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A TECHNIQUE FOR ESTIMATING THE SLOPE-CLIMBING ABILITY OF WHEELED VEHICLES IN SAND

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ABSTRACT

A TECHNIQUE FOR ESTIMATING THE SLOPE-CLIMBING ABILITY OF WHEELED VEHICLES IN SAND

Preface

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This paper was prepared by Mr. D. R. Freitag, Chief, Mobility Section, Army Mobility Research Center, and Mr. S. J. Knight, Chief, Army Mobility Research Center, Waterways Experiment Station, for presentation at the 1963 Society of Automotive Engineers Automotive Engineering Congress and Exposition to be held in January 1963 at Detroit, Michigan. The paper is based on investigations made for the Office, Chief of Engineers, and has been reviewed and approved by that office.

I

ABSTRACT

A TECHNIQUE FOR ESTIMATING THE SLOPE-CLIMBING ABILITY OF WHEELED VEHICLES IN SAND

by

D. R. Freitag and S. J. Knight

In a testing program jointly supported by the Army and the Navy, the U. S. Army Engineer Waterways Experiment Station has conducted approximately 2500 tests of the ability of wheeled military vehicles to climb slopes of loose sand. Tests were conducted on a variety of beach and dune sands. Test procedures and techniques are described briefly. The strength of the sand on the slopes was measured by means of a cone penetrometer. The slope-climbing performance of each of the five sizes of vehicles tested is shown to be determined principally by the strength of the sand and by tire size and inflation pressure. The effect of each of these variables on performance is discussed briefly. An empirical method employing firm-surface tire-print data, wheel load, and sand strength is presented as a means of predicting the sand slope-climbing capability of conventional all-wheel-drive vehicles.

II.

A TECHNIQUE FOR ESTIMATING THE SLOPE-CLIMBING ABILITY OF WHEELED VEHICLES IN SAND

Introduction

1. Those areas of the earth's surface covered with pure sand were long considered major obstacles to overland travel, passable only on camelback. Until oil exploration crews appeared a generation ago, sand dune regions of the world's deserts were traversed only by the adventurous. Under the impetus of the search for oil, desert travel with special wheeled vehicles has become almost commonplace.

2. Sand-covered areas can be of considerable importance in military campaigns also. However, besides the possibility of operations in the dry sands of desert regions, the military must consider crossing the wet-to-moist sand beaches that form the coastlines of most of the world's land masses. Whereas the dry dune sands appear to present very similar problems wherever they are found, it is known that beach sand conditions range from loose and yielding as at Iwo Jima to speedway firmness as at Daytona. Thus from the military point of view, the experience gained in particular sand regions needs to be quantified and expressed in terms of measurable properties of the sand so as to be applicable to any region. Such a development would permit a military commander to compare, on a quantitative basis, the trafficability* of the terrain confronting him with the capability of his vehicles.

3. Late in 1953 a program, jointly supported by the Army and the Navy, was initiated to develop means of measuring the ability of sands to support vehicles and to relate the performance of certain military vehicles to these measurements. This work was conducted by the U. S. Army Engineer Waterways Experiment Station as an extension of trafficability studies being conducted in soft clayey soils.[2**] Since that time more than 2500 vehicle tests have been conducted in sands.[3] Most of the tests were with wheeled vehicles, and the data from these provide the basis for this analysis.

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* The ability of a soil to support traffic is called its trafficability.
** Numbers refer to References listed at end of paper.

4. The data reveal that a fairly definite correlation exists between the strength of a sand and the maximum slope that a given vehicle (equipped with given tires at a given inflation pressure) can climb. However, this correlation varies from vehicle to vehicle and, moreover, changes significantly with tire-inflation pressure. Thus, the development of a single system of relating sand strength to slope-climbing ability, applicable to all trucks, tires, and tire pressures, is very desirable. This paper describes one technique for generalizing the vehicle-sand data, an empirical method incorporating dimensional analysis, which appears to give very satisfactory results on the basis of the data examined.

Test Program

5. Five different vehicles, ranging in size from the 4x4, 1/4-ton jeep to a 6x6, 5-ton truck, were studied extensively. Certain pertinent characteristics of these test vehicles are listed in the following table.

Vehicle Characteristics

Vehicle	Approx Empty Weight lb	Approx Test Weight lb	Number of Tires	Tire Data: Ply Rating	Tire Data: Size
1/4-ton M38A1, 4x4 truck	2,500	3,000	4	6	7.00-16
3/4-ton M37, 4x4 truck	5,600	7,100	4	8	9.00-16
2-1/2-ton M211, 6x6 truck	13,000	18,000	10	8	9.00-20
2-1/2-ton M34 and M135, 6x6 trucks	12,500	17,500	6	12	11.00-20
5-ton M41, 6x6 truck	18,000	28,000	6	12	14.00-20

Note that the two 2-1/2-ton trucks were virtually identical except that one had 9.00-20 dual-tandem rear wheels while the other had 11.00-20 single-tandem rear wheels. All vehicles were standard military trucks. Usually tests were conducted with the truck carrying its rated cross-country load, but some tests were run with loads ranging from 0 to 150 percent of the rated cross-country load. Tire-inflation pressure was considered a test variable, and for each vehicle tests were conducted at several pressures ranging from 10 to 45 psi.

6. Test sites were located in desert dunes and on coastal beaches and dunes. Sands composed of quartz, coral, or volcanic ash were tested. Geographically, the test data are representative of coastal sands on the Atlantic, Gulf, and Pacific coasts of the continental United States, and of beaches on a number of Pacific islands. Desert sands were tested only in southwestern United States.

7. Typically, a test was conducted in the following manner. An area was selected that was approximately 100 ft long with a constant or slowly changing slope and free of vegetation, litter, or other irregularities. Measurements were made of the properties of the sand, and the gradient of the test area was determined accurately. A test vehicle, previously loaded and weighed and with the inflation pressure of the tires adjusted to that desired for the test, was driven slowly up the slope in low gear with all wheels driving. Repeated passes of the vehicle were made in the same path until the vehicle was unable to climb the slope or until it appeared that it could continue indefinitely. In most instances the first pass was the most critical but occasionally, particularly in dunes, the vehicle failed to climb the slope on the second or third trip.

8. In the early phases of the test program the properties of the sand were measured with a number of different instruments, all designed to provide an estimate of the shear strength characteristics of the sand. Water content and density data also were obtained. It soon became evident that measurements from several of these instruments could be used with about equal precision to relate the characteristics of the sand to the performance of the test vehicle. One of these measurements, the cone index, was obtained with a light, portable cone penetrometer that was being employed in the trafficability studies of fine-grained soils. Cone index was therefore used throughout the test program as the primary means of differentiating between the sand conditions of the various tests.

9. Fig. 1 shows the penetrometer used to obtain the cone index of the sand. The point is a 30-degree, right-circular cone of 0.5-in. base area, made of stainless steel. The cone is forced into the soil by means of a shaft of convenient length to which is attached a

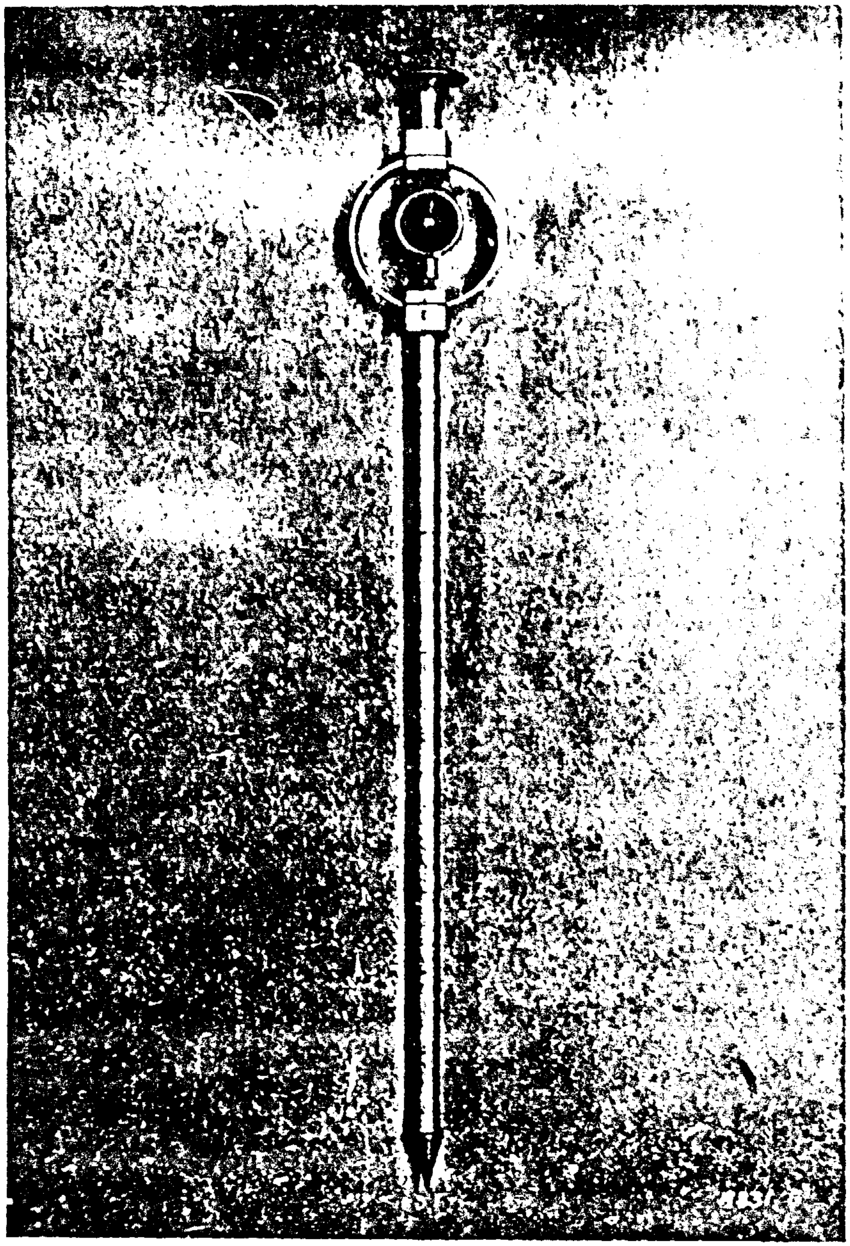


Fig. 1. Close-up of cone penetrometer and cone penetrometer in use

proving ring to measure the required force and a handle for manually applying the load. Cone index is measured at specific depths and is the force in pounds per square inch on the base area of the cone required to cause the cone to penetrate the soil at a constant rate at the depth for which a measurement is desired.

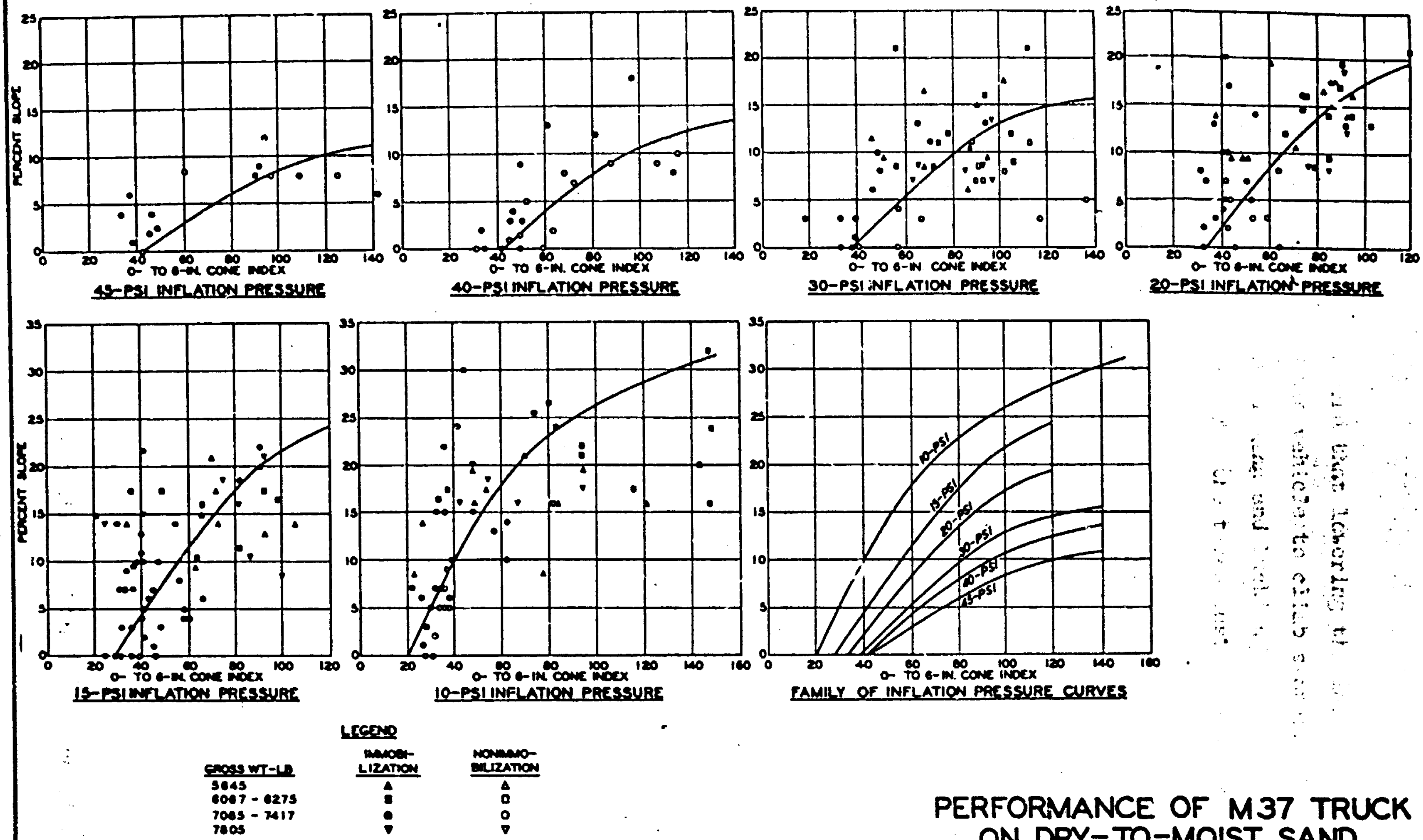
10. In this test program cone index was measured at the sand surface and at 3-in. increments thereafter to a depth of 24 in. From 10 to 20 such penetrations were made in the immediate vicinity of the intended vehicle path to obtain a representative average for the test. Upon analysis of the data it was found that the average cone index in the top 6 in. provided a satisfactory portrayal of the strength of the test area. This is the value that has been used in the analyses.

Test Results

11. In analyzing the results of the vehicle tests, five major variables were considered. These were: the vehicle tested, the inflation pressure of the tires, the slope of the test lane, the strength of the sand, and the performance of the vehicle on a "go" or "no-go" basis. A relatively small number of tests in which the load on the vehicle was varied from 0 to 100 percent of rated capacity indicated that load did not influence the results significantly if all other factors were held constant.

12. Separate data plots were made for each vehicle-tire inflation pressure combination. In the plots, the cone index evaluation of the test lane was plotted against its slope. A data point was marked by a closed symbol if the vehicle was immobilized in the test lane, or by an open symbol if it traversed the lane successfully. Then a line was drawn to separate the "immobilization" points from the "nonimmobilization" points.

13. The results of this type of analysis for the M37 3/4-ton truck are shown in fig. 2. The lines drawn do not separate all of the "go" points from the "no-go" points, but considering the inherent variability of naturally deposited soils and the fact that several different vehicles of the same type are represented, the overall results are considered satisfactory. These curves show that steeper slopes could be climbed on stronger sand, that with 10-psi inflation pressure the vehicle could travel on level terrain on the



PERFORMANCE OF M37 TRUCK
ON DRY-TO-MOIST SAND

Fig. 2

softest sand that could be found, and that lowering the inflation pressure markedly improved the ability of the vehicle to climb slopes. Unfortunately, the occurrence of serious flexing and buckling of the tire puts a lower limit on inflation pressure. For the tires tested this limit was about 10 psi.

14. Similar trends were found for the other vehicles tested, and families of curves were developed for each. However, the curves are applicable only to the specific vehicle for which they were developed. These curves, less the data points, are shown in fig. 3.

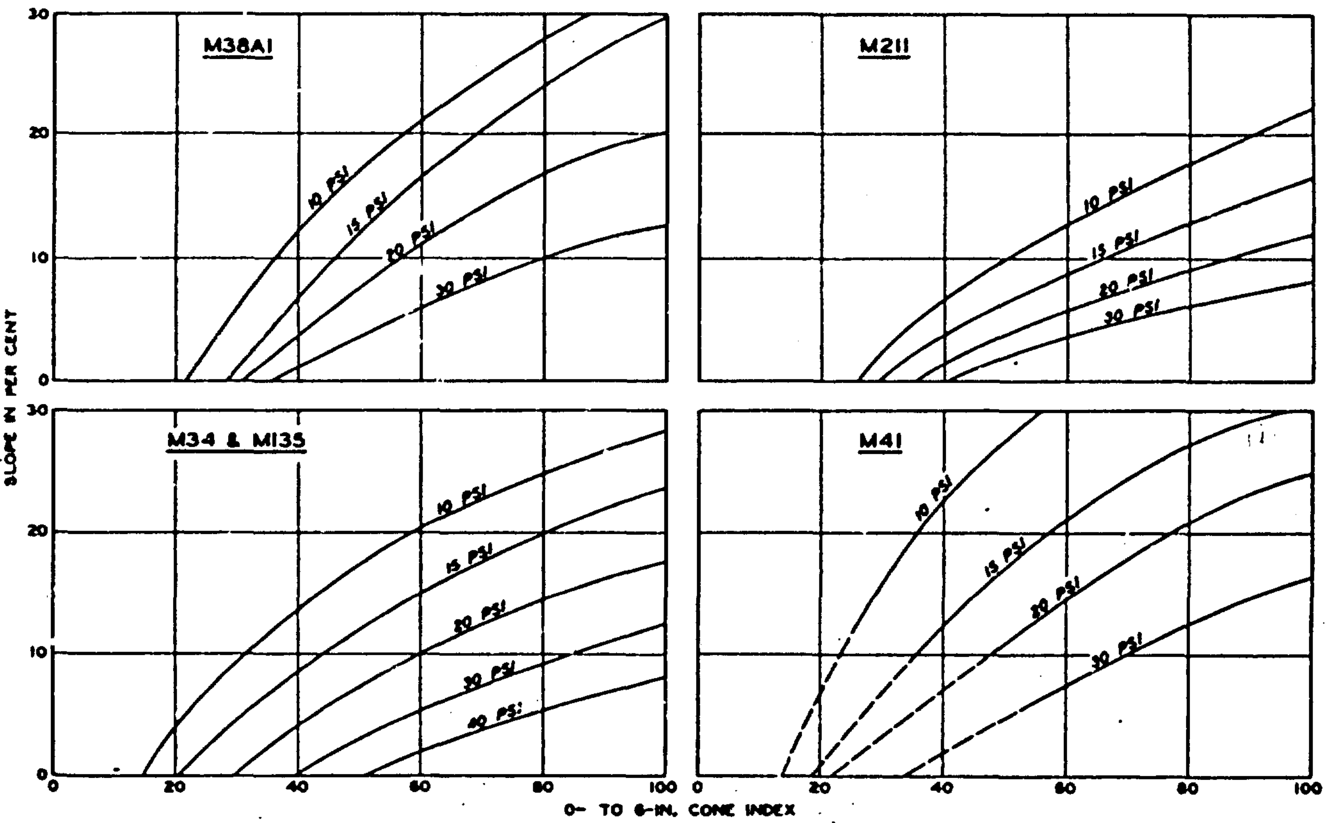


Fig. 3. Vehicle performance, families of tire-pressure curves

15. A striking example of the difference in the performance of two vehicles is illustrated in fig. 4. Here the performances of two types of 6x6, 2-1/2-ton trucks at two inflation pressures are compared. These trucks are virtually identical except for their tires. The M135 is equipped with six 11.00-20 tires while the M211 uses ten 9.00-20 tires, the rear wheels being duals. The larger tires evidently are considerably more efficient. On sand with an average cone index of 60 the 2-1/2-ton truck with 11.00-20 tires at 10-psi inflation pressure can climb a slope

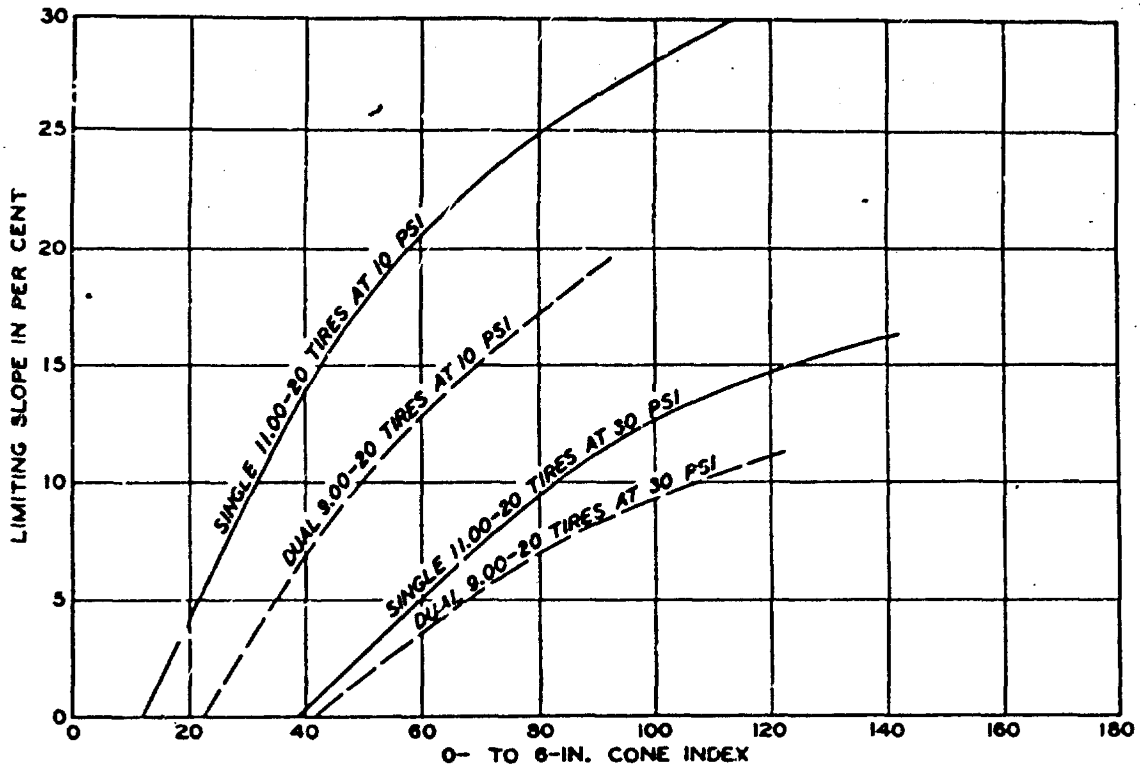


Fig. 4. Effect of tire size and inflation pressure on performance of 2-1/2-ton, 6x6 truck, dry-to-moist sand

of about 21 percent, while the one with 9.00-20 tires at the same inflation pressure can only climb one of about 13 percent. At this point it is of some interest to note that in wet, fine-grained soils the mobility of these two vehicles is almost equal, and that changing the tire-inflation pressure has very little influence on the performance level.

Analysis of Combined Data

16. The consistent and regular patterns of the families of performance curves for the five vehicles strongly invites a more detailed analysis and an attempt to put the relations in a more general form. For any one vehicle, the curves for each tire-inflation pressure are similar in shape and are distinctly offset from each other. However, for different vehicles, the same inflation pressure results in different levels of performance. This indicates that inflation pressure is only a relative evaluation of something more fundamental. This is well illustrated in the comparison of the two types of 2-1/2-ton trucks.

17. It is of some significance also that for a particular vehicle type at a particular tire-inflation pressure, changes in the vehicle weight apparently result in little or no change in performance. Furthermore, there is a general tendency for a given increment of inflation pressure to cause a greater difference in performance for vehicles with large tires than for those with smaller tires.

18. The foregoing observations suggest that the ability of wheeled vehicles to travel up sand slopes is dependent upon the size and shape of the surface their tires present to the soil, and probably also upon the magnitude and distribution of the loading pressures at that surface. Therefore, a study was initiated to determine how these factors varied with wheel load, inflation pressure, tire size, ply rating, etc. As a first approximation, the measurements were made with the tires bearing on a firm, smooth surface. Upon development of appropriate instrumentation, the program was extended to include tire deflection[4,5] and contact pressure measurements in soils of various consistencies. This portion of the study has not yet progressed to the point where sufficient quantitative data are available to conduct an analysis. However, they do suggest that the deflection patterns of tires on a firm surface are similar to those on sand. For example, an increment of vertical deflection of the tire produces about the same amount of change in sidewall bulge on sand as on a firm surface. This is of little real assistance, but it does give some assurance that the analyses based on firm-surface tire-print data are not completely misleading.

19. Using the firm-surface data, it was found that when their respective tire-inflation pressures were such that the vehicles had the same total tire contact areas, the 2-1/2-ton truck with ten 9.00-20 tires left ruts of approximately the same depth as did the 2-1/2 ton truck with six 11.00-20 tires. However, even when the total contact areas were equal, the truck with 11.00-20 tires gave significantly superior performance.

20. This interesting result prompted a systematic study of the relation of the size and shape of the firm-surface tire print to the vehicle's performance. The general approach employed was based on the premise that the family of performance curves for a vehicle could be collapsed into a single curve if the percentage-of-slope factor representing performance was

plotted against a numerical expression that properly combined the variables represented by tire pressure, load, and cone index. Various numerical factors indicative of wheel load, tire-print configuration, and soil strength were arranged to result in dimensionless terms, and these terms were plotted against the corresponding maximum slopes climbed by the vehicle. Proceeding by trial and error, and guided as much by intuition as by theoretical considerations, a large number of dimensionless terms were explored before an expression in the form $\frac{C\ell^3}{W}$ was found to produce consistently satisfactory results. The family of performance curves for the M37 3/4-ton truck collapsed by this factor is shown in fig. 5. This is neither the

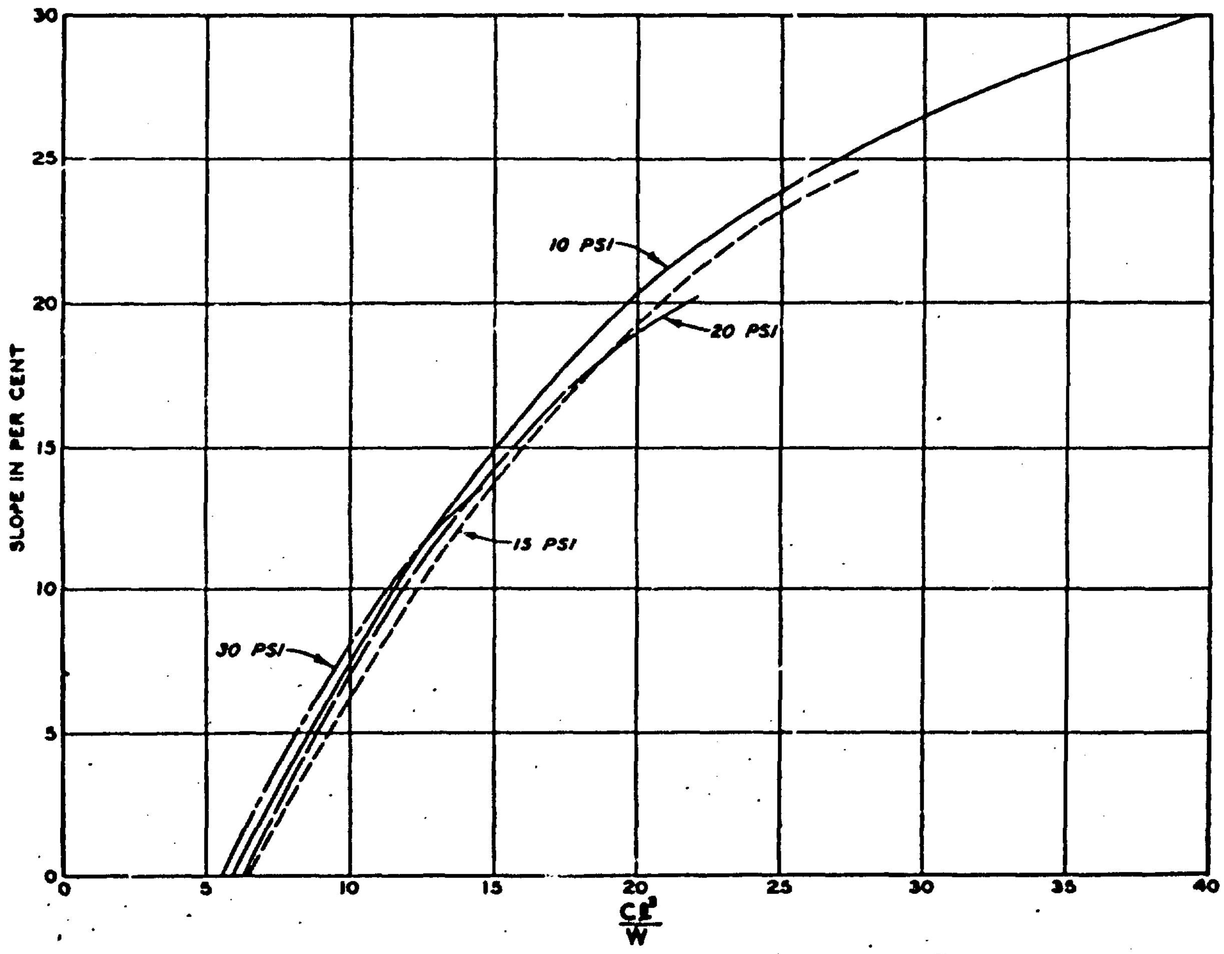


Fig. 5. Collapsed vehicle performance curves for M37 truck

best nor the worst of the relations found for the five test vehicles. The system worked very well in all cases except for the 2-1/2-ton truck with 11.00-20 tires. Here the curves for the various inflation pressures did not collapse as well as for the other vehicles. At the same dimensionless vehicle parameter a spread as great as a 3 percent slope remained.

21. The terms used in the expression are simple and straightforward. The factor W is the average weight in pounds carried by each tire; ℓ is the average length in inches of the firm-surface tire print, which for any tire is a function of both load and inflation pressure; while C is the average slope of the cone index-versus-depth curve in the top 6 in. of the sand and has the dimensions pounds per square inch per inch. The term C may be gotten from the average 0- to 6-in. cone indexes, since examination of the original field data showed that for the large majority of sands tested, cone index increased generally in direct proportion to depth from the surface to depths well beyond 6 in.

22. The numeric $\frac{C\ell^3}{W}$ is closely similar to the expression $\frac{\gamma a^3}{W}$ that can be derived from dimensional analysis of the basic problem. In this expression W is load in pounds, γ is the unit weight of the soil in pounds per cubic foot, and a is a characteristic dimension of the wheel or track in feet. Nuttall[1] and Vincent, Hicks, and Kapur[6] have used this numeric or a variation thereof to collapse scale-model, towed rigid-wheel test data. Both used the wheel diameter as the characteristic dimension, but this value has obvious limitations for pneumatic tires.

23. In fig. 6 the collapsed performance curves for the five vehicles have been superimposed in the same plot. It can be seen that the curves are similar and can be approximated by a single curve. Thus, vehicle performance on sands can be predicted with reasonable precision on the basis of tire load, length of tire print, and a measure of the sand strength in cone index terms. Accurate prediction beyond the range of the test data should, of course, not be expected. Particularly, it should be recognized that no vehicle tested was able to climb slopes steeper than 35 percent on the relatively soft sands investigated.

24. One of the more interesting implications of this finding is that the width of the tire appears to be unimportant except perhaps indirectly as it might affect the load and print-length factors. It should be noted, however, that the tires represented are all of circular cross section and their diameter-width ratio range is narrow, being generally between 3 and 4. Test data are needed on extremely narrow tires to establish the extent of

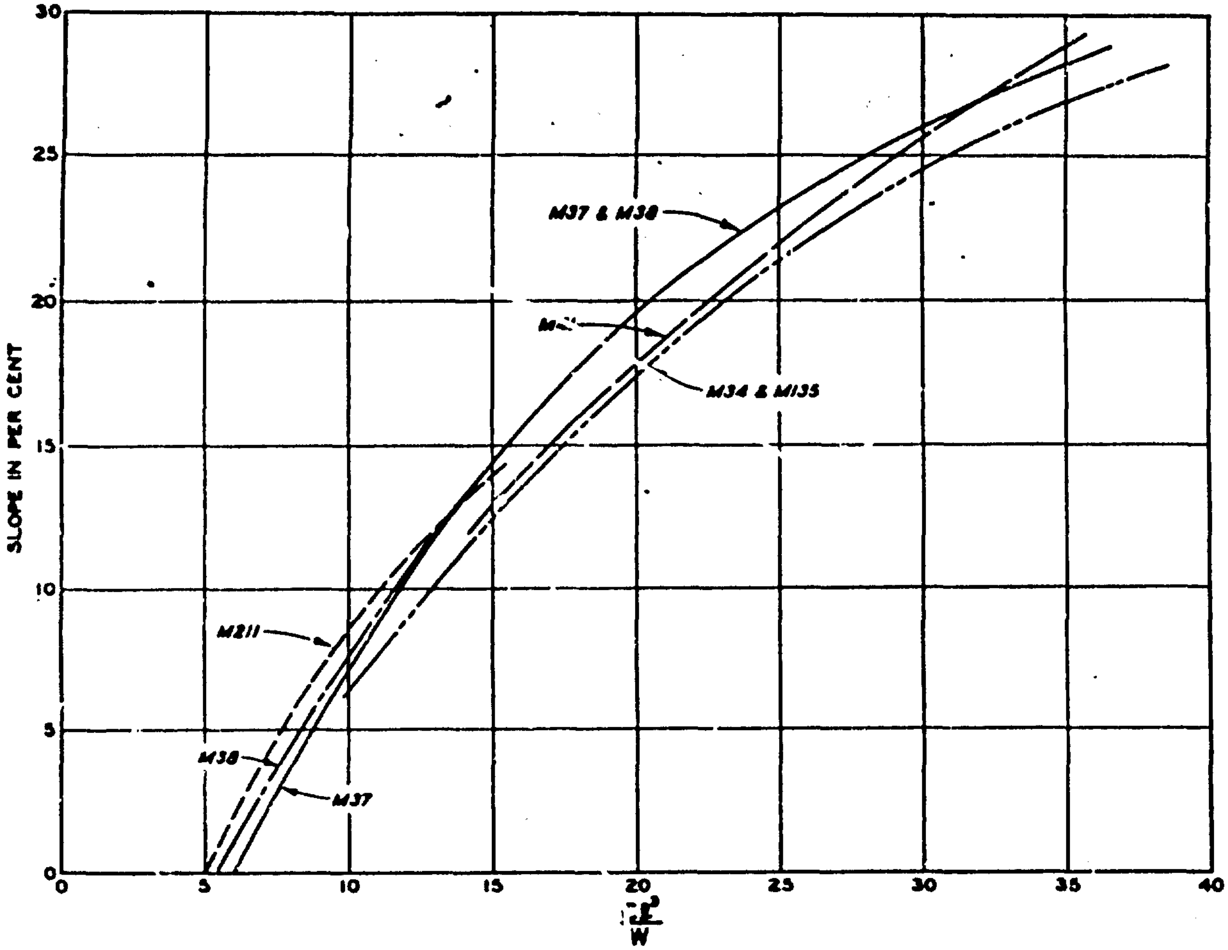


Fig. 6. Vehicle-soil performance relations
(M38, M211, M37, M34, M135, and M41)

the applicability of the derived relations. In the meantime, the performance in sand of vehicles with tires of conventional size and shape can be estimated with some assurance.

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