MISCELLANEOUS PAPER M-70-4

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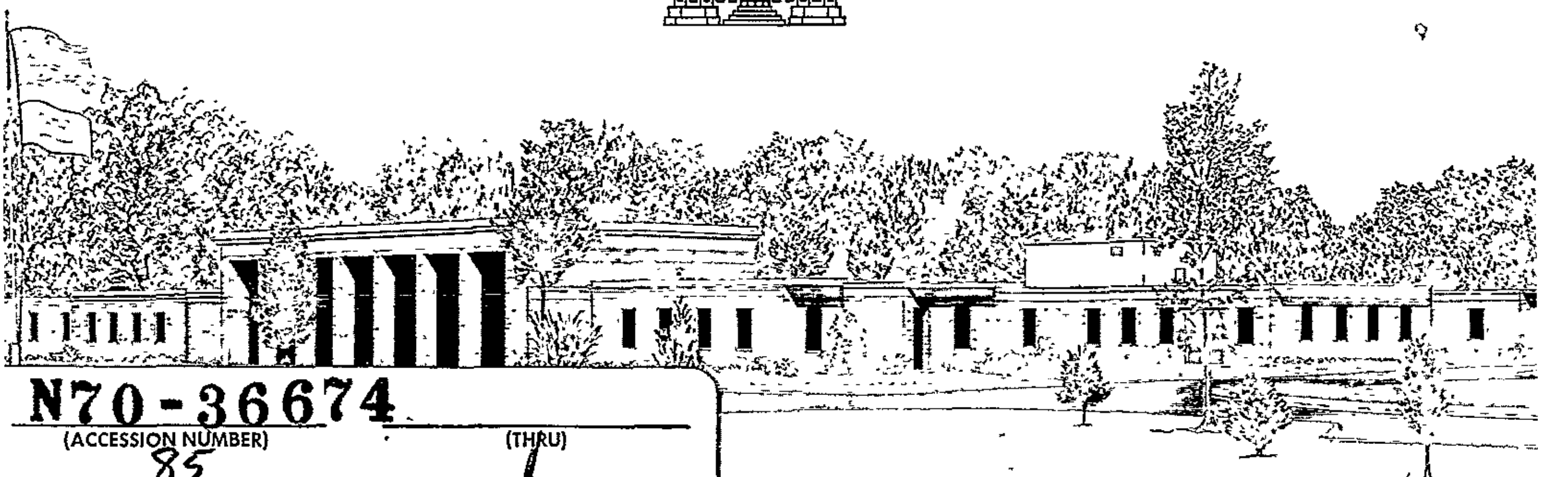
by

D. R. Freitag, A. J. Green, K.-J. Melzer



May 1970

Prepared for George C. Marshall Space Flight Center
National Aeronautics and Space Administration, Huntsville, Alabama

Conducted by Mobility and Environmental Division
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FOREWORD

The study reported herein was conducted by personnel of the Mobility Research Branch (MRB), Mobility and Environmental (M&E) Division, U. S. Army Engineer Waterways Experiment Station (WES). The study was sponsored by the Lunar Exploration Office, National Aeronautics and Space Administration, Washington, and it was under the technical cognizance of Dr. N. C. Costes of the Space Sciences Laboratory, George C. Marshall Space Flight Center (MSFC), under NASA - Defense Purchase Request No. H-58504A, dated 30 April 1969.

The tests were conducted under the general supervision of Messrs. W. G. Shockley and S. J. Knight, Chief and Assistant Chief, respectively, of the M&E Division, and under the direct supervision of Dr. D. R. Freitag, Chief, Office of Technical Programs and Plans, WES, Mr. A. J. Green, Chief, Vehicle Dynamics Section, MRB, and Dr. K.-J. Melzer of the Mobility Fundamentals Section, MRB. This report was prepared by Drs. Freitag and Melzer and Mr. Green.

The Bendix, Boeing-GM, and SLRV wheels used in the study were furnished by MSFC, and the Grumman wheel by Grumman Aircraft Engineering Corp., Bethpage, N. Y. The Jet Propulsion Laboratory, Pasadena, Calif., furnished the Surveyor Lunar Rover Vehicle, and representatives of that laboratory participated in the testing conducted with this vehicle. The 4x4 test vehicle was originally fabricated by WNRE, Inc., Chestertown, Md., as a model of a marsh buggy and was modified by WES for this test program.

Acknowledgment is made to Mr. C. J. Nuttall, Jr., of WNRE, Inc., for his advice and assistance during the study.

COL Levi A. Brown, CE, was Director of WES during the conduct of this study and preparation of this report, and Mr. F. R. Brown was Technical Director.

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NOTATION

A_c	Hard-surface contact area, cm^2 ($in.^2$)
b	Width of wheel; width of grouser, cm (in.)
c	Cohesion of the soil, kN/m^2 (psi)
c_a	Apparent cohesion of the soil, kN/m^2 (psi)
c_b	Cohesion determined from bevameter tests, kN/m^2 (psi)
c_c	Cohesion determined from sheargraph tests, kN/m^2 (psi)
$c_{p\ell}$	Cohesion determined from plate in situ shear tests, kN/m^2 (psi)
c_{tr}	Cohesion determined from trenching tests, kN/m^2 (psi)
C_u	Coefficient of uniformity of the soil = d_{60}/d_{10}
d	Wheel diameter, cm (in.)
d_m	Mean diameter of soil grains, mm (in.)
d_{10}	Grain-size diameter at 10 percent finer by weight, mm (in.)
d_{50}	Grain-size diameter at 50 percent finer by weight, mm (in.)
d_{60}	Grain-size diameter at 60 percent finer by weight, mm (in.)
D'	Compactibility, % = $100\left(\frac{e_{max} - e_{min}}{e_{min}}\right)$
D_r	Relative density, % = $100\left(\frac{e_{max} - e}{e_{max} - e_{min}}\right)$
e	Initial void ratio
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
G	Penetration resistance gradient, MN/m^3 (pci*)
k_c, k_ϕ, n	Bekker soil values
M	Torque, m-N (ft-lb)
M_{20}	Torque at 20 percent slip, m-N (ft-lb)
M/Wr_e	Torque coefficient
M_{20}/Wr_e	Torque coefficient at 20 percent slip
N_1	Sand mobility number = $\frac{Gbd^2}{W}\left(1 - \frac{2\delta}{d}\right)^{-8}$
N_2	Sand mobility number = $G/W \cdot A_c^{3/2}$

*pci = $lb/in.^3$

p_c	Contact pressures, kN/m^2 (psi)
P	Pull, N (lb)
P_{20}	Pull at 20 percent slip, N (lb)
P/W	Pull coefficient
P_{20}/W	Pull coefficient at 20 percent slip
PCR	Power consumption rate = PN x W x 1/3.6
PN	Power number, $M/Wr_e(1 - s)$
PN_{sp}	Power number for self-propelled condition
PN_{15}	Power number for 15-deg slope
PN_{max}	Power number for maximum possible slope
r_e	Effective wheel radius, cm (in.)
s	Slip, % , $1 - \frac{\nu}{r_e\omega}$
v	Translational speed of a wheel, m/sec (fps)
w	Moisture content, % (percent of dry density)
W	Load; weight, N (lb)
α	Slope angle, deg
γ_d	Dry density, (dry unit weight) g/cm^3 (pci)
γ_s	Specific gravity
δ	Wheel deflection, cm
ε	Axial strain, %
η'	Efficiency = ratio of recoverable energy to total energy input = $\frac{P\nu}{M\omega}$
η'_{20}	Efficiency at 20 percent slip
ϕ	Angle of internal friction, deg
ϕ_b	Angle of internal friction determined from bevameter tests, deg
ϕ_c	Angle of internal friction determined from sheargraph tests, deg
ϕ_{ds}	Angle of internal friction determined from direct shear tests, deg
ϕ_p	Peak angle of internal friction determined from plane strain tests, deg
$\phi_{p\ell}$	Angle of internal friction determined from plate in situ shear tests, deg
$\overline{\phi}_s$	Secant angle of internal friction determined from triaxial tests, deg
ϕ_t	Tangent angle of internal friction determined from triaxial tests, deg
ω	Rotational velocity of the wheel, rpm

SUMMARY

One pneumatic and four metal-elastic wheels were laboratory tested in a fine sand to determine their relative performance and to establish a better understanding of the basic principles of the interaction of lightly loaded wheels with a frictional soil containing a small amount of cohesion. Five levels of sand strength were used. The cohesional and frictional properties spanned a range that included the probable range of lunar soil properties. The following tabulation shows average properties (angle of internal friction ϕ_t, cohesion c_{tr}, dry unit weight γ_d, relative density D_r, and moisture content w) for the five strength levels.

Soil Condition	ϕ_t deg	c_{tr} kN/m^2 (psi)	γ_d g/cm^3 (pcf)	D_r %	w %
S_1	37.1	0.0(0.0)	1.47(91.7)	32	0.5
S_2	43.5	0.39(0.06)	1.62(101.1)	87	0.5
C_1	37.9	0.39(0.06)	1.50(93.6)	46	1.1
C_2	38.5	1.08(0.16)	1.52(94.9)	54	1.4
C_3	38.1	1.75(0.25)	1.51(94.3)	48	1.8

Pull-slip tests, in which the slip of the wheel was varied from negative to high positive values, were conducted with a single-wheel dynamometer system. The translational speed of the dynamometer system was approximately 0.5 m/sec (≈1.5 fps). Wheel loads were varied from 67 to 670 N (15 to 150 lb).

Pull-slip tests and slope-climbing tests were conducted with a 4x4 vehicle and a 6x6 vehicle on soils prepared to the same consistency as that used in the single-wheel tests.

For a given soil condition, the pull coefficient did not vary with load for wheel loads less than about 220 N (50 lb); for greater loads the pull coefficient decreased with increasing loads. In addition,

the pull coefficient appeared to be independent of the average wheel contact pressure for pressures ranging from 0.7 to 3.5 kN/m^2 (0.1 to 0.5 psi) for a given soil condition. These results are consistent with the general shear behavior of the soil.

Contrary to expectations, increases in cohesion did not result in a marked improvement in performance over the range of loads and soil conditions used in this study.

Average values of pull coefficient at 20 percent slip (P_{20}/W) and power number at the self-propelled point (PN_{sp}) and on a 15-deg slope (PN_{15}) in a soil with zero cohesion (S_1) and one with a cohesion of 1.08 kN/m^2 = 0.16 psi (C_2) are given in the following tabulation:

	Soil Condition, S_1			Soil Condition, C_2		
Wheel	P_{20}/W*	PN_{sp}*	PN_{15}*	P_{20}/W*	PN_{sp}*	PN_{15}*
Pneumatic	0.448	0.150	0.422	0.548	0.040	0.372
Bendix I	0.452	0.067	0.425	0.505	0.080	0.370
Boeing-GM I	0.274	0.098	0.515	0.343	0.067	0.382
Grumman I	0.281	0.162	0.522	0.272	0.127	0.478
SLRV	0.426	0.080	0.386	0.602	0.165	0.482

*These data are averages for the range of loads used.

The data indicate that power requirements for the Bendix wheel are lower than for the Boeing-GM and Grumman wheels with one exception, the Boeing-GM wheel at PN_{sp} on the C_2 soil condition. For a single wheel operating in loose air-dry sand on a level surface under an assumed 220-N (50-lb) load, the power consumption rates for the Bendix, Boeing-GM, and Grumman wheels were 4, 6, and 10 whr/km, respectively.

The results of tests with the original wheels showed that none could be relied on to propel a vehicle up a 35-deg slope. There was indication that the original Bendix wheel might negotiate slopes up to about 28 to 30 deg, and the original Boeing-GM and Grumman wheels might negotiate slopes on the order of 15 to 20 deg.

The addition of angle iron grousers 30.5 cm (12 in.) wide and 3.2 cm (1-1/4 in.) deep to the Grumman and the Bendix wheels resulted in a substantial increase in the respective pull coefficients (slope-climbing abilities) with corresponding increases in the power demands for both wheels. Reducing the stiffness and adding a cover to the Boeing-GM wheel increased its pulling (slope-climbing) capability.

It was demonstrated that pull data from tests on level soils with the pneumatic and SLRV wheels can be used to predict the slope-climbing ability of a vehicle. Data trends indicate that such predictions tend to be conservative by about 1 to 2 deg. Torque or power requirements for the 4x4 and 6x6 vehicle were slightly higher than predictions based on corresponding single-wheel test results would be.

Results of tests with both the 4x4 and 6x6 vehicles indicate that the torque coefficient at a given slip was not significantly affected by variations in surface slope and soil strength.

Generally, when the vehicles were completely immobilized on a slope, they could not continue climbing by backing down and starting up again as they became immobilized again upon reaching the point where they had previously spun out. When the vehicles were stopped prior to an imminent immobilization, they could retrace their tracks and continue to climb. Any effort to steer the vehicles while they were negotiating a slope tended to degrade their performance. On the basis of observations during these tests, it is estimated that the maximum slope climbable was reduced by 1 to 2 deg when an effort was made to steer the vehicles.

PERFORMANCE EVALUATION OF WHEELS FOR LUNAR VEHICLES (SUMMARY REPORT)

PART I: INTRODUCTION

Background

1. Mobility on the lunar surface is a fundamental requirement for lunar exploration extended beyond the initial Apollo landings. The upper few centimeters of the lunar surface is considered to be composed of a loose, particulate material with an average bulk density of about 1.6 g/cm^3 (99.8 pcf), an angle of internal friction of about 37 deg in the normal stress range of a few kN/m^2 (psi), and a small, but noticeable, amount of cohesion ranging between 0.34 kN/m^2 (0.05 psi) and 1.38 kN/m^2 (0.20 psi) (Costes, et al, 1969). In planned surface traverses on the moon, a lunar roving vehicle will be required to travel on soft deformable soils, in craters, on level ground, and on slopes ranging up to 35 deg. Therefore, a method is needed for predicting the mobility performance capabilities and associated energy requirements related to various proposed lunar roving vehicle concepts.

2. The available methods for predicting the performance of wheeled vehicles on terrestrial soils are inadequate for predicting that of lunar roving vehicles. Thus, carefully controlled tests are necessary to establish maximum performance of vehicles operating on level surfaces and on slopes of loose, slightly cohesive, particulate materials; to quantify the amount of power consumed during these operations; and to relate these parameters to wheel characteristics and soil conditions.

Purpose

3. The general purpose of this study was to investigate principles that would lead to a better understanding of the soil-wheel interaction in the lunar environment and to evaluate the relative effectiveness of various proposed types of lunar roving vehicle wheels as traction and transport devices.

Scope

4. Tests were conducted on a sand from the desert near Yuma, Arizona. The sand was prepared to relative densities varying from loose to very dense, and was mixed with controlled amounts of water so as to exhibit an apparent cohesion ranging from 0 to 1.8 kN/m^2 (0 to 0.26 psi).

5. Single-wheel and vehicle tests were performed in test bins in the humidity-controlled laboratories of the Mobility Research Branch (MRB) of the U. S. Army Engineer Waterways Experiment Station (WES) as follows:

- a. Single-wheel tests on level air-dry and wet sand with a pneumatic wheel and four basic types of metal-elastic wheels and variations thereof.
- b. Tests with a 4x4 vehicle and a 6x6 vehicle on level and sloping air-dry and wet sand surfaces.

The wheel loads were varied from 67 to 670 N (15 to 150 lb). Depending on the flexibility characteristics of each wheel, the corresponding contact pressures ranged from 1.2 to 16.3 kN/m^2 (0.2 to 2.4 psi), and the slope angles used for slope-climbing tests ranged from 0 to 35 deg. Extensive soil testing complemented the single-wheel and vehicle tests.

PART II: TEST PROGRAM

Soil

Description

6. Gradation, classification, and other soil data for the material selected for this study are given in fig. 1.

Preparation

7. Level surfaces. The desired soil condition in dry sand was obtained in the following manner: One or more test bins (fig. 2) were filled and the soil was plowed with a seed fork to a depth of 30.5 cm (12 in.). For loose conditions, no compaction effort was necessary, so the surface of the plowed section was screeded level. To achieve denser conditions, the material was compacted at the surface with a vibrator before screeding. The required compaction effort varied, depending on the relative density desired. To process the wet sand, the desired volume of water was added to the soil, and the material was thoroughly mixed and then placed in the soil bins. Further preparation (i.e. compacting and leveling) was the same as for the dry sand.

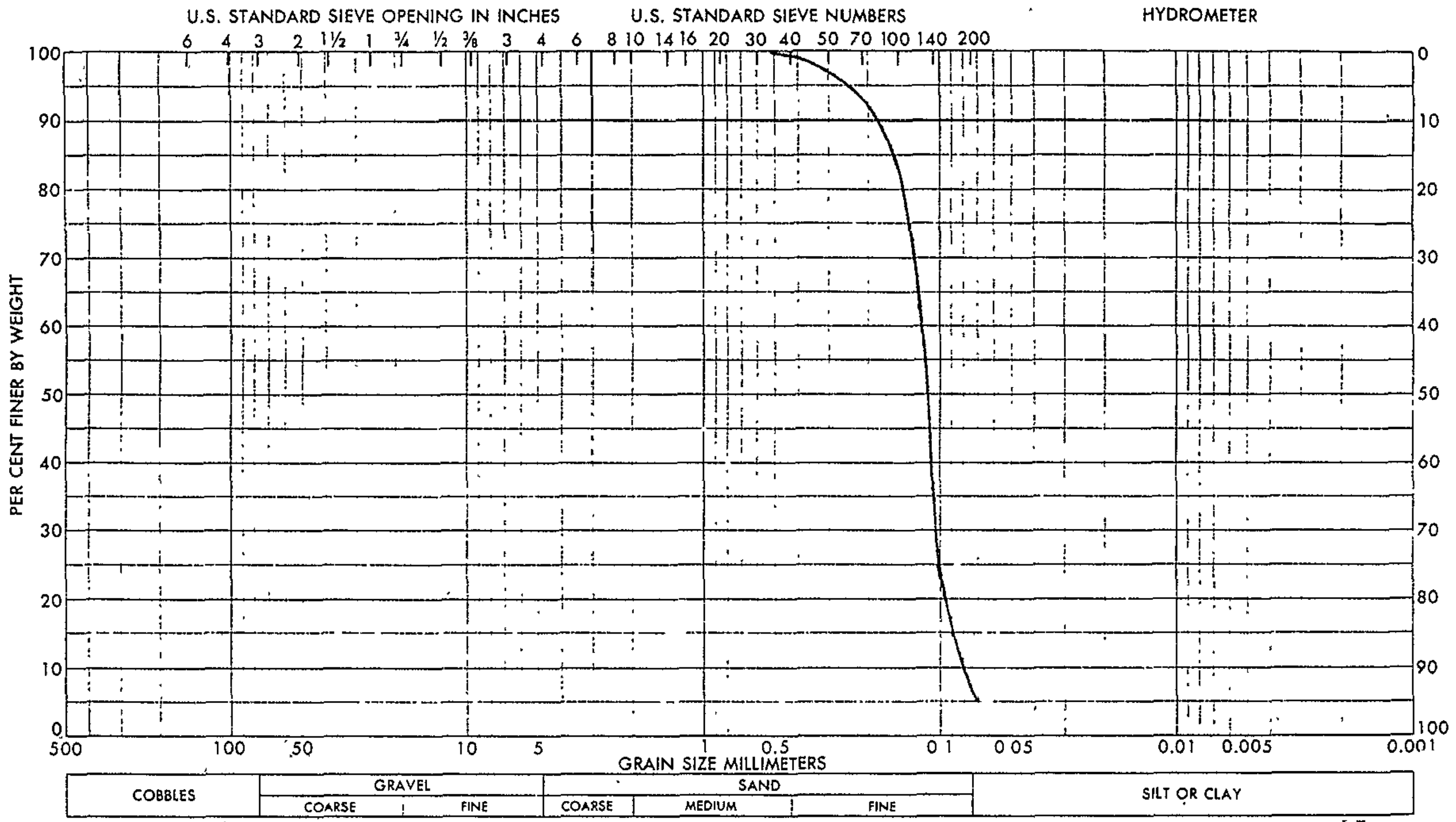
8. Sloping surfaces. The preparation of sloping test surfaces required no special technique. The test bins were prepared in the manner previously described and then lifted to the desired angle with an overhead crane. A soil bin in position for a slope-climbing test is shown in fig. 3.

Soil Tests

9. The soil tests conducted during this study can be divided into three categories according to their purpose, as follows:

- a. Tests conducted to investigate the general shear behavior of the test soil. These tests consisted of conventional and vacuum triaxial compression tests, plate in situ shear tests, and trenching tests.

- b. Routine tests normally conducted in all WES mobility research programs. These included cone penetration resistance tests, water content, and density determinations.



<u>Soil Properties</u>

$C_u = 1.5$ $d_m = 0.12$ mm $e_{min} = 0.608$ $D' = 51.2\%$

$d_{50} = 0.12$ mm $e_{max} = 0.919$ $e_{max} - e_{min} = 0.311$ $\gamma_s = 2.67$

Fig. 1. Grain-size distribution and soil properties of Yuma sand

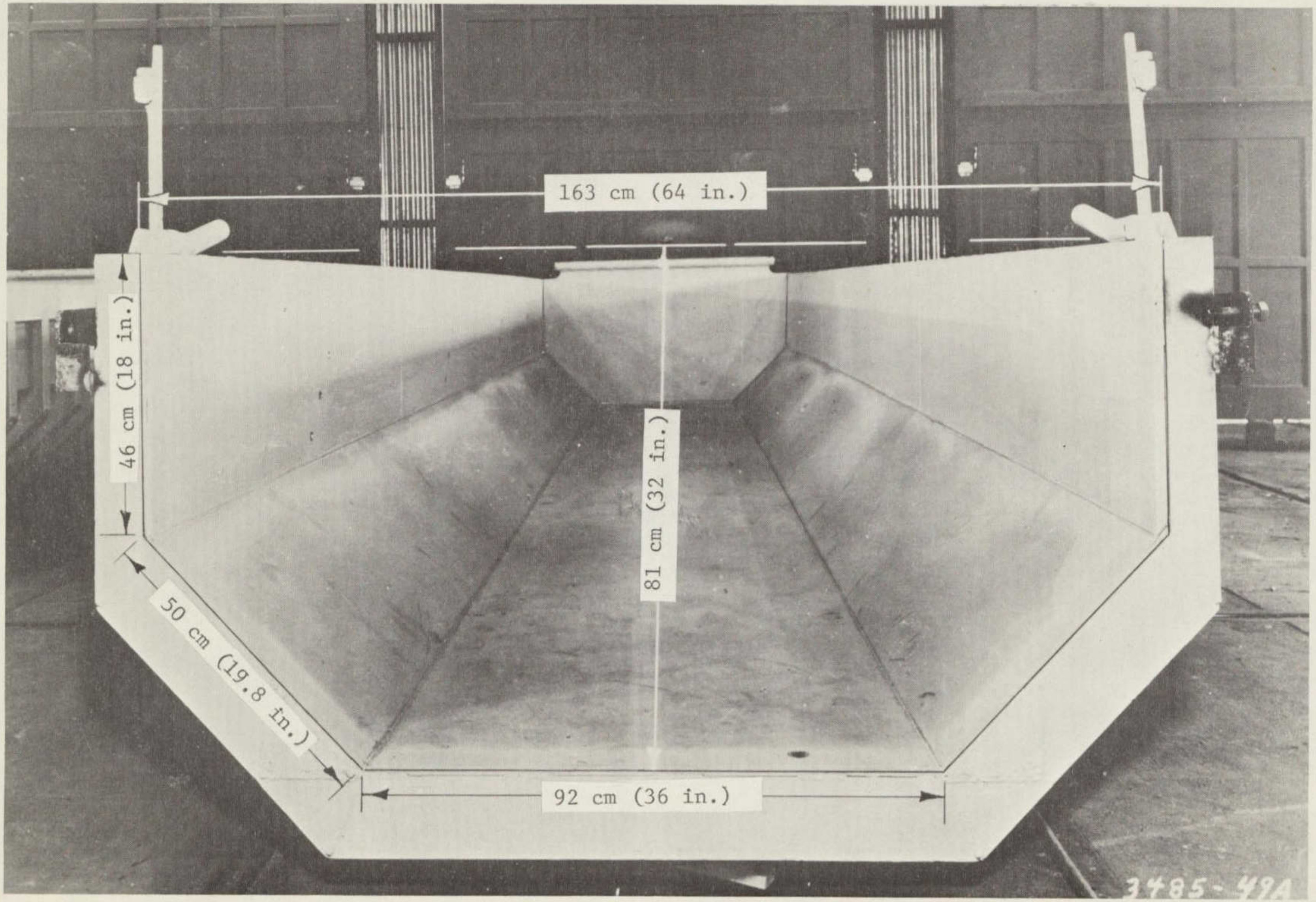


Fig. 2. Soil bin used for single-wheel tests

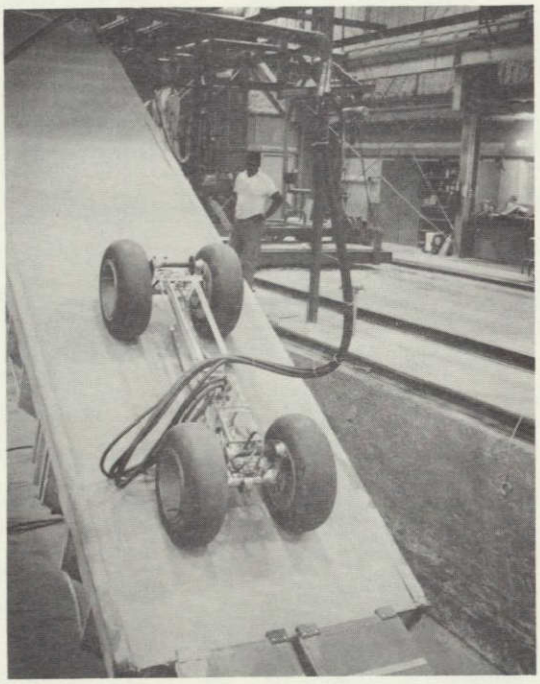


Fig. 3. Soil bin in position for vehicle slope-climbing test

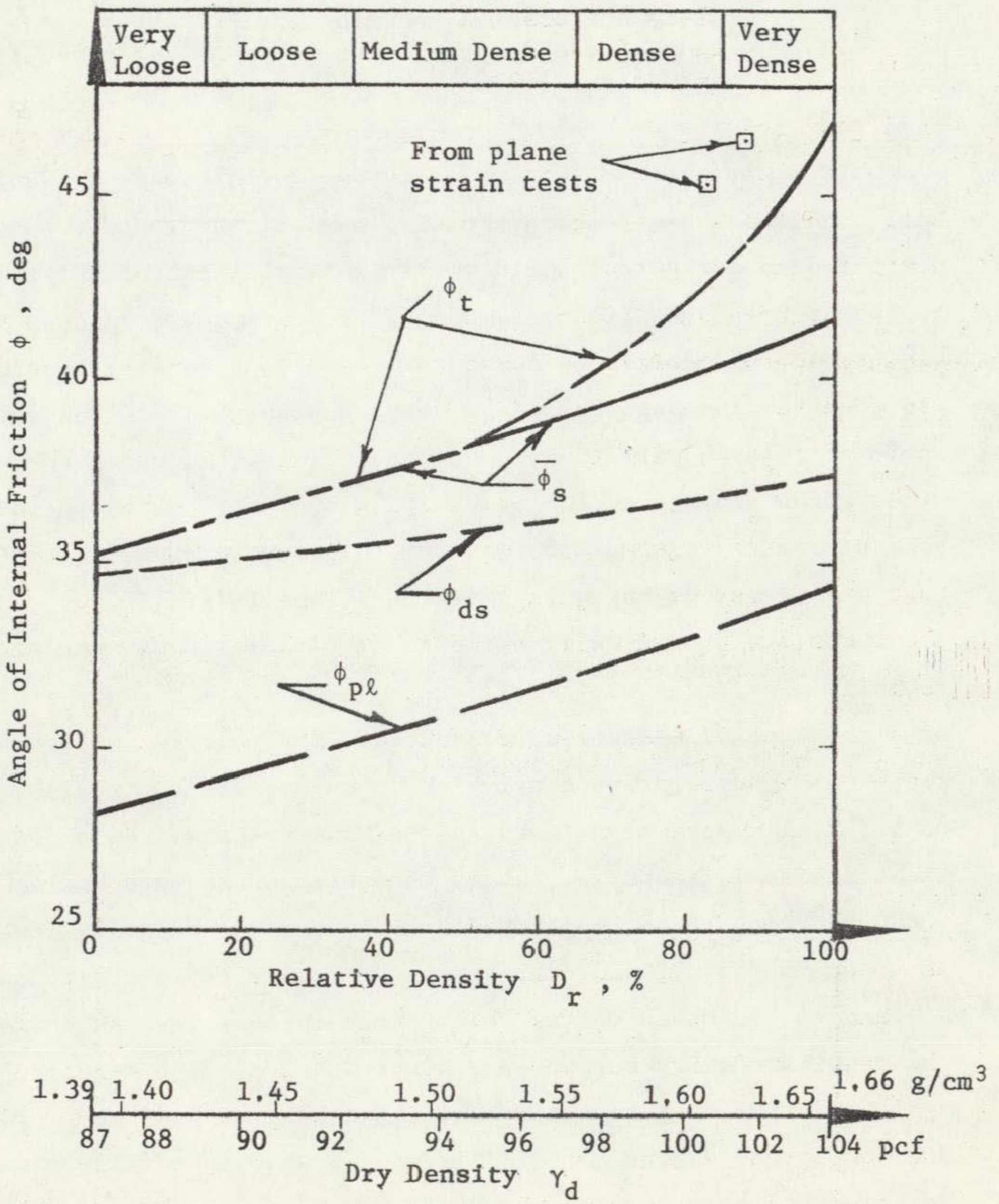
c. Special tests were conducted at the request of the sponsor. These tests were Cohron sheargraph, vane shear, and bevameter plate penetration and ring shear tests. A complete description of each of the tests mentioned is given in Freitag, Green, and Melzer (1970).

Soil test results

10. One basic objective of the soil tests was to identify the soil conditions under which the single-wheel and vehicle tests were performed in terms that would permit an evaluation of the test data by researchers subscribing to one of the several techniques for analyzing and predicting vehicle performance. A second, equally important objective was to determine such basic engineering properties of the material as angle of internal friction, cohesion, density, moisture content, and penetration resistance for maintaining a close control on the soil conditions for this test program. The maximum, minimum, and average measured values that can be associated with soil conditions (e.g. S_1, C_2) used throughout the tests are presented in table 1. The table shows that parameters normally considered basic soil properties, e.g. c and ϕ, vary with the type of test being conducted. The relation between friction angle ϕ and relative density D_r, as determined from several types of triaxial compression tests, direct shear tests, and plate in situ shear tests, is shown in fig. 4. The relation among cohesion c_{tr} determined from trenching tests, moisture content w, and relative density D_r is shown in fig. 5, and that among D_r, penetration resistance gradient G, and w is shown in fig. 6. Both relations were established from the results of very carefully conducted tests. The relative densities evaluated from routine tests during the single-wheel test program follow the same trend as the data in fig. 6 but show more dispersion. A more detailed analysis is given by Freitag, Green, and Melzer (1970).

Application to mobility

11. The angle of internal friction ϕ of the sand employed in these tests, as determined from triaxial compression tests, was larger for low normal stresses than for relatively higher normal stresses, at least when the relative density was greater than 50 percent. These trends were qualitatively confirmed by plate in situ shear tests, but the specific values of ϕ depended on the test method used. Also,



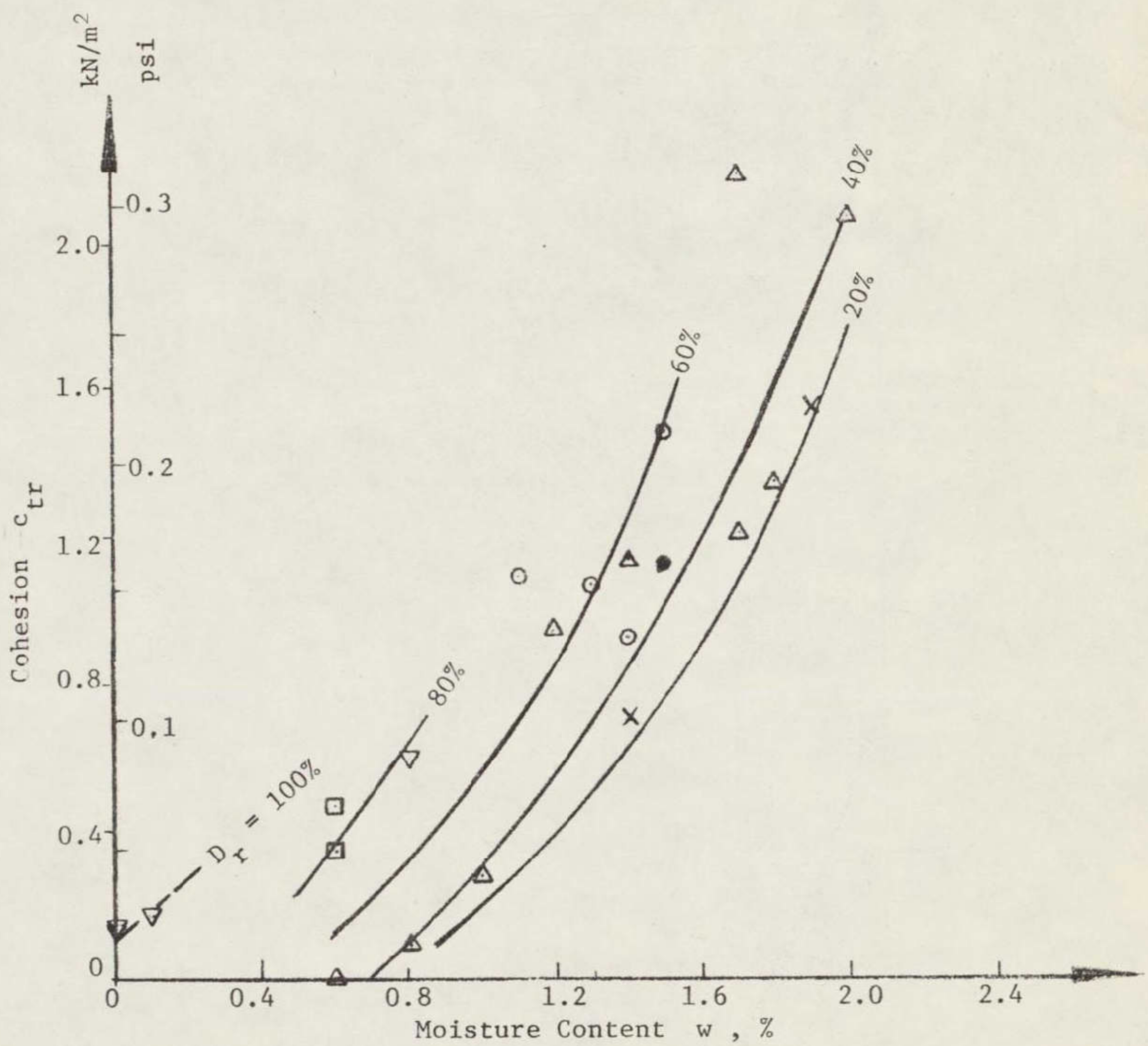
ϕ_t : from vacuum triaxial tests

$\bar{\phi}_s$: from conventional triaxial tests

ϕ_{ds}: from direct shear tests

$\phi_{p\ell}$: from in situ shear tests

Fig. 4. Friction angles from various methods as function of relative density



Legend

Symbol	D_r , %
●	<10
×	10-29
△	30-49
○	50-69
□	70-89
▽	>90

Fig. 5. Relation among cohesion, moisture content, and relative density from trenching tests

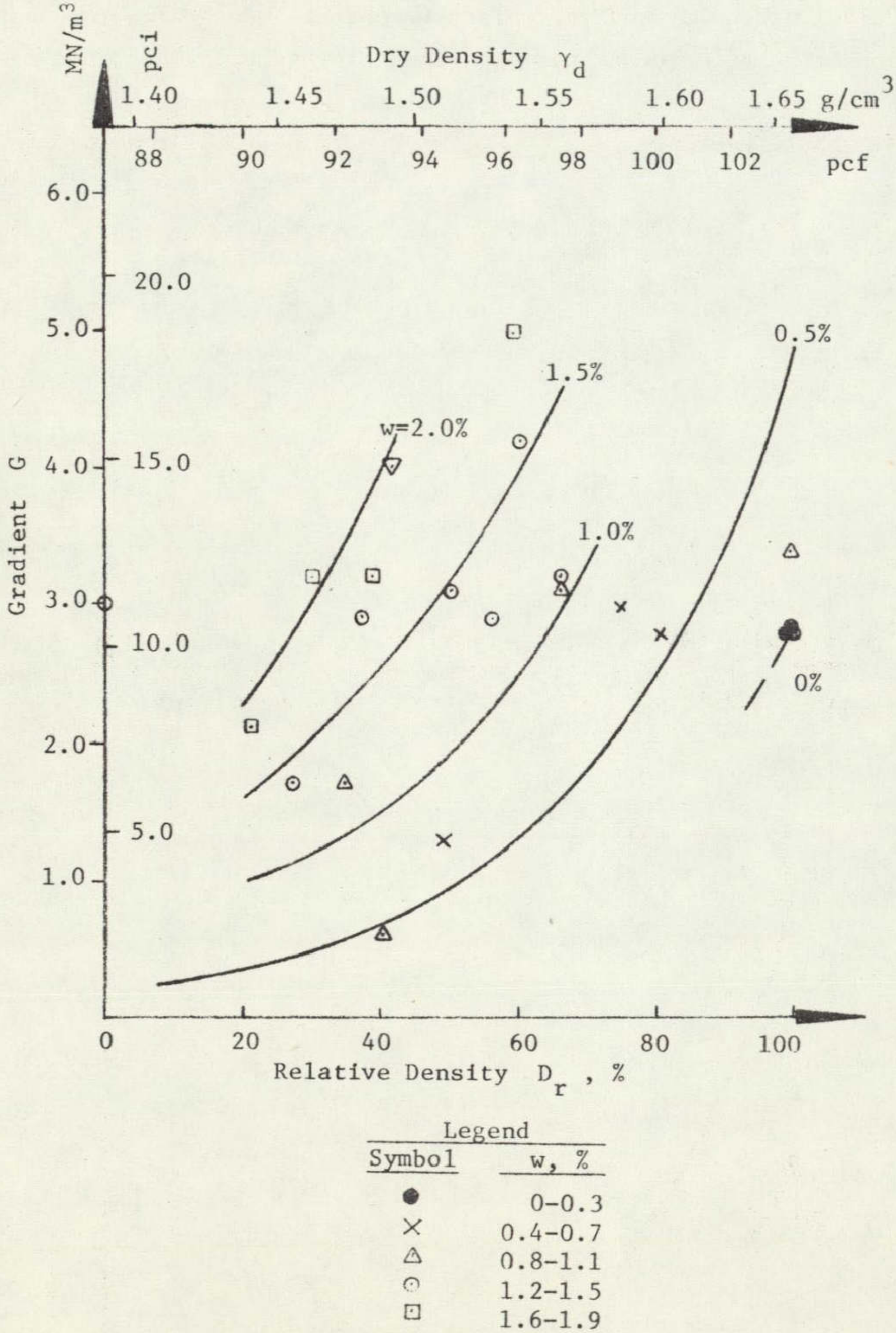


Fig. 6. Relation among relative density, penetration resistance gradient, and moisture content

the sand was found to have a small amount of apparent cohesion, depending on the relative density and the moisture content. Here also the test method appeared to influence the experimental results. This gave rise to the question as to what numerical values for the friction angle and cohesion should be used in connection with data analysis. This problem is discussed in detail by Freitag, Green, and Melzer (1970).

Wheel and Vehicle Test Equipment

Test dynamometers

12. The single-wheel test dynamometer shown in fig. 7 was one of three of the same type used in this test program. Instrumentation provided for continuous recording of wheel load, drawbar pull, torque, sinkage, slip, and speed. The accuracy of pull and torque measurements is estimated to be ±3 percent. This deviation included variations due to electronics, random wheel vibrations, nonuniformity in elastic deformations of the wheels, etc. The wheel test speed was no greater than 0.5 m/sec (1.5 fps) (for further details see Freitag, Green, and Melzer, 1970).

Test wheels

13. The original test wheels were: the pneumatic, the Bendix I, the Boeing-General Motors I, the Grumman I, and the SLRV wheels shown in fig. 8. Modifications during the program included the addition of grousers to the Bendix and the Grumman wheels, and roughening the surface, reducing the stiffness, and adding several different types of fabric covers to the General Motors wheel. Characteristics of these wheels are listed in table 2.

Vehicles

14. An engineering model of the 6x6 Surveyor Lunar Rover Vehicle (SLRV) and a 4x4 vehicle were used in the test program (figs. 9 and 10). Vehicle performance test data included torque at each wheel (or axle), drawbar pull, wheel speed, vehicle speed, wheel slip, slope, rut depth, and soil properties.

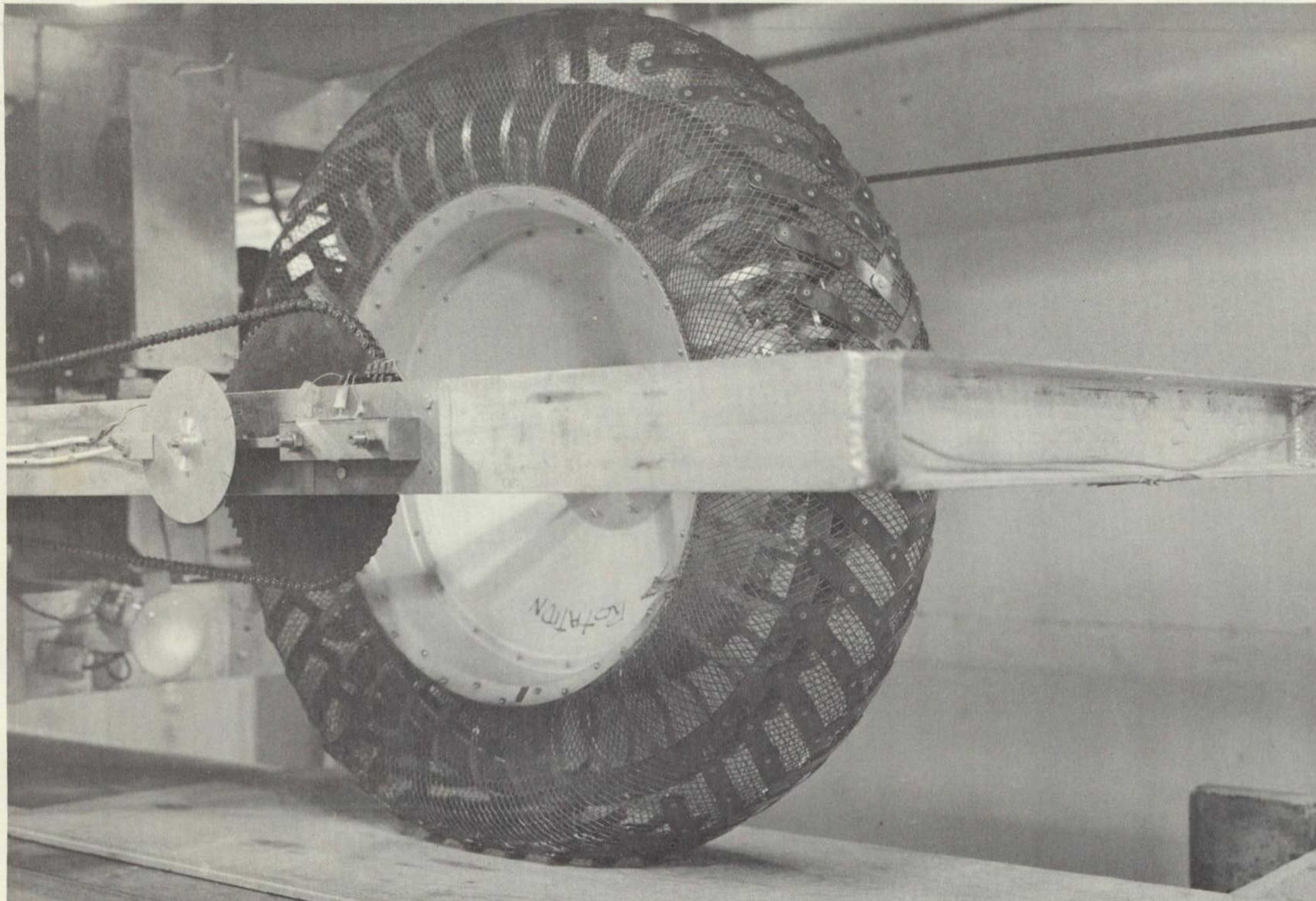
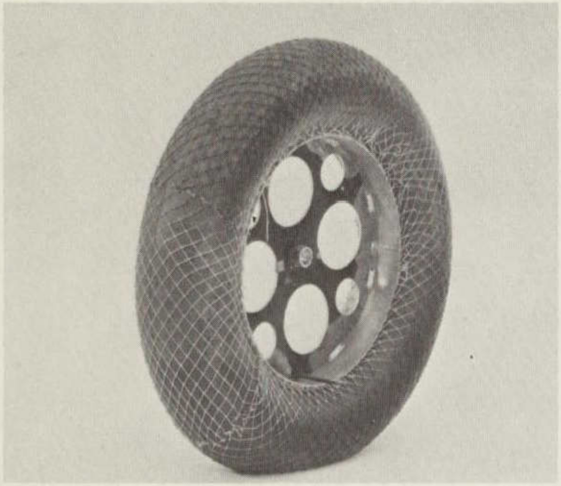
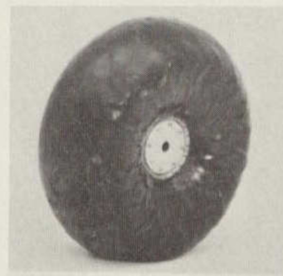


Fig. 7. Cantilevered test carriage with Boeing-GM I wheel

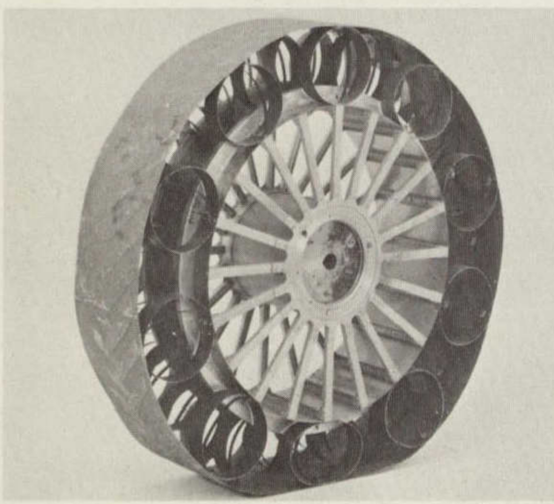


PNEUMATIC

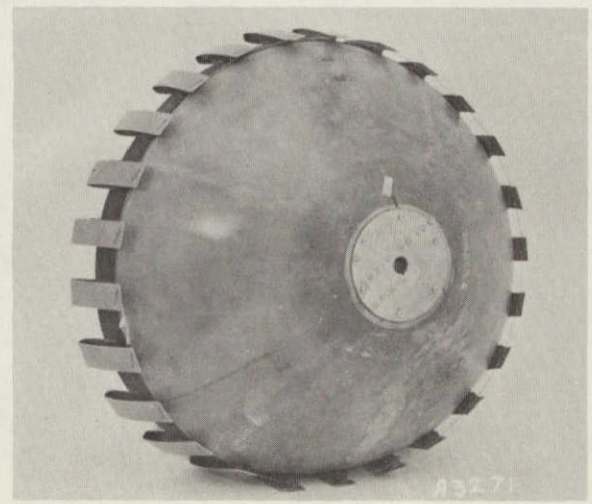


SLRV

BOEING-GM I



BENDIX I



GRUMMAN I

Fig. 8. Original test wheels

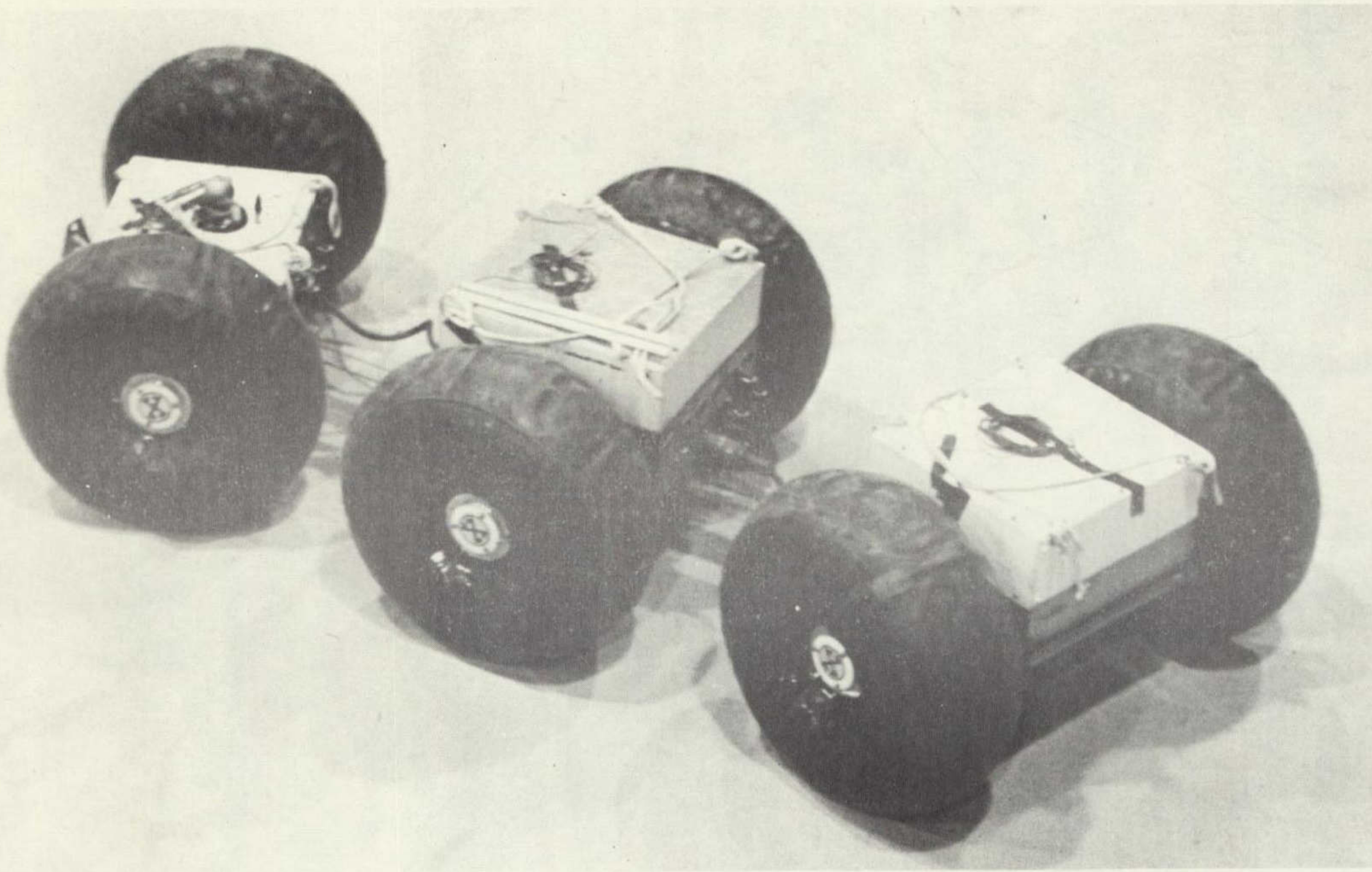


Fig. 9. 6x6 Surveyor Lunar Rover Vehicle (SLRV)

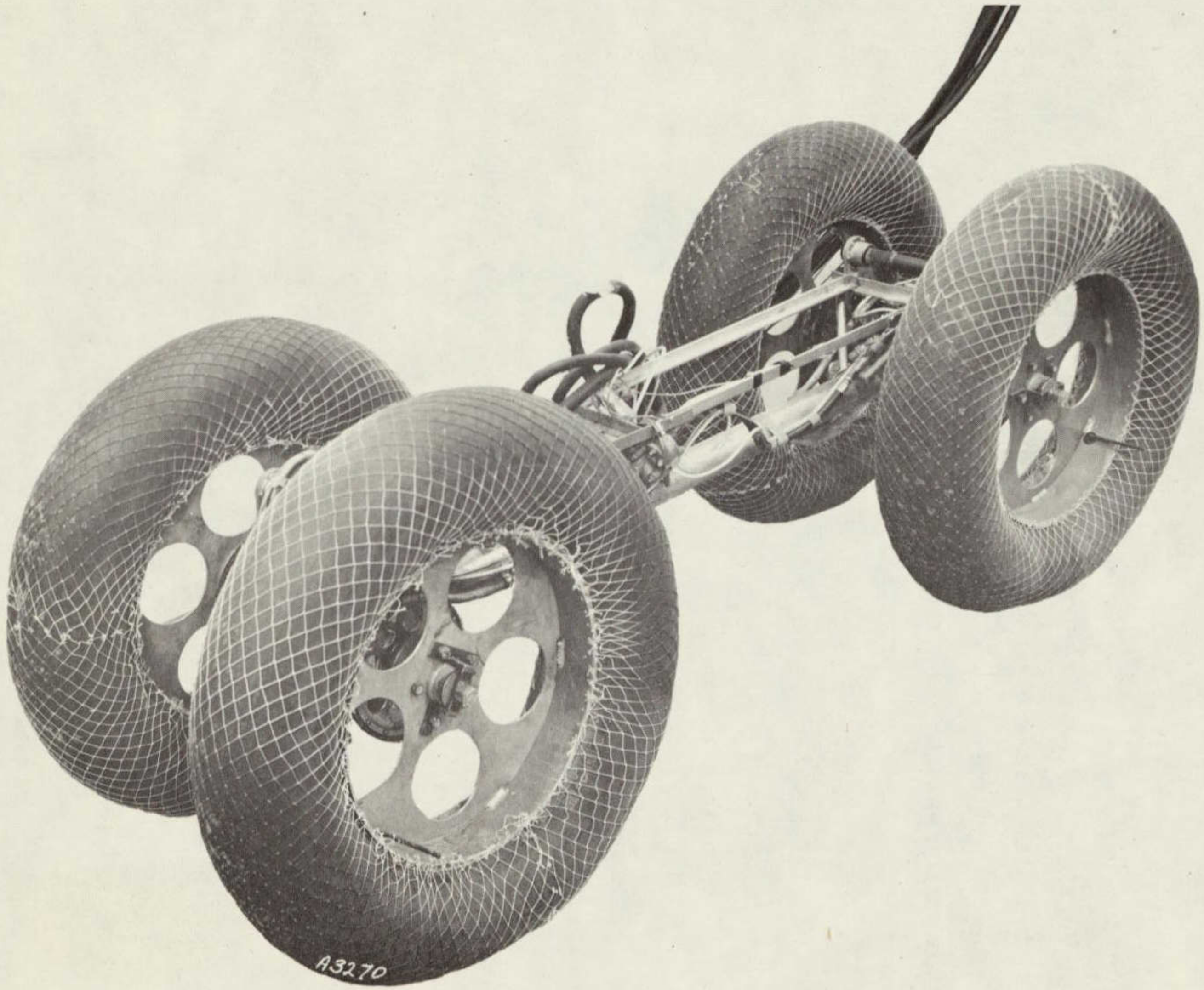


Fig. 10. 4x4 test vehicle

Test Procedures and Interpretation of Data for Single-Wheel and Vehicle Tests

Single-wheel tests

15. Tests were started in the negative slip range and progressed uniformly to 100 percent slip. The relation of the dimensionless pull and torque coefficients to wheel slip can be shown by two curves, such as those in fig. 11 which are representative of data obtained with the pneumatic, Bendix, Boeing-GM, and SLRV wheels, and in fig. 12, representative of data obtained with the Grumman wheel. Pull and torque coefficients reach a point at about 15 percent slip beyond which the rate of change in these parameters rapidly decreases. For this reason, data for comparing performance of all the wheels were read at the 20 percent slip point. A representative curve of efficiency versus slip, which was similar for all of the wheels, is shown in fig. 13. For consistency and ease of comparison, the efficiency at 20 percent slip η'_{20} was recorded for all the tests and is listed in table 3.

16. The plot of the power number PN versus the pull coefficient P/W (fig. 14) is especially important, since it expresses the energy consumed per unit of distance per unit of wheel or vehicle weight in relation to drawbar pull/slope-climbing ability. For example, to obtain the power consumption rate PCR in whr/km on a slope of 10 percent, read the value of PN at P/W = 0.10. Multiply this value by the wheel load or vehicle weight, expressed in newtons, and the fraction 1/3.6. Expressed in equation form:

$$PCR = \frac{PN}{3.6} \times W$$

$$PCR = PN \times \frac{1000\ m}{km} \times \frac{hr}{3600\ sec} \times N$$

$$PCR = PN \times \frac{1000}{3600} \times \frac{m\text{-}N}{sec} \times \frac{hr}{km}$$

Since PN is dimensionless and a watt is torque per unit time, i.e.

$$1\ watt = \frac{1\ m\text{-}N}{sec}\text{, then}$$

$$PCR = \frac{PN}{3.6} \times W = whr/km$$

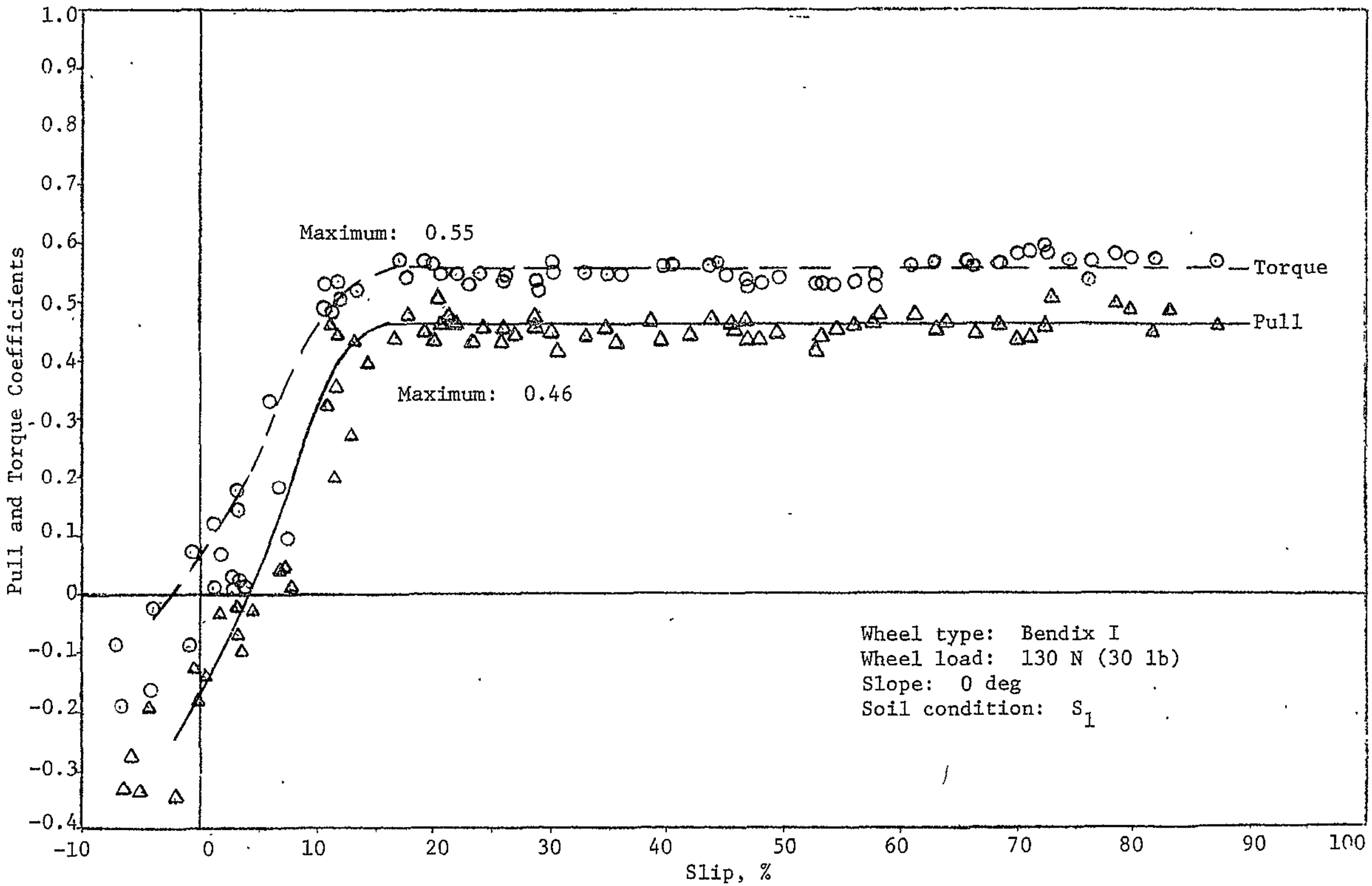


Fig. 11. Representative relations of pull and torque coefficients to slip for pneumatic, Bendix, Boeing-GM, and SLRV wheels

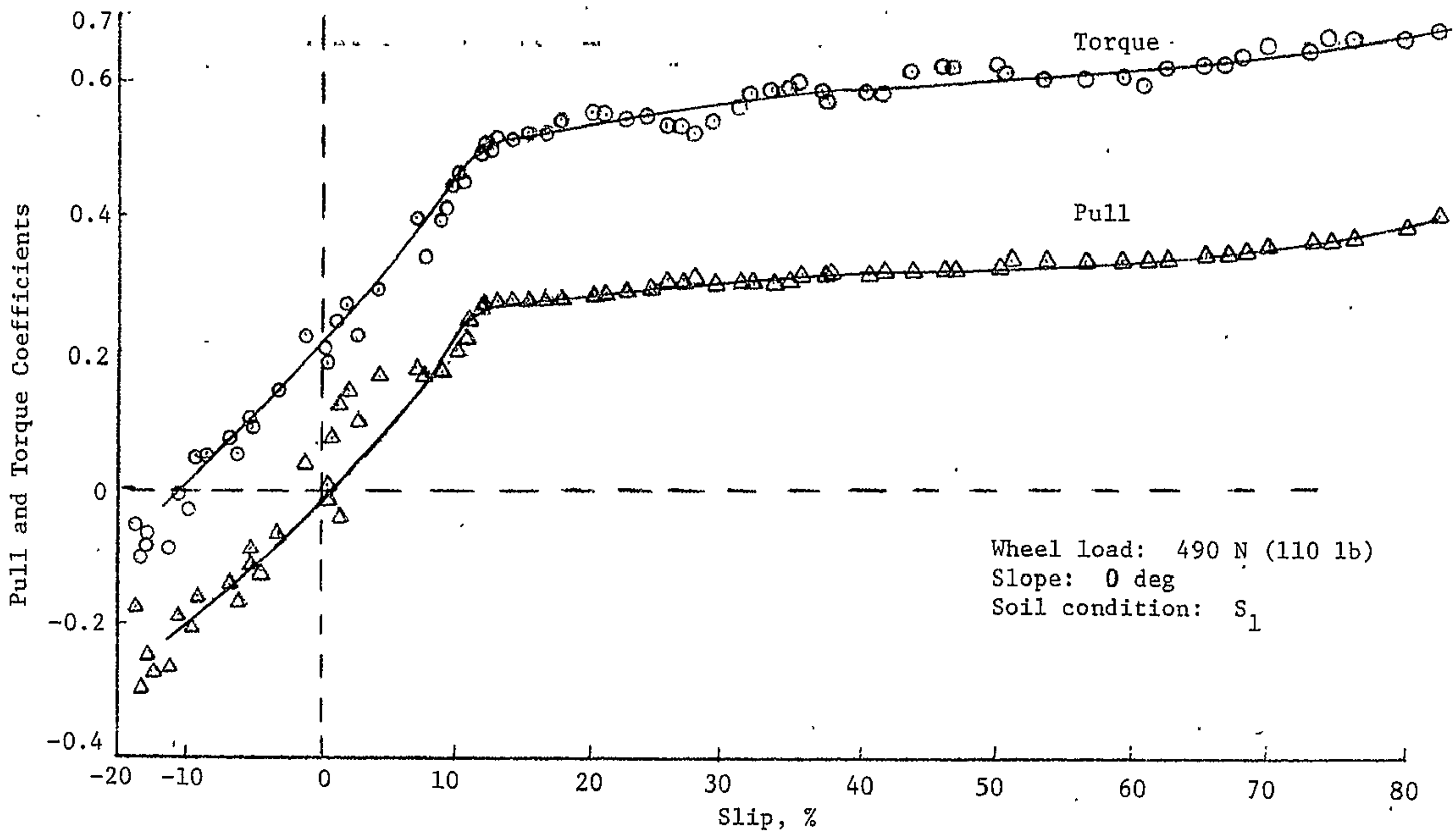


Fig. 12. Representative relations of pull and torque coefficients to slip for Grumman I wheel

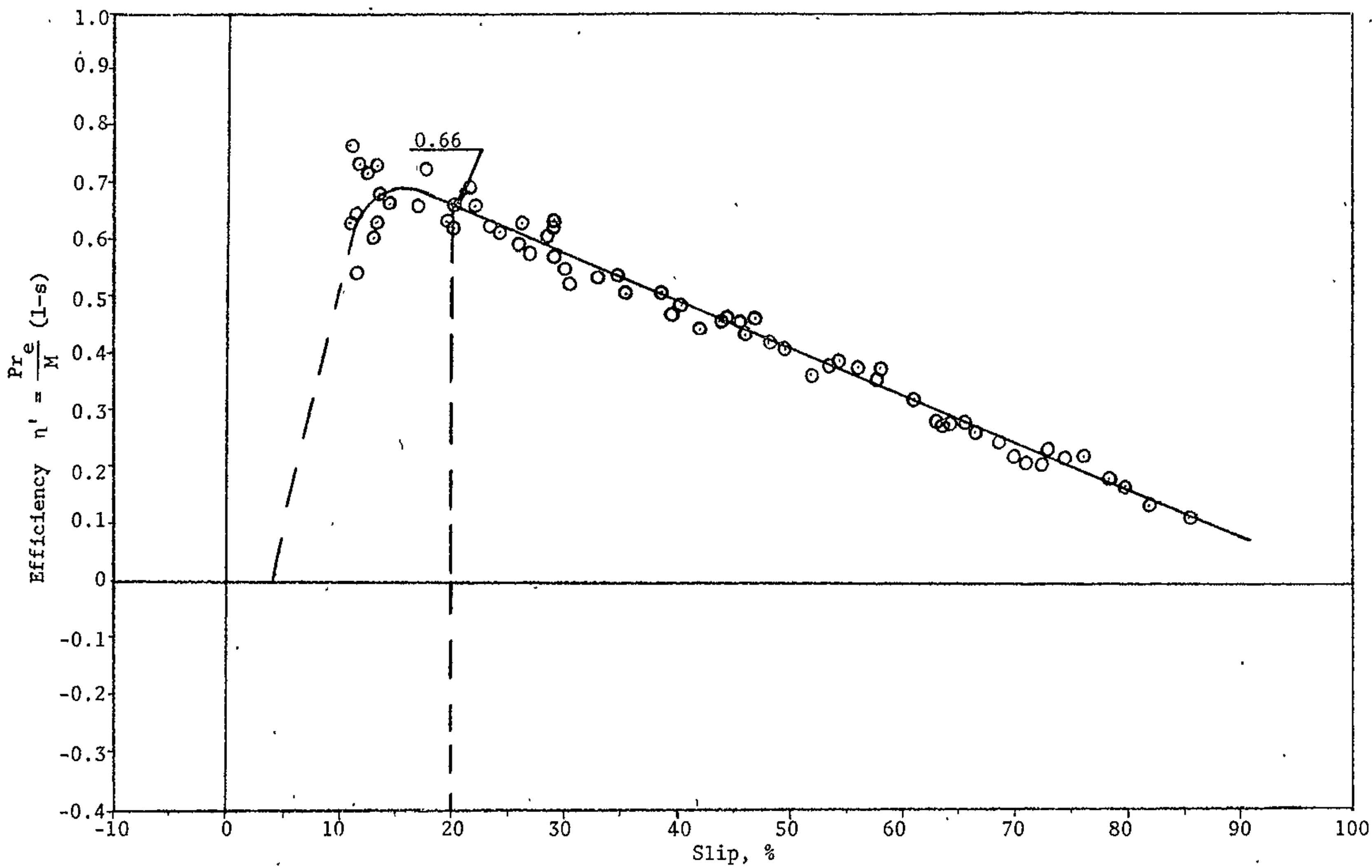


Fig. 13. Representative relation of efficiency to slip; Bendix I wheel; soil condition S_1 ; wheel load 130 N (30 lb)

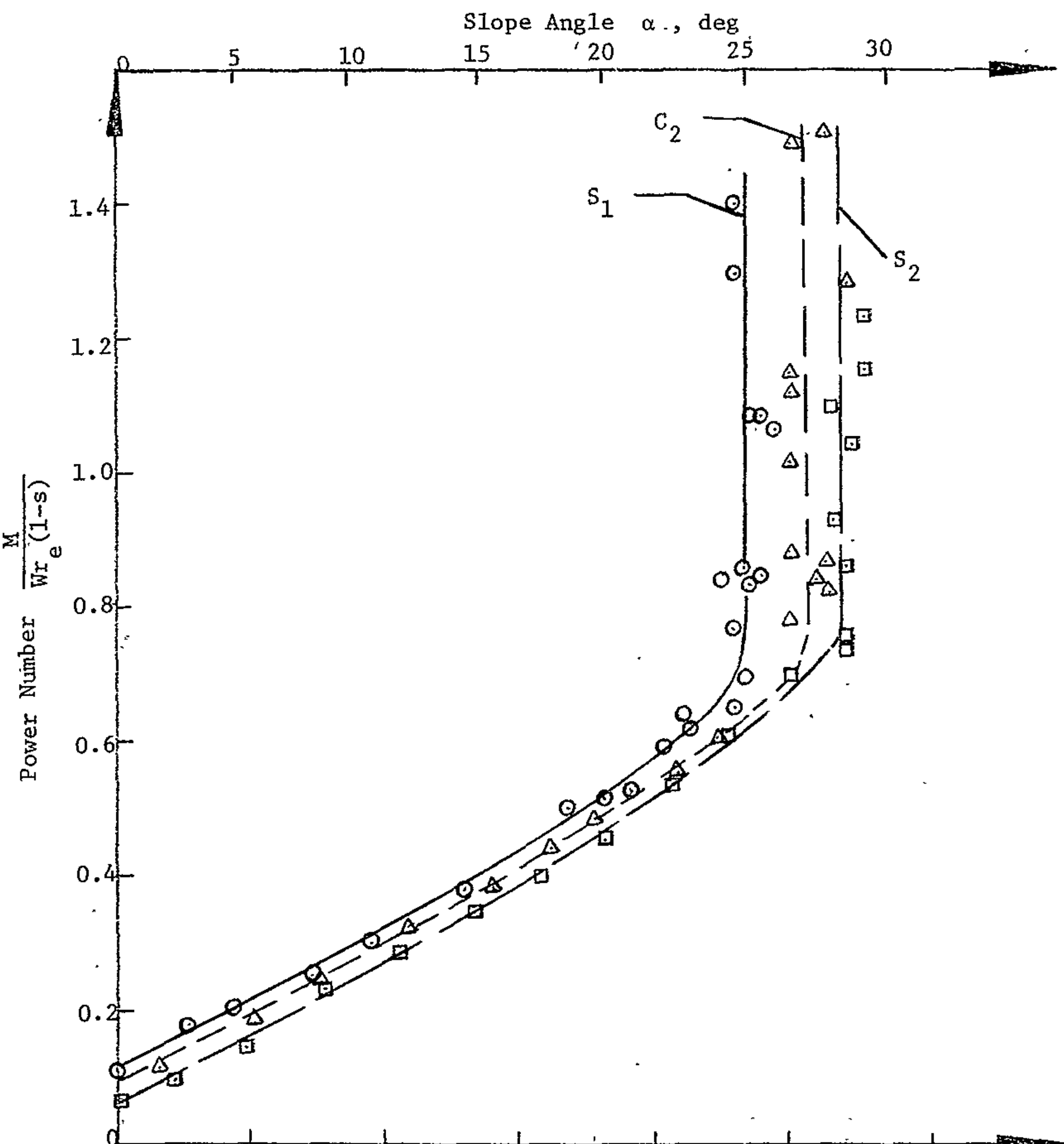


Fig. 14. Representative relations of power number to pull coefficient for various soil conditions; Bendix I wheel; wheel load 310 N (70 lb)

Vehicle tests

17. Representative pull-slip and torque-slip relations from the programmed-slip vehicle tests are shown in fig. 15. Although the average rate of slip change was slightly higher for the vehicle tests (i.e. the vehicle deceleration was slightly greater), the shape of the pull-slip and torque-slip curves was not significantly different from those for the single-wheel tests.

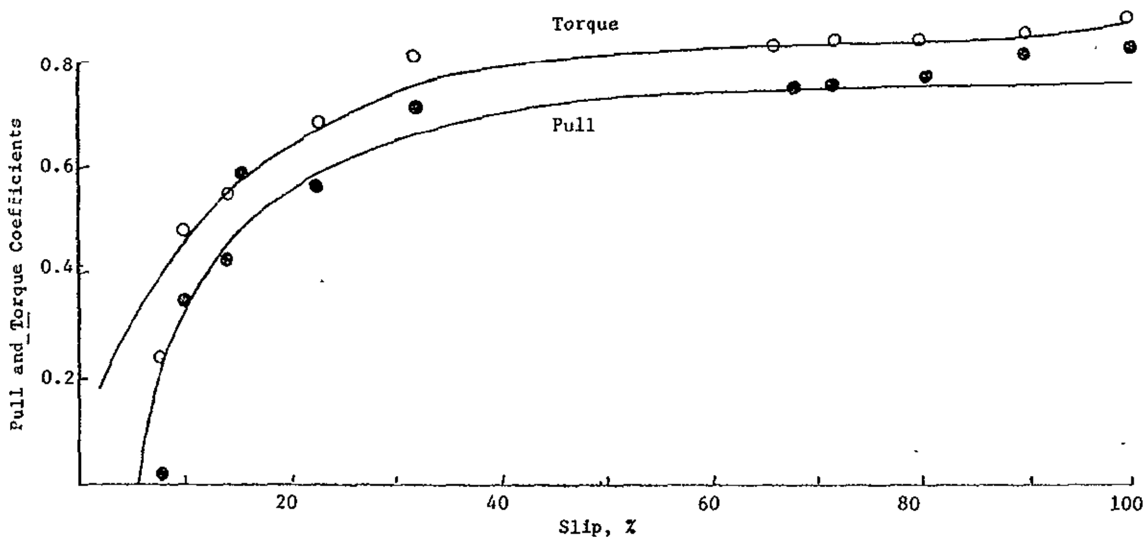


Fig. 15. Representative relations of pull and torque coefficients to slip for the 4x4 vehicle on wet sand; soil condition C_2

PART III: ANALYSIS OF SINGLE-WHEEL AND VEHICLE PERFORMANCE

Effects of Light Loads

Pull

18. The results obtained from tests in this study with the pneumatic and Bendix I wheels show that the pull versus load relation for air-dry sand is a straight line through the origin for loads between 0 and at least 220 N (50 lb) (fig. 16). The largest P/W ratios were obtained within this load range. For higher loads, the pull versus load relation starts to curve downward, showing a tendency to follow the general trend of the pull versus load relation for a more heavily loaded pneumatic wheel (fig. 17). It is pointed out that the deflection of both wheels changed as load changed, but this apparently did not influence the linearity between P and W within the light load range. The pull versus load relation for the wet sand (cohesion levels C_1, C_2, and C_3) is practically linear for the entire load range tested. Furthermore, there is no distinct difference in the results for the two wheels, when the tests were conducted on the same soil condition. [For more information see Freitag, Green, and Melzer (1970)].

Torque

19. The relation between torque at 20 percent slip (M_{20}) and W is practically linear for the pneumatic and the Bendix I wheels (fig. 18). The torque requirements for the pneumatic and Bendix I wheels are practically equal in the range of light loads [less than 220 N (50 lb)] on the same soil condition. [For more information see Freitag, Green, and Melzer (1970).]

Efficiency

20. In the case of all the wheels, except the Grumman, pull and torque are constant for slips higher than 10-20 percent (fig. 11); thus efficiency in the high slip range is a linear function of slip. Based on these data, the efficiency at 20 percent slip is given for a certain test, and the efficiency for every slip higher than 20 percent can be calculated.

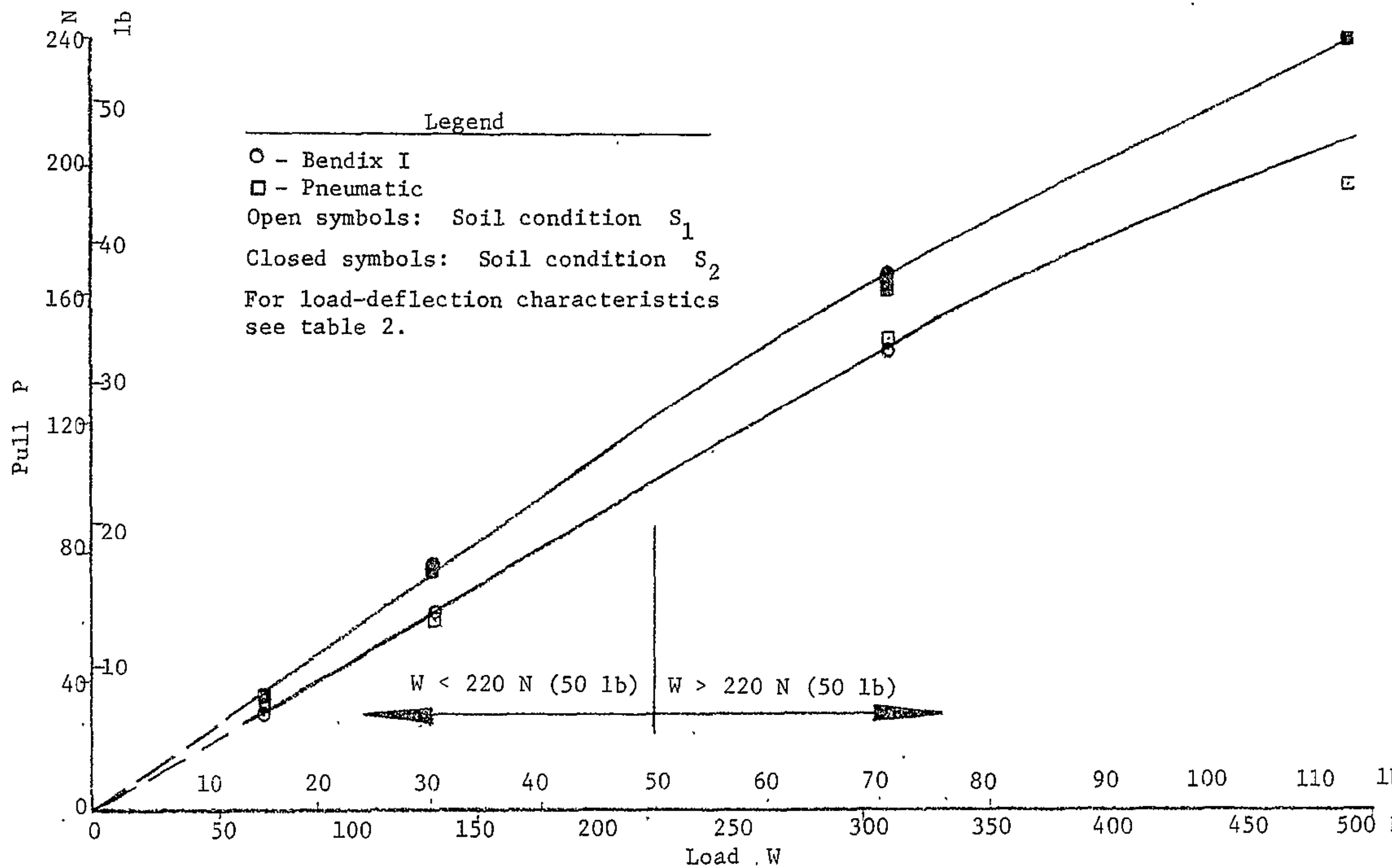


Fig. 16. Representative relation of pull to load for lightly loaded wheels

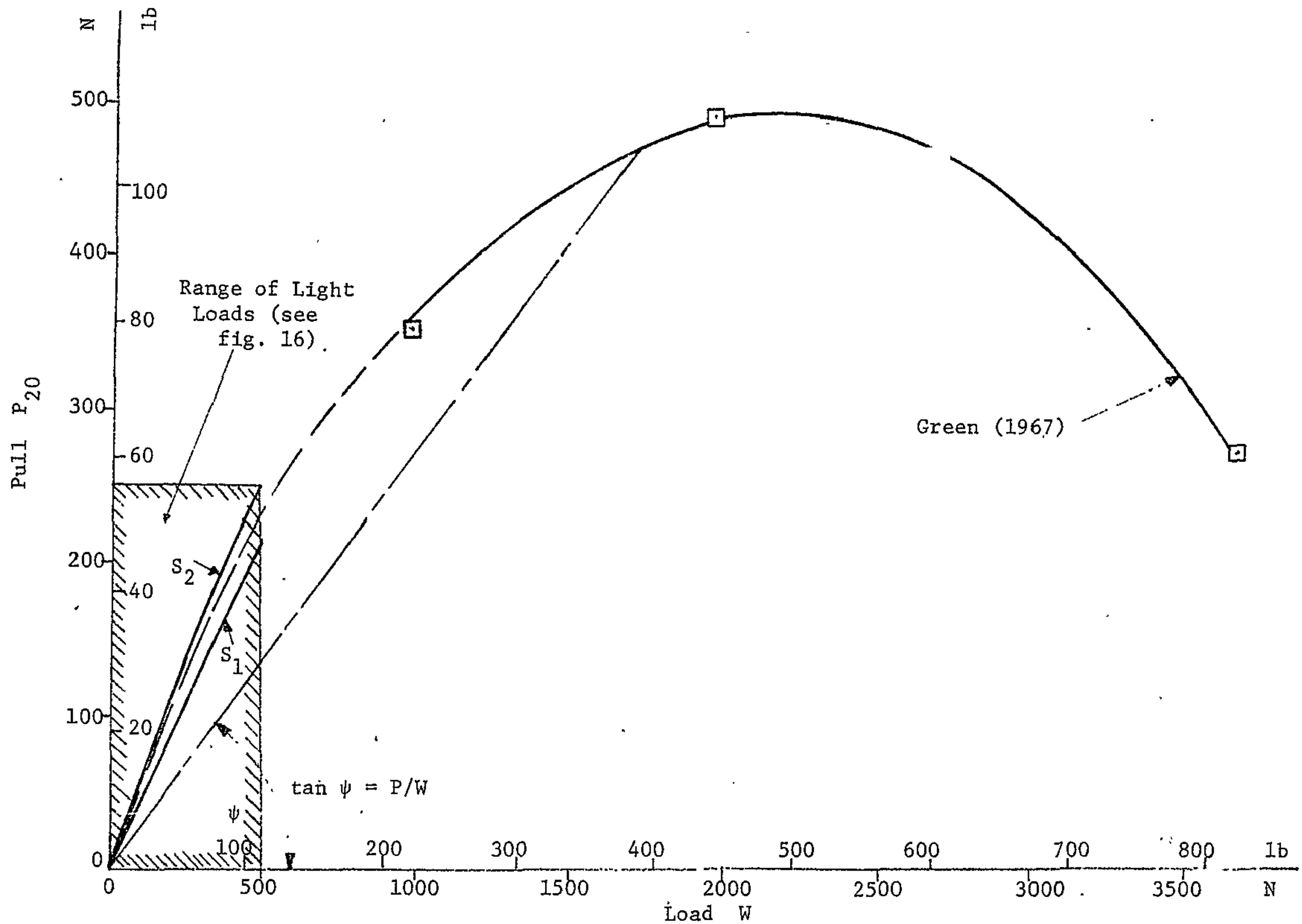
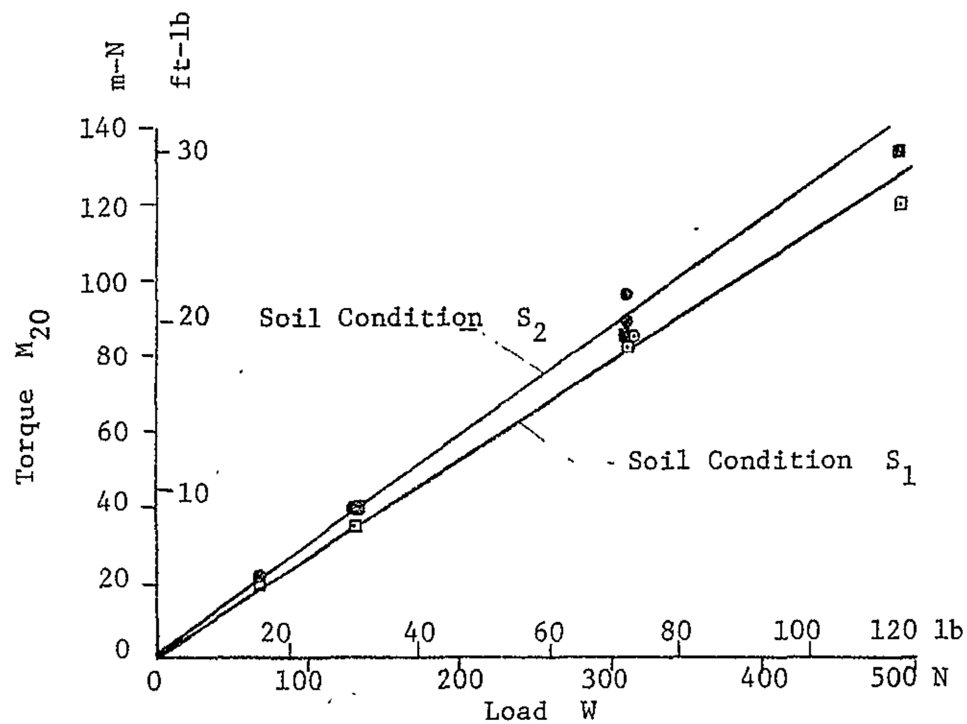


Fig. 17. Representative relation of pull to load for a heavily loaded pneumatic wheel on dense, air-dry yuma sand



Legend

○ - Bendix I
□ - Pneumatic
Open symbols; S_1 soil condition
Closed symbols: S_2 soil condition

Fig. 18. Representative relation of torque to load for lightly loaded wheels on air-dry sand

Power requirement

21. For the lightly loaded wheels, except for the Grumman, the pull/load ratio P/W was constant with increasing power number PN $[M/Wr_e(1-s)]$ after P/W reached its maximum (fig. 14).

Sinkage

22. The sinkages measured during tests at a 310-N (70-lb) load with each of the original metal-elastic wheels on the softest soil condition (S_1) are plotted in fig. 19. The sinkages for most other soil-load combinations are smaller. Because the sinkage values obtained in this study were relatively small, they were not evaluated quantitatively.

Effect of Soil Strength (Cohesion)

23. Two soil parameters, relative density and cohesion, are used herein to represent soil strength. Relative density is a measure of the frictional component of soil strength while cohesion is a direct measure of the cohesive component. Relative density is used instead of angle of internal friction, because the numerical values of the range of relative density are greater than the corresponding numerical values of the range of angle of internal friction. The two may be correlated, however. Pull at 20 percent slip, representing performance, for the test series with the pneumatic wheel was plotted versus relative density (fig. 20). The data are distinguishable by load. The following relations can be shown, based on an evaluation of these and similar data for other wheels (Freitag, Green, and Melzer, 1970):

- a. Pull and P/W ratio increase with relative density, but the rate of increase of P/W decreases with increasing relative density.
- b. There seems to be no influence of cohesion at light loads [lighter than 130 N (30 lb)], but at heavier loads its influence can be seen.

Effect of Deflection

24. Since the static deflection of a given metal-elastic wheel can be changed only by changing the load, but that of a pneumatic

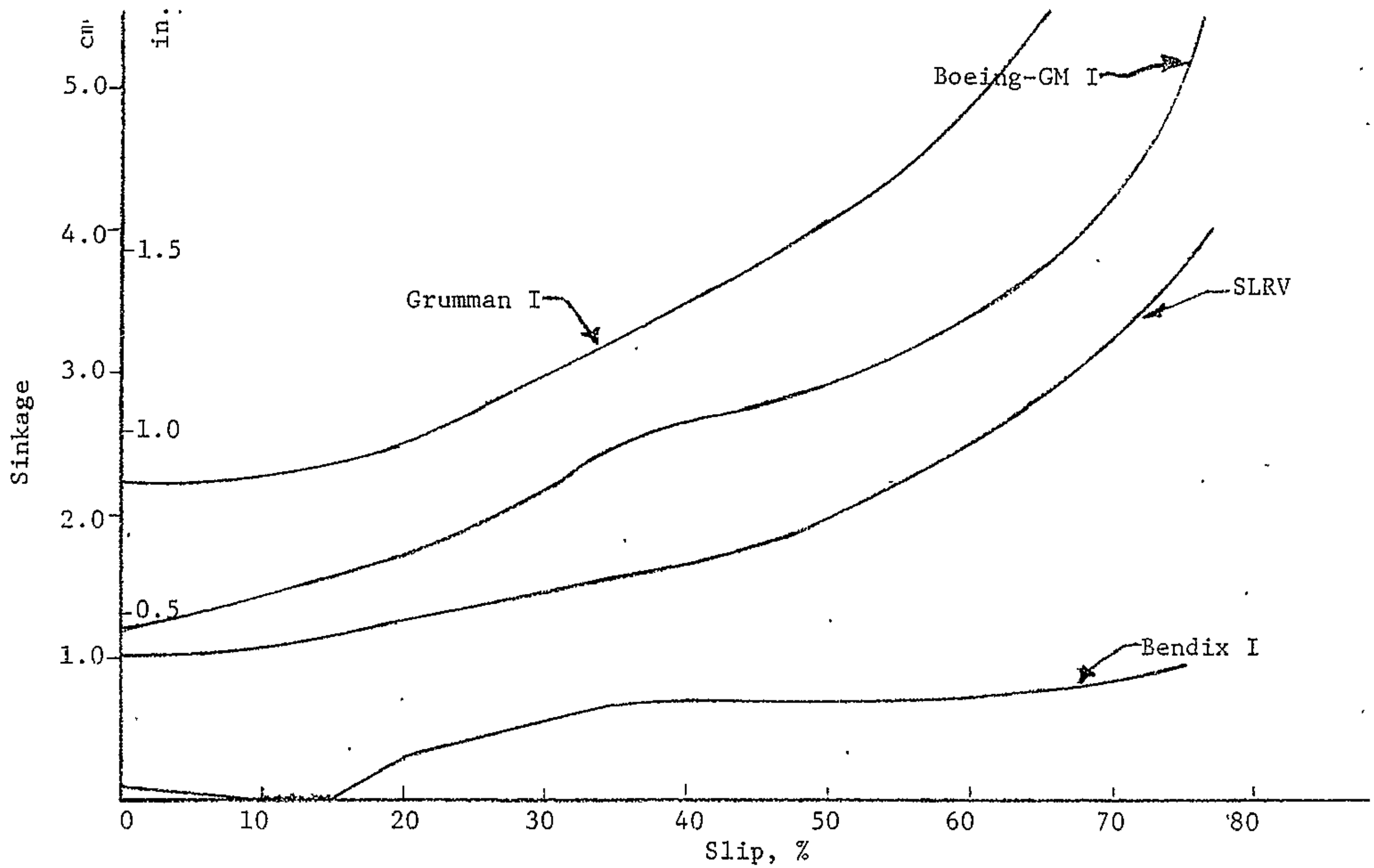
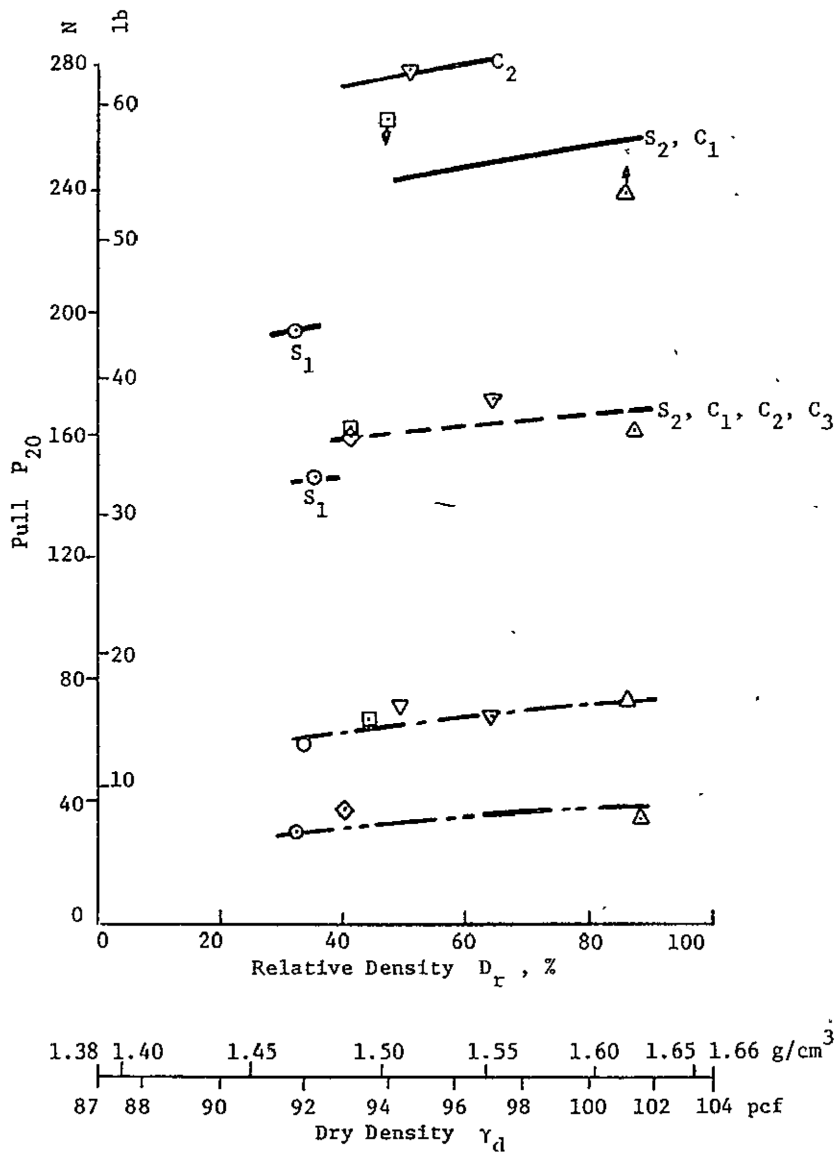


Fig. 19. Relation of sinkage to slip for basic metal-elastic wheels on air-dry Yuma sand (soil condition S_1) at 310-N (70-lb) load



Legend

Symbol	Soil Condition	Cohesion c_{tr} kN/m^2(psi)	Load N(lb)	Inflation Pressure kN/m^2(psi)
○	S_1	0(0)	–	–
△	S_2	0.39(0.06)	–	–
□	C_1	0.39(0.06)	–	–
▽	C_2	1.08(0.16)	–	–
◇	C_3	1.75(0.25	–	–
— ·· —	–	–	67(15)	0.07(0.10)
— · —	–	–	130(30)	2.62(0.38)
--------	–	–	310(70)	2.96(0.43)
————	–	–	490(110)	3.45(0.50)

Fig. 20. Relation of pull to relative density for various wheel loads and soil conditions (pneumatic wheel)

wheel can be changed by changing the inflation pressure, a special series of tests was run with the pneumatic wheel on soil condition S_1 and under a load of 310 N (70 lb), but with deflections ranging from 0.100 to 0.225 (10.0 to 22.5 percent). For the entire deflection range tested, pull or P_{20}/W was constant. This is confirmed qualitatively by the fact that for the same soil condition S_1, the pull versus load relation was linear for loads lighter than or equal to 310 N (70 lb), regardless of the deflection and the wheel type (see fig. 16).

Effect of Contact Pressure

25. Contact pressure is more or less closely related to the wheel load/deflection characteristics, wheel slip, speed, wheel geometry, and soil conditions. To illustrate its influence on performance, results of tests with all the original wheels plus the two modified Boeing-GM versions on soil condition S_1 were plotted versus contact pressure in fig. 21. The following general trends can be observed:

- a. Performance of the pneumatic and the Bendix I wheels was independent of contact pressure p_c when p_c was low. For $p_c > 4.0$ kN/m^2 (0.57 psi), the P_{20}/W ratio started to decrease. Both wheels showed practically the same performance for pressures up to 4.0 kN/m^2 (0.57 psi).
- b. The data from tests with the Grumman I wheel showed a decrease in P_{20}/W with increasing contact pressure, but the contact pressures were not as low as those reached by the pneumatic and Bendix I wheels. A similar trend can be seen from the results with the GM I, GM IV, and GM VI wheels.

Generally, it must be concluded, from the trends observed, that the P_{20}/W ratio is influenced not only by load, contact pressure, deflection, and the shear behavior of the soil, but also by the construction of the wheel, which influences contact pressure distribution. To examine this distribution, a test series was conducted in which the Bendix I, GM I, and Grumman I wheels were towed over a very loose sand in which colored chalk layers were built, a trench was dug into the sand,

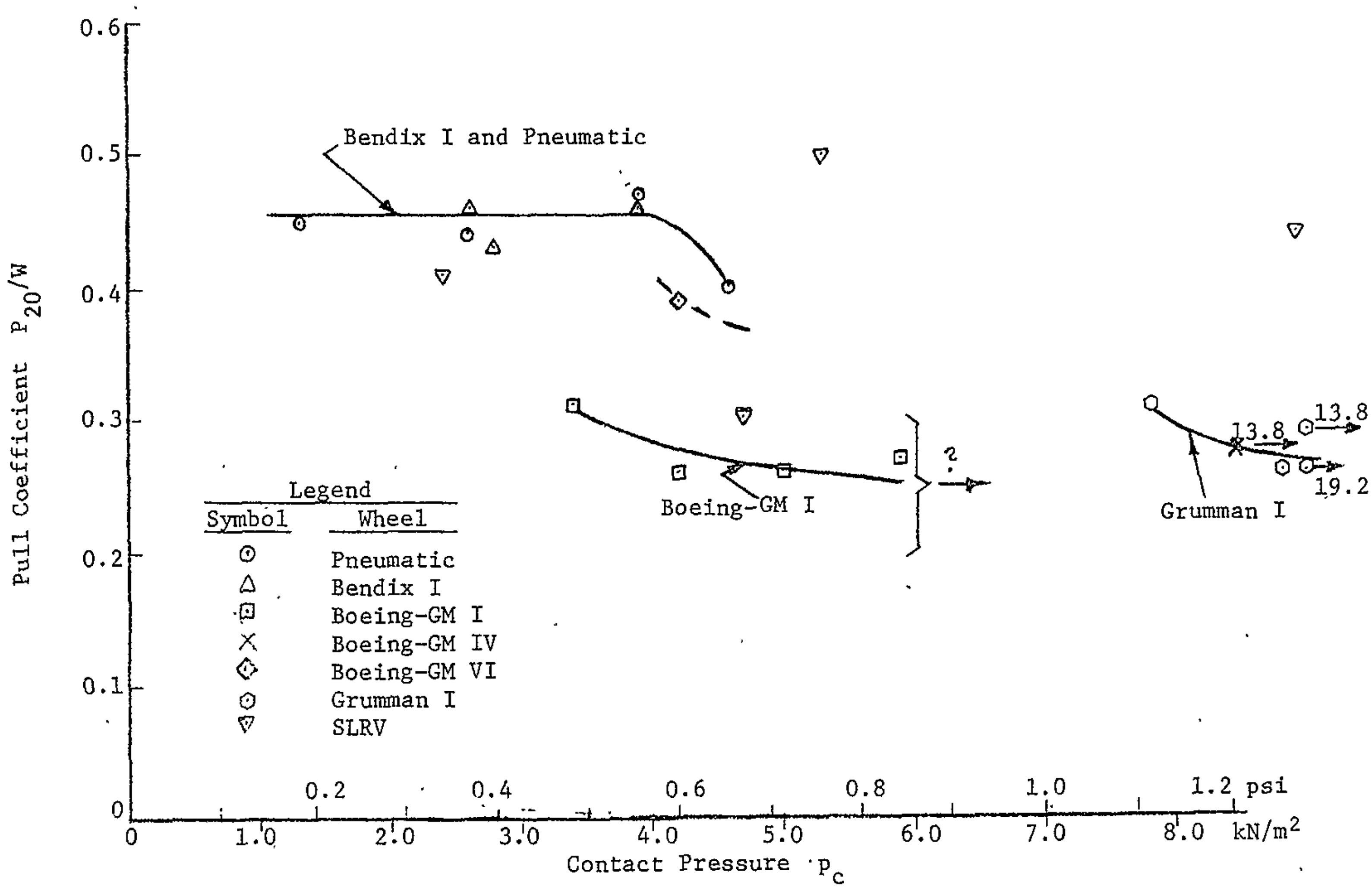


Fig. 21. Relation of pull coefficient to contact pressure for various wheels on soil condition S_1

and the deformation patterns were recorded. From these patterns, it was concluded qualitatively that the pressure distribution under the Bendix I wheel was more uniform than under the GM I and Grumman I wheels (figs. 22 and 23).

Effect of Repetitive Traffic

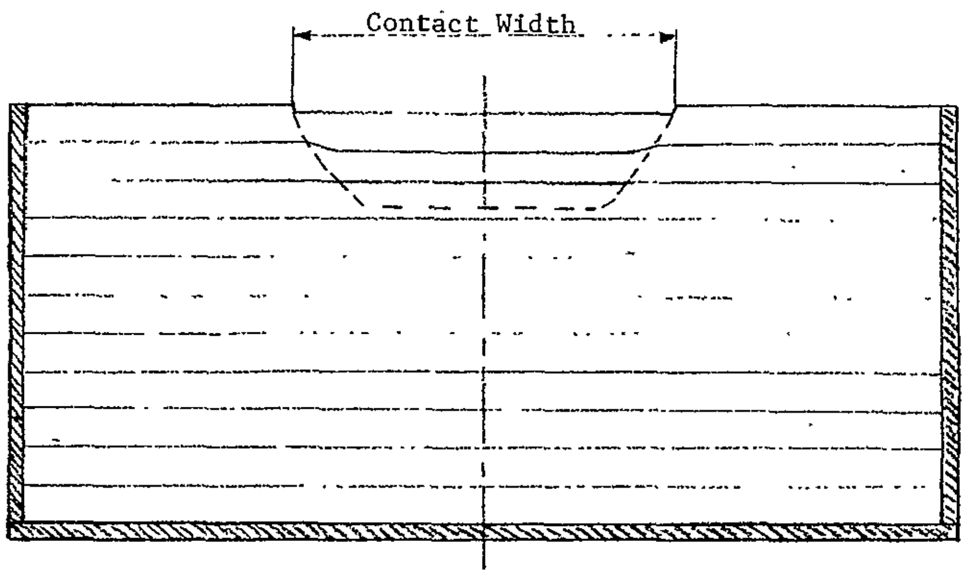
26. In the construction industry, the wheel is well recognized as a soil compaction device. It follows then that the passing of several wheels in the same path can be expected to alter soil conditions. Because of the light loads involved in this test program, the only condition in which considerable alteration was noted was the S_1 condition (loose, air-dry sand). For this case, it was generally observed that the soil strength increased with the number of passes, and the pull showed a corresponding increase of some 10-20 percent following the second pass.

Relative Performance of Pneumatic and Metal-Elastic Wheels

27. The relative performance of pneumatic and metal-elastic wheels is discussed in terms of drawbar pull/slope-climbing ability, total efficiency, and power number.

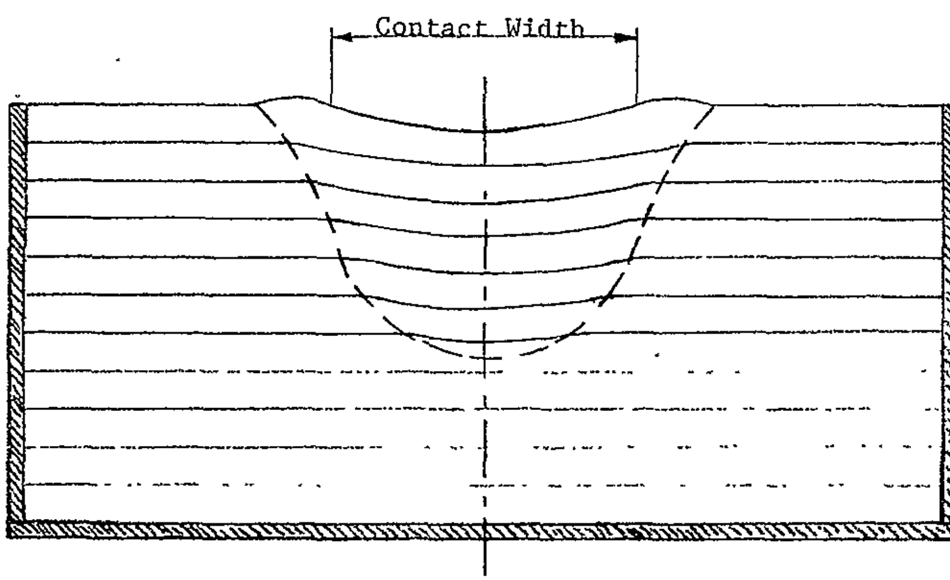
Comparative performance of original wheels

28. A summary of the performance of all the original wheels on two soil conditions is presented in the following tabulation, which lists the average values for tests at various loads. The tabulation indicates the relative pull/slope-climbing ability P_{20}/W ; torque requirements M_{20}/Wr_e ; and power consumption at the self-propelled point PN_{sp} , in operating on a 15-deg slope PN_{15} , and at a point where the slope of the power number versus P/W ratio curve changed abruptly and rapidly approached infinity PN_{max} . This change in slope usually occurred in the 15-20 percent slip range.



a. BENDIX I

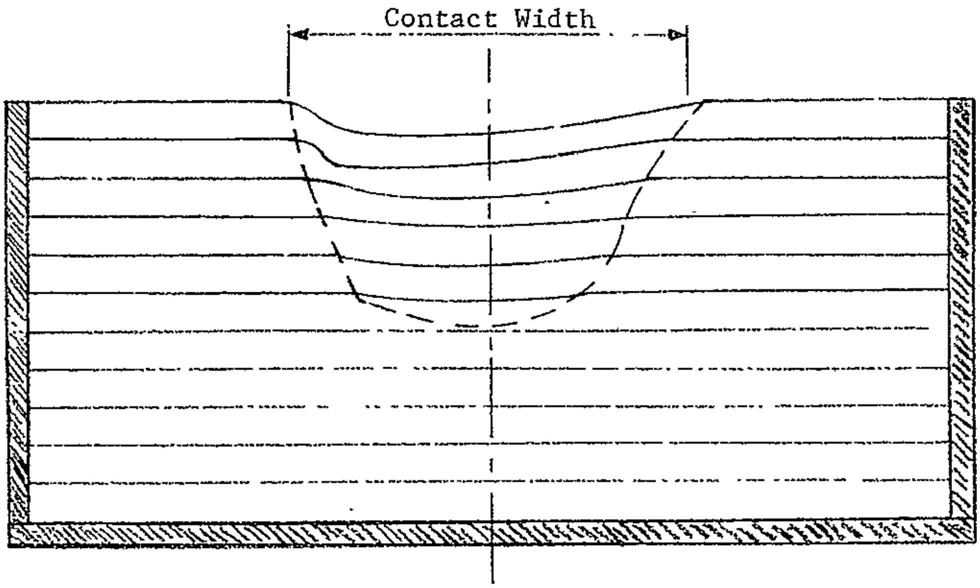
W = 377 N (85 lb)
Very loose sand
w = 1.5%; G = 0.3 MN/m^3 (1.1 pci)
Contact width = 25.4 cm (10 in.)
Contact length = 31.2 cm (12.25 in.)
Layer thickness: 2.5 cm (1 in.)



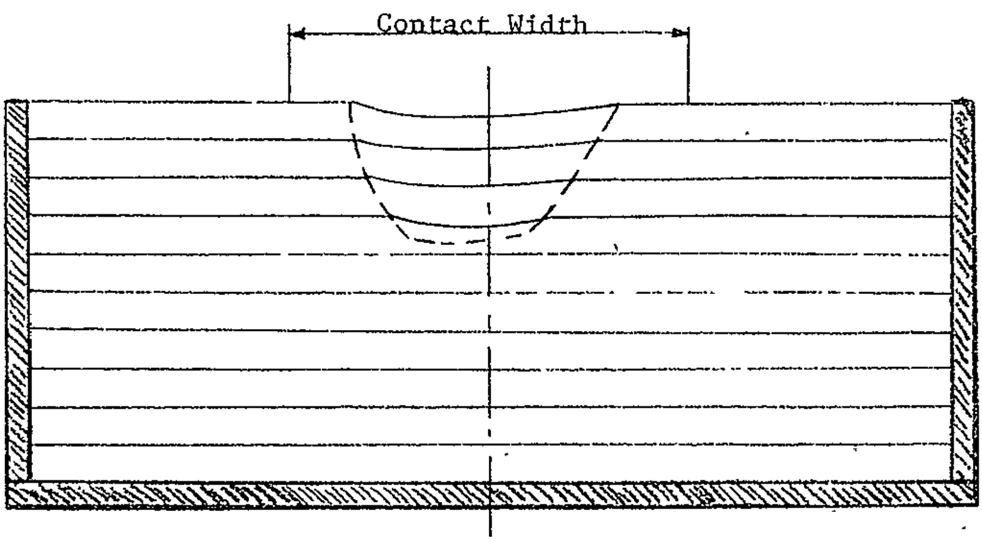
b. BOEING-GM I

W = 341 N (77 lb)
Very loose sand
w = 1.3%; G = 0.4 MN/m^3 (1.5 pci)
Contact width: 20.3 cm (8.0 in.)
Contact length: 32.0 cm (12.6 in.)
Layer thickness: ≈2.5 cm (1 in.)

Fig. 22. Deformation patterns beneath Bendix I and Boeing-GM I wheels



a. CROSS SECTION BENEATH GROUSER



b. CROSS SECTION BETWEEN TWO GROUSERS

W = 335 N (80 lb)
Very loose sand
w = 1.4%; G = 0.4 MN/m^3 (1.5 pci)
Layer thickness: 2.5 cm (1 in.)
Contact width: 26.0 cm (10.3 in.)
Total contact length:* 31.6 cm (12.5 in.)

* Only the grousers were in contact with the soil, not the wheel itself. Actual contact length: 13.6 cm (5.4 in.)

Fig. 23. Deformation patterns beneath Grumman I wheel

Dry Sand, Soil Condition S_1

Load Range W = 67-670 N (15-150 lb)

Wheel	n'_{20}	P_{20}/W	M_{20}/Wr_e	PN_{sp}	PN_{15}	PN_{max}
Pneumatic	0.612	0.448	0.585	0.150	0.422	0.722
Bendix I	0.632	0.452	0.568	0.067	0.425	0.620
Boeing-GM I	0.452	0.274	0.485	0.098	0.515	0.535
Grumman I	0.448	0.281	0.547	0.162	0.522	0.508
SLRV	0.590	0.426	0.581	0.080	0.386	0.643

Wet Sand, Soil Condition C_2

Load Range W = 67-670 N (15-150 lb)

Wheel	n'_{20}	P_{20}/W	M_{20}/Wr_e	PN_{sp}	PN_{15}	PN_{max}
Pneumatic	0.684	0.548	0.613	0.040	0.372	0.725
Bendix I	0.602	0.505	0.609	0.080	0.370	0.643
Boeing-GM I	0.650	0.343	0.472	0.067	0.382	0.503
Grumman I	0.455	0.272	0.507	0.127	0.478*	0.500
SLRV	0.602	0.602	0.613	0.165	0.482	0.700

* One test showed infinity; this value was not considered in computing the arithmetic average.

In general, these data indicate that none of the three original 40-in.-diam wheels could be relied on to propel a vehicle up a 35-deg slope and that the Bendix design gave the best overall traction performance. The close agreement between the performance of the pneumatic and Bendix wheels gave credence to the use of data collected in earlier studies with standard tires to develop a performance number (Freitag, 1965 and Green, 1967) suitable for metal-elastic wheels. This development is given by Freitag, Green, and Melzer (1970). This close agreement also gave assurance to plans to use pneumatic wheels for the slope-climbing tests.

29. For an assumed wheel load of 222 N (50 lb), the power consumption rate (PCR) for each of the three original metal-elastic wheels operating on a level surface of dry, loose sand (S_1) is given in the following tabulation:

Wheel	PN_{sp}	PCR whr/km
Bendix I	0.067	4
Boeing-GM I	0.098	6
Grumman I	0.162	10

Computation of the PCR on a slope less than the critical one can be accomplished as shown in the following example:

a. Assume a linear relation between the power number and the pull coefficient (gradeability) between P/W equals zero and P_{20}/W (which is a reasonably good approximation; see fig. 14).

b. Base computations on an average slope of 25 percent and a vehicle equipped with Bendix wheels carrying an average load of 222 N (50 lb).

c. Use the following data from the preceding paragraph:

$PN_{sp} = 0.067$ at $P/W = 0$

$PN_{max} = 0.620$, roughly corresponds to $P_{20}/W = 0.452$

d. Solve for PN at P/W = 0.25:

$$PN = (m)\ (P/W) + b$$
$$PN = \frac{0.620 - 0.067}{0.452}\ (0.25) + 0.067$$
$$PN = 0.306 + 0.067$$
$$PN = 0.373$$

e. Compute PCR by the equation:

$$PCR = PN \times W \times 1/3.6$$
$$= 0.373 \times 222 \times 1/3.6$$
$$= 23 \text{ whr/km/wheel}$$

Power number versus pull coefficient curves for the original Bendix, Grumman, and Boeing-GM wheels performing in air-dry (S_1) and wet (C_2) sands are shown in figs. 24 and 25, respectively.

Performance of the modified wheels

30. The rather large variations in the performance of the three original metal-elastic wheels made obvious a need for modifications of these wheels in order to increase the soft-soil performance of each, if possible.

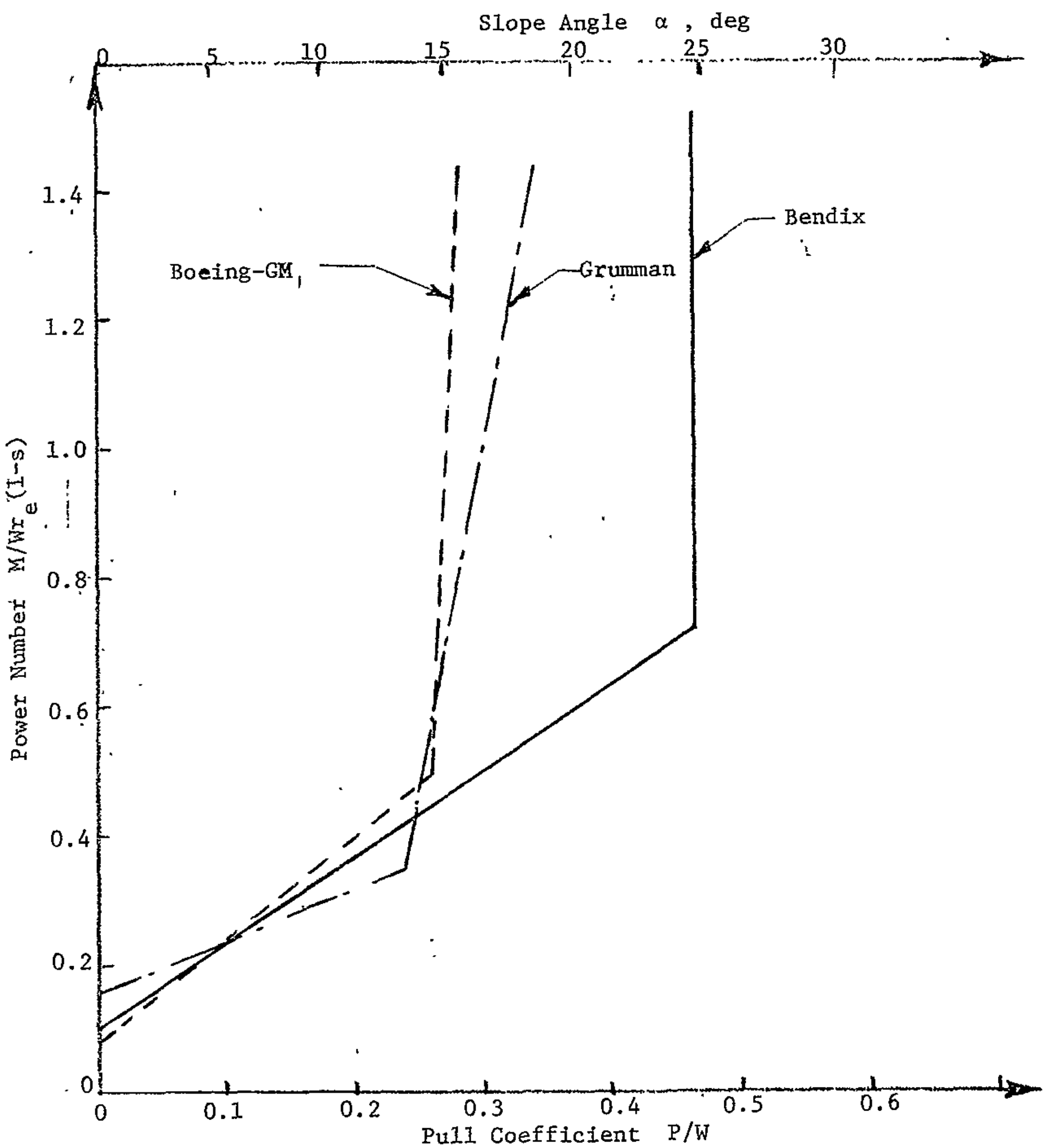


Fig. 24. Relation of power number to pull coefficient for three lunar rover wheels in air-dry sand (S_1); 310-N (70 lb) wheel load

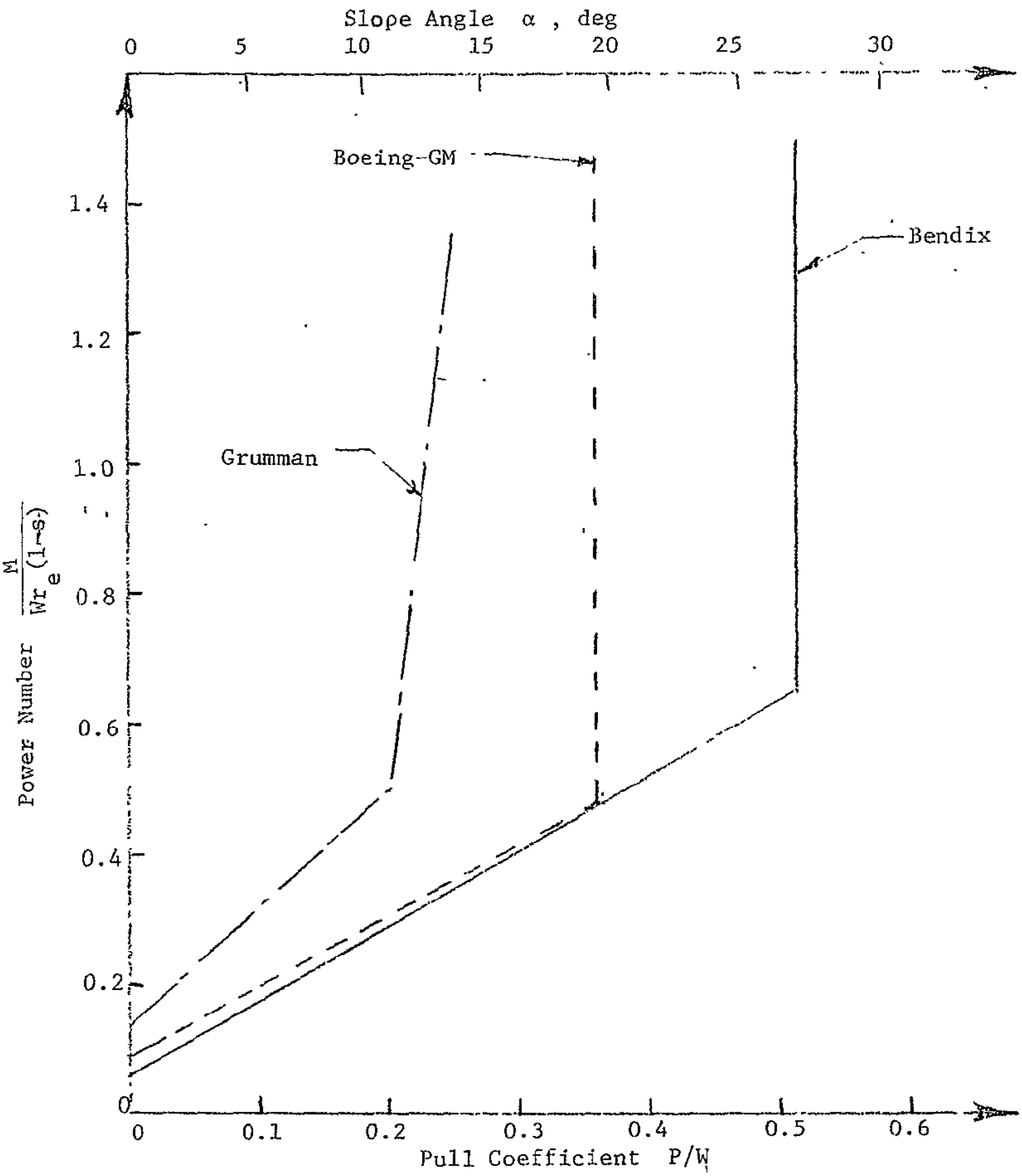


Fig. 25. Relation of power number to pull coefficient for three lunar rover wheels in wet sand (C_2); 310-N (70-lb) wheel load

31. Boeing-GM. Observers of the tests at WES, including WES, NASA, Boeing, and General Motors representatives, agreed that the Boeing-GM I wheel was far too stiff (unfavorable pressure distribution), and that it should be covered to minimize energy losses due to sand transport. Modifications were made, including roughening the surface of the original wheel, covering it with several types of fabric covers, and removing part of the wire structure to reduce stiffness. The fabric-covered, reduced-stiffness version produced the most substantial increase in performance over that of the original version (Boeing-GM I). Comparisons of tests in wet and dry sands show increases in pull/slope-climbing ability of 35 and 50 percent, respectively (see tests 27, 60, 72, and 74-76 in table 3).

32. Grumman. Angle-iron grousers 30.5 cm (12 in.) wide and 3.2 cm (1-1/4 in.) deep were added to the original Grumman wheel. At a wheel load of 310 N (70 lb), the modified wheel (Grumman II) developed 60 to 100 percent greater pull than the Grumman I, was slightly more efficient, and had slightly higher power consumption rates at the self-propelled point, and this latter difference increased as the pull coefficient P/W increased, as shown in the following tabulation:

Wheel	Soil Symbol	η_{20}	P_{20}/W	M_{20}/Wr_e	P_{60}/W	M_{60}/Wr_e	PN_{sp}	PN_{15}	PN_{max}
Grumman I	S_1	0.430	0.260	0.530	0.315	0.580	0.16	0.35	0.34
Grumman II	S_1	0.480	0.529	0.889	0.650	1.010	0.18	1.10	0.61
Grumman I	C_2	0.360	0.200	0.460	0.220	0.540	0.15	0.50	
Grumman II	C_2	0.460	0.565	0.473	0.633	1.015	0.20	0.93	0.54

33. Bendix. While the Bendix I wheel had a favorable overall contact pressure distribution, it was felt that this wheel might perform somewhat better in soft soil with the addition of an aggressive grouser (Bendix III). Several types were tried, and the grouser that resulted in the greatest improvement in performance was identical to that added to the Grumman wheel. These grousers substantially increased the performance of the Bendix wheel, as shown in the following tabulation:

Test No.	Wheel	Soil Symbol	Wheel Load N(lb)	η'_{20}	P_{20}/W	M_{20}/Wr_e	PN_{sp}	PN_{15}	PN_{max}
11	I	S_1	310(70)	0.645	0.465	0.576	0.10	0.38	0.52
89	III	S_1	310(70)	0.560	0.512	0.734	0.10	0.50	0.86
80	I	S_1	67(15)	0.610	0.425	0.553	0.04	0.38	0.58
90	III	S_1	67(15)	0.530	0.697	1.052	0.10	0.43	0.97
24	I	C_2	310(70)	0.675	0.514	0.609	0.08	0.36	0.65
88	III	C_2	310(70)	0.540	0.571	0.848	0.05	0.50	1.01

34. The increase in wheel pulling performance and power demands resulting from the addition of agressive grousers such as those described above may be tentatively explained by considering mobilization of passive earth pressures at the vertical face of the grousers (Freitag, Green, and Melzer, 1970).

Relation of Pull Coefficient to Slope-Climbing Ability and Prediction of Vehicle Performance from Single-Wheel Tests

35. There are many differences in the operations of a single wheel on a level soil surface and a vehicle on level or sloping surfaces: The soil conditions are different for successive wheels; the slip rate at which a wheel of a vehicle passes a given point is different from that of each other wheel; wheels may not track properly; the vehicle transfers load from one axle to another during ascent and descent of slope, acceleration, and deceleration; and the failure patterns in the soil may be different for level and sloping surfaces. The complexities involved preclude any rational attempt to determine which factors are additive and which are not in assessing the difference in performance of a single wheel and a vehicle on level and sloping surfaces.

36. For this reason, comparable single-wheel and vehicle tests have been conducted and the results are shown in tables 3 and 4, respectively. To compare these data two assumptions are made:

a. The performances of a single wheel on the first, second, third, and successive passes in the same rut are averaged for comparison with vehicle performance, with the number of passes used corresponding to the number of axles on the vehicle used in the comparison.

b. The pull coefficient is algebraically equivalent to the tangent of the angle of the slope that a vehicle is climbing, and therefore on slopes less than critical, the pull coefficient plus the tangent of the angle of the slope being climbed approximately equals the tangent of the angle of the critical slope (Rush, 1963).

P/W + tan α (4x4 vehicle)

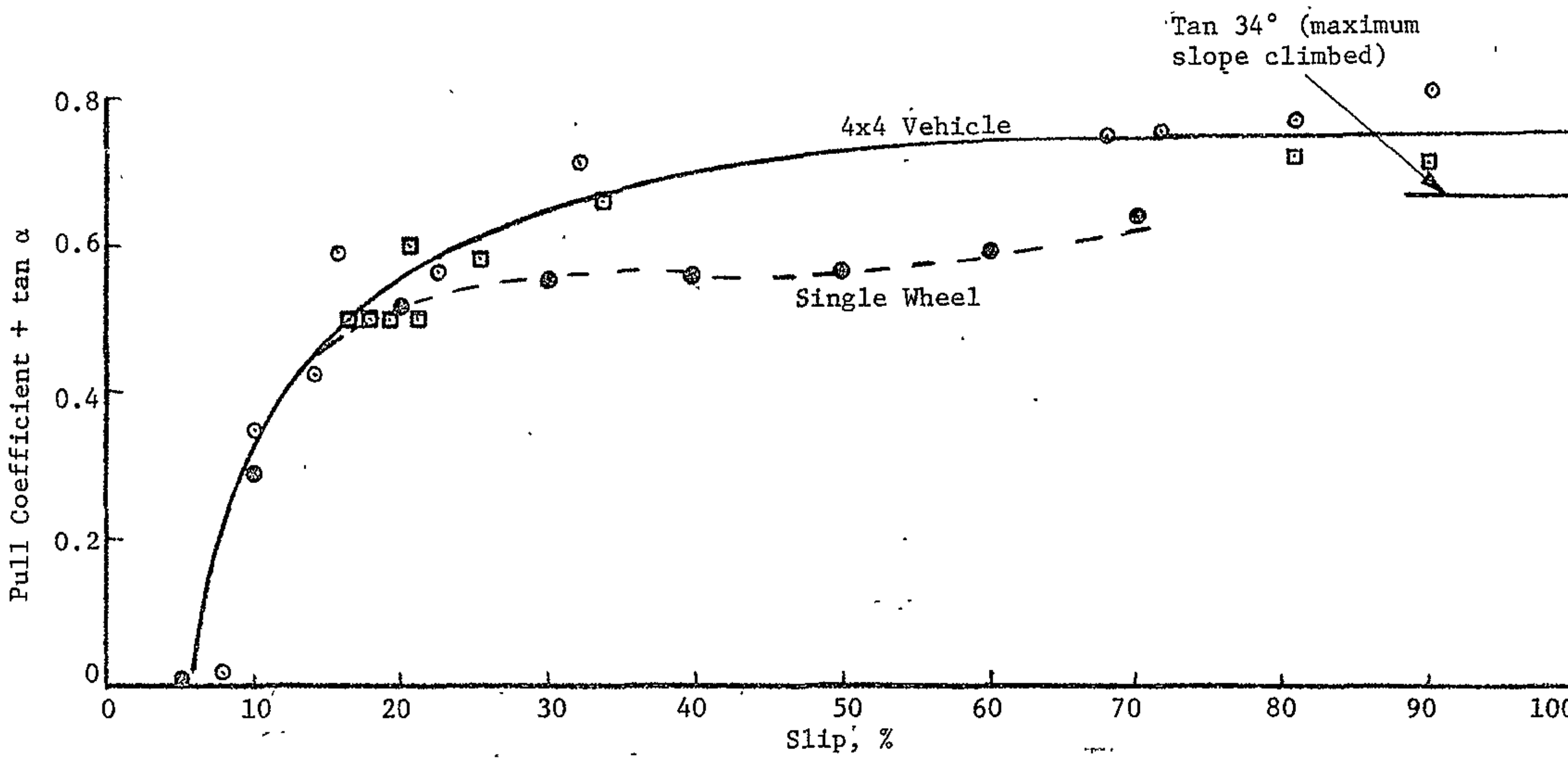
37. The performance data of the 4x4 vehicle with a wheel load of 310 N (70 lb) on level surfaces and on slopes of wet sand (C_2 condition) are shown together with corresponding single-wheel data in fig. 26. These and similar data indicate that the tangent of the maximum slope that the vehicle climbed is slightly less than might be indicated by the summation of the pull coefficient and the tangent of the slope climbed. It is of interest to note that these summations for the various slopes are uniquely related to slip for the vehicle operating on slopes less than critical. Comparable single-wheel data indicate slightly less slope-climbing ability than does a vehicle test. Thus it may be said that the single-wheel tests may give a conservative estimate of slope-climbing ability. This trend is evident for the entire range of loads and soil conditions considered in this program (tables 3 and 4).

Torque (4x4)

38. The curve in fig. 27 is representative of the coefficient versus slip relation for a given load and soil condition regardless of the slope climbed. In addition, this relation is not significantly affected by soil strength at the light load shown [310 N (70 lb)]. Comparable single-wheel data show a similar trend as observed in the comparison of the P/W ratios for the 4x4 vehicle and single-wheel tests, i.e. torque coefficients for the 4x4 are slightly less than those for the vehicle at equivalent slips after a slip of approximately 20 percent is reached.

Load transfer (4x4)

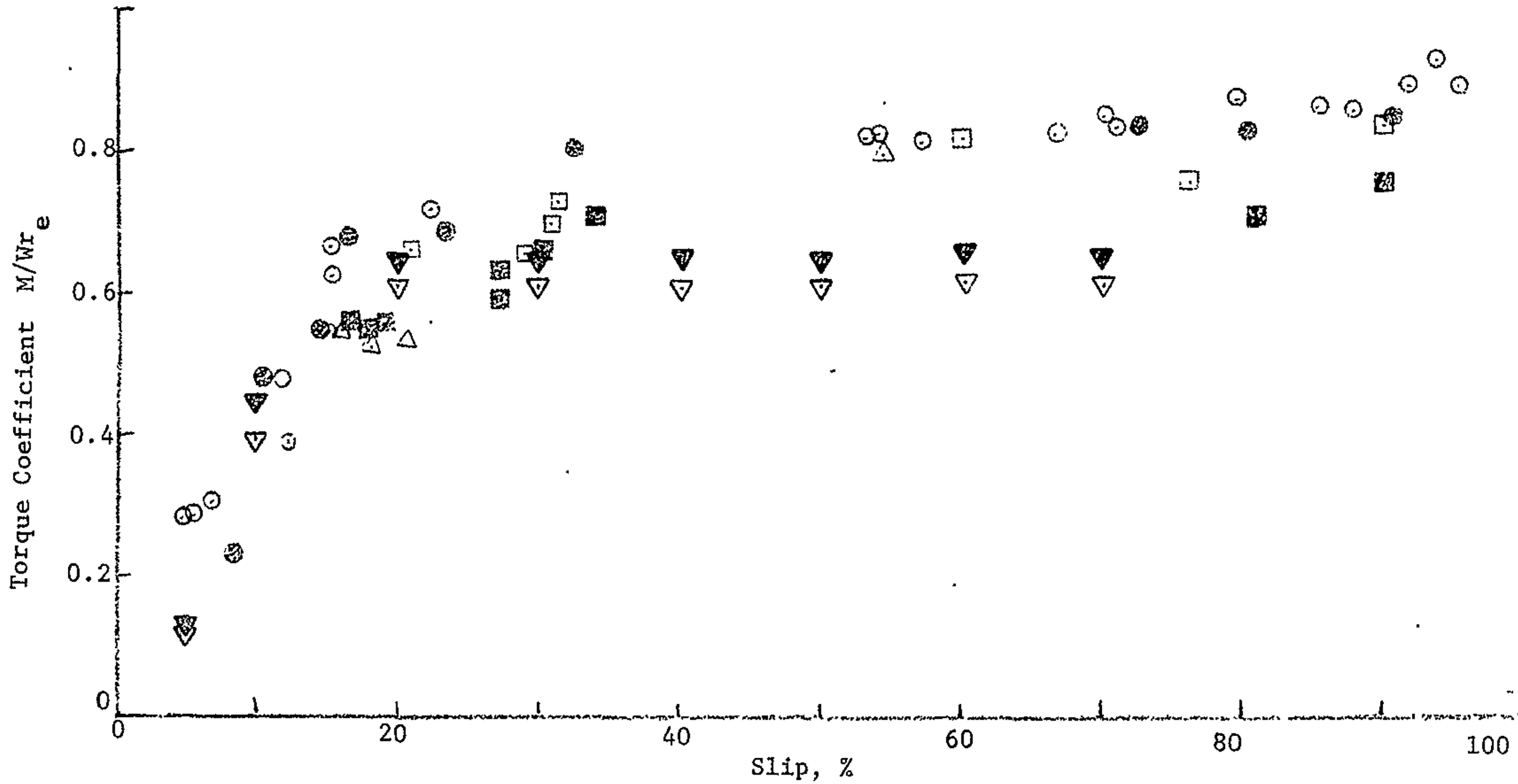
39. The total load transfer from the front to the rear axle was



Legend

Symbol	α, deg
○	0
□	25
⊛	Average of 1st and 2d pass single wheel

Fig. 26. Relation of pull coefficient + tan α to slip for 4x4 vehicle on wet sand (soil condition C_2); 310-N (70-lb) wheel load pneumatic wheels, 3.03-kN/m^2 (0.44-psi) inflation pressure



Legend

Symbol	α, deg
○	0
△	15
□	25
▽	Avg of 1st and 2d pass, single wheel

Open symbols: S_1

Closed symbols: C_2

Fig. 27. Relation of torque coefficient to slip for 4x4 vehicle on loose, dry sand (soil condition S_1), and wet sand (soil condition C_2); 310-N (70-lb) wheel load, pneumatic wheels, 3.03 kN/m^2 (0.44 psi) inflation pressure

computed for each of the 4x4 vehicle tests. On a level surface and with the vehicle towing a load, 6 to 8 percent of the load was transferred to the rear axle at slips higher than about 20 percent. On a 25-deg slope, approximately 20 percent of the load was transferred to the rear axle.

$P/W + \tan \alpha$ (6x6)

40. Single-wheel performance data are compared to those for the 6x6 SLRV in fig. 28 for tests in a wet sand. The maximum slope actually climbed by the vehicle was approximately 3 deg less steep than would have been predicted based on drawbar pull tests with the vehicle. On the other hand estimates of the vehicle's slope-climbing ability based on single-wheel tests would tend to be conservative. This trend is evident for the range of soil conditions considered in this program (see tables 3 and 4).

Torque (6x6)

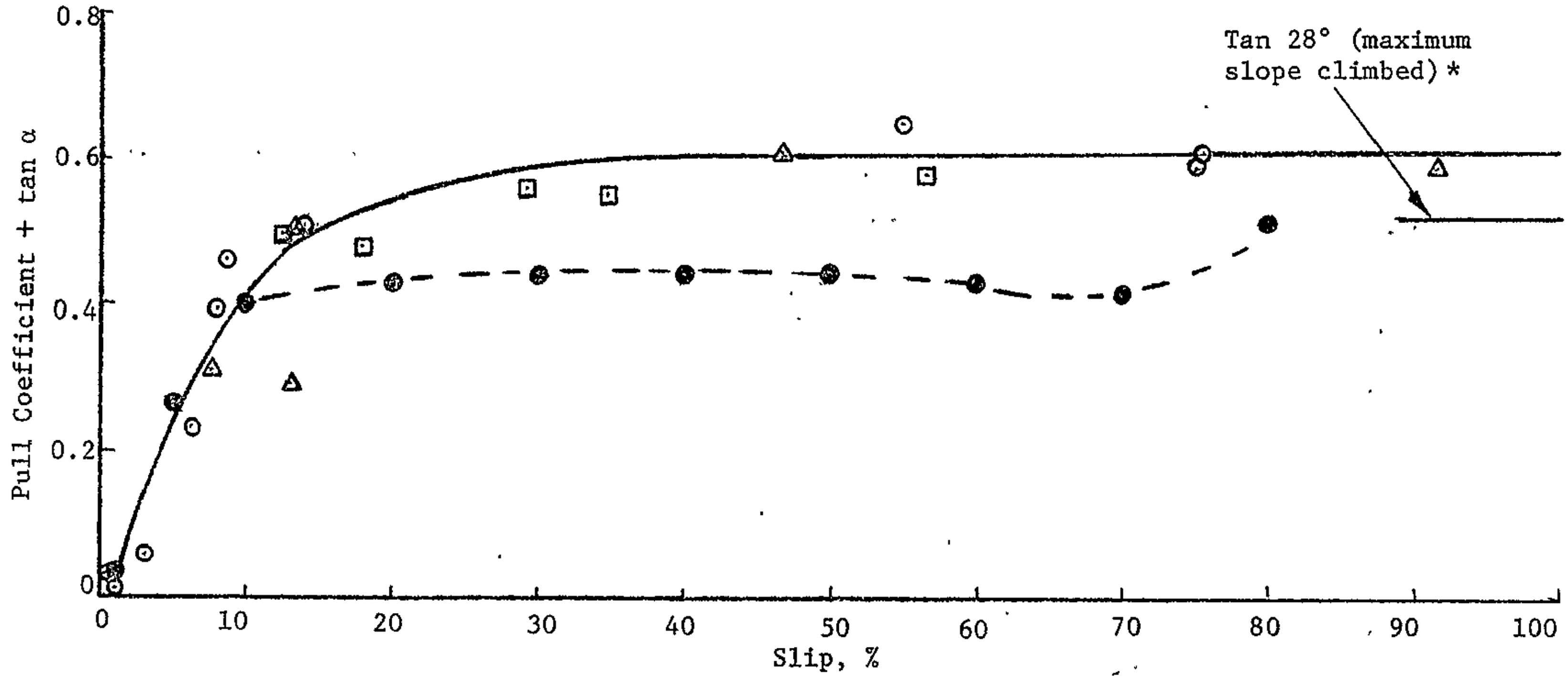
41. The curves of torque coefficient versus slip (fig. 29) illustrate that this relation may be unique for a given load and soil condition, regardless of the slope climbed. For this light wheel load [115 N (26 lb)] the torque-slip relation appears to be practically independent of soil strength as well as load. For comparable single-wheel data the same trend as observed in the comparison of P/W for the vehicle and single wheel exists. However, the differences in single-wheel and vehicle data are not as pronounced as for comparable P/W data.

Restarting on slopes (4x4 and 6x6)

42. Generally, when the vehicles were completely immobilized on a slope, they could not continue climbing by backing down and starting up again because they would become immobilized when they reached the point where they had spun out. On the other hand, when the vehicles' forward motion was stopped prior to immobilization, they could retrace their tracks and continue to climb. On a highly compactible soil, the vehicles could ascend the slopes with greater ease on each successive trial (i.e. less slip).

Steering (4x4 and 6x6)

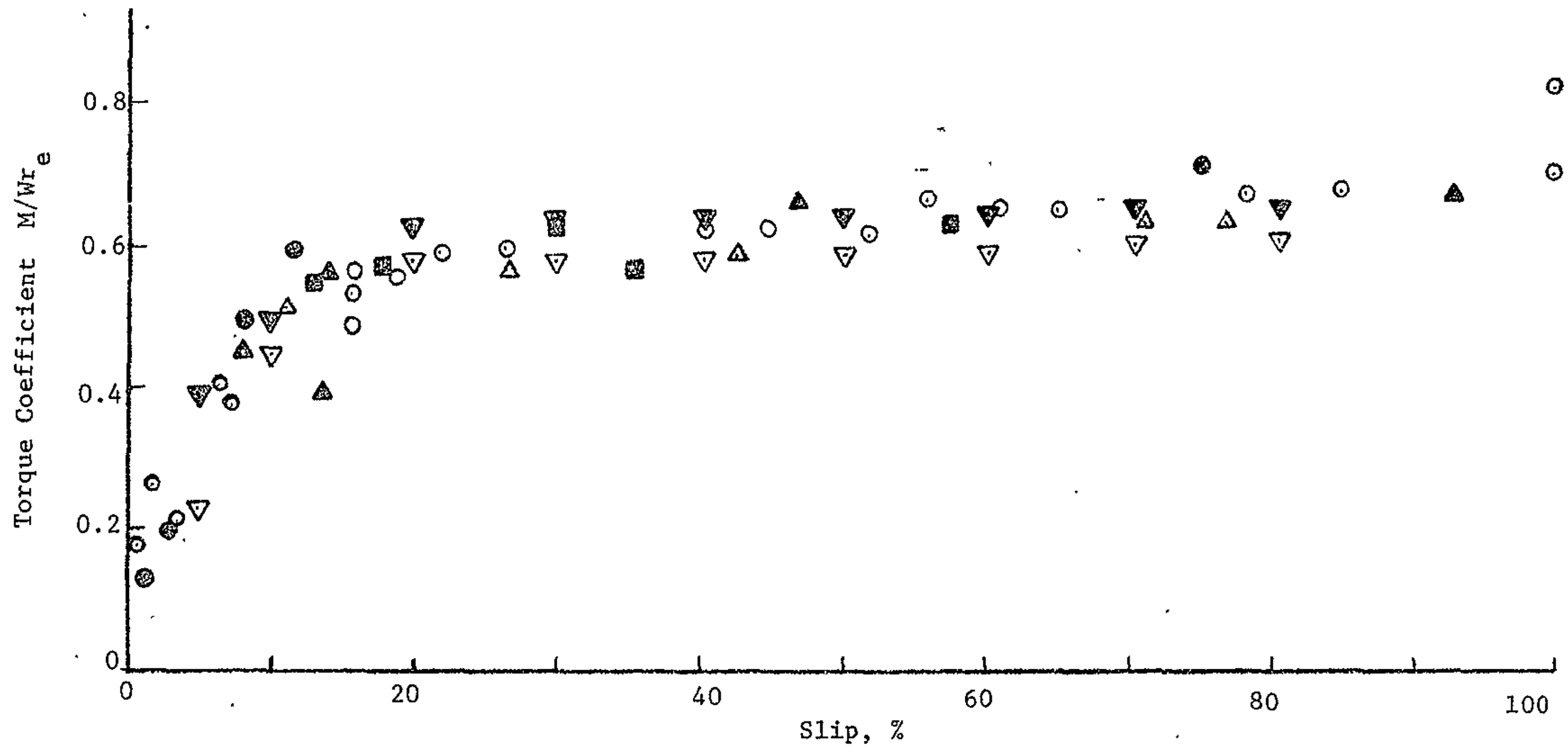
43. An effort to steer the vehicles while they were negotiating



* Vertical oscillations and pitch motions of modules at each axle.

Symbol	α, deg
○	0
△	15
□	25
●	Average of 1st, 2d, & 3d passes single wheel

Fig. 28. Relation of pull coefficient + tan α to slip for 6x6 vehicle on wet sand (soil condition C_2); 115-N (26-lb) wheel load, 8.80 kN/m^2 (1.28 psi) inflation pressure



Legend

Symbol	α, deg
○	0
△	15
□	25
▽	Avg of 1st, 2d, and 3d passes, single wheel

Open symbol: S_1
Closed symbol: C_2

Fig. 29. Relation of torque coefficient to slip for 6x6 vehicle on loose, dry sand (soil condition S_1) and wet sand (soil condition C_2); 115-N (26-lb) wheel load, 8.80 kN/m^2 (1.28 psi) inflation pressure

a slope tended to degrade their performance. On the basis of observations during these tests, it is estimated that the ultimate slope-climbing ability was reduced by 1 to 2 deg when an effort was made to steer the vehicles.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

44. Based on the data and analysis in this report, it is concluded that:

a. For loads less than about 220 N (50 lb), the pull coefficient (pull/load ratio) was constant for a given soil condition. These results are consistent with the shear strength behavior of the soil (paragraph 18).

b. An increase in cohesion did not result in a marked increase in the pull coefficient (paragraph 23).

c. The pull coefficient was independent of the average contact pressure at the soil-wheel interface for pressures ranging from 0.7 to 3.5 kN/m^2 (0.1 to 0.5 psi) for a given soil condition. On the soils with the larger amount of cohesion, the pull coefficient was constant for a greater range of loads and contact pressures (paragraph 25).

d. None of the original wheels could be relied on to propel a vehicle up a 35-deg slope; the Bendix wheel might be used to climb slopes up to about 28 to 30 deg, and the Boeing-GM and Grumman to climb slopes on the order of 15 to 20 deg. The power requirements for operating in a loose, dry sand on a level surface under an assumed 220-N (50-lb) load were 4, 6, and 10 whr/km for the Bendix, Boeing-GM, and Grumman wheels, respectively (paragraphs 28 and 29).

e. The performance of the pneumatic wheel approximately parallelled that of the Bendix wheel, thus offering credence to the use of the data collected in earlier studies with standard tires to develop a performance number suitable for metal-elastic wheels (see Freitag, Green, and Melzer, 1970). This close agreement also gave assurance to the decision to use the pneumatic wheels in the slope-climbing tests (paragraph 28).

f. Modifications to the Bendix and Grumman wheels in the form of the addition of aggressive grousers enhanced their performance to the point that they might be expected to climb slopes in excess of 30 deg. The modified Boeing-GM wheel (modifications included reduction of wheel stiffness and addition of a fabric cover) might be used on slopes up to about 25 deg on certain soil conditions (paragraphs 31-34).

g. Data from single-wheel tests with the pneumatic and SLRV wheels can be used to predict the slope-climbing ability of a vehicle. Such predictions tend to be conservative by about 1 to 2 deg of slope (paragraphs 37 and 40).

h. The torque coefficients for both the 4x4 and 6x6 vehicles at a given slip were not significantly affected by variations in surface slope and soil strength (paragraphs 38 and 41).

i. Generally, when the vehicles were completely immobilized on a slope they could not continue climbing by backing down and starting up again because they would become immobilized when they reached the point where they had spun out. When the vehicles' forward motion was stopped prior to immobilization, they could retrace their tracks and continue to climb (paragraph 42).

j. Any effort to steer the vehicles while they were negotiating a slope tended to degrade their performance. On the basis of observations during these tests, it is estimated that the ultimate slope-climbing ability was reduced by 1 to 2 deg when an effort was made to steer the vehicle (paragraph 43).

Recommendations

45. It is recommended that:

a. Tests be conducted with single wheels or other traction elements to provide information to optimize the shape, size, deflection, and surface design (roughness; grouser height, spacing, and type; etc.) of wheels or other running gears planned for use as traction elements for planetary or lunar rovers. Maximum traction, slope-climbing ability, and energy (power) consumption rates should be examined.

b. A limited number of the type of test mentioned in a. above be conducted under 1/6-g conditions (aboard KC-135 aircraft) with cone penetrometer and density tests performed simultaneously to ascertain functional relations between gradient G and wheel-vehicle performance under 1/6-g conditions.

c. Similitude studies be extended with (1) soils that are better lunar soil simulants than Yuma sand insofar as lunar soil consistency, grain-size distribution, in situ density, etc., and (2) observe the development of air pore pressures in silty lunar soil simulants during triaxial tests and tests with wheels and vehicle models.

d. In situ lunar soil trafficability data be obtained as early as possible and from as many typical morphological physiographic features of lunar surfaces as operationally feasible.

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Table 1

Soil Properties and Parameters for Single-Wheel Tests; Before-Traffic Data

		Soil Condition S_1*			
		No. Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3 (pci**)		170	0.81 (3.0)	0.48 (1.8)	0.54 (2.0)
Dry Density, g/cm^3 (pcf)	Gravimetric	75	1.527 (95.3)	1.446 (90.3)	1.484 (92.6)
	Nuclear	1	-	-	1.500 (93.6)
Moisture Content, %		75	0.6	0.4	0.5
Relative Density, %	Gradient G	34	37	30	32
	Gravimetric	25	48	32	39
	Nuclear	1	-	-	45
Average Friction Angle, deg	ϕ_t	34	37.2	36.9	37.1
	$\phi_{p\ell}$	34	31.0	29.8	30.0
	ϕ_c	5	24.0	12.0	17.1
	ϕ_b	4	30.0	20.5	27.4
Average Cohesion, kN/m^2 (psi)	c_{tr}	34	0	0	0
	$c_{p\ell}$	-	-	-	-
	c_c	5	2.1 (0.30)	0	0.8 (0.12)
	c_b	4	0	0	0
Bekker Soil Values	k_c, (kN/m)(cm^{-n}) ($lb/in.^{1+n}$)	6	0.08 (1.17)	-0.08 (-1.07)	-0.01 (-0.15)
	k_ϕ, (kN/m^2)(cm^{-n}) ($lb/in.^{2+n}$)	6	23.27 (8.03)	4.44 (1.65)	11.41 (3.88)
	n, average	6	0.96	0.84	0.91
Shear Stress s_v, kN/m^2 (psi)		8	0	0	0

*S_1 = air-dry, loose; S_2 = air-dry, very dense; C_1, C_2, C_3 = wet, medium-dense (US Bur. of Reclamation, 1953)
**pci = $lb/in.^3$

Table 1 (Continued)

		Soil Condition S_2			
		No. Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3 (pci)		65	3.56 (13.1)	2.55 (9.4)	3.07 (11.3)
Dry Density, g/cm^3 (pcf)	Gravimetric	21	1.652 (103.1)	1.612 (100.6)	1.637 (102.2)
	Nuclear	2	1.653 (103.2)	1.640 (102.4)	1.647 (102.8)
Moisture Content, %		21	0.5	0.3	0.5
Relative Density, %	Gradient G	13	91	83	87
	Gravimetric	7	96	87	92
	Nuclear	2	97	94	96
Average Friction Angle, deg	ϕ_t	13	44.4	42.6	43.5
	$\phi_{p\ell}$	13	33.8	33.2	33.5
	ϕ_c	4	32.0	14.5	20.6
	ϕ_b	2	16.0	14.5	15.3
Average Cohesion, kN/m^2 (psi)	c_{tr}	13	0.46 (0.07)	0.30 (0.04)	0.39 (0.06)
	$c_{p\ell}$	-	-	-	0.10 (0.015)
	c_c	4	12.7 (1.84)	4.5 (0.65)	6.8 (0.99)
	c_b	2	2.4 (1.84)	2.2 (0.65)	2.3 (0.99)
Bekker Soil Values	k_c, (kN/m)(cm^{-n}) ($lb/in.^{1+n}$)	4	0.16 (1.46)	0.07 (0.63)	0.10 (0.92)
	k_ϕ, (kN/m^2)(cm^{-n}) ($lb/in.^{2+n}$)	4	74.63 (17.14)	58.19 (13.61)	65.07 (15.20)
	n, average	4	0.51	0.49	0.51
Shear Stress s_v, kN/m^2 (psi)		8	4.9 (0.71)	3.0 (0.44)	4.0 (0.58)

Table 1 (Continued)

		Soil Condition C_1			
		No. Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3 (pci)		30	2.27 (8.4)	1.55 (5.7)	1.91 (7.0)
Dry Density, g/cm^3 (pcf)	Gravimetric	18	1.491 (93.1)	1.409 (88.0)	1.453 (90.7)
	Nuclear	3	1.519 (94.8)	1.463 (91.3)	1.494 (93.3)
Moisture Content, %		18	1.1	0.8	1.1
Relative Density, %	Gradient G	6	49	41	46
	Gravimetric	6	34	20	26
	Nuclear	3	52	33	43
Average Friction Angle, deg	ϕ_t	6	38.0	37.6	37.9
	$\phi_{p\ell}$	6	31.2	30.5	30.9
	ϕ_c	6	20.5	8.0	13.2
	ϕ_b	2	22.5	11.0	16.8
Average Cohesion, kN/m^2 (psi)	c_{tr}	6	0.44 (0.06)	0.36 (0.05)	0.39 (0.06)
	$c_{p\ell}$	-	-	-	0.05 (0.007)
	c_c	6	5.0 (0.73)	2.7 (0.39)	4.1 (0.59)
	c_b	2	3.5 (0.51)	1.4 (0.20)	2.5 (0.36)
Bekker Soil Values	k_c, (kN/m)(cm^{-n}) ($lb/in.^{1+n}$)	6	0.41 (4.49)	0.16 (1.72)	0.27 (2.73)
	k_ϕ, (kN/m^2)(cm^{-n}) ($lb/in.^{2+n}$)	6	35.48 (8.98)	19.84 (5.51)	27.75 (7.28)
	n, average	6	0.70	0.61	0.64
Shear Stress s_v, kN/m^2 (psi)		8	2.8 (0.41)	0.9 (0.13)	2.1 (0.30)

Table 1 (Continued)

		Soil Condition C_2			
		No. Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3 (pci)		150	4.00 (14.7)	2.54 (9.3)	3.2 (11.8)
Dry Density, g/cm^3 (pcf)	Gravimetric	84	1.511 (94.3)	1.421 (88.7)	1.471 (91.8)
	Nuclear	4	1.495 (93.3)	1.465 (92.4)	1.480 (92.4)
Moisture Content, %		87	1.9	1.0	1.4
Relative Density, %	Gradient G	30	64	41	54
	Gravimetric	28	43	19	34
	Nuclear	4	43	33	38
Average Friction Angle, deg	ϕ_t	30	39.7	38.0	38.5
	$\phi_{p\ell}$	30	32.0	30.5	31.3
	ϕ_c	12	20.5	11.5	17.9
	ϕ_b	5	26.5	11.4	18.5
Average Cohesion, kN/m^2 (psi)	c_{tr}	30	1.28 (0.19)	0.94 (0.14)	1.08 (0.16)
	$c_{p\ell}$	–	–	–	0.10 (0.015)
	c_c	12	4.9 (0.71)	1.8 (0.26)	3.7 (0.54)
	c_b	5	6.0 (0.87)	0.4 (0.06)	2.5 (0.36)
Bekker Soil Values	k_c, (kN/m)(cm^{-n}) ($lb/in.^{1+n}$)	12	0.62 (6.02)	0.17 (1.70)	0.36 (3.61)
	k_ϕ, (kN/m^2)(cm^{-n}) ($lb/in.^{2+n}$)	12	57.73 (19.97)	42.03 (10.80)	50.97 (13.37)
	n, Average	12	0.79	0.50	0.59
Shear Stress s_v, kN/m^2 (psi)		22	8.5 (1.23)	5.1 (0.74)	7.4 (1.07)

Table 1 (Concluded)

		Soil Condition C_3			
		No. Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3 (pci)		25	4.50 (16.6)	3.61 (13.3)	3.95 (14.5)
Dry Density, g/cm^3 (pcf)	Gravimetric	15	1.465 (91.5)	1.428 (89.2)	1.441 (90.0)
	Nuclear	3	1.496 (93.4)	1.446 (90.3)	1.471 (91.8)
Moisture Content, %		15	2.3	1.5	1.8
Relative Density, %	Gradient G	5	51	41	48
	Gravimetric	5	26	17	21
	Nuclear	3	43	26	34
Average Friction Angle, deg	ϕ_t	5	38.3	37.6	38.1
	$\phi_{p\ell}$	5	31.2	30.5	30.9
	ϕ_c	4	30.0	21.5	26.9
	ϕ_b	4	22.0	19.5	20.8
Average Cohesion, kN/m^2 (psi)	c_{tr}	5	1.98 (0.29)	1.58 (0.23)	1.75 (0.25)
	$c_{p\ell}$	-	-	-	0.15 (0.022)
	c_c	4	4.0 (0.58)	2.0 (0.29)	2.9 (0.42)
	c_b	4	2.4 (0.35)	1.2 (0.17)	1.8 (0.26)
Bekker Soil Values	k_c, (kN/m)(cm^{-n}) ($lb/in.^{1+n}$)	4	0.92 (8.33)	0.51 (4.52)	0.79 (7.08)
	k_ϕ, (kN/m^2)(cm^{-n}) ($lb/in.^{2+n}$)	4	75.94 (16.95)	52.09 (11.96)	67.00 (15.21)
	n, Average	4	0.49	0.46	0.48
Shear Stress s_v, kN/m^2 (psi)		8	10.7 (1.55)	5.8 (0.84)	8.0 (1.16)

Wheel Characteristics*

Tire No.	Deflection cm(in.)	Deflection %	Load N(lb)	Inflation Pressure Unloaded kN/m^2(psi)	Inflation Pressure Loaded kN/m^2(psi)	Carcass Diameter cm(in.)	Section Height Unloaded cm(in.)	Section Height Loaded cm(in.)	Section Width Unloaded cm(in.)	Section Width Loaded cm(in.)	Contact Area sq cm(sq in.)	Tire Print Length cm(in.)	Tire Print Width cm(in.)	Contact Pressure kN/m^2(psi)
Pneumatic; Size, 27.94-50.8; Rim Diam, 54.6 cm (21.50 in.); Rolling Circumference, 2.89 m (9.48 ft)														
--	4.74(1.87)	9.72	133(30)	2.28(0.33)	2.62(0.38)	97.41(38.35)	21.40(8.43)	16.66(6.56)	22.01(8.67)	24.08(9.48)	508.26(78.78)	37.34(14.70)	16.89(6.65)	2.62(0.38)
	8.00(3.15)	16.41	311(70)	2.52(0.37)	2.96(0.43)	97.44(38.36)	21.42(8.43)	13.41(5.28)	21.97(8.65)	26.56(10.46)	808.45(125.31)	48.26(19.00)	20.45(8.05)	3.86(0.56)
	10.24(4.03)	21.04	489(110)	2.76(0.40)	3.45(0.50)	97.27(38.30)	21.33(8.40)	11.09(4.37)	21.89(8.62)	28.14(11.08)	1057.48(163.91)	54.38(21.41)	23.39(9.21)	4.64(0.67)
	12.00(4.73)	24.56	667(150)	3.45(0.50)	4.62(0.67)	97.74(38.48)	21.57(8.47)	9.51(3.75)	21.97(8.65)	29.28(11.53)	1237.22(191.77)	59.44(23.40)	25.24(9.94)	5.42(0.79)
	4.42(1.74)	9.10	67(15)	**	0.07(0.10)	97.23(38.28)	21.31(8.39)	16.89(6.65)	20.70(8.15)	23.19(9.13)	498.71(77.30)	36.14(14.23)	17.50(6.89)	1.30(0.19)
	10.59(4.17)	21.80	310(70)	**	2.07(0.30)	97.23(38.28)	21.31(8.39)	10.72(4.22)	20.70(8.15)	28.19(11.10)	1222.51(189.49)	56.08(22.08)	26.42(10.40)	2.55(0.37)
Bendix; Size 101.6-25.4 Metal Elastic; Width 25.4 cm (10.0 in.)														
--	1.65(0.65)	3.25	67(15)	--	--	101.60(40.00)	17.59(6.93)	15.88(6.25)	25.40(10.00)	25.40(10.00)	243.54(37.75)	9.52(3.75)	25.40(10.00)	2.76(0.40)
	2.73(1.07)	5.38	133(30)	--	--	101.60(40.00)	17.59(6.93)	14.86(5.85)	25.40(10.00)	25.40(10.00)	519.35(80.58)	20.45(8.05)	25.40(10.00)	2.58(0.37)
	5.27(2.07)	10.38	311(70)	--	--	101.60(40.00)	17.59(6.93)	12.32(4.85)	25.40(10.00)	25.40(10.00)	722.58(112.00)	28.45(11.20)	25.40(10.00)	3.93(0.57)
	7.50(2.95)	14.75	489(110)	--	--	101.60(40.00)	17.59(6.93)	10.10(3.97)	25.40(10.00)	25.40(10.00)	1041.90(161.50)	41.02(16.15)	25.40(10.00)	4.72(0.68)
	9.27(3.65)	18.25	667(150)	--	--	101.60(40.00)	17.59(6.93)	8.32(3.28)	25.40(10.00)	25.40(10.00)	1287.09(199.50)	50.68(19.95)	25.40(10.00)	5.17(0.75)
Boeing-GM I (Original Wheel); Size, 102.8-26.67 Wire Mesh; Rim Diam, 59.69 cm (23.50 in.)														
--	1.98(0.78)	3.88	133(30)	--	--	102.87(40.50)	21.59(8.50)	19.60(7.72)	26.65(10.49)	27.72(10.91)	312.71(48.57)	28.37(11.17)	14.05(5.53)	4.24(0.62)
	4.27(1.68)	8.27	311(70)	--	--	102.87(40.50)	21.59(8.50)	17.33(6.83)	26.01(10.24)	29.36(11.56)	629.29(97.54)	41.02(16.15)	19.54(7.69)	4.93(0.72)
	5.87(2.31)	11.41	489(110)	--	--	102.87(40.50)	21.59(8.50)	15.73(6.19)	26.65(10.49)	30.56(12.03)	826.97(128.18)	47.70(18.78)	22.08(8.69)	5.90(0.86)
	7.11(2.80)	13.81	667(150)	--	--	102.87(40.50)	21.59(8.50)	14.49(5.71)	26.65(10.49)	31.68(12.47)	965.07(149.64)	52.05(20.49)	23.57(9.28)	6.93(1.01)
	1.23(0.48)	2.37	67(15)	--	--	102.87(40.50)	21.59(8.50)	20.36(8.02)	26.65(10.49)	27.04(10.65)	197.32(30.58)	22.40(8.82)	11.22(4.42)	3.38(0.49)
Boeing-GM II (GM I covered with polyethylene; data same as GM I.)														
Boeing-GM III (GM II coated with sand; data same as GM I.)														
Boeing-GM IV (GM I Covered with Gray Tape and Coated with Sand); Size, 102.87-26.67 Wire Mesh; Rim Diam, 59.69 cm (23.50 in.)														
--	0.64(0.25)	1.24	67(15)	--	--	102.29(40.27)	21.30(8.39)	20.67(8.14)	27.12(10.68)	27.40(10.78)	41.16(6.38)	8.25(3.24)	6.05(2.38)	16.27(2.36)
	1.50(0.59)	2.93	222(50)	--	--	102.29(40.27)	21.30(8.39)	19.80(7.80)	27.12(10.68)	27.88(10.98)	155.39(24.08)	17.07(6.72)	11.14(4.38)	14.41(2.09)
	2.51(0.99)	4.92	311(70)	--	--	102.29(40.27)	21.30(8.39)	18.80(7.40)	27.12(10.68)	28.36(11.16)	234.10(36.28)	20.81(8.19)	14.20(5.59)	13.31(1.93)

(Continued)

* Averaged from a minimum of two points on tire.
** Remove valve core: O-load; replace and load.

Table 2 (Continued)

Tire No.	Deflection cm(in.)	Deflection %	Load N(lb)	Inflation Pressure Unloaded kN/m^2(psi)	Inflation Pressure Loaded kN/m^2(psi)	Carcass Diameter cm(in.)	Section Height Unloaded cm(in.)	Section Height Loaded cm(in.)	Section Width Unloaded cm(in.)	Section Width Loaded cm(in.)	Contact Area sq cm(sq in.)	Tire Print Length cm(in.)	Tire Print Width cm(in.)	Contact Pressure kN/m^2(psi)
Boeing-GM V														
(GM I coated with sand; data same as GM I.)														
Boeing-GM VI (Straps and 50% of Wire Mesh Removed; Wheel Covered with Gray Tape and Coated with Sand; Size, 102.87-26.67; Rim Diam, 59.69 cm (23.50 in.)														
--	5.59(2.20)	11.20	311(70)	--	--	99.83(39.30)	20.07(7.90)	14.48(5.70)	28.55(11.24)	32.41(12.76)	710.19(109.76)	35.03(13.79)	23.88(9.40)	4.42(0.64)
	6.30(2.48)	12.57	311(70)	--	--	100.28(39.48)	20.30(7.99)	14.00(5.51)	28.44(11.20)	32.45(12.78)	778.77(120.71)	37.73(14.86)	24.28(9.56)	4.04(0.58)
Grumman I (Wheel Mounted at 15-deg Off the Vertical for Tests and Static Wheel Data)														
--	3.30(1.30)	6.10	67(15)	--	--	107.95(42.50)	55.75(21.95)	52.45(20.65)	--	--	983.22(152.40)	38.71(15.24)	25.40(10.00)	0.69(0.10)
	4.32(1.70)	8.00	133(30)	--	--	107.95(42.50)	55.75(21.95)	51.44(20.25)	--	--	1046.45(162.20)	42.21(16.62)	25.40(10.00)	1.24(0.18)
	5.79(2.28)	10.70	311(70)	--	--	107.95(42.50)	55.75(21.95)	49.86(19.63)	--	--	1225.80(190.00)	50.55(19.90)	25.40(10.00)	2.55(0.37)
	7.49(2.95)	13.90	489(110)	--	--	107.95(42.50)	55.75(21.95)	48.26(19.00)	--	--	1374.19(213.00)	54.10(21.30)	25.40(10.00)	3.59(0.52)
	8.64(3.40)	16.00	667(150)	--	--	107.95(42.50)	55.75(21.95)	47.12(18.55)	--	--	1465.80(227.20)	57.66(22.70)	25.40(10.00)	4.55(0.66)
Grumman II														
(Grumman I with angle-iron grousers added.)														
SLRV; Size, 45.72-20.32; Rim Diam, 7.11 cm (2.80 in.)														
--	5.85(2.29)	24.42	130(30)	--	0.00†(0.00)	47.75(18.80)	20.32(8.00)	14.49(5.70)	21.47(8.45)	23.47(9.24)	495.16(76.75)	27.25(10.73)	21.84(8.60)	2.73(0.39)
	2.54(1.00)	10.61	267(60)	11.72(1.70)	12.07(1.75)	47.88(18.85)	20.37(8.02)	17.84(7.02)	21.80(8.58)	22.50(8.86)	196.97(30.53)	17.92(7.05)	13.28(5.23)	13.69(1.98)
	6.96(2.74)	29.13	311(70)	1.72(0.25)	1.72(0.25)	47.88(18.85)	20.39(8.03)	13.42(5.28)	21.43(8.43)	24.59(9.68)	537.90(86.37)	27.56(10.85)	23.50(9.25)	5.79(0.84)
	6.60(2.60)	27.54	311(70)	2.76(0.40)	3.45(0.50)	47.85(18.84)	20.39(8.03)	13.76(5.43)	21.45(8.44)	24.11(9.49)	502.07(77.82)	27.40(10.78)	22.63(8.91)	6.21(0.90)
	4.72(1.86)	19.71	311(70)	6.21(0.90)	6.89(1.00)	47.83(18.83)	20.37(8.02)	15.66(6.16)	21.62(8.51)	22.99(9.05)	351.52(54.48)	21.31(8.39)	19.69(7.75)	8.86(1.28)
	9.47(3.73)	39.60	489(110)	2.41(0.35)	3.45(0.50)	47.85(18.84)	20.37(8.02)	10.90(4.59)	21.48(8.45)	26.88(10.58)	629.68(97.60)	30.48(12.00)	25.04(9.86)	7.76(1.13)
	6.05(2.38)	25.24	489(110)	5.86(0.85)	6.89(1.00)	47.91(18.86)	20.40(8.03)	14.35(5.65)	21.67(8.53)	23.82(9.37)	433.74(67.23)	25.02(9.85)	21.34(8.40)	11.27(1.63)
	3.79(1.49)	18.60	67(15)	--	0.00(0.00)†	47.75(18.80)	20.32(8.00)	16.54(6.51)	21.47(8.45)	22.20(8.74)	283.78(43.99)	21.38(8.42)	16.04(6.32)	2.35(0.34)
	3.62(1.43)	15.10	116(26)	6.21(0.90)	6.89(1.00)	47.88(18.85)	20.39(8.03)	16.77(6.60)	21.62(8.51)	21.99(8.66)	247.75(38.40)	19.42(7.65)	15.56(6.12)	4.66(0.68)
	4.20(1.65)	17.60	222(50)	5.86(0.85)	6.89(1.00)	47.85(18.84)	20.37(8.02)	16.70(6.58)	21.62(8.51)	23.28(9.17)	420.81(65.23)	25.11(9.89)	20.51(8.08)	5.28(0.77)
4x4 Vehicle Wheels; Size, 27.94-50.80; Rim Diam, 54.61 cm (21.50 in.)														
1	5.14(2.03)	10.59	133(30)	2.18(0.32)	2.55(0.37)	97.13(38.24)	21.26(8.37)	16.12(6.35)	21.41(8.43)	23.92(9.42)	525.71(81.48)	38.08(14.99)	17.54(6.91)	2.55(0.37)
	7.96(3.13)	16.42	311(70)	2.44(0.35)	3.03(0.44)	97.00(38.22)	21.22(8.36)	13.26(5.22)	21.64(8.52)	25.32(10.36)	802.68(124.41)	47.12(18.55)	21.03(8.28)	3.90(0.56)
	9.90(3.90)	20.41	489(110)	2.80(0.40)	3.45(0.50)	97.08(38.22)	21.24(8.36)	11.32(4.46)	21.67(8.53)	28.09(11.06)	1005.35(155.83)	53.94(21.23)	23.44(9.22)	4.86(0.70)
	11.60(4.57)	23.88	667(150)	3.45(0.50)	4.62(0.67)	97.21(38.27)	21.30(8.38)	9.69(3.81)	21.69(8.54)	29.24(11.51)	1173.29(181.86)	57.47(22.62)	24.80(9.76)	5.69(0.82)

(Continued)

† Valve core removed.

Table 2 (Concluded)

Tire No.	Deflection cm(in.)	Deflection %	Load N(lb)	Inflation Pressure Unloaded kNm^2(psi)	Inflation Pressure Loaded kN/m^2(psi)	Carcass Diameter cm(in.)	Section Height Unloaded cm(in.)	Section Height Loaded cm(in.)	Section Width Unloaded cm(in.)	Section Width Loaded cm(in.)	Contact Area sq cm(sq in.)	Tire Print Length cm(in.)	Tire Print Width cm(in.)	Contact Pressure kN/m^2(psi)
4x4 Vehicle Wheels; Size, 27.94-50.80; Rim Diam, 54.61 cm (21.50 in.) (Continued)														
2	4.88(1.92)	10.10	133(30)	2.07(0.30)	2.41(0.35)	96.60(38.03)	21.00(8.26)	16.12(6.34)	21.54(8.48)	23.67(9.32)	493.03(76.42)	36.44(14.35)	16.82(6.62)	2.72(0.39)
	7.94(3.12)	16.49	311(70)	2.48(0.36)	2.96(0.43)	96.32(37.92)	20.85(8.21)	12.92(5.08)	21.68(8.53)	26.69(10.50)	823.61(127.66)	47.65(18.76)	21.14(8.32)	3.76(0.54)
	10.66(4.19)	22.10	489(110)	2.69(0.39)	3.45(0.50)	96.37(37.94)	20.88(8.22)	10.22(4.02)	21.63(8.52)	28.20(11.10)	1085.00(168.17)	53.84(21.20)	24.04(9.46)	4.52(0.65)
	11.66(4.59)	24.20	667(150)	3.48(0.50)	4.62(0.67)	96.40(37.95)	20.89(8.22)	9.24(3.63)	22.08(8.69)	29.10(11.46)	1193.22(184.95)	57.22(22.52)	25.30(9.96)	5.58(0.81)
3	4.83(1.90)	9.92	133(30)	2.21(0.32)	2.48(0.36)	97.28(38.30)	21.34(8.40)	16.46(6.48)	21.72(8.55)	23.88(9.40)	457.52(70.91)	35.41(13.94)	15.74(6.20)	2.90(0.42)
	7.86(3.09)	16.21	311(70)	2.62(0.38)	3.06(0.44)	97.13(38.24)	21.26(8.37)	13.40(5.27)	21.77(8.57)	26.59(10.47)	770.06(119.36)	46.48(18.30)	19.96(7.86)	4.04(0.58)
	10.18(4.00)	20.96	489(110)	2.76(0.40)	3.45(0.50)	97.08(38.22)	21.23(8.36)	11.29(4.44)	21.80(8.58)	28.22(11.11)	1058.00(164.01)	53.72(21.15)	23.50(9.25)	4.62(0.67)
	11.51(4.53)	23.80	667(150)	3.45(0.50)	4.62(0.67)	96.72(38.08)	21.06(8.29)	9.50(3.74)	22.10(8.70)	29.18(11.49)	1183.36(183.42)	57.60(22.68)	24.51(9.65)	5.65(0.82)
4	5.11(2.01)	10.50	133(30)	2.18(0.31)	2.48(0.36)	97.28(38.30)	21.44(8.44)	16.23(6.39)	21.52(8.47)	23.71(9.33)	524.84(81.35)	37.28(14.67)	17.13(6.74)	2.55(0.37)
	8.03(3.16)	16.50	311(70)	2.48(0.36)	3.03(0.44)	97.16(38.25)	21.28(8.37)	13.24(5.21)	21.59(8.50)	26.48(10.40)	837.10(129.75)	47.65(18.76)	21.54(8.48)	3.76(0.54)
	10.06(3.96)	20.70	489(110)	2.76(0.40)	3.45(0.50)	97.13(38.24)	21.26(8.37)	11.20(4.41)	21.80(8.58)	28.18(11.09)	1023.55(158.65)	53.58(21.09)	23.44(9.23)	4.80(0.69)
	11.53(4.54)	23.80	667(150)	3.45(0.50)	4.62(0.67)	96.93(38.16)	21.16(8.33)	9.62(3.78)	21.84(8.60)	28.90(11.38)	1197.39(185.59)	57.05(22.46)	25.15(9.90)	5.58(0.81)
SLRV 6x6 Vehicle Wheels; Size, 45.72-20.32; Rim Diam, 7.11 cm (2.80 in.)														
1	2.54(1.00)	10.70	129(29)	--	8.89(1.29)	47.55(18.72)	20.22(7.96)	17.68(6.96)	21.59(8.50)	21.84(8.60)	280.00(43.40)	20.19(7.95)	16.76(6.60)	4.62(0.67)
2	2.69(1.06)	11.20	98(22)	--	7.58(1.10)	47.96(18.88)	20.42(8.04)	17.73(6.98)	21.59(8.50)	21.84(8.60)	201.68(31.26)	17.91(7.05)	13.72(5.40)	4.83(0.70)
3	2.74(1.08)	11.50	116(26)	--	8.76(1.27)	47.85(18.84)	20.37(8.02)	17.63(6.94)	21.72(8.55)	22.10(8.70)	218.19(33.82)	18.54(7.30)	13.97(5.50)	5.31(0.77)
4	2.57(1.01)	10.70	142(32)	--	8.76(1.27)	47.96(18.88)	20.42(8.04)	17.86(7.03)	21.72(8.55)	22.05(8.68)	184.32(28.57)	17.53(6.90)	12.70(5.00)	7.72(1.12)
5	2.64(1.04)	11.20	89(20)	--	7.58(1.10)	47.14(18.56)	20.02(7.88)	17.37(6.84)	21.54(8.48)	21.72(8.55)	206.39(31.99)	18.24(7.18)	14.02(5.52)	4.34(0.63)
6	2.54(1.00)	10.70	116(26)	--	8.83(1.28)	47.65(18.76)	20.27(7.98)	17.73(6.98)	21.54(8.48)	21.84(8.60)	172.00(26.66)	16.51(6.50)	12.90(5.08)	6.76(0.98)

Table 3

Single-Wheel Test Results

Test No.	Wheel Symbol	Wheel Load N(lb)	Soil Condition	Before-Traffic Penetration Resistance Gradient G MN/m^3(pci)	Performance Parameters: Efficiency η'_{20}	Pull/Load P_{20}/W	Torque/Load M_{20}/Wr_e	Power Number PN_{sp}	PN_{15}	PN_{max}	Dimensionless Numeric N_1	N_2
					Pneumatic, First Pass							
7	--	130(30)	s_1	0.56(2.1)	0.615	0.440	0.567	0.09	0.45	0.685	1572	49.5
8	--	130(30)	s_2	2.98(11.2)	0.710	0.553	0.625	0.10	0.37	0.660	8369	265.4
9	--	310(70)	s_1	0.58(2.2)	0.612	0.470	0.600	0.12	0.45	0.705	1480	43.0
10	--	310(70)	s_2	3.12(11.7)	0.680	0.518	0.609	0.08	0.38	0.665	7834	231.5
16	--	310(70)	c_1	1.75(6.4)	0.690	0.524	0.606	0.07	0.34	0.600	4296	127.6
17	--	130(30)	c_1	1.89(7.2)	0.675	0.515	0.608	0.04	0.38	0.680	5148	170.7
18	--	490(110)	c_1	1.78(6.5)	0.690	0.536	0.618	0.08	0.40	0.720	5240	122.5
19	--	130(30)	c_2	3.48(12.3)	0.700	0.521	0.514	0.04	0.38	0.700	9623	291.0
20	--	310(70)	c_2	3.39(12.2)	0.665	0.553	0.663	0.05	0.40	0.780	8403	241.9
21	--	490(110)	c_2	3.00(10.7)	0.702	0.569	0.643	0.01	0.33	0.700	8885	200.9
22	--	130(30)	c_2	3.36(11.3)	0.700	0.549	0.631	0.06	0.38	0.720	10194	267.2
56	--	67(15)	s_1	0.53(2.0)	0.650	0.488	0.585	0.10	0.38	0.700	15596	89.8
57	--	67(15)	s_2	3.22(12.0)	0.640	0.552	0.658	0.60	0.46	0.860	20174	533.5
58	--	490(110)	s_1	0.54(2.0)	0.570	0.395	0.588	0.30	0.41	0.600	1503	37.8
59	--	490(110)	s_2	3.03(11.3)	0.630	0.487	0.619	0.40	0.42	0.740	8451	212.1
84	--	310(70)	c_3	4.09(15.3)	0.620	0.517	0.671	0.80	0.46	0.820	11542	563.4
85	--	67(15)	c_3	3.79(14.2)	0.560	0.554	0.789	0.50	0.36	0.700	23745	627.9
					Pneumatic, Second Pass							
7	--	--	--	--	0.700	0.541	0.618	0.09	0.42	0.750	--	--
8	--	--	--	--	0.620	0.496	0.640	0.13	0.44	0.695	--	--
9	--	--	--	--	0.660	0.512	0.618	0.14	0.43	0.700	--	--
10	--	--	--	--	0.690	0.524	0.609	0.08	0.41	0.720	--	--
16	--	--	--	--	0.770	0.546	0.570	0.01	0.30	0.620	--	--
17	--	--	--	--	0.640	0.509	0.639	0.04	0.39	0.700	--	--
18	--	--	--	--	0.660	0.519	0.629	0.13	0.44	0.745	--	--
19	--	--	--	--	0.690	0.510	0.590	0.04	0.35	0.630	--	--
20	--	--	--	--	0.680	0.538	0.638	0.03	0.33	0.630	--	--
21	--	--	--	--	0.680	0.525	0.617	0.08	0.39	0.700	--	--
22	--	--	--	--	0.750	0.590	0.627	0.02	0.29	0.620	--	--
56	--	--	--	--	0.730	0.521	0.573	0.05	0.36	0.650	--	--
57	--	--	--	--	0.530	0.456	0.688	0.10	0.50	0.790	--	--
58	--	--	--	--	0.590	0.430	0.584	0.06	0.44	0.670	--	--
59	--	--	--	--	0.600	0.461	0.616	0.12	0.45	0.680	--	--
					Pneumatic, Third Pass							
7	--	--	--	--	0.660	0.504	0.614	0.09	0.42	0.715	--	--
8	--	--	--	--	0.640	0.514	0.642	0.11	0.44	0.740	--	--
9	--	--	--	--	0.670	0.512	0.613	0.09	0.40	0.670	--	--
10	--	--	--	--	0.660	0.502	0.611	0.12	0.44	0.710	--	--
16	--	--	--	--	0.740	0.542	0.582	0.01	0.30	0.590	--	--
17	--	--	--	--	0.680	0.553	0.647	0.03	0.30	0.600	--	--
18	--	--	--	--	0.680	0.530	0.607	0.07	0.38	0.690	--	--
19	--	--	--	--	0.700	0.509	0.579	0.04	0.37	0.680	--	--
20	--	--	--	--	0.690	0.565	0.658	0.02	0.37	0.760	--	--
21	--	--	--	--	0.700	0.578	0.658	0.02	0.34	0.720	--	--
22	--	--	--	--	0.700	0.543	0.625	0.05	0.37	0.690	--	--
56	--	--	--	--	0.730	0.512	0.562	0.02	0.34	0.620	--	--
57	--	--	--	--	0.500	0.398	0.631	0.22	0.60	0.780	--	--
58	--	--	--	--	0.560	0.415	0.596	0.11	0.48	0.685	--	--
59	--	--	--	--	0.590	0.470	0.632	0.11	0.45	0.700	--	--

(Continued)

Test No.	Wheel Symbol	Wheel Load N(lb)	Soil Condition	Before-Traffic Penetration Resistance Gradient G MN/m³ (pci)	Efficiency η'_{20}	Pull/Load P_{20}/W	Torque/Load M_{20}/Wr_e	Power Number PN_{sp}	PN_{15}	PN_{max}	Dimensionless Numeric N_1	N_2
					Bendix, First Pass							
3	I	130(30)	S_1	0.55(2.1)	0.665	0.458	0.553	0.03	0.44	0.66	1783	49.9
4		130(30)	S_2	2.68(10.1)	0.740	0.568	0.586	0.03	0.38	0.76	8351	24.5
5		130(30)	S_4	4.67(17.6)	0.720	0.563	0.589	0.01	0.34	0.79	14552	42.7
11		310(70)	S_1	0.53(2.0)	0.645	0.465	0.576	0.10	0.38	0.52	1031	33.2
12		310(70)	S_2	2.73(10.2)	0.725	0.535	0.596	0.06	0.37	0.69	5262	170.8
13		310(70)	C_1	1.79(6.7)	0.682	0.528	0.619	0.05	0.39	0.71	3494	112.0
14		130(30)	C_1	2.12(7.9)	0.690	0.525	0.608	0.02	0.32	0.60	6710	192.4
15		490(110)	C_1	2.13(7.8)	0.700	0.540	0.618	0.03	0.33	0.64	4107	143.3
23		130(30)	C_2	3.28(12.1)	0.650	0.489	0.602	0.06	0.35	0.61	10301	292.2
24		310(70)	C_2	3.04(12.4)	0.675	0.514	0.609	0.08	0.36	0.65	6031	207.8
25	↓	490(110)	C_2	3.33(12.4)	0.670	0.512	0.615	0.10	0.40	0.67	6408	227.0
30	II	130(30)	C_2	3.09(11.5)	0.610	0.512	0.673	--	--	--	9006	278.7
31		490(110)	C_2	3.28(12.0)	0.620	0.528	0.685	0.02	0.36	0.68	6389	220.1
32		670(150)	C_2	3.26(12.0)	0.620	0.529	0.718	0.02	0.38	0.74	6707	208.4
33	↓	310(70)	C_2	2.96(11.0)	0.600	0.516	0.689	0.03	0.35	0.65	5724	218.1
78a	I	310(70)	S_1	0.65(2.1)	0.610	0.460	0.590	0.10	0.50	0.72	1141	34.0
78b		310(70)	S_2	3.24(12.0)	0.640	0.530	0.660	0.08	--	0.77	6150	205.0
80		67(15)	S_1	0.53(2.0)	0.610	0.424	0.553	0.04	0.38	0.58	2713	30.0
81		67(15)	C_3	4.27(16.0)	0.610	0.496	0.656	0.03	0.44	0.78	21857	242.2
82		310(70)	C_3	3.79(14.2)	0.570	0.464	0.648	0.07	0.50	0.80	7448	237.2
83	↓	310(70)	C_3	3.79(14.2)	0.620	0.523	0.678	0.03	0.41	0.78	7445	237.2
86	III	67(15)	C_2	3.05(11.4)	0.530	0.664	1.000	0.25	0.46	0.84	15611	173.0
87		67(15)	C_2	3.07(11.9)	0.550	0.754	1.092	0.18	0.55	1.21	15816	175.2
88		310(70)	C_2	3.44(12.9)	0.540	0.571	0.848	0.05	0.50	1.01	7024	215.9
89		310(70)	S_1	0.50(1.9)	0.560	0.512	0.734	0.10	0.50	0.86	1025	31.0
90	↓	67(15)	S_1	0.49(1.9)	0.530	0.697	1.052	0.10	0.43	0.97	2662	29.5
					Bendix, Second Pass							
3	I	--	--	--	0.710	0.498	0.560	0.03	0.33	0.58	--	--
4		--	--	--	0.700	0.497	0.567	0.03	0.33	0.66	--	--
5		--	--	--	0.700	0.509	0.509	0.02	0.34	0.62	--	--
11		--	--	--	0.700	0.519	0.597	0.02	0.33	0.62	--	--
12		--	--	--	0.680	0.497	0.586	0.04	0.37	0.64	--	--
13		--	--	--	0.700	0.528	0.604	0.03	0.33	0.62	--	--
14		--	--	--	0.710	0.514	0.581	0.04	0.32	0.58	--	--
15		--	--	--	0.710	0.506	0.603	0.06	0.34	0.59	--	--
23		--	--	--	0.750	0.541	0.577	0.01	0.33	0.66	--	--
24		--	--	--	0.660	0.521	0.632	0.03	0.38	0.71	--	--
25	↓	--	--	--	0.660	0.490	0.595	0.05	0.41	0.70	--	--
31	II	--	--	--	0.580	0.499	0.686	0.08	0.40	0.67	--	--
32		--	--	--	0.570	0.485	0.682	0.05	0.46	0.80	--	--
33	↓	--	--	--	0.570	0.478	0.700	0.04	0.44	0.76	--	--
88	III	--	--	--	0.690	0.548	0.819	0.04	0.44	0.85	--	--
					Bendix, Third Pass							
3	I	--	--	--	0.608	0.431	0.567	0.03	0.41	0.60	--	--
4		--	--	--	0.673	0.465	0.553	0.03	0.34	0.57	--	--
5		--	--	--	0.728	0.509	0.559	0.02	0.26	0.60	--	--
11		--	--	--	0.701	0.488	0.559	0.02	0.34	0.60	--	--
12	↓	--	--	--	0.700	0.519	0.591	0.03	0.36	0.65	--	--

(Continued)

Table 3 (Continued)

Test No.	Wheel Symbol	Wheel Load N(lb)	Soil Condition	Before-Traffic Penetration Resistance Gradient G MN/m³ (pci)	Performance Parameters: Efficiency η'_{20}	Pull/Load P_{20}/W	Torque/Load M_{20}/Wr_e	Power Number PN_{sp}	PN_{15}	PN_{max}	Dimensionless Numeric N_1	N_2
					Bendix, Third Pass (Cont'd)							
13	I	--	--	--	0.652	0.496	0.609	0.05	0.35	0.61	--	--
14		--	--	--	0.684	0.467	0.546	0.06	0.38	0.63	--	--
15		--	--	--	0.658	0.485	0.590	0.08	0.34	0.55	--	-
23		--	--	--	0.665	0.534	0.602	0.07	0.40	0.73	--	--
24		--	--	--	0.688	0.535	0.622	0.04	0.34	0.65	--	--
25		--	--	--	0.665	0.481	0.579	0.04	0.34	0.59	--	--
31	II	--	--	--	0.580	0.540	0.690	0.05	0.37	0.65	--	--
32		--	--	--	0.580	0.510	0.701	0.04	0.43	0.68	--	--
33		--	--	--	0.570	0.493	0.691	0.03	0.43	0.76	--	--
88	III	--	--	--	0.510	0.516	0.813	0.10	0.51	0.88	--	--
					Boeing-GM, First Pass							
26	I	130(30)	C_2	3.01(11.1)	0.690	0.380	0.480	0.05	0.47	0.65	4498	127.3
27		310(70)	C_2	3.09(11.5)	0.480	0.340	0.570	--	0.32	--	3939	157.9
28		490(110)	C_2	3.17(11.8)	0.580	0.324	0.443	0.05	0.40	0.45	3830	154.0
29		670(150)	C_2	3.12(11.6)	0.670	0.329	0.397	0.01	0.34	0.41	3923	139.2
60		310(70)	S_1	0.52(1.9)	0.470	0.259	0.432	0.08	0.51	0.50	942	26.5
61		490(110)	S_1	0.52(1.9)	0.470	0.266	0.456	0.13	0.45	0.46	789	25.3
62		130(30)	S_1	0.55(2.1)	0.410	0.261	0.514	0.13	0.48	0.47	1626	23.3
63		67(15)	S_1	0.57(2.1)	0.460	0.312	0.538	0.05	0.62	0.71	--	--
64	II	310(70)	S_1	0.52(1.9)	0.520	0.320	0.497	0.08	0.42	0.48	942	26.5
65	III	310(70)	S_1	0.59(2.2)	0.520	0.332	0.512	0.06	0.40	0.49	1068	30.1
66	IV	67(15)	S_1	0.52(1.9)	0.670	0.467	0.559	0.04	0.34	0.57	2427	3.1
67		220(50)	S_2	2.81(10.7)	0.520	0.371	0.570	0.06	0.43	0.57	4644	33.6
68		310(70)	S_1	0.53(2.0)	0.470	0.280	0.473	0.12	0.42	0.44	725	8.7
69		310(70)	S_2	3.49(13.0)	0.590	0.412	0.555	0.03	0.40	0.60	4778	57.4
70	V	310(70)	S_1	0.51(1.9)	0.500	0.319	0.511	0.06	0.51	0.60	942	26.5
71		310(70)	S_2	2.89(11.1)	0.600	0.383	0.513	0.04	0.42	0.56	5234	147.3
72	VI	310(70)	S_1	0.55(2.1)	0.560	0.391	0.556	0.09	0.46	0.69	1489	49.1
73		310(70)	S_2	3.53(13.2)	0.640	0.472	0.588	0.09	0.46	0.75	9554	315.4
74		310(70)	C_2	2.74(10.2)	0.625	0.451	0.573	0.05	0.45	0.75	7416	244.8
75		310(70)	C_2	3.08(11.5)	0.620	0.453	0.584	0.12	0.50	0.85	8335	275.2
76		310(70)	S_1	0.52(1.9)	0.550	0.377	0.554	0.12	0.52	0.69	1407	46.5
					Boeing-GM, Second Pass							
27	I	--	--	--	0.610	0.362	0.472	0.06	0.31	0.39	--	--
28		--	--	--	0.510	0.292	0.455	0.09	0.46	0.49	--	--
29		--	--	--	0.520	0.277	0.430	0.07	0.34	0.34	--	--
61		--	--	--	0.510	0.285	0.451	0.11	0.33	0.34	--	--
62		--	--	--	0.420	0.258	0.488	0.01	0.48	0.46	--	--
65	III	--	--	--	0.530	0.347	0.524	0.08	0.43	0.53	--	--
66	IV	--	--	--	0.590	0.387	0.522	0.12	0.34	0.43	--	--
					Boeing-GM, Third Pass							
27	I	--	--	--	0.570	0.327	0.458	0.09	0.41	0.48	--	--
28		--	--	--	0.520	0.301	0.447	0.06	0.39	0.44	--	--
29		--	--	--	0.560	0.302	0.429	0.04	0.32	0.36	--	--
60		--	--	--	0.500	0.277	0.444	--	--	--	--	--
61		--	--	--	0.500	0.284	0.457	0.11	0.34	0.35	--	--
62		--	--	--	0.470	0.294	0.498	0.04	0.43	0.47	--	--
63		--	--	--	0.450	0.317	0.560	0.04	0.52	0.60	--	--
65	III	--	--	--	0.520	0.349	0.541	0.04	0.41	0.51	--	--
66	IV	--	--	--	0.520	0.388	0.601	0.04	0.41	0.58	--	--

(Continued)

Table 3 (Continued)

Test No.	Wheel Symbol	Wheel Load N(lb)	Soil Condition	Before-Traffic Penetration Resistance Gradient G MN/m³ (pci)	Efficiency η'_{20}	Pull/Load P_{20}/W	Torque/Load M_{20}/Wr_e	Pull/Load P_{60}/W	Torque/Load M_{60}/Wr_e	Power Number PN_{sp}	PN_{15}	PN_{max}	Dimensionless Numeric N_1	N_2
					Grumman, First Pass									
34	I	310(70)	C_2	3.33(12.5)	0.36	0.200	0.460	0.220	0.540	0.15	∞*	0.50	8015	137.5
35		130(30)	C_2	3.25(12.2)	0.57	0.351	0.491	0.390	0.650	0.15	0.43	0.52	14688	307.5
36		490(110)	C_2	3.31(12.4)	0.45	0.262	0.469	0.295	0.560	0.08	0.44	0.46	6625	89.2
37		670(150)	C_2	3.20(12.0)	0.44	0.277	0.507	0.290	0.550	0.13	0.50	0.52	5708	63.0
38		670(150)	S_1	0.57(2.1)	0.40	0.264	0.556	0.315	0.620	0.24	0.60	0.60	1016	11.2
39		490(110)	S_1	0.55(2.1)	0.44	0.287	0.542	0.335	0.610	0.11	0.66	0.70	1102	14.8
40		310(70)	S_1	0.53(2.0)	0.43	0.260	0.530	0.315	0.580	0.16	0.35	0.34	1275	21.9
41		130(30)	S_1	0.51(1.9)	0.52	0.312	0.560	0.410	0.685	0.14	0.39	0.43	2304	48.3
42	II	310(70)	S_1	0.54(2.0)	0.48	0.529	0.889	0.650	1.010	0.18	0.61	1.10	1299	22.3
43		310(70)	S_2	3.16(11.6)	0.47	0.529	0.955	0.618	1.005	0.20	0.62	1.20	7464	128.0
44		310(70)	C_2	3.52(13.2)	0.46	0.565	0.973	0.633	1.015	0.20	0.54	0.93	8474	145.3
45		310(70)	C_4	0.63(2.4)	0.44	0.597	1.097	0.680	1.025	0.20	0.63	1.15	1516	26.0
					Grumman, Second Pass									
34	I	--	--	--	0.38	0.220	0.468	0.266	0.613	0.14	∞*	0.36	--	--
35		--	--	--	0.40	0.280	0.559	0.381	0.678	0.19	0.52	0.53	--	--
36		--	--	--	0.41	0.221	0.511	0.299	0.575	0.11	0.54	0.56	--	--
37		--	--	--	0.42	0.258	0.493	0.315	0.585	0.11	0.54	0.57	--	--
38		--	--	--	0.42	0.289	0.552	0.281	0.611	0.07	0.67	0.71	--	--
39		--	--	--	0.47	0.305	0.524	0.314	0.617	0.18	0.56	0.60	--	--
40		--	--	--	0.45	0.269	0.477	0.325	0.581	0.08	0.61	0.67	--	--
41		--	--	--	0.38	0.283	0.600	0.238	0.584	0.12	0.46	0.48	--	--
42	II	--	--	--	0.38	0.504	0.895	--	--	0.21	0.49	0.74	--	--
43		--	--	--	0.47	0.510	0.864	0.788	1.256	0.12	0.59	1.01	--	--
44		--	--	--	0.45	0.586	1.050	--	--	0.16	0.60	1.14	--	--
45		--	--	--	0.44	0.596	1.074	--	--	0.26	0.56	1.36	--	--
					Grumman, Third Pass									
34	I	--	--	--	0.37	0.191	0.413	--	--	0.11	∞*	0.41	--	--
35		--	--	--	0.36	0.292	0.647	0.338	0.658	0.17	0.48	0.29	--	--
36		--	--	--	0.45	0.298	0.535	0.360	0.628	0.15	0.66	0.73	--	--
37		--	--	--	0.38	0.237	0.502	0.299	0.588	0.17	0.46	0.46	--	--
38		--	--	--	0.47	0.293	0.503	0.287	0.605	0.37	0.40	0.40	--	--
39		--	--	--	0.40	0.208	0.416	0.289	0.627	0.08	0.55	0.50	--	--
40		--	--	--	0.42	0.298	0.572	0.345	0.580	0.15	0.54	0.65	--	--
41		--	--	--	0.39	0.317	0.651	--	--	0.25	0.67	0.82	--	--
42	II	--	--	--	0.41	0.543	0.877	--	--	0.20	0.50	0.81	--	--
43		--	--	--	0.46	0.526	0.915	--	--	0.17	0.60	1.00	--	--
44		--	--	--	0.46	0.592	1.028	--	--	0.23	0.53	1.23	--	--
45		--	--	--	0.44	0.605	1.094	--	--	0.16	0.61	1.10	--	--

(Continued)

* Vehicle unable to negotiate 15-deg slope.

Table 3 (Concluded)

Test No.	Wheel Symbol	Wheel Load N(lb)	Soil Condition	Before-Traffic Penetration Resistance Gradient G MN/m^3 (pci)	Efficiency η'_{20}	Pull/Load P_{20}/W	Torque/Load M_{20}/Wr_e	Power Number PN_{sp}	Power Number PN_{15}	Power Number PN_{max}	Dimensionless Numeric N_1	Dimensionless Numeric N'_2
					SLRV, First Pass							
46	--	115(26)	C_2	3.31(12.4)	0.53	0.392	0.588	0.18	0.50	0.66	5295	111.3
47	--	67(15)	C_2	3.05(11.9)	0.70	0.538	0.650	0.20	0.48	0.75	8819	218.5
48	--	220(50)	C_2	3.24(12.1)	0.58	0.446	0.619	0.22	0.53	0.74	5790	125.5
49	--	310(70)	C_2	3.42(12.8)	0.60	0.435	0.576	0.06	0.42	0.64	3154	72.8
50	--	310(70)	S_1	0.57(2.1)	0.64	0.439	0.546	0.08	0.36	0.54	920	12.1
51	--	220(50)	S_1	0.55(2.1)	0.68	0.501	0.586	0.06	0.33	0.55	986	21.3
52	--	115(26)	S_1	0.57(2.1)	0.43	0.303	0.567	0.06	0.44	0.49	910	19.2
53	--	67(15)	S_1	0.51(1.9)	0.48	0.412	0.693	0.10	0.35	0.49	--	--
54	--	67(15)	S_1	0.56(2.1)	0.76	0.537	0.564	0.06	0.34	0.61	1620	40.1
55	--	115(26)	S_1	0.53(2.0)	0.55	0.364	0.530	0.12	0.46	0.58	846	17:8
					SLRV, Second Pass							
46	--	--	--	--	0.53	0.404	0.613	0.18	0.45	0.58	--	--
47	--	--	--	--	0.71	0.551	0.618	0.22	0.45	0.70	--	--
48	--	--	--	--	0.53	0.405	0.613	0.20	0.54	0.72	--	--
49	--	--	--	--	0.61	0.458	0.597	0.07	0.38	0.60	--	--
50	--	--	--	--	0.65	0.459	0.567	0.07	0.37	0.57	--	--
51	--	--	--	--	0.60	0.445	0.597	0.08	0.43	0.65	--	--
52	--	--	--	--	0.60	0.441	0.589	0.10	0.40	0.59	--	--
53	--	--	--	--	0.64	0.541	0.675	0.10	0.40	0.70	--	--
54	--	--	--	--	0.75	0.576	0.615	0.04	0.30	0.61	--	--
55	--	--	--	--	0.50	0.329	0.529	0.12	0.43	0.51	--	--
					SLRV, Third Pass							
46	--	--	--	--	0.55	0.482	0.697	0.03	0.40	0.70	--	--
47	--	--	--	--	0.66	0.452	0.552	0.04	0.23	0.36	--	--
48	--	--	--	--	0.54	0.442	0.656	0.18	0.50	0.72	--	--
49	--	--	--	--	0.67	0.466	0.557	0.10	0.37	0.57	--	--
50	--	--	--	--	0.49	0.339	0.553	0.20	0.55	0.64	--	--
51	--	--	--	--	0.53	0.386	0.578	0.14	0.41	0.54	--	--
52	--	--	--	--	0.64	0.468	0.581	0.03	0.30	0.51	--	--
53	--	--	--	--	--	--	--	--	--	--	--	--
54	--	--	--	--	0.74	0.574	0.624	0.20	0.44	0.72	--	--
55	--	--	--	--	0.56	0.378	0.544	0.20	0.49	0.61	--	--

Table 4

Vehicle Test Results

Test No.	Soil Condition	Soil G MN/m³(pci)	Slip, % 1st Axle	Slip, % 2d Axle	Slip, % 3d Axle	Slip, % Avg	Load Transfer N(lb)	Avg Wheel Load N(lb)	Total Load N(lb)	Torque, m-N(ft-lb) 1st Axle	Torque 2d Axle	Torque 3d Axle	Torque Sum	Pull, N(lb)	Velocity m/sec(ft/sec)	Test Bin Slope %	Test Bin Slope deg	M/Wr_e	P/W	η'	Power No.
											4x4 Test Vehicle										
109	S_1	0.6(2.0)	·6.3	7.0	--	6.7	52(12)	310(70)	1240(280)	40.7(30.0)	127.8(94.3)	--	168.5(124.3)	444(100)	--	0	0	0.300	0.356	1.107	0.322
			12.0	10.8	--	11.4	68(15)			89.5(66.0)	177.4(130 8)	--	267.0(196.8)	652(147)	--			0 474	0.524	0.979	0.535
			15.8	13.2	--	14.6	70(16)			89.5(66.0)	214.0(157.8)	--	303.0(223.8)	680(153)	--			0.538	0 545	0.865	0.630
110	S_1	0.5(1.8)	7.8	7.8	--	7.8	44(10)	490(110)	1960(440)	85.6(63.1)	127.8(94.3)	--	213.4(157.4)	196(44)	--	0	0	0.243	0.099	0.375	0.264
			13.3	12.2	--	14.3	88(20)			225.2(166.0)	248.8(183.5)	--	474.0(349.5)	783(176)	--			0.540	0.400	0.645	0.634
			16.4	14.3	--	15.4	90(20)			225.2(166.0)	251.5(185.5)	--	476.7(351.5)	801(180)	--			0.543	0.409	0.627	0.638
111	S_1	0.5(1.8)	17.2	16.2	--	16.7	85(19)	490(110)	1960(440)	203.1(149.8)	231.7(170.9)	--	434.8(320.7)	745(167)	--	0	0	0.496	0.381	0.640	0.595
			34.4	25.4	--	29.9	106(24)			269 8(199.0)	250.1(184.5)	--	520.8(384.1)	1023(230)	--			0.594	0.523	0.617	0.847
			65.3	52.5	--	58.9	120(27)			288.7(212.9)	264.8(195.3)	--	553.4(408.7)	1203(270)	--			0.631	0.614	0.430	1.535
			80.5	69.2	--	74.8	125(28)			293.9(216.8)	295.2(217.7)	--	549.1(405.0)	1275(287)	--			0.671	0.651	0.262	2.484
112	S_1	0.5(2.0)	11.7	11.7	--	11.7	36(8)	310(70)	1240(280)	92.2(68.0)	120.0(188.5)	--	212.2(156.5)	236(53)	--	0	0	0 377	0.189	0.442	0.427
			--	--	--	20.0	64(14)			165.9(122.4)	185.2(136.6)	--	351 1(259.0)	594(134)	--			0.624	0.477	0.612	0.780
			56.2	58.6	--	57.4	82(18)			205.4(151.5)	250.4(184.7)	--	455.8(336.2)	839(189	--			0.810	0.675	0.377	1.901
			85.6	84.4	--	85.0	88(20)			216.0(159.3)	268.7(198.2)	--	484.7(357.5)	926(208)	--			0.861	0.744	0.130	5.740
			87.7	86.7	--	87.2	86(19)			216.0(159.3)	260.8(192.4)	--	476.8(351.7)	891(200)	--			0.847	0.715	0.121	6.617
			90.6	89.5	--	90.1	94(21)			221.3(163.2)	281.7(207 8)	--	503.0(371.0)	996(224)	--			0.894	0 800	0.075	9.030
113	S_1	0.5(1.7)	5.3	3.8	--	4.5	25(8)	310(70)	1240(280)	65.9(48.6)	91.1(67.2)	--	157.0(115.8)	87(20)	--	0	0	0.279	0.070	0.239	0.292
			13.2	13.2	--	13.2	50(11)			142.2(104.9)	155.5(114.7)	--	297.7(219.6)	411(92)	--			0.529	0.330	0.541	0.609
			--	--	--	20.0	66(15)			181.8(134.1)	190.3(140.4)	--	372.1(274.4)	629(141)	--			0.661	0.500	0.605	0.826
			55.2	53.6	--	54.4	79(18)			210.7(155.4)	252.0(185.9)	--	462.7(341.3)	795(179)	--			0.822	0.640	0.355	1.803
			79.6	78.2	--	78.9	83(19)			226.5(167.1)	262.7(193.8)	--	489.2(360.8)	857(193)	--			0.869	0.690	0.167	4.118
			91.9	91.3	--	91.6	88(20)			229.1(169.0)	273.5(201.7)	--	502.6(370.7)	927(208)	--			0.893	0.740	0.070	10.631
114	S_1	0.5(1.7)	4.7	6 1	--	5.4	27(6)	310(70)	1240(280)	56.9(42.0)	100.6(74.2)	--	157.5(116.2)	116(26)	--	0	0	0.280	0.093	0.314	0.296
			24.2	19.5	--	21.8	71(16)			178.9(131.9)	223.0(164.5)	--	402 0(296.5)	694(156)	--			0.715	0.559	0 611	0.914
			54.8	51.3	--	53.0	78(17)			206.0(151.9)	252.8(186 5)	--	458.9(338.5)	783(176)	--			--	--	0.556	1.468
			69.7	70.0	--	69.8	80(18)			203.4(150.0)	269.3(198.6)	--	472.6(348.6)	818(184)	--			0.841	0.657	0.236	2.785
			82.0	79.7	--	80.8	83(19)			200.7(148.0)	266.4(196.5)	--	467.1(344.5)	858(193)	--			0.831	0.629	0.145	4.328
			93.8	93.0	--	93.4	91(20)			225.4(166.2)	301.8(222.6)	--	524.2(386.6)	961(216)	--			0.932	0.770	0.055	14.121
115	S_1	0.5(1.7)	17.1	14.2	--	15.6	148(33)	310(70)	1240(280)	136.9(101.0)	166.2(122.6)	--	303.1(223.6)	157(35)	--	27	15	0 539	0.136	0.213	0.639
			18.4	17.6	--	18.0	155(35)			94.8(70.0)	195.8(144.4)	--	290.[illegible]	245(55)	--			0.517	0.197	0.312	0.630
			18.7	22.4	--	20.5	157(35)			94.8(70.0)	203.8(150.3)	--	29[illegible]	271(61)	--			0.531	0.218	0.326	0.668
			62.2	46.1	--	54.2	170(38)			173.8(128.2)	273.5(201.7)	--	447.3(3[illegible].9)	455(102)	--			0.796	0.367	0.211	1.738
116	S_1	0.5(1.8)	32.3	25.1	--	28.7	236(53)	310(70)	1240(280)	(110.7)	(156.1)	--	362.7(267.5)	26(6)	--	47	25	0.645	0.020	0.022	0.905
			41.6	20.8	--	31.2	237(53)			(126.3)	(174.0)	--	407.2(300.3)	35(8)	--			0.724	0.028	0.027	1.052
			--	--	--	--	251(56)			(116.6)	(243.4)	--	461.1(340.0)	223(50)	--			0.820	0.179	--	--
117	S_1	0.5(1.8)	25.3	16.2	--	20.7	236(53)	310(70)	1240(280)	147.5(108.8)	222.6(164.2)	--	370.1(273.0)	26(6)	--	47	25	0.658	0.021	0.025	0.830
			40.8	30.5	--	35.6	263(53)			169.9(104.9)	296.2(182.8)	--	466.1(287.7)	38(10)	--			0.694	0.035	0.032	1.078
			79.9	72.5	--	76.2	238(59)			142.2(114.6)	247.9(194.8)	--	390.1(309.4)	44(83)	--			0.746	0.297	0.095	3.134
			--	--	--	--	262(59)			155.4(125.3)	264.1(218.5)	--	419.5(343.8)	370(86)	--			0.829	0.307	--	--
119	S_1	0.5(1.8)	44.1	22.5	--	33.3	250(56)	310(70)	1240(280)	133.0(98.1)	231.9(171.0)	--	364.9(269.1)	0(0)	--	50	27	0.649	0.000	0.000	0.973
			47.7	26.6	--	37.2	252(57)			133.0(98.1)	242.7(179 0)	--	375.7(277.1)	22(5)	--			0.668	0 017	0.016	1.064
			90.3	89.3	--	89.8	261(58)			135.7(100.1)	256.1(188.9)	--	391.8(289.0)	151(34)	--			0.697	0.121	0.018	6.833
			92.9	84.9	--	88.9	263(59)			147.5(108.8)	289.6(213 6)	--	437.1(322.4)	178(40)	--			0.777	0.143	0.020	7.000
120	S_1	0.5(1.8)	84.9	88.2	--	86.5	288(65)	310(70)	1240(280)	134.4(99.1)	163.1(120.3)	--	297.5(219.4)	4(1)	--	58	30	0.390	0.003	0 001	2.889
			92.4	94.9	--	93.6	289(65)			138.3(102.0)	176.1(130.0)	--	314.4(231.9)	18(4)	--			0.412	0.014	0.002	6.438
			96.4	97.6	--	97.0	289(65)			138.3(102.0)	189.1(139.5)	--	327.4(241.5)	18(4)	--			0.430	0.014	0.001	14.333
122	S_1	0.5(1.8)	9.2	5.9	--	7.5	43(10)	670(150)	2680(600)	84.3(62.2)	111.7(82.4)	--	196.0(144.6)	34(8)	--	0	0	0.165	0.013	0.073	0.178
			14.7	12.0	--	13.3	68(15)			147.5(108.8)	172.7(127.4)	--	320.2(236.2)	364(82)	--			0.269	0.136	0.438	0.310
			15.8	21.2	--	18.5	107(24)			263.4(194.3)	299.8(221.1)	--	563.2(415.4)	893(201)	--			0.473	0.335	0.577	0.580
			31.1	38.0	--	34.5	134(30)			331 9(244.8)	401.3(296.0)	--	733.2(540.8)	1254(282)	--			0.616	0.470	0.500	0.940

(Continued)

Page 5 of 5 (Table 3) missing from original document

Test No.	Soil Con-dition	Soil G MN/m^3(pci)	Slip, % 1st Axle	Slip, % 2d Axle	Slip, % 3d Axle	Slip, % Avg	Load Transfer N(lb)	Avg Wheel Load N(lb)	Total Load N(lb)	Torque, m-N(ft-lb) 1st Axle	Torque, m-N(ft-lb) 2d Axle	Torque, m-N(ft-lb) 3d Axle	Torque, m-N(ft-lb) Sum	Pull, N(lb)	Velocity m/sec(ft/sec)	Test Bin Slope %	Test Bin Slope deg	W/Wr_e	P/W	η'	Power No.
4x4 Test Vehicle (Continued)																					
123	S_1	0.5(1.8)	17.0	17.0	--	17.0	296(66)	670(150)	2680(600)	233.7(172.4)	253.9(187.3)	--	487.7(359.7)	53(12)	--	27	15	0.410	0 020	0.040	0.494
			18.6	24.4	--	21.5	308(69)			275.2(203.0)	301 5(222.4)	--	576.8(425.4)	265(60)	--			0 485	0.099	0.160	0.618
			19.5	48.8	--	34.0	333(75)			296.1(218 4)	444.3(327.7)	--	740.4(546.1)	599(135)	--			0 622	0.225	0.239	0 942
			41.7	72 4	--	57.0	337(76)			301.3(222 2)	534.2(394.0)	--	835.4(616.2)	652(147)	--			0.702	0.244	0.149	1.633
129	S_1	0.5(2.0)	58.2	34.7	--	46.4	502(113)	670(150)	2680(600)	236.0(174.0)	371.0(273.6)	--	607.0(447.7)	88(20)	--	47	25	0.510	0.033	0.035	0 951
			70.4	50.1	--	60.2	507(114)			225.0(166.0)	426.0(314.2)	--	651.0(480.2)	154(35)	--			0.547	0.058	0.042	1.374
			83.8	70.0,	--	76.9	513(115)			246.0(181.4)	445.0(328.2)	--	691.0(509.7)	229(51)	--			0.581	0.086	0.034	2.515
130	S_1	0.6(2.2)	55.9	32.3	--	44.1	500(112)	670(150)	2680(600)	230.0(169.6)	380.0(280.3)	--	611.0(450.7)	52(12)	--	47	25	0.513	0.019	0.021	0.917
			60.7	41.7	--	51.2	506(114)			237.0(174.8)	370.0(272.9)	--	607.0(447.7)	140(31)	--			0.510	0.052	0.050	1.045
			70.8	46.8	--	58.8	512(115)			241.0(177.8)	413.0(304.6)	--	654.0(482.4)	222(50)	--			0 550	0.083	0.063	1.325
			87.2	73.4	--	80.3	514(116)			236.0(174.1)	442.0(326.0)	--	678.0(500.1)	249(56)	--			0.570	0.093	0.032	2.893
131	S_1	0.5(2.0)	--	--	--	--	--	670(150)	2680(600)	The maximum slope climbed was 27.5 deg			--	--	--	52	28	--	--	--	--
132	C_2	3.1(11.4)	26.7	19.6	--	23.1	112(25)	670(150)	2680(600)	269.8(199.0)	238.6(176.0)	--	508.4(375.0)	951(214)	--	0	0	0.427	0.356	0.641	0.552
			28.2	23.7	--	25.9	90(20)			232.8(171.7)	175.0(129 1)	--	407.8(300.8)	669(150)	--			0.343	0.251	0.542	0.563
			32.7	28.5	--	30.6	131(30)			370.3(273.1)	296.9(219.0)	--	767.2(565.9)	1216(273)	--			0.645	0.455	0 489	0.929
			46.3	37.7	--	42.0	154(35)			359.7(265.3)	365.9(269.9)	--	725.6(535.2)	1515(341)	--			0.610	0.567	0.539	1.052
			65.7	53.8	--	59.7	167(38)			380.8(280.9)	434 8(320.7)	--	815.6(601.6)	1691(380)	--			0.685	0.634	0.373	1.700
			--	--	--	100.0	170(38)			407.3(300.4)	445.4(328.5)	--	852.7(628.9)	1726(388)	--			0.717	0.647	0.000	∞
133	C_2	3.1(11.4)	14.9	13.3	--	14.1	43(10)	490(110)	1960(440)	85.7(63.2)	90 2(66.5)	--	175.9(129.7)	176(40)	--	0	0	0.200	0.090	0.387	0.233
			18.9	13.3	--	16.1	62(14)			155.4(114.6)	153.7(113.4)	--	309.1(228.0)	428(96)	--			0.352	0.218	0 520	0 420
			31.3	19.7	--	25.5	103(23)			257.1(189.6)	275.7(203.3)	--	532.8(393.0)	987(221)	--			0.607	0.504	0.618	0.815
			54.9	46.3	--	50.6	114(26)			299.9(221.2)	291.6(215.1)	--	591.5(436.3)	1128(253)	--			0.674	0.576	0.422	1.364
			86.5	82.6	--	84.5	133(30)			305.3(225 2)	376.5(277.7)	--	681 8(502.9)	1374(309)	--			0.777	0.702	0 140	5.013
			--	--	--	100.0	143(32)			321.3(237.0)	381.8(281.6)	--	703.1(518.6)	1515(341)	--			0.801	0.774	0.000	∞
134	C_2	3.0(11.0)	7.2	9.0	--	8.1	20(5)	310(70)	1240(280)	60.1(44.3)	65.6(48.4)	--	125.7(19.0)	17(4)	--	0	0	0.224	0 014	0.057	0.244
			12.9	7.2	--	10.0	51(11)			117.5(86.7)	152.1(112.2)	--	269.6(198.8)	428(96)	--			0.480	0.343	0.603	0.503
			18.6	12.9	--	15.7	73(16)			182.9(134.9)	196.7(145.1)	--	379.6(235.6)	727(163)	--			0.675	0.584	0.729	0.801
			74.5	68.9	--	71.7	89(20)			190.8(140.7)	275.4(203.1)	--	466 2(343.8)	941(212)	--			0.829	0.755	0.258	2.929
			91.4	89.3	--	90.3	95(21)			190.8(140.7)	280 5(206.9)	--	471.3(347.6)	1009(229)	--			0.838	0.818	0.102	8.639
135	C_2	2.8(10.3)	17.2	11.5	--	14.3	58(13)	310(70)	1240(280)	158.6(117.0)	145.9(107.6)	--	304 5(224.6)	525(118)	--	0	0	0.542	0.421	0.665	0.632
			25.1	20.3	--	22.7	72(16)			195.6(144.3)	185.6(136.9)	--	381.2(281.2)	703(158)	--			0.678	0.565	0 644	0.877
			34.8	29.7	--	32.2	85(19)			222.2(163.9)	225.3(166.2)	--	447.5(330.1)	881(198)	--			0.796	0.705	0.600	1.174
			67.9	65.3	--	66.6	89(20)			216 9(160.0)	243.9(179.9)	--	460.8(339.9)	934(210)	--			0.820	0.750	0.305	2.455
			82.2	79.3	--	80.7	91(20)			224.8(165.8)	241.3(178.0)	--	466.1(343.8)	960(216)	--			0.829	0.771	0.179	4.295
			--	--	--	100.0	96(22)			238.1(175.6)	251.9(185.8)	--	490.0(361.4)	1032(232)	--			0.872	0.828	0.000	∞
138	C_2	2.9(10 8)	22.4	15.8	--	19 1	237(53)	310(70)	1240(280)	127.0(93.7)	187.2(138.1)	--	315.2(232.5)	36(8)	--	47	25	0.557	0.028	0.041	0.689
			20.0	13.1	--	16.5	237(53)			127.0(93.7)	188.2(138 8)	--	315.2(232.5)	44(10)	--			0.557	0.035	0.052	0.668
			27.0	14.5	--	20.7	246(55)			124.6(91.9)	233.3(172.1)	--	357.9(264.0)	156(35)	--			0 633	0.126	0.158	0.798
			21.4	14.5	--	17.9	236(53)			127.0(93.7)	182.9(134.9)	--	309.9(228.6)	36(8)	--			0.548	0.028	0.042	0.668
139	C_2	3.1(11.6)	32.7	11.7	--	22 2	237(53)	310(70)	1240(280)	148.0(109.2)	182.9(134.9)	--	330.9(244.1)	44(10)	--	47	25	0.585	0.035	0.047	0.752
			32.5	18.0	--	25.3	244(55)			142.8(105.3)	230.6(170.1)	--	373.4(275.4)	138(31)	--			0.660	0.112	0.127	0.883
			39 8	27.9	--	33.8	252(57)			145 5(107.3)	257.2(189.7)	--	402.7(297.0)	244(53)	--			0.712	0.189	0.176	1.076
			83.0	78.7	--	80.8	257(58)			156 0(115.1)	281.1(207.3)	--	437.1(322.4)	307(69)	--			0 733	0.245	0.061	4.026
			91.0	88.7	--	89.8	256(58)			142.8(105.3)	288.9(213.1)	--	431.7(318.4)	298(67)	--			0.763	0 238	0.032	7.485
141	C_2	3.0(11.2)	--	--	--	--	--	310(70)	1240(280)	The vehicle was able to negotiate a 33-deg slope while operating at about 60% slip. It finally spun out on a 34.5-deg slope											
142	C_2	3.1(11.6)	--	--	--	--	--	310(70)	1240(280)	This test was a repeat of the previous one. It was deemed necessary in view of the steep slope angle. The results were about the same. The vehicle was barely propelling itself on a 34-deg slope											
143	C_2	3.2(11.8)	29.2	17.7	--	23.4	(71)	670(150)	2680(600)	281.2(207.4)	259.8(191.6)	--	541.0(399.0)	370(83)	--	27	15	0.455	0.138	0.232	0.594
			37.4	19.4	--	28.4	316(75)			315 9(233 0)	334.1(246.4)	--	650.0(479.4)	616(138)	--			0.546	0.231	0.303	0.763
			38.4	24.1	--	31.2	334(67)			251.7(185.6)	220.0(162.2)	--	471.7(347.9)	176(40)	--			0.396	0.066	0.115	0.576
			66.1	46.4	--	56.2	301(79)			318.6(235 0)	400.4(295.3)	--	719.0(530.3)	872(196)	--			0.604.	0.327	0.237	1 379
			81.7	41 8	--	61.7	354(79)			334.7(246.9)	448 1(330.5)	--	782.8(577.4)	863(194)	--			0.658	0.323	0.188	1.718
			--	--	--	100 0	356(80)			361.6(266.7)	445.4(328.5)	--	807.0(595.2)	907(204)	--			0 678	0.340	0.000	∞

Table 4 (Continued)

Test No.	Soil Condition	Soil G MN/m^3(pci)	Slip, % 1st Axle	Slip, % 2d Axle	Slip, % 3d Axle	Slip, % Avg	Load Transfer N(lb)	Avg Wheel Load N(lb)	Total Load N(lb)	Torque, m-N(ft-lb) 1st Axle	Torque 2d Axle	Torque 3d Axle	Torque Sum	Pull, N(lb)	Velocity m/sec(ft/sec)	Test Bin Slope %	Test Bin Slope deg	M/Wr_e	P/W	η'	Power No.
										4x4 Test Vehicle (Continued)											
144	C_2	3.1(11.4)	39.9	20.7	--	30.3	500(112)	670(150)	2680(600)	241.1(177.8)	328 8(242.5)	--	569.9(420.3)	53(12)	--	47	25	0.479	0.020	0.029	0.687
			56 3	29.1	--	42.7	511(115)			246.3(181.7)	387.1(285.5)	--	633.4(467.2)	202(45)	--			0.532	0.075	0.081	0.928
			35.9	51.0	--	43.4	522(117)			251.6(185.6)	302.2(222.9)	--	553.8(408.5)	351(79)	--			0.465	0.132	0.161	0.822
			62.8	37.7	--	50.2	512(115)			251.8(185.7)	413.5(305.0)	--	665.3(490.7)	220(49)	--			0.559	0.082	0.073	1.122
			66.5	34.9	--	50.7	519(117)			246.3(181.7)	387.1(285.5)	--	633.4(467 2)	317(71)	--			0.532	0.119	0.110	1.079
			74.7	51.9	--	63.3	523(118)			262.5(193.6)	424.1(312.9)	--	686 7(506.5)	370(83)	--			0 577	0.138	0.088	1.572
146	C_2	3.2(12.0)	--	--	--	--	--	670(150)	2680(600)	The vehicle climbed a 28.5-deg slope and finally stalled on a 30-deg slope due to lack of power at rear wheels as evidenced by the very low slip on the rear wheels and high slip on the front wheels. Dynamic load transfer to the rear wheels contributed to this power stall											
147	C_2	3.1(11.4)	4.8	0.1	--	2.4	22(5)	250(56)	1000(225)	Torque not recorded				92(21)	--	0	0	--	0 091	--	--
			3.5	2.6	--	3.1	18(4)							35(8)	--			--	0.035	--	--
			8.7	2.0	--	5.3	36(8)							273(61)	--			--	0.269	--	--
			17.7	14.9	--	16.3	54(12)							516(116)	--			--	0.509	--	--
			30.2	25.4	--	27.8	73(17)							771(173)	--			--	0.760	--	--
			60.5	58.6	--	59.6	81(18)							873(196)	--			--	0.860	--	--
			81.6	79.4	--	80.5	62(14)							630(142)	--			--	0.621	--	--
			--	--	--	100.0	68(15)							710(160)	--			--	0.700	--	--
148	C_2	3.0(11.2)	--	--	--	--	--	250(57)	1000(228)	The vehicle successfully climbed a 34-deg slope but could not climb a 35-deg slope											
150	C_2	3.1(11.4)	2.8	0.9	--	1.8	21(5)	250(57)	1000(228)	Torque not recorded				71(16)	--	0	0	--	0 069	--	--
			7.2	4.0	--	5.6	41(9)							339(76)	--			--	0.334	--	--
			55.3	51.3	--	53.3	68(15)							697(157)	--			--	0.687	--	--
			91.6	90.8	--	91.2	71(16)							745(168)	--			--	0.735	--	--
151	C_2	3.1(11.4)	2.6	2.6	--	2.6	16(4)	250(57)	1000(228)	Torque not recorded				31(7)	--	0	0	--	0.031	--	--
			8.7	7.0	--	7.8	25(6)							129(29)	--			--	0.127	--	--
			8.8	3.8	--	6.3	44(10)							387(87)	--			--	0.381	--	--
			17.9	12.1	--	15.0	58(13)							666(129)	--			--	0.566	--	--
			76.4	73.1	--	74 7	70(16)							697(164)	--			--	0.719	--	--
			85.8	83 8	--	84.8	71(16)							706(166)	--			--	0.728	--	--
			96.2	95.7	--	95.9	74(17)							769(177)	--			--	0.774	--	--
152	C_2	3.1(11.6)	2.6	0.7	--	1.6	17(4)	250(57)	1000(228)	Torque not recorded				27(6)	--	0	0	--	0.026	--	--
			6.6	3.0	--	4.8	24(6)							116(26)	--			--	0.114	--	--
			7.1	2.0	--	4.5	44(10)							384(86)	--			--	0.379	--	--
			39.0	33.0	--	36.0	65(15)							666(150)	--			--	0 656	--	--
			76.6	73.3	--	74.9	68(15)							697(157)	--			--	0.687	--	--
			85.3	83.2	--	84.2	68(15)							706(159)	--			--	0.696	--	--
			--	--	--	100.0	73(16)							719(173)	--			--	0.758	--	--
										Surveyor Lunar Rover Vehicle (6x6)											
1	C_2	3.0(11.0)	--	--	--	--	--	116(26)	696(155)	Inoperative circuits				22(5)	0.30(1.00)	0	0	--	0.030	--	--
			5.7	8.8	4.5	6.4	--							156(35)	(0.85)			--	0.230	--	--
			5.2	15.9	4 7	8.6	--							320(72)	0.21(0.69)			--	0.460	--	--
			54.5	60.5	49 7	54.9	--							446(100)	(0.31)			--	0.650	--	--
			74.6	78 1	72.4	75.0	--							407(92)	(0.14)			--	0.590	--	--
2	C_2	3 0(11.0)	-1.9	5.6	-0.4	1.1	--	116(26)	696(155)	6.49(4.78)	9.17(6.76)	3.15(2.32)	18.80(13 87)	9(2)	0.33(1.08)	0	0	0 130	0.010	0.10	0.130
			2.3	3.7	3.1	3.0				9.54(7.04)	12.94(9 54)	7.43(5.48)	29.91(22.06)	39(9)	0.30(0.98)			0.200	0.060	0.27	0.210
			6.4	10 1	6.6	7.7	--			23.60(17.40)	22.67(16.72)	26 19(19.31)	72.45(53.44)	269(60)	0.24(0.80)			0.490	0.390	0.74	0.530
			10.6	20.2	11.1	13 9	--			29.64(21.86)	24.04(17.73)	34.06(25.12)	87.74(64.71)	351(79)	0.21(0.70)			0.590	0.510	0.74	0.680
			75.4	78.4	72 2	75.3	--			34.16(25.19)	26.52(19.56)	46.21(34.08)	106.89(78.83)	420(95)	0.05(0.18)			0.720	0.610	0.21	2.910
3	C_2	3.1(11.3)	10.6	19.2	9.5	13.1	--	116(26)	696(155)	17.27(12.74)	19.93(14.70)	20.95(15.45)	58.15(42.89)	13(3)	0.23(0.76)	27	15	0.390	0.020	0.04	0.450
			6.1	12.4	4.3	7.6	--			19.14(14.12)	20.13(14.85)	25.60(18.88)	64.87(47.85)	30(7)	0.25(0.82)			0.440	0.040	0.09	0.470
			10.1	20 5	10 1	13.6	--			26.89(19.83)	22.66(16.71)	33.57(24.76)	83.11(61.30)	160(36)	0.21(0 68)			0.560	0.230	0.36	0.650
			46.9	53.1	40.1	46.7	--			29.65(21.87)	23.63(17.43)	44.48(32.81)	97.77(72.11)	234(53)	0.08(0.26)			0.660	0.340	0.28	1.230
			92.6	93.4	91.4	92.5	--			30.51(22.50)	24 53(18.10)	44.07(32.50)	99.11(73 10)	221(50)	0.03(0 10)			0.670	0.320	0.04	8.880

Table 4 (Continued)

Test No.	Soil Condition	Soil G MN/m³(pci)	Slip, % 1st Axle	Slip, % 2d Axle	Slip, % 3d Axle	Slip, % Avg	Load Transfer N(lb)	Avg Wheel Load N(lb)	Total Load N(lb)	Torque, m-N(ft-lb) 1st Axle	Torque, m-N(ft-lb) 2d Axle	Torque, m-N(ft-lb) 3d Axle	Torque, m-N(ft-lb) Sum	Pull, N(lb)	Velocity m/sec(ft/sec)	Test Bin Slope %	Test Bin Slope deg	M/Wr_e	P/W	η'	Power No.
										Surveyor Lunar Rover Vehicle (6x6) (Continued)											
4	C_2	3.1(11.4)	15.6	26.4	10.0	17.3	--	116(26)	696(155)	27.64(20.39)	20.44(15.07)	36.04(26.58)	84.12(62.04)	9(2)	0.21(0.69)	47	25	0.570	0.010	0.02	0.680
			17.2	27.2	10.1	12.4	--			24.93(18.39)	19.61(14.47)	37.51(27.66)	82.05(60.52)	22(5)	0.22(0.73)			0.550	0.030	0.05	0.630
			34.2	42.6	27.5	34.8	--			28.62(21.11)	21.06(15.53)	33.58(24.77)	83.26(61.41)	57(13)	0.16(0.54)			0.560	0.080	0.10	0.860
			30.5	36.2	21.5	29.4	--			29.12(21.48)	20.85(15.38)	42.12(31.07)	92.09(67.92)	61(14)	0.17(0.56)			0.620	0.090	0.10	0.880
			56.0	63.6	51.0	56.9	--			28.38(20.93)	20.68(15.25)	43.71(32.24)	92.77(68.42)	74(17)	0.09(0.30)			0.620	0.110	0.07	1.450
5	C_2	2.9(10.8)	Vehicle unable to negotiate this slope													62	32				
6	C_2	2.9(10.7)	Vehicle was able to negotiate a 23-deg slope, but could not develop any pull capability. Slip at 0 pull was moderate (40 to 60%). The addition of 3 to 5 lb of drawbar load caused the vehicle to spin out, i.e. 100% slip													53	28				
7	S_1	0.5(1.8)	Vehicle unable to negotiate this slope													47	25				
8	S_1	0.5(1.9)	0.4	4.1	-3.4	0.4	--	116(26)	696(155)	8.13(5.99)	11.75(8.67)	7.18(5.30)	27.06(19.96)	8(2)	0.32(1.04)	0	0	0.180	0.010	0.07	0.180
			2.2	5.4	2.9	3.5	--			9.40(6.93)	12.18(8.98)	8.96(6.61)	30.54(22.53)	22(5)	0.31(1.02)			0.210	0.030	0.15	0.210
			0.2	4.4	0.2	1.6	--			12.96(9.56)	13.89(10.24)	12.03(8.87)	38.87(28.67)	70(16)	0.30(0.98)			0.260	0.100	0.38	0.270
			7.5	7.6	3.8	6.3	--			18.74(13.82)	19.14(14.12)	21.66(15.97)	59.54(43.91)	179(40)	0.27(0.90)			0.400	0.260	0 61	0.430
			20.0	24.6	11.1	18.6	--			25.69(18.95)	22.28(16.43)	34.55(25.48)	82.51(60.86)	293(66)	0.21(0.70)			0.550	0.420	0.62	0.680
			56.5	59.6	52.0	56.0				32.08(23.66)	24.75(18.25)	41.61(30.69)	98.43(72.60)	336(76)	0.10(0.32)			0.660	0.490	0.32	1.500
9	S_1	0.6(2.2)	7.9	19.7	4.7	10.8	--	116(26)	696(155)	25.83(19.05)	20.27(14.95)	30.18(22.26)	76.28(56.26)	108(24)	0.23(0.75)	27	15	0.510	0.160	0.27	0.570
			26.5	34.3	18.7	26.5	--			26.79(19.76)	20.27(14.95)	36.47(26.90)	83.53(61.61)	108(24)	0.16(0.54)			0.560	0.160	0.21	0.760
			46.3	40.0	41.3	42.5	--			27.27(20.11)	20.69(15.26)	38.16(28.15)	86.12(63.52)	104(23)	0.13(0.42)			0.580	0.150	0.15	1.010
			71.6	75.0	66.9	71.2	--			29.29(21.61)	20.88(15.40)	42.99(31.71)	93.16(68.71)	113(25)	0.05(0.18)			0.630	0.160	0 08	2.170
			77.3	79.9	73.7	76.9	--			28.94(21.34)	21.49(15.85)	43.71(32.24)	94.14(69.43)	113(25)	0.05(0.18)			0.630	0.160	0.06	2.740
10	S_4	4.5(16.4)	1.1	3.3	-1.9	0.8	--	116(26)	696(155)	6.87(5.06)	10.79(7.96)	6.93(5.11)	24.59(18.13)	17(4)	0.32(1.04)	0	0	0.170	0.030	0.15	0.170
			1.8	5.9	1.1	2.9	--			10.18(7.51)	13.92(10.27)	10.01(7.38)	34.10(25.15)	52(12)	0.30(0.98)			0.230	0.070	0.32	0.240
			3.7	7.5	1.8	4.3	--			17.05(12.57)	18.54(13.67)	18.24(13.45)	53.82(39.70)	160(36)	0.28(0.92)			0.360	0.230	0.61	0.380
			9.0	13.8	3.6	8.8	--			27.35(20.18)	22.97(16.94)	30.19(22.27)	80.52(59.39)	316(71)	0.22(0.74)			0.540	0.460	0.77	0.590
			49.6	57.7	47.5	51.6	--			32.43(23.92)	23.97(17.68)	42.08(31.04)	98.48(72.63)	377(85)	0.10(0.34)			0.660	0.550	0.40	1.370
11	S_4	4.4(16.3)	The vehicle was unable to negotiate this slope													58	30				
12	C_3	4.4(16.1)	8.3	16.3	4.4	9.7	--	116(26)	696(155)	20.68(15.25)	20.16(14.87)	27.31(20.14)	68.14(50.26)	26(6)	0.24(0.80)	36	20	0.460	0.040	0.07	0.510
			17.9	20.5	10.1	16.2	--			20.47(15.10)	19.96(14.72)	26.83(19.79)	67.26(49.61)	13(3)	0.22(0.74)			0.450	0.020	0.03	0.540
			11.2	18.1	4.2	11.2	--			22.85(16.85)	20.77(15.32)	33.61(24.79)	77.23(56.96)	56(13)	0.23(0.76)			0.520	0.080	0.14	0.580
			14.5	25.4	10.1	16.7	--			28.20(20.80)	20.78(15.33)	35.25(26.00)	84.23(62.13)	103(23)	0.21(0.70)			0.570	0.150	0.22	0.680
			9.5	17.9	1.2	9.5	--			30.02(22.15)	22.77(16.80)	42.69(31.49)	95.48(70.43)	120(27)	0.19(0.62)			0.640	0.170	0 25	0.710
			47.2	51.3	30.0	45.8	--			27.50(20.28)	21.59(15.92)	38.65(28.50)	87.74(64.71)	137(31)	0.14(0.45)			0.590	0.200	0.18	1.090
			67.5	71.7	63.4	67.5	--			27.53(20.30	21.21(15.64)	42.58(31.41)	91.31(67.35)	150(34)	0.08(0.25)			0.610	0.220	0.12	1.890
			89.5	90.8	87.5	89.3	--			31.41(23.17)	23.35(17.22)	46.59(34.36)	101.35(74.75)	163(37)	0.02(0.08)			0.680	0.240	0.04	6.360
13	C_3	4.3(16.0)	4.4	5.2	3.0	4.2	--	116(26)	696(155)	8.49(6.26)	12.68(9.36)	7.72(5.69)	28.90(21.31)	26(6)	0.31(1.01)	0	0	0.190	0.040	0.18	0.200
			-8.8	0.6	-2.9	-3.7	--			10.77(7.94)	13.60(10.03)	8.85(6.53)	33.22(24.50)	65(15)	0.31(1.03)			0.220	0.090	0.43	0.220
			4.9	6.2	4.9	5.3	--			16.12(11.89)	17.53(12.93)	14.94(11.02)	48.59(35.84)	146(33)	0.29(0.95)			0.330	0.210	0.61	0.340
			8.3	11.8	4.2	8.1	--			19.76(14.57)	20.16(14.87)	23.08(17.03)	63.01(46.47)	219(49)	0.26(0.87)			0.420	0.320	0.69	0.460
			4.3	14.1	3.8	7.4	--			25.72(18.97)	21.17(15.61)	26.61(19.62)	73.50(54.21)	275(62)	0.27(0.89)			0.490	0.400	0.75	0.530
			21.6	27.5	12.8	20.6	--			28.54(21.05)	23.76(17.53)	36.59(26.99)	88.89(65.56)	357(80)	0.20(0.65)			0.600	0.520	0.69	0.750
			40.1	49.5	35.5	41.7	--			33.76(24.90)	23.97(17.68)	43.54(32.11)	101.27(74.69)	387(87)	0.15(0.48)			0.680	0.560	0.48	1.170
			71.5	76.0	68.6	72.0	--			33.04(24.37)	23.38(17.25)	45.47(33.53)	101.89(75.15)	387(87)	0.05(0.18)			0.680	0.560	0.23	2.440
14	C_3	4.2(15.5)	Vehicle was able to negotiate 26-27-deg slope and restart after the stopping in ruts. On slope greater than 27 deg the vehicle could not restart after stopping in ruts. The ultimate slope-climbing ability for this condition was 31 deg																		
15	C_2	3.2(11.8)	The vehicle barely negotiated a 28.5-deg slope while operating at an estimated slip of 80-90%. Any effort to steer the vehicle caused it to spin out, i.e. 100% slip. On a slope of 27 deg, the vehicle could be steered and continued to climb at an estimated slip of 40-70%.																		
16	C_0	0.3(1.1)	The ultimate slope-climbing ability of the vehicle was 25.5 deg. It was operating at 90-100% slip. Any effort to steer vehicle resulted in a decrease in ultimate slope-climbing ability of 1.5 to 2.5 deg. On a slope of 23 deg, the vehicle could negotiate the slope after being stopped and restarted in the on-slope position																		
17	S_1	0.5(1.8)	The ultimate slope-climbing ability is approximately 21.5 deg. On a slope of 20 deg, the vehicle could be steered while negotiating the slope																		
18	S_2	3.1(11.4)	The ultimate slope-climbing ability is estimated at 24 deg																		

Table 4 (Concluded)

Test No.	Soil: Condition	Soil: G MN/m³(pci)	Slip, %: 1st Axle	Slip, %: 2d Axle	Slip, %: 3d Axle	Slip, %: Avg	Load Transfer N(lb)	Avg Wheel Load N(lb)	Total Load N(lb)	Torque, m-N(ft-lb): 1st Axle	Torque, m-N(ft-lb): 2d Axle	Torque, m-N(ft-lb): 3d Axle	Torque, m-N(ft-lb): Sum	Pull, N(lb)	Velocity m/sec(ft/sec)	Test Bin Slope %	Test Bin Slope deg	M/Wr_e	P/W	η'	Power No.
										Surveyor Lunar Rover Vehicle (6x6) (Continued)											
19	S_1	0.5(1.8)	14.4	21.8	9.0	15.1	--	116(26)	696(155)	22.89(16.89)	19.94(14.71)	27.90(20.58)	70.73(52.17)	236(53)	0.22(0.74)	0	0	0.480	0.340	0.61	0.560
			15.6	22.4	9.1	15.7	--			27.17(20.04)	21.15(15.60)	35.46(26.15)	83.77(61.79)	271(61)	0.22(0.72)			0.560	0.390	0.59	0.670
			33.4	36.6	25.3	31.8	--			27.83(20.52)	22.76(16.79)	37.03(27.31)	87.62(64.62)	297(67)	0.18(0.58)			0.590	0.430	0.50	0.860
			43.9	51.9	39.2	45.0	--			31.16(22.98)	22.76(16.79)	38.20(28.17)	92.12(67.94)	284(64)	0.13(0.42)			0.620	0.410	0.37	1.130
			61.0	64.3	57.8	61.0	--			32.09(23.67)	23.37(17.24)	40.78(30.08)	96.24(70.98)	297(67)	0.10(0.32)			0.650	0.430	0.26	1.660
			78.1	80.6	76.1	78.3	--			32.32(23.84)	23.56(17.38)	43.35(31.98)	99.23(73.19)	302(68)	0.05(0.16)			0.670	0.440	0.14	3.070
			--	--	--	100.0	--			40.12(29.59)	29.06(21.43)	53.57(39.51)	122.75(90.54)	66(15)	0.00(0.00)			0.820	0.740	0.00	0.000
20	S_1	0.5(1.8)	7.6	7.6	5.5	6.9	--	116(26)	696(155)	18.11(13.36)	17.27(12.73)	19.63(14.48)	55.01(40.57)	127(29)	0.28(0.91)	0	0	0.370	0.180	0.46	0.400
			16.3	21.4	9.0	15.6	--			24.65(18.18)	21.85(16.12)	33.11(24.42)	79.61(58.72)	284(64)	0.22(0.73)			0.530	0.410	0.65	0.630
			24.9	32.7	21.5	26.4	--			29.52(21.77)	21.85(16.11)	37.19(27.43)	88.56(65.32)	275(62)	0.20(0.67)			0.590	0.400	0.49	0.810
			39.9	45.2	35.7	40.3	--			30.22(22.29)	23.66(17.45)	38.64(28.50)	92.51(68.23)	262(59)	0.15(0.50)			0.620	0.380	0.37	1.040
			52.0	58.1	49.2	53.1	--			29.07(21.44)	24.28(17.91)	37.38(27.57)	90.72(66.92)	275(62)	0.12(0.40)			0.610	0.400	0.31	1.300
			65.1	67.7	62.1	64.9	--			31.08(22.92)	25.66(18.92)	40.36(29.77)	97.09(71.61)	297(67)	0.08(0.28)			0.650	0.430	0.23	1.860
			85.3	86.8	83.8	85.3	--			31.63(23.33)	25.26(18.63)	42.81(31.58)	99.70(73.54)	319(72)	0.04(0.12)			0.670	0.460	0.10	4.560
			--	--	--	100.0	--			33.86(24.97)	24.85(18.33)	44.11(32.53)	102.81(75.83)	358(81)	0.01(0.04)			0.690	0.520	0.00	0.000
21	S_2	3.7(13.6)	-0.3	9.9	-2.2	2.5	--	116(26)	696(155)	6.45(4.76)	8.70(6.41)	5.59(4.12)	20.74(15.30)	0(0)	0.32(1.06)	0	0	0.140	0.000	0.00	0.140
			2.1	5.4	-2.2	1.8	--			10.50(7.74)	14.33(10.57)	11.04(8.15)	35.87(26.46)	86(19)	0.30(1.00)			0.240	0.120	0.51	0.250
			24.8	35.1	18.2	26.0	--			33.22(24.50)	22.28(16.43)	40.61(29.95)	96.11(70.89)	355(80)	0.19(0.64)			0.650	0.510	0.59	0.870
			46.7	52.9	41.9	47.2	--			32.59(24.04)	24.07(17.75)	39.68(29.26)	96.34(71.05)	348(78)	0.13(0.44)			0.650	0.500	0.41	1.230
			73.7	74.5	64.3	70.8	--			30.41(22.43)	22.68(16.73)	39.59(29.20)	92.68(68.36)	326(73)	0.07(0.24)			0.620	0.470	0.22	2.130
			56.5	61.0	51.7	53.1	--			32.80(24.19)	24.07(17.75)	42.59(31.41)	99.45(73.35)	357(80)	0.11(0.38)			0.670	0.520	0.36	1.420
			--	--	--	100.0	--			34.77(25.64)	22.78(16.80)	47.86(35.30)	105.41(77.74)	403(91)	0.00(0.00)			0.710	0.580	0.00	0.000
22	S_2	3.5(12.7)	8.6	8.7	3.7	7.0	--	116(26)	696(155)	8.40(6.19)	11.55(8.52)	6.54(4.82)	26.49(19.53)	0(0)	0.30(0.99)	0	0	0.180	0.000	0.00	0.190
			4.6	12.8	0.5	5.9	--			11.74(8.66)	14.74(10.87)	9.61(7.09)	36.08(26.61)	71(16)	0.29(0.95)			0.240	0.100	0.40	0.260
			4.3	8.8	3.6	5.6	--			18.26(13.47)	17.66(13.03)	16.91(12.48)	52.83(38.97)	168(38)	0.27(0.89)			0.350	0.240	0.65	0.380
			4.2	10.1	0.6	4.9	--			23.77(17.53)	21.95(16.19)	26.47(19.52)	72.20(53.25)	256(58)	0.25(0.81)			0.490	0.370	0.73	0.510
			11.6	21.4	4.9	12.6	--			28.53(21.04)	21.97(16.20)	34.69(25.58)	85.18(62.83)	282(63)	0.22(0.71)			0.570	0.410	0.62	0.650
			23.6	31.3	19.3	24.7	--			32.90(24.26)	23.37(17.24)	38.67(28.52)	94.94(70.02)	357(80)	0.18(0.61)			0.640	0.520	0.61	0.850
			35.2	27.8	30.4	31.1	--			34.46(25.41)	23.38(17.24)	39.05(28.80)	96.88(71.46)	375(84)	0.15(0.50)			0.650	0.540	0.58	0.940
			44.3	52.6	41.8	46.2	--			31.25(23.05)	23.17(17.09)	40.21(29.66)	94.63(69.80)	353(79)	0.12(0.40)			0.640	0.510	0.43	1.180
			57.4	63.1	52.9	57.8	--			32.40(23.90)	23.16(17.08)	41.01(30.25)	96.58(71.23)	357(80)	0.09(0.30)			0.650	0.520	0.34	1.540
			72.3	76.3	69.8	72.8	--			33.32(24.57)	23.38(17.24)	42.06(31.02)	98.76(72.84)	344(77)	0.05(0.18)			0.660	0.500	0.20	2.440
			89.2	90.4	87.4	89.0	--			32.64(24.07)	22.19(16.37)	43.69(32.23)	98.52(72.66)	357(80)	0.02(0.06)			0.660	0.520	0.09	6.020
			--	--	--	100.0	--			35.41(26.12)	25.75(18.99)	46.26(34.12)	107.42(79.23)	428(96)	0.00(0.00)			0.720	0.620	0.00	0.000

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13. ABSTRACT

One pneumatic wheel, four metal-elastic wheels, and two instrumented vehicles were laboratory tested in a fine sand to determine their relative performance and to establish a better understanding of the basic principles of the interaction of very lightly loaded wheels with a soil whose properties were varied to include the probable range of lunar soil properties. Programmed-slip tests were conducted with the single wheels and the vehicles, the latter being tested on both slopes and level surfaces. Data indicate that for loads less than about 220 N (50lb), the pull/slope-climbing ability was constant for a given soil condition. At greater loads, the rate of increase in performance decreased. The effect of cohesion on performance was negligible at loads less than about 220 N (50 lb), but the effect could be seen at higher loads. The results of tests with the metal-elastic wheels showed that none could be relied on to propel a vehicle up a 35-deg slope. Modifications of the Bendix and Grumman wheels enhanced their performance to the point that they might be expected to climb slopes in excess of 30 deg. Tests with modified Boeing-GM wheels indicated that they might be used on slopes up to about 25 deg. on certain soil conditions. The power required, in whr/km, for operation of the wheels on level and sloping soil surfaces was determined. It was demonstrated that data from single-wheel tests can be used to predict the slope-climbing ability of a vehicle; such predictions tend to be slightly conservative. Results of tests with the vehicles indicate that the torque coefficient at a given slip was not significantly affected by variations in surface slope and soil strength.

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