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MEASURING SOIL PROPERTIES IN VEHICLE MOBILITY RESEARCH

Report 7

BEHAVIOR OF FINE-GRAINED SOILS UNDER HIGH-SPEED TIRE LOADS

by

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at speeds to at least 18 ft/sec if the value of C_s in N_{cl} is adjusted to reflect viscouslike soil strength behavior caused by tire-soil interaction. Results from WES speed tests of five prototype wheeled vehicles in the field indicated that the same velocity-adjusted numeric as above (except that rating cone index RCI replaces cone index C_s) is closely related to the soil motion resistance coefficient R_s/W_v . Data from tests conducted for the U. S. Air Force showed that for one particular combination of aircraft, running gear, and wing-flap setting, a clay-tire numeric, $N_{co} = (C_s bd/W) \times (\delta/h)^{1/2}$, is closely associated with the percent increase in takeoff distance required on unsurfaced clay runways as compared to that on a paved runway. From another study conducted for the Air Force, data revealed that a relation between the dimensionless drag coefficient and the Reynolds number (modified from fluid mechanics to fit the clay-tire situation) can be used to describe the combined influence of viscouslike and inertial changes in soil strength on the drag of a free-rolling tire at speeds to about 150 ft/sec. For the braked-wheel operational mode, a simple method of predicting drag ratio (D/W) was developed on the basis of a reasonably stable, linear relation that exists between D/W and the rut depth coefficient (r/d) for wheel speeds to about 150 ft/sec.

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PREFACE

The study reported herein was funded by Department of the Army Project 4A061101A91D, "In-House Laboratory Independent Research," under the sponsorship of the Assistant Secretary of the Army (R&D). The study was conducted during 1973-1974.

The project was conceived by Mr. G. W. Turnage, Mobility Research and Methodology Branch (MRMB), Mobility Systems Division (MSD), Mobility and Environmental Systems Laboratory (MESL), at the U. S. Army Engineer Waterways Experiment Station (WES). Most of the data analyzed in this report were obtained from tabulations in the published literature. Also presented are some hitherto unreported data from a previous test program accomplished by personnel of MRMB and the Mobility Investigations Branch (MIB), MESL. This study was conducted under the general supervision of Messrs. W. G. Shockley, Chief of MESL, and A. A. Rula, Chief of MSD, and under the direct supervision of Mr. C. J. Nuttall, Jr., Chief of MRMB. The report was prepared by Mr. Turnage.

Special acknowledgment is made to Dr. E. T. Selig and Mr. C. T. Wang, State University of New York at Buffalo, Buffalo, New York, for furnishing the author with a corrected tabulation of data from tests conducted at the NASA Langley Research Center, Landing Loads Test Track, and for their permission to use these data.

BG E. D. Peixotto, CE, and COL G. H. Hilt, CE, were Directors of WES during the conduct of the study and the preparation of the report. Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimetres
feet	0.3048	metres
square inches	6.4516	square centimetres
square feet	0.09290304	square metres
pounds (mass)	0.4535924	kilograms
pounds (force)	4.448222	newtons
tons (mass)	907.1847	kilograms
pounds (force) per square inch	6.894757	kilopascals
inches per minute	2.54	centimetres per minute
feet per second	0.3048	metres per second
knots (international)	0.5144444	metres per second
miles per hour (U. S. Statute)	1.609344	kilometres per hour

MEASURING SOIL PROPERTIES IN VEHICLE MOBILITY RESEARCH

BEHAVIOR OF FINE-GRAINED SOILS UNDER HIGH-SPEED TIRE LOADS

PART I: INTRODUCTION

Background

1. Under present-day concepts of warfare, it is essential that a military organization be able to deploy its men and equipment quickly into any area of operation and to furnish them support while there. Very often, this requires the use of ground vehicles on off-road, cross-country routes, or aircraft on hastily prepared earth airstrips, or both. For effective operation in these difficult environments, rational, accurate mathematical descriptions would be of great assistance in forecasting the in-soil performance of the ground vehicles or aircraft to be used or, alternatively, in designing or choosing the best ground vehicle or aircraft for the in-soil conditions of concern.

2. A key element in the cross-country performance of ground vehicles and in the landing and takeoff of aircraft from unsurfaced airfields is the effect of speed on the interaction between the soil and the vehicle's running gear. In Reports 3¹ and 5² in this series, basic descriptions were developed for the changes in probe penetration resistance of fine-grained soils caused by variations in probe size, shape, and speed. Reference 3 demonstrated that straightforward modifications enabled these descriptions to be used for the tire-soil situation (at wheel speeds to 18 ft/sec*). This report extends the range of application of results from Reports 3 and 5 by describing the behavior of fine-grained soils under tire loads at wheel speeds much faster than heretofore considered (to about 30 mph for ground vehicles in off-road conditions, and about 105 mph for aircraft wheels on unsurfaced strips).

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

Also used and emphasized throughout this report is a system of forecasting tire performance (described in Reference 3) in which dimensionless prediction terms (or numerics) composed of important soil, tire, and wheel variables are related to tire performance expressed in dimensionless forms (pull/load, sinkage/tire diameter, etc.).

Purpose

3. The general purpose of the study reported herein was to gain insight into the behavior of fine-grained soils under high-speed tire loads. In satisfying this purpose, three particular objectives were:

- a. To delineate the effects of wheel speed and soil strength on the powered-wheel performance of pneumatic tires and wheeled vehicles in near-saturated, fine-grained soil.
- b. To examine the influence of soil strength on aircraft takeoff distance for powered-wheel aircraft operating from unsurfaced clay runways.
- c. To develop a quantitative description of the effects on tire drag caused by wheel speeds to about 105 mph for aircraft tires operating in the free-rolling and braked-wheel modes (i.e. the landing mode) in near-saturated, fine-grained soil.

Scope

4. The numeric system for describing the performance of a single powered wheel in near-saturated, fine-grained soil³ was adjusted to account for changes in soil strength produced by variations in wheel speed. Maximum vehicle speed versus soil strength relations were examined for wheeled ground vehicles, using data from an earlier U. S. Army Engineer Waterways Experiment Station (WES) report⁴ and from a previous unpublished study.

5. Relative to aircraft performance in clay, the WES numeric system was used to consolidate to a single relation the several relations for takeoff distance versus soil strength given in References 5 and 6 for a particular powered-wheel aircraft at a designated wing-flap setting and a range of wheel loads and tire inflation pressures. A

technique was developed for predicting in-soil wheel drag at velocities from near zero to about 105 mph for the free-rolling condition, using as input a known or an estimated value of tire rut depth along with known values of wheel speed, wheel load, and some easily measured tire dimensions. For the braked-wheel operational mode, a simple method of predicting wheel drag was developed on the basis of a linear relation between drag ratio (drag force/load) and rut depth coefficient (rut depth/tire diameter). Data and background information used in the study of aircraft wheel drag in clay were extracted from References 7 and 8, except that some of these data were replaced with corrected data supplied by Dr. E. T. Selig and Mr. C. T. Wang of the State University of New York at Buffalo.

PART II: SPEED-INFLUENCED POWERED-WHEEL PERFORMANCE IN CLAY

Pull Performance of Single Pneumatic Tires

6. Since 1960 the WES had conducted many systematic tests with single pneumatic tires in carefully controlled laboratory tests and peripheral studies that were designed to further a basic understanding of tire-soil interactions. Most of the single-tire tests were conducted in large bins⁹ of remolded fat clay (classified CH according to the Unified Soil Classification System (USCS)) with a plasticity index of 38. The soil in the bins was at approximately 95 percent saturation and was so emplaced that the strength profile was uniform.

Basic clay numeric

7. One major result of the WES laboratory tire test program was the development, by means of dimensional analysis¹⁰ coupled with test results, of a basic dimensionless prediction term, or numeric N_{cl} ,³ to describe pneumatic tire performance in near-saturated fine-grained soils:

$$N_{cl} = \frac{C_s b d}{W} \times \left(\frac{\delta}{h} \right)^{1/2} \times \frac{1}{1 + \frac{b}{2d}} \quad (1)$$

where

C_s = standard cone index*

b = unloaded tire section width

d = unloaded tire diameter

W = load on a single wheel

δ = tire deflection (difference between loaded and unloaded tire section heights at a given inflation pressure)

h = unloaded tire section height

Tire performance predicted with N_{cl} may be expressed by certain dimensionless ratios, or coefficients, at specified tire performance levels, e.g. pull coefficient at 20 percent slip (P_{20}/W). The results of many

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

single-wheel laboratory tests have shown that N_{cl} can be used to predict single-tire P_{20}/W performance with good accuracy for a wide range of values of each of the variables listed above.³ One important limiting factor in these tests, however, has been that the experimental wheel translational velocity analyzed covered only a very narrow range of values, approximately 5 to 6 ft/sec.

Adjusting N_{cl} to
account for velocity effects

8. To investigate the influence of wheel velocity on pneumatic tire P_{20}/W performance, results were examined from tests that had been conducted with two essentially 2:1-scale model tires (a 9.00-14, 2-PR, and a 4.00-7, 2-PR) at one deflection condition ($\delta/h = 0.25$) over a wide range of soil strengths and wheel loads and at velocities that ranged from 0.5 to 18 ft/sec (near the upper limit of the laboratory test equipment). These results (plotted in Plate 1a) show that, for a given value of pull coefficient, the value of N_{cl} generally decreases slightly with increasing values of translational velocity for each tire size. Also, values of N_{cl} are generally larger for the 9.00-14 tire than for the 4.00-7 tire at corresponding values of pull coefficient.

9. Taken together, References 3 and 11 have shown that the trend above can be diminished or removed by increasing the value of standard cone index C_s as wheel translational velocity V_w increases and by scaling the size of this increase in inverse proportion to tire size. By following the same procedures as used in these references, an expression was developed for velocity-adjusted C_s (i.e. C_x) as follows:

$$C_x = C_s \times \left(\frac{0.16 V_w/b}{V_s/\ell_s} \right)^{0.100} \quad (2)$$

where

V_s = standard rate of cone penetration (72 in./min)

ℓ_s = square root of the base area of a standard cone (0.707 in.)

The multiplier 0.16 reduces the fraction in Equation 2 to 1.0 when

$V_w = 5.5$ ft/sec (average value for routine WES laboratory tire tests)

and $b = 6.2$ in. (average unloaded tire section width for the 9.00-14 and 4.00-7 tires).

10. Substituting Equation 2 for C_s in Equation 1 should normalize the relation in Plate 1a to the $V_w = 5$ to 6 ft/sec condition. Plate 1b shows that this is the case. Scatter of the test data in Plate 1b is considerably less than in Plate 1a. The curve in Plate 1a and 1b is the same one used in Reference 3 to describe the P_{20}/W versus N_{cl} relation for many tire sizes and shapes at $V_w = 5$ to 6 ft/sec.

11. References 1, 2, and 11 relate the change in cone index in near-saturated clay to the viscous behavior of pseudoplastic fluids,¹² and References 1 and 2 have shown that the viscouslike behavior of C_x/C_s occurs over a very broad range of soil strengths (C_s values of 13 to 287 in those references). Thus, the substitution of C_x for C_s values to account for the effects of wheel velocity appears to be applicable for a broad spectrum of soil strengths.

Speed Performance of Wheeled Vehicles

Test conditions

12. Test vehicles. Reference 4 presents the results of in-soil and on-pavement speed tests performed with four 2-1/2-ton wheeled vehicles--the XM410E1, 8x8 truck; the M35A2 (modified), 6x6 truck; the MEXA* 10x10; and the MEXA 8x8. Photos of these vehicles appear in Figure 1, and data describing each vehicle are given in the first ten columns in Table 1. Unreported before now, similar speed tests have also been conducted with a special high-powered 4x4 test bed called the "Mudder" (shown in Figure 2 and described by data in the first ten columns in Table 2).

13. Field test sites and soils. Wheeled vehicle speed tests

* MEXA stands for Mobility Exercise A. The MEXA 10x10 and 8x8 wheeled vehicles were fabricated and field-tested to satisfy, in part, the principal purposes of MEXA, which were (a) to design vehicles capable of operating in remote areas of the world where extremely soft soils predominate, and (b) to develop a program of tests for evaluating these vehicles in soft soils.

a. XM410E1

b. M35A2 (mod)

c. MEXA 10x10

d. MEXA 8x8

Figure 1. Four 2-1/2-ton wheeled vehicles (Reference 4)

Figure 2. The "Mudder" 4x4 test bed

reported in Reference 4 were conducted at six field sites near Fallon, Nevada (four at Carson Sink and two at Four Mile Flat). The 4x4 Mudder was also tested at Four Mile Flat. At three of the Carson Sink test sites, the soil was lean clay (CL) in the 0- to 5-in. soil layer and fat clay (CH) in the 5- to 18-in. layer. At Four Mile Flat and at the other Carson Sink test site, the soil in the top 18 in. was fat clay (CH). Gradation curves and classification data for the test sites are shown in Figure 3.

14. Both the Carson Sink and the Four Mile Flat test sites were large, flat, barren playas. Each site was free of surface water, and, overall, the test sites included a very broad range of soil strengths (0- to 6-in. average cone index values from 10 to 105) as shown in Tables 1 and 2. In addition, each test vehicle was also tested on pavement.

15. Test procedures. A lane long enough to accommodate a given test was selected and staked, and a sufficient number of cone index measurements were made to determine that the clay strength in the lane was uniform and at the desired level. Additionally, measurements were

a. Carson Sink test sites (Reference 4)

b. Four Mile Flat (Reference 4)

Figure 3. Soil gradation curves and classification data

taken to determine the remolding index (RI*) of the soil in the test lane, and, subsequently, rating cone index (RCI), the product of in situ before-traffic average cone index in a specified soil layer (0 to 6 in. herein) times RI for that layer.

16. For a given test either on soil or on pavement, the wheeled vehicle began its self-propelled, straight-line run from a standstill (zero speed) condition in its lowest gear and at full throttle and continued progressively through each higher gear until maximum speed (V_v) was reached. Then the power train was disengaged, and the vehicle was allowed to roll to a stop. Vehicle speed was measured throughout each test run; maximum vehicle speeds are recorded in Tables 1 and 2.

Analysis of test results

17. Development of a consolidated relation to describe V_v .

The basic relation developed in the tests described in paragraphs 15 and 16 is that of maximum vehicle speed (V_v) versus soil strength (described herein in terms of RCI in the 0- to 6-in. soil layer). RCI is used as the index of fine-grained soil strength for these field tests, in agreement with the conclusion in Reference 3 that RCI is appropriate to describe one-pass wheeled vehicle performance because "WES experience has shown that RCI effectively describes soil strength on a common basis for a wide variety of types and consistencies of fine-grained soils." A separate V_v versus RCI curve resulted from each of the five test vehicles, as shown in Plate 2.

18. A useful approach to consolidate the data in Plate 2 is, first, to compute the driving or tractive force (F_t) at the wheels of each test vehicle in terms of engine brake horsepower (HP) and maximum vehicle speed (V_v). For a vehicle operating at full throttle, but not within an engine rpm range where a governor is acting,

$$F_t = \frac{375 \times \text{HP} \times e_f}{V_v}, \text{ lb} \quad (3)$$

* The ratio of the sum of cone index values obtained in a cylinder of compacted soil to the sum of those obtained before compaction, expressed as a decimal.³

where V_v is in miles per hour and e_f represents full throttle efficiency (i.e., total horsepower delivered through the driveline to the wheels, divided by engine brake horsepower and expressed as a decimal value between 0 and 1). Values of e_f listed in Reference 13 for various combinations of total wheels and total wheels powered (e.g. 4x2, 4x4, 6x4, etc.), together with knowledge of the drive-train characteristics of the MEXA 10x10 and MEXA 8x8, led to the values of e_f listed for the test vehicles in Tables 1 and 2.

19. For dynamic equilibrium to be maintained, dynamic force F_t must equal the sum of external motion resistance R_e and internal motion resistance R_i at the vehicle's wheels, i.e.,

$$F_t = R_e + R_i \quad (4)$$

where

R_e = the resistance to movement of a vehicle provided by the surface on and through which it moves

R_i = the resistance to movement of a vehicle provided by the internal friction of its moving parts and the energy losses in the traction elements

20. For a vehicle operating in soil, it is convenient to replace R_e with R_s , motion resistance of the vehicle due to the soil, and to estimate R_i as R_p , motion resistance of the vehicle as it operates straight-line on flat, level pavement (or some other hard surface). That is,

$$F_t = R_s + R_p \quad (5)$$

for a vehicle operating in soil. Note that R_p equals F_t when a vehicle operates on pavement.

21. Tables 1 and 2 show that each vehicle was tested in clay at a single combination of vehicle load, tire size, and tire deflection. Except for the XM410E1, a test run was also made on pavement for each vehicle at the same combination of load and tire conditions. Thus, it was possible to use Equation 3 to compute F_t and an associated R_p

value for each test run in Tables 1 and 2.*

22. In consolidating the tire performance data from Tables 1 and 2, the vehicle performance term of primary interest is R_s/W_v , soil motion resistance coefficient. In Plate 3a, the relation of R_s/W_v to N_{c2}^{**} is not characterized by excessive data scatter, but there does appear to be an ordering of the relation for the five test tires as shown by the three curves.

23. Plate 3b shows that separation of the data in Plate 3a is reduced slightly when clay-tire numeric N_{c2} is adjusted to N_{c2x} by replacing RCI in N_{c2} with

$$(RCI)_x = RCI \times \left(\frac{kV_v/b}{V_s/\ell_s} \right)^{0.100} \quad (6)$$

where k is the constant for a vehicle with tires of width b that causes $(kV_v/b)/(V_s/\ell_s)$ to equal 1.0 when 5.5 ft/sec is substituted for V_v .† More important, this normalization of the test data to the 5 to 6 ft/sec condition allows the relation in Plate 3b to be described reasonably well by the single (solid) curve for all five tire sizes.

24. Data for tests 2 and 3 of the 4x4 Mudder are not plotted in Plate 3b (or in 3a) because these two tests were conducted with the vehicle in an engine rpm range where a governor was acting, i.e., in a condition in which the available power was less than the maximum by some unknown amount. Thus, for these two tests, data were not complete enough to use the present analysis.

25. Some important features of the relation in Plate 3b. It is of interest to compare the solid curve used to describe the test data in Plate 3b with the dashed curve taken from Reference 3. The dashed

* For the XM410E1, a reasonable estimate of R_p was made by assuming that R_p/W_v for the XM410E1 was in the same ratio to its F_t/W_v value at RCI = 189 (item No. 153 in Table 1) as R_p/W_v for the M35A2 (mod) was to its F_t/W_v value at RCI = 189 (item No. 157).

** N_{c2} is the same as N_{c1} (Equation 1) except that RCI is used instead of C_s .

† Equation 6 modifies RCI to $(RCI)_x$ for a given wheeled vehicle in the same way that Equation 2 modified C_s to C_x for two particular single tires.

curve describes the relation of towed force coefficient P_T/W to clay-tire numeric N_{c2} based on many laboratory single-wheel tests of free-rolling buffed smooth pneumatic tires at 5 to 6 ft/sec in fat clay. The dynamometer and tires used for these tests were so constructed that essentially zero internal motion resistance R_i was reflected in measurements of towed force P_T .⁹ Thus, P_T is analogous to soil motion resistance R_s for a towed (i.e. an unpowered) wheel.

26. The two curves in Plate 3b are alike, in that each represents soil motion resistance (in coefficient form). The major reason for separation between the two curves is that the dashed curve describes soil motion resistance coefficient R_s/W for the towed condition (at slightly negative wheel slip) and the solid curve describes R_s/W for the self-propelled condition (at slightly positive wheel slip). Soil motion resistance R_s increases with increasing slip,¹⁴ so the relative positions of the two curves in Plate 3b are correct.

27. In Plate 3b, both curves are rectangular hyperbolas, each with a nominal horizontal asymptote of 0.010. The vertical asymptote of the solid curve is 2, indicating that soil motion resistance becomes excessive, and that maximum vehicle speed V_v approaches zero as the value of the numeric N_{c2x} approaches 2.

28. If maximum vehicle speed approaching 0 is taken to represent the immobilization condition, then the above observation suggests that RCI computed for N_{c2x} approaching 2 can be taken as an estimate of the minimum soil strength for a vehicle to be on the verge of immobilization. In this application, the term $[(kV_v/b)/(V_s/\ell_s)]^{0.100}$ in Plate 3b becomes essentially inoperative because V_v is approaching 0, and RCI computed at N_{c2} (not N_{c2x}) = 2 provides an estimate of immobilization soil strength.

29. Computed values of RCI at $N_{c2} = 2$ for the five wheeled vehicles under consideration appear in the second column of the following tabulation:

<u>Wheeled Vehicle</u>	<u>RCI at $N_{c2} = 2$</u>	<u>VCI_{1t} Values</u>
XM410E1	17	18
M35A2 (mod)	30	27
MEXA 10x10	7	7
MEXA 8x8	9	11
4x4 Mudder	8	8

For the first four vehicles above, the third column lists values of VCI_{1t} from Reference 4, where VCI_{1t} is "an experimental determination of the maximum RCI of the critical (soil) layer required for a vehicle to complete one pass. The critical layer for most vehicles is usually the 0- to 6-in. layer." For the 4x4 Mudder, the third column lists an approximate value of VCI_{1t} based on the observation that in Plate 2 data points for the Mudder include one of $V_v = 0$ at $RCI = 7$ and one of $V_v = 18.7$ mph at $RCI = 9$. Comparison of the values in the second and third columns suggests that RCI computed at $N_{c2} = 2$ does provide a good estimate of the minimum RCI needed to overcome immobilization.

Takeoff Performance of Aircraft from Clay Runways

30. For a number of years the U. S. Air Force has been developing and refining analytical techniques for computing aircraft taxi, landing, and takeoff performance on unsurfaced airstrips. WES has been involved in this work through the conduct for the Air Force of specific tire-soil studies.⁵⁻⁸ In addition, the WES tire-soil numeric work has provided the general framework for predicting tire sinkage and motion resistance.

31. References 5 and 6 present a comprehensive analytical model for the prediction of aircraft takeoff distances on soil runways. As used in those reports and herein, takeoff distance is defined as aircraft ground-roll distance from zero speed to lift-off.

32. The analytical model incorporates an early version of the soil-tire numeric for clay¹⁰

$$N_{c0} = \frac{C_s b d}{W} \times \left(\frac{\delta}{h} \right)^{1/2} \quad (7)$$

modified by a dynamic term derived from results of limited tests of small plates under different pulse loadings. The numeric N_{c0} was used to compute various assumed soil-related aspects of soil motion resistance. The model integrates soil drag and aerodynamic drag and lift forces in the aircraft to predict takeoff distance. Computed takeoff distances closely matched measured distances in two test cases, one on a paved surface, and the other on a soil having a CBR* strength of 3.5 (assumed in the calculations to be equivalent to $C_s = 140$).

33. Using the model simulations, a series of computations was made for the 367-80 (707/KC-135 prototype) aircraft mounted on 46x16 tires (Figure 4). Full-thrust takeoff distances were developed at one flap setting (20°) for three gross weights (120,000, 150,000, and 180,000 lb), each at two tire inflation pressures (30 and 80 psi), and on runway conditions from hard pavement through a range of soil runways with standard cone index values (C_s) down to 100 (Figure 5, for example).** Results for each gross load and tire inflation pressure were normalized in terms of the percent increase in takeoff distance at the given soil strength when compared to the takeoff distance required on a paved runway at the same load and inflation pressure. The computed curves of percent increase in takeoff distance versus soil strength (C_s) are shown in Plate 4, taken from Reference 6.

34. The solid curve in Plate 5 shows the relation of percent increase in takeoff distance versus slow speed soil-tire numeric N_{c0} ,

* California Bearing Ratio.

** "Full thrust" indicates that total available forward force was utilized by the aircraft. "Flap settings" are used to influence the wings' drag and lift characteristics.

Figure 4. 367-80 airplane (Reference 5)

Figure 5. Takeoff distance on a paved surface for a range of 367-80 aircraft gross weights (Reference 5)

which is basic to all computed soil drag influences.* Despite the complexity of the overall model simulation, this curve demonstrates that the final computed results for a particular aircraft, flap setting, etc., can be expressed by a single, simple relation. The dot-dash curve in the same plate represents arbitrary superposition of the relation of slow-speed, free-rolling drag ratio versus N_{c0} from Reference 3. Comparison of the solid and dot-dash curves shows that the increase in takeoff distance for this case is almost directly related to the slow-speed drag ratio.

35. The consolidation of the data in Plate 5 should prove useful in making more general comparisons from the simulations, where different aircraft or aircraft characteristics are involved. Perhaps more important, the consolidation demonstrates a possible means by which experimental data from a small number of tests on a single aircraft can be readily generalized to cover all the gross weight, tire inflation pressure, and soil strength variations of interest. For example, tests could be run in a single (properly selected) soil strength, and variations in N_{c0} , sufficient to define the function, could be achieved by a small number of load and inflation pressure changes. Such testing might be most useful in a relatively inexpensive validation of the simulated results, once an aircraft becomes available for engineering tests.

* In numeric N_{c0} , wheel load W was estimated nominally as aircraft gross weight W_v divided by the total number of aircraft wheels, 20 for the 367-80 airplane. The diameter d for the 46x16 tire was taken as 46 in. and width b as 16 in. Deflection ratio (δ/h) values were 0.15, 0.19, 0.20, and 0.07, 0.09, 0.10 for the 6000-, 7500-, and 9000-lb wheel loads at 30- and 80-psi inflation pressures, respectively (as supplied to the author by Messrs. L. D. Richmond and K. J. Debord, coauthors of References 5 and 6).

PART III: SPEED-INFLUENCED FREE-ROLLING AND
BRAKED-WHEEL TIRE PERFORMANCE

Background

36. Since 1958, at least three large aircraft cargo transport types, the C-130, the C141A, and the C-5A, have been operated from or tested on unpaved landing surfaces.⁸ In large part, these operations were aimed at defining the in-soil performance characteristics of the particular aircraft under scrutiny (landing and takeoff distances, etc.). Results of such testing revealed the need (at least on a short-term basis) for aircraft capable of operating from unsurfaced airstrips.

37. Certainly, in the long run, there is also a need for an accurate, quantitative description of the influence of soil-tire interactions on in-soil aircraft tire performance. Only if such information is available can the running gear for aircraft expected to operate in soil be selected or designed on a rational basis. Unfortunately, very little has been obtained in full-scale aircraft tests to date. For example, "No single instance...has been found...where surface ruts have been measured and correlated with wheel loading."⁸ Data on soil strength, wheel loading, tire ruts, and wheel drag from full-scale aircraft tests would be extremely useful, if not in the development of the description mentioned above, then in verification of its accuracy and usefulness.

38. Lacking such information, a more basic approach was taken in 1967 when a program of single-wheel tests was conducted by the Air Force using the Landing Loads Test Track at the National Aeronautic and Space Administration (NASA)/Langley Research Center to study soil-wheel interaction under controlled conditions. Results of these tests appear in References 7 and 8. Corrected data from that test program are analyzed herein to develop a description of the drag performance of an

aircraft pneumatic tire operating over a range of wheel speeds in clay.*

Test Conditions

Test tire

39. Only one tire, the 29x11-10, 8 PR,** was tested singly, using the high-speed test carriage at NASA's Landing Loads Test Track. Average wheel loads ranged from 5013 to 6311 lb for 9 of the 11 test series considered herein and equaled 2417 and 4233 lb for the other two series. Tire inflation pressures were 30, 45, 55, and 70 psi. Tire widths, diameters, and deflection ratios for the test conditions considered appear in Table 3.

Test soil

40. The fine-grained test soil was fat clay with a USCS classification of CH, shipped from WES to the NASA/Langley Research Center. For all tests considered herein, the clay was prepared to approximately 90 percent saturation, resulting in a consistency almost identical with that used in the WES laboratory single-tire tests.

Test equipment

41. The Landing Loads Test Track is used primarily to study landing and ground handling problems of aircraft. A schematic of the track facility is shown in Figure 6. Power to propel the test carriage down the track is derived from impingement of a high-pressure water jet. Carriage speed is governed by the duration of time that the water jet is permitted to impinge on the carriage. Values of test run average speeds reported herein range from near zero to over 150 ft/sec.

42. A special test fixture was fabricated that could be attached

* Dr. E. T. Selig and Mr. C. T. Wang, Professor of Civil Engineering and graduate student, respectively, at State University of New York at Buffalo, Buffalo, New York, collaborated with Mr. B. M. Crenshaw, author of Reference 8, in reexamining basic records (oscillograph traces, etc.) of results from the test program mentioned in paragraph 38. Values in Table 3 reflect the corrected data resulting from that reexamination, as supplied to the author by Mr. Wang.

** Used on the main gear of the OV-10 aircraft.

Figure 6. Schematic of the NASA/Langley Landing Loads Test Track facility (Reference 7)

to the instrumented dynamometer of the already existent high-speed hydrodynamic test carriage, thereby allowing testing of the single 29x11-10, 8-PR tire. A detailed description of this fixture and its instrumentation is included in Reference 7.

43. Large-scale soil processing equipment was used to prepare soil test beds approximately 250 ft long, 8 ft wide, and 3 ft deep.

Test procedures and measurements

44. Before a given test run, the clay test bed was prepared to as homogeneous soil strength and consistency as soil processing equipment and procedures allowed. Several types of soil strength measurements were made in each bed, but the one used for control purposes and for most subsequent analyses of soil-tire interactions was cone index C_s .

45. Three C_s measurement series were made in each clay test bed--one after bed construction, one just before tire testing, and one prior to bed removal. Each series of measurements comprised a total of

26 cone penetrations to a 15-in. depth, with spacing of individual penetrations along the length of the bed set at 10 ft and locations across the width of the bed selected randomly.

46. Several indicators of the variability of C_s values were computed. For example, data points in Figure 7 represent values of average C_s in the 0- to 15-in. soil layer for individual penetrations made in the three measurement series within each of three test beds. For a given bed, the dashed line indicates the overall mean value of C_s from all penetrations, and the solid line connects adjacent average values of C_s (with each average obtained from three penetrations at a given distance along a given bed). The patterns of the three solid

Figure 7. Variation in cone index C_s along the length of three clay test beds (modified from Reference 7)

lines in the figure are fairly random relative to their corresponding means, both within a given test bed and among beds. For each bed, a range of approximately ± 30 percent of the overall mean includes all data points, indicating a fairly wide dispersion band for average C_s values and a sizable variation in C_s along a given soil bed.

47. In addition to the graphic description of C_s variation illustrated in Figure 7, numerical descriptions were also determined for three test beds as follows:

Test Bed (1)	Measurement Series (2)	Mean Cone Index C_s (3)	Variations of All Values of C_s		Variations of C_s with Depth	
			Standard Deviation		Avg Range of C_s (6)	Avg Range Mean (7)
			σ (4)	σ/Mean (5)		
I	1	182	29.2	0.16	107	0.59
	2	200	19.5	0.10	128	0.64
	3	200	21.6	0.11	120	0.60
	Average	194	23.4	0.12	118	0.61
II	1	88	7.4	0.09	30	0.34
	2	98	11.6	0.12	38	0.39
	3	84	11.6	0.14	28	0.33
	Average	90	10.2	0.12	32	0.35
III	1	102	12.0	0.12	36	0.35
	2	107	10.8	0.10	46	0.43
	3	108	14.3	0.13	40	0.37
	Average	106	12.4	0.12	41	0.38

Column 4 lists values of standard deviation (σ) of C_s for the three measurement series of a given bed and for the bed as a whole (the overall average σ value). Values of σ/mean in column 5 are reasonably stable, with an overall average value equal to 0.12 for each test bed.

48. A description of the variability of C_s with depth was obtained by:

- a. Determining the minimum and maximum values of C_s within the 0- to 15-in. soil layer for each cone penetration.
- b. Defining the difference between these two values as the "range."

- c. Computing the "average range" and the "average range/mean" for all C_s penetrations in a given measurement series or test bed (values listed in columns 6 and 7, respectively).

As indicated by the values in columns 6 and 7, variability of C_s values with depth was large.

49. The value of C_s used herein for a given tire test run is the 0- to 15-in. average value for all 26 penetrations made in that soil bed just before the tire run. The primary intent of paragraphs 45-48 was to demonstrate that, even with considerable efforts in soil preparation, rather large variations in values of C_s were obtained for a given test bed. These C_s variations undoubtedly caused much of the scatter in subsequent tire performance measurements for a given run.

50. After the test bed preparation was completed and appropriate checks on test instrumentation were made, the basic elements of a given test run were to load the 29x11-10, 8-PR tire, bring the speed of the dynamometer fixture quickly up to the desired value, maintain this speed nearly constant for a sizable portion of the 250-ft test bed length, and then decelerate quickly to zero velocity. Measurements of in-soil tire performance analyzed herein were those made during the near-constant-speed portion of a test run.

51. The 29x11-10, 8-PR tire was tested in two operating modes, free-rolling and braked-wheel. For both modes, the wheel was unpowered. Unfortunately, the brakes applied during the braked-wheel mode could not develop sufficient torque to fully lock the test wheel at speeds above approximately 40-50 knots. Thus, data in the braked-wheel mode were obtained under conditions that varied with speed--a fully locked condition for speeds up to about 40-50 knots and locked to some unknown level less than 100 percent for greater speeds.

52. Values of free-rolling wheel slip were also not reported because "equivalent forward velocities determined by the magnetic pickup and toothed gear differed by approximately 15 percent from the carriage velocities as determined by track timers," and because it was "assumed that a zero slip condition exists in the soil..." for the free-rolling mode.

53. The free-rolling mode is identical with the towed-wheel condition described in various WES reports,^{3,9,10} for which wheel slip is never zero, but rather takes a (generally small) negative value. It is not surprising that measured wheel theoretical velocity V_t should differ from measured wheel translational velocity V_w by as much as 15 percent.

54. The absence of reported slip data, however, does not present particular difficulties in analyzing tire performance (in terms of drag and rut depth) for the free-rolling test mode. Several successful studies have been made of in-soil pneumatic tire towed performance at slow speeds without reference to the slip values that prevailed.

55. On the other hand, full analysis of braked-wheel tire performance requires consideration of the associated slip values. Data from braked-wheel pneumatic tire tests conducted at slow speed have shown a strong dependence of tire performance on braked-wheel slip.¹⁵ It is unlikely that this dependence would not also be manifest in high-speed situations.

56. Average values of rut depth reported in Table 3 were determined from discrete measurements of before- and after-traffic soil profiles taken with a surveyor's rod and level at 10-ft intervals along the tire path. Attempts early in the program to record in-soil tire deflection and rut depth profile continuously were abandoned because there proved to be no suitable tire deflection gage available and because the associated bicycle wheel profilometer was demolished during early testing.

57. Continuous measurements were made during a given test run of vertical wheel load (W), horizontal drag force (D), and wheel translational velocity (V_w). Average values of these variables for a given test run are presented in Table 3. Although load W was applied by dead weight, sizable variations in measured W occurred during many test runs because of dynamically induced vertical oscillations of the tire. This was generally reflected in the records by large deviations between mean values of W and the nominally applied static load.

Speed-Adjusted Numeric Description
of Free-Rolling Tire Drag

The basic approach

58. One approach in describing the drag of a free-rolling tire in clay is to determine a well-defined relation between a dimensionless clay-tire numeric and drag ratio (D/W). In a study of aircraft tire drag developed at about 3 ft/sec in very nearly the same clay used in tests of the 29x11-10, 8-PR tire,¹⁶ drag ratio was found to be closely related to a variation on the basic clay-tire numeric* (N_{c1} or N_{c2}) thus far used, as follows:

$$N_{c3} = \frac{C_s b d}{W} \times \frac{1}{\left(1 - \frac{\delta}{h}\right)^2} \times \frac{1}{1 + \frac{b}{2d}} \quad (8)$$

59. To account for the effects of the broad range of speeds at which the 29x11-10, 8-PR tire was tested, numeric N_{c3} was rewritten as

$$N_{c3x} = \frac{C_x b d}{W} \times \frac{1}{\left(1 - \frac{\delta}{h}\right)^2} \times \frac{1}{1 + \frac{b}{2d}} \quad (9)$$

where

$$C_x = C_s \times \left(\frac{0.275 V_w / b}{V_s / \ell_s} \right)^{0.100} \quad (10)$$

That is, standard cone index C_s was changed to C_x by using the same technique that was demonstrated in Plate 1 and paragraphs 9-11 to

* Compared to clay-tire numerics N_{c1} and N_{c2} , N_{c3} has the advantage of describing tire performance better for very small values of tire deflection ratio δ/h . For δ/h values in the normal aircraft tire operating range (i.e., δ/h from 0.15 to 0.40), N_{c1}/N_{c3} varies only from 0.28 to 0.23. In addition, in the numeric used in Reference 16, soil strength was described by airfield index AI instead of standard cone index C_s . For the buckshot clay used in both Reference 16 and this study, C_s can be approximated from AI by $C_s = 50AI$.

normalize tire data to $V_w = 5.5$ ft/sec and thereby account for the effects on tire performance of viscouslike soil forces at wheel speeds up to 18 ft/sec. (Constants 0.275 and 0.16 resulted in Equations 10 and 2, respectively, because a tire of width $b = 10.71$ in. was considered in Equation 10 and tires of average width $b = 6.2$ in. were considered in Equation 2.)

Characteristics of the
D/W versus N_{c3x} relation

60. In Plate 6, drag ratio (D/W) data from all 11 of the in-soil test series conducted with the 29x11-10, 8-PR tire are plotted in logarithmic coordinates as a function of clay-tire numeric N_{c3x} (Equation 9). Each test run for a given test series was conducted at a different wheel translational velocity V_w in a soil bed prepared for that particular run. Values of load W , cone index C_s , and tire inflation pressure were maintained nominally at the same levels for each run of a given series. A rather large amount of data scatter is shown, but the curve defined by

$$D/W = 95.2N_{c3x}^{-2.50} \quad (11)$$

appears to describe the relation reasonably well.

61. Equation 11 can be taken, then, to provide at least a nominal means of describing in-soil tire drag. How sensitive this description is can be seen in Plate 7, which shows arithmetic plots of measured drag ratio versus wheel speed for 10 of the test series portrayed in Plate 6. (Test series 3 had only 3 test runs, and its data are not shown in Plate 7.) Curves of Equation 11 are also plotted, based upon the average value of N_{c3x} for each series. While soil strength, test load, and tire deflection were nominally constant for a given test series, the standard deviations of the mean values for N_{c3x} for all test runs in a series are of the order of 15 percent of the overall mean value for the series. This, plus the variations in soil strength (C_s) and test load, discussed in paragraphs 45-48 and 57, respectively, accounts for much of the data scatter.

62. Despite the scatter, for most of the test series in Plate 7, plotted data indicate that drag ratio at about 150 ft/sec decreased from its value at about 3 ft/sec. Each curve in this plate also shows a decrease in drag ratio with increasing wheel speed. It is clear, however, that the curves provide a less-than-satisfactory representation of the relation of drag ratio to speed.

63. Again, despite the scatter, the performance pattern in Plate 7 for most of the test series appears to be a decrease in drag ratio with increasing wheel speed to about 30 ft/sec, followed by an increase in drag ratio to about 70 ft/sec, and then a decrease again as wheel speed continues to increase. Clearly, a mathematical description whose only function of wheel speed is $V_w^{0.100}$ cannot follow such a complex pattern. A description that does follow this pattern is developed in the following paragraphs.

Modified Reynolds Number Description of Free-Rolling Tire Drag

Approach

64. In the speed-adjusted numeric account of tire drag discussed in the preceding paragraphs, changes in soil strength due to increasing wheel speed were taken as being entirely viscous in nature. For wheel speeds as fast as those in the 29x11-10, 8-PR tire tests, some investigators consider these changes to be strongly influenced by inertial effects (References 5 through 8, for example).

65. A technique borrowed from fluid mechanics was successfully used in References 2 and 17 to describe the combined influence of viscous and inertial effects on the soil lift force acting on rigid plates towed in near-fluid muds at speeds up to 90 ft/sec. This approach has been modified in the succeeding paragraphs to describe tire drag over a broad range of wheel speeds in clay.

66. The technique of interest involves two dimensionless terms, drag coefficient C_D = drag force/inertial force and Reynolds number N_R = inertial force/viscous force. For the free-rolling tire tests under consideration, drag force is to be predicted. Viscous force F_v is defined as

$$F_v = C_s \times \left(\frac{V_w/\ell}{V_s/\ell_s} \right)^{0.100} \times A \quad (12)$$

where $A = b \times r =$ a nominal projection of the clay-tire contact area, and $\ell = \sqrt{A}$. Inertial force F_i is $\rho A V_w^2 / 2$, where ρ is clay wet mass density.*

67. In a logarithmic plot of C_D versus N_R , the curve for a particular system material (soil) density and body (tire) geometry fixed can be divided into three ranges: a viscous range (viscous effects acting, inertial effects insignificant); a transition range (sizable viscous and inertial effects acting); and a dynamic range (inertial effects dominant). In the viscous range, the slope of the curve is -45 deg, i.e. negative 1:1, indicating that drag is directly proportional to viscous forces. In the dynamic range, the curve is practically flat, so C_D is a constant, i.e., drag is directly proportional to inertial forces only. The shape of the curve in the transition range depends on both the viscous and the inertial properties of the fluid.

68. Relations among C_D , body shape, and N_R have been developed by means of dimensional analysis in a number of studies reported in the literature (Reference 18, among many). One major result of these analyses is that immersed bodies of the same shape and alignment with the flow (i.e. models of each other) penetrating homogeneous fluids at subsonic speeds possess the same drag coefficient if their Reynolds numbers are the same.

Interpretation of 29x11-10, 8-PR tire test results

69. Use of measured rut depth in area A. One complication in using a C_D versus N_R relation to describe in-soil tire drag is that rut depth varies with wheel speed (Figure 8). This situation differs from the classic one in which the body of interest is immersed well below the surface of a homogeneous fluid, so that the projected body-fluid

* $\rho = \gamma_w / g$, where γ_w is clay unit wet weight and g is acceleration due to gravity.

Figure 8. Representative rut depth versus wheel speed relations for the 29x11-10, 8-PR tire in clay

contact area A used in computing viscous and inertial forces is a constant. To distinguish between the classic situation and the one of interest here (clay-tire contact area varying with wheel speed), modified clay-tire drag coefficient and Reynolds number will hereafter be designated C'_D and N'_R , respectively.

70. Data from free-rolling tests of the 29x11-10, 8-PR tire can be treated in a manner similar to the classic fluid mechanics approach by using for projected area A the quantity $b \times r$, where b = tire width and r = measured rut depth. That is, A was taken as a nominal rectangular area projected normal to the direction of travel, with width equal to the tire's width and variable depth equal to the tire's rut depth.

71. Using A as defined above, Plate 8 shows the logarithmic relation between C'_D and N'_R for the 29x11-10, 8-PR tire tests. This relation can be described by a straight line of negative 1:1 slope for N'_R values up to about 0.15, followed by a curved line whose slope decreases as N'_R continues to increase.* Even on logarithmic paper, however, scatter of the data is sizable, and the description of tire performance in this plate clearly needs improvement.

72. Use of predicted rut depth in area A . From a practical point of view, rut depths over a range of wheel speeds cannot be treated as known values in the prediction of tire drag, since these values are not known beforehand. Also, because the primary intent is to predict tire drag, and because the pattern of change of rut depth with wheel speed is similar to that of tire drag with speed (compare data trends in Figure 8 and in Plate 7), it is superfluous to develop a method for predicting rut depth for a range of wheel speeds.

73. A more accessible approach is to provide a means of predicting rut depth r' for slow wheel speed, and then define a constant projected area $A' = br'$ to be used in computing C'_D and N'_R for a

* Data for test series 16 and 17 could not be plotted in Plate 8 since values of measured rut depth r were reported only as near-zero (~ 0) for these series, so that nominal area $A = br \approx 0$; therefore, C'_D and N'_R could not be computed.

given soil-tire condition. Obviously, A' in the real world does not remain constant over a broad range of wheel speeds, other soil and tire conditions being constant. Use of A' as a constant has the advantages of making entry into the C'_D versus N'_R relation easy, and (as will be seen) causing the data that define the C'_D versus N'_R relation to show much less scatter than resulted from using variable area $A = br$ (paragraphs 70 and 71).*

74. In selecting slow wheel speed data from tests of the 29x11-10, 8-PR tire to develop a method for predicting tire rut depth, one consideration was that the data should exhibit a stable relationship of drag ratio (D/W) to rut depth coefficient (r/d). Plate 9 shows the relation of D/W to r/d for all the in-clay test runs of the 29x11-10, 8-PR tire.

75. Data from two types of slow-speed test runs are specially identified in Plate 9. The closed-symbol data represent "ST" or "sink and tow" tests in which a given run was made at a very slow speed (about 3 ft/sec) only after the tire had been maintained at a standstill and allowed to sink into the clay until a full deadweight load was applied. The flagged-symbol data identify "T" test runs, which were started with the tire on concrete, with wheel drag being measured as the tire was subsequently towed in clay at about 5 knots (8.45 ft/sec). (Test runs in Table 3 whose velocities are listed as 3 and 8.45 ft/sec are "ST" and "T" tests, respectively.)

76. In Plate 9, the "ST" data (closed symbols) lie consistently along the bottom edge of the scatter band defined by the other test data. On the other hand, the "T" data (flagged symbols) lie generally near the least-squares straight line defined by all the test data. Thus, the "T" test data were more stable than the "ST" data relative to the D/W versus r/d relation defined by test results covering the full range of in-soil 29x11-10, 8-PR wheel speeds tested.

* In the C'_D versus N'_R relation, variables A' , ℓ' , F'_i , and F'_v are computed in the same way as A , ℓ , F_i , and F_v except that the first four variables incorporate predicted slow-speed rut depth r' and the latter four use measured rut depth r .

77. Based on the above observation, the slow-speed test condition selected for defining r' was that of the "T" tests ($V_w = 8.45$ ft/sec). Using the "T" data, Plate 10 shows a log-linear relation between r'/d and clay-tire numeric N_{c3} , defined by

$$\frac{r'}{d} = 7.2N_{c3}^{-2.27} \quad (13)$$

Clay-tire numeric N_{c3} is used in Plate 10 and Equation 13 instead of velocity-adjusted numeric N_{c3x} primarily because it is easier to predict slow-speed r' (and subsequently $A' = br'$) from a relation that contains no velocity term. It is worthwhile to note, also, that Equation 13 is the same equation that was developed in Reference 16 to describe first-pass rut depth coefficient for slow-moving tires (after airfield index AI in Reference 16 was converted to C_s by the relation $C_s = 50AI$).

78. For each of the 11 free-rolling tire test series, single average values were used for W , C_s , and ρ . Rut depth r' was computed from Equation 13, using a value of N_{c3} computed with the average values of W and C_s . $A' = br'$ was then used as a constant for all test runs of a given series. Under these constraints, the clay-tire relation of drag coefficient C'_D to Reynolds number N'_R was determined (Plate 11).

79. The complete data set for all test series in Table 3 consists of measurements from 79 discrete tests; all 79 points are plotted in Plate 11. Of these, 16 lie at greater than ± 50 percent from the drag values represented by the solid line drawn through the points. The variation is not randomly distributed, however. Relative to the actual measured values of drag, the outliers in Plate 11 fall as follows:

<u>Measured Drag, lb</u>	<u>Total No. of Measurements</u>	<u>No. of Outliers</u>
<500	23	14
>500, <1000	26	1
>1000, <1500	20	0
>1500, <2000	5	1
>2000	5	0

The outliers thus seem to be associated with the extremes of the measurement range, and particularly with the low end of the range. This suggests that the greatest data scatter in Plate 11 is due, in part at least, to the test measurement and setup problems, which inevitably occur when a single apparatus is used over a wide range of loading conditions.

80. The remainder of the scatter, while great, is no more than might be expected in view of the variations in average values of cone index and load among the test runs in a series, and/or from the rather large variations in C_s values within a given bed (paragraphs 45-48 and 57).

81. The pragmatic test of the relation in Plate 11 is its ability to describe tire drag as a function of wheel speed for a broad range of tire, load, and soil conditions. In Plate 12, curves of drag ratio (D/W) versus wheel velocity, computed from the relation depicted in Plate 11, are plotted along with the basic data. As was done in Plate 7, a single curve is presented for each test series, using average values for W , C_s , ρ , and N_{c3} for each, with a corresponding constant value for A' . The curves in Plate 12 generally follow the drag ratio-versus-speed trends of the test data reasonably well, and much better than did the curves in Plate 7 (based only on the speed-adjusted numeric). The still great scatter appears, as already mentioned, due to the variations in wheel load, soil strength, etc., from the means used for the computations.

82. An interesting feature in Plates 11 and 12 is that the rather mild curvature of the C'_D versus N'_R logarithmic curve (Plate 11) becomes much more pronounced when the relation is expressed arithmetically in terms of drag ratio versus wheel speed (Plate 12). The shape of the C'_D versus N'_R curve in Plate 11 is unlike that obtained in conventional towing tests of a body within a homogeneous fluid and reflects the fact that actual soil-tire contact area at constant wheel load in a given clay test bed does not remain constant, but varies with wheel speed.

83 The modified C'_D versus N'_R relation in Plate 11 provides a reasonable tentative description of the combined influence of

viscouslike and inertial effects on the drag experienced by a free-rolling pneumatic tire operating at speeds to over 150 ft/sec in clay. To verify or improve this relation, data are needed from tests covering a broad range of tire conditions (sizes, shapes, ply ratings, inflation pressures, etc.), wheel loads and velocities, and soil strengths and types.

Tire Braked-Wheel Drag Performance

84. In Reference 15, data were analyzed from tests at WES of two pneumatic tires (a 4.00-7, 2-PR and a 9.00-14, 2-PR) conducted at slow wheel speed ($V_w \approx 5$ ft/sec) in several test beds of fat clay (C_s values from 17 to 39) over a range of braked-wheel slip values* (3.4 to 93.4 percent). For these test conditions, it was determined that numeric descriptions of drag ratio and rut depth coefficient strongly depend on the level of braked-wheel slip.

85. Because slip values were not reported for the braked-wheel tests of the 29x11-10, 8-PR tire, it was not possible to use the relations in Reference 15 as a starting point to describe in-soil tire drag at fast wheel speeds. A reexamination was made of the test data in Reference 15, however, and a nominal relation was obtained that has at least limited usefulness.

86. Plate 13a shows the relation between drag ratio and the rut depth coefficient for test data from Reference 15 with braked-wheel slip values in the 15 to 93 percent range.** (Data from Reference 15

* For the braked-wheel condition, wheel slip in percent can be defined as $1 - (V_t/V_w) \times 100$, where V_t = theoretical wheel velocity = $r_a \omega$; r_a is the tire active radius and equals $\frac{d - \delta}{2}$ (which closely approximates the rolling circumference $\div 2\pi$); ω is wheel angular velocity; and V_w = actual wheel translational velocity. By defining slip this way, a fully braked wheel (i.e. a locked wheel) operates at 100 percent positive slip.

** Data from 18 braked-wheel tests in clay are reported in Reference 15. Plate 13 represents data from all these tests except one (test 52) whose D/W versus r/d relation was markedly different from that of the other 17 tests.

at lower slip values showed smaller values of D/W at a given value of r/d). This range encompasses slip values for the moderately braked to almost fully braked condition for a tire operating in clay. Although data scatter in the plate is very large, a linear relation appears to describe the D/W versus r/d relation reasonably well. Thus, the relation of D/W to r/d for the braked condition considered appears to be defined well enough to allow this relation to be used in at least a limited way without consideration of the slip values that prevailed.

87. The dashed lines (95 percent confidence limits on D/W) in Plate 13a are superimposed in Plate 13b for the relation of D/W to r/d for data from braked-wheel tests of the 29x11-10, 8-PR tire (Table 4). Nineteen of the 23 data points in Plate 13b are included between these lines. The point that lies above the dashed lines was obtained in a test run whose reported average load was over 20 percent smaller than the average load during the free-rolling part of that run.

88. On balance, then, the relation

$$\frac{D}{W} = 0.46 + 3.67 \frac{r}{d} \quad (14)$$

obtained from slow-speed Reference 15 data in Plate 13a appears to over-predict slightly the D/W values obtained in braked-wheel tests of the 29x11-10, 8-PR tire at wheel speeds to 157 ft/sec (Plate 13b). This suggests that, with reasonable caution, Equation 14 can be used to predict D/W and, subsequently, tire drag if r/d is known for the particular tire-clay combination of interest at a given wheel speed in the 3- to 150-ft/sec range.

89. A major weakness that limits use of the technique described in paragraph 88 is that r/d must be measured for the tire-clay combination of concern.* Even with a measured value of r/d in hand, Equation 14 must be used with caution until tests over a broad range of tire, soil, load, and speed conditions verify the equation's accuracy.

* No "ST" tests and only two "T" tests with measured r/d values were included in the braked-wheel tests of the 29x11-10, 8-PR tire in Table 4. This paucity of slow-speed data disallowed establishment of a more refined technique to predict r/d specifically under braking conditions.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

90. The foregoing analysis leads to the general conclusions that pneumatic tire performance in fine-grained soils is affected by wheel speed; that these effects become noticeable at relatively small wheel speeds (say, less than 10 ft/sec); and that they generally become more and more important as wheel speed increases. Analysis herein of particular sets of data taken from the literature is considered adequate basis for the following tentative conclusions:

- a. The dimensionless prediction term N_{c1} (Equation 1) that was developed to describe dimensionless tire performance (pull/load, for example) at slow wheel speeds (5 to 6 ft/sec) can be used to describe tire performance at speeds up to at least 18 ft/sec by adjusting the values of the soil strength term (cone index C_s) to reflect viscouslike soil strength behavior caused by tire-soil interaction (paragraphs 6-11).
- b. Results from in-the-field speed tests of five prototype wheeled vehicles indicate that the same velocity-adjusted numeric as in a above (except that rating cone index, RCI, is used instead of cone index, C_s) is closely related to soil motion resistance coefficient R_s/W_v (paragraphs 12-29).
- c. For the 367-80 (707/KC-135 prototype) aircraft mounted on 46x16 tires and operated at full throttle and a 20-deg flap setting, clay-tire numeric N_{c0} (Equation 7) is closely related to the percent increase in takeoff distance required on clay runways as compared to that on a paved runway (paragraphs 30-35).
- d. Alternative clay-tire numeric N_{c3} (Equation 8), which was determined in Reference 16 to be closely related to tire drag ratio (D/W) and rut depth coefficient (r/d) for free-rolling tire tests at slow wheel speed (about 3 ft/sec), cannot be adjusted to describe drag ratio at wheel speeds to about 150 ft/sec by considering only viscouslike changes in soil strength (paragraphs 58-63).
- e. A relation between dimensionless terms, drag coefficient C_D and Reynolds number N_R , which was modified from fluid mechanics to fit the clay-tire situation, can be used to describe free-rolling tire drag under the combined influence of viscouslike and inertial changes in

soil strength caused by wheel speed to about 150 ft/sec. Ease of use and precision in description of the C_D' versus N_R' relation both increase if clay-tire nominal projected contact area A' , included in both C_D' and N_R' , is taken as a (predicted) constant instead of a variable (paragraphs 64-83).

- f. For the braked-wheel condition, a simple approach to predict tire drag ratio at wheel speeds to about 150 ft/sec is to measure rut depth for the low-speed condition and then use Equation 14 $[D/W = 0.46 + 3.67 (r/d)]$ (paragraphs 84-89).

Recommendations

91. It is recommended that:

- a. Tests similar to those examined from the literature in this report be conducted in a coordinated program over a much broader range of values of each variable that influences a given relation mentioned in tentative conclusions a through f above, so that results of these new tests can be used to extend or improve these relations.
- b. For those tentative conclusions above that are based on results from single-wheel tire tests (a and d-f), similar tests can be conducted with prototype wheeled vehicles (a) or aircraft (d-f) to determine what modifications, if any, are needed to extrapolate from the single tire to the prototype vehicle situation.

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Table 1
Speed Performance Tests of Two Military and Two MEXA 2-1/2-Ton Wheeled
Vehicles in Clay and on Pavement

Vehicle	Vehicle Weight lb		Tire Size	Nominal Tire Width* in.	Nominal Tire Diameter* in.	Tire Inflation Pressure psi	Tire Deflec- tion Ratio δ/h	Brake Horse- Power	Full Throttle Effi- ciency** e _f	Item No.	Site Location	No.	Maximum Vehicle Speed V _v mph	0-6 in. Cone Index C _s	0-6 in. Remolding Index RI	0-6 in. RCI	Tractive Force Coefficient†	Soil Motion Resistance Coefficient††	Velocity- Adjusted Clay-Tire Numeric N _{c2x} ‡				
	Total W _v	Average per Wheel W																					
XM40E1	16,504	2063	14.00-18, 6-PR	14	40	12.2	0.25	154	0.78	152	Carson Sink	3	12.1	34	0.71	24	0.226	0.163	3.11				
						↓	↓																
M35A2 (mod)	18,225	3038	11.00-20, 12-PR	11	42	20.1	0.25	220	0.82	156	Carson Sink	2	8.2	46	0.77	35	0.453	0.359	2.54				
						↓	↓																
MEXA 10x10	18,030	1803	42x40-16A, 4-PR	40	42	7.3	0.20	214	0.70	167	Four Mile Flat	6	7.6	21	0.52	11	0.410	0.261	3.34				
						↓	↓																
MEXA 8x8	19,013	2377	48x31-16A, 4-PR	31	48	9.0	0.20	214	0.75	177	Four Mile Flat	6	4.9	19	0.63	12	0.646	0.503	2.61				
						↓	↓																

* Nominal tire width and diameter are used for b and d, respectively, in velocity-adjusted clay-tire numeric N_{c2x}.

** Estimated from data in Reference 13.

† Tractive force coefficient $F_t/W_v = \frac{375 \times \text{HP} \times e_f}{V_v \times W_v}$, either in soil or on pavement.

†† Soil motion resistance $R_s/W_v = (F_t/W_v)_{\text{soil}} - (F_t/W_v)_{\text{pavement}}$. For the XM40E1, estimated $(F_t/W_v)_{\text{pavement}} = 0.063$.

‡ Velocity-adjusted clay-tire numeric $N_{c2x} = \frac{(RCI)_x \times b \times d}{W} \times \left(\frac{\delta}{h}\right)^{1/2} \times \frac{1}{1 + \frac{b}{2d}}$, where $(RCI)_x = RCI \times \left(\frac{kV_v/b}{V_s/\delta_s}\right)^{0.100}$.

‡‡ P stands for pavement.

Table 2
Speed Performance Tests of 4x4 "Mudder" Test Bed in Clay and on Pavement

Vehicle	Vehicle Weight		Tire Width b in.	Tire Diameter d in.	Tire Inflation Pressure psi	Tire Deflec- tion Ratio s/h	Brake Horse- power	Full Throttle Effi- ciency* e _f	Test No.	Site		Maximum Vehicle Speed V _v mph	0-6 in. Cone Index C _s	0-6 in. Remolding Index RI	0-6 in. RCI	Tractive Force Coefficient**	Soil Motion Resistance Coefficient†	Velocity- Adjusted Clay-Time Numeric N _{c2x} ††	
	Total W _v	Average per Wheel W								Location	No.								
4x4 "Mudder" Test Bed	4840	1210	46x18-16R, 4-PR	19.6	46.3	3.0	0.15	140	0.86	1	Four Mile Flat	6	40.0	--	--	Pavement	0.233	--	--
										2			36.3	73	0.93	68	0.257	0.024	20.46
										3			37.1	81	0.92	75	0.251	0.018	22.62
										4			28.0	19	0.59	11	0.333	0.100	3.23
										5			27.7	19	0.59	11	0.337	0.104	3.23
										6			0†	14	0.44	6	--	--	--
										7			0	11	0.46	5	--	--	--
										8			18.7	15	0.59	9	0.499	0.266	2.54
										9			0	10	0.68	7	--	--	--
										10			25.5††	23	0.61	14	0.366	0.133	4.07
										11			26.1††	23	0.61	14	0.357	0.124	4.08
										12			21.4	14	0.66	9	0.436	0.203	2.57
										13			30.8	23	0.61	14	0.303	0.070	4.15
										14			30.2	23	0.61	14	0.309	0.076	4.14

* Estimated from data in Reference 13.

** Tractive force coefficient $F_t/W_v = \frac{375 \times HP \times e_f}{V_v \times W_v}$, either in soil or on pavement.

† Soil motion resistance $R_s/W_v = (F_t/W_v)_{\text{soil}} - (F_t/W_v)_{\text{pavement}}$.

†† Velocity-adjusted clay-tire numeric $N_{c2x} = \frac{(RCI)_x^{bd}}{W} \times \left(\frac{s}{h}\right)^{1/2} \times \frac{1}{1 + \frac{b}{2d}}$, where $(RCI)_x = RCI \times \left(\frac{kV_v/b}{V_s/l_s}\right)^{0.100}$.

‡ Entries of 0 for maximum speed indicate that the test vehicle became immobilized.

†† Test bed was still accelerating at end of test run. Data for these tests are not plotted in Plates 2 and 3.

Table 3
Free-Rolling Speed Tests of the 20x11-10, 8-PR Tire in Buckshot Clay

Test Series	Wheel Velocity V_w ft/sec	Cone Index C_s	Clay Wet Mass Density ρ lb-sec ² /ft ⁴	Wheel Load W lb	Tire Width b in.	Tire Diameter d in.	Tire Section Height h in.	Tire Inflation Pressure p_{si}	Tire Deflection Ratio δ/h	Measured Drag Force D lb	Drag Ratio D/W	Measured Rut Depth r in.	Rut Depth Ratio r/d	Clay-Tire Numeric N_{c3}	Clay-Tire Numeric N_{c3x}	Area $A = br$ ft ²	Inertial Force $F_i = \rho A V_w^2 / 2$ lb	Drag Coefficient $C_D = D/F_i$	Viscous Force $F_v = C_s \times \left(\frac{V_w}{V_s} \sqrt{\frac{A}{A'}} \right)^{0.100}$ $\times A', \text{ lb}$	Clay-Tire Reynolds Number $N_R = F_i/F_v$	Predicted Rut Depth $r' \dagger \dagger$ in.	Predicted Area $A' = br' \dagger \dagger$ ft ²	Inertial Force $F_i = \rho A' V_w^2 / 2$ lb	Drag Coefficient $C_D' = D/F_i$	Viscous Force $F_v = C_s \times \left(\frac{V_w}{V_s} \sqrt{\frac{A'}{A}} \right)^{0.100}$ $\times A', \text{ lb}$	Clay-Tire Reynolds Number $N_R' = F_i'/F_v'$	
1	#3	84	3.490	5600	10.71	28.65	9.32	30	0.402	1013	0.181	1.32	0.046	10.8	10.2	0.0982	1.54	658	1410	0.00109			1.15	881	1060	0.00108	
	#8.45	85	3.491	5918					0.420	1186	0.200	1.16	0.040	11.0	11.5	0.0863	10.8	110	1400	0.00771			9.15	130	1140	0.00803	
	37.2	75	3.475	5819					0.413	700	0.120	0.63	0.022	9.67	11.7	0.0469	113	6.19	803	0.141			177	3.95	1330	0.133	
	59.1	75	3.475	5879					0.418	883	0.150	0.62	0.022	9.74	12.3	0.0461	280	3.15	830	0.337			448	1.97	1390	0.322	
	83.9	83	3.487	5779					0.410	1211	0.210	0.78	0.027	10.7	14.0	0.0580	712	1.70	1180	0.603			902	1.34	1440	0.626	
	108	86	3.492	5846					0.418	990	0.169	0.45	0.016	11.2	15.1	0.0335	682	1.45	742	0.919			1500	0.660	1490	1.26	
	121	81	3.484	6243					0.440	865	0.139	0.39	0.014	10.7	14.6	0.0290	740	1.17	618	1.20			1880	0.460	1490	1.26	
	139	86	3.492	5919					0.420	801	0.135	0.41	0.014	11.2	15.5	0.0305	1030	0.778	698	1.48			2480	0.323	1520	1.63	
	154	80	3.483	5605					0.402	816	0.146	0.29	0.010	10.3	14.4	0.0216	892	0.915	472	1.89			3040	0.268	1530	1.99	
	152	71	3.466	5679					0.408	821	0.145	0.52	0.018	9.22	12.8	0.0387	1550	0.530	730	2.12			2960	0.277	1530	1.93	
	Avg	80.6	3.484	5829										10.5							0.99	0.0736	1.73	1260	1580	0.00109	
2	3	84	3.490	5744	10.71	28.65	9.32	45	0.343	2173	0.378	2.90	0.101	8.76	8.24	0.216	3.39	641	2980	0.00114			1.73	1260	1580	0.00109	
	8.45	76	3.477	6151					0.364	1520	0.247	1.57	0.055	7.90	8.25	0.117	14.5	105	1660	0.00873			13.7	111	1760	0.00778	
	35.8	81	3.484	5969					0.354	1318	0.221	1.18	0.041	8.41	10.1	0.0878	196	6.72	1570	0.125			246	5.36	2030	0.121	
	54.6	81	3.484	5761					0.344	1489	0.258	1.31	0.046	8.45	10.6	0.0974	506	2.94	1810	0.280			572	2.60	2120	0.270	
	73.5	89	3.497	6700					0.388	1200	0.179	1.65	0.058	9.17	11.9	0.123	1160	1.03	2540	0.457			1040	1.15	2180	0.477	
	103	76	3.477	6181					0.364	1370	0.222	1.19	0.041	7.86	10.5	0.0885	1630	0.840	1640	0.994			2040	0.672	2250	0.907	
	140	96	3.507	5856					0.352	907	0.155	0.74	0.026	10.1	14.0	0.0550	1890	0.480	1370	1.36			3760	0.241	2330	1.61	
	157	93	3.503	6115					0.362	822	0.134	0.43	0.015	9.66	13.5	0.0320	1380	0.596	801	1.73			4730	0.174	2350	2.01	
		Avg	84.5	3.489	6060										8.79							1.48	0.110	2.57	872	2150	0.00119
	3	84	3.490	5830	10.71	28.65	9.32	55	0.314	2340	0.384	3.09	0.108	7.92	7.45	0.230	3.61	620	3180	0.00114			1.31	1180	3120	1.34	
121	78	3.479	6516					0.347	1309	0.201	1.21	0.042	7.26	9.89	0.0900	2290	0.572	1750	1.31			6590	0.156	3200	2.06		
152	74	3.473	6138					0.329	1029	0.168	1.18	0.041	6.92	9.64	0.0878	3520	0.292	1660	2.12								
	Avg	78.7	3.481	6161										7.37							2.21	0.164	2.82	801	2630	0.00107	
4	3	84	3.490	5675	10.71	28.65	9.32	70	0.256	2260	0.398	2.91	0.102	6.91	6.50	0.216	3.39	667	2990	0.00113			2.82	801	2630	0.00107	
	34.5	90	3.499	5996					0.267	1875	0.313	1.99	0.059	7.22	8.67	0.148	308	6.09	2860	0.108			373	5.03	3380	0.110	
	54.7	90	3.499	6308					0.279	2649	0.420	2.24	0.078	7.10	8.93	0.167	874	3.03	3340	0.254			937	2.83	3540	0.265	
	105	89	3.497	8100					0.337	2075	0.256	1.72	0.050	6.46	8.67	0.128	2470	0.840	2750	0.898			3450	0.601	3770	0.915	
	139	91	3.500	5350					0.247	1680	0.314	1.20	0.042	7.76	10.7	0.0893	3020	0.556	2060	1.47			6050	0.278	3870	1.56	
	154	89	3.497	5937					0.266	1147	0.193	1.33	0.046	7.19	10.0	0.0989	4100	0.280	2240	1.83			7420	0.155	3920	1.89	
		Avg	88.8	3.497	6228										7.11							2.40	0.179				
	3	114	3.530	5200	10.71	28.65	9.32	30	0.378	175	0.034	0.48	0.017	14.6	13.7	0.0357	0.567	309	735	0.000771			0.567	309	725	0.000782	
	8.45	128	3.546	5482					0.396	355	0.065	0.44	0.015	16.5	17.2	0.0327	4.14	85.7	839	0.00493			4.50	78.9	802	0.00561	
	32.9	116	3.531	5625					0.406	467	0.083	0.24	0.008	15.1	18.1	0.0179	34.2	13.7	492	0.0695			68.2	6.85	920	0.0741	
56.8	112	3.528	5695					0.408	506	0.089	0.16	0.006	14.5	18.3	0.0119	67.7	7.47	341	0.199			203	2.49	972	0.209		
79.0	110	3.526	5613					0.406	482	0.086	0.29	0.010	14.4	18.8	0.0216	238	2.03	610	0.390			393	1.23	1000	0.393		
102	111	3.528	5350					0.386	400	0.075	0.24	0.008	14.2	19.0	0.0179	329	1.22	526	0.625			655	0.611	1030	0.636		
135	106	3.521	5540					0.397	250	0.045	0.12	0.004	13.6	18.7	0.00893	287	0.871	267	1.07			1150	0.217	1060	1.08		
149	102	3.516	5125					0.374	425	0.083	0.08	0.003	13.1	18.2	0.00595	232	1.83	177	1.31			1400	0.304	1070	1.31		
	Avg	112.4	3.528	5454										14.5							0.48	0.0357	0.779	963	990	0.000866	
6	3	114	3.530	5300	10.71	28.65	9.32	45	0.322	750	0.142	1.50	0.052	12.1	11.4	0.112	1.78	421	2180	0.000817			0.779	963	990	0.000866	
	8.45	128	3.546	5481					0.333	400	0.073	0.32	0.011	13.6	14.2	0.0238	3.01	133	620	0.00485			6.18	64.7	1100	0.00562	
	32.6	116	3.531	5446					0.333	388	0.071	0.56	0.020	12.4	14.8	0.0417	78.2	4.96	1100	0.0711			92.0	4.22	1260	0.0730	
	40.2	117	3.532	5449					0.333	779	0.143	0.72	0.025	12.5	15.2	0.0536	153	5.									

(Continued)

$$* N_{c3} = \frac{C_s b d}{W} \times \frac{1}{\left(1 - \frac{\delta}{h}\right)^2} \times \frac{1}{1 + \frac{b}{2d}}$$

$$** N_{c3x} = N_{c3} \times \left(\frac{0.275 V_w / b}{V_s / l_s} \right)^{0.100}, \text{ where } V_s = 0.1 \text{ ft/sec and } l_s = \sqrt{0.50 \text{ in.}^2} = 0.707 \text{ in.} = 0.0589 \text{ ft.}$$

† Areas A and A' are nominal projected clay-tire contact areas.

†† Predicted rut depth $r' = d \times 7.2 \left(\text{avg } N_{c3} \right)^{-2.27}$

* All test runs with wheel velocities of 3 and 8.45 ft/sec are "ST" and "T" test runs, respectively, as described in paragraph 75.

Table 3 (Concluded)

Test Series	Wheel Velocity V_w ft/sec	Cone Index C_s	Clay Wet Mass Density ρ lb-sec ² /ft ⁴	Wheel Load W lb	Tire Width b in.	Tire Diameter d in.	Tire Section Height h in.	Tire Inflation Pressure psi	Tire Deflection Ratio δ/h	Measured Drag Force D lb	Drag Ratio D/W	Measured Rut Depth r in.	Rut Depth Ratio r/d	Clay-Tire Numeric N_{c3}	Clay-Tire Numeric N_{c3x}	Area $A = br$ ft ²	Inertial Force $F_i = \rho A V_w^2 / 2$ lb	Drag Coefficient $C'_D = D/F'_i$	Viscous Force $F'_v = C_s \times \left(\frac{V_w \sqrt{A}}{V_s / k_s} \right)^{0.100} \times A, \text{ lb}$	Clay-Tire Reynolds Number $N_R = F_i / F'_v$	Predicted Rut Depth r' in.	Predicted Area $A' = br'$ ft ²	Inertial Force $F'_i = \rho A' V_w^2 / 2$ lb	Drag Coefficient $C'_D = D/F'_i$	Viscous Force $F'_v = C_s \times \left(\frac{V_w \sqrt{A'}}{V_s / k_s} \right)^{0.100} \times A', \text{ lb}$	Clay-Tire Reynolds Number $N'_R = F'_i / F'_v$
8	3	91	3.500	4380	10.71	28.65	9.32	70	0.214	1360	0.311	2.04	0.071	8.69	8.18	0.152	2.39	569	2320	0.00103			1.72	791	1670	0.00103
	8.45	91	3.500	4260					0.212	1340	0.315	1.32	0.046	8.89	9.28	0.0982	12.3	109	1700	0.00724			13.6	98.5	1850	0.00735
	35.5	90	3.499	4220					0.210	1320	0.313	1.62	0.056	8.83	10.6	0.120	265	4.98	2350	0.113			240	5.50	2130	0.113
	46.1	87	3.493	4080					0.204	1400	0.343	1.65	0.058	8.70	10.8	0.123	457	3.06	2370	0.193			405	3.46	2190	0.185
	73.5	89	3.497	4350					0.225	1760	0.405	1.67	0.058	8.81	11.4	0.124	1170	1.50	2570	0.455			1030	1.71	2300	0.448
	106	91	3.500	4200					0.209	1060	0.252	1.18	0.041	8.95	12.0	0.0878	1730	0.613	1960	0.883			2140	0.495	2380	0.899
	132	91	3.500	4320					0.214	880	0.240	1.20	0.042	8.81	12.1	0.0893	2720	0.324	2040	1.33			3320	0.265	2440	1.36
	147	91	3.500	4050					0.204	760	0.188	1.04	0.036	9.17	12.7	0.0774	2930	0.259	1810	1.62			4120	0.184	2460	1.67
Avg	90.1	3.499	4233											8.86							1.46	0.109				
9	3	114	3.530	2650	10.71	28.65	9.32	70	0.144	400	0.151	1.02	0.036	15.2	14.3	0.0759	1.21	331	1500	0.000807			0.390	1030	534	0.000730
	8.45	124	3.542	2512					0.138	435	0.173	0.64	0.022	17.2	21.3	0.0476	6.02	72.3	1170	0.00515			3.09	141	594	0.00520
	38.3	124	3.542	2500					0.137	420	0.168	0.76	0.027	17.2	20.9	0.0565	147	2.86	1590	0.0925			63.5	6.61	721	0.0881
	72.5	120	3.537	2473					0.136	548	0.222	0.36	0.013	16.8	21.7	0.0268	249	2.20	807	0.309			228	2.40	735	0.310
	99.0	107	3.523	2000					0.113	520	0.260	0.27	0.009	17.6	23.5	0.0201	347	1.50	564	0.615			424	1.23	760	0.558
	137	119	3.535	2470					0.136	428	0.173	0.18	0.006	16.7	23.0	0.0134	445	0.962	442	1.01			813	0.526	785	1.04
	157	123	3.541	2313					0.129	375	0.162	0.28	0.010	18.1	25.3	0.0208	908	0.413	704	1.29			1070	0.350	795	1.35
	Avg	118.7	3.536	2417										17.0							0.33	0.0245				
16	8.45	200	3.602	5420	10.71	28.65	9.32	45	0.332	140	0.026	~0	~0	21.4	22.3	--	--	--	--	--			1.81	77.3	592	0.000306
	75.8	200	3.602	5348					0.323	204	0.038	~0	~0	21.1	27.4	--	--	--	--	--			146	1.40	737	0.198
	96.1	200	3.602	5577					0.334	261	0.047	~0	~0	20.9	27.8	--	--	--	--	--			235	1.11	755	0.311
	112	200	3.602	5494					0.333	117	0.021	~0	~0	21.2	28.7	--	--	--	--	--			319	0.367	765	0.417
	153	200	3.602	3881					0.255	279	0.072	~0	~0	24.0	33.5	--	--	--	--	--			595	0.469	790	0.753
	Avg	200	3.602	5144										21.7							0.19	0.0141				
17	8.45	200	3.602	8900	10.71	28.65	9.32	70	0.364	1510	0.170	~0	~0	14.4	15.0	--	--	--	--	--			3.64	415	1130	0.00322
	102	200	3.602	5459					0.250	461	0.084	~0	~0	16.8	22.5	--	--	--	--	--			530	0.870	1450	0.366
	129	189	3.592	5285					0.246	608	0.115	~0	~0	16.3	22.3	--	--	--	--	--			847	0.718	1480	0.572
	154	200	3.602	5601					0.255	597	0.107	~0	~0	16.6	23.2	--	--	--	--	--			1210	0.493	1510	0.801
	Avg	197.3	3.600	6311										16.0							0.38	0.0283				

Table 4

Braked-Wheel Speed Tests of the 29x11-10, 8-PR Tire in Buckshot Clay

Test Series	Tire Inflation Pressure psi	Cone Index C _s	Wheel Load W lb	Measured Drag Force D lb	Drag Ratio D/W	Measured Rut Depth r in.	Rut Depth Coefficient r/d	Wheel Velocity V _w ft/sec
1	30	85	6166	4143	0.672	2.08	0.073	8.45*
		83	7020	3488	0.497	1.39	0.048	83.9
		86	6466	2976	0.460	0.72	0.025	108
		86	6315	2396	0.379	0.42	0.015	139
		80	6003	2544	0.424	0.46	0.016	154
2	45	76	6201	4045	0.652	2.32	0.081	8.45
		89	4900	3700	0.755	2.94	0.102	73.5
		76	6131	2775	0.452	2.27	0.079	103
		96	6389	2754	0.431	0.92	0.032	140
		93	6339	2466	0.389	0.83	0.029	157
4	70	89	7000	3150	0.450	2.12	0.074	105
		91	5500	2710	0.493	1.44	0.050	139
		89	5965	2497	0.419	1.59	0.055	154
5	30	112	4839	2574	0.532	0.35	0.012	56.8
		110	5280	2128	0.403	0.36	0.013	79.0
		111	4900	1950	0.398	0.12	0.034	102
		106	6500	2100	0.323	0.24	0.008	135
		102	5150	2300	0.447	0.24	0.008	149
6	45	109	4599	3075	0.669	0.85	0.030	73.8
		101	3951	3292	0.833	1.30	0.045	103
		108	5506	2429	0.441	0.54	0.019	131
		106	4860	2625	0.540	0.42	0.015	153
7	70	120	4389	3443	0.784	**	--	71.3
		111	3747	3527	0.941	1.83	0.064	100
16	45	200	4828	3566	0.738	--	--	8.45
		200	4945	2073	0.419	--	--	75.8
		200	5006	2411	0.482	--	--	96.1
		200	5047	1977	0.392	--	--	112
		200	5150	2009	0.390	--	--	153

* Test runs with velocity = 8.45 ft/sec are "T" test runs, as described in paragraph 75.

** No values of rut depth were reported for one run of test series 7 or for any of test series 16 in References 7 or 8.

LEGEND

V_w , FT/SEC	
0.5	○
1.25	□
2	△
5	◇
9	◊
13	◈
18	◉

NOTE: OPEN SYMBOLS: 9.00-14, 2-PR TIRE
CLOSED SYMBOLS: 4.00-7, 2-PR TIRE

USE OF VELOCITY ADJUSTMENT TO ACCOUNT FOR THE EFFECTS ON TIRE PULL PERFORMANCE OF VISCOUSLIKE SOIL STRENGTH BEHAVIOR

TIRE DEFLECTION RATIO, $\delta/h = 0.25$
38- TO 1848-LB WHEEL LOADS, $C_s = 16$ TO 50
20 PERCENT SLIP
FAT CLAY

LEGEND

<u>VEHICLE</u>	<u>TIRE SIZE</u>
● XM410E1	14.00-18, 6-PR
▲ M35A2 (MOD)	11.00-20, 12-PR
□ MEXA 10x10	42x40-16A, 4-PR
○ MEXA 8x8	48x31-16A, 4-PR
◇ 4x4 "MUDDER"	46x18-16R, 4-PR

COMPARISON OF MAXIMUM VEHICLE SPEED
VERSUS 0- TO 6-IN. RCI FOR FIVE WHEELED
VEHICLES IN CLAY

a.

b.

LEGEND

VEHICLE	TIRE SIZE
● XM410E1	14.00-18, 6-PR
▲ M35A2 (MOD)	11.00-20, 12-PR
□ MEXA 10x10	41x40-16A, 4-PR
○ MEXA 8x8	48x31-16A, 4-PR
◇ 4x4 "MUDDER"	46x18-16R, 4-PR

RELATIONS OF MOTION RESISTANCE COEFFICIENT
TO CLAY-TIRE NUMERICS, N_{c2} AND N_{c2x}

FIVE WHEELED VEHICLES
FIELD TESTS IN CLAY

NOTE: NOMINAL AIRCRAFT WHEEL LOAD
EQUALS AIRCRAFT GROSS WEIGHT
DIVIDED BY THE NUMBER OF
AIRCRAFT WHEELS.

PERCENT INCREASE IN TAKEOFF DISTANCE
OF 367-80 AIRCRAFT ON CLAY SOIL
(MODIFIED FROM REFERENCE 6)

NOTE: $N_{c0} = \frac{C_s b d}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2}$

20-DEG FLAPS, MAXIMUM AVAILABLE THRUST USED
30- AND 80-PSI TIRE INFLATION PRESSURES
AIRPLANE GROSS WEIGHTS OF 120,000 TO 180,000 LB

RELATIONS OF PERCENT INCREASE IN TAKEOFF
DISTANCE AND SLOW-SPEED DRAG RATIO TO
CLAY-TIRE NUMERIC N_{c0}

367-80 AIRCRAFT WITH 46x16 TIRES
CLAY SOIL, CONE INDEXES OF 80 TO 400

NOTE: $N_{c3x} = \frac{C_x b d}{W} \cdot \left(\frac{1}{1 - \frac{\delta}{h}} \right)^2 \cdot \frac{1}{1 + \frac{b}{2d}}$

WHERE

$$C_x = C_s \cdot \left(\frac{0.275 V_w / b}{V_s / \ell_s} \right)^{0.100}$$

LOGARITHMIC RELATION OF DRAG RATIO TO
VELOCITY-ADJUSTED CLAY-TIRE NUMERIC
 N_{c3x} FOR FREE-ROLLING TESTS OF THE
29x11-10, 8-PR AIRCRAFT TIRE

WHEEL SPEEDS FROM 3 TO 157 FT/SEC

NOTE: EACH CURVE IS DESCRIBED BY THE EQUATION
 $D/W = 95.2 (N_{c3x})^{-2.50}$, WHERE

$$N_{c3x} = \frac{C_x b d}{W} \cdot \frac{1}{(1 - \delta/h)^2} \cdot \frac{1}{1 + \frac{b}{2d}} \cdot \left(\frac{0.275 V_w/b}{V_s/\ell_s} \right)^{0.10}$$

AND AVERAGE VALUES OF C_s AND W WERE USED
 FOR EACH TEST SERIES.

LEGEND

CURVE	SYMBOL	TEST SERIES	INFLATION PRESSURE PSI	RANGE OF AVG LOADS LB	RANGE OF AVG CONE INDEXES
—○—	○	1	30	5600-6243	71-86
---△---	△	2	45	5744-6700	76-96
---□---	□	4	70	5350-8100	84-91
—○—	○	5	30	5125-5695	102-128
---△---	△	6	45	2512-5492	101-128
---□---	□	7	70	5117-5607	106-120
—○—	○	8	70	4050-4390	87-91
---△---	△	9	70	2000-2650	107-124
---□---	□	16	45	3881-5577	ALL REPORTED AS 200
---X---	⊗	17	70	5285-8900	189-200

DESCRIPTION OF DRAG RATIO VERSUS WHEEL VELOCITY BY
 CURVES BASED ON VELOCITY-ADJUSTED CLAY-TIRE NUMERIC, N_{c3x}

29X11-10, 8-PR AIRCRAFT TIRE
 FREE-ROLLING TESTS IN CLAY

RELATION OF DRAG COEFFICIENT C'_D
 TO REYNOLDS NUMBER N'_R , MODIFIED
 TO DESCRIBE CLAY-TIRE INTERACTIONS

VARIABLE AREA A IN C'_D AND N'_R BASED ON
 MEASURED RUT DEPTH AT GIVEN WHEEL SPEED

29x11-10, 8-PR AIRCRAFT TIRE

FREE-ROLLING TESTS IN CLAY

NOTES: CLOSED SYMBOLS: "ST" TEST RUNS (WHEEL SPEED = 3 FT/SEC)
 FLAGGED SYMBOLS: "T" TEST RUNS (WHEEL SPEED = 8.45 FT/SEC)
 OPEN SYMBOLS: TEST RUNS AT WHEEL SPEEDS UP TO 157 FT/SEC

RELATION OF DRAG RATIO TO RUT DEPTH COEFFICIENT FOR FREE-ROLLING TESTS IN CLAY

29x11-10, 8-PR AIRCRAFT TIRE
 WHEEL LOADS FROM 2000 TO 8100 LB
 WHEEL SPEEDS FROM 3 TO 157 FT/SEC
 CONE INDEX FROM 71 TO 200

NOTES: TEST SERIES 3 HAD NO "T" TEST RUN REPORTED, AND TEST SERIES 16 AND 17 HAD ONLY NEAR-ZERO RUT DEPTHS.

ONLY DATA FOR "T" TEST RUNS ARE PLOTTED. (SEE PARAGRAPH 75 FOR A DESCRIPTION OF "T" TEST RUNS.)

$$N_{c3} = \frac{C_s b d}{W} \cdot \frac{1}{\left(1 - \frac{\delta}{h}\right)^2} \cdot \frac{1}{1 + \frac{b}{2d}}$$

LOGARITHMIC RELATION OF RUT DEPTH COEFFICIENT TO CLAY-TIRE NUMERIC N_{c3} FOR FREE-ROLLING TESTS IN CLAY

29x11-10, 8-PR AIRCRAFT TIRE
8 "T" TEST RUNS AT WHEEL SPEED = 8.45 FT/SEC

RELATION OF DRAG COEFFICIENT C_D'
 TO REYNOLDS NUMBER N_R' , MODIFIED
 TO DESCRIBE CLAY-TIRE INTERACTIONS

AREA A' IN C_D' AND N_R' BASED ON
 PREDICTED RUT DEPTH AT LOW WHEEL SPEED

29×11-10, 8-PR AIRCRAFT TIRE

FREE-ROLLING TESTS IN CLAY

NOTE: EACH CURVE IS DESCRIBED BY THE C_D^1 VERSUS N_R^1 CURVE IN PLATE 11, TOGETHER WITH AVERAGE VALUES OF W , C_s , ρ , AND N_{c3x} FOR A GIVEN TEST SERIES.

LEGEND					
CURVE	SYMBOL	TEST SERIES	INFLATION PRESSURE PSI	RANGE OF AVG LOADS LB	RANGE OF AVG CONE INDEXES
—○—	○	1	30	5600-6243	71-86
—△—	△	2	45	5744-6700	76-96
—□—	□	4	70	5350-8100	84-91
—○—	○	5	30	5125-5695	102-128
—△—	△	6	45	2512-5492	101-128
—□—	□	7	70	5117-5607	106-128
—○—	○	8	70	4050-4380	87-91
—△—	△	9	70	2000-2650	107-124
—□—	□	16	45	3881-5577	ALL REPORTED AS 200
—X—	⊗	17	70	5285-8900	189-200

DESCRIPTION OF DRAG RATIO VERSUS WHEEL VELOCITY BY CURVES BASED ON THE C_D VERSUS N_R^1 RELATION MODIFIED TO DESCRIBE CLAY-TIRE INTERACTIONS

29X11-10, 8-PR AIRCRAFT TIRE
FREE-ROLLING TESTS IN CLAY

RELATION OF DRAG RATIO TO RUT DEPTH COEFFICIENT
FOR BRAKED-WHEEL TESTS OF THREE PNEUMATIC TIRES

DATA FROM TWO SEPARATE TEST PROGRAMS
WHEEL SPEEDS FROM 3 TO 157 FT/SEC

APPENDIX A: NOTATION

A, A'	Nominal projected clay-tire contact areas equal to br and br' , respectively
AI	Airfield index
b	Tire section width
C_D, C'_D	Drag coefficient and drag coefficient modified to describe clay-tire interactions, respectively
C_s, C_x	Cone index of the soil obtained with a standard 0.5-sq-in.-base-area, right circular 30-deg-apex-angle cone at 72 in./min, and cone index adjusted to account for soil viscous-like effects, respectively
d	Tire diameter
D	Drag force
D/W	Drag ratio
e_f	Full throttle efficiency
F_i, F'_i	Inertial forces related to areas A and A' , respectively
F_t	Tractive force
F_v, F'_v	Viscous force related to areas A and A' , respectively
g	Acceleration due to gravity
h	Tire section height
HP	Brake horsepower
ℓ, ℓ'	Linear terms equal to the square root of areas A and A' , respectively
ℓ_s	Square root of the base area of the standard 0.5-sq-in.-base-area cone (0.707 in.)
$\left. \begin{matrix} N_{c0}, N_{c1} \\ N_{c2}, N_{c3} \end{matrix} \right\}$	Clay-tire numerics (dimensionless prediction terms)
$\left. \begin{matrix} N_{clx}, N_{c2x} \\ N_{c3x} \end{matrix} \right\}$	Clay-tire numerics adjusted to account for soil viscous-like effects
N_R, N'_R	Reynolds number and Reynolds number modified to describe clay-tire interactions, respectively
P_{20}	Pull at 20 percent slip
P_{20}/W	Pull coefficient at 20 percent slip

P_T	Towed force
r, r'	Measured rut depth and predicted rut depth, respectively
r_a	Active radius of tire
r/d	Rut depth coefficient
R_e	External motion resistance
R_i	Internal motion resistance
R_p	Motion resistance on pavement
R_s	Motion resistance in soil
R_s/W_v	Soil motion resistance coefficient
RCI, RCI_x	Rating cone index and rating cone index adjusted to account for soil viscous-like effects, respectively
RI	Remolding index
V_s	Standard cone penetration velocity (72 in./min)
V_t	Theoretical wheel translational velocity (equals $r_a \omega$)
V_v	Vehicle maximum speed
V_w	Actual wheel translational velocity
VCI_{lt}	Maximum RCI of the critical soil layer required for a vehicle to complete one pass
W, W_v	Load on a single wheel and load on a vehicle, respectively
δ	Tire deflection
δ/h	Tire deflection ratio
γ_w	Clay unit wet weight
ω	Wheel angular velocity
ρ	Clay wet mass density γ_w/g

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