	20	-0.112	27
29-4	35	890	172	20	0.193	36

Table 11

Summary of Test Results

Mortar Sand, 4x4 Vehicle, Constant 20% Slip Tests

9.00-14, 2-PR Tire

Test No.	Deflection %	Load (W) lb	Pull (P_{20}) lb	Slip %	$\frac{P_{20}}{W}$	0- to 6-in. Avg Cone Index
12-4	15	890	410	20	0.461	54
13-4	15	890	230	20	0.258	44
14-4	15	890	70	20	0.079	34
15-4	15	890	-30	20	-0.034	24
16-4	15	890	140	20	0.157	37
18-4	15	890	88	20	0.099	32
19-4	15	890	-15	20	-0.017	26
4-4	35	890	1200	20	1.348	49
8-4	35	890	990	20	1.124	40
9-4	35	890	800	20	0.899	29
10-4	35	890	520	20	0.584	20
11-4	35	890	1250	20	1.404	62
12-4	35	890	1240	20	1.393	49

Table 12

In Situ Density Measurements

Yuma Sand			Mortar Sand		
Cone Index		Dry Density lb/cu ft	Cone Index		Dry Density lb/cu ft
0- to 2-in. Average	0- to 6-in. Average		0- to 2-in. Average	0- to 6-in. Average	
3.75	7	90.3	5.0	11	94.6
7.0	12	94.8	6.0	13	94.3
6.0	14	95.0	5.0	12	95.1
8.25	17	95.1	8.0	19	95.3
6.0	19	96.4	6.0	14	95.8
15.0	45	100.2	9.0	--	97.3
18.0	55	101.5	10.0	17	97.9
16.0	64	102.4	11.0	23	97.9
18.0	60	102.7	11.0	26	97.8
19.0	69	103.0	6.0	30	98.0
			14.0	30	98.1
			13.0	28	98.4
			13.0	33	100.6
			13.0	28	100.7
			15.0	35	101.2
			20.0	50	101.8
			15.25	--	102.0
			--	45	102.1
			17.25	49	102.6
			20.0	44	103.1
			--	43	103.2
			17.0	41	103.7
			16.0	38	103.9
			20.0	52	104.0
			20.0	54	104.6

Table 13

Direct Shear Test Results

Yuma Sand						Mortar Sand					
Dry Density (γ_d) lb/cu ft	Normal Stress (σ_n) psi	Max Shear Stress (S_d) psi	Friction Angle (ϕ_d) deg	Tan ϕ_d	Cohesion (c_d) psi	Dry Density (γ_d) lb/cu ft	Normal Stress (σ_n) psi	Max Shear Stress (S_d) psi	Friction Angle (ϕ_d) deg	Tan ϕ_d	Cohesion (c_d) psi
90.4	6.9 20.8 41.7	5.26 15.91 31.55	37.2	0.759	0.0						
91.8	6.9 20.8 41.7	4.81 14.57 29.16	35.1	0.703	0.0						
91.8	6.9 20.8 41.7	4.96 14.87 29.76	35.6	0.716	0.0						
91.8	6.9 20.8 41.7	4.80 14.40 28.78	35.1	0.703	0.0						
92.0	6.9 20.8 41.7	4.80 14.88 29.76	35.6	0.716	0.0	92.5	6.9 20.8 41.7	3.61 10.70 21.67	27.5	0.521	0.0
96.0	6.9 20.8 41.7	4.66 15.03 30.66	36.4	0.737	0.0	96.3	6.9 20.8 41.7	3.75 11.11 22.50	28.4	0.541	0.0
96.7	6.9 20.8 41.7	4.96 14.88 29.76	35.1	0.703	0.0						
97.5	6.9 20.8 41.7	5.11 15.79 31.54	37.2	0.759	0.0						
97.5	6.9 20.8 41.7	4.80 14.62 29.43	35.1	0.703	0.0						
97.5	6.9 20.8 41.7	4.80 15.31 30.62	36.1	0.729	0.0						
97.5	6.9 20.8 41.7	5.11 15.31 30.62	36.7	0.745	0.0						
97.6	6.9 20.8 41.7	5.41 17.26 31.54	38.2		0.0						
99.9	6.9 20.8 41.7	4.11 14.34 29.62	36.1		1.0						
100.1	6.9 20.8 41.7	5.26 15.08 32.16	37.6		0.0	100.4	6.9 20.8 41.7	4.17 12.36 25.14	31.1	0.603	0.0
103.2	6.9 20.8 41.7	5.26 16.23 31.54	37.2		0.0						
103.4	6.9 20.8 41.7	5.41 16.23 32.46	37.2		0.0						
103.8	6.9 20.8 41.7	5.41 16.[illegible] 29.43	38.2		0.0						
103.9	6.9 20.8 41.7	5.11 15.34 31.54	37.2		0.0						
105.2	6.9 20.8 41.7	3.50 14.47 [illegible]	36.1		1.0	104.9	6.9 20.8 41.7	4.58 13.61 27.82	33.2	0.654	0.0
105.2	6.9 20.8 41.7	5.11 15.31 30.62	36.7		0.0						

Table 14

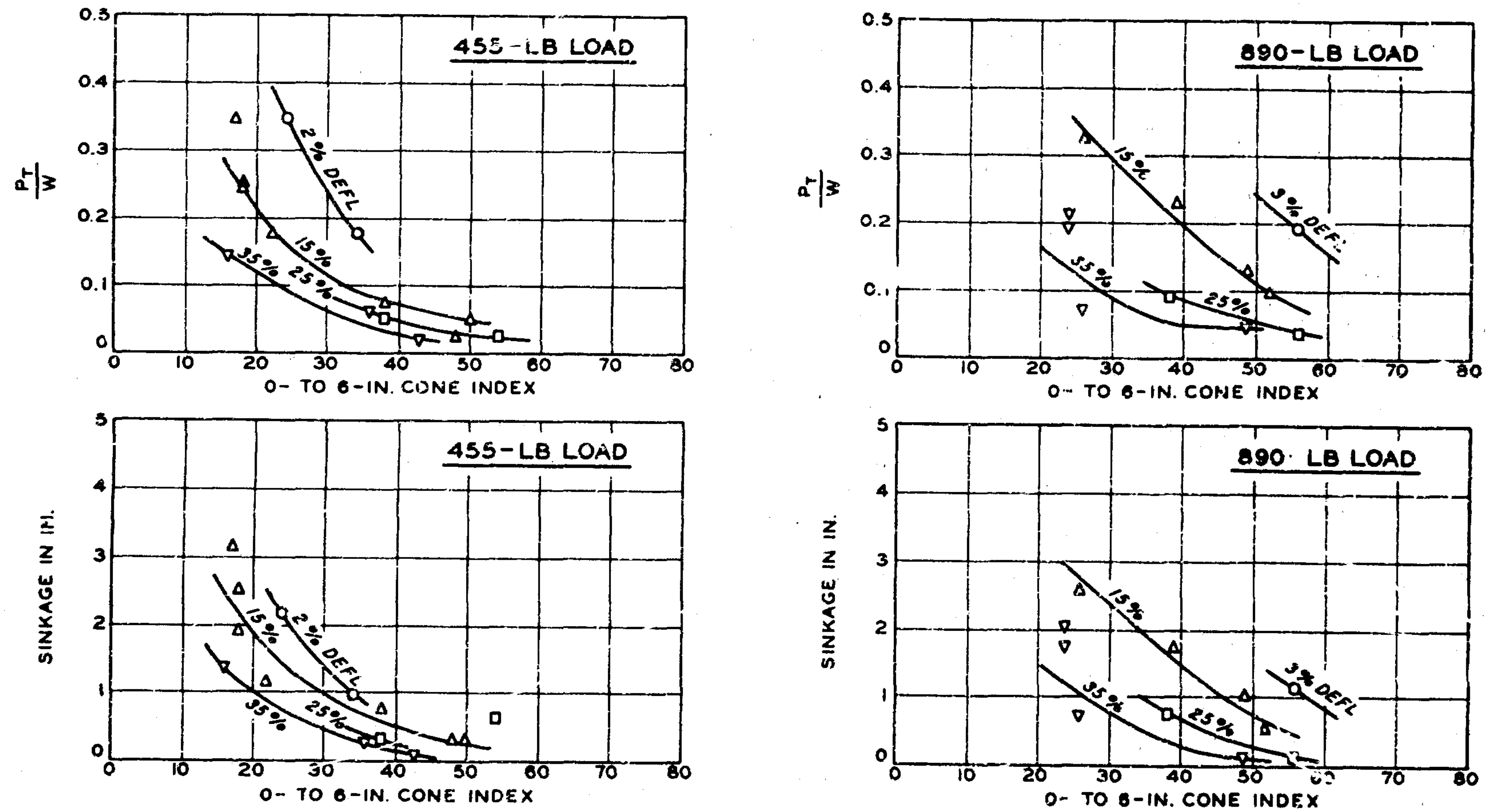
Triaxial Shear Test Results

Yuma Sand									Mortar Sand								
Dry Density (γ_d) lb/cu ft	Principal Stress, psi: Minor (σ_3)	Principal Stress, psi: Major (σ_1)	Max* Shear Stress (S_t) psi	Cohesion (C_t) psi	Friction Angle (ϕ_t) deg	Tan ϕ_t	Max** Frictional Shear Stress ($S_{t(f)}$), psi		Dry Density (γ_d) lb/cu ft	Principal Stress, psi: Minor (σ_3)	Principal Stress, psi: Major (σ_1)	Max* Shear Stress (S_t) psi	Cohesion (C_t) psi	Friction Angle (ϕ_t) deg	Tan ϕ_t	Max** Frictional Shear Stress ($S_{t(f)}$), psi	
92.4	7.0	31.7	12.35	1.5	35.8	0.721	10.85		92.5	6.9	22.9	8.00	0.5	28.8	0.550	7.50	
	21.0	91.0	35.00				33.50			20.8	62.7	20.95				20.45	
	42.0	166.8	62.40				60.90			41.7	123.1	40.70				40.20	
92.4	6.8	26.9	10.05	0.0	36.3	0.735	10.05										
	20.9	83.4	31.25				31.25										
	42.0	164.5	61.25				61.25										
96.2	7.0	30.0	11.50	0.5	37.5	0.767	11.00		96.3	6.9	24.3	8.70	0.3	30.4	0.587	8.40	
	21.0	92.9	35.95				35.45			20.8	67.1	23.15				22.85	
	42.0	176.1	67.05				66.55			41.7	128.8	43.55				43.25	
96.[illegible]	7.0	33.7	13.35	1.5	37.0	0.754	11.85										
	21.0	92.9	35.95				34.45										
	42.0	176.4	67.20				65.70										
100.2	7.0	32.9	12.95	1.0	38.3	0.790	11.95		100.4	6.9	26.1	9.60	0.7	31.5	0.613	8.90	
	21.0	94.5	36.75				35.75			20.8	71.4	25.30				24.60	
	42.0	183.6	70.80				69.80			41.7	137.9	47.90				47.20	
100.2	7.0	35.0	14.00	1.4	38.4	0.793	12.60										
	21.0	99.2	39.10				37.70										
	42.0	185.0	71.50				70.10										

Note: Specimen height and diameter for all tests were 5.61 and 2.81 in., respectively.

* $S_t = \frac{\sigma_1 - \sigma_3}{2}$.

** $S_{t(f)} = \frac{\sigma_1 - \sigma_3}{2} - C_t$.



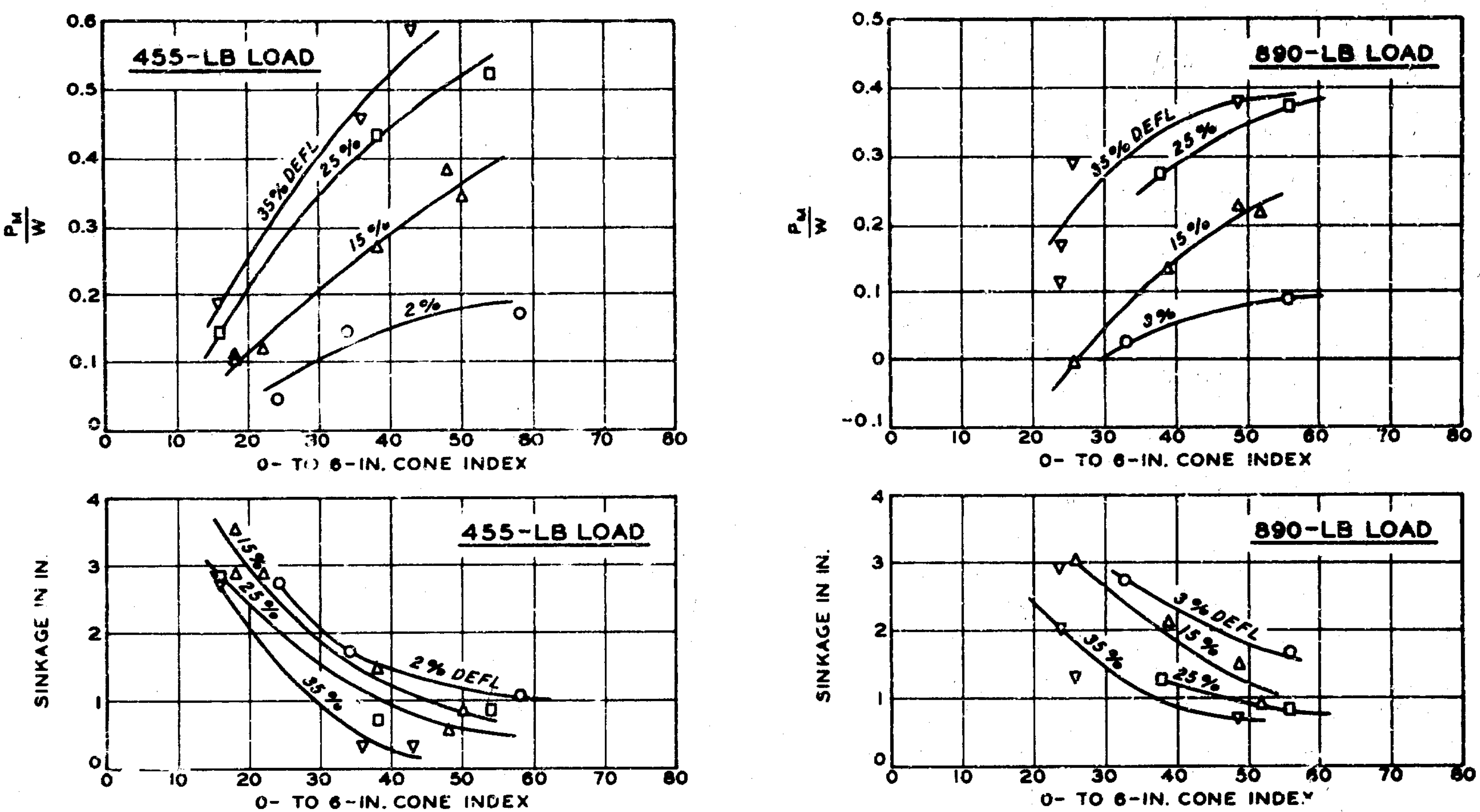
LEGEND

	TIRE SIZE	b, IN.	d, IN.	DEFLECTION, %
o	6.00-16 SOLID TIRE	7.00	28.1	2 AND 3
Δ	6.00-16, 2-PR	6.50	27.6	15
□	6.00-16, 2-PR	6.50	27.6	25
∇	6.00-16, 2-PR	6.50	27.6	35

INFLUENCE OF DEFLECTION

$\frac{P_T}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

TOWED POINT - YUMA SAND
FIRST PASS



LEGEND

	TIRE SIZE	b, IN.	d, IN.	DEFLECTION, %
○	6.00-16 SOLID TIRE	7.00	28.1	2 AND 3
△	6.00-16, 2-PR	6.50	27.6	15
□	6.00-16, 2-PR	6.50	27.6	25
▽	6.00-16, 2-PR	6.50	27.6	35

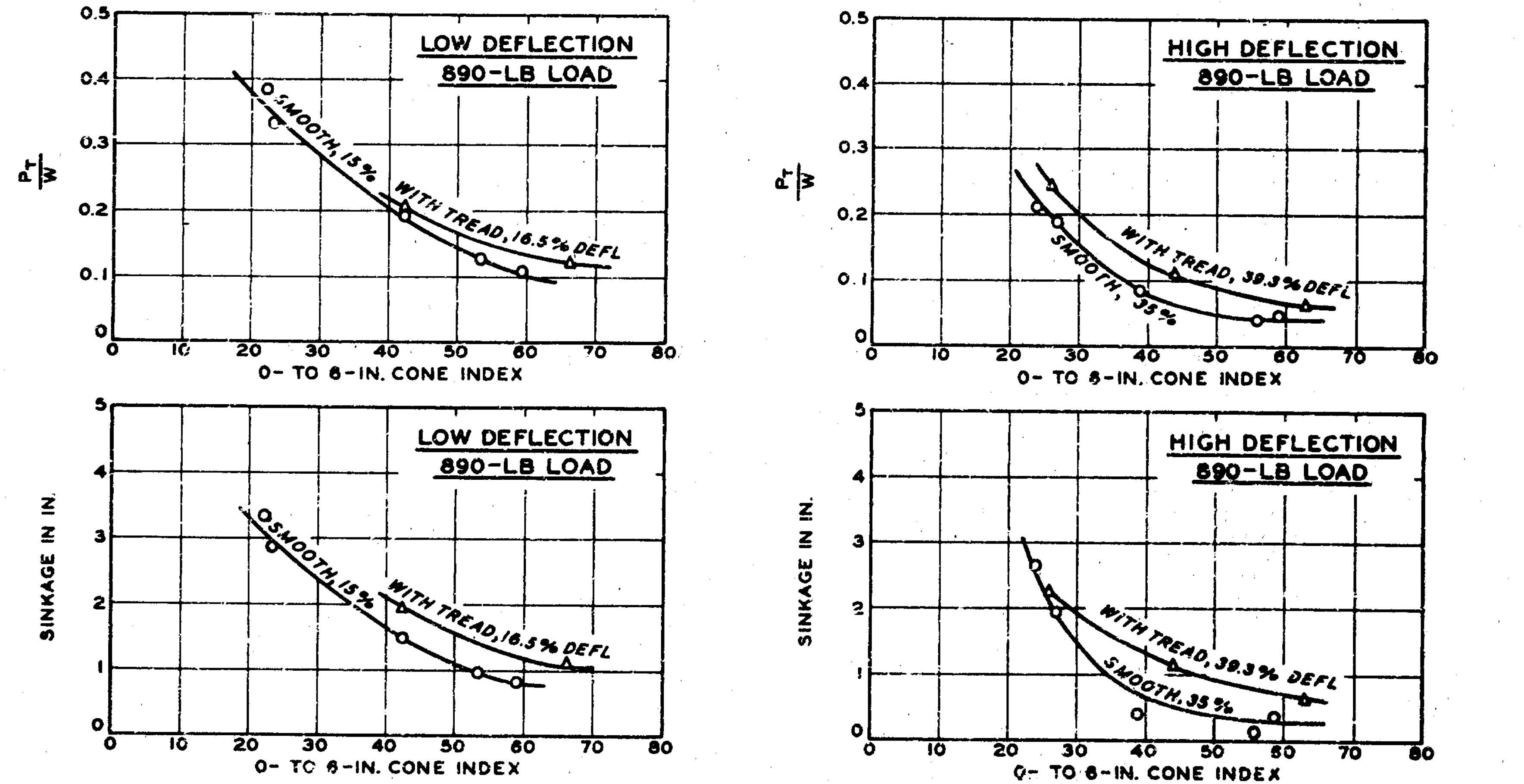
INFLUENCE OF DEFLECTION

$\frac{P_M}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

MAXIMUM PULL POINT - YUMA SAND

FIRST PASS

PLATE 2



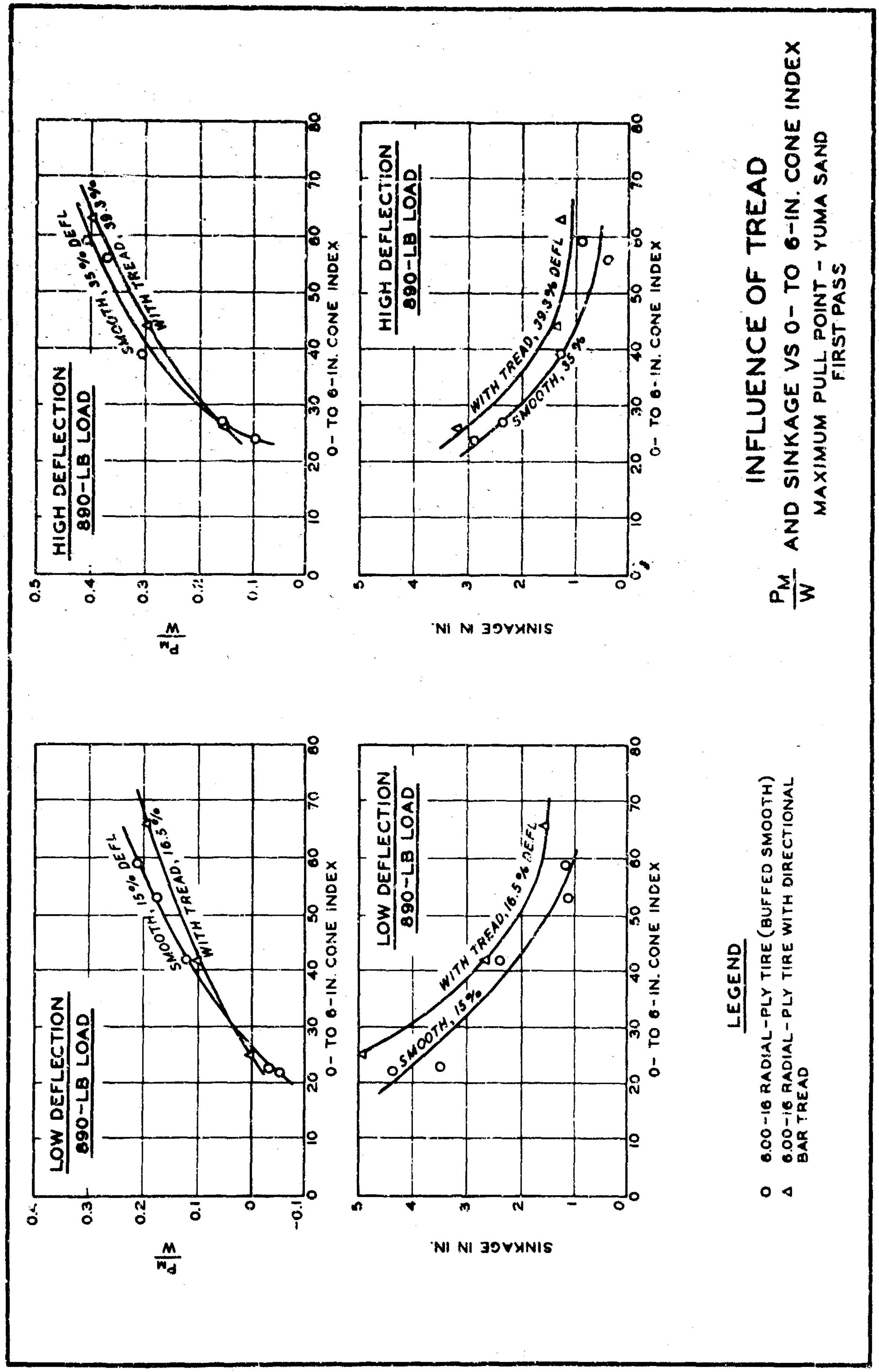
LEGEND

- O 6.00-16 RADIAL-PLY TIRE (BUFFED SMOOTH)
- Δ 6.00-16 RADIAL-PLY TIRE WITH DIRECTIONAL BAR TREAD

INFLUENCE OF TREAD

$\frac{P_T}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

TOWED POINT - YUMA SAND
FIRST PASS



INFLUENCE OF TREAD

$\frac{P_M}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

MAXIMUM PULL POINT - YUMA SAND
FIRST PASS

PLATE 4

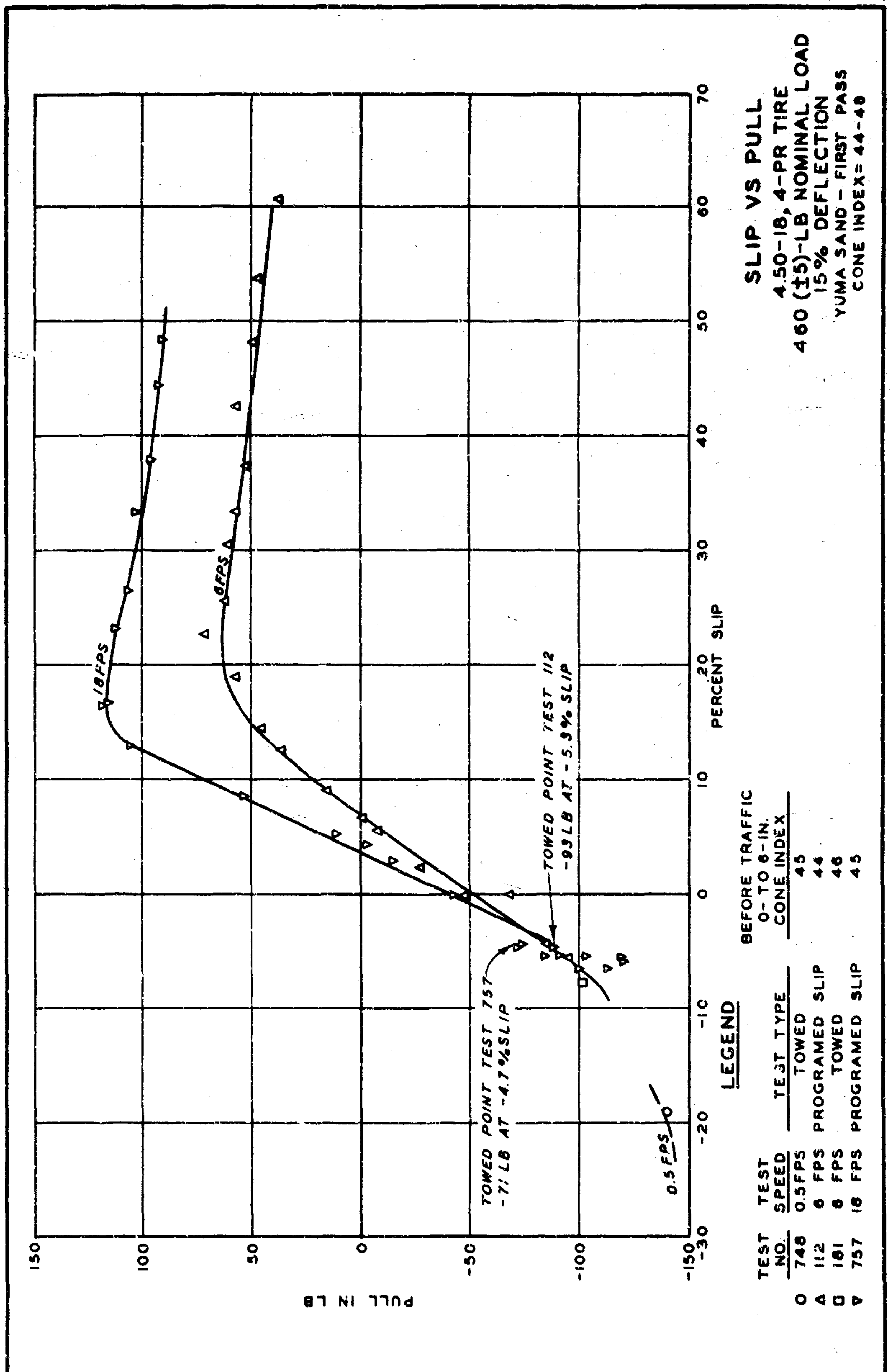

SLIP VS PULL
4.50-16, 4-PR TIRE
460 (±5)-LB NOMINAL LOAD
15% DEFLECTION
YUMA SAND - FIRST PASS
CONE INDEX= 44-46
PULL IN LB
PERCENT SLIP
18FPS
6FPS
0.5 FPS
TOWED POINT TEST 112
-93 LB AT -5.3% SLIP
TOWED POINT TEST 757
-71 LB AT -4.7% SLIP
LEGEND
TEST NO. | TEST SPEED | TEST TYPE | BEFORE TRAFFIC 0- TO 6-IN. CONE INDEX
748 | 0.5 FPS | TOWED | 45
112 | 6 FPS | PROGRAMED SLIP | 44
181 | 6 FPS | TOWED | 46
757 | 18 FPS | PROGRAMED SLIP | 45

PLATE 5

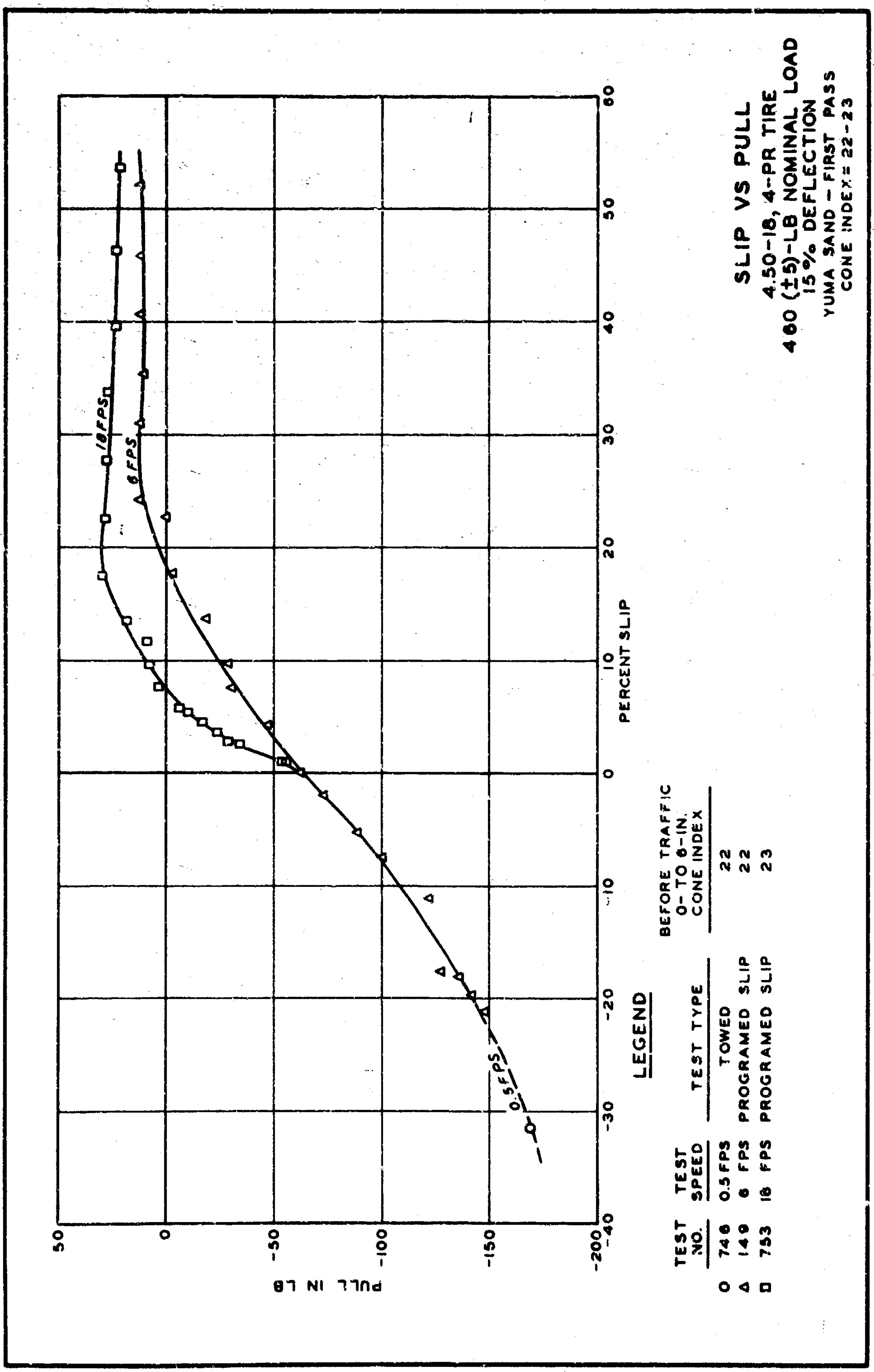
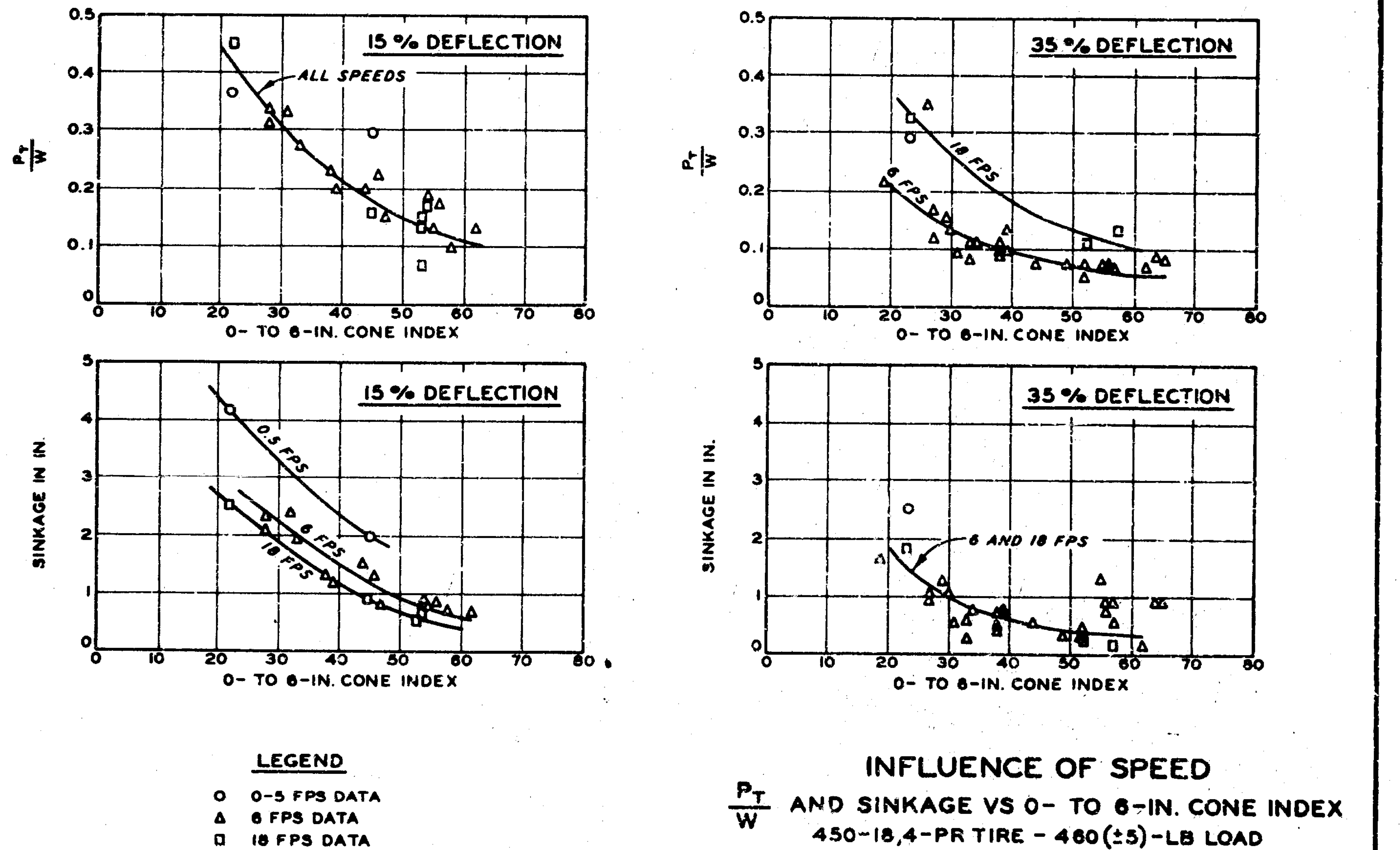

SLIP VS PULL
4.50-16, 4-PR TIRE
460 (±5)-LB NOMINAL LOAD
15% DEFLECTION
YUMA SAND — FIRST PASS
CONE INDEX = 22-23
PULL IN LB
PERCENT SLIP
18 FPS
6 FPS
0.5 FPS
LEGEND
TEST NO. | TEST SPEED | TEST TYPE | BEFORE TRAFFIC 0- TO 6-IN. CONE INDEX
○ 746 | 0.5 FPS | TOWED | 22
△ 149 | 6 FPS | PROGRAMED SLIP | 22
□ 753 | 18 FPS | PROGRAMED SLIP | 23

PLATE 6



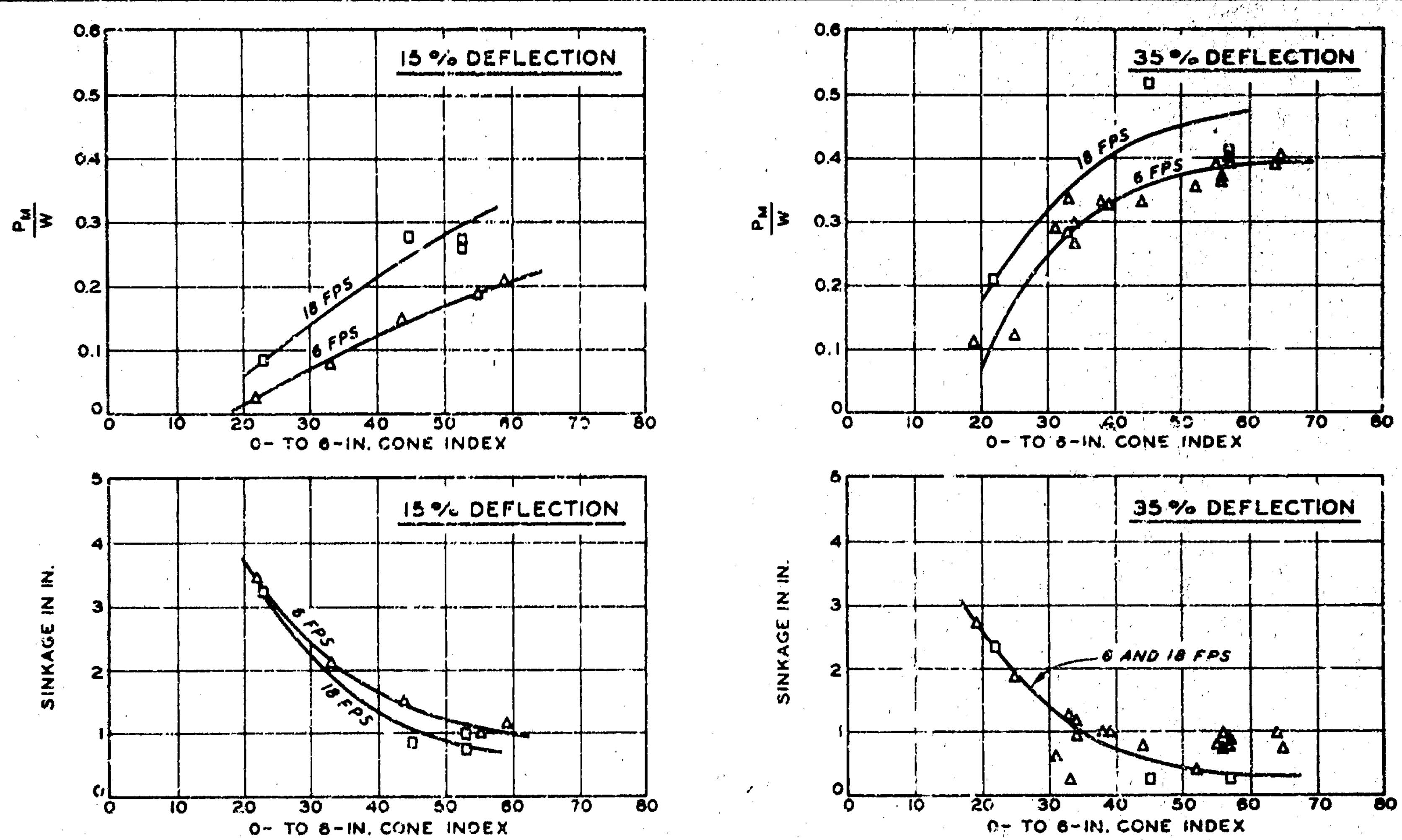
INFLUENCE OF SPEED

$\frac{P_T}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

450-18,4-PR TIRE - 460(±5)-LB LOAD

TOWED POINT - YUMA SAND

FIRST PASS



LEGEND

- Δ 6 FPS DATA
- □ 18 FPS DATA

INFLUENCE OF SPEED

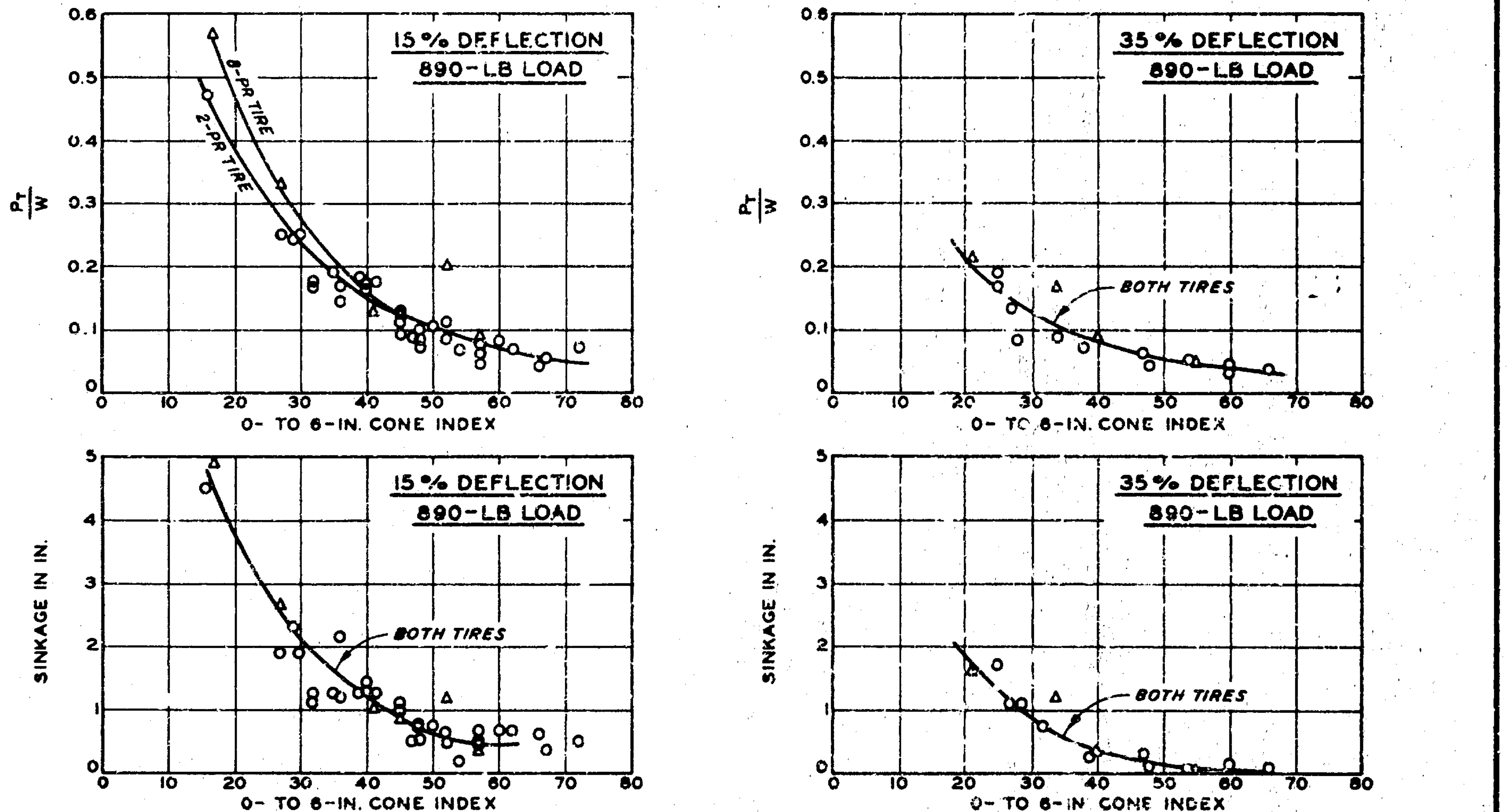
$\frac{P_M}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

450-18, 4-PR TIRE - 460(±5)-LB LOAD

MAXIMUM PULL POINT - YUMA SAND

FIRST PASS

PLATE 8



LEGEND

O 9.00-14, 2-PR TIRE
Δ 9.00-14, 8-PR TIRE

INFLUENCE OF CARCASS STIFFNESS

$\frac{P_T}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

TOWED POINT - YUMA SAND
FIRST PASS

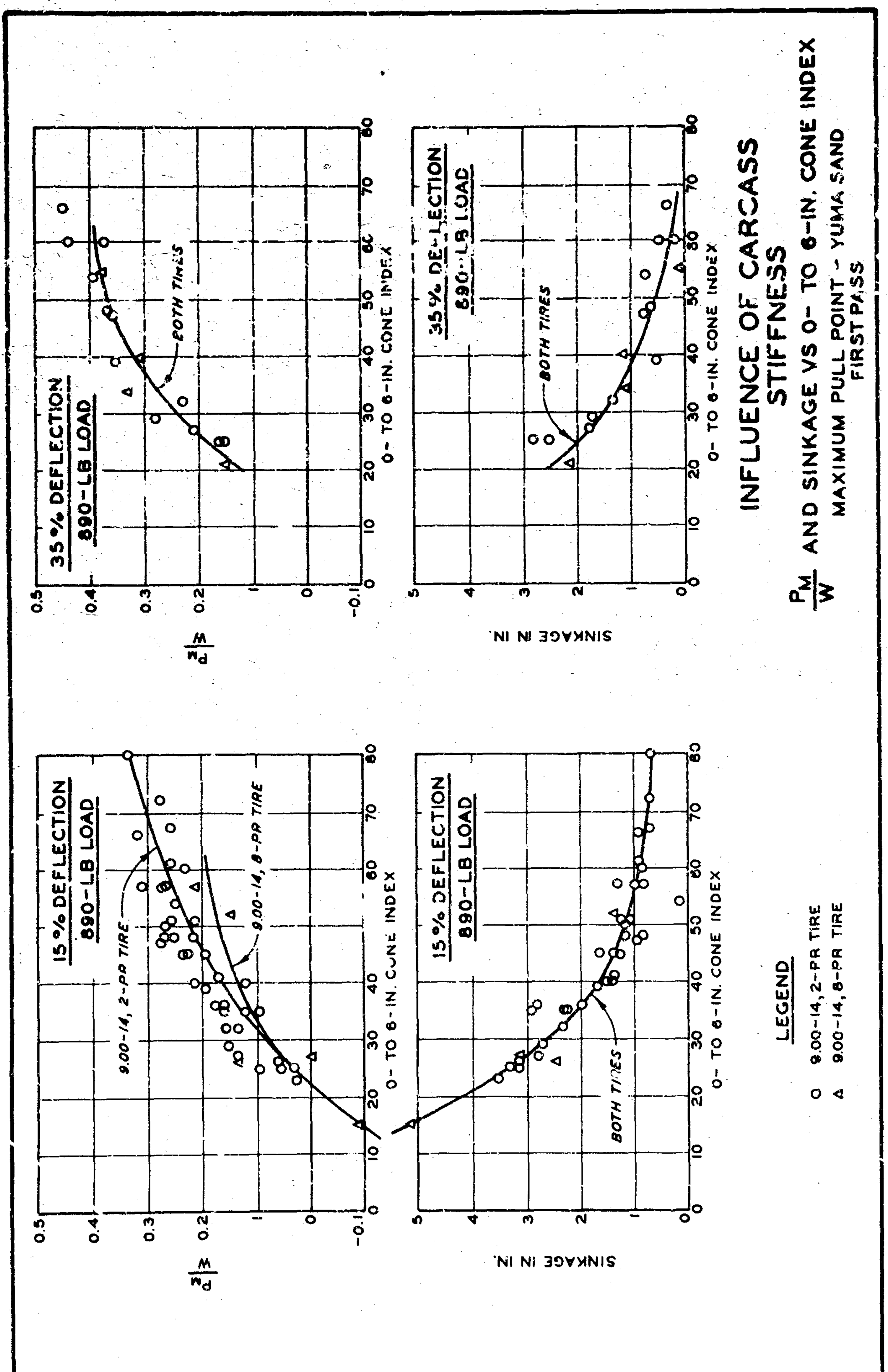
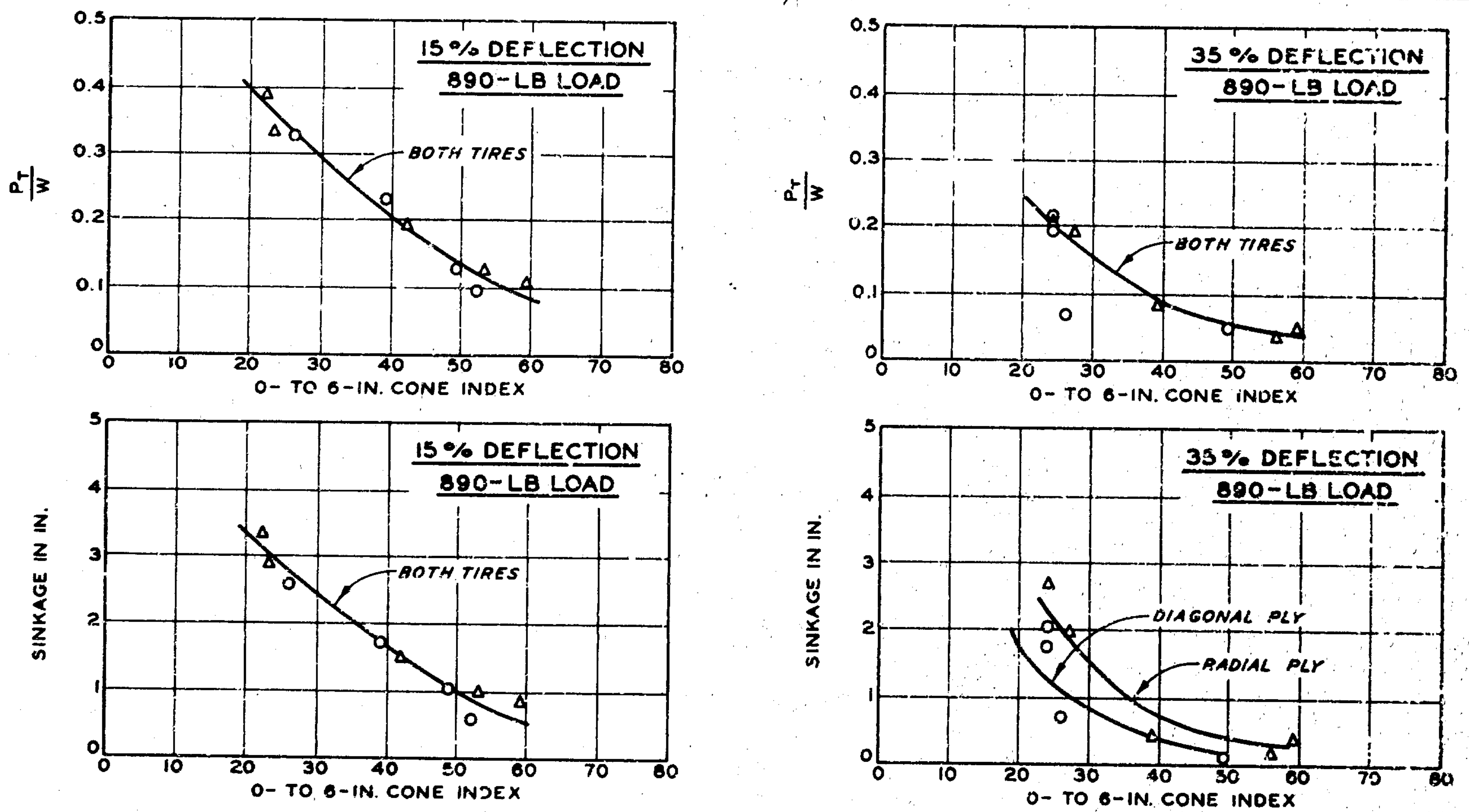

INFLUENCE OF CARCASS STIFFNESS
$\frac{P_M}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX
MAXIMUM PULL POINT - YUMA SAND
FIRST PASS
15 % DEFLECTION
890-LB LOAD
35 % DEFLECTION
890-LB LOAD
9.00-14, 2-PR TIRE
9.00-14, 8-PR TIRE
BOTH TIRES
0- TO 6-IN. CONE INDEX
$\frac{P_M}{W}$
SINKAGE IN IN.
LEGEND
O 9.00-14, 2-PR TIRE
Δ 9.00-14, 8-PR TIRE

PLATE 10



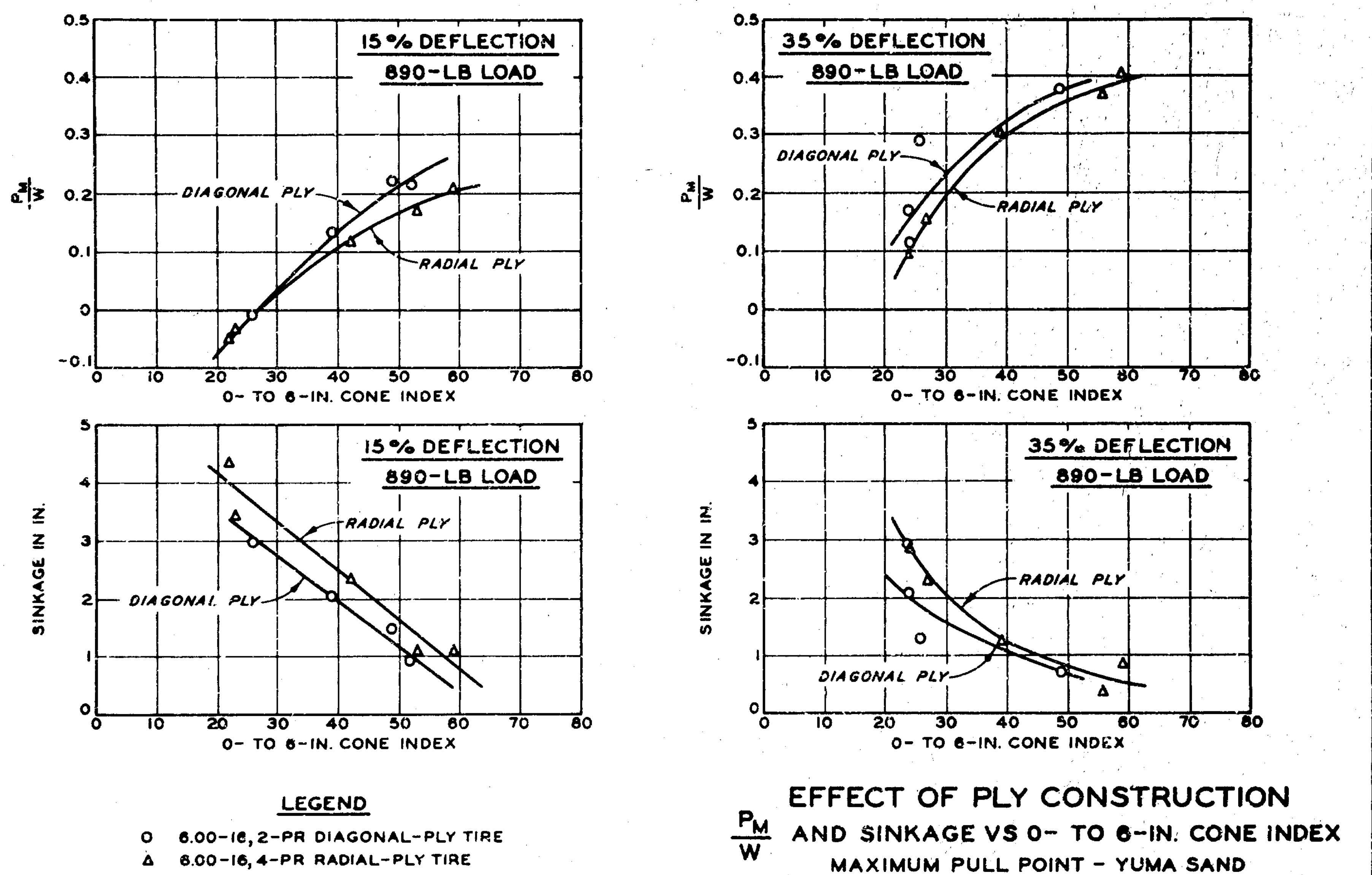
LEGEND

○ 6.00-16, 2-PR DIAGONAL-PLY TIRE
△ 6.00-16, 4-PR RADIAL-PLY TIRE

EFFECT OF PLY CONSTRUCTION

$\frac{P_T}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

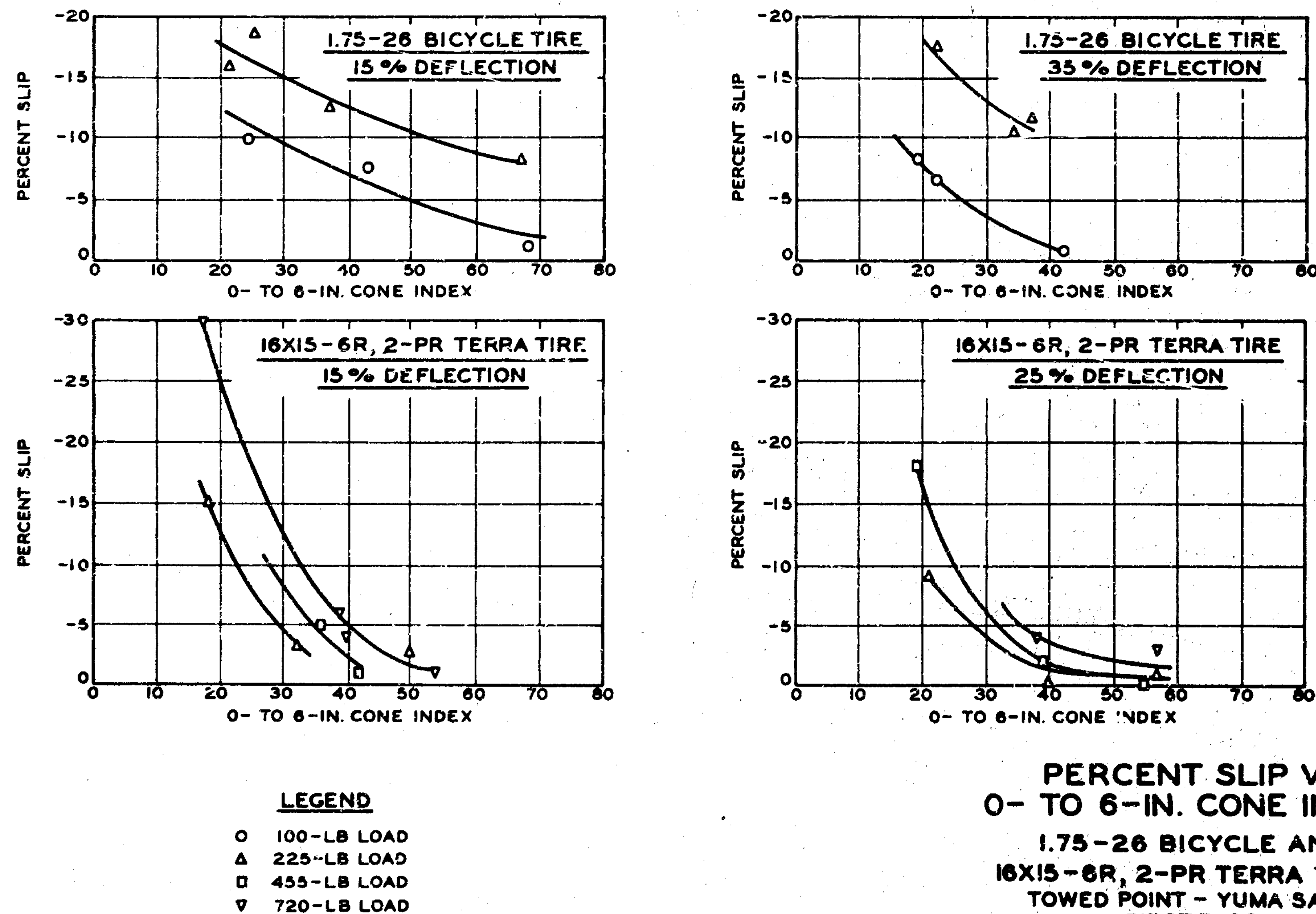
TOWED POINT - YUMA SAND
FIRST PASS



EFFECT OF PLY CONSTRUCTION

$\frac{P_M}{W}$ AND SINKAGE VS 0- TO 6-IN. CONE INDEX

MAXIMUM PULL POINT - YUMA SAND
FIRST PASS

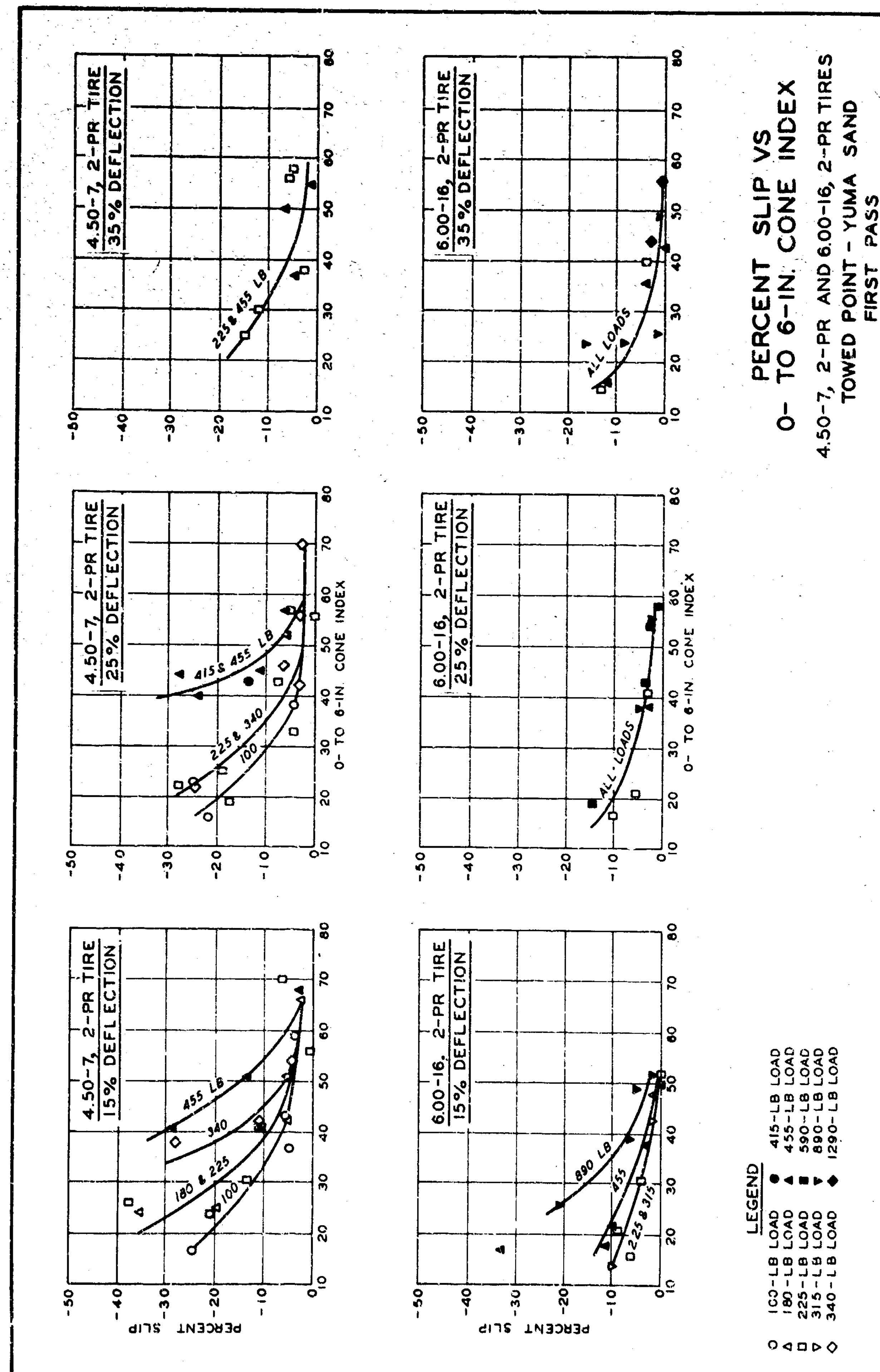


PERCENT SLIP VS 0- TO 6-IN. CONE INDEX

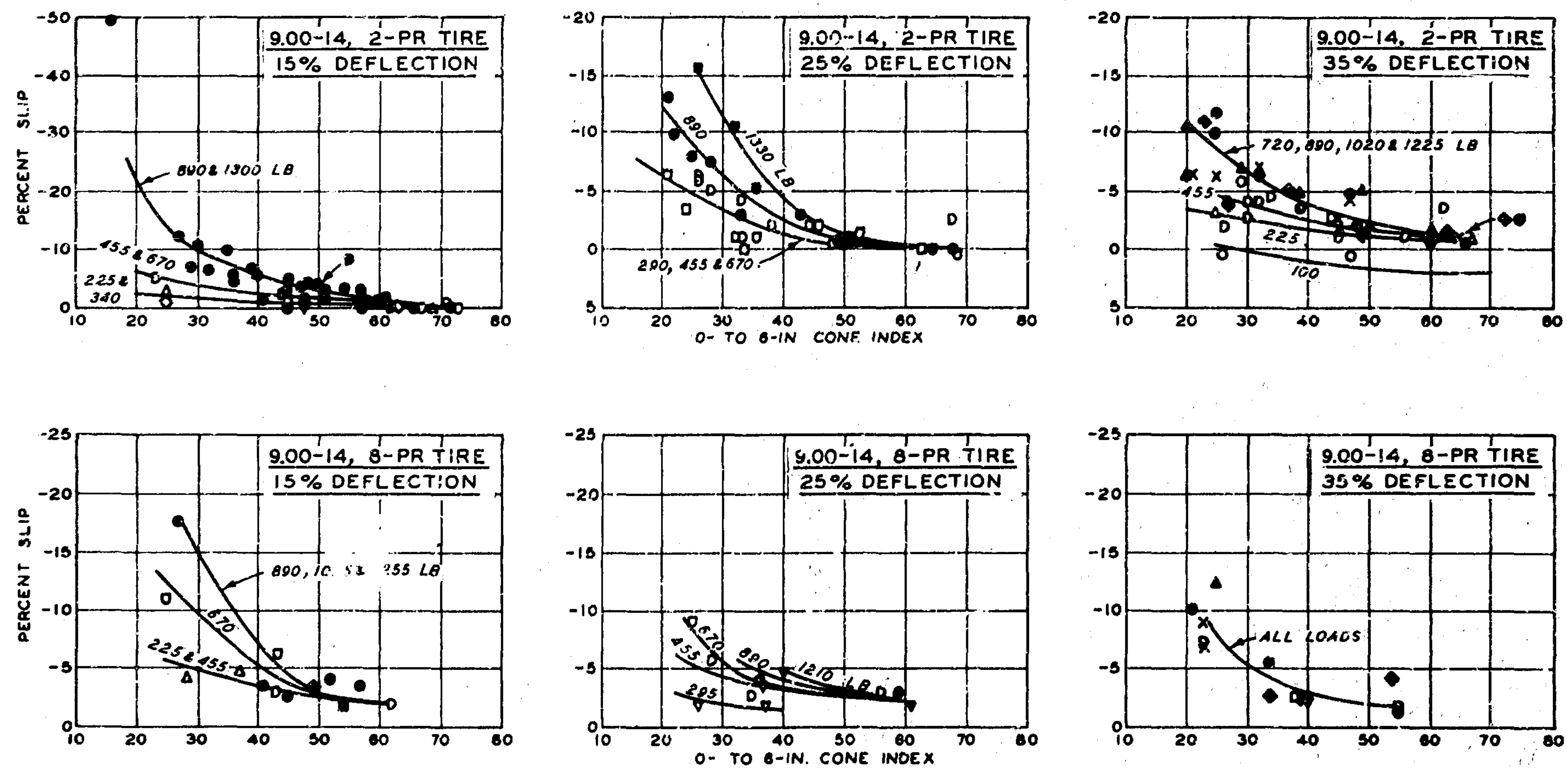
1.75-26 BICYCLE AND 16X15-6R, 2-PR TERRA TIRES

TOWED POINT - YUMA SAND

FIRST PASS



PERCENT SLIP VS
0- TO 6-IN. CONE INDEX
4.50-7, 2-PR AND 6.00-16, 2-PR TIRES
TOWED POINT - YUMA SAND
FIRST PASS



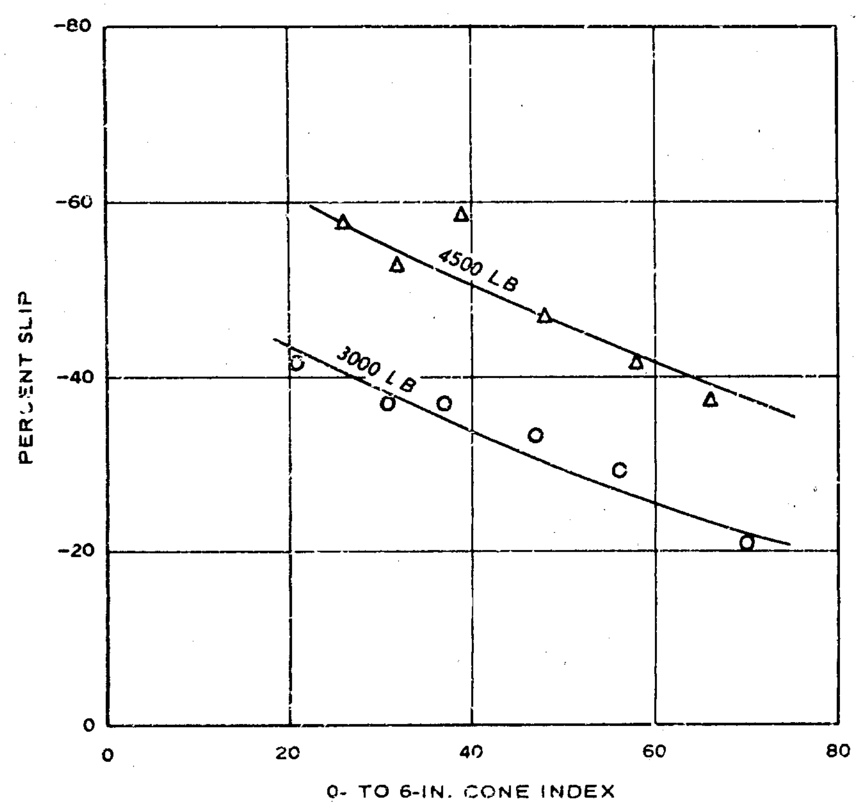
LEGEND

○ 100-LB LOAD	● 890-LB LOAD
△ 225-LB LOAD	▲ 1020-LB LOAD
□ 290-LB LOAD	■ 1025-LB LOAD
▽ 295-LB LOAD	▼ 1210-LB LOAD
◇ 340-LB LOAD	◆ 1225-LB LOAD
D 455-LB LOAD	1300-LB LOAD
670-LB LOAD	1330-LB LOAD
X 720-LB LOAD	

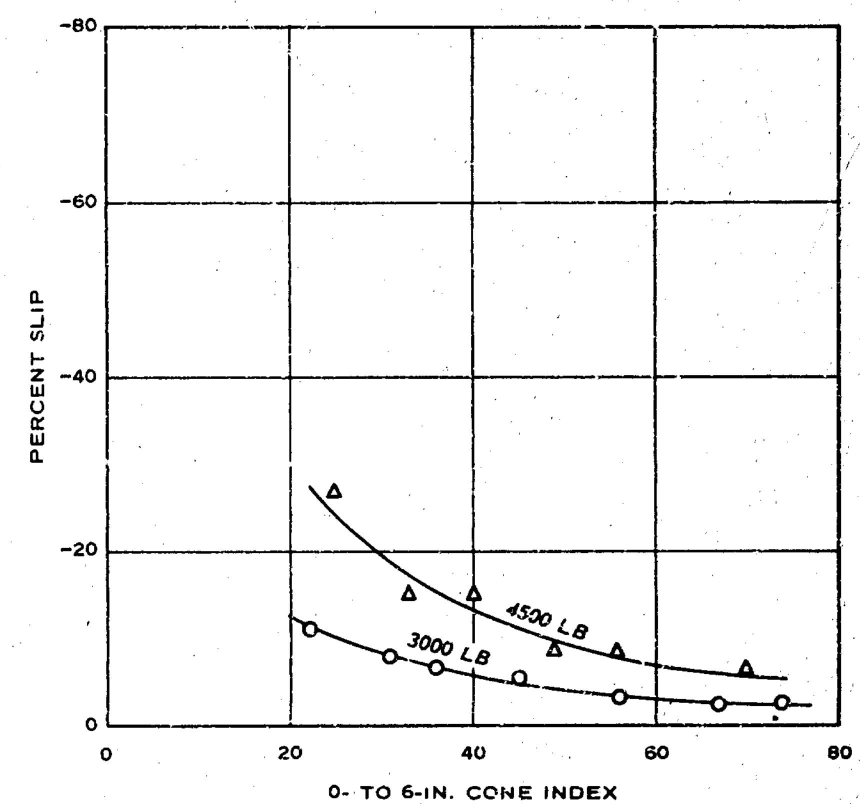
NOTE: SCALE OF PLOT OF 9.00-14, 2-PR TIRE AT 15% DEFLECTION IS DIFFERENT FROM SCALE OF REMAINING PLOTS.
AVAILABLE DATA FOR THE 9.00-14, 8-PR TIRE ARE INSUFFICIENT TO ESTABLISH SEPARATION OF CURVES FOR THE PERCENT SLIP VS 0- TO 6-IN. CONE INDEX RELATION AT 35% DEFLECTION.

PERCENT SLIP VS
0- TO 6-IN. CONE INDEX

9.00-14, 2-PR AND 9.00-14, 8-PR TIRES
TOWED POINT - YUMA SAND
FIRST PASS



15% DEFLECTION



35% DEFLECTION

LEGEND

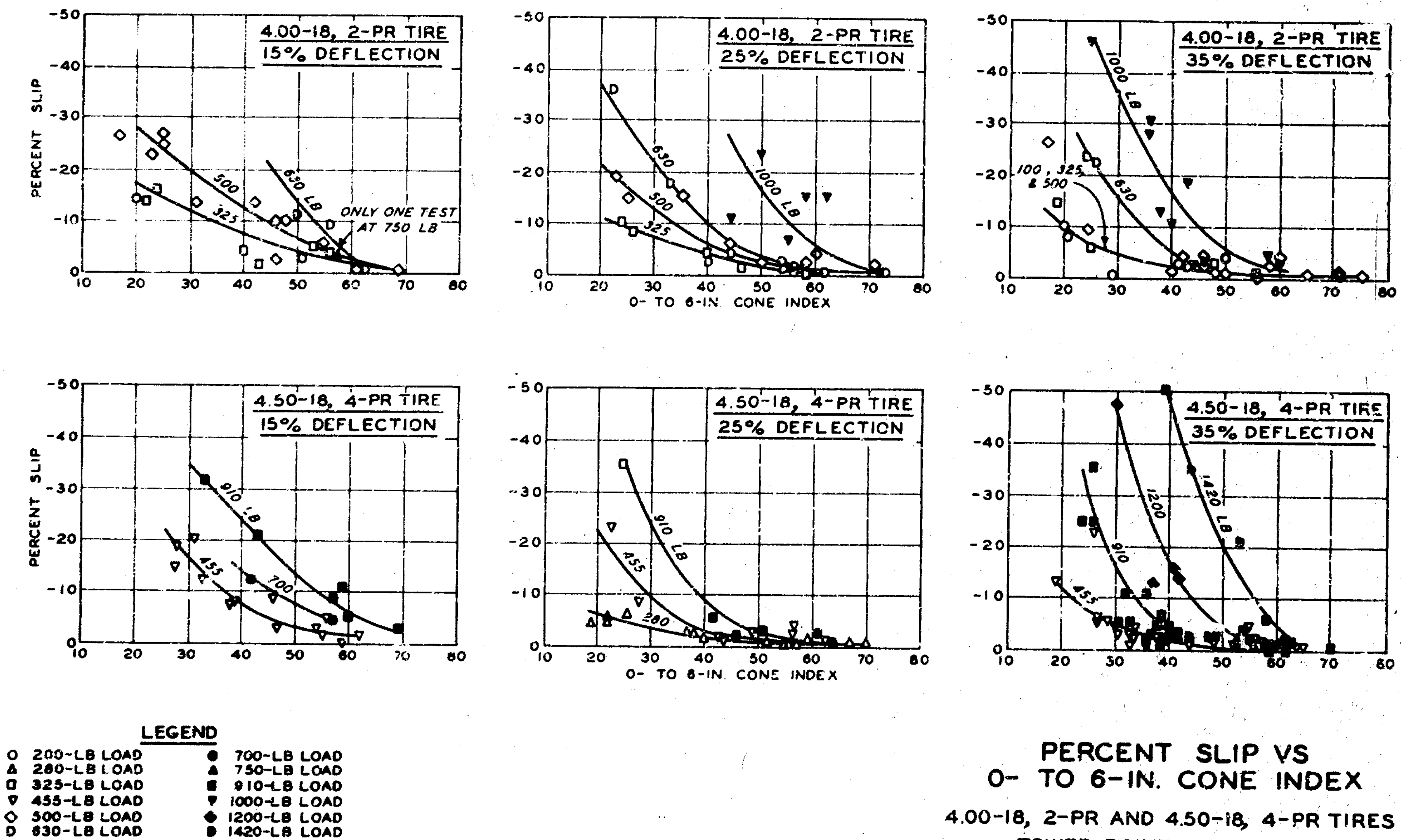
O 3000-LB LOAD
Δ 4500-LB LOAD

PERCENT SLIP VS 0- TO 6-IN. CONE INDEX

11.00-20, 12-PR TIRE

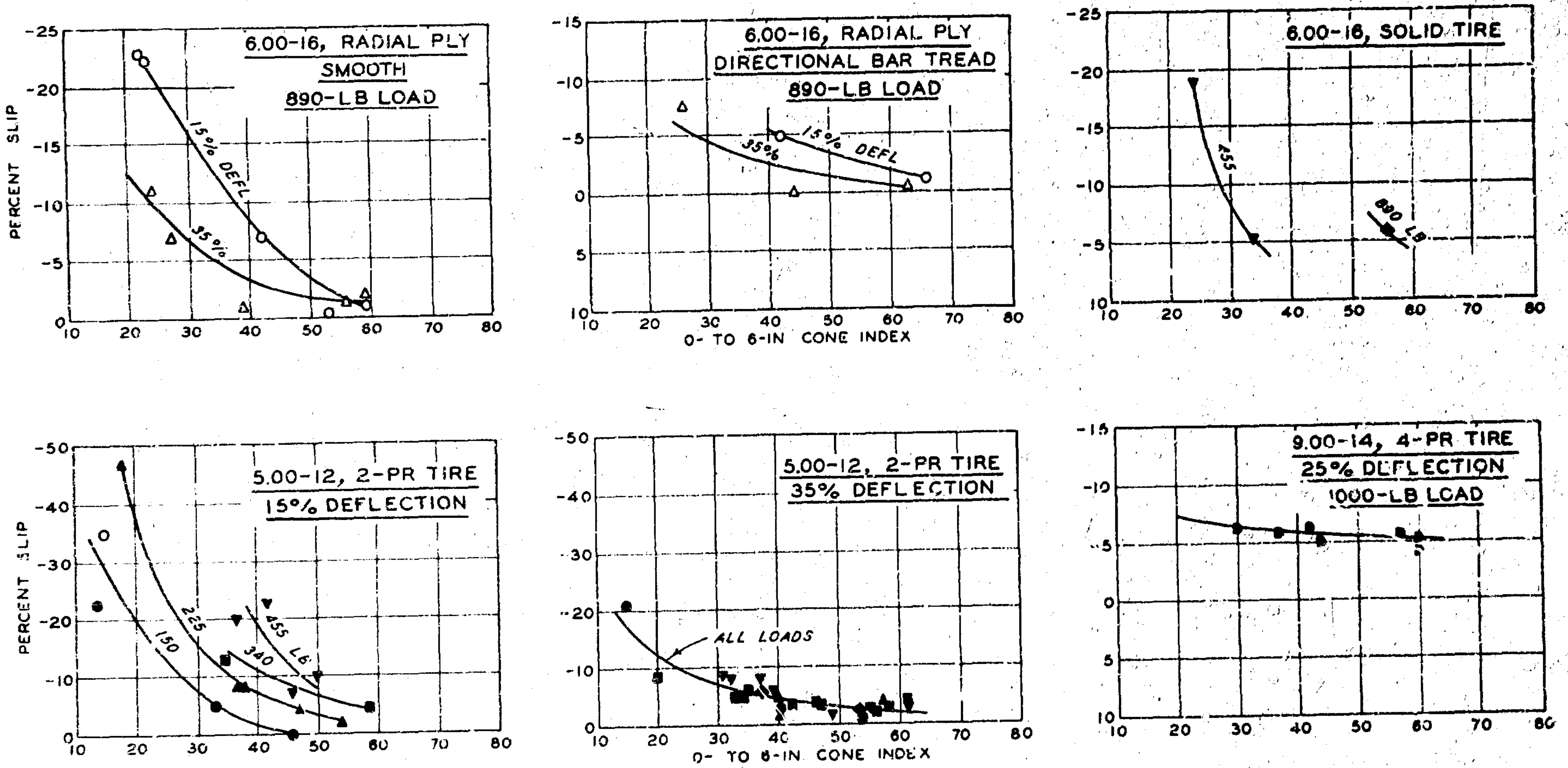
TOWED POINT-YUMA SAND

FIRST PASS



PERCENT SLIP VS
0- TO 6-IN. CONE INDEX

4.00-18, 2-PR AND 4.50-18, 4-PR TIRES
TOWED POINT - YUMA SAND
FIRST PASS



LEGEND

- O 15% DEFLECTION
- △ 35% DEFLECTION
- ● 150-LB LOAD
- ▲ 225-LB LOAD
- ■ 340-LB LOAD
- ▼ 455-LB LOAD
- ◆ 890-LB LOAD
- ● 1000-LB LOAD

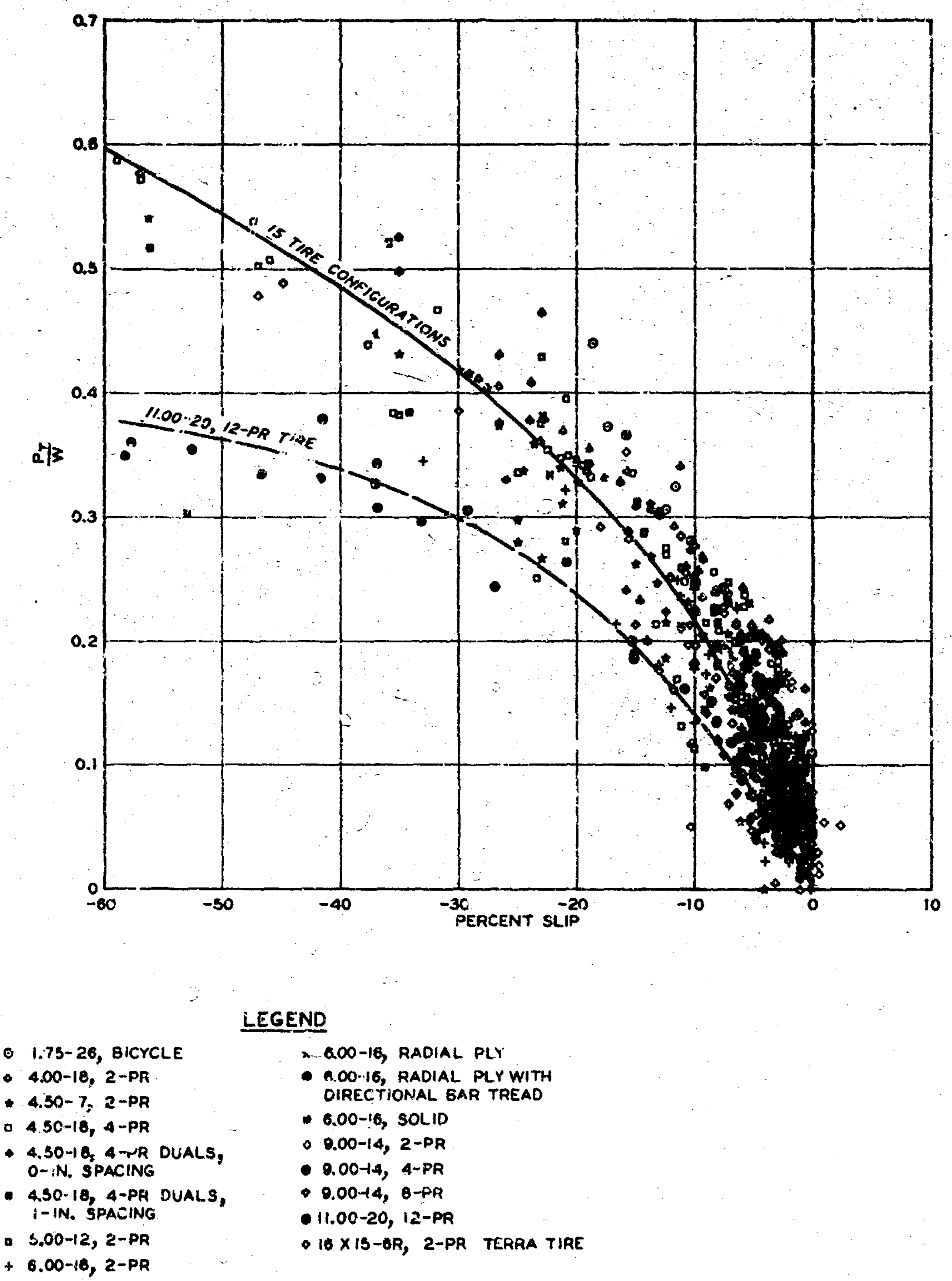
NOTE: SCALE OF PLOTS OF 5.00-12, 2-PR TIRE IS DIFFERENT FROM SCALE OF PLOTS FOR REMAINING TIRES.

PERCENT SLIP VS 0- TO 6-IN. CONE INDEX

6.00-16, 2-PR; 5.00-12, 2-PR; AND 9.00-14, 4-PR TIRES

TOWED POINT - YUMA SAND
FIRST PASS

PLATE 18

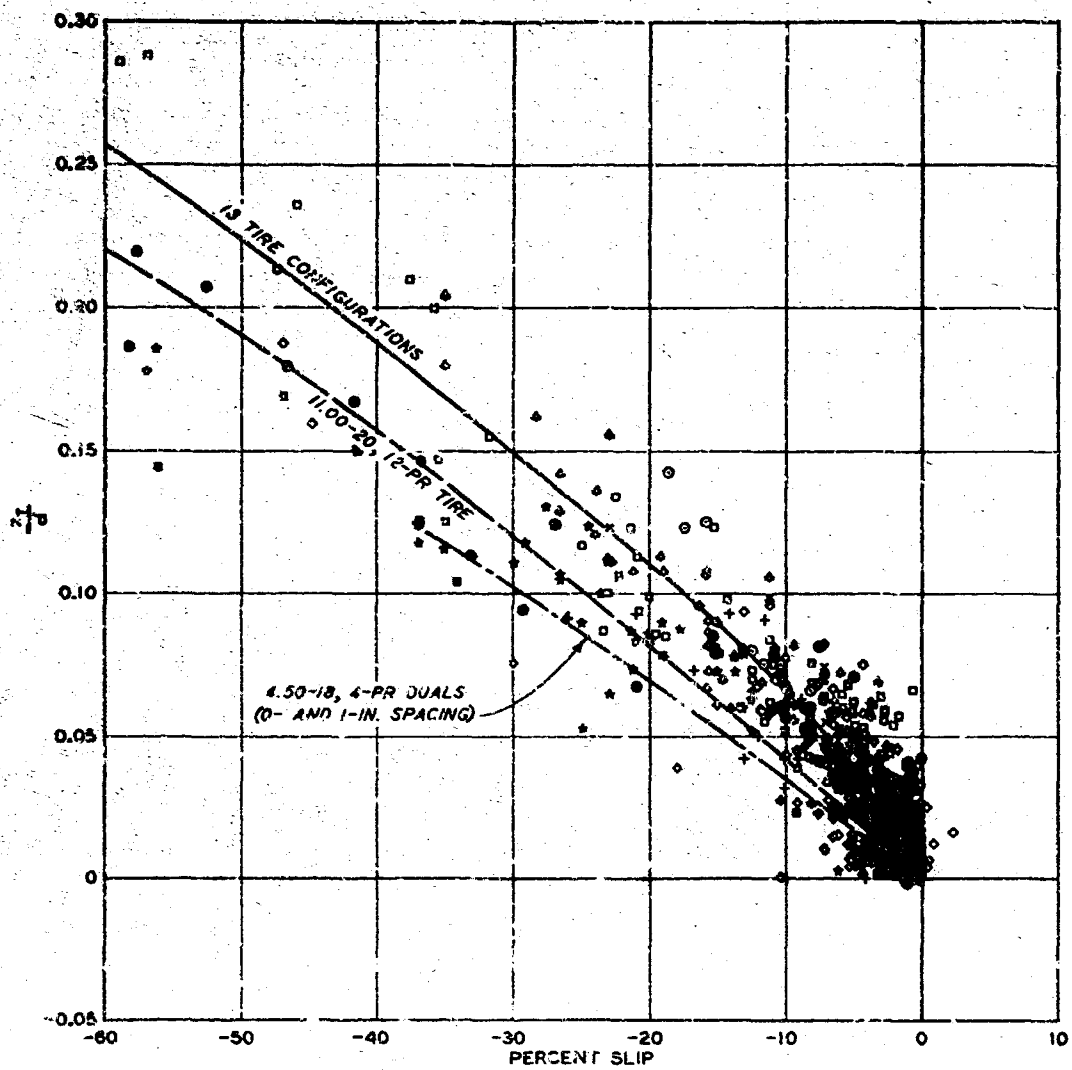


PERCENT SLIP VS $\frac{P_T}{W}$

ALL TIRES, LOADS, AND DEFLECTIONS

TOWED POINT- YUMA SAND

FIRST PASS



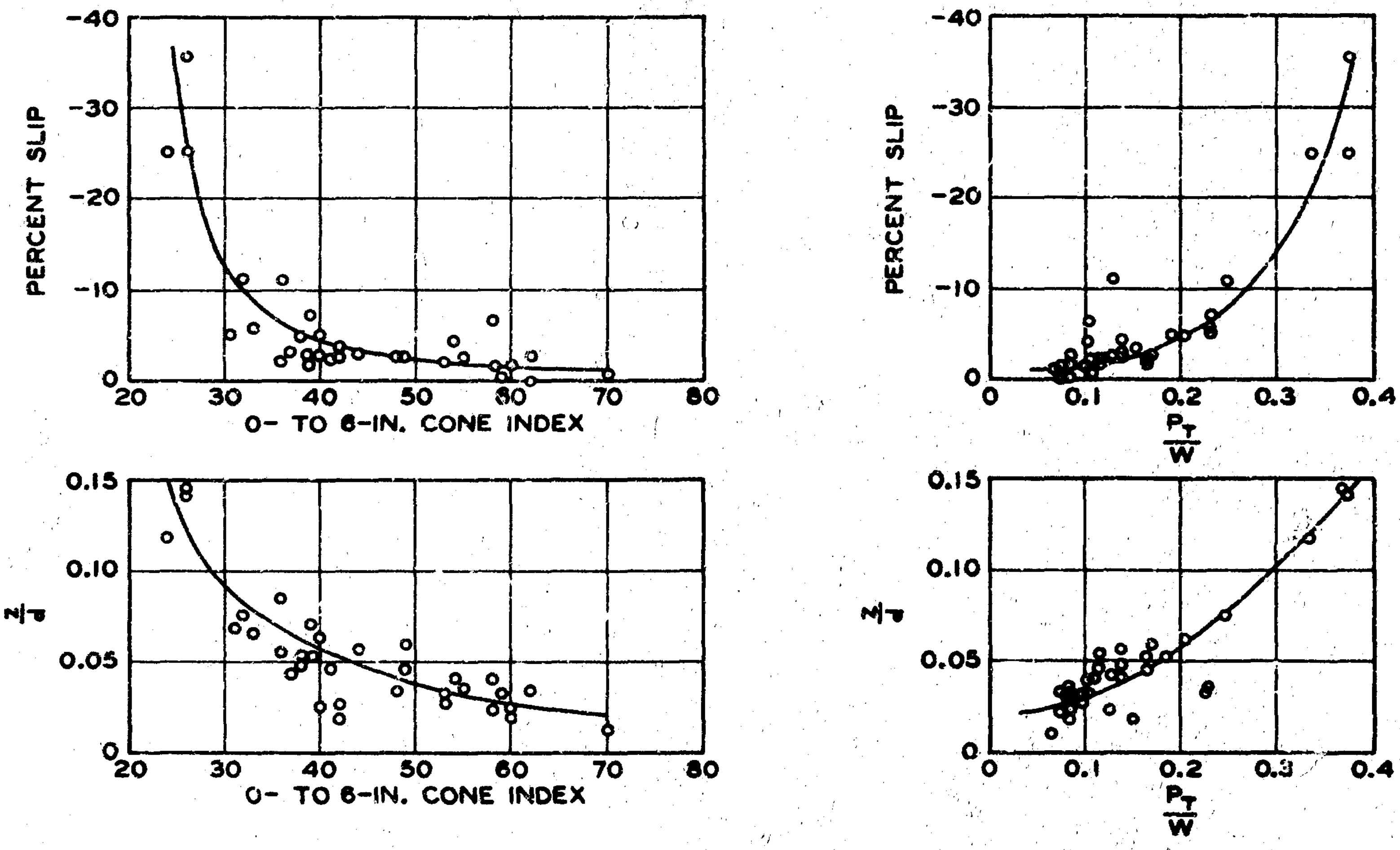
LEGEND

- ⊙ 1.75-26, BICYCLE
- 4.00-18, 2-PR
- 4.50-7, 2-PR
- ▫ 4.50-13, 4-PR
- 4.50-18, 4-PR DUALS, 0-IN. SPACING
- 4.50-18, 4-PR DUALS, 1-IN. SPACING
- 5.00-12, 2-PR
- \+ 6.00-16, 2-PR
- × 6.00-16, RADIAL PLY
- 6.00-16, RADIAL PLY WITH DIRECTIONAL BAR TREAD
- 6.00-16, SOLID
- ◇ 9.00-14, 2-PR
- ● 9.00-14, 4-PR
- 9.00-14, 8-PR
- ● 11.00-20, 12-PR
- ◇ 16 X 15-6R, 2-PR TERRA TIRE

PERCENT SLIP VS $\frac{z_T}{d}$

ALL TIRES, LOADS, AND DEFLECTIONS

TOWED POINT - YUMA SAND
FIRST PASS

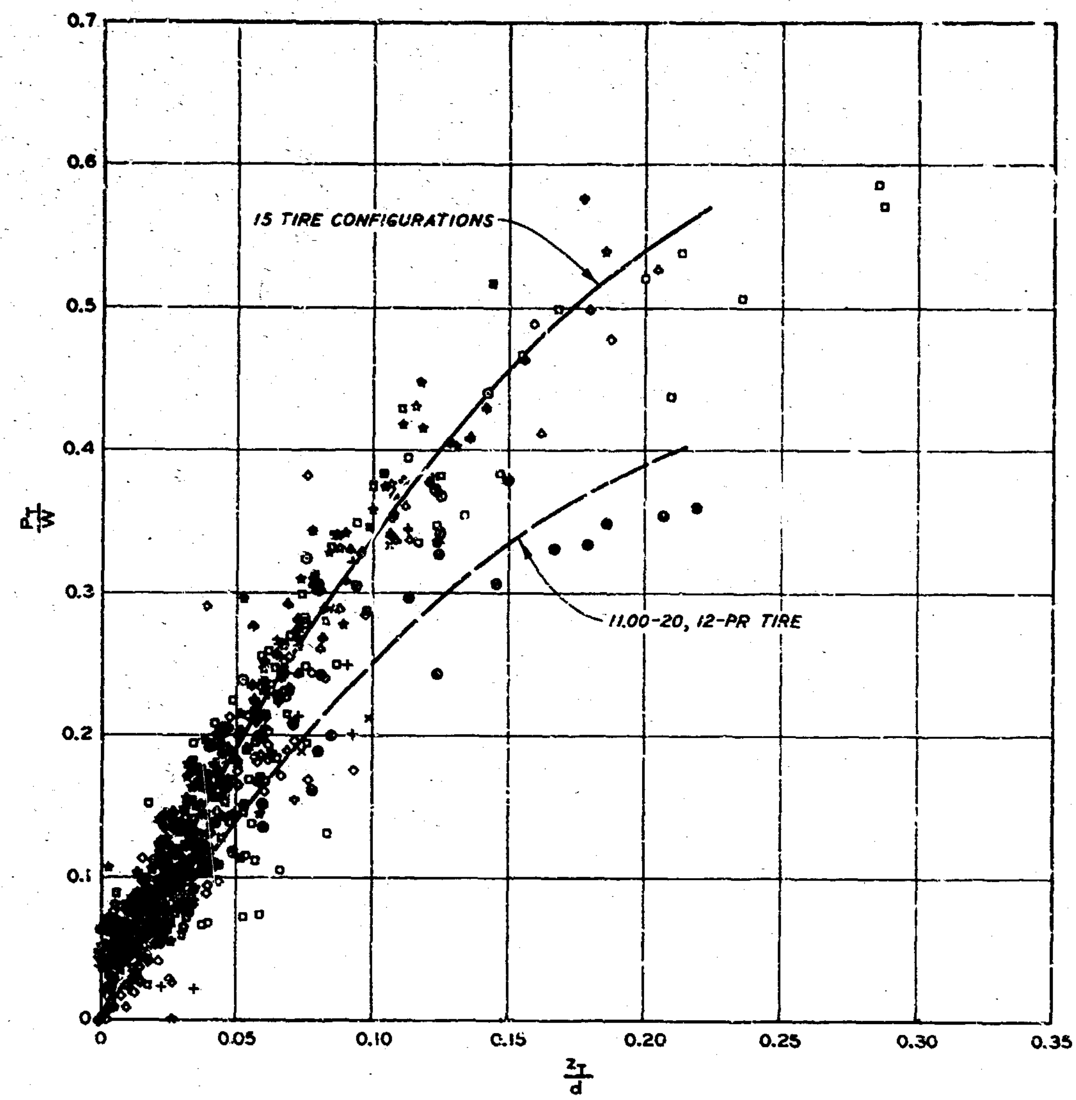


INTERRELATIONS BETWEEN THE DEPENDENT VARIABLES SLIP, SINKAGE, AND PULL AT THE TOWED POINT

4.50-18, 4-PR TIRE

35% DEFLECTION – 910-LB LOAD

YUMA SAND



LEGEND

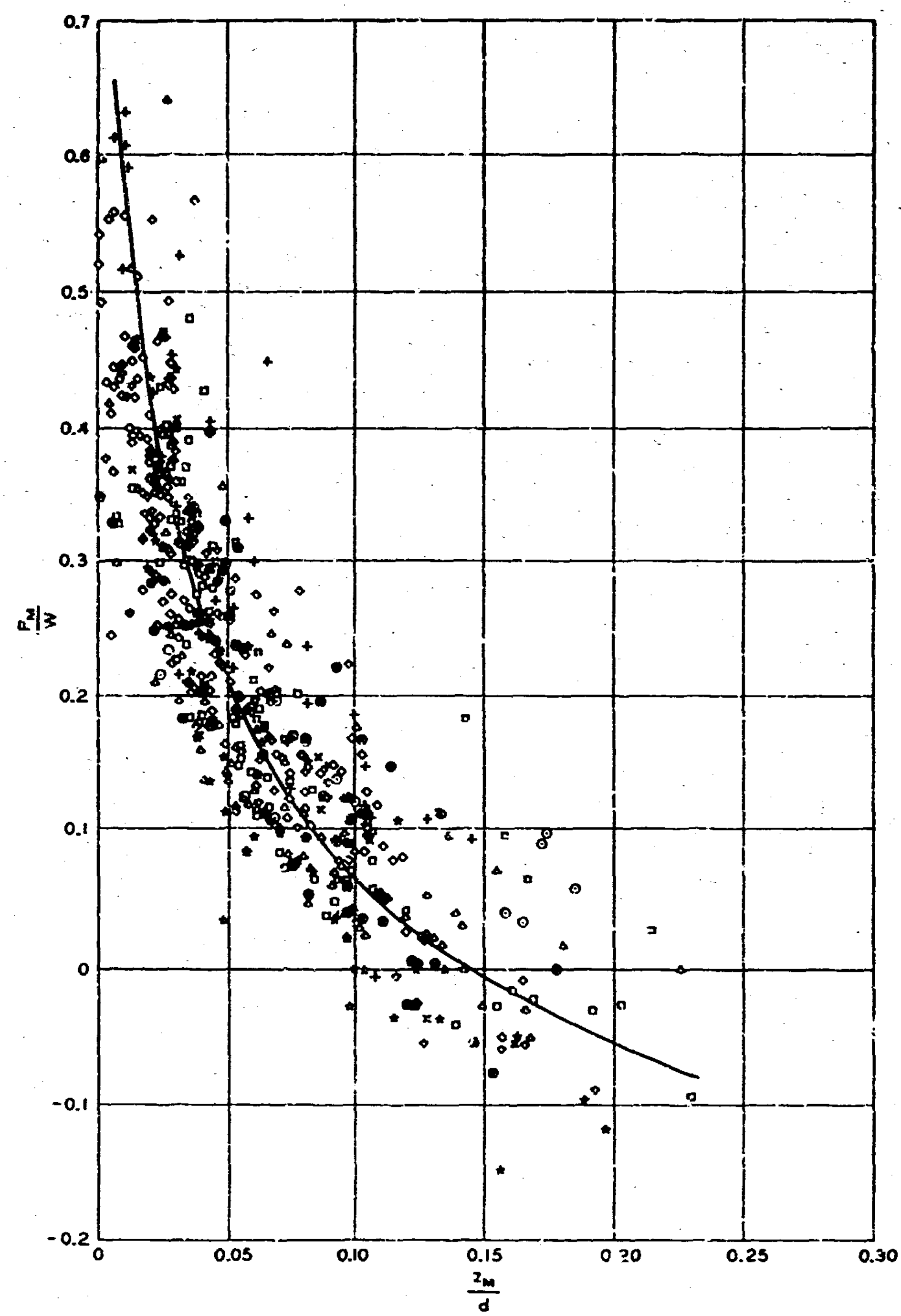
- 1.75-26, BICYCLE
- 4.00-18, 2-PR
- 4.50-7, 2-PR
- 4.50-18, 4-PR
- 4.50-18, 4-PR DUALS, 0-IN. SPACING
- 4.50-18, 4-PR DUALS, 1-IN. SPACING
- 5.00-12, 2-PR
- 6.00-16, 2-PR
- 6.00-16, RADIAL PLY
- 6.00-16, RADIAL PLY WITH DIRECTIONAL BAR TREAD
- 6.00-16, SOLID
- 9.00-14, 2-PR
- 9.00-14, 4-PR
- 9.00-14, 8-PR
- 11.00-20, 12-PR
- 16 X 15-6R, 2-PR TERRA TIRE

$\frac{P_T}{W}$ VS $\frac{z_T}{d}$

ALL TIRES, LOADS, AND DEFLECTIONS

TOWED POINT- YUMA SAND

FIRST PASS



LEGEND

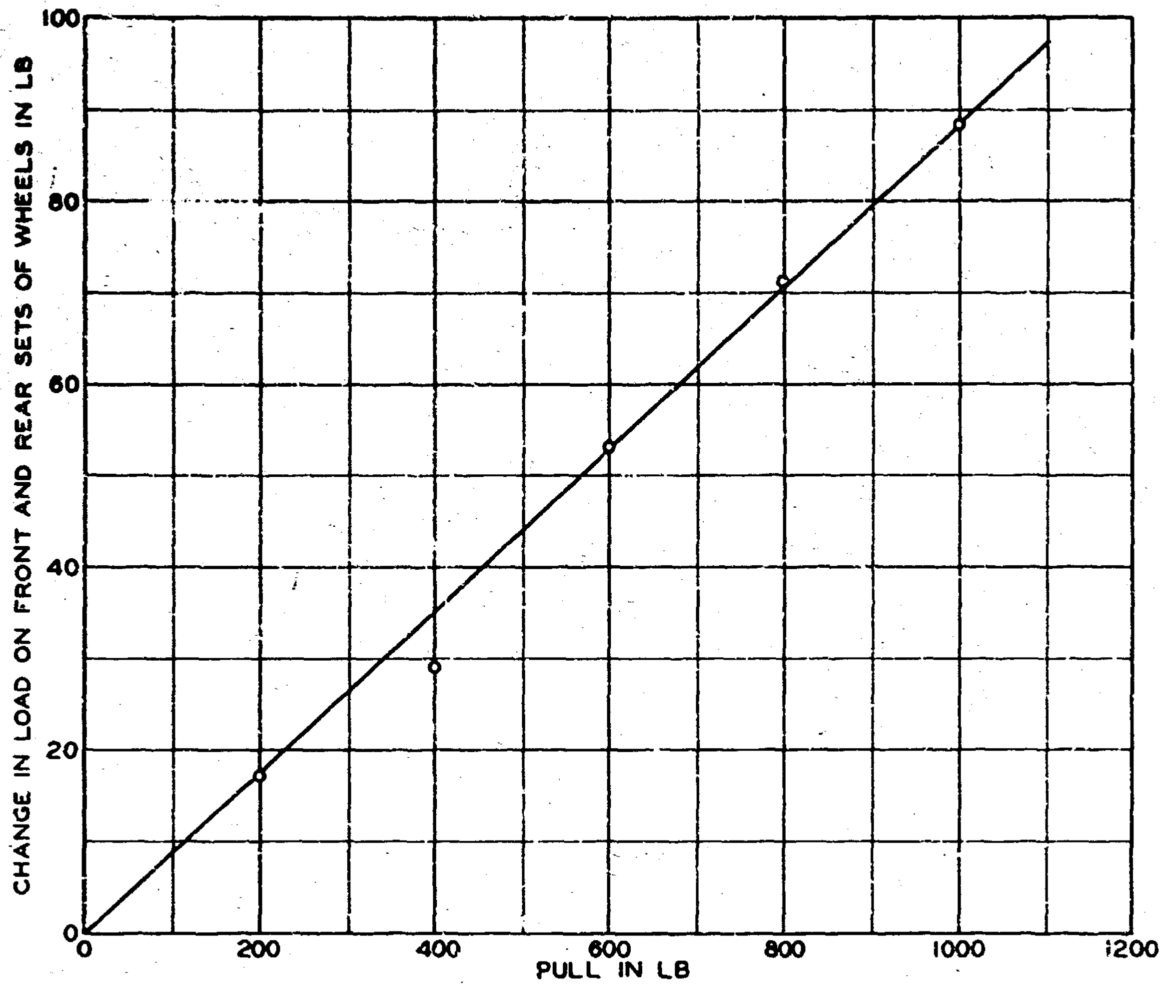
- 1.75-26, BICYCLE
- 4.00-18, 2-PR
- 4.50-7, 2-PR
- 4.50-18, 4-PR
- 4.50-18, 4-PR DUALS, 0-IN. SPACING
- 4.50-18, 4-PR DUALS, 1-IN. SPACING
- 5.00-12, 2-PR
- 6.00-16, 2-PR
- 6.00-16, RADIAL PLY
- 6.00-16, RADIAL PLY WITH DIRECTIONAL BAR TREAD
- 6.00-16, SOLID
- 9.00-14, 2-PR
- 9.00-14, 4-PR
- 9.00-14, 8-PR
- 11.00-20, 12-PR
- 16 X 15-6R, 2-PR TERRA TIRE

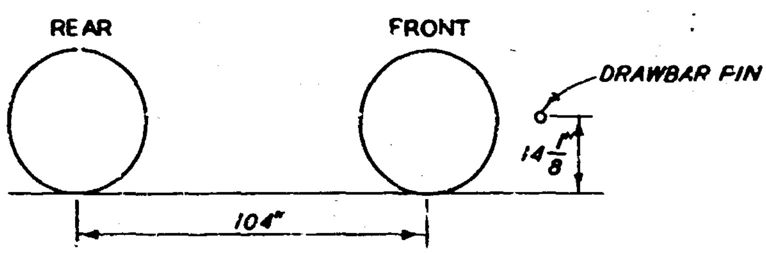
$\frac{P_M}{W}$ VS $\frac{z_M}{d}$

ALL TIRES, LOADS, AND DEFLECTIONS

MAXIMUM PULL POINT - YUMA SAND

FIRST PASS



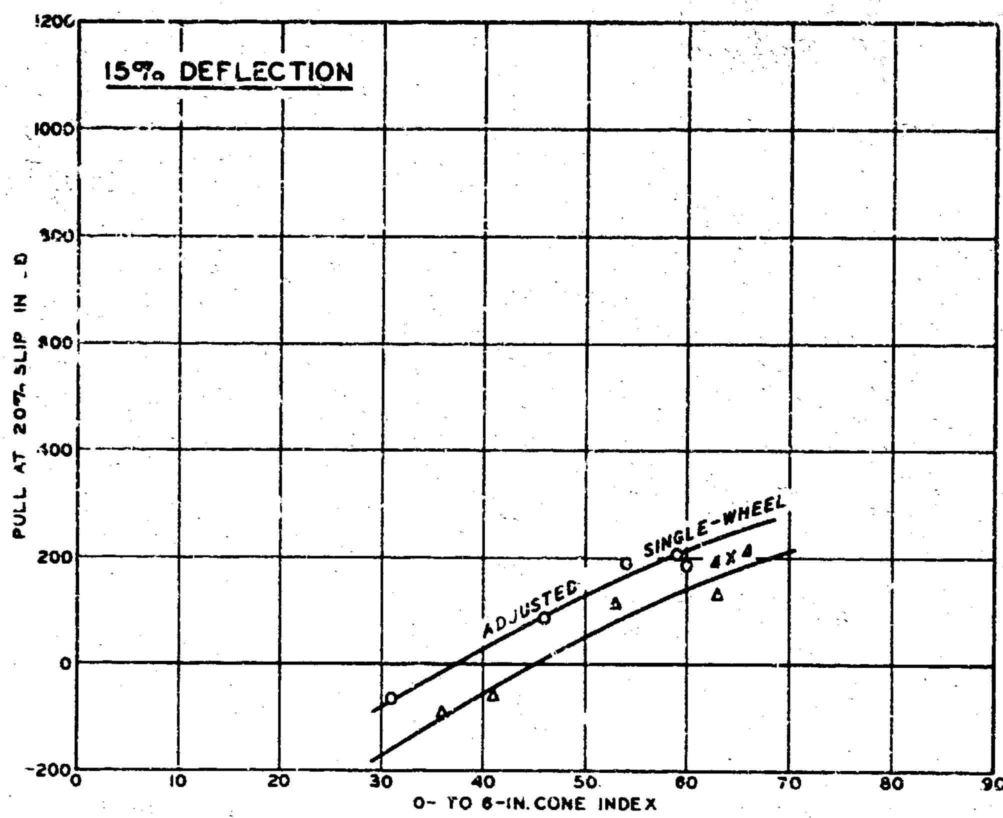


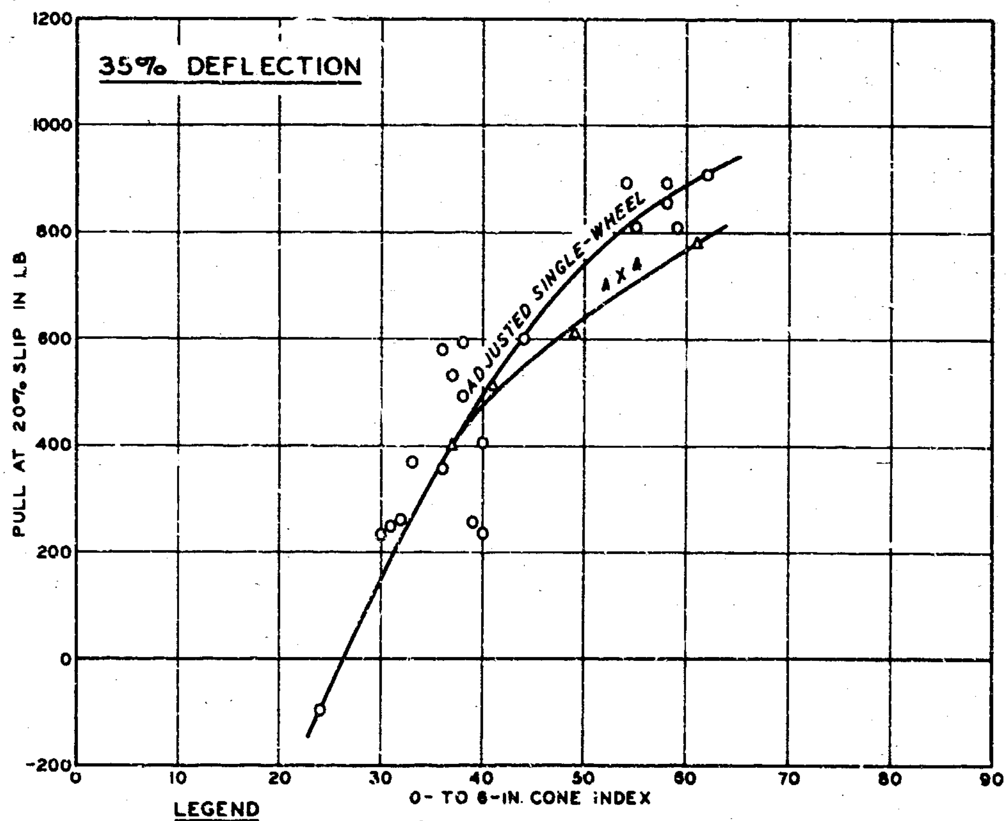
NOTE: WEIGHTS SHOWN IN TABLE INCLUDE WEIGHT OF VEHICLE AND DRIVER.
TOTAL WEIGHT OF SYSTEM IS 3560 LB.

APPLIED PULL LB	WEIGHT ON FRONT WHEELS LB	WEIGHT ON REAR WHEELS LB
0	1800	1760
200	1817	1743
400	1829	1731
600	1853	1707
800	1871	1689
1000	1888	1672

WEIGHT TRANSFER
IN 4 X 4 VEHICLE

PLATE 24





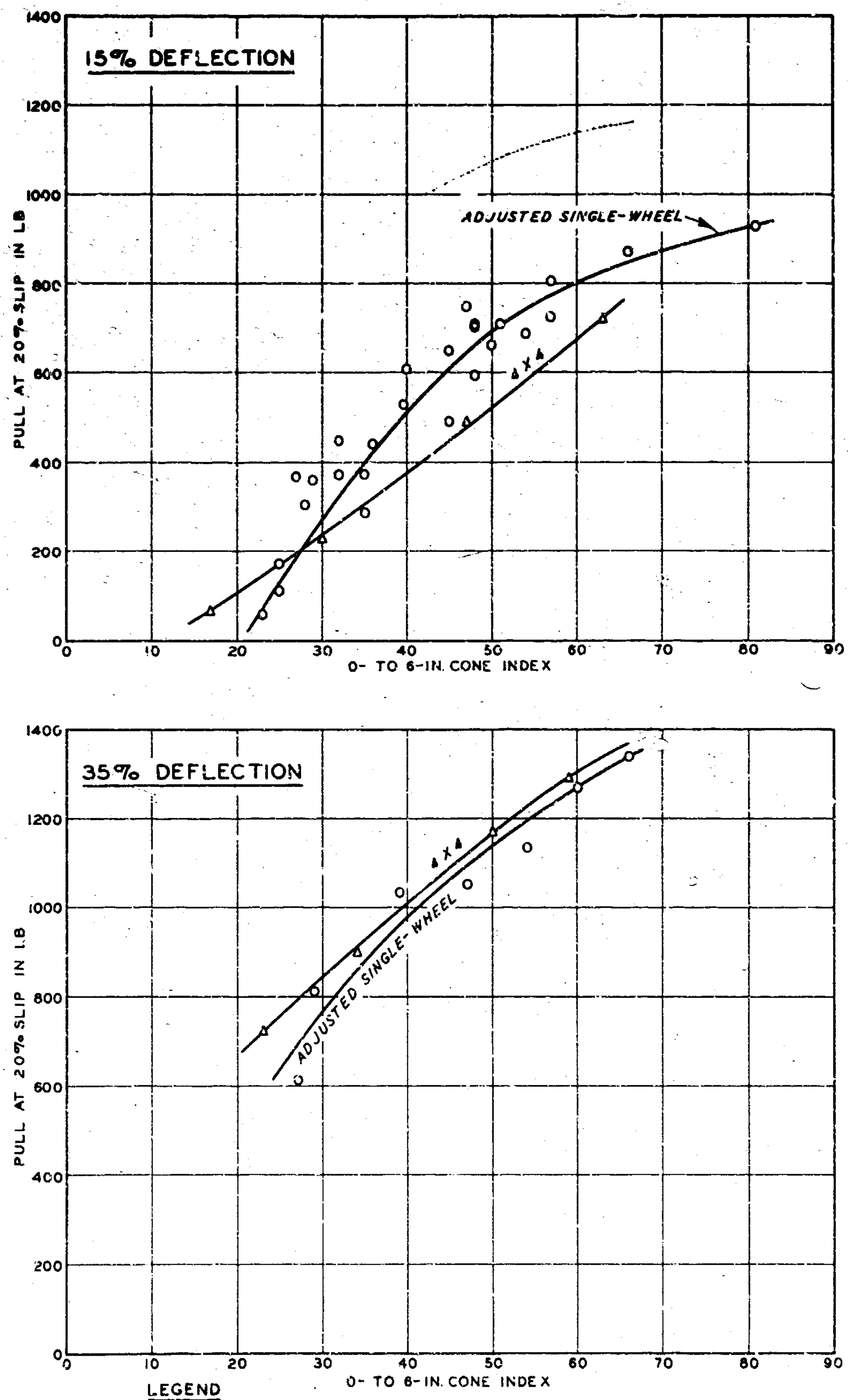
LEGEND

O $P_{20} = [P_{20}(\text{FIRST PASS}) + P_{20}(\text{SECOND PASS})] \times 2$ USING SINGLE-WHEEL TEST DATA

Δ 4 X 4 VEHICLE PULL AT 20% SLIP

NOTE: ALL CONE INDEX VALUES SHOWN ARE BEFORE-TRAFFIC SOIL STRENGTH MEASUREMENTS.

CORRELATION OF SINGLE-WHEEL AND 4 X 4 VEHICLE PULL DATA AT 20% SLIP
4.50-18, 4-PR TIRE
900(±10)-LB WHEEL LOAD
YUMA SAND



LEGEND

○ $P_{20} = [P_{20}(\text{FIRST PASS}) + P_{20}(\text{SECOND PASS})] \times 2$ USING SINGLE-WHEEL TEST DATA

Δ 4 X 4 VEHICLE PULL AT 20% SLIP

NOTE: ALL CONE INDEX VALUES SHOWN ARE BEFORE-TRAFFIC SOIL STRENGTH MEASUREMENTS.

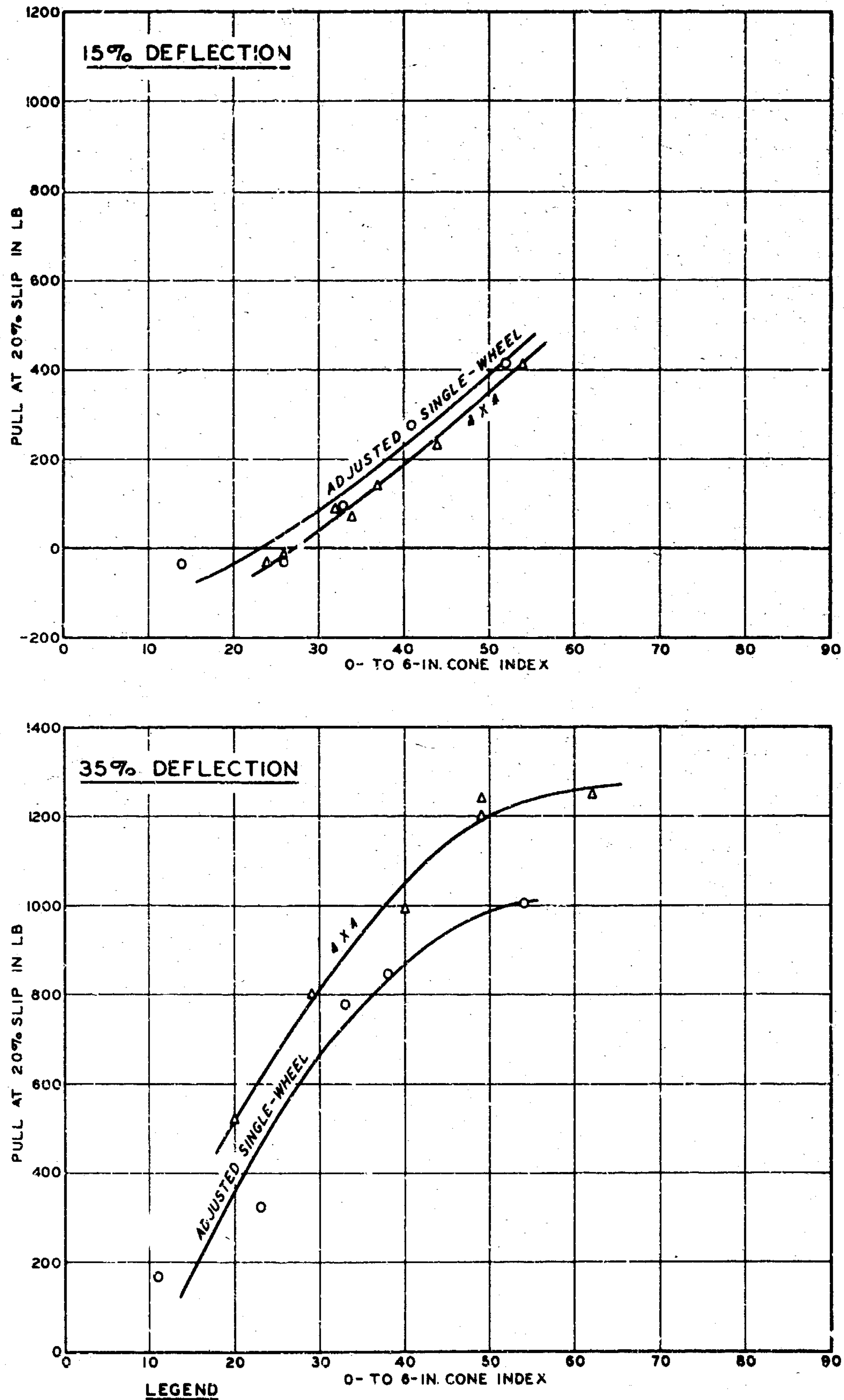
CORRELATION OF SINGLE-WHEEL AND 4 X 4 VEHICLE PULL DATA AT 20% SLIP

9.00-14, 2-PR TIRE

890-LB WHEEL LOAD

YUMA SAND

PLATE 26



LEGEND

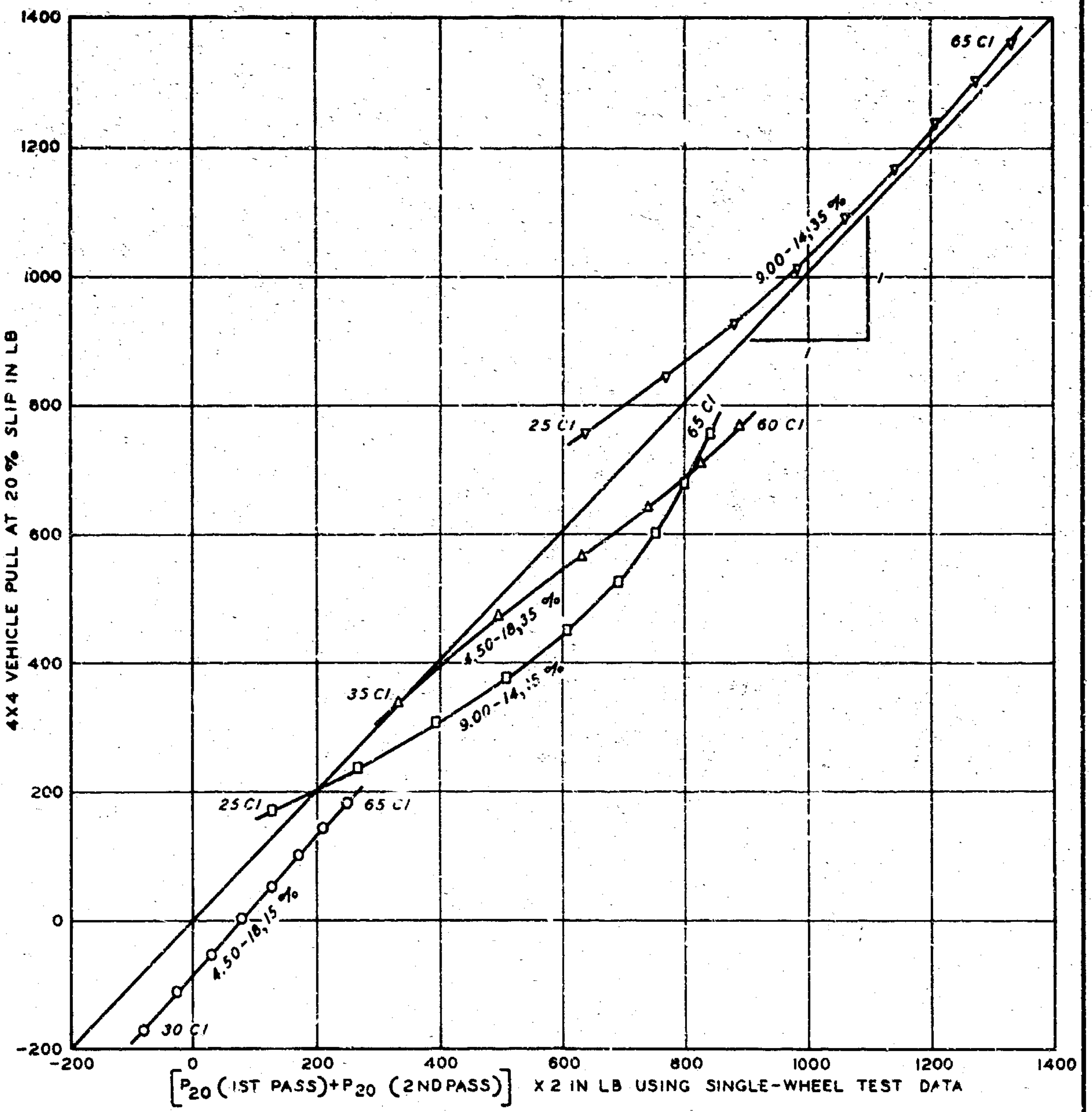
O $P_{20} = [P_{20}(\text{FIRST PASS}) + P_{20}(\text{SECOND PASS})] \times 2$ USING SINGLE-WHEEL TEST DATA

Δ 4 X 4 VEHICLE PULL AT 20% SLIP

NOTE: ALL CONE INDEX VALUES SHOWN ARE BEFORE-TRAFFIC SOIL STRENGTH MEASUREMENTS.

CORRELATION OF SINGLE-WHEEL AND 4 X 4 VEHICLE PULL DATA AT 20% SLIP

9.00-14, 2-PR TIRE
890-LB WHEEL LOAD
MORTAR SAND



LEGEND

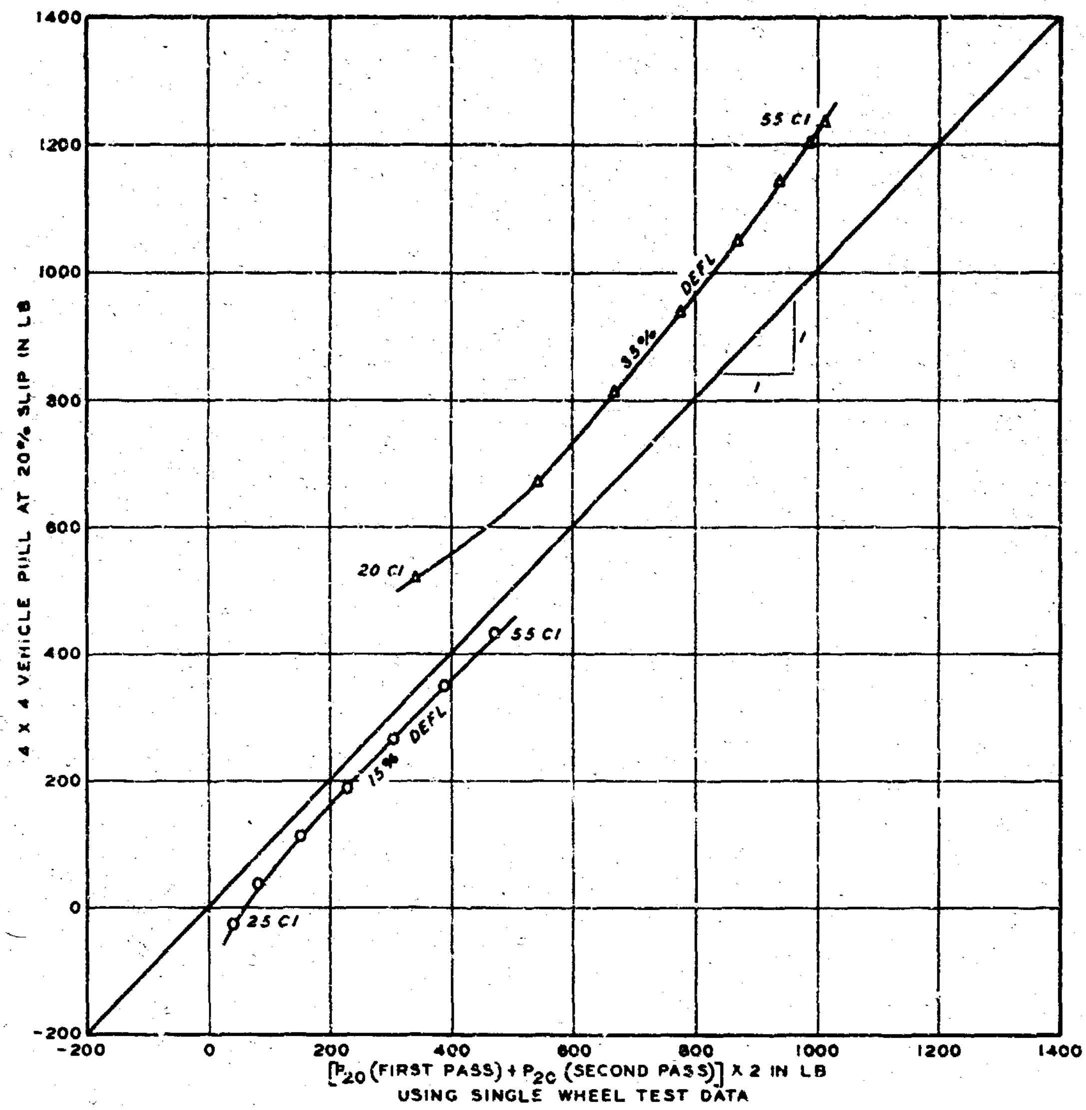
	TIRE SIZE	% DEFL
O	4.50-18, 4-PR	15
Δ	4.50-18, 4-PR	35
□	9.00-14, 2-PR	15
∇	9.00-14, 2-PR	35

NOTE: PLOTTED POINTS ARE TAKEN FROM AVERAGE CURVES IN PLATES 25 AND 26 AT INTERVALS OF 5 CI.

4X4 VEHICLE PULL VS ADJUSTED SINGLE-WHEEL PULL

4.50-18, 4-PR AND 9.00-14, 2-PR TIRES
900 (±10)-LB WHEEL LOADS
20% SLIP DATA
YUMA SAND

PLATE 28



LEGEND

O 15% DEFLECTION

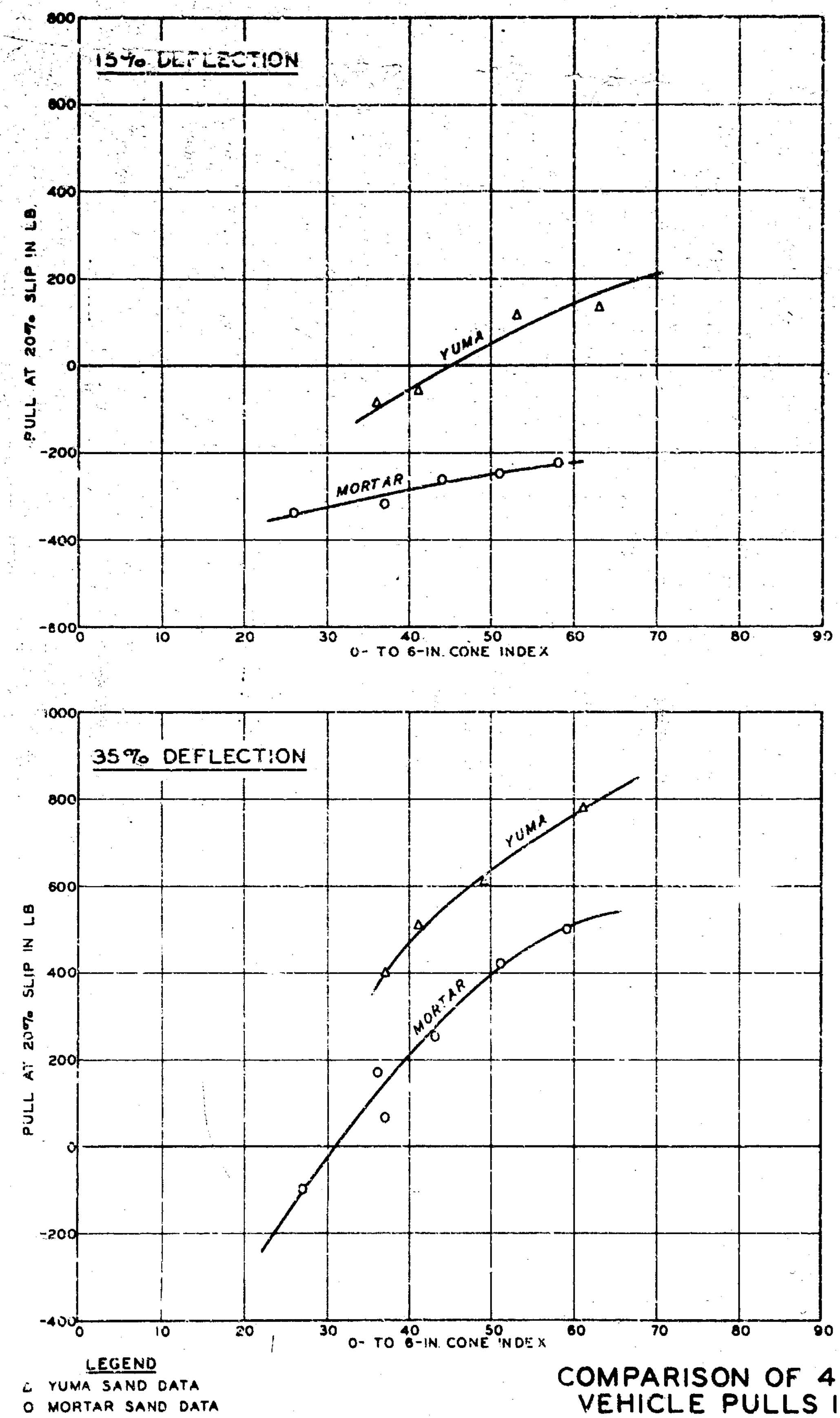
Δ 35% DEFLECTION

NOTE: PLOTTED POINTS ARE TAKEN FROM AVERAGE CURVES IN PLATE 27 AT INTERVALS OF 5 CI.

4 X 4 VEHICLE PULL VS ADJUSTED SINGLE-WHEEL PULL

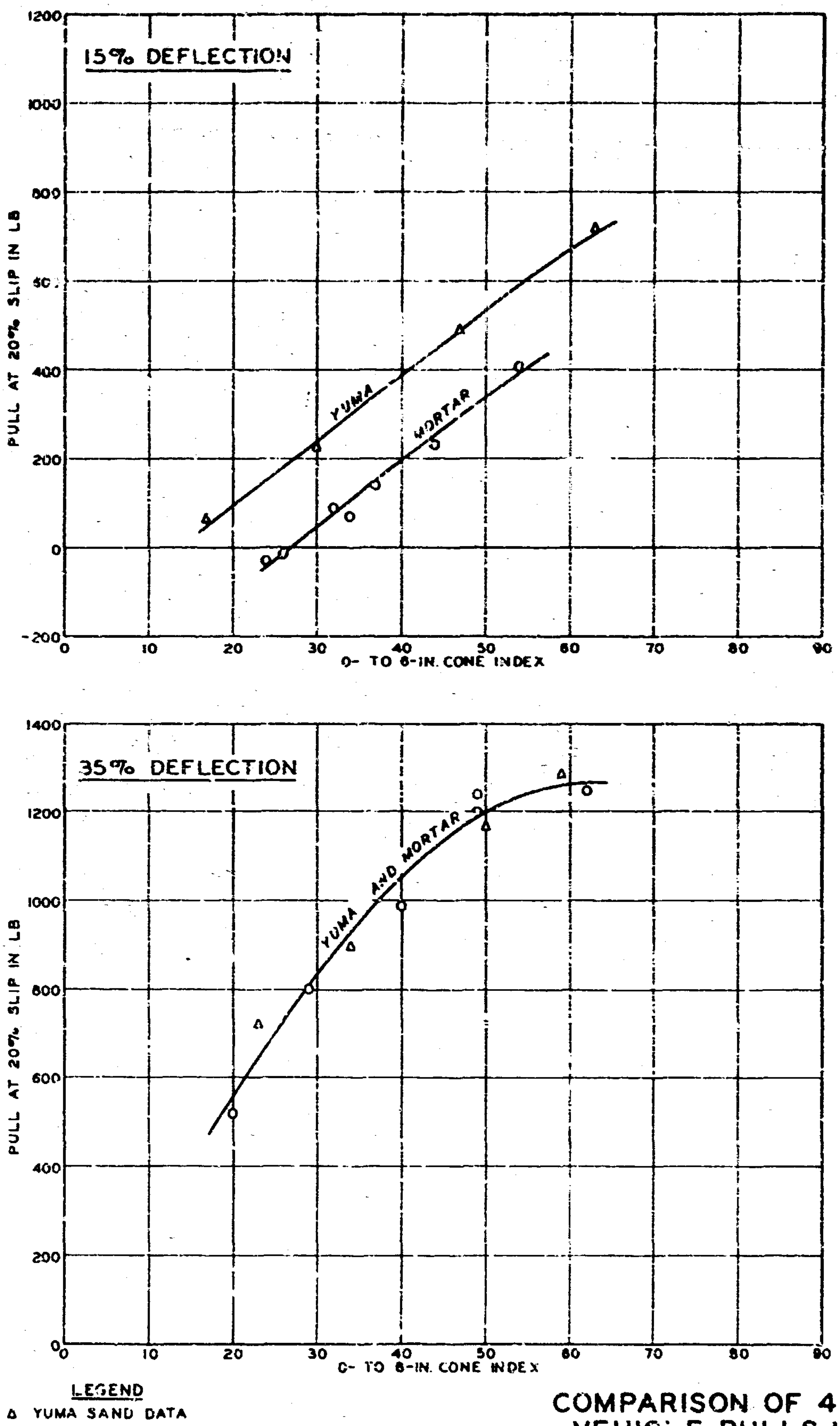
9.00-14, 2-PR TIRE
890-LB WHEEL LOAD
20% SLIP DATA

MORTAR SAND

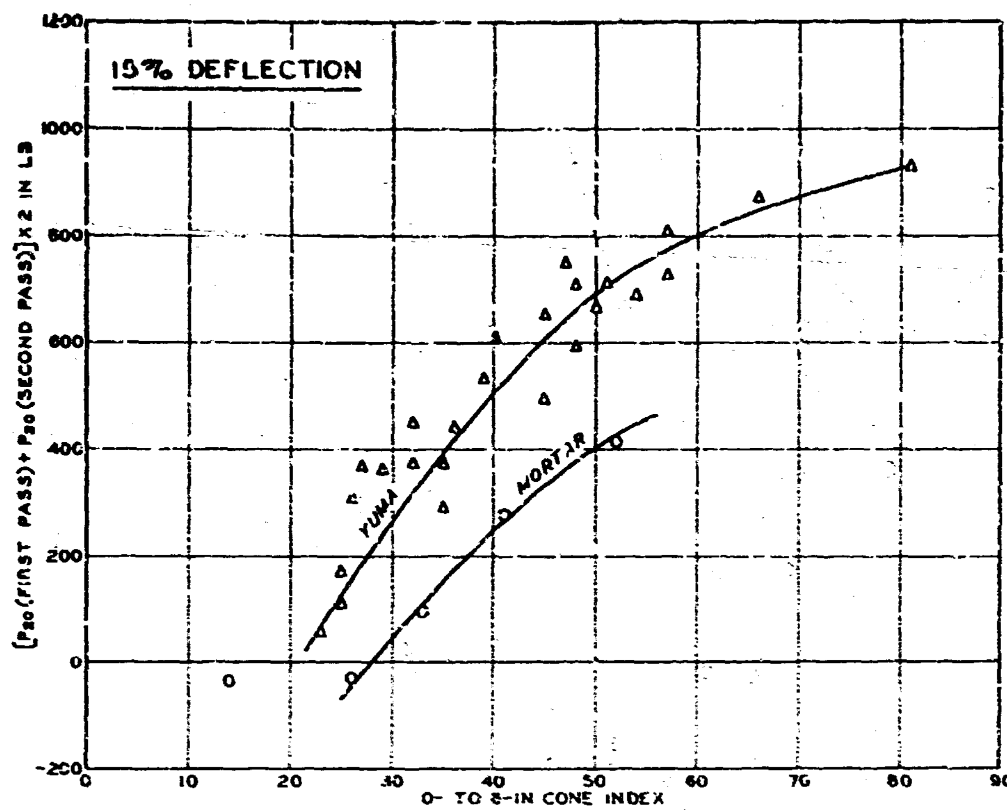


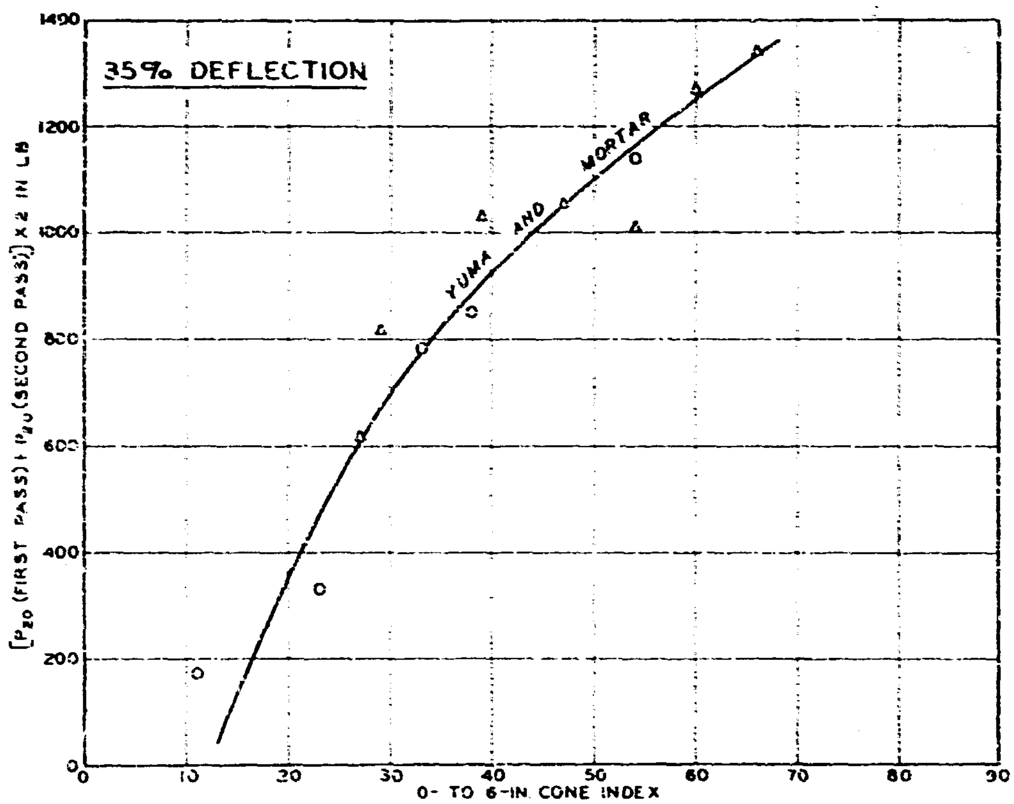
COMPARISON OF 4X4
VEHICLE PULLS IN
YUMA AND MORTAR SAND
4.50-18, 4-PR TIRE
890-LB WHEEL LOAD
20% SLIP DATA

PLATE 30



COMPARISON OF 4X4
VEHICLE PULLS IN
YUMA AND MORTAR SANDS
9.00-14, 2-PR TIRE
890-LB WHEEL LOAD
20% SLIP DATA





LEGEND

Δ YUMA SAND DATA

O MORTAR SAND DATA

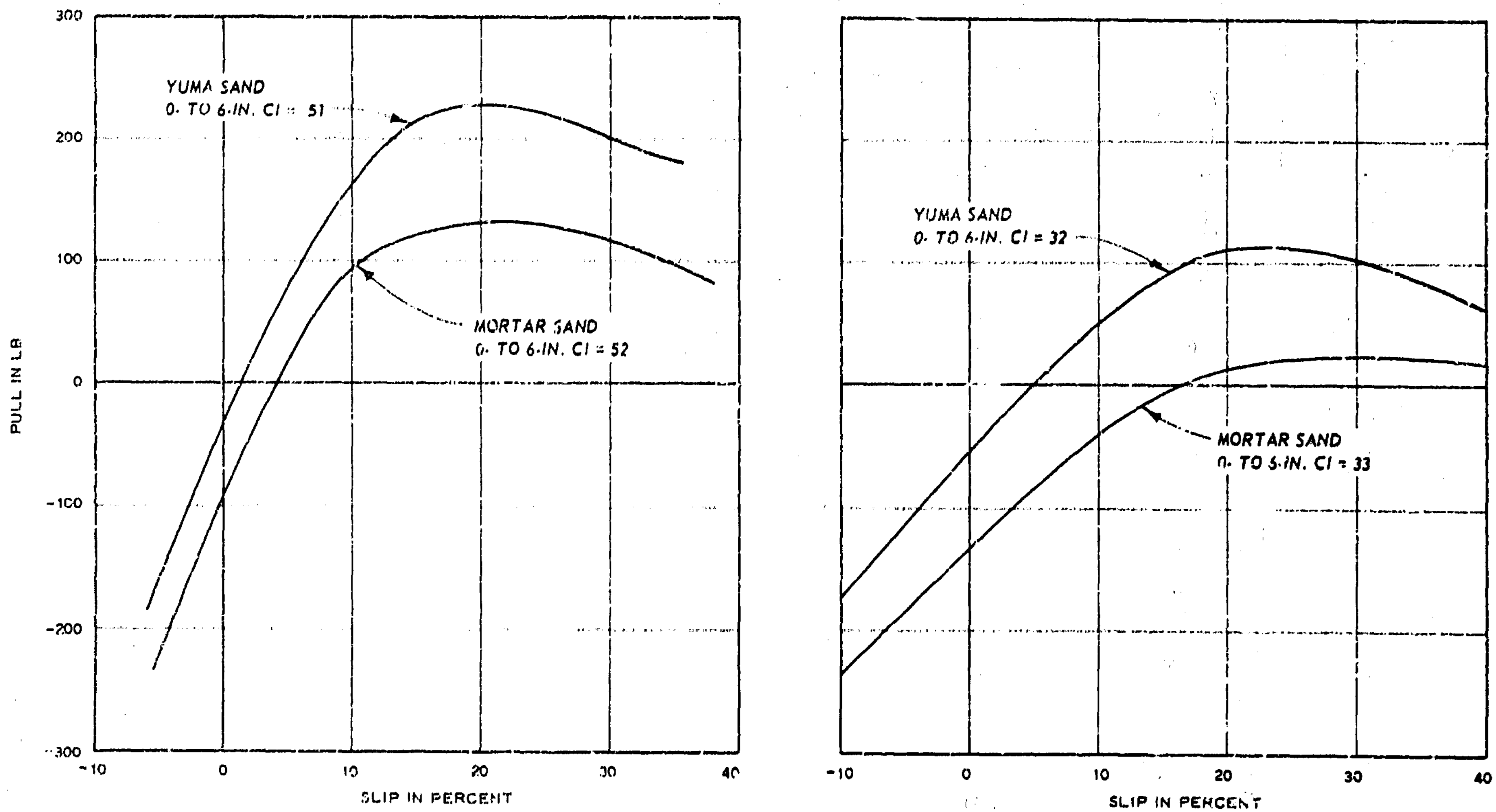
COMPARISON OF ADJUSTED SINGLE-WHEEL PULLS IN YUMA AND MORTAR SANDS

9.00-14, 2-PR TIRE

890-LB WHEEL LOAD

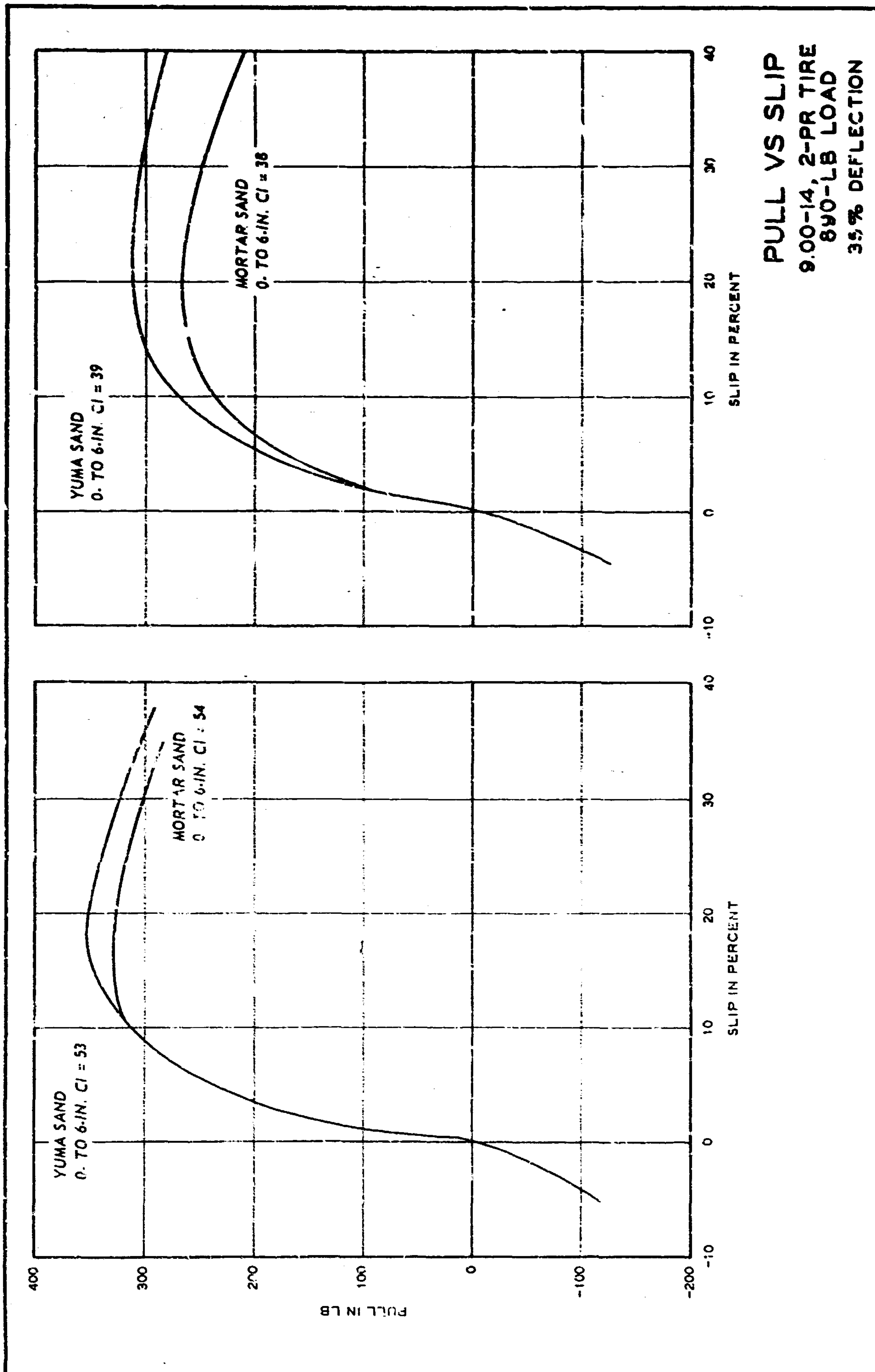
20% SLIP DATA

PLATE 32



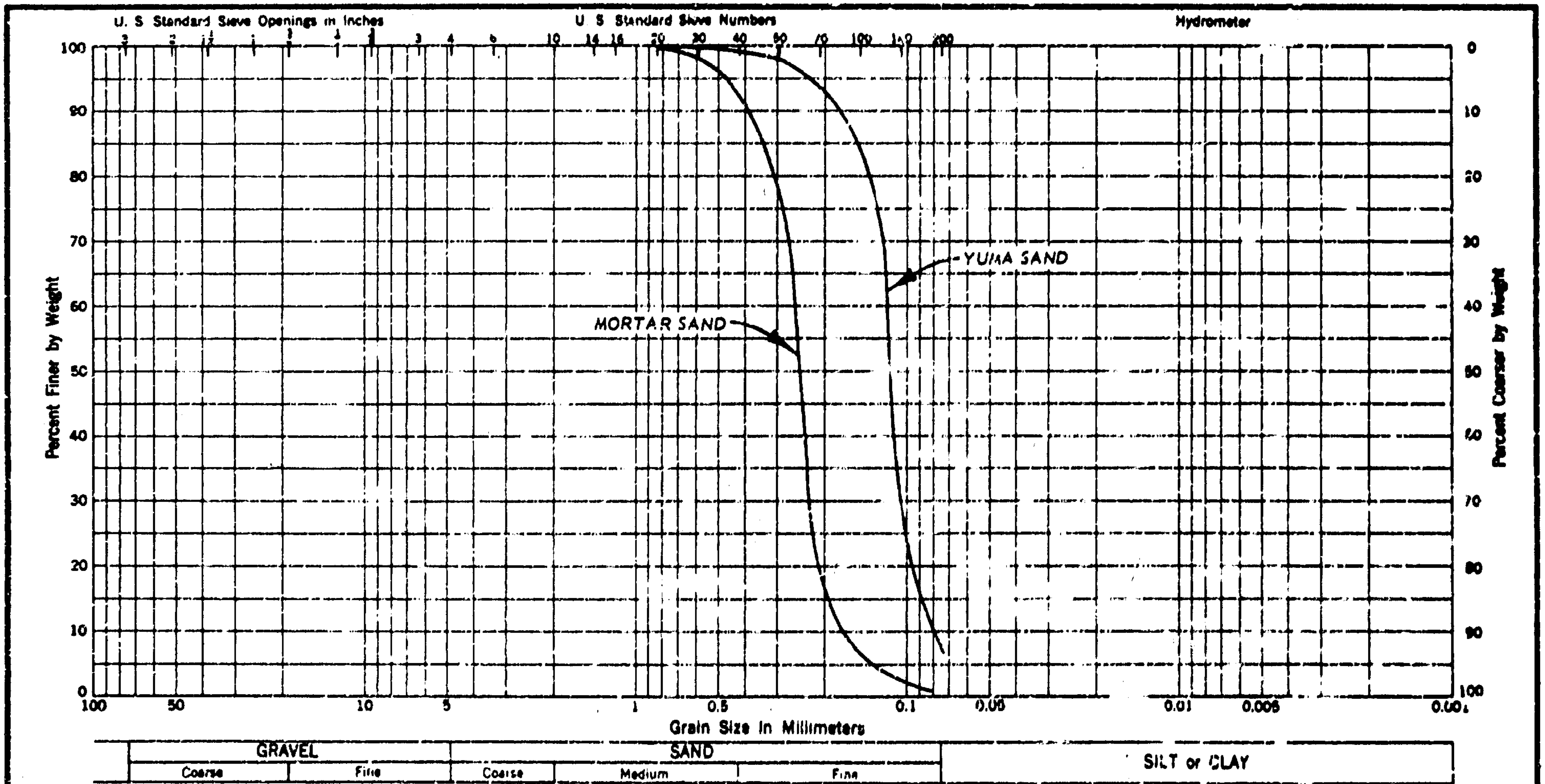
PULL VS SLIP

9.00-14, 2-PR TIRE
890-LB LOAD
15% DEFLECTION



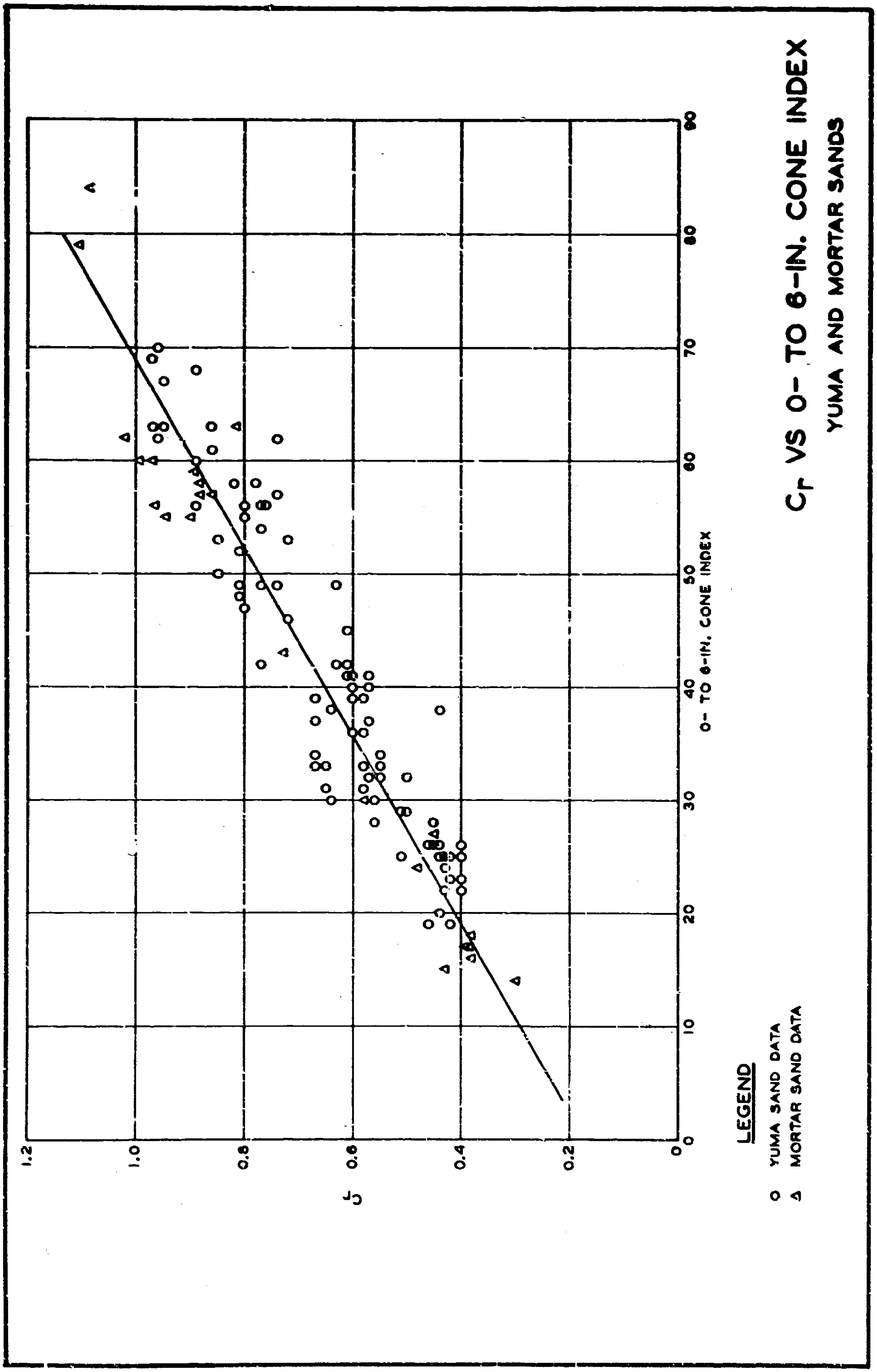
PULL VS SLIP
9.00-14, 2-PR TIRE
8Y0-LB LOAD
35% DEFLECTION
YUMA SAND
0. TO 6-IN. CI = 39
MORTAR SAND
0. TO 6-IN. CI = 38
YUMA SAND
0. TO 6-IN. CI = 53
MORTAR SAND
PULL IN LB
SLIP IN PERCENT
SLIP IN PERCENT
400
300
200
100
0
-100
-200
-10
0
10
20
30
40

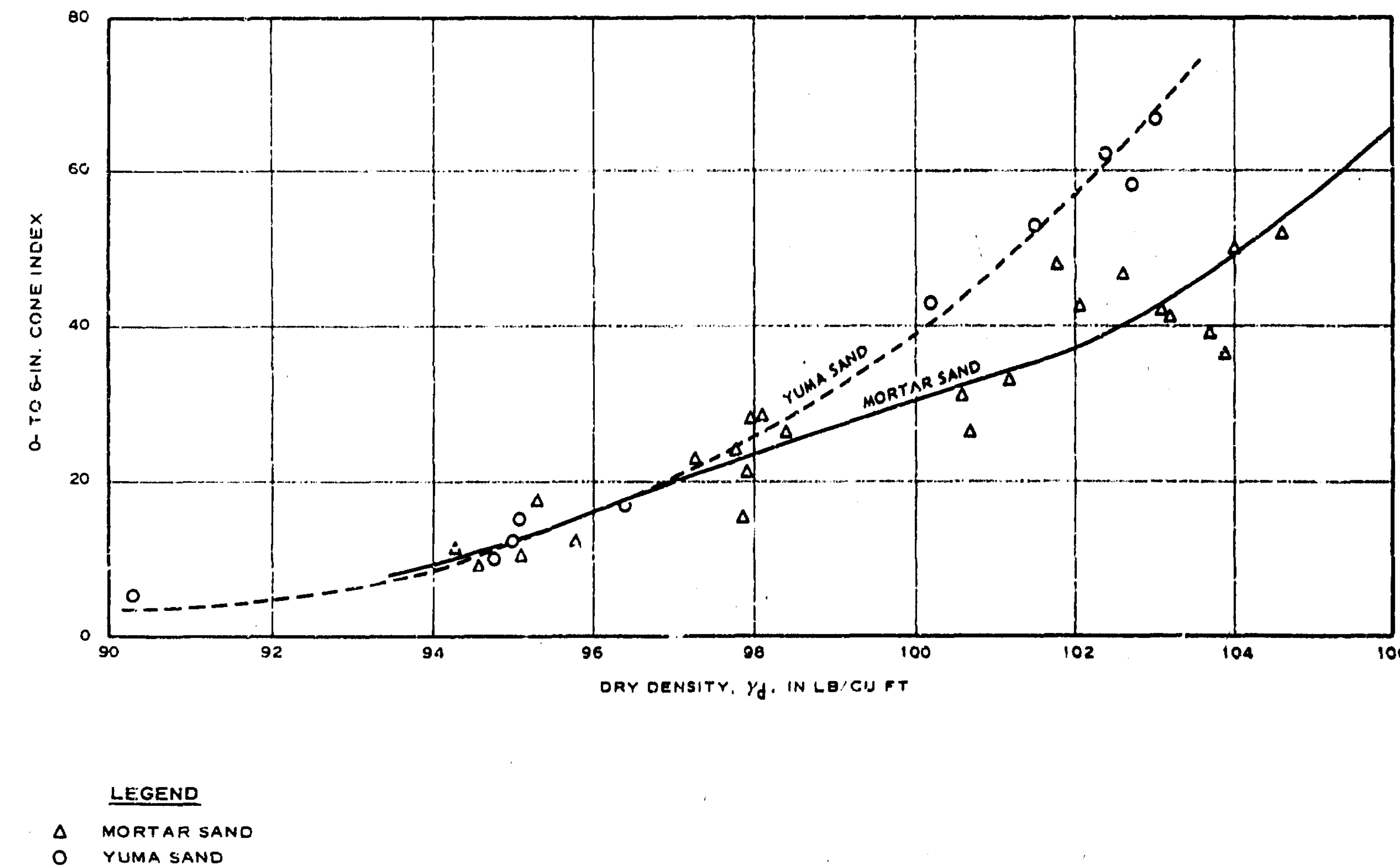
PLATE 34



Number	Depth	Natural Moisture	L.L.	P.L.	P.I.	Classification	MAX DENSITY	MIN DENSITY
						MORTAR SAND (SP)	106.1	87.4
						YUMA SAND (SP-SM)	104.0	87.0

SOIL GRADATION AND CLASSIFICATION DATA


C_r VS 0- TO 6-IN. CONE INDEX
YUMA AND MORTAR SANDS
C_r
0- TO 6-IN. CONE INDEX
LEGEND
o YUMA SAND DATA
Δ MORTAR SAND DATA



DRY DENSITY VS
0- TO 6-IN. CONE INDEX
YUMA AND MORTAR SANDS

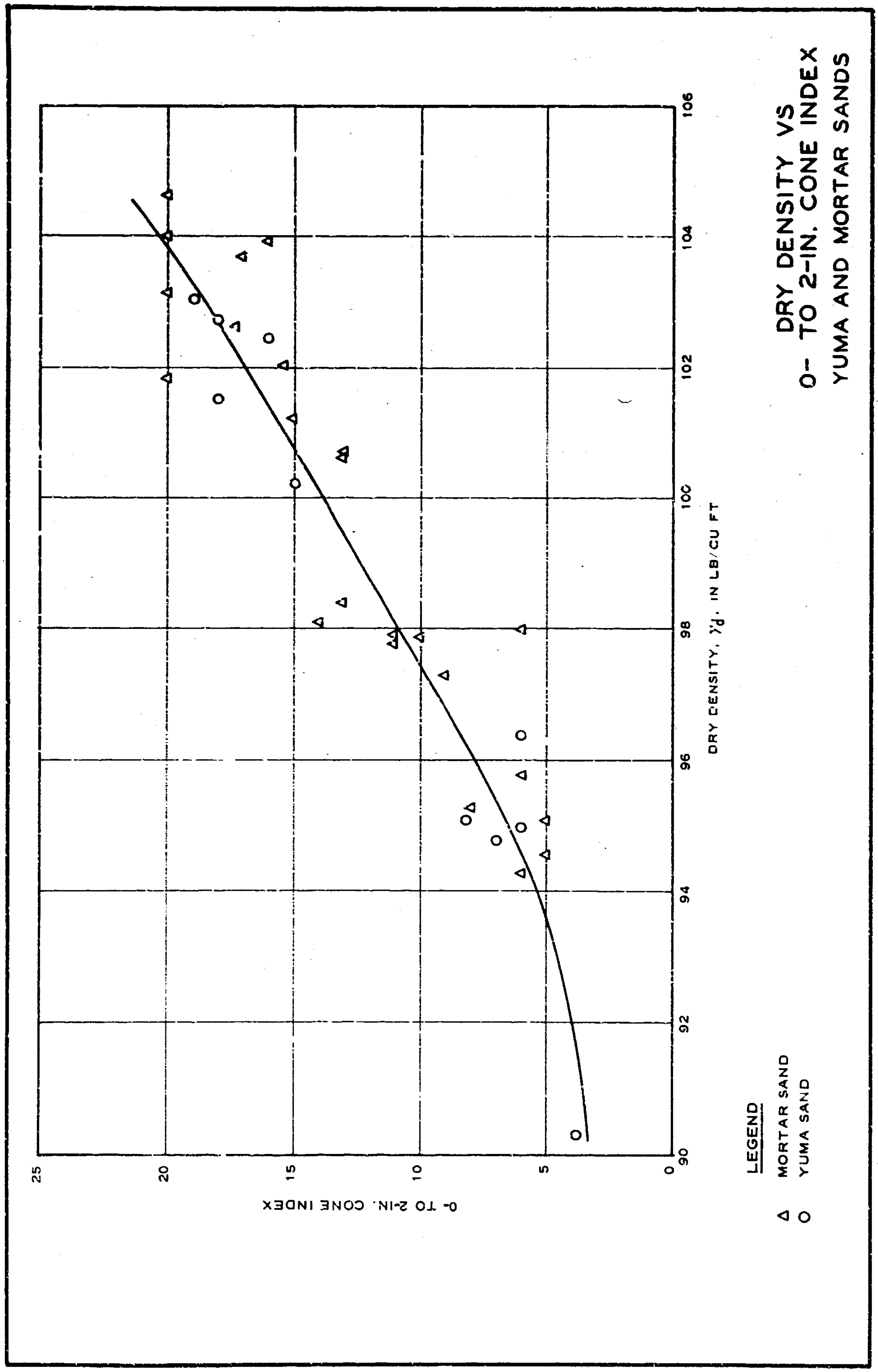
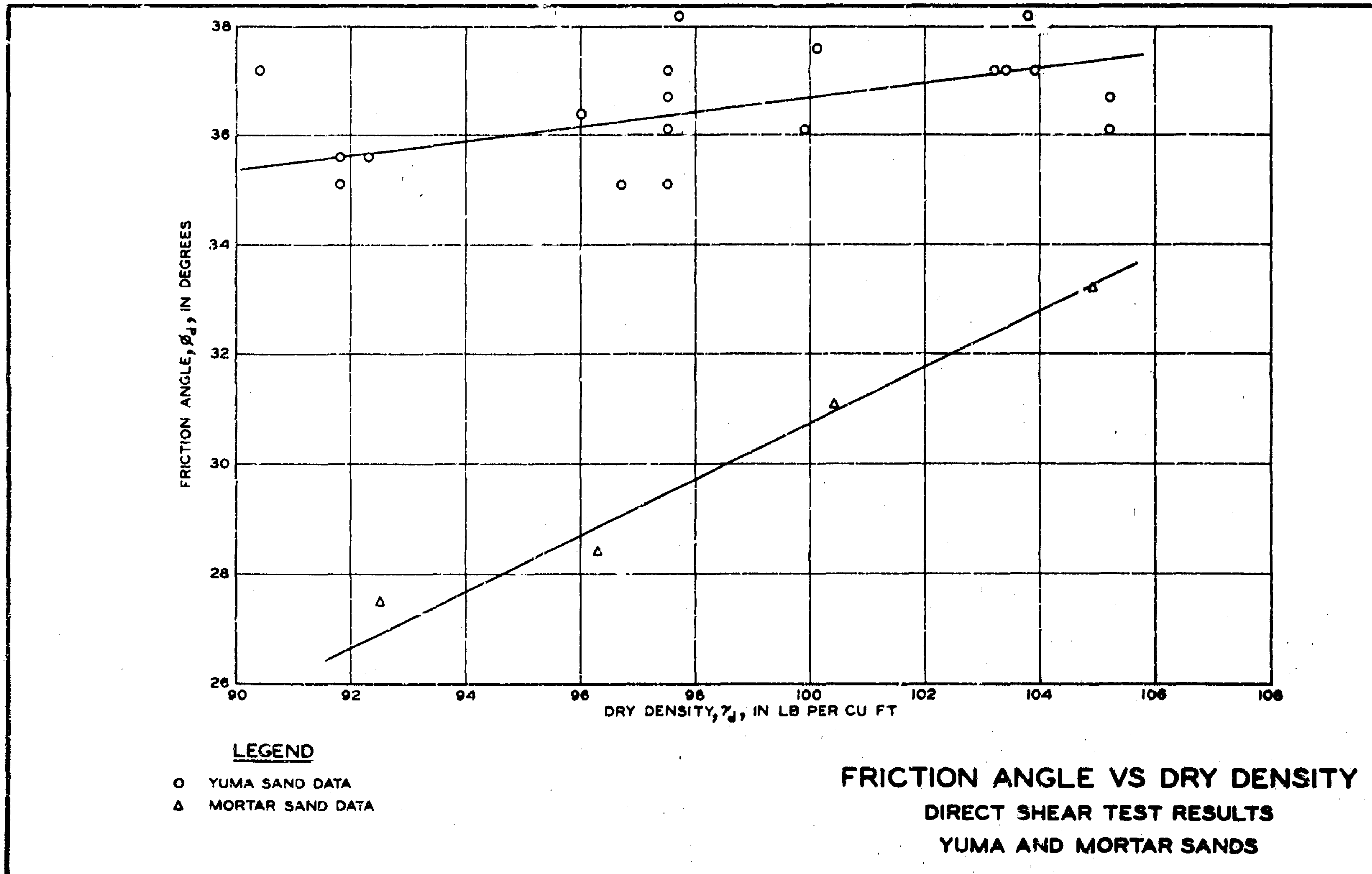
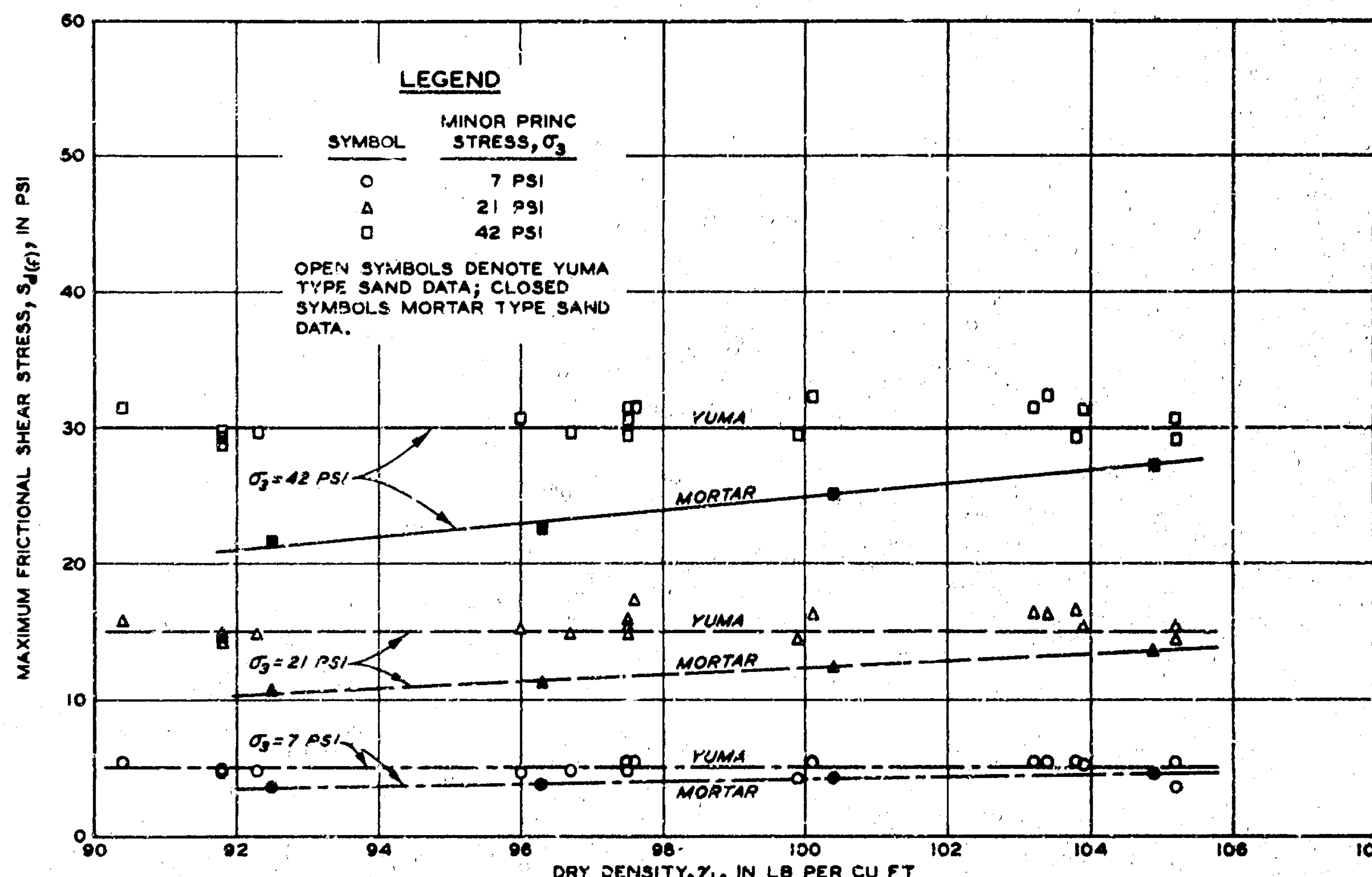

DRY DENSITY VS
0- TO 2-IN. CONE INDEX
YUMA AND MORTAR SANDS
0- TO 2-IN. CONE INDEX
DRY DENSITY, γ_d, IN LB/CU FT
0
5
10
15
20
25
90
92
94
96
98
100
102
104
106
LEGEND
△ MORTAR SAND
○ YUMA SAND

PLATE 38


FRICTION ANGLE, ϕ_d, IN DEGREES
38
36
34
32
30
28
26
90
92
94
96
98
100
102
104
106
108
DRY DENSITY, γ_d, IN LB PER CU FT
LEGEND
○ YUMA SAND DATA
Δ MORTAR SAND DATA
FRICTION ANGLE VS DRY DENSITY
DIRECT SHEAR TEST RESULTS
YUMA AND MORTAR SANDS



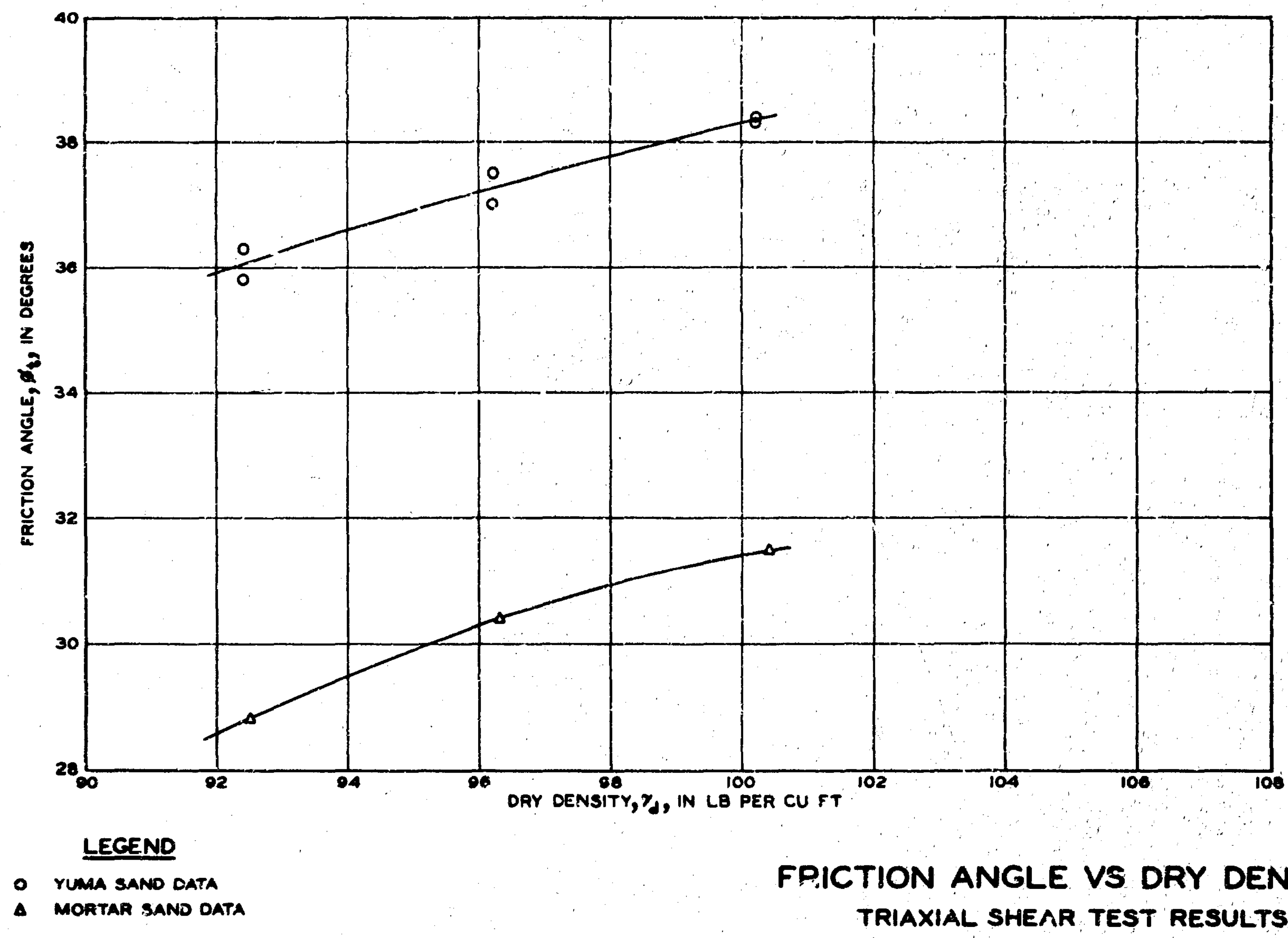
NOTE: MAXIMUM FRICTIONAL SHEAR STRESS VALUES PLOTTED HERE ARE THE SAME AS MAXIMUM SHEAR STRESS VALUES IN TABLE 13 EXCEPT THAT FOR THE TWO YUMA SAND TESTS THAT SHOWED SOME COHESION, COHESION WAS SUBTRACTED FROM MAXIMUM SHEAR STRESS TO YIELD MAXIMUM FRICTIONAL SHEAR STRESS.

MAXIMUM FRICTIONAL SHEAR STRESS VS DRY DENSITY

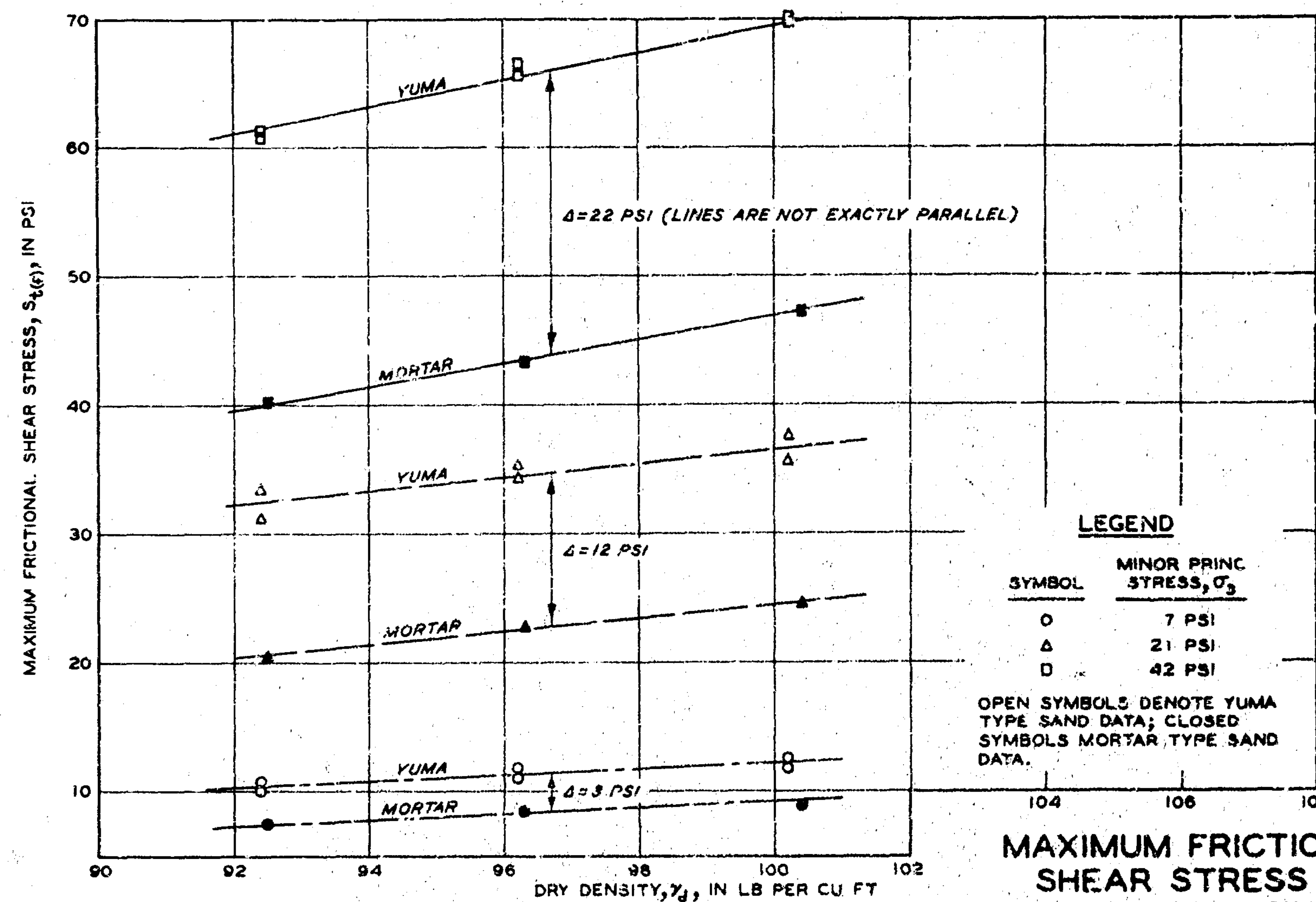
DIRECT SHEAR TEST RESULTS

YUMA AND MORTAR SANDS

PLATE 40



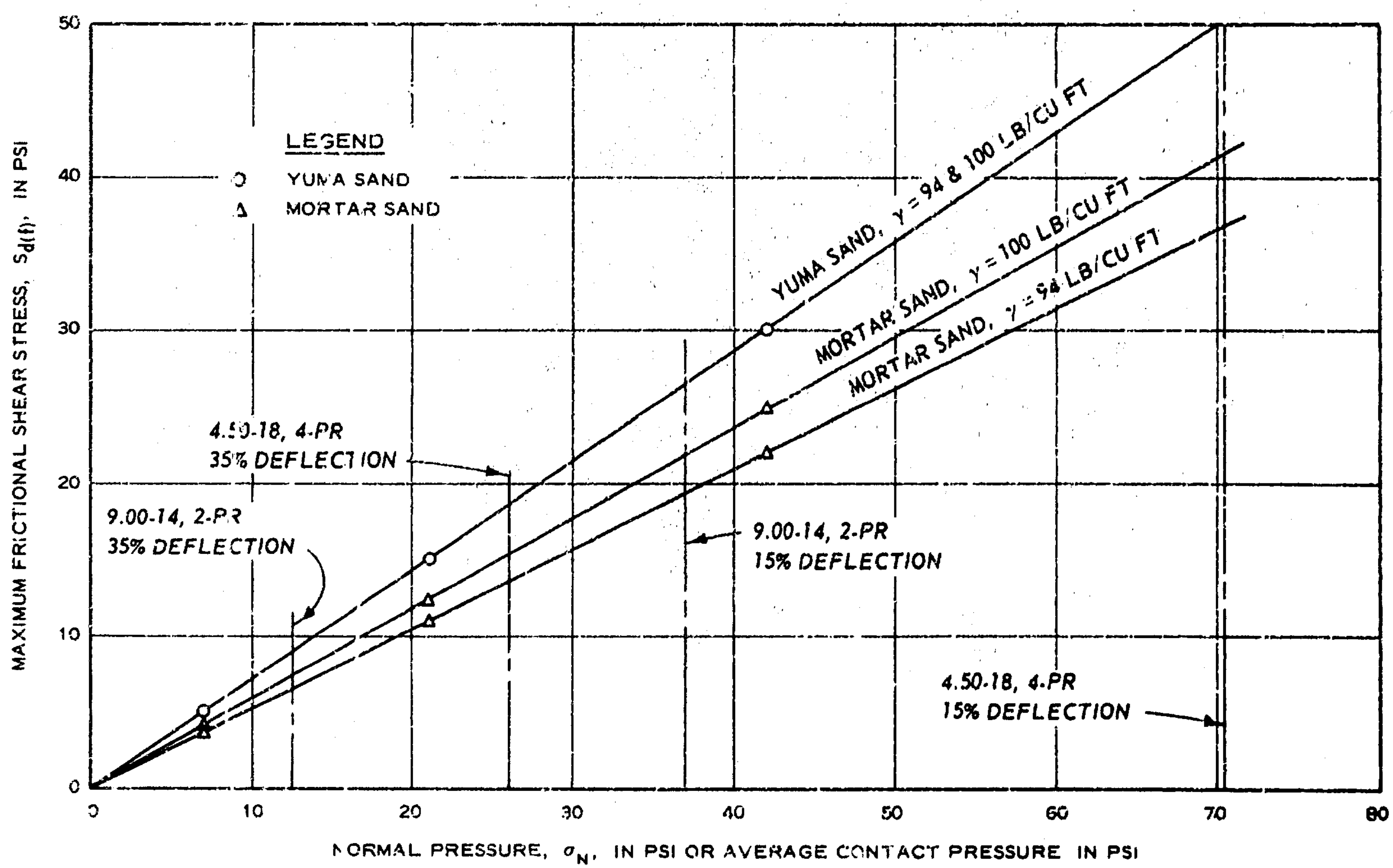
FRICTION ANGLE VS DRY DENSITY
TRIAXIAL SHEAR TEST RESULTS
YUMA AND MORTAR SANDS



NOTE: Δ IS THE CONSTANT OR NEARLY CONSTANT DIFFERENCE BETWEEN MAXIMUM FRICTIONAL SHEAR STRESS VALUES FOR COMPARABLE GROUPS OF YUMA AND MORTAR SAND TESTS.

MAXIMUM FRICTIONAL SHEAR STRESS VS DRY DENSITY

TRIAXIAL SHEAR TEST RESULTS
YUMA AND MORTAR SANDS



MAXIMUM FRICTIONAL SHEAR STRESS
VS NORMAL AND CONTACT PRESSURE

APPENDIX A: DYNAMIC WEIGHT TRANSFER FOR WHEELED VEHICLES

1. When comparing the performance of a single wheel with that of a wheeled vehicle, it is necessary to determine those factors inherent in the vehicle design that may be expected to produce differences in performance. One of these factors is dynamic weight transfer. The transfer of weight from the front to the rear wheels (or vice versa) is a product of a number of considerations. Some of these are torque, acceleration, slope of surface, differential sinkage (front to rear), motion resistance, and external pull (drawbar or pintle load).

2. The free-body diagram shown in fig. A1 will be used to describe the general force conditions of a four-wheel-drive vehicle on a horizontal

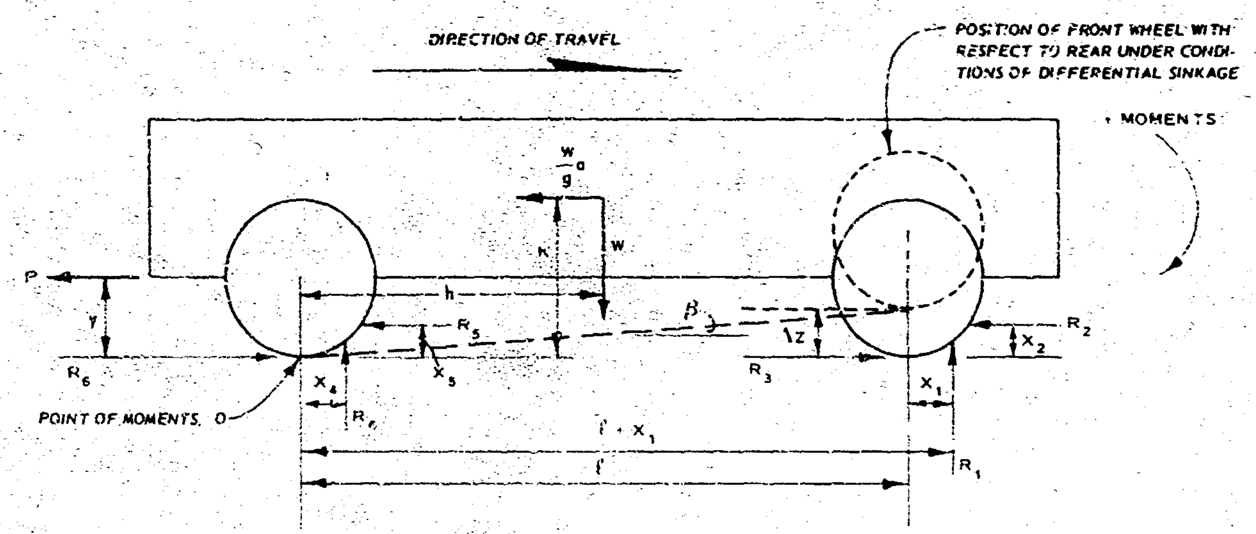


Fig. A1. Free-body diagram of four-wheel-drive vehicle traveling on a horizontal surface

surface. This diagram shows a four-wheel-drive vehicle traveling on a horizontal surface with equal sinkages of front and rear wheels. Assuming that the vehicle is traveling in a straight line such that there are no turning forces and that the wind resistance is negligible, all of the forces acting on the vehicle are shown (e.g. tractive forces, motion resistance forces, support forces, weight of the vehicle, inertial force of acceleration, and external pull). In addition, the attitude the vehicle assumes when differential sinkage between the front and rear wheels is experienced is superimposed on this diagram as dashed lines. This illustration will be used in a part of the derivation which follows.

3. The dynamic weight transfer, W_T, of a vehicle is defined in equation A1.

$$W_T = R_{1s} - R_{1d} \qquad \text{(A1)}$$

where

R_{1s} = static value of R_1

R_{1d} = dynamic value of R_1

The initial condition which will be considered is a vehicle at rest, on a firm, horizontal surface, with no external pull applied. Under these imposed conditions, the support forces, R_1 and R_4, will move to a point directly underneath the axle, thereby forcing the distances, X_1 and X_4, to become zero. Since the vehicle is at rest, the motion resistance forces, R_2 and R_5, also become zero. By summing moments about point 0, the reaction R_{1s} can be formulated as shown in equation A2.

$$R_{1s} = \frac{Wh}{\ell} \qquad \text{(A2)}$$

4. In order to complete the detailed weight transfer equation, it is necessary to evaluate the reaction R_1 in the dynamic state. The dynamic value of R_1 is dependent upon the following specific conditions under which the vehicle may be operating:

a. The vehicle is on a firm or a yielding surface.

b. The vehicle is at constant velocity or it is accelerating or decelerating.

c. External pull is or is not applied.

d. The vehicle is traveling on the level or on a slope.

5. The first dynamic condition to be considered is motion of the vehicle on a firm, horizontal surface, at constant velocity with no external pull applied. It has been found from tire deflection and contact pressure studies that, if a pneumatic-tired vehicle is in motion on a firm surface, there is the possibility that the support reactions, R_{1d} and R_{4d} occur at distances X_1 and X_4, respectively, in front of the axles. It is thought that these distances are very small and perhaps insignificant.

However, they will not be ignored in this derivation. The tractive forces, R_3 and R_6, pass through the point of moments and therefore do not contribute to weight transfer. Likewise, when the vehicle is traveling on a firm surface, the motion resistance forces, R_2 and R_5, are acting at ground level and consequently drop from the moment equation. This condition leads to equation A3.

$$\Sigma M_o = 0 = Wh - R_{4d}X_4 - R_{1d}(\ell + X_1)$$

but

$$R_{4d} = R_{4s} + W_T$$

solving for R_{1d},

$$R_{1d} = \frac{Wh - (R_{4s} + W_T)X_4}{\ell + X_1} \tag{A3}$$

Thus, weight transfer for conditions of constant velocity, on a firm horizontal surface, with no external pull applied, will be as shown in equation A4.

Since

$$W_T = \frac{Wh}{\ell} - R_{1d} \quad \text{(equations A1 and A2)}$$

$$W_T = \frac{Wh}{\ell} - \left[\frac{Wh - (R_{4s} + W_T)X_4}{\ell + X_1}\right]$$

Collecting terms

$$W_T\left(1 - \frac{X_4}{\ell + X_1}\right) = \frac{Wh}{\ell} - \frac{Wh}{\ell + X_1} + \frac{R_{4s}X_4}{\ell + X_1}$$

Rearranging terms with common denominator and multiplying numerator and denominator by ℓ

$$W_T = \frac{Wh(\ell + X_1)}{\ell(\ell + X_1 - X_4)} - \frac{Wh(\ell + X_1)\ell}{\ell(\ell + X_1 - X_4)} + \frac{R_{4s}X_4(\ell + X_1)\ell}{\ell(\ell + X_1 - X_4)}$$

Simplifying

$$W_T = \frac{WhX_1 + R_{4s}X_4\ell}{\ell(\ell + X_1 - X_4)} \tag{A4}$$

If the vehicle is now considered to travel, not on a firm surface but in a yielding medium such that sinkage of the vehicle is present, then X_2 and X_5 will no longer be zero and, consequently, the motion resistance forces, R_2 and R_5, will contribute to weight transfer. By expanding the moment equation shown for equation A3 to include the two motion resistance moments, R_2X_2 and R_5X_5, and carrying these moments through the steps shown for equation A4, the result is found to be a simple addition of R_2X_2 and R_5X_5 to equation A4 with the result being equation A5.

$$W_T = \frac{WhX_1 + (R_{4s}X_4 + R_2X_2 + R_5X_5)\ell}{\ell(\ell + X_1 - X_4)} \tag{A5}$$

Thus, equation A5 is a general expression for the dynamic weight transfer of a four-wheel-drive vehicle, operating at constant velocity, on a yielding medium, in a horizontal attitude, with no external pull applied.

6. The two preceding considerations have been for a vehicle traveling at constant velocity. However, if the vehicle either accelerates or decelerates, a new force and its resulting moment will cause an additional change in the weight transfer. This is shown by inserting the term for the inertial moment into equation A5 and rewriting as equation A6.

$$\text{Inertial moment} = \frac{W}{g} aK$$

$$W_T = \frac{WhX_1 + \left(R_{4s}X_4 + R_2X_2 + R_5X_5 + \frac{W}{g} aK\right)\ell}{\ell(\ell + X_1 - X_4)} \tag{A6}$$

7. When an external pull is applied, such as the force a trailer imparts to the vehicle pulling it, an additional unbalanced moment exists which must be accounted for by additional weight transfer. This new factor alters the previous weight transfer equation (equation A6) as follows:

$$\text{Moment due to external pull} = Py$$

$$W_T = \frac{WhX_1 + \left(R_{4s}X_4 + R_2X_2 + R_5X_5 + \frac{W}{g} aK + Py\right)\ell}{\ell(\ell + X_1 - X_4)} \tag{A7}$$

8. All of the conditions considered thus far have been with the

vehicle operating on a horizontal surface. The next and last condition will be that of a vehicle operating on a slope (fig. A2). For reasons of

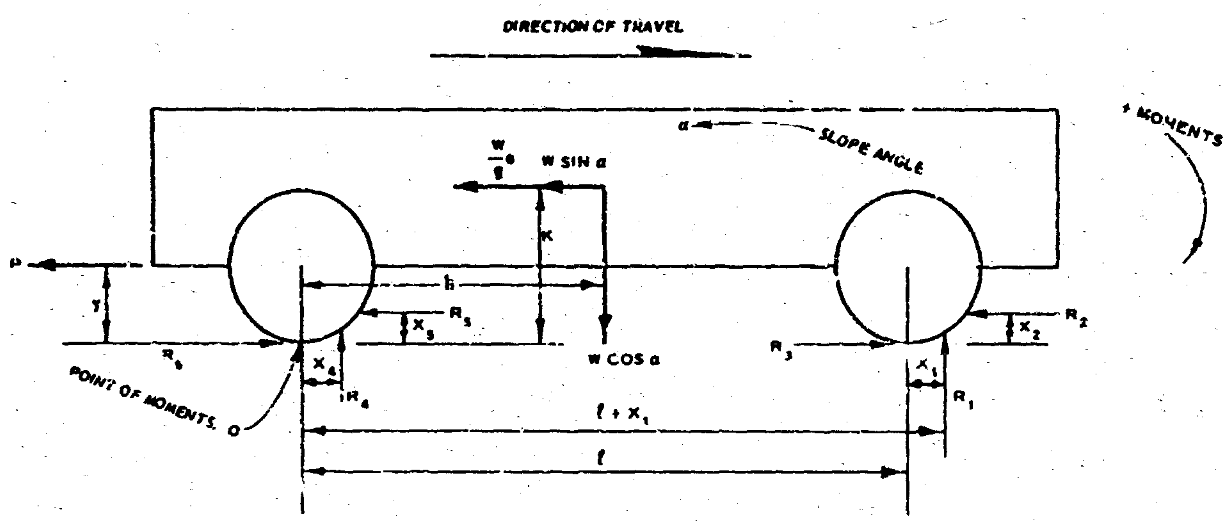


Fig. A2. Free-body diagram of four-wheel-drive vehicle traveling on a slope

mathematical simplicity, the weight, W , of the vehicle has been separated into its components parallel and perpendicular to the slope. Otherwise the diagram is the same as fig. A1. The resulting weight transfer relation is then defined in equation A8.

$$W_T = \frac{WhX_1 + \ell\left[Wh - W(\cos\alpha)h + W(\sin\alpha)K + R_5X_5 + R_2X_2 + R_{4s}X_4 + \frac{W}{g}aK + Py\right]}{\ell(\ell + X_1 - X_4)} \tag{A8}$$

9. Equation A8 is not precisely correct for vehicles operating in soft soils because vehicles equipped with tracking wheels experience differential sinkage. This causes the vehicle to be inclined at an angle β whose sine is $\frac{\Delta z}{\ell}$, where Δz is the differential sinkage (see fig. A1). In addition, differential sinkage will cause the tractive force, R_3 , to contribute to the final value of weight transfer, since its line of action under these conditions will not pass through the point of moments. Furthermore, the moment arm of the motion resistance force, R_2 , on the front wheels will become $(X_2 + \Delta z)$. Adding these effects to equation A8 will result in equation A9.

$$W_T = \frac{WhX_1 + \ell\left[Wh - W(\cos\alpha)h + W(\sin\alpha)K + R_5X_5 + R_2(X_2 + \Delta z) + R_{4s}X_4 + \frac{W}{g}aK + Py - R_3\Delta z\right]}{\ell(\ell + X_1 - X_4)} \tag{A9}$$

10. This theoretical weight transfer equation (A9) is considered to be a general expression for the weight transfer of a four-wheel-drive vehicle that will account for the effect of motion resistance, the effect of acceleration, the effect of torque, the effect of external pull, and the effects of differential sinkage and slope climbing. It is believed that the use of this weight transfer equation will help produce a meaningful comparison of single-wheel performance data and the performance of a four-wheel-drive vehicle when the factors mentioned, singularly or collectively, produce an appreciable amount of load transfer.

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4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Report 4 of series

5. AUTHOR(S) *(Last name, first name, initial)*

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Off-road mobility						
Pneumatic tires						
Sand						

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

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