TECHNICAL REPORT M-71-10

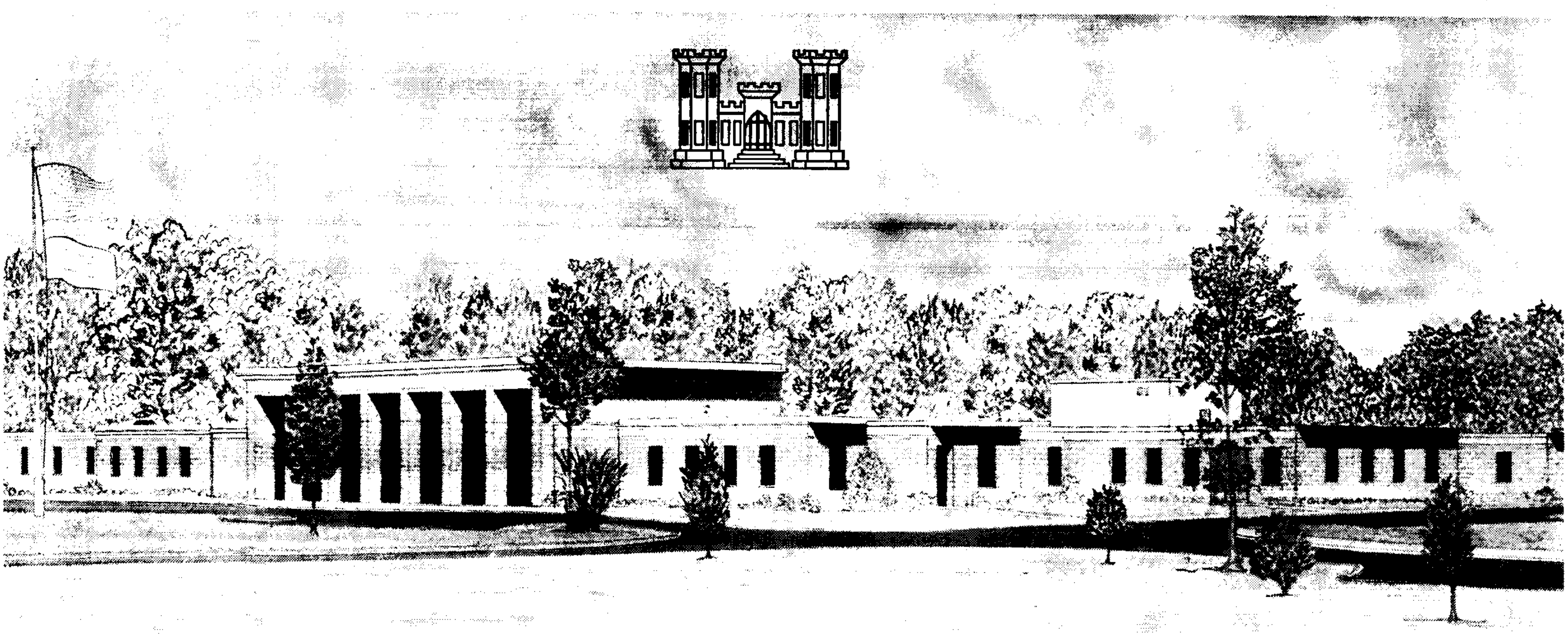
PERFORMANCE OF THE BOEING LRV WHEELS IN A LUNAR SOIL SIMULANT

Report 2

EFFECTS OF SPEED, WHEEL LOAD, AND SOIL

by

K.-J. Melzer



December 1971

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

Conducted by Mobility and Environmental Division
U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

TECHNICAL REPORT M-71-10

PERFORMANCE OF THE BOEING LRV WHEELS IN A LUNAR SOIL SIMULANT

Report 2

EFFECTS OF SPEED, WHEEL LOAD, AND SOIL

by

K.-J. Melzer

December 1971

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

Conducted by Mobility and Environmental Division
U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

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 Apollo Program Office, National Aeronautics and Space Administration (NASA), Washington, D. C., and was under the technical cognizance of Dr. N. C. Costes of the Space Sciences Laboratory and Mr. E. B. George of the Astrionics Laboratory of the George C. Marshall Space Flight Center, Huntsville, Alabama. The work was performed under NASA - Defense Purchase Request No. H-79205, dated 12 October 1970.

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 Mr. A. J. Green, Dr. K.-J. Melzer, and MAJ G. D. Swanson of the Research Projects Group, MRB. This report was prepared by Dr. Melzer.

Acknowledgment is made to Dr. D. R. Freitag, Assistant Technical Director, WES, and Mr. J. L. Smith, MRB, for their advice and assistance during this study.

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

CONTENTS

NOTATION

c_{tr}	Cohesion determined from trenching tests, kN/m^2 (psi)
C_u	Coefficient of uniformity of the soil = d_{60}/d_{10}
d	Unloaded wheel diameter, cm (in.)
d_{50}	Grain diameter at 50 percent finer by weight, mm (in.)
D'	Compactibility, $\frac{e_{max} - e_{min}}{e_{min}}$
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)*
h	Unloaded wheel section height, cm (in.)
h'	Loaded wheel section height, cm (in.)
M	Wheel torque, m-N (ft-lb)
M/Wr_e	Torque coefficient, dimensionless
M_x/Wr_e	Value of M/Wr_e at a given slip x (e.g. 20 and 50%)
P	Pull (drawbar pull), N (lb)
PN	Power number $M\omega/Wv_a$, dimensionless
PN_{sp}	Value of PN at self-propelled point (P/W = 0)
PN_{20}	Value of PN at 20 percent slip
PN_{50}	Value of PN at 50 percent slip
P/W	Pull coefficient, dimensionless
P_T/W	Value of P/W when torque = 0
P_x/W	Value of P/W at a given slip x (e.g. 20 or 50%)
r	Unloaded wheel radius, cm (in.)
r_e	Effective wheel radius, cm (in.)
r_r	Rolling radius of the wheel, cm (in.)
r'	Correlation coefficient

---

*pci = $lb/in.^3$

$s_{y \cdot x}$	Standard error of estimate (standard deviation)
v_a	Translational (carriage) speed, m/sec (ft/sec)
v_w	Translational (wheel) speed, m/sec (ft/sec)
w	Moisture content, % (percent of dry density)
W	Wheel load; weight, N (lb)
z	Sinkage, cm (in.)
z_{sp}	Sinkage at self-propelled point, cm (in.)
z_x	Sinkage at a given slip x (e.g. 20 or 50%), cm (in.)
α	Slope angle, deg
γ	Wet density, g/cm^3 (pci)
γ_d	Dry density, g/cm^3 (pci)
γ_s	Specific gravity
δ	Wheel deflection, %
η	Efficiency $Pv_a/M\omega$, dimensionless
σ_n	Normal stress, kN/m^2 (psi)
$\phi_{p\ell}$	Angle of internal friction determined from in situ plate tests, deg
ϕ_s	Secant friction angle determined from triaxial tests, deg
ω	Rotational velocity of the wheel, radians/sec

CONVERSION FACTORS

METRIC TO BRITISH UNITS OF MEASUREMENT

Metric units (S.I.) are used in this report according to NASA and the Corps of Engineers regulations. However, in the text and figures British units also are given. Metric units used in the tables containing test results can be converted to British units as follows:

Multiply	By	To Obtain
centimeters	0.3937	inches
meters	3.2808	feet
newtons	0.2248	pounds (force)
kilonewtons per square meter	0.1450	pounds per square inch
meganewtons per cubic meter	3.684	pounds per cubic inch
meter-newtons	0.7375	foot-pounds
grams per cubic centimeter	62.43	pounds per cubic foot

SUMMARY

Two nearly identical Boeing-GM wire-mesh Lunar Roving Vehicle (LRV) wheels were laboratory tested in a lunar soil simulant to determine the influence of wheel speed and acceleration, wheel load, presence of a fender, travel direction, and soil strength on the wheel performance. Constant-slip and three types of programmed-slip tests were conducted with the U. S. Army Engineer Waterways Experiment Station single-wheel dynamometer system.

Test results indicated that performance of single LRV wheels in terms of pull coefficient, power number, and efficiency were not influenced by wheel speed and acceleration, travel direction, the presence of a fender, or wheel load. Of these variables, only load influenced sinkage, which increased with increasing load. For a given slip, the pull coefficient and power number increased with increasing soil strength. However, for a given pull coefficient or slope, slip was less in firmer soil; thus, the power number decreased and efficiency increased with increasing soil strength.

PERFORMANCE OF THE BOEING LRV WHEELS IN A LUNAR SOIL SIMULANT

EFFECT OF SPEED, WHEEL LOAD, AND SOIL

PART I: INTRODUCTION

Background

1. Following the award of a contract to the Boeing Company for the construction of the manned Lunar Roving Vehicle (LRV), the U. S. Army Engineer Waterways Experiment Station (WES), at request of the George C. Marshall Space Flight Center (MSFC), evaluated the relative performance of several versions of the basic 81-cm (32-in.)-diam wire-mesh wheels, which were fabricated by General Motors Corporation (GMC) under contract with the Boeing Company. These tests were performed on soft soils (fine sand, lunar soil simulant) (Green and Melzer, 1971a and 1971b). After the flight wheel (50 percent chevron-covered) was selected, the MSFC requested the WES to evaluate its performance in terms of parameters not previously tested. The results of these investigations are reported herein.

Purpose

2. The purpose of this test program was to investigate the effect of the following factors on the performance of the LRV wheel:

- *a*. Wheel speed and acceleration
- *b*. Presence of a wheel fender
- *c*. Wheel load
- *d*. Soil
- *e*. Forward and backward travel

Scope

3. The test program was divided into two phases. During phase I, 20 two-pass, single-wheel tests were conducted with a 50 percent

chevron-covered wheel (GM XIII*) without a fender, which had been tested during an earlier study (Green and Melzer, 1971b). Various programmed-slip, combined with constant-slip, techniques were used. Wheel speeds ranged between 0.75 m/sec (2.5 ft/sec) and 3.14 m/sec (10.3 ft/sec), and wheel acceleration between 0 and 0.78 m/sec^2 (2.6 ft/sec^2). The wheel load was 253 N (57 lb). The tests were conducted on a lunar soil simulant (LSS) at a consistency designated as LSS_4, which, based on the soil samples from the Apollo 11 and 12 flights, was believed to be predominant on the lunar surface. In addition, a small amount of data was collected during tests in a dune sand that exhibited a slightly higher strength than LSS_4.

4. During phase II of the program, 37 two-pass, single-wheel, "classical" programmed-slip tests were conducted, also with a 50 percent chevron-covered wheel (GM XV*), which had basically the same overall dimensions as the GM XIII wheel, but was slightly stiffer. Wheel speeds ranged from 0.44 m/sec (1.4 ft/sec) to 3.12 m/sec (10.2 ft/sec) with no wheel acceleration. Wheel loads ranged from 178 N (40 lb) to 377 N (85 lb). Tests with and without a fender were conducted on LSS at two consistencies designated as LSS_4 (21 tests) and LSS_5 (16 tests), the latter representing a high soil strength level that could be expected on the lunar surface. In addition, seven four-pass tests on LSS_4 were conducted with reversed chevron direction to simulate a wheel traveling backward.

* Numbers indicate the number and sequence of the Boeing-GM wheels tested during the last 2-1/2 years at the WES. The GM XIII had been used in an earlier program, but was replaced by the GM XV during this program at the request of NASA.

PART II: TEST PROGRAM

Soil

Description

5. The LSS was the same material as that used in previous studies (Green and Melzer, 1971b). The dune sand used in some of the phase I tests was a fine sand from the desert near Yuma, Arizona; it also had been used in earlier programs (Freitag, Green, and Melzer, 1970a and 1970b; Green and Melzer, 1971a). Extensive tests were performed to determine the shear strength characteristics and cone penetration resistance of both soils. Gradation and classification data, along with density and void ratio values, are given in fig. 1.

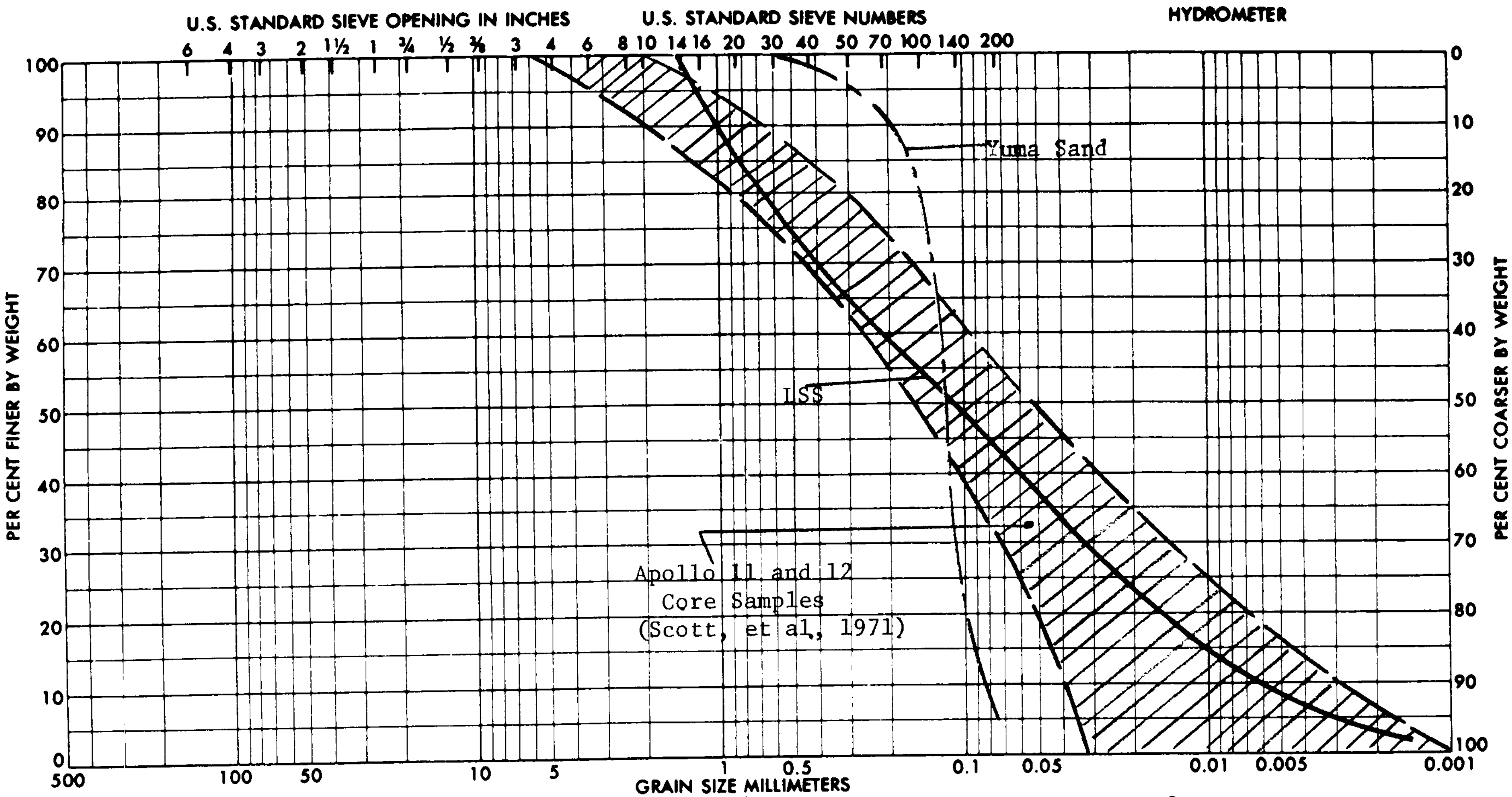
6. Based on the results of the soil mechanics tests following the Apollo 11 and 12 missions (Costes, et al., 1970; Scott, et al., 1971), LSS_4 appeared to have the predominant strength condition of the lunar soil. Some indications from the results of the Apollo 12 and 14 missions (Scott, et al., 1971; Mitchell, et al., 1971), however, made it desirable to extend the range of strength levels tested (LSS_1, LSS_2, LSS_3, and LSS_4; very loose to medium dense*) to an even higher strength level designated as LSS_5 (medium dense to dense, with essentially higher cohesion).

Preparation

7. Both soil conditions, LSS_4 and LSS_5, were prepared with wet LSS at average moisture contents of 1.8 percent (±0.2 percent) and 1.9 percent (±0.3 percent), respectively. The soil was thoroughly mixed in the test bins with water to produce a soil with a nearly uniform distribution of moisture. The moisture content was held constant by covering the test bins when not in use and occasionally spraying the surface slightly with water to compensate for evaporation. The soil was processed in place

---

* For more detailed description of the soil properties for these conditions, see Green and Melzer, 1971b.



	C_u	d_{50}, mm	e_{max}	e_{min}	D'	γ_s, g/cm^3
LSS	33.00	0.11	1.116	0.360	2.10	2.85
Yuma sand	1.5	0.12	0.919	0.608	0.51	2.67

Fig. 1. Gradation and classification data for the lunar soil simulant and for Yuma sand and approximate gradation band for Apollo 11 and 12 soil core samples

before each test by plowing it with a seed fork to a depth of 30 cm (12 in.) and applying compaction with a surface vibrator until the desired density was reached. During the testing cycles, the uniformity of the soil conditions was ensured by frequent determination of moisture content and density and by measurements with the WES cone penetrometer. The ranges of LSS_4 and LSS_5 soil properties of interest in this study are given in table 1.

8. A soil bin with air-dry, dense Yuma sand (moisture content = 0.5 percent) was used as an approach to the test bin of LSS. During certain tests in phase I of this program, a third soil bin containing Yuma sand was placed at the other end of the LSS_4 bin. During these tests,* the wheel encountered the following sequence of soils: Yuma sand--LSS_4--Yuma sand. It was not intended to create exactly the same strength level for the sand as for LSS_4; however, by screeding the sand and vibrating it twice with a surface vibrator, it was possible to attain a sand strength level (in terms of penetration resistance) that came close to that of LSS_4. The uniformity of the sand was ensured by measurements with the WES cone penetrometer. The ranges of soil properties of interest are given in table 1.

Soil tests

9. Cone penetration resistance. The standard WES mechanical cone penetrometer was used throughout this study to measure the penetration resistance gradient G (Freitag, Green, and Melzer, 1970a). During the single-wheel tests in phase I, G was usually determined at three points along the center line of an LSS test section (length $\approx$7 m; $\approx$22 ft) prior to testing (tables 1 and 2). Three additional penetrations were made 25 cm (10 in.) to the left and 25 cm to the right of the center line. Three center-line penetrations also were made after completion of the first pass and after the last pass of a test. In phase II, the number of the above-mentioned penetrations was increased from three to five. However, in the last 12 tests of the program (No. 71-094-6 to 71-105-6),

---

* These tests served to check whether certain influences observed in tests on LSS were also present in tests on sand (paragraph 33).

penetrations were not conducted after completion of the first pass. Maximum, minimum, and average G values for each test are summarized in table 2.

10. During the tests in phase I in which Yuma sand was placed about 3.0 m (10 ft) before and after the LSS lane, four penetrations were conducted in the sand before traffic (tables 1 and 3), after completion of the first pass, and after traffic. Maximum, minimum, and average G values for each test are listed in table 3.

11. As has been pointed out in the references already cited, relations between gradient G and dry density γ_d were established and used as calibration diagrams to determine the dry density and the relative density of the test lanes. The relation between G and γ_d for LSS at a moisture content of 0.8 percent (fig. 2) had already been determined; whereas the relation for a moisture content of 1.8 percent, which originally covered only a density range of 1.48 g/cm^3 (92.5 lb/ft^3) to 1.57 g/cm^3 (98.0 lb/ft^3), was extended to 1.78 g/cm^3 (111.0 lb/ft^3) (fig. 2). Existing relations were used to determine density and relative density of the Yuma sand test lanes. Minimum, maximum, and average values of dry density and relative density before traffic for the various soil conditions tested are listed in table 1.

12. Moisture content and density determinations. The surface moisture content of the LSS was determined in all tests before and after traffic, except in a few cases. In addition, density and bulk moisture content were occasionally determined by means of a density box. Usually, one or two measurements were made before and after traffic. Minimum, maximum, and average values of surface moisture content and density are given in tables 1 and 2.

13. Shear strength parameter. Angles of internal friction based on vacuum triaxial and in situ plate shear tests were determined for LSS and Yuma sand conditions from results of the earlier studies. Average values for the various soil conditions are given in table 1.

14. Cohesion, based on trenching tests, was determined as in the previous test programs. A few trenching tests were conducted for soil

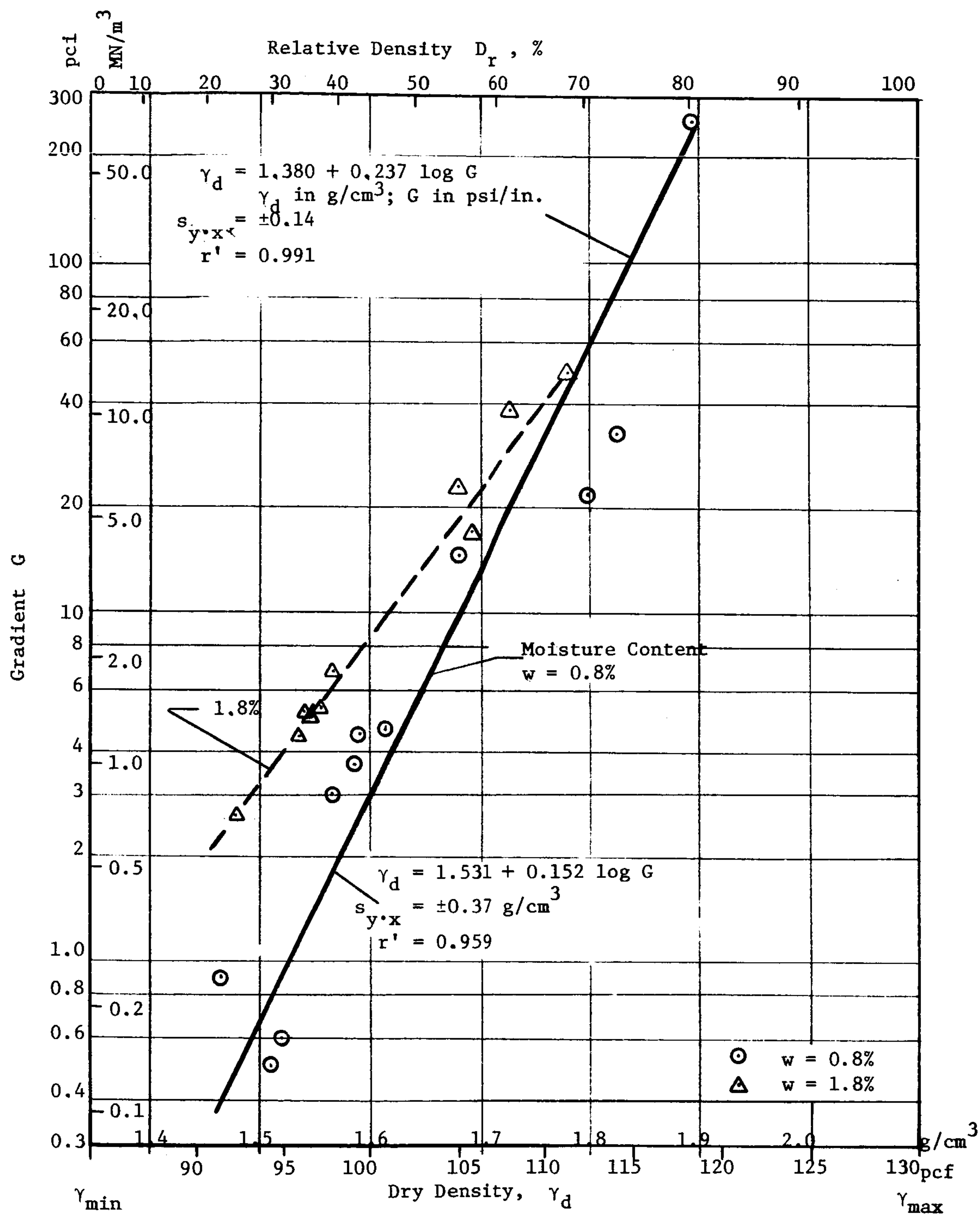


Fig. 2. Relations among cone penetration resistance gradient, dry density,relative density, and moisture content for the lunar soil simulant (from mold tests).

condition LSS_5, which had not been tested before. Average cohesion values for the various soil conditions are given in table 1.

Test Equipment

Dynamometer

15. The dynamometer system used in these tests (fig. 3) can accommodate loads from approximately 67 N (15 lb) to 900 N (200 lb), and wheels ranging from about 45 cm (18 in.) to 114 cm (45 in.) in diameter. The system is equipped with instrumentation for continuous measurements of wheel load, pull, torque, sinkage (hub movement), carriage speed, and wheel speed. For more detailed description see Report 1 in this series (Green and Melzer, 1971b).

Recording systems

16. The primary data recording system was an on-line digital computer. With this system the electrical (analog) signals reach the computer in a raw form with no signal conditioning. The signals are converted to digital form by the computer and stored on magnetic tape for subsequent data processing. Alternatively, the analog signals can be recorded on tape and digitized later. This alternative was used in phase II of the program. The estimated accuracy of the system is 3 to 4 percent.

17. A secondary recording system was a 36-channel, direct-writing oscillograph, which requires signal conditioning. This secondary system affords the test engineer an opportunity to take a quick look at the data as required to assist in planning subsequent tests and to rapidly determine whether all circuits are functioning properly for a given test. The accuracy of the oscillograph readings depends on the scale used and the expertise of the reader. Results obtained with this system are estimated to be accurate within 6 to 8 percent. Only results obtained from the primary recording system were used in the analysis. For more detailed description of the two systems see Report 1 of this series (Green and Melzer, 1971b).

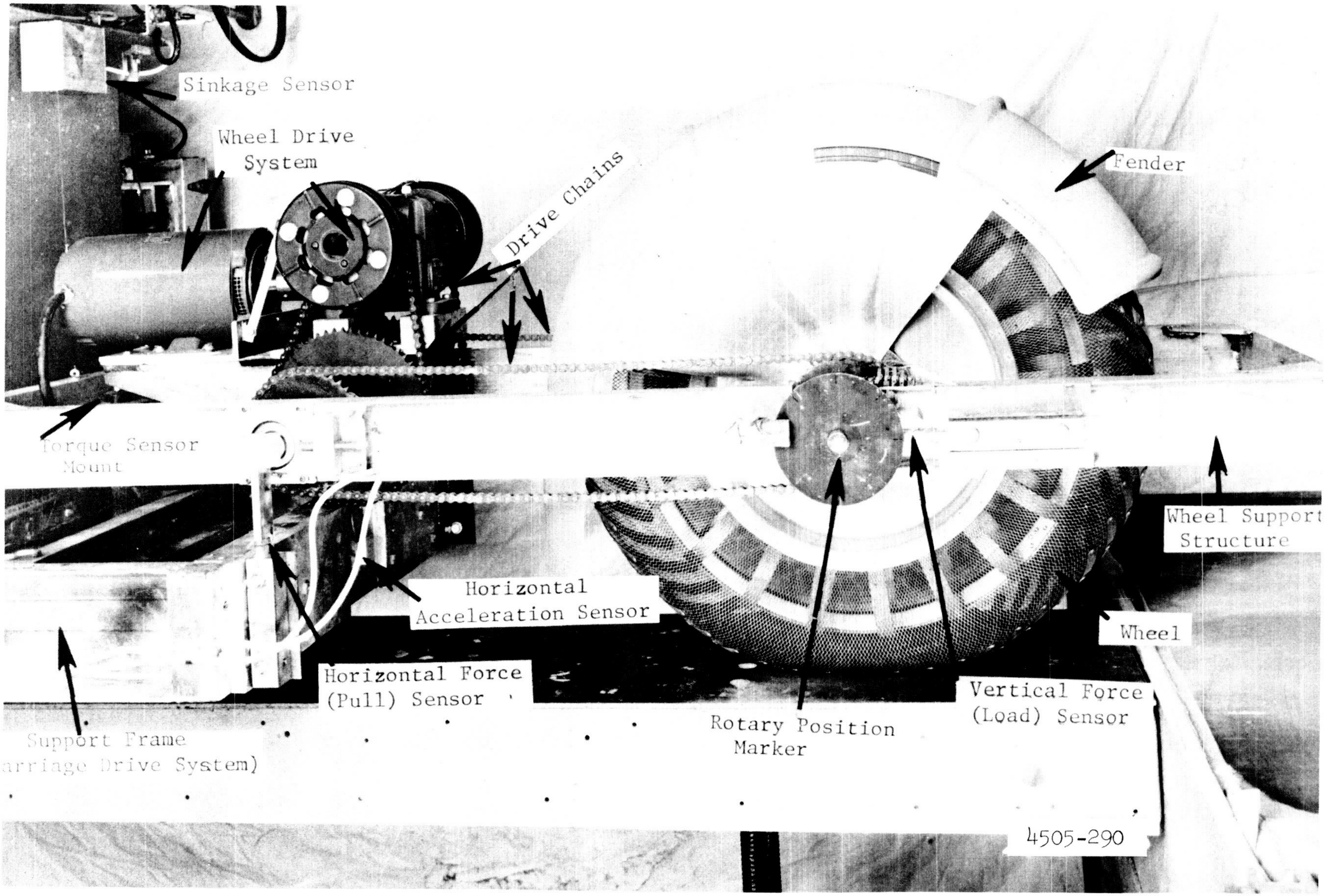


Fig. 3. LRV wheel mounted in dynamometer system

Test wheels

18. Two nearly identical wire-mesh wheels were tested: the 82.2-cm (32.4-in.)-diam GM XIII during phase I, and the 81.5-cm (32.1-in.)-diam GM XV during phase II. Both wheels had a 50 percent chevron-tread cover. The GM XIII was slightly more flexible than the GM XV under the same static loading conditions on a hard surface. Wheel data are given in table 4.

Test Procedures

Phase I (GM XIII)

19. Three different test techniques were used during this phase of the program:

- a. Classical programmed-slip (CPS), identical to the programmed-slip technique used in the earlier studies
- b. Ramped-slip (RS)
- c. Modified programmed-slip (MPS)

These three test techniques, which are described in the following paragraphs, were used to investigate primarily whether the wheel acceleration influenced the wheel performance. A secondary purpose was to check whether using different test techniques would generally influence the outcome of the tests. The test condition simulating the relative motion of an actual vehicle wheel would be between the CPS and the MPS modes.

20. CPS test. The CPS test technique was used in five tests during phase I. The test was started with the wheel in the negative slip range (fig. 4a), i.e. the translational speed of the carriage (v_a) was greater than that (v_w) of the wheel. The carriage was slowed at a programmed, uniform rate (wheel speed was approximately constant during the test) to cause the wheel to pass through the towed condition (torque $M = 0$), the zero percent slip condition (carriage speed = wheel speed), the self-propelled condition (pull $P = 0$), etc., as slip progressively increased up to 90 percent, and in some instances to 100 percent (carriage speed = 0). Wheel speeds were changed from test to test, covering a range from 1.5 m/sec (4.9 ft/sec) to 3.0 m/sec (9.9 ft/sec). Wheel

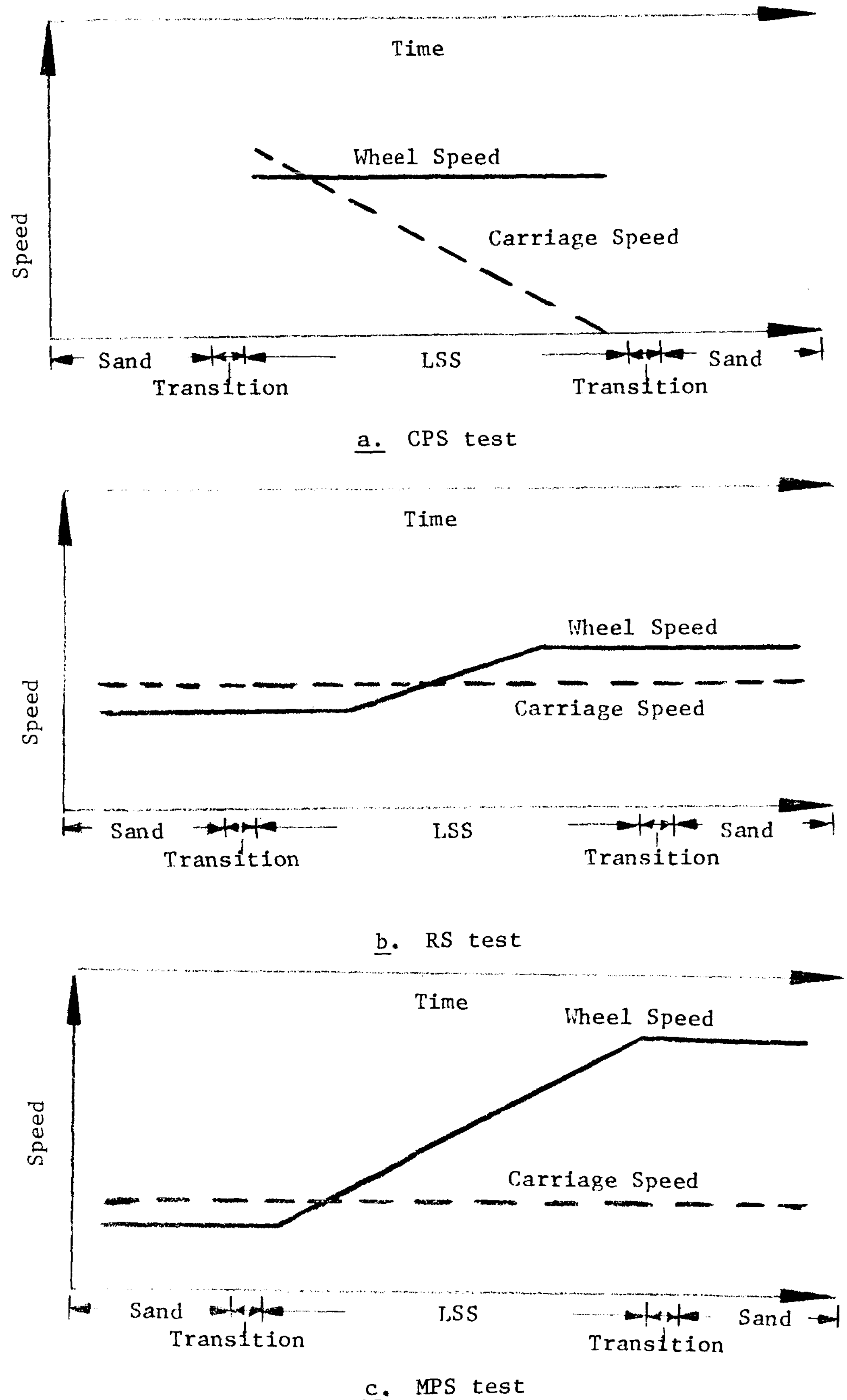


Fig. 4. Speed-time relations for different test techniques

acceleration was zero (ω was constant), and carriage acceleration varied from test to test between $-0.07\ m/sec^2$ ($0.23\ ft/sec^2$) and $-1.14\ m/sec^2$ ($3.74\ ft/sec^2$)* (table 5). Wheel load was constant (253 N; 57 lb) in all tests during phase I. Also included in the analysis were the average data from three CPS tests conducted in an earlier program (Green and Melzer, 1971b) on LSS_4 at wheel speeds of 0.75 m/sec (2.5 ft/sec) (table 5).

21. RS test. The RS test technique was used in seven tests during phase I. A test was started in the sand test lane with wheel and carriage speed held constant (first constant-slip portion of the test, fig. 4b). After the wheel had entered the LSS test lane and had traveled for 1 m (3.3 ft) or more, the wheel speed was increased at a relatively small rate ("ramped slip"), which led to a slight increase in slip (about 7 to 9 percent). After this, the wheel speed was kept constant, with the wheel traveling on LSS and subsequently on sand (second constant-slip portion of the test). Slip during the RS tests ranged from -17 to +15 percent. The carriage speed, which was held constant during a specific test, was changed from test to test within a range from 1.50 m/sec (4.9 ft/sec) to 3.45 m/sec (11.3 ft/sec) (tables 5 and 6). The wheel speed was varied over a total range from 1.56 m/sec (5.1 ft/sec) to 3.14 m/sec (10.3 ft/sec), with accelerations between $0.19\ m/sec^2$ ($0.62\ ft/sec^2$) and $0.36\ m/sec^2$ ($1.18\ ft/sec^2$).**

22. MPS test. The MPS test technique was used in eight tests during phase I. Whereas the emphasis in the RS tests was on the constant-slip portions, which were connected by the ramped-slip portion, the emphasis in the MPS tests (fig. 4c) was on the acceleration of the wheel over a larger range of slip. As in the case of the RS tests, a test was started at constant slip in the sand test lane. Constant slip was maintained thereafter until the wheel had traveled for 1 m (3.3 ft) or more

---

* The test lane was relatively short, especially for the tests at high speeds, which resulted in the relatively large range of deceleration.

** This was the largest acceleration that could be recorded in this specific test series because of time-setting limits of the speed control system.

on the LSS (first constant-slip portion of the test). Thereafter, the wheel speed was increased (carriage speed was held constant) in a fashion that resulted in a considerable increase in slip (minimum absolute increase of slip was 20 percent; maximum absolute increase was 88 percent). After the maximum wheel slip was attained for a given test, the wheel speed was kept constant, with the wheel traveling on LSS and subsequently on sand (second constant-slip portion of the test). Because of the restricted length of the LSS lane, constant-slip data on LSS could be recorded for only the first constant-slip portion of three tests and for the second constant-slip portion of two tests (table 5).

23. The total slip range covered in the MPS tests was from -24 to +69 percent. The carriage speed, which was held constant during a specific test, was changed from test to test within a range from 0.89 m/sec (2.9 ft/sec) to 3.14 m/sec (10.3 ft/sec) (table 5). Wheel speeds ranged from 0.76 m/sec (2.5 ft/sec) to 3.14 m/sec (10.3 ft/sec), with accelerations between 0.25 m/sec^2 (0.82 ft/sec^2) and 0.78 m/sec^2 (2.56 ft/sec^2).

Phase II (GM XV)

24. The CPS technique (paragraph 20) was used during 44 tests of this phase of the program. Thirty-seven of these tests were conducted as two-pass tests (21 tests on LSS_4, table 7; 16 tests on LSS_5, table 8). The speed ranged from 0.44 m/sec (1.4 ft/sec) to 3.12 m/sec (10.2 ft/sec),* with wheel acceleration zero and carriage acceleration ranging from -0.06 m/sec^2 (0.20 ft/sec^2) to -1.60 m/sec^2 (5.25 ft/sec^2). Wheel loads ranged from 178 N (40 lb) to 377 N (85 lb), embracing the minimum and maximum LRV wheel load to be anticipated on the lunar surface due to load transfer, including the final nominal load of 289 N (65 lb).** Seven (six on LSS_4 and one on LSS_5) of these 37 tests were

* This range covered the speeds at which the LRV was to travel during the Apollo 15 mission.

** The nominal load had to be changed during the program from 253 N (57 lb) to 271 N (63 lb), and finally to 289 N (65 lb) because of changes in the payload of the LRV.

conducted without the fender. During the first passes of the other 30 tests, the right-front fender was attached to the wheel, and during the second passes, the right-rear fender was attached to the wheel, thus simulating the right-path performance of the LRV.

25. In seven additional four-pass tests on LSS_4, the wheel with fender was tested with reversed chevron direction to simulate backing-off and crater-extrication maneuvers. In these tests the fender sequence was as follows:

- a. Pass 1: Rear fender
- b. Pass 2: Front fender
- c. Pass 3: Rear fender
- d. Pass 4: Front fender

Thus, the average parameters of passes 1 and 2 represented the performance of the LRV backing into undisturbed soil, and the average parameters of passes 3 and 4 represented the performance of the LRV backing in its own ruts. Wheel loads during these tests were 178 N (40 lb), 253 N (57 lb), and 377 N (85 lb). The average wheel speed during these tests was 0.75 m/sec (2.5 ft/sec).

Data Presentation

CPS tests

26. The relations of pull and torque to slip can be shown by two plots, such as those in fig. 5, which represent the average relations* of the phase I tests. The pull coefficient P/W and the torque coefficient M/Wr_e increased at a decreased rate after a slip of about 20 percent had been reached. Generally, these relations agree with the relations found for all Boeing-GM wheels tested on LSS. The average variation of the power number PN $(M\omega/Wv_a)$ versus pull coefficient

* In the framework of this study, these relations will not be presented separately for each test, as was done in earlier studies. Plots for each test have been furnished to MSFC continuously during the time the tests were conducted. In addition, complete copies of the computer print-outs of all tests were sent to MSFC on 19 February 1971 (phase I) and on 28 June 1971 (phase II).

P/W and slope angle α , for a large number of tests is also presented (e.g. fig. 6 for phase I), under the assumption that the pull coefficient measured at a given slip on a level surface with a single wheel is roughly equivalent to the tangent of the angle of the slope that a four-wheeled vehicle equipped with similar wheels can climb. The PN versus P/W relation is especially important, because it expresses the energy consumed per unit of distance of travel per unit wheel load or vehicle weight in relation to pull or slope-climbing ability. To obtain whr/km conforming to a certain P/W , or slope, the corresponding PN is read and multiplied by the wheel load or vehicle weight in newtons and the fraction 1000/3600.

27. For each test the relative performance of the wheels tested was assessed from data (in parentheses below) obtained under the following conditions (figs. 5 and 6; tables 5, 7, and 8):

a. Towed condition (P_T ; slip)
b. Self-propelled condition (PN_{sp} ; slip)
c. 20 percent slip (P_{20}/W ; M_{20}/Wr_e ; PN_{20})
d. 50 percent slip (P_{50}/W ; M_{50}/Wr_e ; PN_{50})

In addition to these parameters, the wheel hub movement, which is a measure of the wheel sinkage into the soil, was recorded.

28. If a more detailed assessment of the influence of a certain variable (e.g. wheel speed) was necessary, the analysis was based on a comparison of the following performance parameters: power number PN_{sp} and sinkage z_{sp} at the self-propelled condition (pull = 0); and pull coefficient P_{20}/W , power number PN_{20} , and sinkage z_{20} for the 20 percent slip condition. These two conditions were selected because (a) the self-propelled condition corresponds to the LRV traveling on level ground, and (b) the 20 percent slip condition corresponds approximately to the maximum slope the LRV can climb in a steady-state condition before power consumption rates become excessive. The same procedure was also used whenever data from RS or MPS tests were included in a specific analysis.

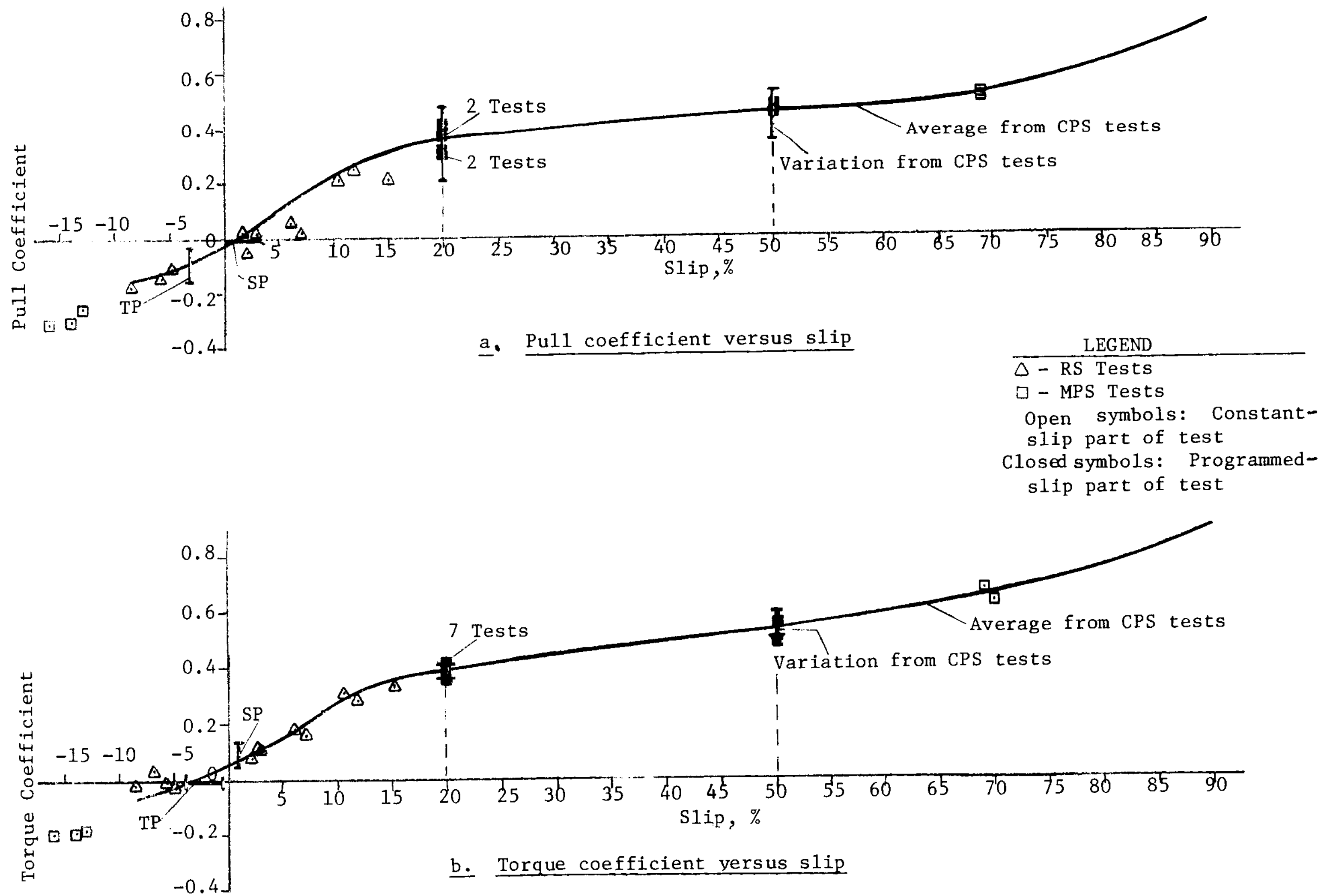
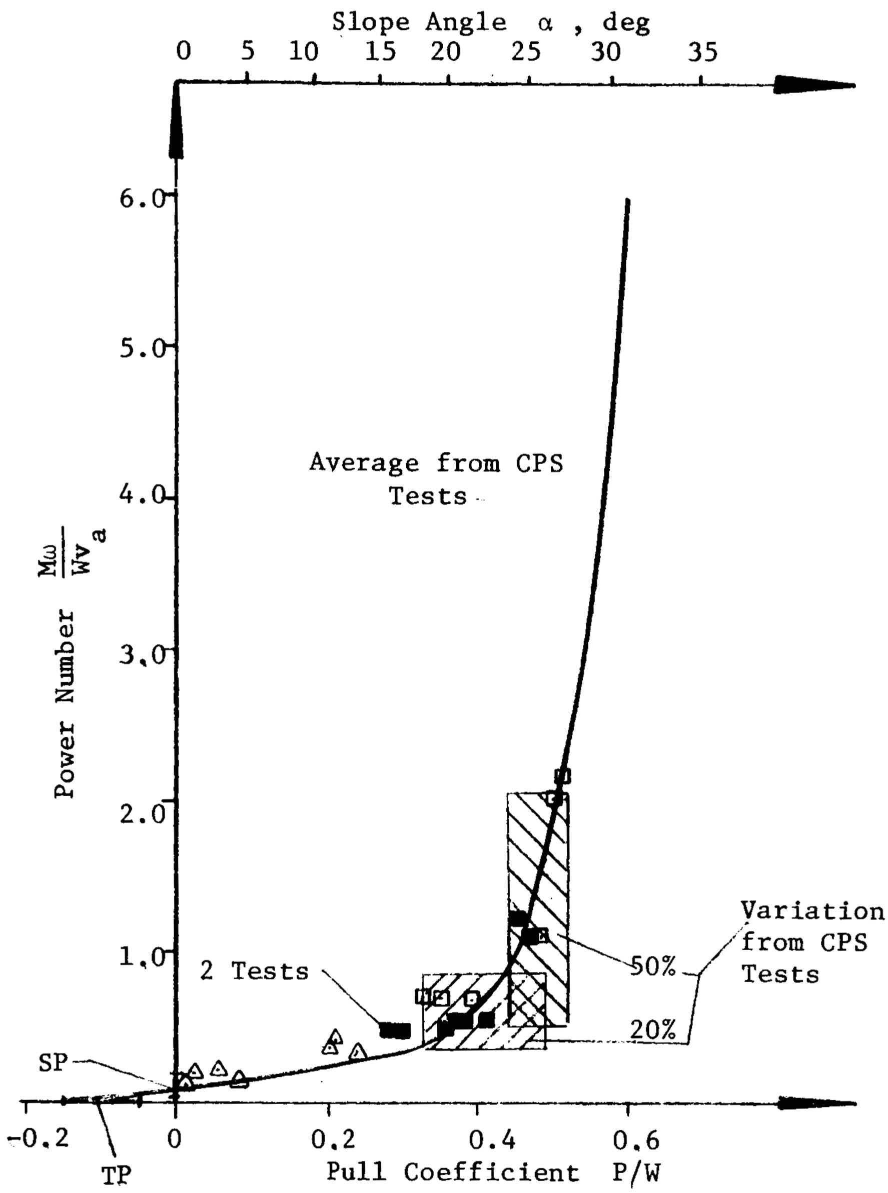


Fig. 5. Relations of pull and torque coefficients to slip from three test techniques; GM XIII wheel under 253-N (57-lb) load on LSS_4 (1st and 2d passes)



LEGEND

△ - RS Tests
□ - MPS Tests
Open symbols: constant-slip part of test
Closed symbols: programmed-slip part of test

Fig. 6. Relations of power number to pull coefficient and slope angle from three test techniques; GM XIII wheel under 253-N (57-lb) load on LSS_4 (1st and 2d passes)

RS and MPS tests

29. Average values of pull and torque coefficients, together with power numbers and values of sinkage and slip, were recorded for both constant-slip portions of the tests (see paragraphs 21 and 22) whenever they were included (tables 5 and 6). Each of these averages was calculated from at least 20 data points, one for each 5-cm (2-in.) length of test lane. Signals collected within the transition zones from sand to LSS (figs. 4b and 4c) were not included in the averages. If one of the constant-slip portions was not included, which was the case in most of the MPS tests (paragraph 22), the performance parameters for the lowest and highest slips during the test were recorded. In addition, performance parameters for the towed and the self-propelled conditions and for 20 and 50 percent slips were included (table 5) whenever the wheel passed through one or more of these points.

PART III: ANALYSIS AND DISCUSSION OF RESULTS

Phase I (GM XIII): Effect of Wheel Speed, Wheel Acceleration, and Soil Type

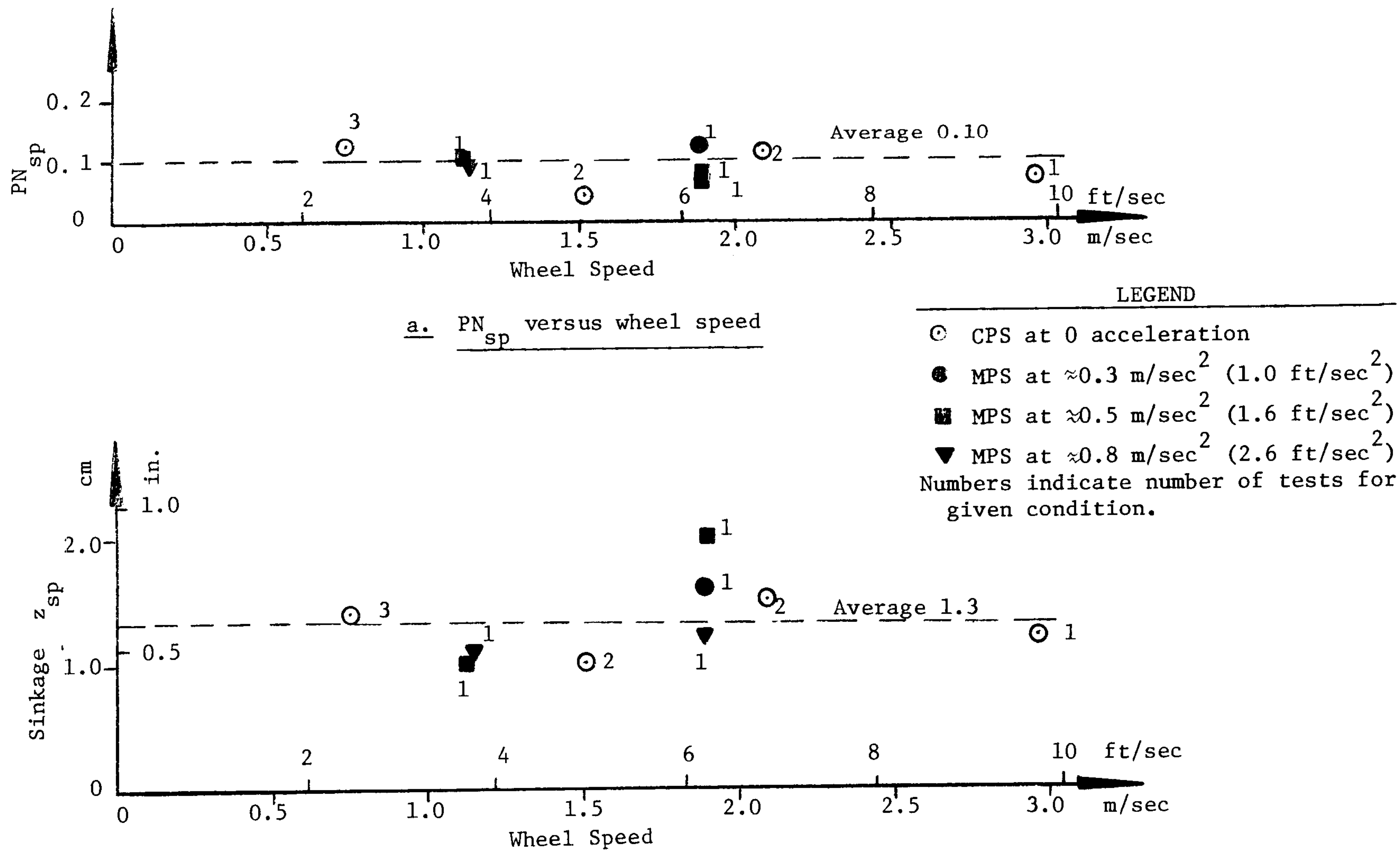
Wheel speed

30. Plots of the three basic relations, P/W versus slip, M/Wr_e versus slip, and PN versus P/W , obtained from the CPS tests, indicated no observable effect of wheel speed on the test results. The three average relations with their maximum variations at four characteristic points--towed (TP), self-propelled point (SP), 20 percent slip, and 50 percent slip--are shown in figs. 5a, 5b, and 6. These figures contain also results from the constant-slip portions of the RS and MPS tests, for different wheel speeds. The data points fall well within the deviations of the relations obtained from the CPS tests. From these trends, it was concluded that the mobility performance characteristics of the wheels tested were not affected by either the mode of testing (CPS, RS, or MPS), or the wheel speed.

31. To examine the effect of wheel speed more closely, the performance parameters for the self-propelled condition PN_{sp} and z_{sp} (open circles in fig. 7), and for 20 percent slip P_{20}/W , z_{20} , and PN_{20} (open circles in figs. 7 through 9) from the CPS tests were plotted versus wheel speed. Within the range of speeds tested, the performance parameters were practically constant, i.e. independent of wheel speed.

Wheel acceleration

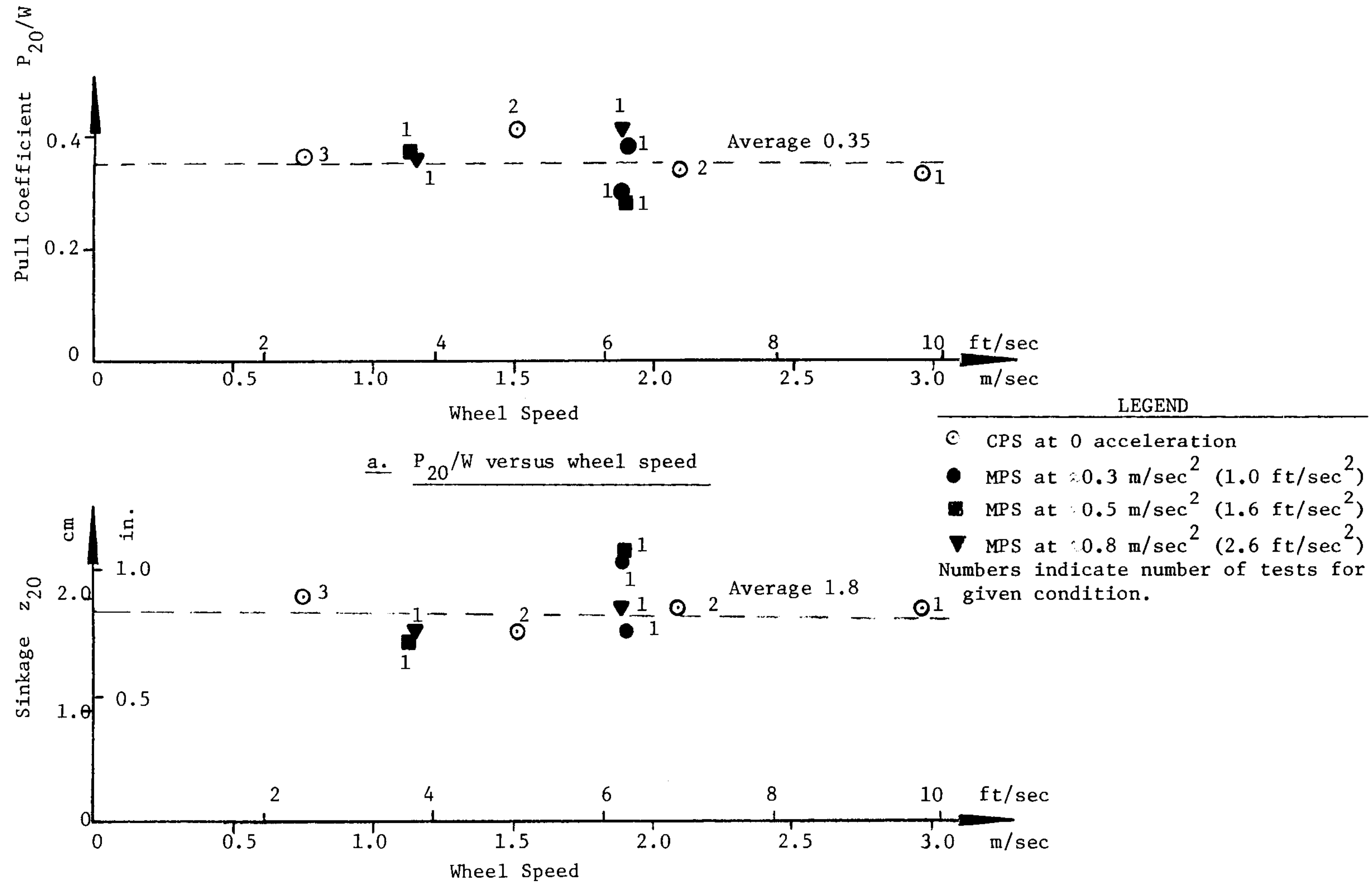
32. The effect of wheel acceleration on the mobility performance characteristics of the wheels tested was assessed in the same manner as the influence of wheel speed. Performance parameters at 20 percent and 50 percent slip from the MPS tests (programmed-slip portion of the tests) were compared with the three average basic performance relations (figs. 5a, 5b, and 5c) from the CPS tests; the MPS test results fall within the range of the CPS test results. Further, the performance parameters of the MPS tests for the self-propelled condition and for 20 percent slip were plotted (together with the CPS tests performance



a. PN_{sp} versus wheel speed

b. z_{sp} versus wheel speed

Fig. 7. Influence ot wheel speed on power number and sinkage at the self-propelled condition; GM XIII wheel; average of 1st and 2d passes; 253-N (57-lb) wheel load; soil condition LSS_4



a. P_{20}/W versus wheel speed

b. z_{20} versus wheel speed

Fig. 8. Influence of wheel speed on pull coefficient and sinkage at 20% slip; GM XIII wheel; average of 1st and 2d passes; 253-N (57-lb) wheel load; soil condition LSS_4

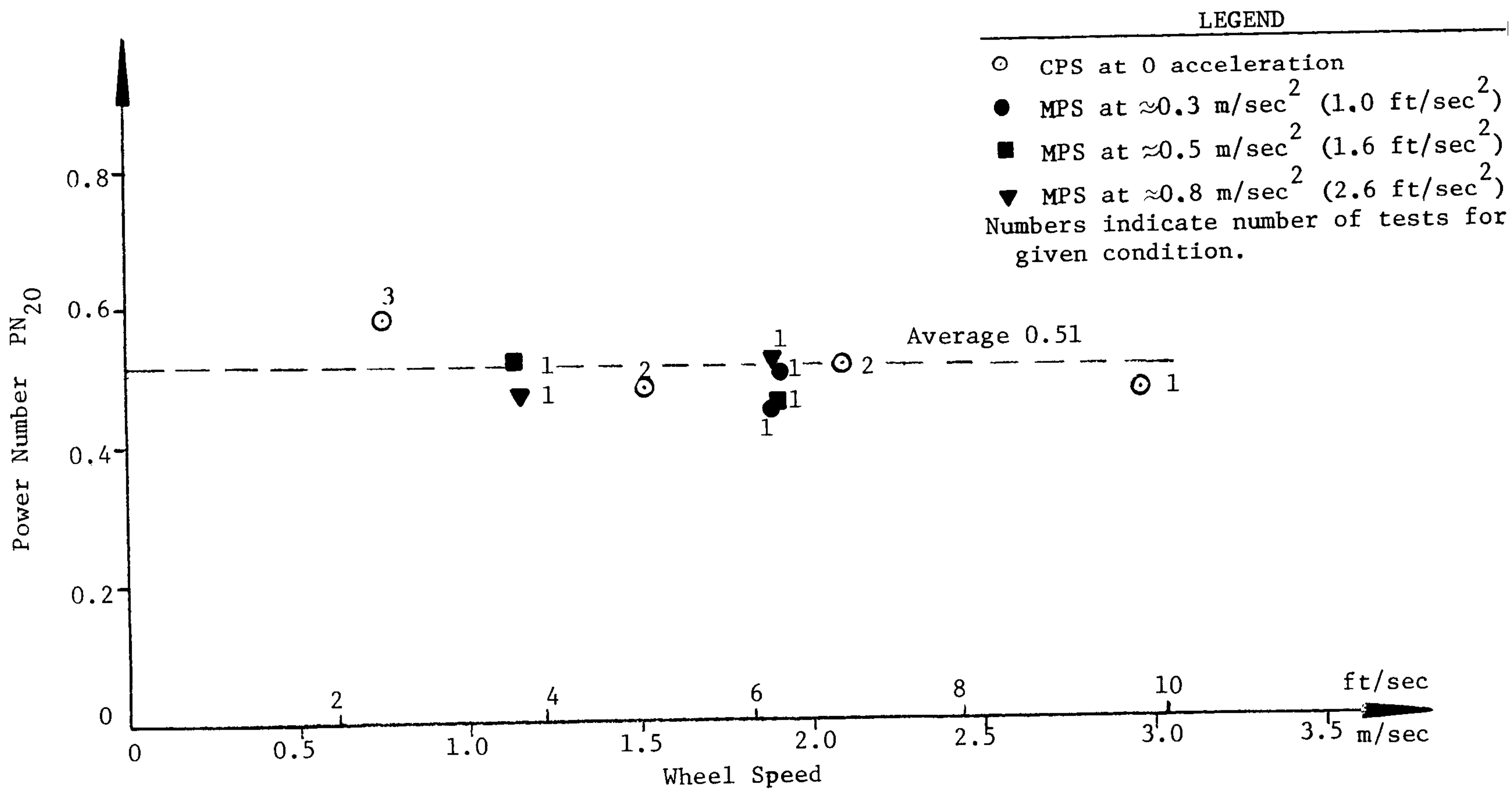


Fig. 9. Influence of wheel speed on power number at 20% slip; GM XIII wheel; average of 1st and 2d passes; 253-N (57-lb) wheel load; soil condition LSS_4

parameters) versus the corresponding wheel speeds (closed symbols in figs. 7 through 9), for three acceleration levels. The results of this analysis show (figs. 7 through 9) no influence of wheel acceleration on the performance parameters under consideration. In addition, the data from the MPS tests confirm the conclusion drawn above (paragraph 30), that, within the range of wheel speeds tested, the performance parameters considered were practically independent of wheel speed.

Soil type

33. Pull and torque coefficients resulting from the constant-slip portions of the RS and MPS tests on Yuma sand (table 6) were plotted versus slip for three different wheel speeds (indicated by different symbols in figs. 10a and 10b). In the positive slip range, only data from the two higher speed levels were available; the results at both speeds can be represented by one relation, because the limited amount of data did not indicate any considerable separation by wheel speed. In addition, the P/W and M/Wr_e relations are shown in figs. 10a and 10b for a CPS test from an earlier program conducted with a similar wheel (GM VIII) under nearly the same load on Yuma sand at approximately the same soil strength, but at a wheel speed of 0.9 m/sec (2 ft/sec). These data allowed the following, at least qualitative, comparison between the performance of the wheels on sand and on LSS:

Soil	G MN/m^3	Wheel Speed m/sec	PN_{sp}	P_{20}/W	M_{20}/Wr_e	P_{50}/W	M_{50}/Wr_e
LSS_4*	1.0	0.75-3.00	0.10	0.35	0.41	0.45	0.55
Sand	1.3	0.90	0.12	0.34	0.47	0.42	0.63
Sand	1.3	1.40-3.00	0.06	0.43	0.47	0.59	0.65

*Performance parameters for LSS_4 are independent of speed.

34. This comparison shows that the wheel on sand at a speed of 0.9 m/sec (3.0 ft/sec) performed approximately the same as the wheel on LSS_4 at all speeds under consideration (including 0.9 m/sec; 3 ft/sec), although the efficiency in LSS_4 seemed to be slightly higher than in sand (less input at the same output). However, it can be concluded that, for nearly the same strength level, the wheels behaved more-or-less the

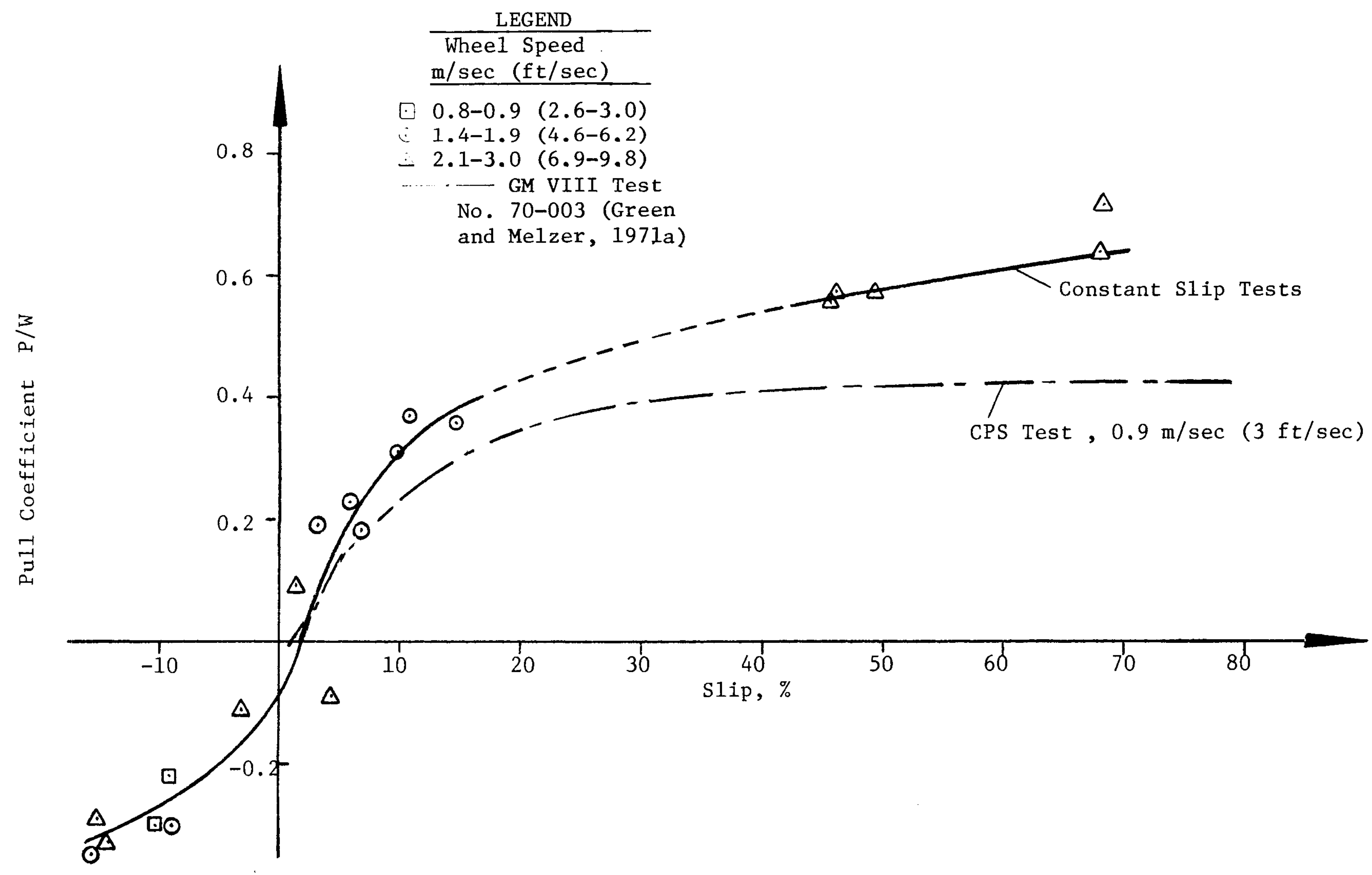


Fig. 10a. Influence of speed on pull coefficient versus slip relations; GM XIII wheel; $\simeq$253-N (57-lb) load; Yuma sand, G$\simeq$1.3 MN/m^3 (4.8 psi/in.)

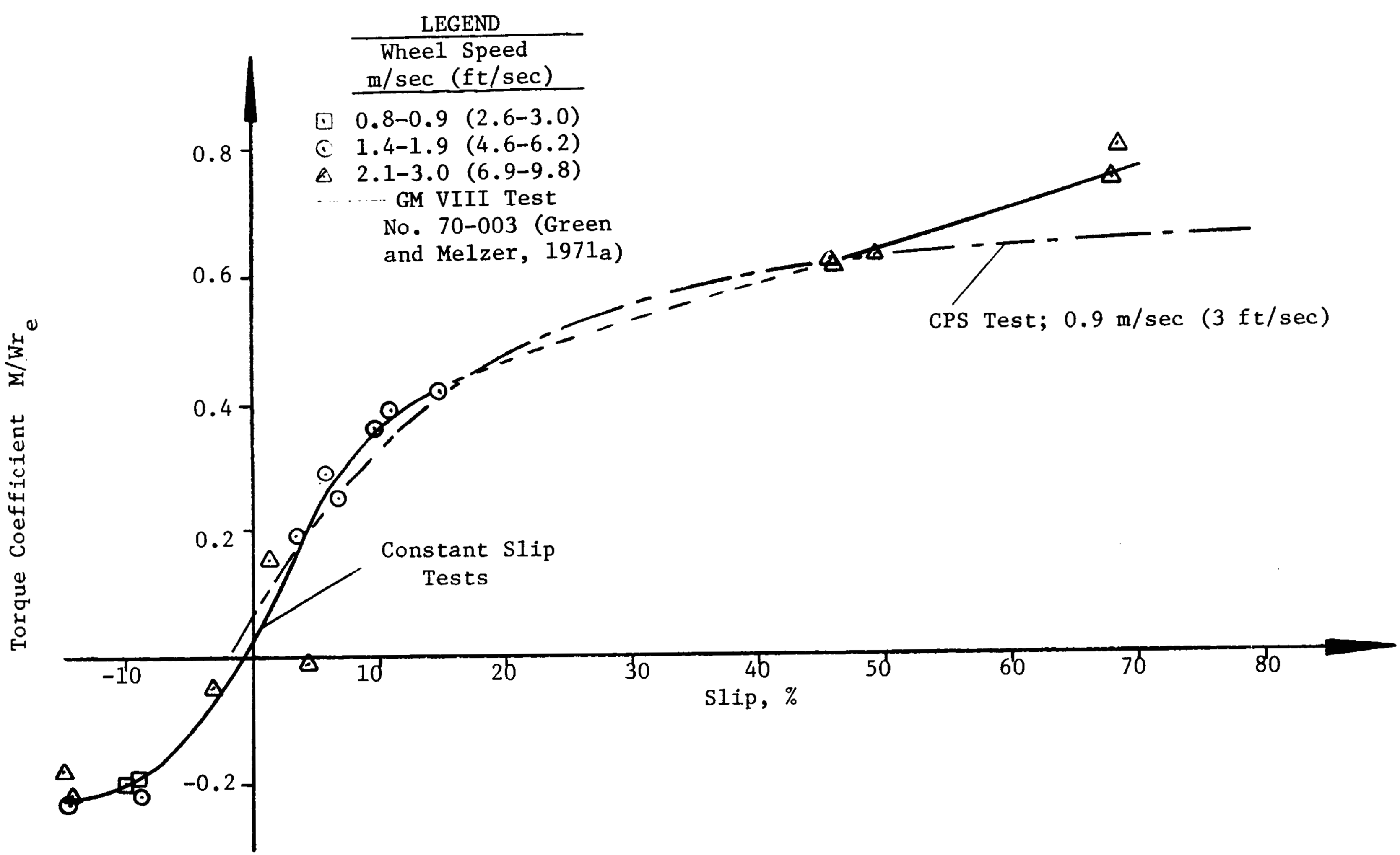


Fig. 10b. Influence of speed on pull coefficient versus slip relations; GM XIII wheel; $\approx$ 253-N (57-lb) load; Yuma sand, $G \approx 1.3$ MN/m^3 (4.8 psi/in.)

same in the two different soils when the wheel speed was 0.9 m/sec (3 ft/sec). On the other hand, when the wheel speed in sand exceeded 1.4 m/sec (4.6 ft/sec), the power requirements for the self-propelled condition decreased, and the system output increased at the same input as for 0.9 m/sec (3.0 ft/sec). Thus, the overall efficiency in sand increased with increasing wheel speed, which is contrary to the performance in LSS_4, where the performance parameters were found to be independent of wheel speed. A qualitative explanation for this is given in the following paragraphs.*

35. Recent investigations with pneumatic tires in sand (Turnage, 1972) showed an increase in pull at a given slip with an increase in wheel speed. It also was found that this increase in pull was larger for higher slips than for lower. A qualitative theoretical explanation for this phenomenon was given earlier by Leflaive and Wiendieck (1965), who found that the angle of internal friction (or the "shear potential") of the cohesionless soil was independent of speed, which is a well-known fact from classical soil mechanics. Therefore, a theoretical explanation of the observed speed dependence of pull was not sought in a possible variation of the pertinent soil parameters. However, contrary to most conventional soil testing devices, a moving wheel is constantly in touch with fresh soil masses to which a certain momentum is communicated by the wheel action. The soil momentum per unit of time was then considered to represent an additional dynamic force acting on the wheel-soil system. This force can be resolved into a horizontal component, which acts in the same direction as pull does, and into a vertical component, which acts in an upward direction. Thus, the horizontal dynamic component adds directly to the pull (resulting from the shear potential of the soil), and the vertical dynamic component, together with the soil potential, supports the wheel load. This results in smaller sinkages than those experienced at slower speed, thus leading

* This explanation is equally valid for all test modes described earlier (paragraphs 20-23), because it had been shown that test modes (wheel at constant speed or wheel accelerated during test, etc.) did not influence the performance parameters (paragraphs 30 and 32).

again to a higher efficiency.* For further development, it might be assumed that the relation between P/W at a given slip, e.g. 20 percent, and wheel speed has the shape of line A in fig. 11.

36. In comparing LSS with sand from a soil mechanics viewpoint, it appears logical to classify LSS as "frictional soil," based on the knowledge of the soil mechanics properties of the LSS. Therefore, similar effects of speed on tests in the two soils should have been expected. This was, in fact, not true, as mentioned above (paragraphs 31 and 34). In a reexamination of the soil mechanics properties, however, one cannot exclude the possible existence of air-pore pressure in this basically frictional soil, because of the low permeability of the silt-to-fine-sand lunar soil simulant. Air-pore pressure, the magnitude of which depends on the shear velocity, would in general have a degrading effect on the shear potential of the soil, and, thus, would lead to a decrease in pull. If the dynamic speed effects outlined in paragraph 35 were disregarded, the general shape** of the P/W versus wheel speed relation, due to air-pore pressure effects, can qualitatively be depicted by the line B in fig. 11. From a comparison of the general tendencies of the two relations (dynamic speed effects and air-pore pressure effects), it can be qualitatively concluded that the two effects could compensate each other, which indeed would lead to P/W being independent of wheel speed. From this discussion, the very cautious conclusion might be drawn that the LRV wheels could be more efficient at higher speeds under lunar conditions (no air-pore pressure) than under terrestrial conditions on the same soil.

---

* The influence of vertical component on sinkage is disregarded in further considerations, since sinkage is not a very important performance parameter because of the light loads used during this study.

** The effect of speed on P/W , beyond a certain speed, could be considered constant and similar to the "total stress condition" of a soil if inertia effects did not take place. Because this speed in unknown, this fact was not considered in the assumption about the shape of the relation B .

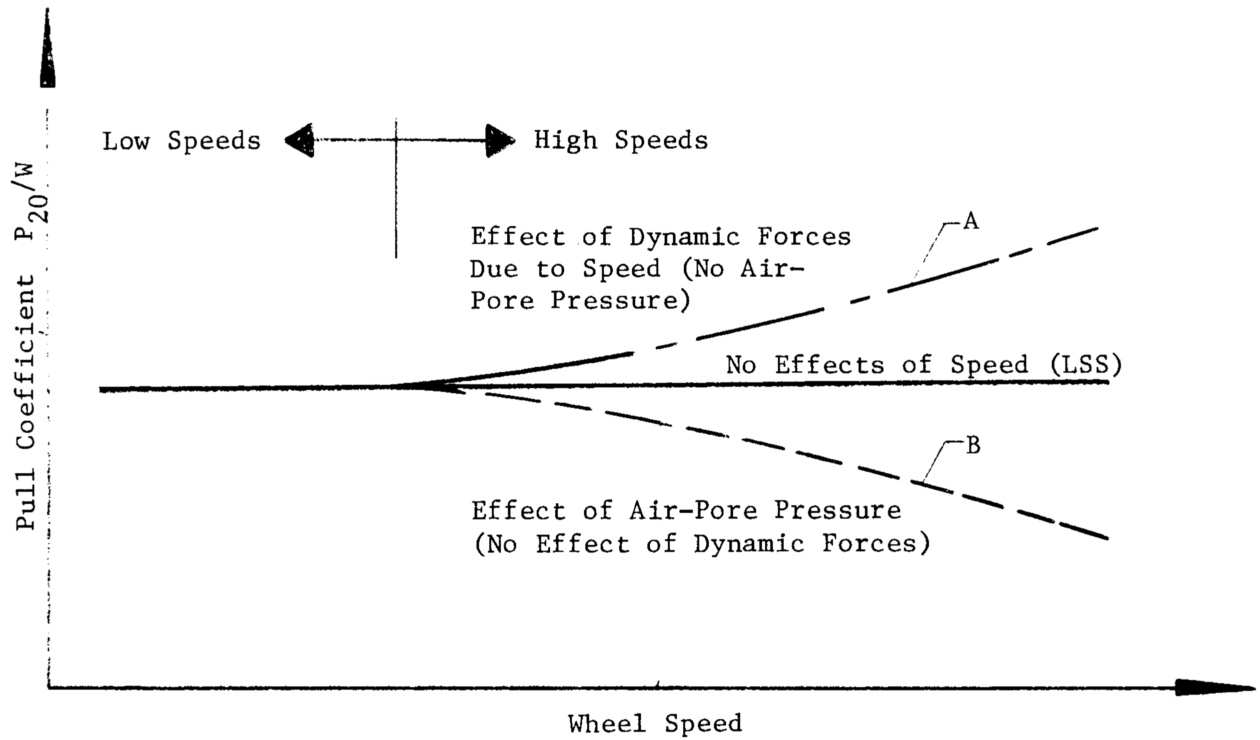


Fig. 11. Qualitative scheme of the effects of dynamic forces and air-pore pressure on the relation between pull coefficient at 20 percent slip and wheel speed

Phase II (GM XV): Effect of Fender, Wheel Load, Wheel Speed, Direction of Chevron, and Soil Strength

Soil condition LSS_4

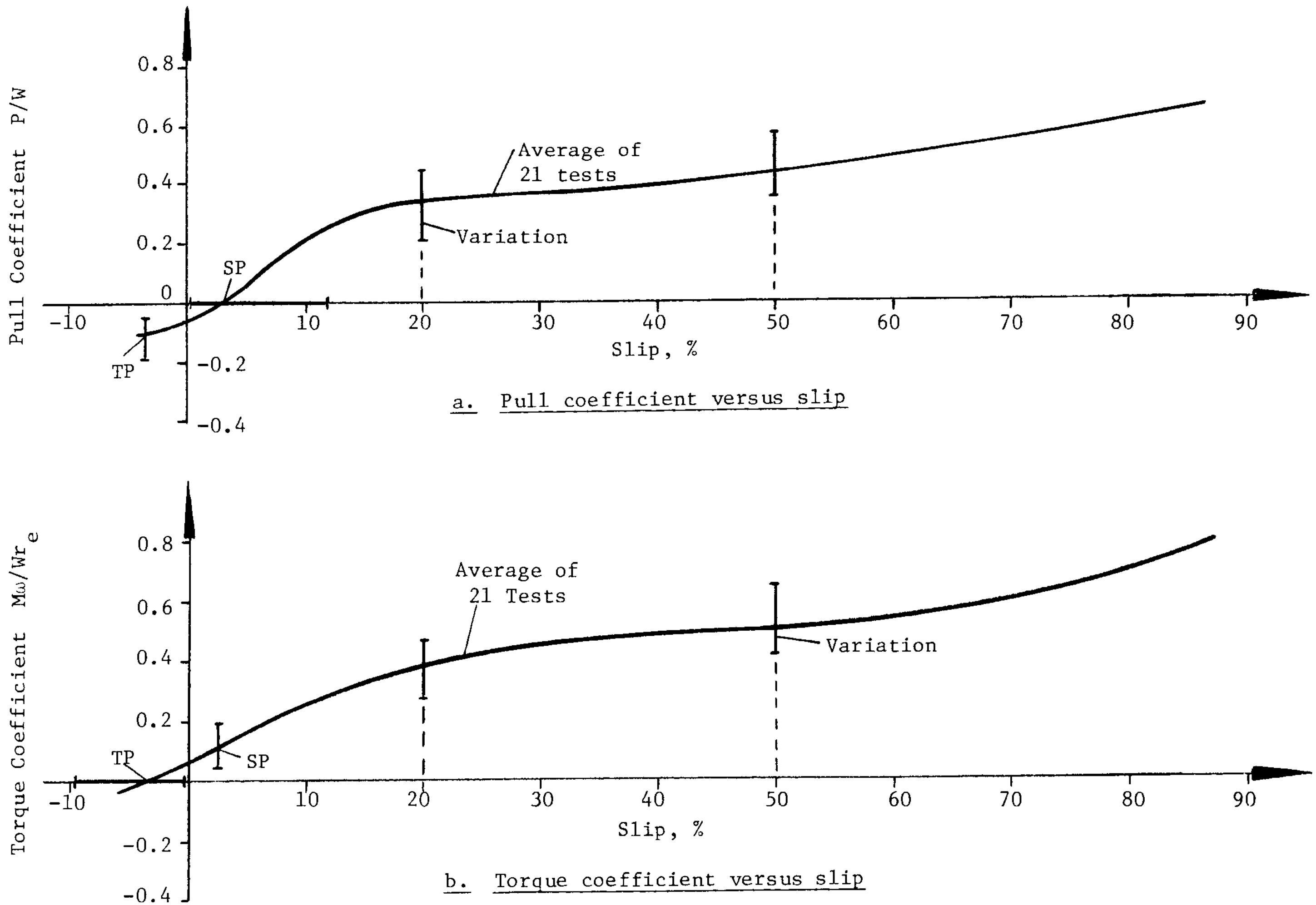
37. The approach used to analyze the results of the 21 two-pass CPS tests* of this series was the same as that used in the analysis of the phase I data (paragraph 30). The plots of P/W versus slip, M/Wr_e versus slip, and PN versus P/W indicated that these parameters were independent of wheel speed, wheel load, or presence or absence of the fender. Therefore, the results were averaged. The average relations with their maximum and minimum deviations at the characteristic conditions (towed condition, etc., see paragraph 30) are displayed in figs. 12 and 13. For further evaluation, the performance parameters for the self-propelled condition and for 20 percent slip were plotted versus wheel speed in figs. 14-16; the various test conditions (with and without fender, etc.) are indicated by different symbols.

38. Effect of fender. A comparison of the results of the tests with the fender (open symbols in figs. 14-16) and without the fender (closed symbols in figs. 14-16) at a given load and at a given speed shows that the performance parameters for the self-propelled (fig. 14) and the 20 percent slip conditions (figs. 15 and 16) were practically uninfluenced by the presence of the fender.

39. Effect of wheel load. According to the results in figs. 14-16 for the self-propelled and the 20 percent slip conditions, wheel load at a given speed level within the range tested (178 N or 40 lb to 377 N or 85 lb) did not influence the performance parameters under consideration, except sinkage (figs. 14 and 15) for which a slight, but not very pronounced, dependency exists insofar as sinkage increased with load. However, at this point it should be emphasized that the absolute power requirements increased linearly with the wheel load.

---

* Because of the results of phase I, i.e. the test technique did not influence the performance characteristics (paragraph 30), only the CPS test technique was used during phase II.



a. Pull coefficient versus slip

b. Torque coefficient versus slip

Fig. 12. Relations of pull and torque coefficients to slip for the GM XV wheel on LSS_4 (1st and 2d passes)

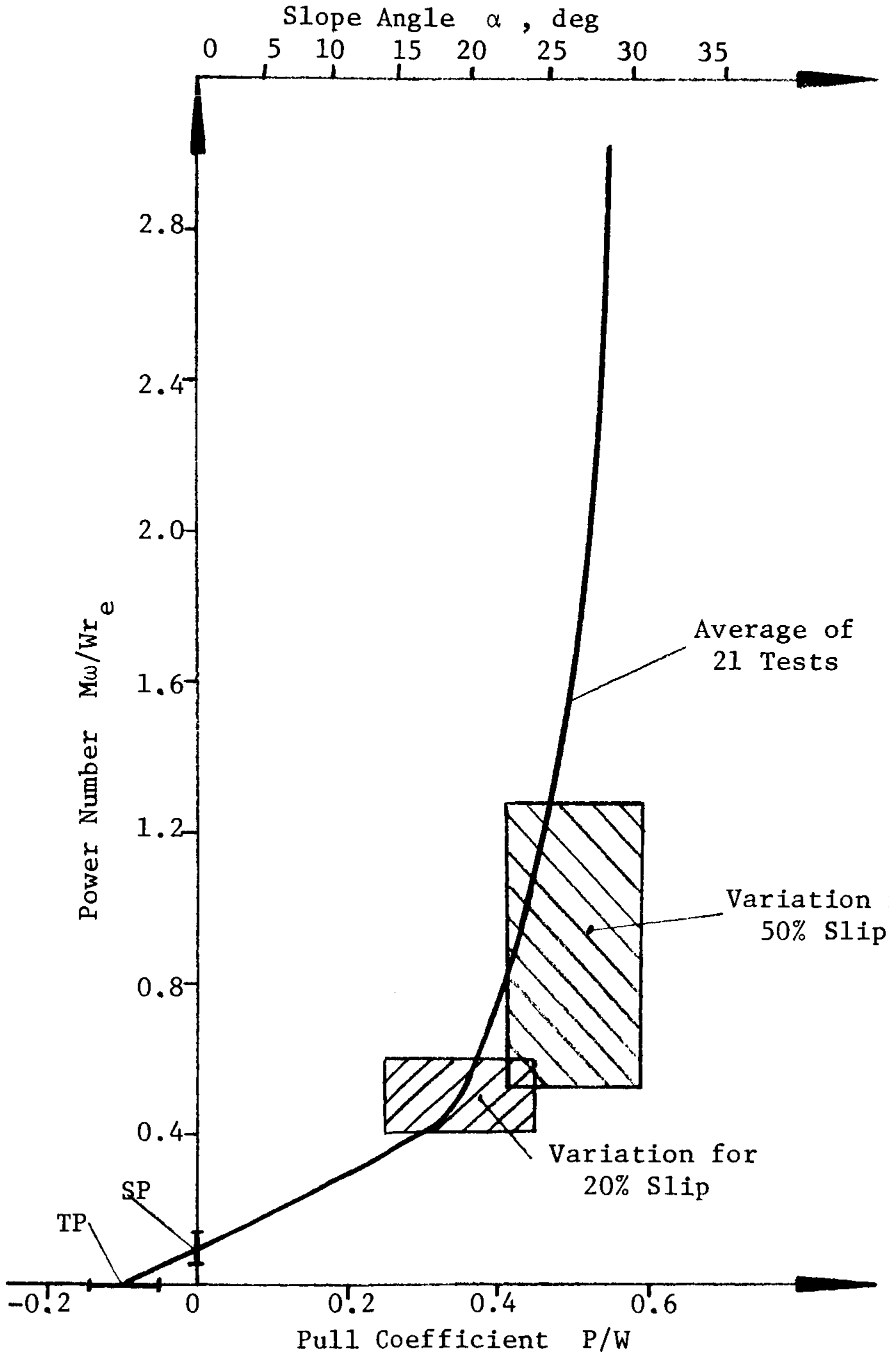


Fig. 13. Relation of power number to pull coefficient and slope angle for GM XV wheel on LSS_4 (1st and 2d passes)

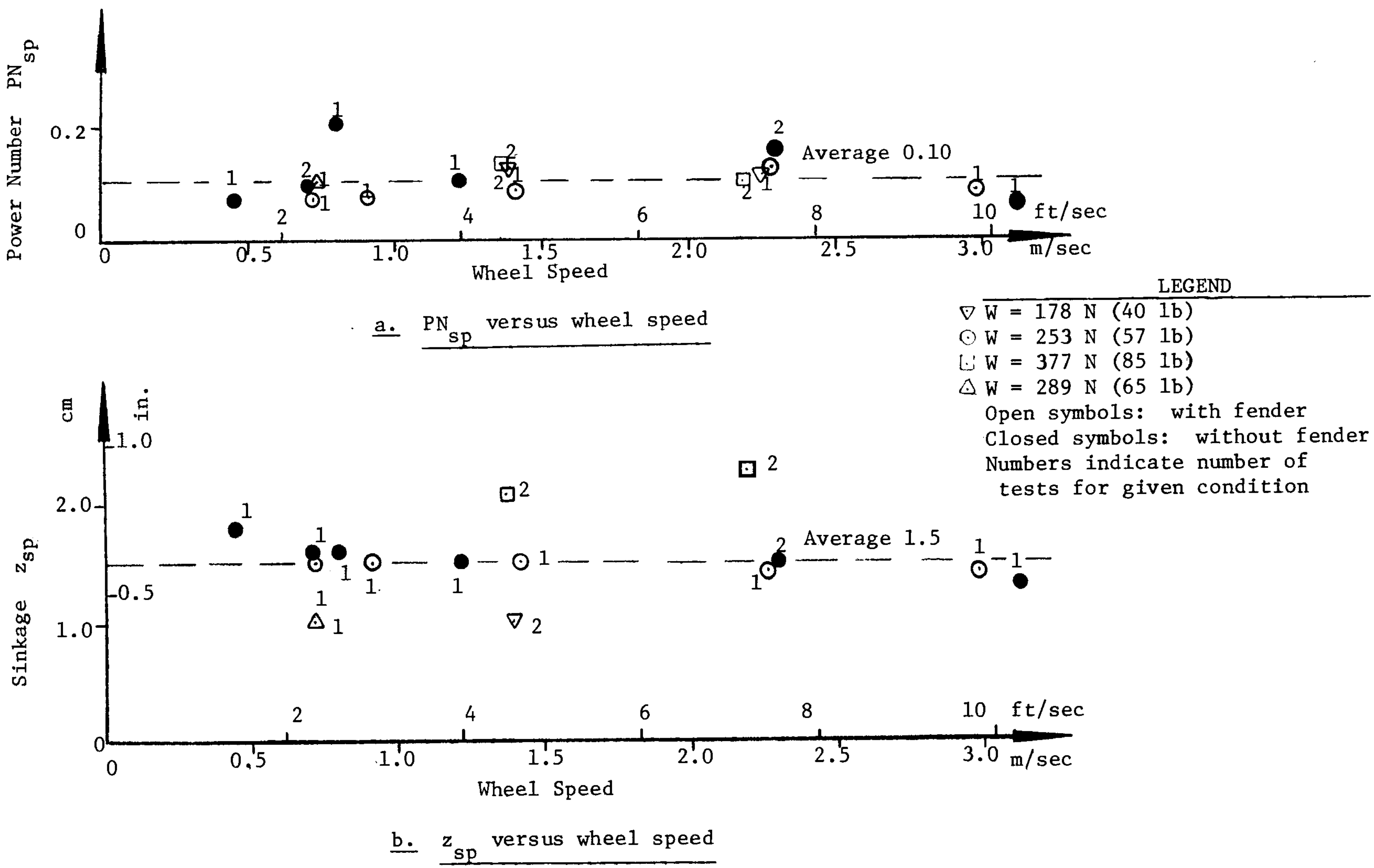
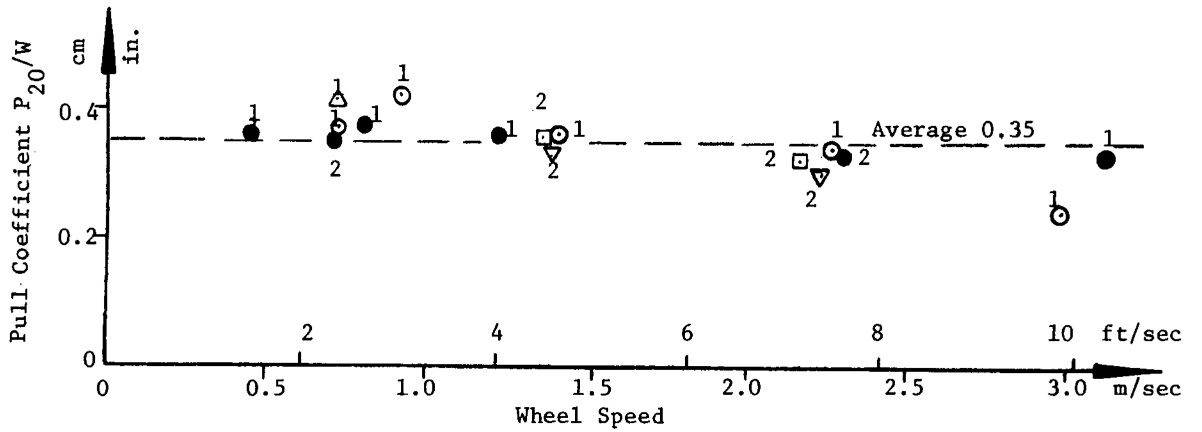
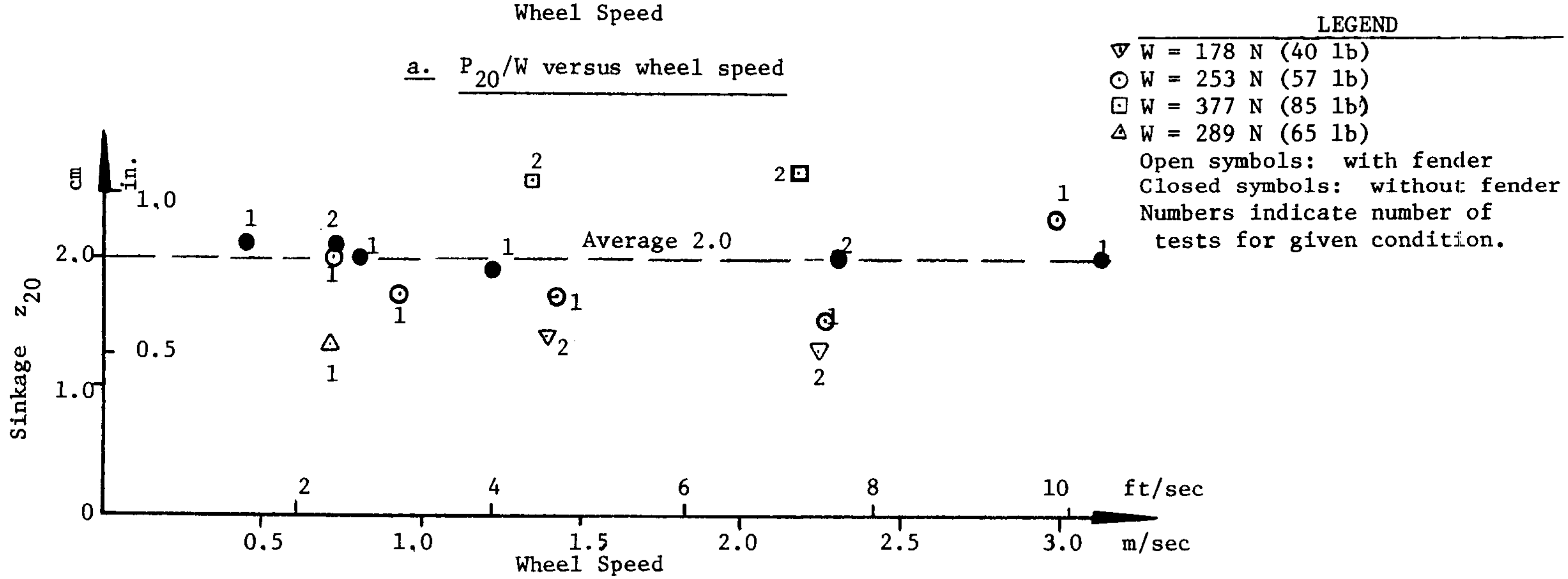


Fig. 14. Influence of wheel speed on power number and sinkage at self-propelled condition; GM XV wheel; average first and second passes; soil condition LSS_4



a. P_{20}/W versus wheel speed



b. z_{sp} versus wheel speed

Fig. 15. Influence of wheel speed on pull coefficient and sinkage at 20% slip; GM XV wheel; average first and second pass tests; soil condition LSS_4

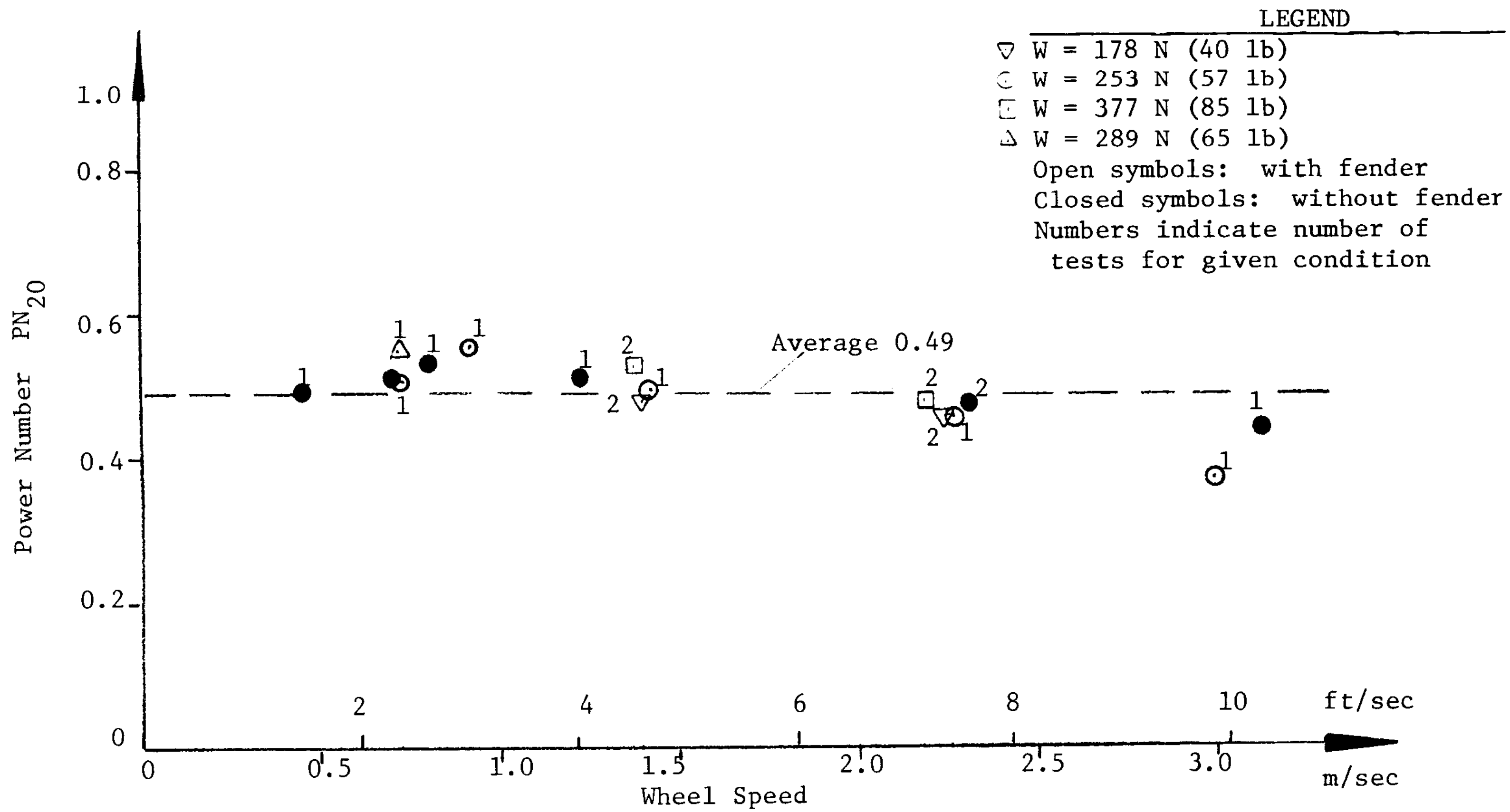


Fig. 16. Influence of wheel speed on power number at 20% slip; GM XV wheel; average of first and second passes; soil condition LSS_4

Only the dimensionless performance parameters, such as P_{20}/W or $PN_{sp} = M\omega/Wv_a$, were independent of wheel load.

40. Effect of wheel speed. Because the performance parameters were not influenced by the presence of the fender (paragraph 38) and by changes in wheel load (paragraph 39), all data were included in the analysis of the effect of wheel speed. As has been observed in the analysis of the GM XIII test results (paragraph 31), none of the performance parameters at the self-propelled (fig. 14) and 20 percent slip conditions (figs. 15 and 16) were clearly influenced by wheel speed. Therefore, it appears to be justifiable to represent the corresponding parameters for this given wheel (GM XV) and the soil condition LSS_4 as average values that are independent of fender effects, wheel load, and wheel speed (figs. 14-16).

41. Comparison of GM XIII and GM XV performance. The average performance parameters for the self-propelled and 20 percent slip conditions for the GM XIII (figs. 7-9) and the GM XV (figs. 14-16) wheels are summarized in the following tabulation.

	Self-Propelled Condition		20 Percent Slip Condition		
Wheel	PN_{sp}	z_{sp}, cm	P_{20}/W	PN_{20}	z_{20}, cm
GM XIII	0.10	1.3	0.35	0.51	1.8
GM XV	0.10	1.5	0.35	0.49	2.0

It is concluded that both wheels performed essentially the same on the given soil condition LSS_4. Further, the statistical value of the information on the performance of the LRV wheels on LSS_4 can be increased by combining the data from at least the CPS tests with the data from the tests with the GM XIII and the GM XV wheels (29 tests).

42. Effect of chevron direction. The results of the seven four-pass tests with reversed direction of the chevron cover of the wheel are shown as performance parameters versus wheel load relations in figs. 17 and 18. Each data point at a given load represents the average

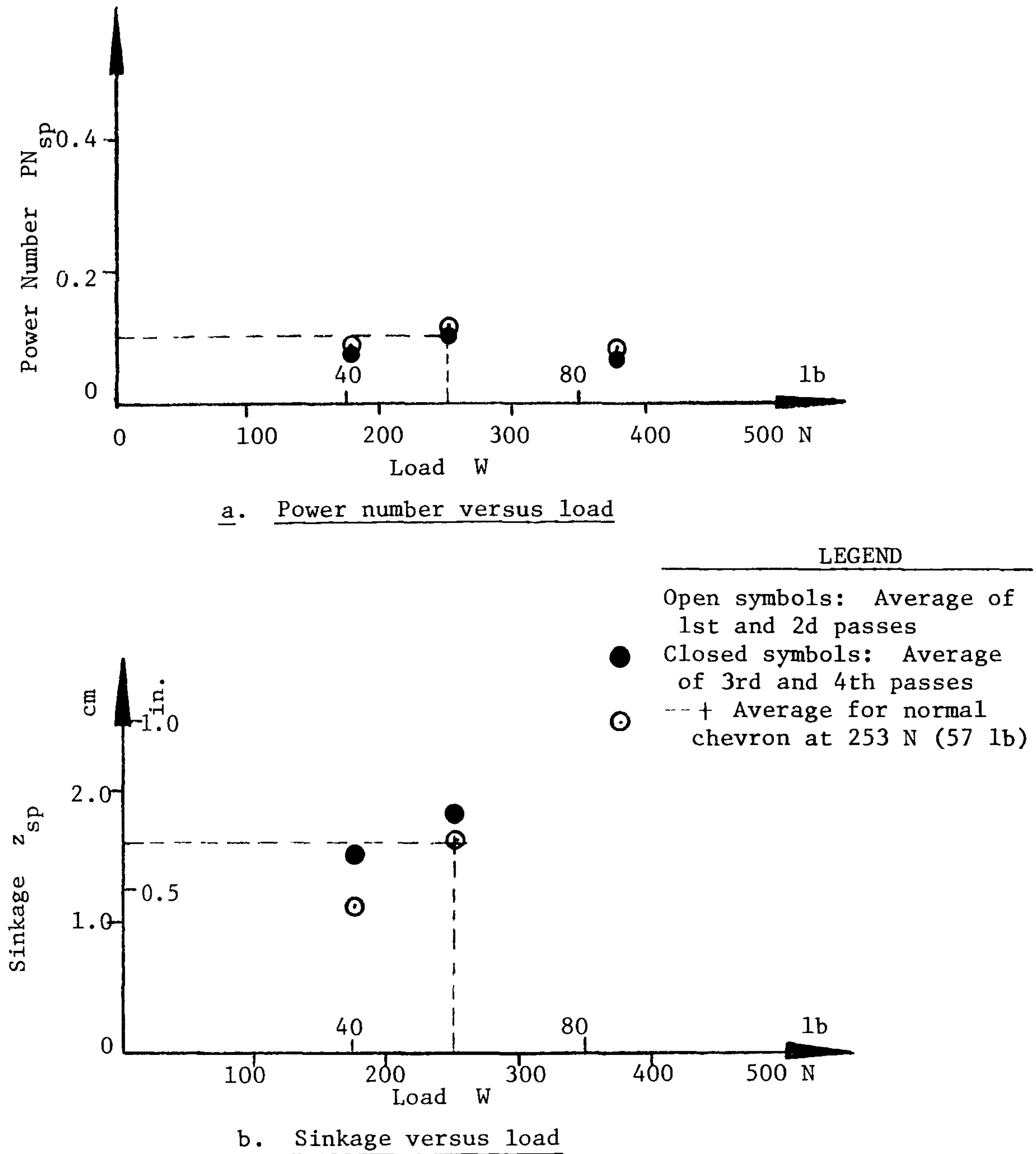


Fig. 17. Influence of wheel load on performance parameters at self-propelled condition; GM XV wheel with fender and reversed chevron; wheel speed 0.75 m/sec (2.5 ft/sec); soil condition LSS_4

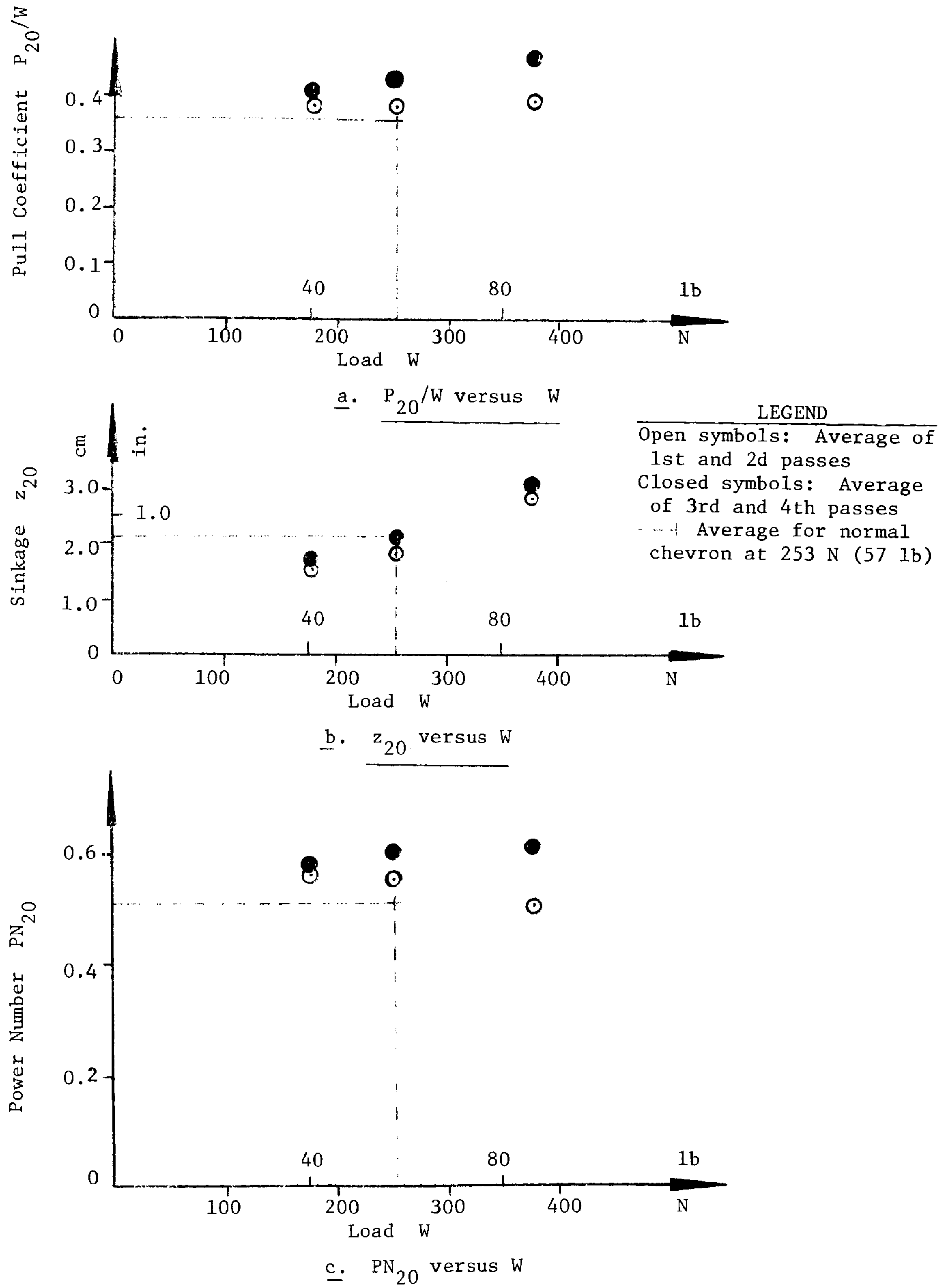


Fig. 18. Influence of wheel load on performance parameters at 20% slip; GM XV wheel with fender and reversed chevron; wheel speed 0.75 m/sec (2.5 ft/sec); soil condition LSS_4

value for the first and second passes* (open symbols), or for the third and fourth passes** (closed symbols) from three tests [253-N (57-lb)-wheel load] or two tests [178-N (40-lb) and 377-N (85-lb) wheel loads].

43. The power number at the self-propelled condition appears to be independent of wheel load (fig. 17a), which is a confirmation of the findings stated in paragraph 39; whereas PN_{sp} seems to be slightly lower for the third and fourth passes than for first and second passes. The reason for this lies in the fact that the soil was compacted during the first and second passes; thus, less power was required to propel the wheel during third and fourth passes. This is also indicated by the sinkage (hub movement) versus wheel load relation for the same condition (fig. 17b). The difference in z_{sp} between third and fourth passes (closed symbols) and first and second passes (open symbols) represents the additional sinkage the wheel experienced during the third and fourth passes. This sinkage is smaller at a given load for the latter than for first and second passes, thus following the tendency of the power requirements. Generally, the sinkage increased with increasing load for a given pass (paragraph 39).

44. Basically, the same observations as for the self-propelled condition were made for the 20 percent slip condition (fig. 18). Slightly more pull was generated for the given slip of 20 percent during the third and fourth passes than during the first and second passes (fig. 18a), because sinkage was smaller in the former than in the latter (fig. 18b). Accordingly, the power requirements increased with increasing number of passes (fig. 18c). Further, sinkage increased with increasing wheel load; whereas P_{20}/W and PN_{20} were essentially independent of wheel load.

45. Generally, the same tendencies concerning the effect of wheel load as found for the forward-traveling wheel (normal chevron, paragraph 39) were observed for the backward-traveling (reversed chevron direction) wheel (paragraphs 43 and 44). In addition, a direct comparison

*Representing the LRV backing into undisturbed soil.
**Representing the LRV backing in its own ruts.

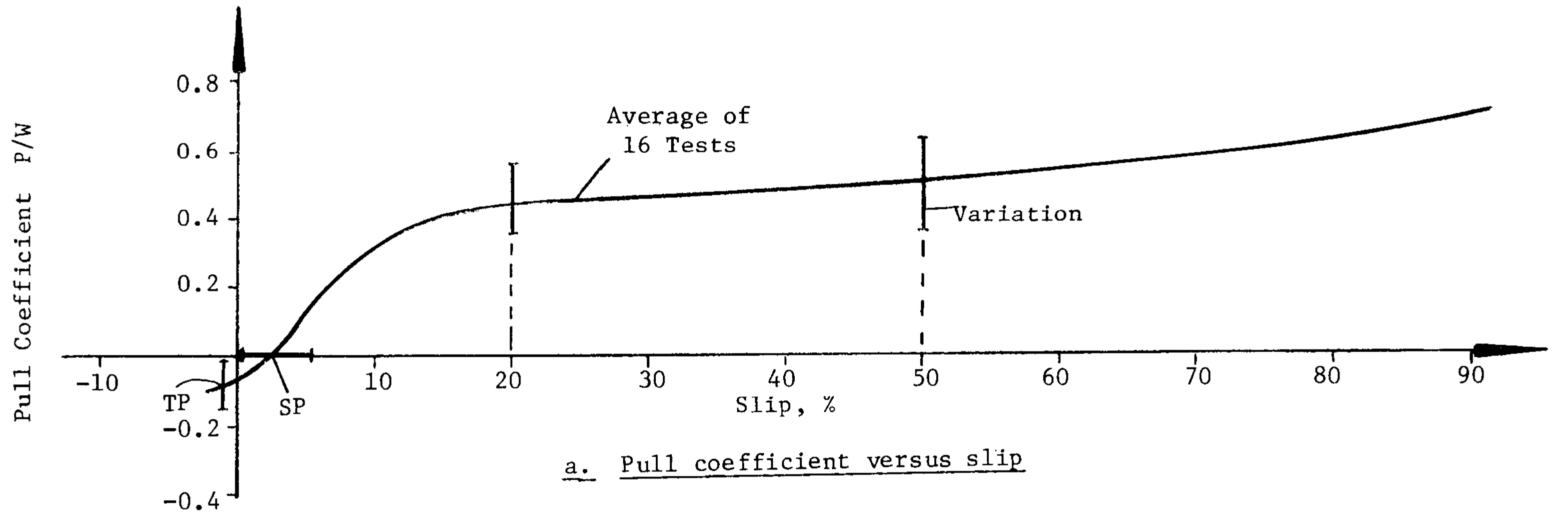
of the performance parameters for the forward- and the backward-traveling wheel under the same loading condition (253 N; 57 lb) and for average first- and second-pass data shows no significant difference (figs. 17 and 18). Thus, for all practical purposes, the performances of the forward- and the backward-traveling wheel appear to be the same. Furthermore, the only slightly superior performance of the wheel when backing in its own rut (reversed chevron, third and fourth passes) will most probably be diminished by the power required to steer the wheel so that it maintains its travel in the rut. Thus, it seems to be more practicable to back the vehicle into undisturbed soil than in its own rut.

Soil condition LSS_5

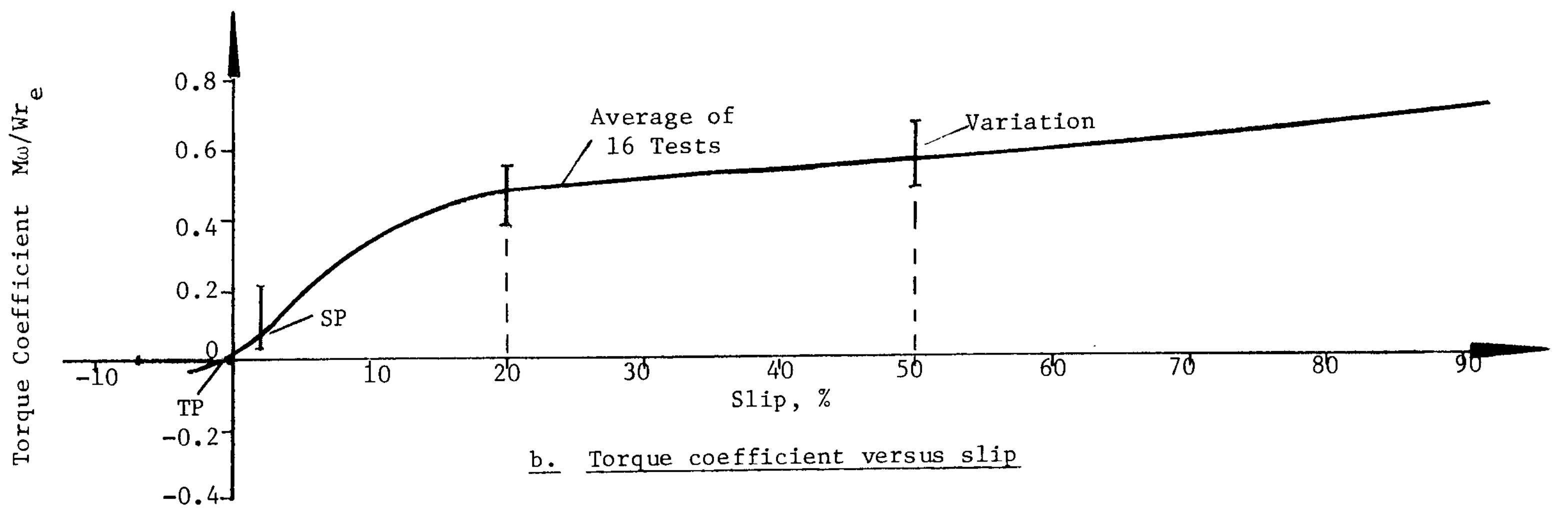
46. Following the same line of thought as in the analysis of the GM XV test results (paragraphs 30 and 37), the P/W versus slip, M/Wr_e versus slip, and PN versus P/W relations for the 16 CPS tests conducted on LSS_5 indicate no dependence of these parameters on wheel speed, wheel load, or the presence or absence of the fender. The average relations, with their maximum and minimum deviations at the characteristic conditions (paragraph 30), are shown in figs. 19 and 20. For a more detailed analysis the performance parameters for the self-propelled and the 20 percent slip conditions were plotted versus wheel speed, and the various test conditions were indicated by different symbols (figs. 21-23).

47. Effect of fender. Because it was found that the presence of the fender did not influence the performance of the wheel on soil condition LSS_4 (paragraph 38), only one of the 16 tests on soil condition LSS_5 was conducted without the fender to check this conclusion. The results of this test (closed symbol in figs. 21-23) confirm the above findings for LSS_4.

48. Effect of wheel load. Comparison of the performance parameters PN_{sp}, P_{20}/W, and PN_{20} at a given speed (figs. 21-23) leads, as in the case of soil condition LSS_4 (paragraph 39), to the conclusion that these parameters were independent of wheel load. Only sinkage (z_{sp}, fig. 21b; z_{20}, fig. 22b) showed a tendency to increase with increasing



a. Pull coefficient versus slip



b. Torque coefficient versus slip

Fig. 19. Relations of pull and torque coefficient to slip for GM XV wheel on LSS_5 (1st and 2d passes)

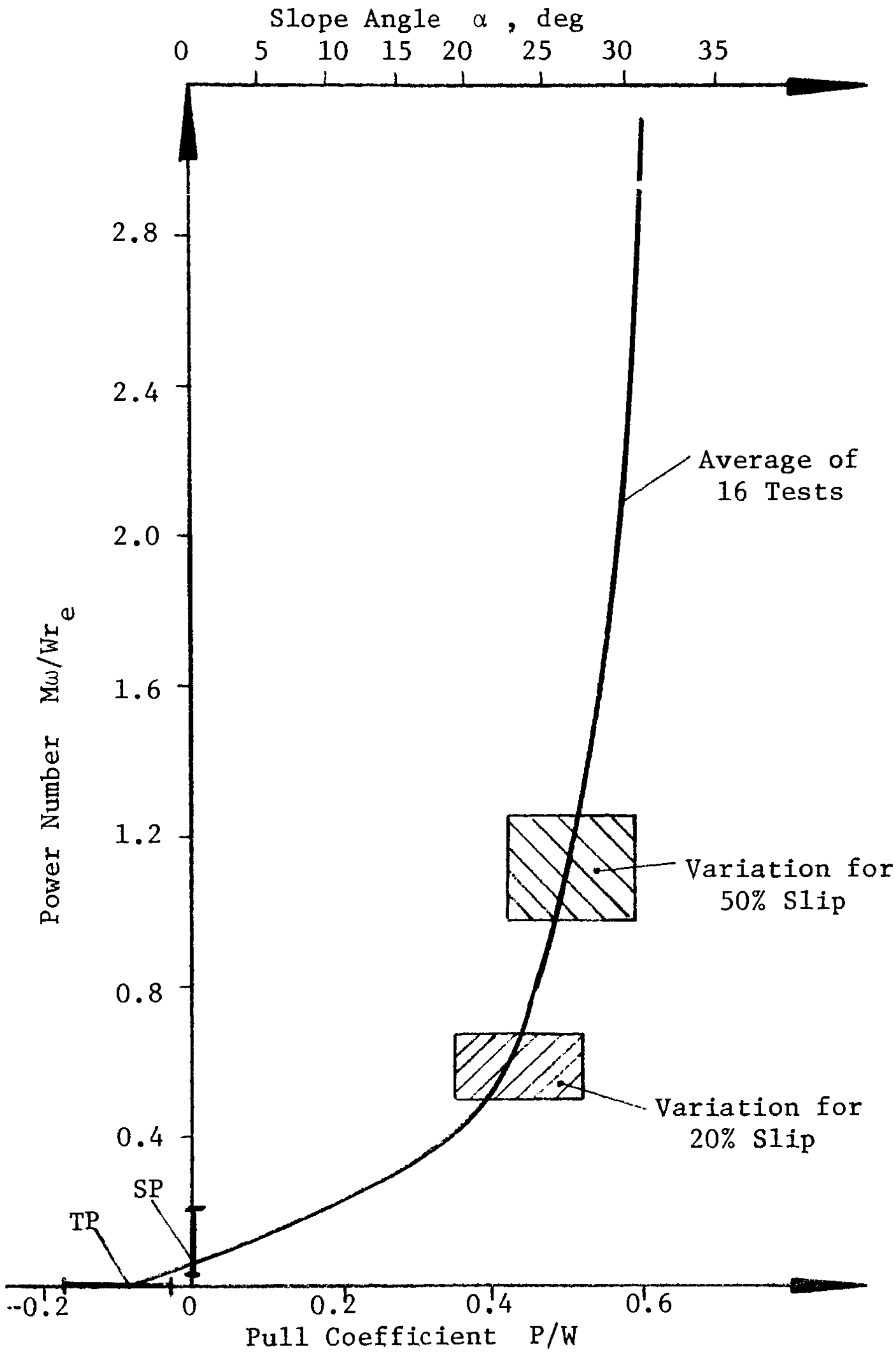
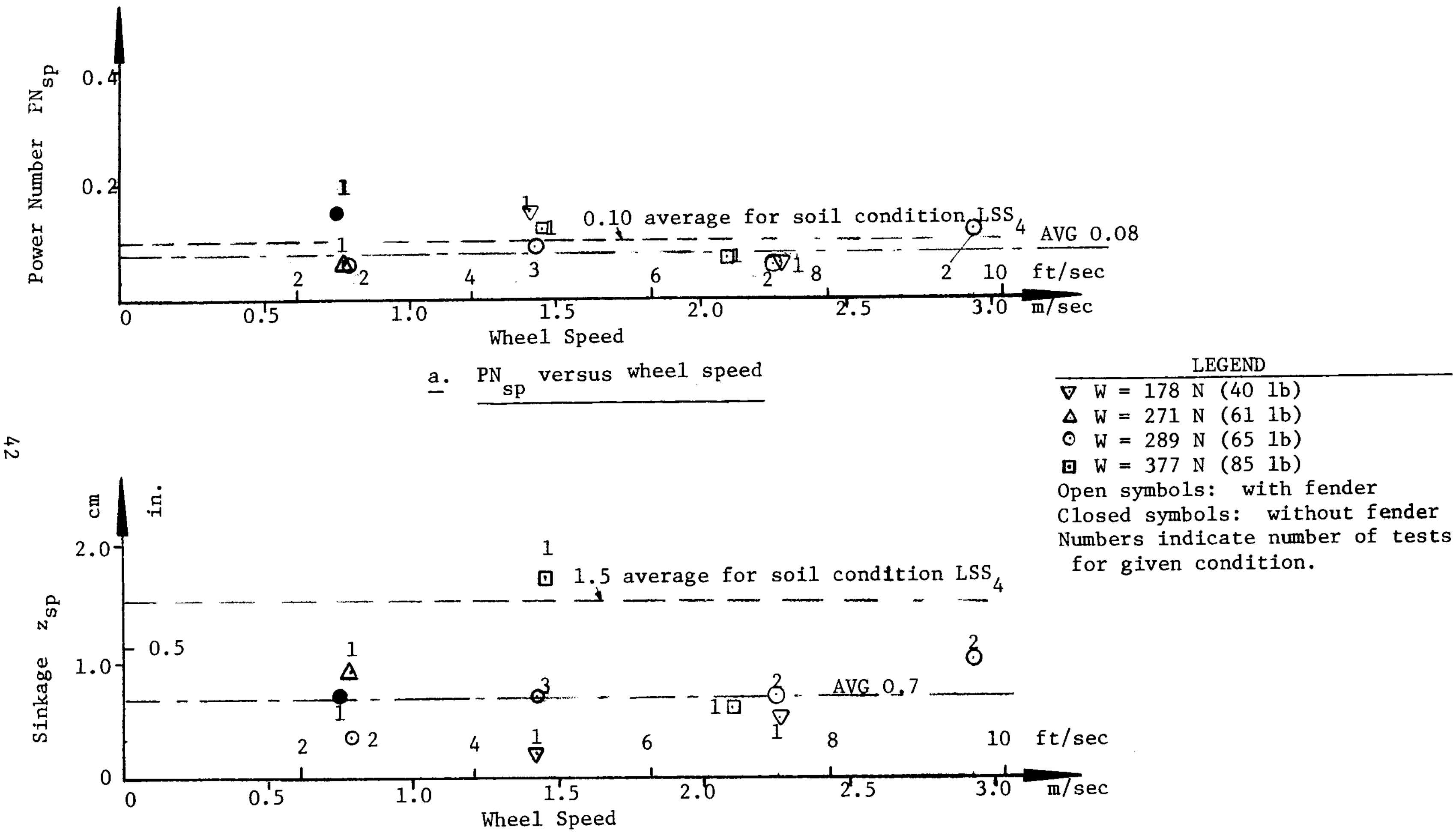


Fig. 20. Relation of power number to pull coefficient and slope angle for GM XV wheel on LSS_5 (1st and 2d passes)



a. PN_{sp} versus wheel speed

b. z_{sp} versus wheel speed

Fig. 21. Influence of wheel speed on power number and sinkage at self-propelled condition; GM XV wheel; average of 1st and 2d passes; soil condition LSS_5

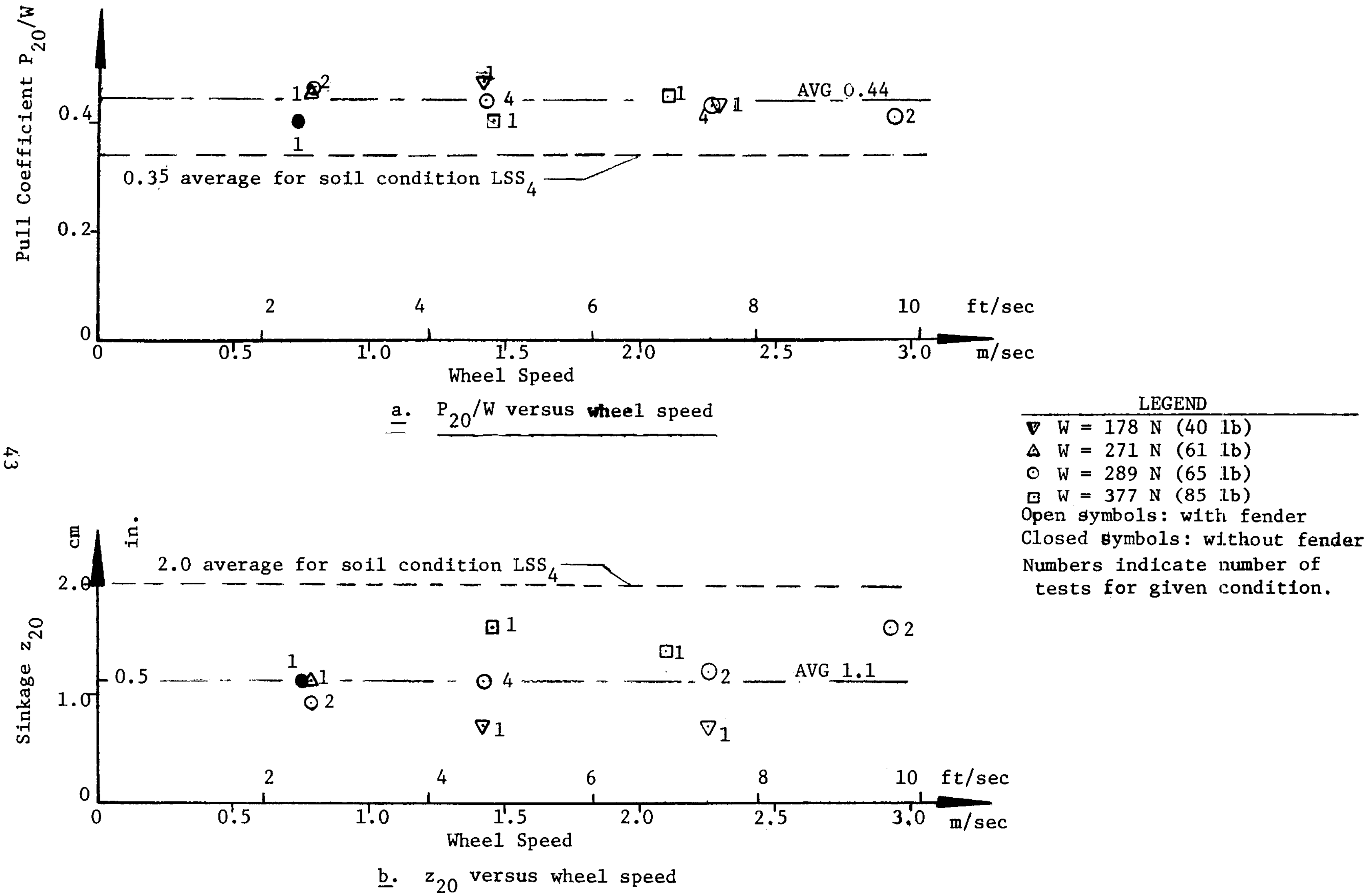


Fig. 22. Influence of wheel speed on pull coefficient and sinkage at 20% slip; GM XV wheel; average of 1st and 2d passes; soil condition LSS_5

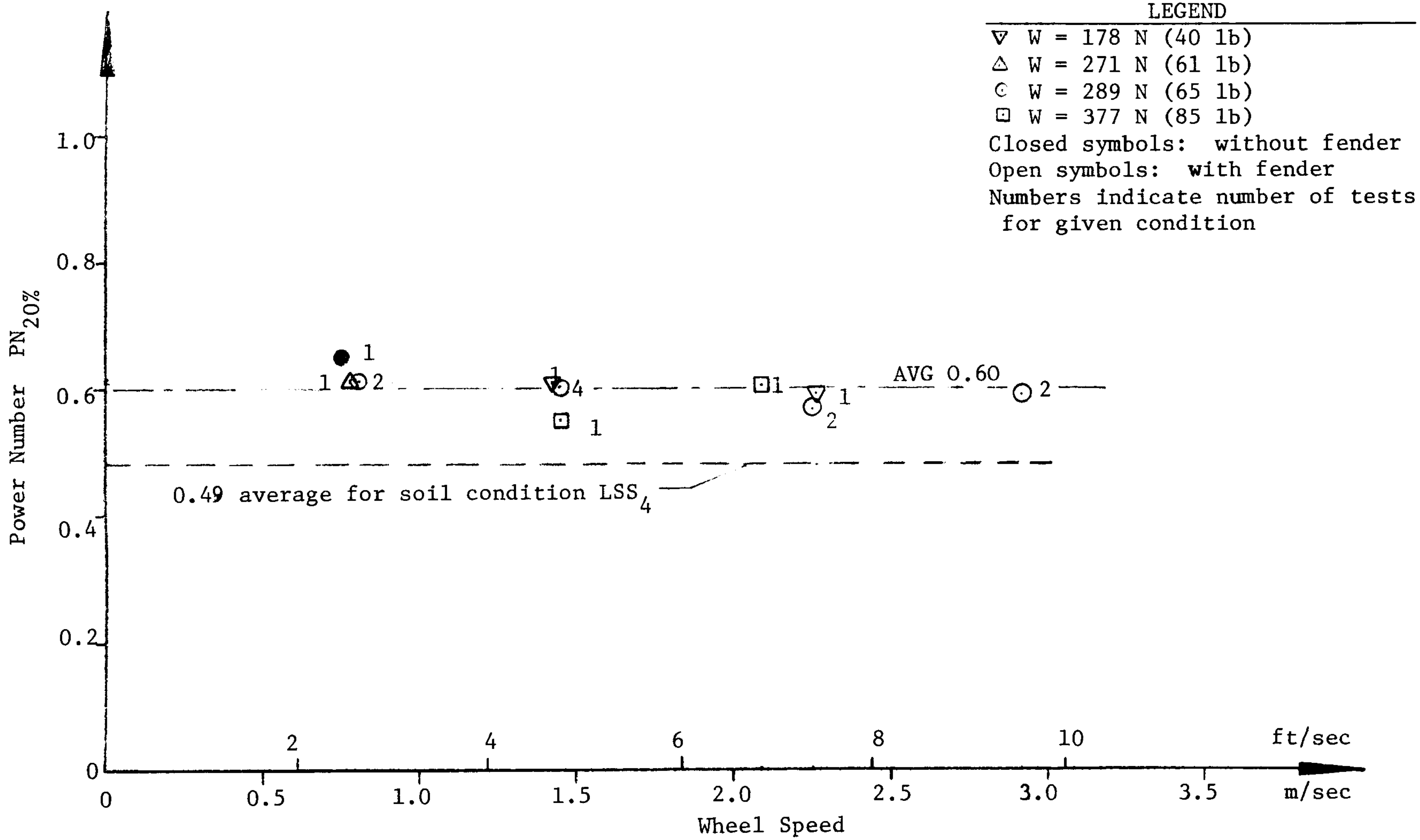


Fig. 23. Influence of wheel speed on power number at 20% slip; GM XV wheel; average of 1st and 2d passes; soil condition LSS_5

wheel load.

49. Effect of wheel speed. The same observation as for soil condition LSS_4 (paragraph 40) was made for soil condition LSS_5. The relation between the performance parameters for the self-propelled condition and for 20 percent slip and the wheel speed (figs. 21-23) did not show any influence of wheel speed. Therefore, the performance parameters were averaged regardless of wheel speed, etc. (figs. 21-23).

Influence of soil strength

50. In addition to the average performance parameters for soil condition LSS_5, the average values for soil condition LSS_4 (GM XV wheel) are displayed in figs. 21-23. The power requirements (represented by the power number) for the self-propelled condition were higher for LSS_4 than for LSS_5 (fig. 21a). On the other hand, at a given slip of 20 percent, more pull was developed on LSS_5 than on LSS_4, (fig. 22a) and, consequently, the power requirements (fig. 23) increased from soil condition LSS_4 to LSS_5.

51. To clarify the influence of soil strength on performance, the average pull and torque coefficient versus slip relations from the tests with the GM XV wheel on soil condition LSS_4 (from fig. 12) and on soil condition LSS_5 (from fig. 19) were plotted together (fig. 24). From this comparison, it follows that, in general, P/W was larger for LSS_5 than for LSS_4 at a given wheel slip. This tendency may be attributed to the fact that the available shear potential of the soil was greater for LSS_5 than for LSS_4. Corresponding to this increase in P/W was the increase in the torque (M/Wr_e) required to utilize the shear potential of this stronger material (LSS_5). The towed force and the torque coefficient at the self-propelled condition (paragraph 50) were smaller for LSS_5, and less slippage occurred. This behavior was as expected, because the wheel experienced less sinkage in stronger soil; thus, there was less energy loss due to sinkage and bulldozing. Finally, which is most important, for a given P/W (or slope the LRV climbed), e.g. $P/W = 0.25$ (fig. 24), the slip developed in LSS_5 was smaller (8 percent) than in LSS_4 (11.5 percent). As a consequence, the necessary

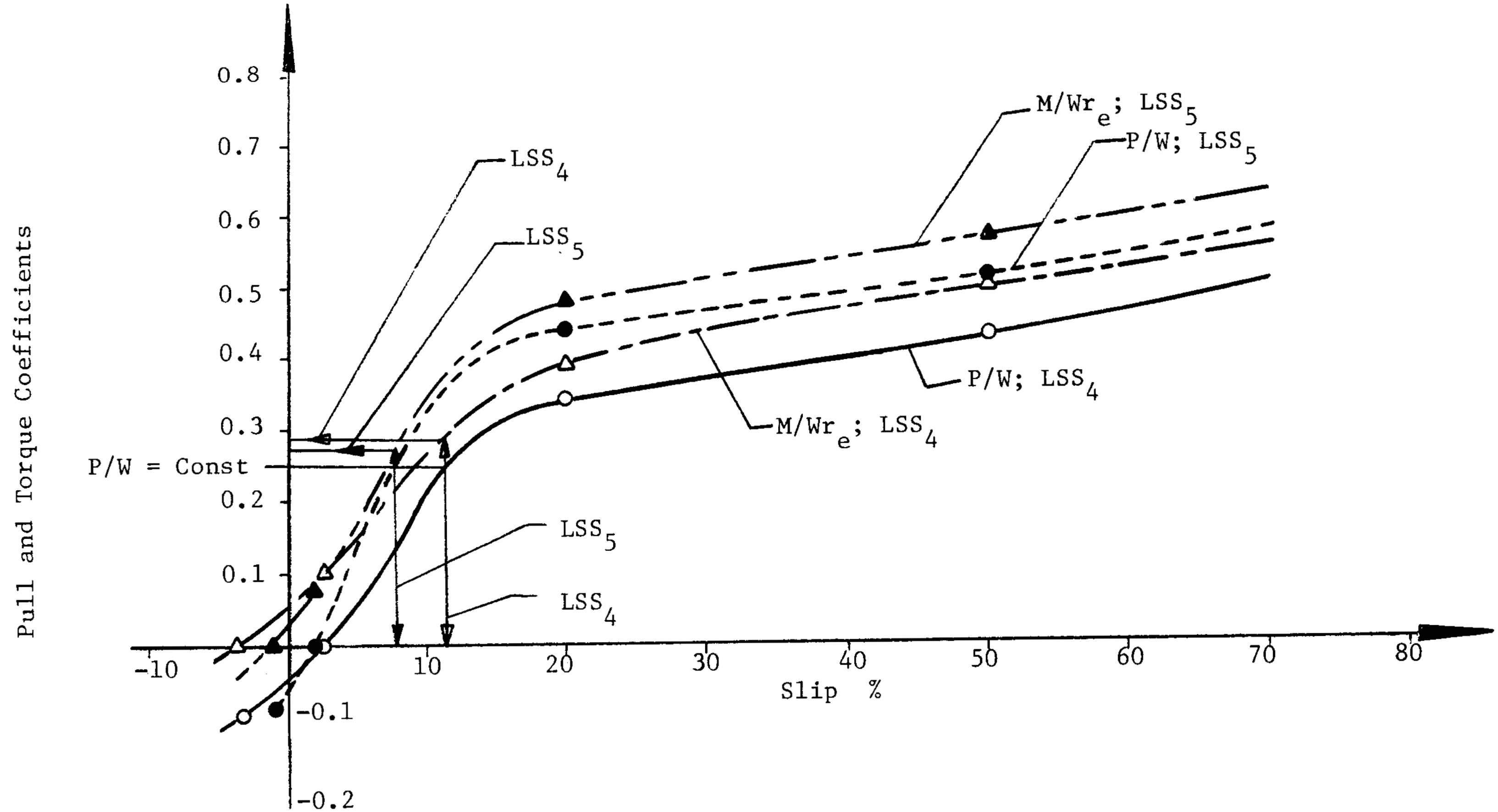


Fig. 24. Comparison of relations of pull and torque coefficients to slip for GM XV wheel on LSS_4 and LSS_5

torque requirement (M/Wr_e) was slightly less for LSS_5 (0.28) than for LSS_4 (0.29).

52. The interrelation between torque required and slip developed for a certain pull for the two soil conditions becomes even more obvious in the comparison of the relations between power number (torque required per unit weight per unit distance of travel) and pull coefficient and/or slope angle, respectively (fig. 25).* From these relations, it can be concluded that the power requirements for the LRV are larger for the softer soil (LSS_4) on any given slope (any given P/W) than for the stronger soil (LSS_5). Further, the maximum slope the vehicle could climb without using excessive power was about 19 ±6 deg in LSS_4 and about 23 ±5 deg in LSS_5.

53. Another point of interest is the influence of soil strength on efficiency. The specific efficiency term ($Pv_a/M\omega$) used herein is defined as the ratio of recoverable energy to total energy input; thus, this term reflects the ratio of the net pull that is developed over and above the pull that allows the wheel or vehicle to propel itself, to the total energy input. As a consequence, the efficiency was zero for the self-propelled condition (P/W = 0) and for 100 percent slip (carriage, or vehicle speed $v_a = 0$). For any given P/W (except P/W = 0) or slope angle α, the maximum efficiency occurred at P/W = 0.31 ±0.15, or α = 17 ±8 deg, in LSS_4 and at P/W = 0.33 ±0.14, or α = 18 ±7 deg, in LSS_5. The corresponding torque coefficients and power numbers for maximum efficiencies were M/Wr_e = 0.35 ±0.11 and PN = 0.42 ±0.13 for LSS_4 and M/Wr_e = 0.32 ±0.10 and PN = 0.36 ±0.12 for LSS_5. Furthermore, for any given torque requirement (M/Wr_e) or power requirement (PN), efficiency was higher on LSS_5 than on LSS_4 (fig. 26).

54. For an overall picture of the influence of soil strength on the performance of the Boeing-GM wheels, data from an earlier study, in which the GM X and GM XIII wheels (both 50 percent chevron covered) were

* The power number and efficiency versus pull coefficient relations represent, as in figs. 24 and 26, the average results of 21 tests on LSS_4 and 16 tests on LSS_5.

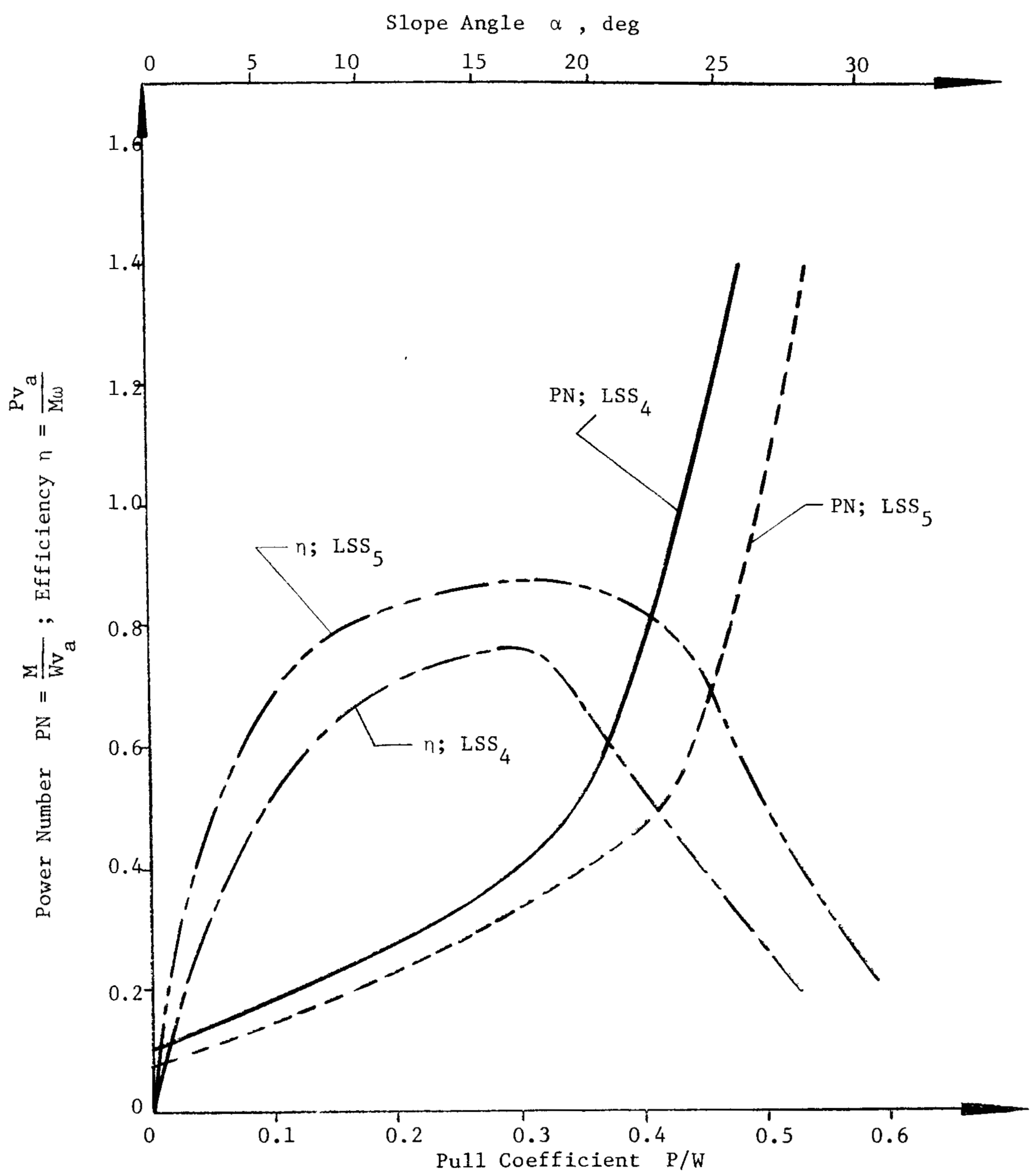


Fig. 25. Comparison of relations of average power number and efficiency to pull coefficient and slope angle for GM XV wheel on LSS_4 and LSS_5

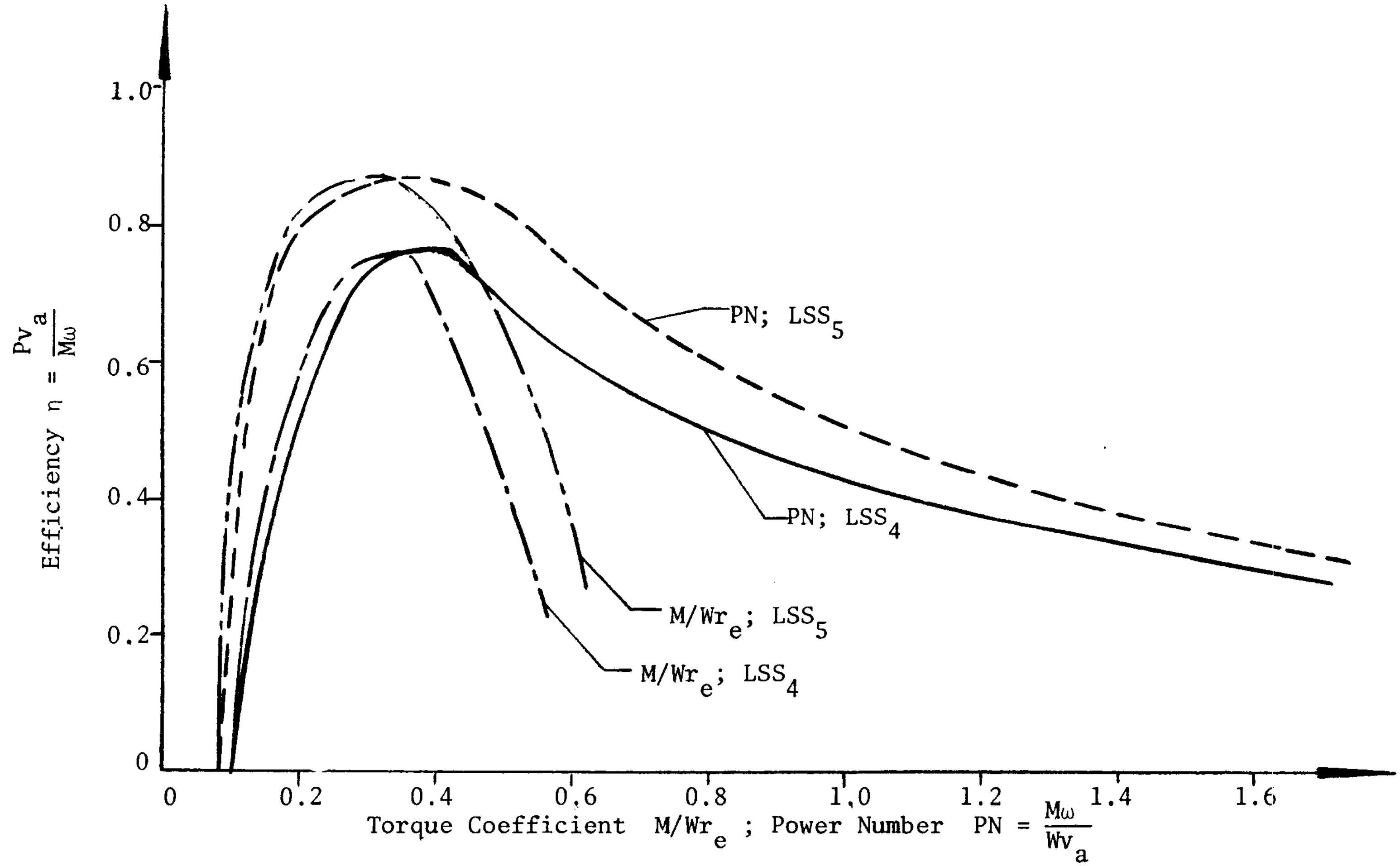


Fig. 26. Comparison of relations of average efficiency to torque coefficient and power number for GM XV wheel on LSS_4 and LSS_5

tested on various LSS conditions (Green and Melzer, 1971b), and corresponding data from the investigations reported herein were used to show the influence of the cone penetration resistance gradient G (representing "soil strength") on pull coefficient, power number, and efficiency at 20 percent slip (fig. 27). The increase of performance in terms of P_{20}/W was approximately 50 percent over the whole range of G tested. Since this range covers G values from 0.22 MN/m^3 (0.8 psi/in.)* to 6.39 MN/m^3 (23.6 psi/in.)**, the increase in G is not reflected very clearly in the increase in performance. However, this range of G corresponds only to a change in the relative density of the soil from 30 to 60 percent. This small change in relative density, together with the fact that for lightly loaded wire-mesh wheels a change in soil strength does not contribute too much to the performance, explains the increase of only 50 percent in P_{20}/W. In addition to relative density, cohesion also increased, from zero for LSS_1 to 2.9 kN/m^2 (0.42 psi) for LSS_5, a fact that is partially reflected in the high variation of G. However, it was found earlier that such relatively small amounts of cohesion do not have a very pronounced effect on the performance of lightly loaded wire-mesh wheels.

---

*Average G for soil condition LSS_4 (fig. 27).

**Average G for soil condition LSS_5 (fig. 27).

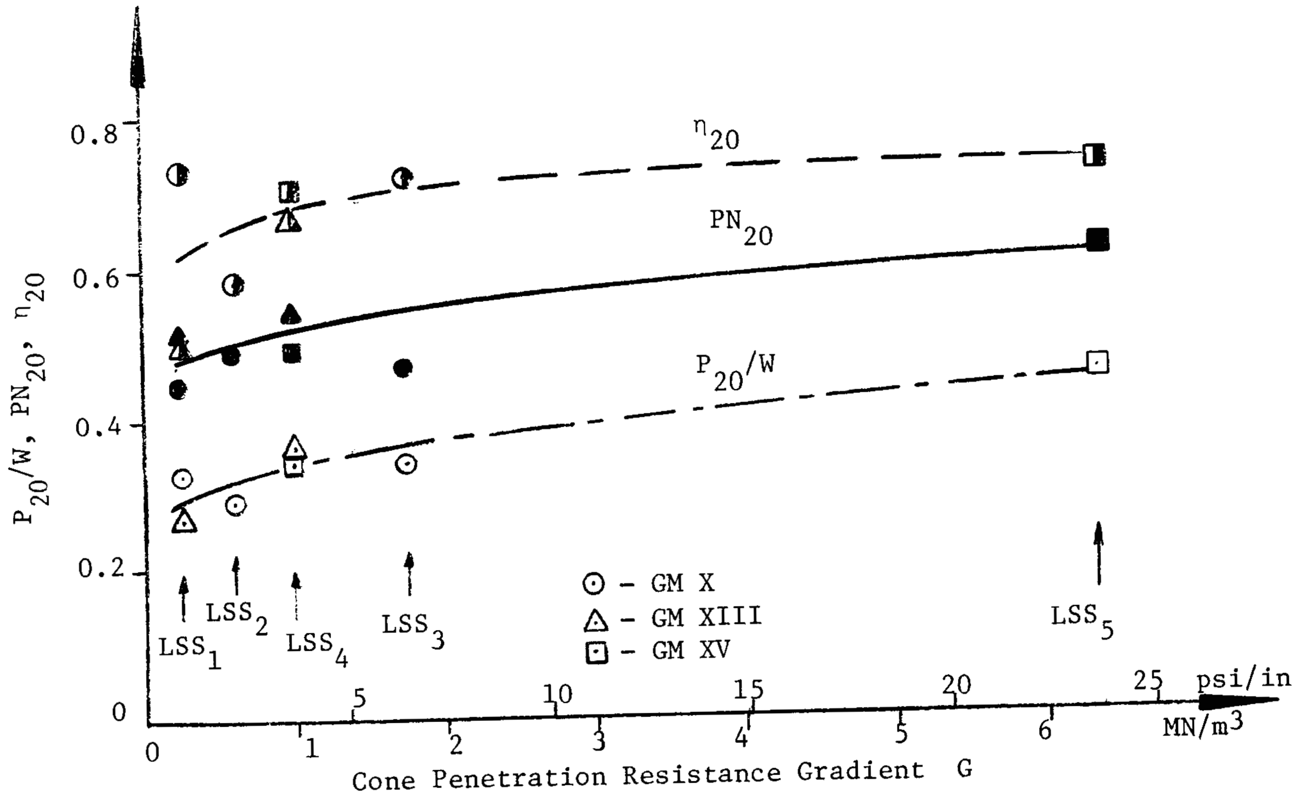


Fig. 27. Effect of soil strength on performance parameters at 20% slip; wheel speed 0.75 m/sec (2.5 ft/sec); load 253-289 N (57-65 lb)

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

55. Based on the findings of this study, it was concluded that:

- a. The performance parameters for the GM XIII and GM XV wheels on lunar soil simulant were independent of wheel speed (paragraphs 30, 40, and 49); but performance increased with speed in the tests with the GM XIII on sand (paragraph 33). This discrepancy might have been caused by occurrence of air-pore pressure in the LSS (paragraph 36). This was the only comparison possible between performances on LSS and on sand.

- b. The performance parameters were independent of wheel acceleration (paragraph 32).

- c. Classical programmed-slip, ramped-slip, and modified programmed-slip test techniques gave the same results for given test conditions (paragraphs 30 and 32).

- d. Except for sinkage (hub movement), which increased with wheel load, performance parameters were not influenced by changes in wheel load (paragraphs 39 and 48).

- e. The presence of a fender did not influence the wheel performance (paragraphs 38 and 47).

- f. The GM XIII and GM XV wheels showed practically the same performance on the same soil condition (LSS_4) (paragraph 41).

- g. Soil strength in terms of penetration resistance gradient G influenced wheel performance (paragraphs 50-54); for a given slip, pull coefficient and power requirements increased with increasing soil strength. However, for a given pull coefficient or slope, slip was less in firmer soil; thus, power requirements decreased and efficiency increased with increasing soil strength. Torque coefficients and power numbers at which maximum efficiency occurred were 0.35 ±0.11 and 0.42 ±0.13, respectively, for the LSS_4; and 0.32 ±0.10 and 0.36 ±0.12, respectively, for the LSS_5 (paragraph 53).

- h. The maximum slope the LRV could climb without using excessive power would be about 19 deg, ±6 deg, in LSS_4 and about 23 deg, ±5 deg, in LSS_5 (paragraph 52).

i. The performance of the wheel was the same if it traveled forward or backward into undisturbed soil. The performance was slightly better if it backed in its own rut. However, this advantage might be lost by the power requirements due to steering to keep the wheel (or vehicle) in the rut (paragraphs 42-45).

Recommendations

56. It is recommended that:

a. Series of triaxial tests be conducted to check the influence of possible air-pore pressure on the shear characteristics of the lunar soil simulant.

b. Series of single-wheel tests be conducted with air-pore pressure measured (e.g. with piezometers), or scale-model tests be conducted under vacuum conditions, to investigate the influence of air-pore pressure on the wheel performance.

c. All possible information about the performance of the LRV collected during the Apollo 15 mission be carefully evaluated with regard to the performance prediction potential of the information assembled in this study.

LITERATURE CITED

Costes, N. C., Carrier, W. D., Mitchell, J. K., and Scott, R. F. (1970), "Apollo 11: Soil Mechanics Results," Proceedings of The American Society of Civil Engineers, Soil Mechanics and Foundation Engineering Division, Vol 96, SM6, p 2045.

Freitag, D. R., Green, A. J., and Melzer, K.-J. (1970a), "Performance Evaluation of Wheels for Lunar Vehicles," Technical Report No. M-70-2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

____________ (1970b), "Performance Evaluation of Wheels for Lunar Vehicles (Summary Report)," Miscellaneous Paper No. M-70-4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Green, A. J. and Melzer K.-J. (1971a), "The Performance of Two Boeing-GM Wheels (GM VII and GM VIII) for the Manned Lunar Rover Vehicle," Miscellaneous Paper No. M-71-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

____________ (1971b), "Performance of the Boeing LRV Wheels in a Lunar Soil Simulant; Effect of Wheel Design and Soil," Technical Report No. M-71-10, Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Leflaive, E. and Wiendieck, K. W. (1965), "Theoretical Evaluation of the Speed Effect on Drawbar Pull of Powered Wheels on Dry Sand," Memorandum for Record (unpublished), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Melzer, K.-J. and Green, A. J. (1971), "Performance Evaluation of a First-Generation Elastic Loop Mobility System," Technical Report No. M-71-1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Mitchell, J. K. Bromwell, L. G., Carrier, W. D., Costes, N. C. and Scott, R. F. (1971), "Apollo 14 - Preliminary Science Report; Soil Mechanics Experiment," NASA Special Report SP-272, Section 4, National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Ala.

Scott, R. F., Carrier, W. D., Costes, N. C., and Mitchell, J. K. (1971), "Apollo 12 Soil Mechanics Investigations," Geotechnique, Vol 21, p 1.

Turnage, G. W. (1972), "Performance of Soils Under Tire Loads; Application of Test Results to Tire Selection for Off-Road Vehicles," Technical Report No. 3-666, Report 8 (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Table 1

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

		LSS_4				LSS_5				Yuma Sand			
		No. of Tests	Maximum	Minimum	Average	No. of Tests	Maximum	Minimum	Average	No. of Tests	Maximum	Minimum	Average
Penetration Resistance Gradient, MN/m^3		200	1.34	0.72	1.01	75	7.27	5.91	6.39	64	1.72	0.99	1.30
Dry Density, g/cm^3	Gradient G	200	1.545	1.481	1.516	75	1.720	1.696	1.706	64	1.564	1.516	1.542
	Gravimetric	10	1.608	1.521	1.561	7	1.730	1.608	1.654	-	-	-	-
Moisture Content, %	Soil Bin	10	2.1	1.7	1.9	7	2.3	1.8	2.0	-	-	-	-
	Surface	140	2.1	1.6	1.8	45	2.2	1.6	1.9	-	-	-	-
Relative Density, %	Gradient G	200	36.0	25.0	31.0	75	61.0	58.0	59.0	64	68.0	51.0	60.0
	Gravimetric	10	45.0	32.0	38.0	7	62.0	46.0	52.0	-	-	-	-
Shear Strength													
Friction Angle, deg	ϕ_s*	-	-	-	38.5	-	-	-	41.5	-	-	-	39.2
Friction Angle, deg	$\phi_{p\ell}$**	-	-	-	34.0	-	-	-	36.0	-	-	-	32.0
Cohesion, kN/m^2	c_{tr}	-	-	-	0.76	-	-	-	2.90	-	-	-	$\approx$0.0

*σ_n = 5.8 kN/m^2

**σ_n = 7.32 kN/m^2

Table 2

Soil Properties and Parameters of Lunar Soil Simulant for Single-Wheel Tests; During-Traffic Data

			Penetration Resistance Gradient G, MN/m^3			Surface Moisture Content w, %			Dry Density γ_d, g/cm^3 (Gravimetric)			Moisture Content w, %		
Test No.	Soil	Pass No.	Max	Min	Avg	Max	Min	Avg	Reading No. 1	Reading No. 2	Avg	Reading No. 1	Reading No. 2	Avg
A71-001-6	LSS_4	0	1.16	1.13	1.14	1.9	1.8	1.8	-	-	-	-	-	-
		0*	2.05	1.13	1.67	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	1.24	1.15	1.20	2.0	1.9	2.0	-	-	-	-	-	-
A71-002-6	LSS_4	0	1.26	0.91	1.03	2.1	2.0	2.1	1.529	1.521	1.525	2.0	2.1	2.1
		0*	1.44	0.91	1.30	-	-	-	-	-	-	-	-	-
		1	1.06	0.97	1.02	-	-	-	-	-	-	-	-	-
		2	1.13	1.08	1.11	2.0	-	2.0	1.602	-	1.602	2.0	-	2.0
A71-003-6	LSS_4	0	1.22	0.90	1.04	1.8	1.7	1.8	-	-	-	-	-	-
		0*	1.76	0.90	1.30	-	-	-	-	-	-	-	-	-
		1	1.14	1.09	1.12	-	-	-	-	-	-	-	-	-
		2	1.23	1.06	1.15	2.0	1.8	1.9	-	-	-	-	-	-
A71-004-6	LSS_4	0	1.09	0.92	0.97	1.8	1.7	1.7	-	-	-	-	-	-
		0*	2.02	0.92	1.43	-	-	-	-	-	-	-	-	-
		1	1.12	1.04	1.08	-	-	-	-	-	-	-	-	-
		2	1.12	1.10	1.11	1.8	1.7	1.8	-	-	-	-	-	-
A71-005-6	LSS_4	0	1.27	1.11	1.17	1.8	-	1.8	-	-	-	-	-	-
		0*	2.02	1.05	1.39	-	-	-	-	-	-	-	-	-
		1	1.40	1.33	1.35	-	-	-	-	-	-	-	-	-
		2	1.56	1.42	1.51	1.9	1.8	1.9	-	-	-	-	-	-

*Offset center line.

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-006-6	LSS_4	0	1.17	1.02	1.10	1.9	1.8	1.9	-	-	-	-	-	-
		0*	2.01	1.09	1.52	-	-	-	-	-	-	-	-	-
		1	1.29	1.25	1.35	-	-	-	-	-	-	-	-	-
		2	1.52	1.31	1.38	1.8	1.7	1.8	-	-	-	-	-	-
A71-007-6	LSS_4	0	0.86	0.82	0.84	1.8	1.7	1.7	-	-	-	-	-	-
		0*	1.92	0.82	1.39	-	-	-	-	-	-	-	-	-
		1	1.05	0.96	0.97	-	-	-	-	-	-	-	-	-
		2	1.15	1.07	1.11	1.9	1.7	1.9	-	-	-	-	-	-
A71-008-6	LSS_4	0	0.97	0.90	0.92	1.8	1.7	1.8	-	-	-	-	-	-
		0*	1.94	0.90	1.49	-	-	-	-	-	-	-	-	-
		1	1.12	0.99	1.06	-	-	-	-	-	-	-	-	-
		2	1.30	1.13	1.20	1.9	1.7	1.8	-	-	-	-	-	-
A71-009-6	LSS_4	0	0.87	0.79	0.82	1.8	1.6	1.7	-	-	-	-	-	-
		0*	1.21	0.79	1.06	-	-	-	-	-	-	-	-	-
		1	1.03	0.94	0.98	-	-	-	-	-	-	-	-	-
		2	1.27	1.12	1.19	1.8	1.7	1.8	-	-	-	-	-	-
A71-010-6	LSS_4	0	1.19	1.13	1.15	1.8	1.7	1.8	-	-	-	-	-	-
		0*	2.19	1.13	1.67	-	-	-	-	-	-	-	-	-
		1	1.39	1.31	1.35	-	-	-	-	-	-	-	-	-
		2	1.51	1.35	1.41	1.9	1.7	1.8	-	-	-	-	-	-
A71-011-6	LSS_4	0	1.14	1.06	1.09	1.8	1.7	1.8	-	-	-	-	-	-
		0*	1.66	1.06	1.32	-	-	-	-	-	-	-	-	-
		1	1.29	1.22	1.25	-	-	-	-	-	-	-	-	-
		2	1.34	1.20	1.25	1.8	1.7	1.7	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-012-6	LSS_4	0	1.17	1.06	1.11	1.8	-	1.8	1.553	-	1.553	1.8	-	1.8
		0*	1.80	1.06	1.42	-	-	-	-	-	-	-	-	-
		1	1.31	1.12	1.19	-	-	-	-	-	-	-	-	-
		2	1.59	1.17	1.33	1.9	-	1.9	1.605	-	1.605	1.9	-	1.9
A71-013-6	LSS_4	0	0.92	0.86	0.89	1.8	1.6	1.7	-	-	-	-	-	-
		0*	2.04	0.86	1.61	-	-	-	-	-	-	-	-	-
		1	1.05	1.03	1.04	-	-	-	-	-	-	-	-	-
		2	1.21	0.85	1.08	1.7	1.6	1.7	-	-	-	-	-	-
A71-014-6	LSS_4	0	1.25	1.12	1.19	1.9	1.8	1.9	-	-	-	-	-	-
		0*	2.02	0.82	1.32	-	-	-	-	-	-	-	-	-
		1	1.46	1.21	1.32	-	-	-	-	-	-	-	-	-
		2	1.59	1.36	1.45	1.9	1.7	1.8	-	-	-	-	-	-
A71-015-6	LSS_4	0	1.07	1.03	1.06	1.8	1.7	1.7	-	-	-	-	-	-
		0*	2.10	1.03	1.69	-	-	-	-	-	-	-	-	-
		1	1.27	1.09	1.15	-	-	-	-	-	-	-	-	-
		2	1.42	1.20	1.30	1.8	1.7	1.8	-	-	-	-	-	-
A71-016-6	LSS_4	0	1.02	0.87	0.93	1.9	1.8	1.8	-	-	-	-	-	-
		0*	1.71	0.87	1.23	-	-	-	-	-	-	-	-	-
		1	1.14	0.99	1.06	-	-	-	-	-	-	-	-	-
		2	1.31	1.20	1.27	1.9	1.7	1.8	-	-	-	-	-	-
A71-017-6	LSS_4	0	1.05	0.96	1.00	1.9	1.8	1.9	-	-	-	-	-	-
		0*	1.84	0.98	1.41	-	-	-	-	-	-	-	-	-
		1	1.25	1.14	1.19	-	-	-	-	-	-	-	-	-
		2	1.46	1.18	1.32	1.9	1.8	1.8	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w_s, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 1	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-018-6	LSS_4	0	0.94	0.90	0.92	1.8	-	1.8	-	-	-	-	-	-
		0*	1.44	0.91	1.08	-	-	-	-	-	-	-	-	-
		1	1.10	1.05	1.07	-	-	-	-	-	-	-	-	-
		2	1.27	1.11	1.18	1.9	1.7	1.8	-	-	-	-	-	-
A71-019-6	LSS_4	0	1.03	0.94	0.98	1.9	1.8	1.8	-	-	-	-	-	-
		0*	2.01	0.94	1.57	-	-	-	-	-	-	-	-	-
		1	1.24	1.11	1.18	-	-	-	-	-	-	-	-	-
		2	1.42	1.22	1.29	1.8	1.7	1.8	-	-	-	-	-	-
A71-020-6	LSS_4	0	1.21	1.11	1.16	1.7	-	1.7	1.608	-	1.608	1.7	-	1.7
		0*	2.06	1.11	1.57	-	-	-	-	-	-	-	-	-
		1	1.37	1.22	1.29	-	-	-	-	-	-	-	-	-
		2	1.60	1.25	1.43	1.8	-	1.8	1.608	-	1.608	1.8	-	1.8
A71-049-6	LSS_4	0	1.09	0.83	0.93	1.7	1.6	1.7	-	-	-	-	-	-
		0*	2.40	1.35	1.73	-	-	-	-	-	-	-	-	-
		1	1.00	0.83	0.91	-	-	-	-	-	-	-	-	-
		2	1.34	1.11	1.21	1.8	1.6	1.7	-	-	-	-	-	-
A71-050-6	LSS_4	0	1.34	1.11	1.18	-	-	-	1.541	1.561	1.551	1.7	1.7	1.7
		0*	1.63	1.12	1.31	-	-	-	-	-	-	-	-	-
		1	1.46	1.05	1.28	-	-	-	-	-	-	-	-	-
		2	1.75	1.23	1.39	-	-	-	1.703	-	1.703	1.7	-	1.7
A71-051-6	LSS_4	0	0.99	0.88	0.93	2.0	1.8	1.9	-	-	-	-	-	-
		0*	1.62	1.41	1.50	-	-	-	-	-	-	-	-	-
		1	1.29	1.02	1.13	-	-	-	-	-	-	-	-	-
		2	1.30	0.93	1.14	1.9	1.8	1.9	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-052-6	LSS_4	0	0.96	0.69	0.85	1.8	1.6	1.7	-	-	-	-	-	-
		0*	2.23	0.91	1.55	-	-	-	-	-	-	-	-	-
		1	1.30	1.06	1.19	-	-	-	-	-	-	-	-	-
		2	1.14	1.02	1.10	1.7	-	1.7	-	-	-	-	-	-
A71-053-6	LSS_4	0	1.20	0.62	0.94	1.9	1.7	1.8	1.582	1.571	1.577	1.9	2.0	2.0
		0*	1.73	0.93	1.40	-	-	-	-	-	-	-	-	-
		1	0.93	0.70	0.80	-	-	-	-	-	-	-	-	-
		2	1.29	0.68	0.95	1.8	1.6	1.7	1.584	1.571	1.577	2.0	2.0	2.0
A71-054-6	LSS_4	0	1.15	0.98	1.02	1.7	-	1.7	-	-	-	-	-	-
		0*	1.69	1.16	1.44	-	-	-	-	-	-	-	-	-
		1	1.17	1.03	1.10	-	-	-	-	-	-	-	-	-
		2	1.32	1.10	1.22	1.7	1.6	1.7	-	-	-	-	-	-
A71-055-6	LSS_4	0	1.06	0.94	1.01	1.6	1.5	1.6	-	-	-	-	-	-
		0*	1.79	1.44	1.59	-	-	-	-	-	-	-	-	-
		1	1.50	1.03	1.24	-	-	-	-	-	-	-	-	-
		2	1.53	1.20	1.32	1.6	-	1.6	-	-	-	-	-	-
A71-056-6	LSS_4	0	0.91	0.77	0.84	-	-	-	1.573	1.567	1.570	1.8	1.9	1.9
		0*	2.37	1.49	1.97	-	-	-	-	-	-	-	-	-
		1	1.07	0.88	0.99	-	-	-	-	-	-	-	-	-
		2	1.24	1.00	1.10	-	-	-	1.641	1.601	1.621	1.8	1.9	1.9
A71-057-6	LSS_4	0	1.14	1.06	1.10	1.9	1.8	1.9	-	-	-	-	-	-
		0*	2.20	1.43	1.79	-	-	-	-	-	-	-	-	-
		1	1.34	1.08	1.20	-	-	-	-	-	-	-	-	-
		2	1.40	1.06	1.21	1.9	1.7	1.8	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-058-6	LSS_4	0	1.05	0.69	0.88	1.8	1.7	1.8	-	-	-	-	-	-
		0*	1.63	0.90	1.34	-	-	-	-	-	-	-	-	-
		1	1.04	0.92	0.99	-	-	-	-	-	-	-	-	-
		2	1.16	0.79	0.99	1.7	1.6	1.7	-	-	-	-	-	-
A71-059-6	LSS_4	0	1.05	0.96	1.01	2.0	1.6	1.8	-	-	-	-	-	-
		0*	1.89	1.22	1.44	-	-	-	-	-	-	-	-	-
		1	1.03	0.79	0.95	-	-	-	-	-	-	-	-	-
		2	1.19	0.93	1.06	1.9	1.8	1.8	-	-	-	-	-	-
A71-060-6	LSS_5	0	7.90	6.19	7.27	1.7	1.5	1.6	1.657	-	1.657	1.9	-	1.9
		0*	8.37	5.35	7.33	-	-	-	-	-	-	-	-	-
		1	7.60	5.66	6.65	-	-	-	-	-	-	-	-	-
		2	7.73	5.63	6.90	1.6	-	1.6	-	-	-	-	-	-
A71-061-6	LSS_5	0	7.09	6.08	6.65	2.0	1.8	1.9	1.649	-	1.649	1.8	-	1.8
		0*	7.88	5.18	6.51	-	-	-	-	-	-	-	-	-
		1	6.82	5.78	6.26	-	-	-	-	-	-	-	-	-
		2	8.18	5.94	6.71	2.1	1.9	2.0	-	-	-	-	-	-
A71-063-6	LSS_5	0	6.46	6.07	6.27	1.6	1.5	1.6	1.730	1.707	1.719	1.9	2.0	2.0
		0*	8.58	6.25	7.60	-	-	-	-	-	-	-	-	-
		1	7.54	6.30	6.59	-	-	-	-	-	-	-	-	-
		2	6.57	6.09	6.35	1.7	-	1.7	1.673	1.700	1.687	2.0	1.8	1.9
A71-064-6	LSS_5	0	6.18	5.61	6.00	1.9	1.8	1.9	-	-	-	-	-	-
		0*	8.72	6.80	7.74	-	-	-	-	-	-	-	-	-
		1	6.79	4.48	6.04	-	-	-	-	-	-	-	-	-
		2	7.11	5.51	6.20	1.9	-	1.9	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-065-6	LSS_5	0	6.31	5.41	5.91	2.0	1.8	1.9	1.635	–	1.635	2.1	–	2.1
		0*	9.88	7.22	8.26	–	–	–	–	–	–	–	–	–
		1	6.81	5.09	6.07	–	–	–	–	–	–	–	–	–
		2	7.43	4.94	6.05	2.0	1.8	1.9	–	–	–	–	–	–
A71-068-6	LSS_5	0	6.52	5.45	5.97	2.2	2.1	2.1	–	–	–	–	–	–
		0*	9.04	7.77	8.33	–	–	–	–	–	–	–	–	–
		1	6.19	5.35	5.78	–	–	–	–	–	–	–	–	–
		2	6.43	4.92	5.77	2.1	1.9	2.0	–	–	–	–	–	–
A71-069-6	LSS_5	0	7.57	6.28	7.05	2.1	1.9	2.0	1.633	–	1.633	2.0	–	2.0
		0*	9.32	7.42	8.75	–	–	–	–	–	–	–	–	–
		1	7.06	6.00	6.35	–	–	–	–	–	–	–	–	–
		2	7.62	6.29	6.72	2.1	1.8	2.0	–	–	–	–	–	–
A71-072-6	LSS_5	0	7.04	6.26	6.62	2.1	2.0	2.0	1.608	–	1.608	2.3	–	2.3
		0*	7.55	5.22	6.58	–	–	–	–	–	–	–	–	–
		1	6.64	6.22	6.39	–	–	–	–	–	–	–	–	–
		2	7.14	5.84	6.49	2.2	2.0	2.1	1.616	–	1.616	2.2	–	2.2
A71-075-6	LSS_5	0	5.52	2.85	4.26**	1.9	1.7	1.8	–	–	–	–	–	–
		0*	6.71	5.35	6.24	–	–	–	–	–	–	–	–	–
		1	5.71	4.47	5.04	–	–	–	–	–	–	–	–	–
		2	5.26	3.43	4.34	2.0	1.8	1.9	–	–	–	–	–	–
A71-077-6	LSS_4	0	1.13	0.88	1.01	2.1	2.0	2.0	–	–	–	–	–	–
		0*	1.92	1.01	1.38	–	–	–	–	–	–	–	–	–
		1	1.54	1.04	1.26	–	–	–	–	–	–	–	–	–
		2	1.40	0.63	1.01	2.0	1.9	1.9	–	–	–	–	–	–

**Outlier; not included in the soil mechanics evaluation.

(Continued)

Table 2 (Continued)

			Penetration Resistance Gradient G, MN/m^3			Surface Moisture Content w, %			Dry Density γ_d, g/cm^3 (Gravimetric)			Moisture Content w, %		
Test No.	Soil	Pass No.	Max	Min	Avg	Max	Min	Avg	Reading No. 1	Reading No. 2	Avg	Reading No. 1	Reading No. 2	Avg
A71-078-6	LSS_4	0	1.22	0.78	1.05	2.0	1.9	1.9	-	-	-	-	-	-
		0*	2.40	0.59	1.43	-	-	-	-	-	-	-	-	-
		1	1.47	0.74	1.15	-	-	-	-	-	-	-	-	-
		2	1.49	1.07	1.32	1.9	1.8	1.8	-	-	-	-	-	-
A71-079-6	LSS_4	0	1.18	0.96	1.09	1.9	1.8	1.8	-	-	-	-	-	-
		0*	2.34	0.66	1.45	-	-	-	-	-	-	-	-	-
		1	1.45	0.84	1.17	-	-	-	-	-	-	-	-	-
		2	1.63	1.03	1.30	2.1	1.7	1.8	-	-	-	-	-	-
A71-082-6	LSS_4	0	0.95	0.62	0.82	1.8	1.7	1.8	-	-	-	-	-	-
		0*	1.50	0.80	1.12	-	-	-	-	-	-	-	-	-
		1	1.18	0.60	0.93	-	-	-	-	-	-	-	-	-
		2	1.32	0.59	0.91	1.8	1.7	1.8	-	-	-	-	-	-
A71-083-6	LSS_4	0	1.22	0.82	1.01	2.0	1.9	1.9	-	-	-	-	-	-
		0*	1.59	0.91	1.23	-	-	-	-	-	-	-	-	-
		1	1.21	0.67	0.87	-	-	-	-	-	-	-	-	-
		2	1.23	0.46	0.88	1.9	1.8	1.8	-	-	-	-	-	-
A71-087-6	LSS_4	0	1.08	0.82	0.92	1.8	1.7	1.8	-	-	-	-	-	-
		0*	2.21	1.38	1.78	-	-	-	-	-	-	-	-	-
		1	1.22	0.87	1.09	-	-	-	-	-	-	-	-	-
		4	1.53	0.64	1.09	1.7	1.5	1.6	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-088-6	LSS_4	0	1.30	0.97	1.17	1.7	-	1.7	-	-	-	-	-	-
		0*	2.50	1.52	1.89	-	-	-	-	-	-	-	-	-
		1	1.37	1.06	1.18	-	-	-	-	-	-	-	-	-
		4	1.53	0.91	1.21	1.9	1.7	1.8	-	-	-	-	-	-
A71-089-6	LSS_4	0	1.01	0.77	0.92	-	-	-	-	-	-	-	-	-
		0*	1.35	0.87	1.16	-	-	-	-	-	-	-	-	-
		1	1.59	0.66	1.15	-	-	-	-	-	-	-	-	-
		4	-	-	-	-	-	-	-	-	-	-	-	-
A71-090-6	LSS_4	0	1.25	0.85	1.07	2.2	2.0	2.1	-	-	-	-	-	-
		0*	1.76	1.01	1.41	-	-	-	-	-	-	-	-	-
		1	1.29	1.08	1.19	-	-	-	-	-	-	-	-	-
		4	1.21	0.87	1.01	1.9	-	1.9	-	-	-	-	-	-
A71-091-6	LSS_4	0	1.36	0.70	1.03	1.8	1.7	1.8	-	-	-	-	-	-
		0*	2.36	1.75	1.99	-	-	-	-	-	-	-	-	-
		1	1.23	0.99	1.10	-	-	-	-	-	-	-	-	-
		4	1.50	0.72	1.10	1.8	1.7	1.8	-	-	-	-	-	-
A71-092-6	LSS_4	0	1.19	0.54	0.72	2.0	1.7	1.8	-	-	-	-	-	-
		0*	2.33	1.57	1.92	-	-	-	-	-	-	-	-	-
		1	1.38	0.96	1.22	-	-	-	-	-	-	-	-	-
		4	1.43	0.72	1.09	1.7	1.6	1.6	-	-	-	-	-	-
A71-093-6	LSS_4	0	1.38	0.44	1.09	1.9	1.8	1.9	-	-	-	-	-	-
		0*	1.66	0.84	1.25	-	-	-	-	-	-	-	-	-
		1	1.55	1.17	1.39	-	-	-	-	-	-	-	-	-
		4	1.83	1.18	1.54	1.7	1.6	1.7	-	-	-	-	-	-

(Continued)

Table 2 (Continued)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-094-6	LSS_5	0	7.46	5.07	5.95	-	-	-	-	-	-	-	-	-
		0*	8.20	4.18	5.76	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	6.00	5.82	5.91	-	-	-	-	-	-	-	-	-
A71-095-6	LSS_5	0	7.69	5.53	6.94	1.7	1.5	1.6	-	-	-	-	-	-
		0*	8.36	6.46	7.55	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	6.49	4.84	5.46	-	-	-	-	-	-	-	-	-
A71-096-6	LSS_5	0	7.80	5.52	6.30	1.8	1.6	1.7	-	-	-	-	-	-
		0*	8.39	5.39	6.51	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	7.50	6.50	7.00	-	-	-	-	-	-	-	-	-
A71-097-6	LSS_5	0	8.71	5.76	6.53	2.5	2.0	2.2	-	-	-	-	-	-
		0*	8.64	6.25	7.62	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	6.39	5.28	6.08	-	-	-	-	-	-	-	-	-
A71-098-6	LSS_5	0	8.79	6.24	6.95	1.9	1.8	1.9	-	-	-	-	-	-
		0*	8.40	6.31	7.5[illegible]	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	8.11	6.72	7.11	-	-	-	-	-	-	-	-	-
A71-099-6	LSS_5	0	9.10	6.33	6.91	2.1	1.9	2.0	-	-	-	-	-	-
		0*	8.84	6.96	7.66	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	7.56	6.02	6.68	-	-	-	-	-	-	-	-	-

(Continued)

Table 2 (Concluded)

Test No.	Soil	Pass No.	Penetration Resistance Gradient G, MN/m^3 Max	Min	Avg	Surface Moisture Content w, % Max	Min	Avg	Dry Density γ_d, g/cm^3 (Gravimetric) Reading No. 1	Reading No. 2	Avg	Moisture Content w, % Reading No. 1	Reading No. 2	Avg
A71-100-6	LSS_5	0	9.54	5.74	6.59	-	-	-	-	-	-	-	-	-
		0*	7.01	4.12	6.05	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	6.30	5.04	5.63	-	-	-	-	-	-	-	-	-
A71-101-6	LSS_4	0	1.32	0.80	1.06	1.9	1.6	1.8	-	-	-	-	-	-
		0*	2.75	2.05	2.38	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	1.37	0.67	1.00	-	-	-	-	-	-	-	-	-
A71-102-6	LSS_4	0	1.79	0.82	1.31	1.8	1.6	1.7	-	-	-	-	-	-
		0*	2.46	1.71	2.18	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	1.53	0.91	1.27	-	-	-	-	-	-	-	-	-
A71-103-6	LSS_4	0	1.38	0.57	1.09	1.7	1.6	1.7	-	-	-	-	-	-
		0*	2.24	1.23	1.78	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	2.08	1.16	1.73	-	-	-	-	-	-	-	-	-
A71-104-6	LSS_4	0	1.81	0.58	1.24	1.7	1.6	1.7	-	-	-	-	-	-
		0*	2.59	1.42	2.08	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	1.80	1.18	1.49	-	-	-	-	-	-	-	-	-
A71-105-6	LSS_4	0	1.32	0.76	1.03	-	-	-	-	-	-	-	-	-
		0*	1.64	0.99	1.29	-	-	-	-	-	-	-	-	-
		1	-	-	-	-	-	-	-	-	-	-	-	-
		2	1.48	1.00	1.28	-	-	-	-	-	-	-	-	-

(11 of 11 Sheets)

Table 3

Values of Cone Penetration Resistance Gradient
Single-Wheel Tests in Yuma Sand
During-Traffic Data

		Penetration Resistance Gradient G, MN/m^3					
		First Constant-Slip Portion*			Second Constant-Slip Portion*		
Test No.	Pass No.	Reading No. 1	Reading No. 2	Avg	Reading No. 1	Reading No. 2	Avg
A71-005	0	1.29	1.28	1.29	1.24	1.27	1.26
	1	1.22	1.27	1.24	1.29	1.21	1.25
	2	1.26	1.30	1.28	1.32	1.31	1.32
A71-006	0	1.37	1.38	1.38	1.35	1.49	1.42
	1	1.30	1.32	1.31	1.40	-	1.40
	2	1.32	1.40	1.36	1.53	1.43	1.48
A71-007	0	1.05	1.13	1.09	1.17	1.23	1.20
	1	0.82	1.07	0.95	1.48	1.21	1.35
	2	0.67	1.06	0.86	1.24	1.25	1.25
A71-008	0	1.36	1.43	1.40	1.18	1.33	1.26
	1	1.15	1.29	1.22	1.41	1.27	1.34
	2	-	-	-	1.28	1.30	1.29
A71-009	0	1.10	1.13	1.12	1.16	1.27	1.22
	1	0.96	1.03	1.00	1.31	1.23	1.27
	2	1.16	1.22	1.19	1.25	1.24	1.25
A71-010	0	1.03	1.14	1.08	1.25	1.30	1.28
	1	1.11	1.08	1.10	1.23	1.23	1.23
	2	1.08	1.18	1.13	1.19	1.33	1.26
A71-011	0	0.99	1.05	1.02	1.21	1.20	1.21
	1	0.97	1.09	1.03	1.20	1.18	1.19
	2	1.11	1.14	1.12	1.20	1.15	1.18
A71-012	0	1.06	1.08	1.07	1.57	1.12	1.34
	1	1.08	1.12	1.10	1.43	1.24	1.34
	2	1.16	1.18	1.17	1.24	1.15	1.20
A71-013	0	1.21	1.20	1.21	1.72	1.49	1.61
	1	1.23	1.19	1.21	1.52	1.40	1.46
	2	1.19	1.19	1.19	1.38	1.27	1.33
A71-014	0	1.22	1.25	1.24	1.55	1.47	1.51
	1	1.22	1.22	1.22	1.45	1.26	1.36
	2	1.22	1.31	1.26	1.37	1.36	1.37

*See figs. 4b and 4c.

Table 3 (Concluded)

Test No.	Pass No.	Penetration Resistance Gradient G, MN/m³ — First Constant-Slip Portion: Reading No. 1	Reading No. 2	Avg	Second Constant-Slip Portion: Reading No. 1	Reading No. 2	Avg
A71-015	0	1.25	1.24	1.25	1.29	1.31	1.30
	1	1.29	1.20	1.25	1.34	1.23	1.27
	2	1.24	1.27	1.26	1.29	1.31	1.30
A71-016	0	1.26	1.28	1.27	1.25	1.26	1.26
	1	1.13	1.15	1.14	1.19	1.26	1.23
	2	1.19	1.19	1.19	1.30	1.28	1.29
A71-017	0	1.15	1.12	1.14	1.21	1.10	1.16
	1	1.13	1.12	1.13	1.18	1.18	1.18
	2	1.17	1.17	1.17	1.20	1.21	1.21
A71-018	0	1.13	1.18	1.16	1.29	1.17	1.23
	1	1.19	1.11	1.15	1.18	1.23	1.21
	2	1.16	1.22	1.19	1.25	1.19	1.22
A71-019	0	1.04	1.16	1.10	1.21	1.37	1.29
	1	1.15	1.17	1.16	1.30	1.31	1.31
	2	1.16	1.20	1.18	1.36	1.25	1.30
A71-020	0	1.16	1.21	1.19	1.68	1.60	1.64
	1	1.14	1.15	1.15	1.55	1.46	1.51
	2	1.15	1.25	1.20	1.53	1.66	1.60

(2 of 2 Sheets)

Table 4

Wheel Data

Wheel	Load N	Unloaded Width b cm	Unloaded Diameter d, cm	Radius		Section Height		Deflection		Contact Pressure kN/m^2
				Effective r_e^*, cm	Rolling r_r, cm	Unloaded h, cm	Loaded h', cm	h-h' cm	δ** %	
GM XIII	253	-	82.2	38.4	33.9	18.6	13.3	5.3	13.0	-
GM XV	178	23.2	81.5	38.9	35.8	18.6	15.0	3.6	8.8	-
	253	23.2	81.5	38.5	34.5	18.6	14.1	4.5	11.0	5.58
	271	23.2	81.5	38.4	34.3	18.6	13.8	4.8	11.8	-
	289	23.2	81.5	38.2	34.1	18.6	13.5	5.1	12.5	5.71
	377	23.2	81.5	37.9	33.1	18.6	13.0	5.6	13.7	-

* $r_e = \frac{d}{2} - \frac{h-h'}{2}$

** $\delta = \frac{2(h-h')}{d} \times 100$

Table 5

Summary of Performance Parameters for GM XIII Wheel on LSS_4; Wheel Load = 253N

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Towed Point Data			Self-Propelled Point Data			Data for x-Percent Slip									
					P_T/W	Slip %	Sinkage cm	PN_{sp}	Slip %	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A70-026-6 *	CPS	1	0.74	-0.07	0.08	-1.8	-	0.17	2.1	1.3	20.0	0.35	0.46	0.58	1.9	50.0	0.37	0.61	1.21	2.3
-027-6		2	0.75	-0.08	0.05	-1.1	-	0.11	1.7	1.5	20.0	0.37	0.47	0.58	2.0	50.0	0.43	0.59	1.19	2.7
-028-6		Avg	0.75	-0.08	0.07	-1.4	-	0.12	1.9	1.4	20.0	0.36	0.47	0.58	2.0	50.0	0.40	0.60	1.20	2.5
A71-001-6	CPS	1	1.51	-0.18	0.06	-3.0	1.1	0.06	0.5	1.2	20.0	0.35	0.37	0.46	1.7	50.0	0.46	0.53	0.97	3.2
-012-6		1	1.48	-0.22	0.08	-2.5	1.0	0.05	0.5	1.0	20.0	0.36	0.37	0.45	1.6	50.0	0.48	0.53	1.06	2.2
		Avg	1.50	-0.20	0.07	-2.8	1.1	0.05	0.5	1.1	20.0	0.36	0.37	0.46	1.7	50.0	0.47	0.53	1.01	2.7
-001-6**		2	1.52	-0.19	-	-	-	0.02	0.5	1.3	20.0	0.46	0.41	0.51	1.8	50.0	0.53	0.53	1.06	3.2
-012-6**		2	1.50	-0.22	0.04	-2.5	0.8	0.02	0	0.6	20.0	0.41	0.41	0.51	1.5	50.0	0.50	0.53	1.06	2.1
		Avg	1.51	-0.21	0.04	-2.5	0.8	0.02	0.3	1.0	20.0	0.46	0.41	0.51	1.7	50.0	0.52	0.53	1.06	2.7
		Avg	1.51	-0.21	0.06	-2.7	1.0	0.04	0.4	1.0	20.0	0.41	0.39	0.48	1.7	50.0	0.50	0.53	1.04	2.7
A71-002-6	CPS	1	2.07	-0.44	0.12	-3.0	1.2	0.10	2.5	1.4	20.0	0.32	0.37	0.47	1.8	50.0	0.42	0.50	0.97	2.8
-004-6		1	2.10	-0.54	0.16	-3.6	1.3	0.10	3.5	1.3	20.0	0.22	0.37	0.46	1.6	50.0	0.35	0.51	1.04	2.7
		Avg	2.09	-0.49	0.14	-3.3	1.3	0.10	3.0	1.4	20.0	0.27	0.37	0.47	1.7	50.0	0.39	0.51	1.00	2.8
-002-6		2	2.08	-0.44	0.06	-3.0	1.0	0.06	0	1.5	20.0	0.40	0.43	0.56	2.0	50.0	0.47	0.58	1.06	3.2
-004-6		2	2.11	-0.54	0.14	-4.0	1.2	0.17	3.0	1.5	20.0	0.40	0.43	0.53	1.9	50.0	0.44	0.59	1.11	3.0
		Avg	2.10	-0.49	0.10	-3.5	1.1	0.12	1.5	1.5	20.0	0.40	0.43	0.55	2.0	50.0	0.46	0.58	1.09	3.1
		Avg	2.09	-0.49	0.12	-3.4	1.2	0.11	2.3	1.5	20.0	0.34	0.40	0.51	1.9	50.0	0.43	0.55	1.05	3.0
A71-003-6	CPS	1	2.96	-1.14	-	-	-	0.07	0	1.2	20.0	0.33	0.37	0.47	1.9	50.0	0.48	0.54	1.08	2.7

* From A. J. Green and K.-J. Melzer (1971b); values for pass 1 and pass 2 are averages from these three tests.

**Pass 2 probably erroneous.

(Continued)

(1 of 4 Sheets)

Table 5 (Continued)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Towed Point Data P_T/W	Towed Point Data Slip %	Towed Point Data Sinkage cm	Self-Propelled Point Data PN_{sp}	Self-Propelled Point Data Slip %	Self-Propelled Point Data Sinkage cm	Data for x-Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-005-6	RS	1	1.50	+0.19	-	-	-	-	-	-	5.9†	0.06	0.14	0.15	2.0	10.6†	0.22	0.26	0.30	1.5
		2	1.50	+0.18	-	-	-	-	-	-	6.2†	0.03	0.22	0.24	2.1	10.4†	0.18	0.35	0.39	1.7
		Avg	1.50	+0.19	-	-	-	-	-	-	6.1	0.05	0.18	0.20	2.1	10.5	0.20	0.31	0.35	1.6
A71-006-6	RS	1	1.51	+0.20	-	-	-	-	-	-	7.0†	0.02	0.16	0.17	1.9	15.1†	0.21	0.33	0.40	1.7
A71-007-6	RS	1	2.23	+0.19	0.15	-5.0	2.3	-	-	-	-5.8†	-0.15	-0.01	-	1.6	2.1†	-0.06	0.07	0.08	2.1
A71-008-6	RS	1	2.19	+0.21	0.13	-2.0	2.0	-	-	-	-5.5†	-0.16	-0.06	-	1.2	2.6†	-0.08	0.06	0.06	2.1
		2	2.16	+0.21	0.07	-3.5	2.4	0.05	0.5	2.4	-4.3†	-0.07	-0.02	-	1.9	3.0†	0.09	0.13	0.13	2.4
		Avg	2.18	+0.21	0.10	-2.8	2.2	0.05	0.5	2.4	-4.9	-0.12	-0.03	-	1.6	2.8	0.01	0.10	0.10	2.3
A71-009-6	RS	1	3.37	+0.34	0.13	-8.6	1.6	-	-	-	-16.9	-0.28	-0.09	-	2.3	-8.4†	-0.12	0.01	0	1.6
		2	3.30	+0.30	0.15	-10.5	2.0	-	-	-	-15.4	-0.17	-0.06	-	0.8	-5.0†	-0.07	+0.07	0.07	2.0
		Avg	3.34	+0.32	0.14	-9.6	1.8	-	-	-	-16.2	-0.23	-0.08	-	1.6	-6.7	-0.10	+0.03	0.03	1.8
A71-010-6	RS	1	3.37	+0.34	-	-	-	-	-	-	-14.0	-0.30	-0.12	-	2.3	-7.6†	-0.19	-0.01	-	1.8
		2	3.45	+0.36	-	-	-	-	-	-	-14.0	-0.33	-0.17	-	2.0	-9.5†	-0.17	-0.04	-	1.8
		Avg	3.41	+0.35	-	-	-	-	-	-	-14.0	-0.32	-0.14	-	2.2	-8.5	-0.18	-0.03	-	1.8
A71-011-6	RS	1	1.51	+0.27	-	-	-	-	-	-	2.8†	0.05	0.07	0.08	1.5	11.8†	0.18	0.23	0.27	1.9
		2	1.50	+0.30	-	-	-	-	-	-	2.8†	0.11	0.15	0.15	1.5	11.7†	0.28	0.32	0.37	2.0
		Avg	1.51	+0.29	-	-	-	-	-	-	2.8	0.08	0.11	0.12	1.5	11.8	0.24	0.28	0.32	2.0
A71-013-6	MPS	1	0.89	+0.52	0.10	-2.0	0.9	0.12	8.0	1.1	20.0	0.33	0.42	0.51	1.4	50.0	0.40	0.55	0.97	2.5
		2	0.90	+0.52	0.10	-3.5	0.8	0.07	1.0	0.9	20.0	0.41	0.42	0.53	1.7	50.0	0.51	0.60	1.21	3.0
		Avg	0.90	+0.52	0.10	-2.8	0.9	0.10	4.5	1.0	20.0	0.37	0.42	0.52	1.6	50.0	0.46	0.57	1.09	2.8
		1									-19.0†	-0.34	-0.19	-	0.8	69.0†	0.42	0.60	1.91	3.9
		2									-12.0†	-0.27	-0.19	-	1.0	68.0†	0.57	0.66	2.08	4.3
		Avg									-16.0	-0.31	-0.19	-	0.9	69.0	0.50	0.63	2.00	4.1

† From constant-slip portion of the test.

(Continued)

Table 5 (Continued)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Towed Point Data			Self-Propelled Point Data			Data for x-Percent Slip										
					P_T/W	Slip %	Sinkage cm	PN_{sp}	Slip %	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-014-6	HPS	1	1.52	+0.50	0.04	0	1.8	0.04	2.0	1.9	20.0	0.21	0.31	0.41	2.4	-	-	-	-	-
		2	1.52	+0.50	0.12	0	1.9	0.07	4.0	2.0	20.0	0.34	0.39	0.51	2.4	-	-	-	-	-
		Avg	1.52	+0.50	0.08	0	1.9	0.06	3.0	2.0	20.0	0.28	0.35	0.46	2.4	-	-	-	-	-
		1									-18.0†	-0.30	-0.18	-	1.5	42.0	0.30	0.45	0.65	3.0
		2									-10.0†	-0.29	-0.21	-	1.3	40.0	0.40	0.53	0.68	2.9
		Avg									-14.0	-0.30	-0.19	-	1.4	41.0	0.35	0.49	0.67	3.0
A71-015-6	HPS	1	2.15	+0.45	0.12	-6.0	1.2	0.17	2.5	1.4	-24.0	-0.33	-0.14	-	0.9	20.0	0.21	0.33	0.41	2.1
		2	2.13	+0.44	0.04	-8.5	1.3	0.17	1.5	1.5	-10.0	-0.16	-0.06	-	1.2	20.0	0.34	0.43	0.51	2.4
		Avg	2.14	+0.45	0.08	-7.3	1.3	0.17	2.0	1.5	-16.0	-0.25	-0.10	-	1.1	20.0	0.28	0.38	0.46	2.3
A71-016-6	HPS	1	2.88	+0.46	0.11	-6.5	1.2	0.14	2.5	1.4	-20.0	-0.27	-0.12	-	1.[illegible]	+5.0	0.07	0.14	0.15	1.5
		2	3.14	+0.27	0.13	-8.5	1.3	0.14††	1.0	1.5	-20.0	-0.27	-0.11	-	1.2	-1.0	0.03	0.10	0.10	1.4
		Avg	3.01	+0.37	0.12	-7.5	1.3	0.14	1.3	1.5	-20.0	-0.27	-0.12	-	1.2	-	-	-	-	-
A71-017-6	HPS	1	1.51	+0.29	0.08	-4.0	1.2	0.11	3.0	1.3	20.0	0.26	0.33	0.41	1.9	-	-	-	-	-
		2	1.51	+0.28	0.08	-6.0	1.3	0.13	1.5	1.9	20.0	0.32	0.41	0.49	2.6	-	-	-	-	-
		Avg	1.51	+0.29	0.08	-5.0	1.3	0.12	2.3	1.6	20.0	0.30	0.37	0.45	2.3	-	-	-	-	-
		1									-16.0	-0.23	-0.10	-	1.0	35.0	0.30	0.40	0.60	2.6
		2									-12.0	-0.26	-0.13	-	1.7	34.0	0.35	0.47	0.72	3.4
		Avg									-14.0	-0.25	-0.11	-	1.4	35.0	0.33	0.43	0.67	3.0
A71-018-6	HPS	1	1.53	+0.25	-	-	-	-	-	-	20.0	0.34	0.37	0.46	1.5	45.0	0.35	0.46	0.58	2.9
		2	1.53	+0.27	-	-	-	-	-	-	20.0	0.42	0.43	0.53	1.9	45.0	0.43	0.51	0.72	3.3
		Avg	1.53	+0.26	-	-	-	-	-	-	20.0	0.38	0.40	0.50	1.7	45.0	0.39	0.49	0.65	3.1

†† Extrapolated.

(Continued)

Table 5 (Concluded)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Towed Point Data P_T/W	Towed Point Data Slip %	Towed Point Data Sinkage cm	Self-Propelled Point Data PN_{sp}	Self-Propelled Point Data Slip %	Self-Propelled Point Data Sinkage cm	Data for x-Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-019-6	MPS	1	0.92	+0.77	0.08	-3.0	0.9	0.07	1.0	1.0	20.0	0.32	0.35	0.43	1.6	50.0	0.44	0.57	1.09	2.4
		2	0.91	+0.79	0.10	-3.5	1.0	0.10	0.5	1.1	20.0	0.40	0.42	0.51	1.7	50.0	0.45	0.58	1.30	3.2
		Avg	0.92	+0.78	0.09	-3.3	1.0	0.09	0.8	1.1	20.0	0.36	0.38	0.47	1.7	50.0	0.45	0.49	1.20	2.8
		1									-15.0†	-0.25	-0.18	-	0.8	69.0†	0.49	0.62	2.01	4.1
		2									-11.0†	-0.27	-0.17	-	1.1	68.0†	0.53	0.73	2.29	4.7
		Avg									-13.0	-0.26	-0.18	-	1.0	69.0	0.51	0.68	2.15	4.4
A71-020-6	MPS	1	1.51	+0.75	0.05	-2.0	1.0	0.06	1.0	1.1	20.0	0.40	0.40	0.51	1.8	-	-	-	-	-
		2	1.52	+0.78	0.08	-4.0	1.1	0.07	0.5	1.2	20.0	0.42	0.44	0.53	1.9	-	-	-	-	-
		Avg	1.52	+0 [illegible]	0.07	-3.0	1.1	0.07	0.8	1.2	20.0	0.41	0.42	0.52	1.9	-	-	-	-	-
		1									-10.0	-0.25	-0.14	-	0.8	48.0	0.50	0.56	1.04	2.7
		2									-10.0	-0.24	-0.14	-	1.0	50.0	0.46	0.56	1.11	3.1
		Avg									-10.0	-0.25	-0.14	-	0.9	49.0	0.48	0.56	1.08	2.9

Table 6

Summary of Performance Parameters for Tests with GM XIII

Wheel on Sand; Wheel Load = 253 N

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	First Constant-Slip Portion* Slip %	P/W	M/Wr_e	PN	Sinkage cm	Second Constant-Slip Portion* Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-005-6	RS	1	1.50	5.9	0.28	0.28	0.30	0.4	9.8	0.35	0.33	0.37	0.7
		2	1.50	5.6	0.17	0.30	0.32	0.5	9.8	0.26	0.39	0.43	–
		Avg	1.50	5.8	0.23	0.29	0.31	0.5	9.8	0.31	0.36	0.40	0.7
A71-006-6	RS	1	1.51	6.8	0.18	0.25	0.27	0.5	14.7	0.36	0.42	0.49	0.9
A71-007-6	RS	1	2.23	4.3	-0.09	-0.01	–	0.7	1.4	0.09	0.15	0.15	0.9
A71-008-6	RS	1	2.19	-3.2	-0.14	-0.04	–	0.5	–	–	–	–	–
		2	2.16	-2.9	-0.08	-0.05	–	0.7	–	–	–	–	–
		Avg	2.18	-3.1	-0.11	-0.05	–	0.6	–	–	–	–	–
A71-009-6	RS	1	3.37	-16.9	-0.28	-0.17	–	0.5	–	–	–	–	–
		2	3.30	-13.2	-0.29	-0.18	–	0.8	–	–	–	–	–
		Avg	3.34	-15.1	-0.29	-0.18	–	0.7	–	–	–	–	–
A71-010-6	RS	1	3.37	-13.9	-0.29	-0.18	–	0.8	–	–	–	–	–
		2	3.45	-14.7	-0.36	-0.26	–	0.9	–	–	–	–	–
		Avg	3.41	-14.3	-0.33	-0.22	–	0.9	–	–	–	–	–
A71-011-6	RS	1	1.51	2.8	0.13	0.14	0.14	0.5	10.5	0.37	0.38	0.43	0.3
		2	1.50	3.7	0.22	0.23	0.24	0.4	11.2	0.36	0.40	0.45	0.3
		Avg	1.51	3.3	0.18	0.19	0.19	0.5	10.9	0.37	0.39	0.44	0.3
A71-013-6	MPS	1	0.89	-11.5	-0.32	-0.20	–	0.5	68.5	0.55	0.67	2.13	2.3
		2	0.90	-8.9	-0.27	-0.19	–	–	67.3	0.73	0.83	2.60	2.3
		Avg	0.90	-10.2	-0.30	-0.20	–	0.5	67.9	0.64	0.75	2.37	2.3
A71-014-6	MPS	1	1.52	-9.4	-0.30	-0.22	–	0.5	49.0	0.57	0.62	1.23	1.5
		2	1.52	-8.4	-0.29	-0.22	–	0.2	49.3	0.56	0.63	1.25	1.9
		Avg	1.52	-8.9	-0.30	-0.22	–	0.4	49.2	0.57	0.63	1.24	1.7

*See figs. 4b and 4c.

(1 of 2 Sheets)

(Continued)

Table 6 (Concluded)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	First Constant-Slip Portion Slip %	P/W	M/Wr_e	PN	Sinkage cm	Second Constant-Slip Portion Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-015-6	MPS	1	2.15	-14.5	-0.35	-0.23	-	0.3	-	-	-	-	-
A71-017-6	MPS	1	1.51	-	-	-	-	-	46.1	0.55	0.62	1.14	1.4
		2	1.51	-	-	-	-	-	45.0	0.56	0.62	1.13	2.1
		Avg	1.51	-	-	-	-	-	45.6	0.56	0.62	1.14	1.8
A71-018-6	MPS	1	1.53	-	-	-	-	-	45.9	0.57	0.61	1.13	1.21
A71-019-6	MPS	1	0.92	-9.8	-0.23	-0.19	-	1.0	69.0	0.66	0.71	2.23	2.7
		2	0.91	-8.4	-0.24	-0.18	-	0.6	67.3	0.77	0.88	2.69	3.2
		Avg	0.92	-9.1	-0.24	-0.19	-	0.8	68.2	0.72	0.80	2.46	3.0

Table 7

Summary of Performance Parameters for Tests with the GM XV Wheel on LSS_4

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	Towed Point Data P_T/W	Towed Point Data Slip %	Towed Point Data Sinkage cm	Self-Propelled Point Data PN_{sp}	Self-Propelled Point Data Slip %	Self-Propelled Point Data Sinkage cm	Data for 20 and 50 Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-055-6	CPS	1	0.44	-0.03	253	0.08	-4.5	1.7	0.07	0.5	1.9	20	0.31	0.35	0.44	2.1	50	0.44	0.49	0.98	2.8
		2	0.45	-0.03	253	0.08	-4.0	1.6	0.06	0.5	1.7	20	0.40	0.43	0.54	2.1	50	0.45	0.51	1.02	2.6
		Avg	0.45	-0.03	253	0.08	-4.3	1.7	0.07	0.5	1.8	20	0.36	0.39	0.49	2.1	50	0.45	0.50	1.00	2.7
A71-049-6	CPS	1	0.70	-0.11	253	0.16	0	1.6	0.14	6.5	1.5	20	0.27	0.34	0.41	2.0	50	0.35	0.44	0.90	3.3
A71-079-6	CPS	1	0.71	-0.08	253	0.12	-4.0	1.4	0.09	3.5	1.4	20	0.30	0.41	0.51	2.0	-	-	-	-	-
		Avg	0.71	-0.10	253	0.14	-2.0	1.5	0.12	5.0	1.5	20	0.29	0.38	0.46	2.0	50	0.35	0.44	0.90	3.3
A71-049-6	CPS	2	0.75	-0.10	253	-	-	-	0.07	7.5	2.0	20	0.42	0.44	0.55	2.2	50	0.45	0.49	0.98	2.7
A71-079-6		2	0.68	-0.08	253	0.05	-1.0	1.5	0.04	0	1.5	20	0.39	0.44	0.55	2.4	50	0.47	0.51	1.02	2.8
		Avg	0.72	-0.09	253	0.05	-1.0	1.5	0.06	3.8	1.8	20	0.41	0.44	0.55	2.3	50	0.46	0.50	1.00	2.8
		Avg	0.71	-0.09	253	0.11	-1.7	1.5	0.09	4.4	1.6	20	0.35	0.41	0.51	2.2	50	0.42	0.45	0.97	2.9
A71-050-6	CPS	1	0.80	-0.11	253	0.10	-1.5	1.4	0.20	1.5	1.5	20	0.32	0.40	0.50	2.0	50	0.26	0.51	1.02	2.5
		2	0.80	-0.09	253	0.11	-4.0	1.5	0.19	0	1.7	20	0.42	0.45	0.56	2.0	50	0.49	0.52	1.04	2.4
		Avg	0.80	-0.10	253	0.11	-2.8	1.5	0.20	0.8	1.6	20	0.37	0.43	0.53	2.0	50	0.38	0.52	1.03	2.5
A71-051-6	CPS	1	1.20	-0.27	253	0.15	-10.0	1.4	0.08	0	1.5	20	0.34	0.38	0.48	1.8	50	0.44	0.50	1.00	2.4
		2	1.24	-0.28	253	0.13	-5.5	1.6	0.11	1.0	1.4	20	0.38	0.43	0.54	1.9	50	0.45	0.51	1.02	2.4
		Avg	1.22	-0.28	253	0.14	-7.8	1.5	0.10	0.5	1.5	20	0.36	0.41	0.51	1.9	50	0.45	0.51	1.01	2.4
A71-052-6	CPS	1	2.24	-0.62	253	0.12	-10.0	2.1	0.14	0	1.6	20	0.31	0.38	0.48	1.9	50	0.45	0.47	0.94	2.4
		2	2.35	-0.79	253	0.09	-5.0	1.8	0.16	2.0	1.4	20	0.34	0.36	0.45	2.0	50	0.48	0.50	1.00	2.7
		Avg	2.30	-0.71	253	0.11	-7.5	2.0	0.15	1.0	1.5	20	0.33	0.37	0.47	2.0	50	0.47	0.49	0.97	2.6
A71-053-6	CPS	1	3.11	-1.51	253	0.07	-6.0	0.7	0.06	0	1.0	20	0.31	0.34	0.43	1.8	50	0.35	0.46	0.92	2.7
		2	3.12	-1.40	253	0.10	-4.0	0.8	0.06	1.0	1.5	20	0.35	0.36	0.45	2.1	50	0.38	0.52	1.04	2.9
		Avg	3.12	-1.46	253	0.09	-5.0	0.8	0.06	0.5	1.3	20	0.33	0.35	0.44	2.0	50	0.37	0.51	0.98	2.8
A71-082-6	CPS*	1	1.38	-0.26	178	0.19	-1.0	0.9	0.18	12.0	1.3	20	0.30	0.35	0.44	1.8	50	0.37	0.49	0.98	2.5
A71-102-6		1	1.40	-0.26	178	0.12	-1.0	0.8	0.10	4.0	0.7	20	0.34	0.39	0.49	1.1	50	0.58	0.64	1.28	1.6
		Avg	1.39	-0.26	178	0.16	-1.0	0.9	0.14	8.0	1.0	20	0.32	0.37	0.47	1.5	50	0.48	0.57	1.13	2.1
A71-082-6		2	1.38	-0.27	178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A71-102-6		2	1.41	-0.25	178	0.06	-1.0	1.0	0.09	2.0	1.0	20	0.36	0.40	0.50	1.3	50	0.49	0.52	1.04	2.1
		Avg	1.40	-0.26	178	0.06	-1.0	1.0	0.09	2.0	1.0	20	0.36	0.40	0.50	1.3	50	0.49	0.52	1.04	2.1
		Avg	1.39	-0.26	178	0.12	-1.0	1.0	0.12	6.0	1.0	20	0.33	0.38	0.48	1.4	50	0.48	0.55	1.10	2.1

*Tests with fender.

(Continued)

Table 7 (Continued)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	Towed Point Data: P_T/W	Towed Point Data: Slip %	Towed Point Data: Sinkage cm	Self-Propelled Point Data: PN_{sp}	Self-Propelled Point Data: Slip %	Self-Propelled Point Data: Sinkage cm	Data for 20 and 50 Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-101-6	CPS*	1	2.28	-0.65	178	-	-	-	0.08	4.0	0.6	20	0.34	0.36	0.45	1.3	50	0.54	0.59	1.18	1.2
A71-083-6	CPS*	1	2.23	-0.94	178	-	-	-	-	-	-	20	0.30	0.34	0.43	1.2	50	0.32	0.45	0.90	1.6
		Avg	2.26	-0.80	178	-	-	-	0.08	4.0	0.6	20	0.32	0.35	0.44	1.3	50	0.43	0.52	1.04	1.4
A71-101-6		2	2.27	-0.72	178	0.12	0	0.5	0.13	5.0	1.3	20	0.40	0.41	0.51	1.3	50	0.52	0.60	1.20	1.7
A71-083-6		2	2.23	-0.76	178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	2.25	-0.74	178	0.12	0	0.5	0.13	5.0	1.3	20	0.40	0.41	0.51	1.3	50	0.52	0.60	1.20	1.7
		Avg	2.25	-0.77	178	0.12	0	0.5	0.11	4.5	1.0	20	0.35	0.37	0.46	1.3	50	0.46	0.55	1.09	1.5
A71-056-6	CPS*	1	0.71	-0.08	253	0.10	-4.0	1.5	0.07	2.5	1.6	20	0.33	0.37	0.47	2.1	50	0.44	0.49	0.98	2.7
		2	0.72	-0.08	253	0.07	-2.5	1.3	0.06	3.0	1.3	20	0.40	0.42	0.53	1.8	50	0.45	0.49	0.98	2.3
		Avg	0.72	-0.08	253	0.09	-3.3	1.4	0.07	2.8	1.5	20	0.37	0.40	0.50	2.0	50	0.45	0.49	0.98	2.5
A71-057-6	CPS*	1	0.91	-0.11	253	0.08	-2.0	1.2	0.06	2.0	1.4	20	0.40	0.42	0.53	1.7	50	0.50	0.53	1.06	2.0
		2	0.91	-0.10	253	0.06	-2.0	1.1	0.08	2.0	1.5	20	0.43	0.45	0.56	1.6	50	0.50	0.53	1.06	2.1
		Avg	0.91	-0.11	253	0.07	-2.0	1.2	0.07	2.0	1.5	20	0.42	0.44	0.55	1.7	50	0.50	0.53	1.06	2.1
A71-058-6	CPS*	1	1.41	-0.21	253	0.10	-2.0	1.8	0.11	4.0	1.3	20	0.32	0.35	0.44	1.6	50	0.44	0.49	0.98	2.3
		2	1.41	-0.31	253	0.06	-2.0	1.9	0.05	3.0	1.6	20	0.39	0.43	0.54	1.8	50	0.47	0.51	1.02	2.5
		Avg	1.41	-0.36	253	0.08	-2.0	1.9	0.08	3.5	1.5	20	0.36	0.39	0.49	1.7	50	0.46	0.50	1.00	2.4
A71-059-6	CPS*	1	2.26	-0.71	253	0.08	-1.0	1.5	0.12	4.0	1.4	20	0.34	0.36	0.45	1.5	50	0.43	0.52	1.04	2.4
		2	2.25	-0.74	253	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	2.26	-0.73	253	0.08	-1.0	1.5	0.12	4.0	1.4	20	0.34	0.36	0.45	1.5	50	0.43	0.52	1.04	2.4
A71-054-6	CPS*	1	2.93	-1.47	253	0.07	-8.0	0.8	0.09	0	1.4	20	0.20	0.27	0.34	2.1	50	0.29	0.46	0.92	3.0
		2	3.02	-1.60	253	0.11	-6.0	1.0	0.06	0	1.4	20	0.27	0.32	0.40	2.5	50	0.39	0.46	0.92	3.1
		Avg	2.98	-1.54	253	0.09	-7.0	0.9	0.08	0	1.4	20	0.24	0.30	0.37	2.3	50	0.34	0.46	0.92	3.1
A71-105-6	CPS*	1	0.72	-0.07	289	0.11	2.5	0.9	0.11	3.0	0.9	20	0.37	0.41	0.51	1.2	50	0.51	0.53	1.06	1.6
		2	0.72	-0.08	289	0.08	2.5	0.7	0.09	1.0	1.0	20	0.45	0.48	0.60	1.4	50	0.54	0.57	1.14	2.0
		Avg	0.72	-0.08	289	0.10	2.5	0.8	0.10	2.0	1.0	20	0.41	0.45	0.55	1.3	50	0.53	0.55	1.10	1.8
A71-103-6	CPS*	1	1.38	-0.24	377	0.10	-2.5	1.9	0.12	3.0	2.0	20	0.31	0.39	0.49	2.4	50	0.46	0.50	1.00	3.2
A71-078-6	CPS*	1	1.35	-0.27	377	0.16	-3.0	1.9	0.15	6.0	1.9	20	0.37	0.42	0.52	2.5	50	0.50	0.56	1.12	3.3
		Avg	1.37	-0.26	377	0.13	-2.8	1.9	0.14	4.5	2.0	20	0.34	0.41	0.51	2.5	50	0.48	0.53	1.06	3.3
A71-103-6		2	1.38	-0.26	377	0.10	-1.5	2.1	0.09	2.5	2.0	20	0.40	0.42	0.53	2.7	50	0.44	0.46	0.92	3.7
A71-078-6		2	1.33	-0.27	377	0.10	-1.0	2.1	0.15	3.0	2.1	20	-	0.42	0.53	2.7	50	0.48	0.54	1.08	3.5
		Avg	1.36	-0.27	377	0.10	-1.3	2.1	0.12	2.8	2.1	20	0.40	0.42	0.53	2.7	50	0.46	0.50	1.00	3.6
		Avg	1.36	-0.26	377	0.12	-2.0	2.0	0.13	3.6	2.0	20	0.36	0.42	0.52	2.6	50	0.47	0.52	1.03	3.5

(2 of 4 Sheets)

(Continued)

Table 7 (Continued)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	Towed Point Data P_T/W	Towed Point Data Slip %	Towed Point Data Sinkage cm	Self Propelled Point Data PN_{sp}	Self Propelled Point Data Slip %	Self Propelled Point Data Sinkage cm	Data for 20 and 50 Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-077-6	CPS*	1	2.21	-0.94	377	0.14	-2.0	1.9	0.17	5.0	1.9	20	0.31	0.39	0.49	2.1	50	0.39	0.57	1.14	3.2
A71-104-6	CPS*	1	2.14	-0.64	377	-	-	-	0.08	5.0	2.6	20	0.28	0.37	0.46	3.0	50	0.36	0.42	0.84	3.6
		Avg	2.18	-0.79	377	0.14	-2.0	1.9	0.13	5.0	2.3	20	0.30	0.38	0.48	2.6	50	0.38	0.50	0.99	3.4
A71-077-6		2	2.20	-0.90	377	0.15	0	1.7	0.10	3.5	1.5	20	0.33	0.37	0.46	2.4	50	0.52	0.57	1.14	3.5
A71-104-6		2	2.11	-0.65	377	0.10	-2.5	2.5	0.06	1.5	3.0	20	0.37	0.38	0.48	3.4	50	0.43	0.45	0.90	4.0
		Avg	2.16	-0.78	377	0.13	-1.3	2.1	0.08	2.5	2.3	20	0.35	0.38	0.47	2.9	50	0.48	0.51	1.02	3.8
		Avg	2.17	-0.78	377	0.13	-1.5	2.0	0.10	3.8	2.3	20	0.32	0.38	0.47	2.7	50	0.43	0.50	1.01	3.6
A71-088-6	CPS**	1	0.75	-0.08	178	0.13	0	1.0	0.08	5.0	1.1	20	0.29	0.43	0.54	1.3	50	0.51	0.56	1.12	1.8
A71-091-6	CPS**	1	0.73	-0.09	178	0.13	0	0.8	0.11	4.0	1.0	20	0.35	0.41	0.51	1.7	50	0.49	0.50	1.00	2.0
		Avg	0.74	-0.09	178	0.13	0	0.9	0.10	4.5	1.1	20	0.32	0.42	0.53	1.5	50	0.50	0.53	1.06	1.9
A71-088-6		2	0.74	-0.10	178	0.16	0	0.9	0.19	6.0	1.1	20	0.41	0.47	0.59	1.4	50	-	0.54	1.08	2.0
A71-091-6		2	0.74	-0.11	178	0.08	0	1.2	0.06	2.0	1.3	20	0.45	0.47	0.59	1.6	50	0.49	0.54	1.08	2.2
		Avg	0.74	-0.11	178	0.12	0	1.1	0.13	4.0	1.2	20	0.43	0.47	0.59	1.5	50	0.49	0.54	1.08	2.1
		Avg	0.74	-0.10	178	0.13	0	1.0	0.11	4.3	1.1	20	0.38	0.45	0.56	1.5	50	0.50	0.54	1.07	2.0
A71-088-6		3	0.75	-0.08	178	0.12	-1.0	1.2	0.08	3.0	1.4	20	0.42	0.43	0.54	1.6	50	0.52	0.55	1.10	2.1
A71-091-6		3	0.74	-0.06	178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	0.75	-0.07	178	0.12	-1.0	1.2	0.08	3.0	1.4	20	0.42	0.43	0.54	1.6	50	0.52	0.55	1.10	2.1
A71-088-6		4	0.74	-0.08	178	0.08	0	1.3	0.06	2.0	1.4	20	0.37	0.48	0.60	1.6	50	0.46	0.58	1.16	2.2
A71-091-6		4	0.73	-0.19	178	0.07	-1.0	1.5	0.08	1.0	1.7	20	0.43	0.47	0.59	1.9	50	0.51	0.54	1.08	2.1
		Avg	0.74	-0.14	178	0.08	-0.5	1.4	0.07	1.5	1.6	20	0.40	0.48	0.60	1.8	50	0.49	0.56	1.12	2.2
		Avg	0.74	-0.10	178	0.09	-0.7	1.3	0.07	2.0	1.5	20	0.41	0.46	0.58	1.7	50	0.50	0.56	1.11	2.1
A71-087-6	CPS**	1	0.73	-0.09	253	0.11	-1.5	1.5	0.16	4.0	1.6	20	0.40	0.43	0.54	1.8	50	0.52	0.55	1.10	2.5
A71-090-6	CPS**	1	0.73	-0.09	253	0.11	0	1.4	0.12	4.0	1.7	20	0.31	0.41	0.51	1.9	50	0.49	0.53	1.06	2.7
A71-092-6	CPS**	1	0.72	-0.09	253	0.10	-1.0	1.0	0.09	4.0	1.1	20	0.37	0.41	0.51	1.5	50	0.54	0.57	1.14	1.8
		Avg	0.73	-0.09	253	0.11	-0.8	1.3	0.12	4.0	1.5	20	0.36	0.42	0.52	1.7	50	0.52	0.55	1.10	2.3
A71-087-6		2	0.73	-0.08	253	0.13	-1.5	1.3	0.08	1.5	1.4	20	0.34	0.47	0.59	1.6	50	0.41	0.50	1.00	2.4
A71-090-6		2	0.71	-0.10	253	0.15	0	1.6	0.11	4.5	1.8	20	0.44	0.46	0.58	2.3	50	-	0.48	0.96	2.4
A71-092-6		2	0.70	-0.08	253	0.10	0	1.6	0.08	2.0	1.5	20	-	0.43	0.54	1.4	50	0.54	0.58	1.16	2.2
		Avg	0.71	-0.09	253	0.13	-0.5	1.5	0.09	2.7	1.6	20	0.39	0.45	0.57	1.9	50	0.45	0.52	1.04	2.3
		Avg	0.72	-0.09	253	0.12	-0.7	1.4	0.11	3.4	1.6	20	0.38	0.44	0.55	1.8	50	0.49	0.54	1.07	2.3

**Tests with fender and reversed chevron.

(Continued)

Table 7 (Concluded)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	Towed Point Data P_T/W	Towed Point Data Slip %	Towed Point Data Sinkage cm	Self-Propelled Point Data PN_{sp}	Self-Propelled Point Data Slip %	Self-Propelled Point Data Sinkage cm	Data for 20 and 50 Percent Slip: Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-087-6		3	0.74	-0.07	253	0.13	0	1.7	0.17	4.0	1.7	20	0.46	0.52	0.65	1.9	50	0.57	0.60	1.20	2.7
A71-090-6		3	0.71	-0.07	253	0.10	0	1.9	0.11	3.0	2.0	20	0.30	0.48	0.60	2.0	50	0.47	0.52	1.04	2.6
A71-092-6		3	0.70	-0.09	253	0.08	0	1.3	0.05	2.0	1.5	20	0.40	0.42	0.53	1.6	50	0.50	0.54	1.08	2.5
		Avg	0.72	-0.08	253	0.10	0	1.6	0.11	3.0	1.7	20	0.39	0.47	0.59	1.8	50	0.51	0.55	1.11	2.6
A71-087-6		4	0.73	-0.08	253	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A71-090-6		4	0.72	-0.08	253	-	-	-	0.07	2.5	2.0	20	0.47	0.48	0.60	2.3	50	0.54	0.58	1.16	2.8
A71-092-6		4	0.72	-0.10	253	0.08	0	1.5	0.08	2.0	1.7	20	0.46	0.48	0.60	2.2	50	0.55	0.58	1.16	2.8
		Avg	0.72	-0.09	253	0.08	0	1.5	0.08	2.3	1.9	20	0.47	0.48	0.60	2.3	50	0.55	0.58	1.16	2.8
		Avg	0.72	-0.09	253	0.09	0	1.6	0.10	2.7	1.8	20	0.43	0.48	0.60	2.1	50	0.53	0.57	1.14	2.7
A71-089-6	CPS**	1	0.76	-0.08	377	0.07	0.5	1.9	0.06	3.0	2.3	20	0.39	0.41	0.51	2.4	50	0.51	0.52	1.04	3.4
A71-093-6	CPS**	1	0.73	-0.08	377	0.11	0	2.3	0.10	4.5	2.5	20	0.34	0.36	0.40	3.0	50	0.50	0.53	1.06	3.8
		Avg	0.75	-0.08	377	0.09	0.3	2.1	0.08	3.8	2.4	20	0.37	0.39	0.46	2.7	50	0.51	0.53	1.05	3.6
A71-089-6		2	-	-	377	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A71-093-6		2	0.71	-0.09	377	0.11	0	2.6	0.08	4.0	2.6	20	0.45	0.47	0.59	3.1	50	0.46	0.48	0.96	3.4
		Avg	0.71	-0.09	377	0.11	0	2.6	0.08	4.0	2.6	20	0.45	0.47	0.59	3.1	50	0.46	0.48	0.96	3.4
		Avg	0.73	-0.08	377	0.10	0.2	2.3	0.08	3.9	2.5	20	0.39	0.41	0.50	2.8	50	0.49	0.51	1.02	3.5
A71-089-6		3	0.77	-0.09	377	-	-	-	0.05	1.0	3.0	20	0.45	0.48	0.60	3.2	50	0.52	0.59	1.18	3.8
A71-093-6		3	0.74	-0.08	377	-	-	-	0.08	5.5	3.1	20	0.48	0.48	0.60	3.2	50	0.52	0.53	1.06	4.0
		Avg	0.76	-0.09	377	-	-	-	0.07	3.3	3.1	20	0.47	0.48	0.60	3.2	50	0.52	0.56	1.12	3.9
A71-089-6		4	-	-	377	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A71-093-6		4	0.71	-0.09	377	0.05	-0.5	2.9	0.04	0.5	2.8	20	0.49	0.50	0.63	2.8	50	0.54	0.55	1.10	3.9
		Avg	0.71	-0.09	377	0.05	-0.5	2.9	0.04	0.5	2.8	20	0.49	0.50	0.63	2.8	50	0.54	0.55	1.10	3.9
		Avg	0.74	-0.09	377	0.05	-0.5	2.9	0.06	2.3	3.0	20	0.47	0.49	0.61	3.1	50	0.53	0.56	1.10	3.9

(4 of 4 Sheets)

Table 8

Summary of Performance Parameters for Tests With the GM XV Wheel on LSS_5

						Towed Point Data			Self-Propelled Point Data			Data for 20 and 50 Percent Slip									
Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	P_T/W	Slip %	Sinkage cm	PN_{sp}	Slip %	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-068-6	CPS	1	0.75	-0.10	289	0.15	-1.5	0.7	0.15	3.0	0.7	20	0.40	0.52	0.65	1.1	50	0.46	0.56	1.12	1.3
		2	0.75	-0.08	289	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	0.75	-0.09	289	0.15	-1.5	0.7	0.15	3.0	0.7	20	0.40	0.52	0.65	1.1	50	0.46	0.56	1.12	1.3
A71-072-6	CPS*	1	1.41	-0.27	178	0.09	-1.5	0.5	0.15	2.5	0.2	20	0.47	0.49	0.61	0.7	50	0.55	0.62	1.24	1.1
		2	1.40	-0.25	178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	1.41	-0.26	178	0.09	-1.5	0.5	0.15	2.5	0.2	20	0.47	0.49	0.61	0.7	50	0.55	0.62	1.24	1.1
A71-100-6	CPS*	1	2.25	-0.65	178	0.06	0	0.5	0.07	2.0	0.5	20	0.44	0.50	0.63	0.7	50	0.52	0.57	1.14	0.8
		2	2.26	-0.70	178	0.05	-0.5	0.5	0.05	1.0	0.5	20	0.42	0.44	0.55	0.6	50	0.51	0.60	1.20	1.0
		Avg	2.26	-0.68	178	0.06	-0.3	0.5	0.06	1.5	0.5	20	0.43	0.47	0.59	0.7	50	0.52	0.59	1.17	0.9
A71-060-6	CPS*	1	0.77	-0.07	271	0.10	0	0.7	0.07	5.0	0.8	20	0.44	0.47	0.59	0.9	50	0.49	0.52	1.04	1.8
		2	0.79	-0.14	271	0.15	0	0.9	0.04	2.5	0.9	20	0.45	0.50	0.63	1.2	50	0.47	0.52	1.04	2.1
		Avg	0.78	-0.10	271	0.13	0	0.8	0.06	3.8	0.9	20	0.45	0.49	0.61	1.1	50	0.48	0.52	1.04	2.0
A71-064-6	CPS*	1	0.82	-0.10	289	0.08	0	0.8	0.07	1.5	0.7	20	0.44	0.47	0.59	1.1	50	0.48	0.55	1.10	1.5
-096-6	CPS*	1	0.73	-0.09	289	0.05	0	0.1	0.05	1.5	0.2	20	0.49	0.52	0.65	0.5	50	0.56	0.57	1.14	1.0
		Avg	0.78	-0.10	289	0.07	0	0.5	0.06	1.5	0.5	20	0.47	0.50	0.62	0.8	50	0.52	0.56	1.12	1.3
-064-6		2	0.85	-0.11	289	0.09	0	1.0	0.08	5.5	1.1	20	0.40	0.45	0.56	1.4	50	0.48	0.55	1.10	2.0
-096-6		2	0.73	-0.05	289	0.06	-1.5	0.1	0.06	0.5	0.2	20	0.52	0.54	0.68	0.7	50	0.56	0.61	1.22	1.4
		Avg	0.79	-0.08	289	0.08	-0.8	0.6	0.07	3.0	0.7	20	0.44	0.50	0.62	1.1	50	0.52	0.58	1.16	1.7
		Avg	0.78	-0.09	289	0.07	-0.4	0.5	0.07	2.3	0.6	20	0.46	0.50	0.62	0.9	50	0.52	0.57	1.14	1.5

*Tests with fender.

(Continued)

Table 8 (Continued)

						Towed Point Data			Self-Propelled Point Data			Data for 20 and 50 Percent Slip									
Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	P_T/W	Slip %	Sinkage cm	PN_{sp}	Slip %	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-061-6	CPS*	1	1.42	-0.22	289	-	-	-	-	-	-	20	0.42	0.49	0.61	0.8	50	0.51	0.55	1.10	1.5
-065-6	CPS*	1	1.45	-0.25	289	0.13	0	0.9	0.15	5.0	0.5	20	0.43	0.50	0.63	1.1	50	0.52	0.57	1.14	1.5
-069-6	CPS*	1	1.41	-0.26	289	0.17	0	1.0	0.11	3.5	0.9	20	0.39	0.49	0.61	1.4	50	0.46	0.52	1.04	2.0
-098-6	CPS*	1	1.38	-0.23	289	0.03	-0.5	0.6	0.04	0.5	0.5	20	0.46	0.50	0.63	1.1	50	0.57	0.63	1.26	1.5
		Avg	1.42	-0.24	289	0.11	-0.2	0.8	0.10	3.0	0.6	20	0.43	0.50	0.62	1.1	50	0.52	0.57	1.14	1.6
-061-6		2	1.47	-0.18	289	-	-	-	-	-	-	20	0.37	0.42	0.53	1.1	50	0.47	0.55	1.10	2.1
-065-6		2	1.45	-0.25	289	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-069-6		2	1.44	-0.26	289	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-098-6		2	1.37	-0.26	289	0.07	-1.0	0.7	0.06	0.5	0.7	20	0.48	0.53	0.66	1.3	50	0.54	0.60	1.20	1.8
		Avg	1.43	-0.24	289	0.07	-1.0	0.7	0.06	0.5	0.7	20	0.43	0.48	0.60	1.2	50	0.51	0.58	1.15	2.0
		Avg	1.42	-0.24	289	0.10	-0.4	0.8	0.09	2.4	0.7	20	0.43	0.49	0.61	1.1	50	0.51	0.57	1.14	1.7
A71-097-6	CPS*	1	2.30	-0.70	289	0.03	-0.5	0.4	0.03	1.0	1.0	20	0.45	0.49	0.61	1.4	50	0.59	0.61	1.22	1.8
-099-6	CPS*	1	2.19	-0.59	289	0.09	0	0.3	0.09	4.5	0.3	20	0.39	0.40	0.50	0.8	50	-	-	-	-
		Avg	2.24	-0.65	289	0.06	-0.3	0.4	0.06	2.8	0.7	20	0.42	0.45	0.56	1.1	50	0.59	0.61	1.22	1.8
-097-6		2	2.32	-0.69	289	0.07	0	0.8	0.05	1.5	0.9	20	0.46	0.47	0.59	1.5	50	0.55	0.56	1.12	2.0
-099-6		2	2.19	-0.65	289	0.07	0	0.5	0.07	2.5	0.4	20	0.43	0.47	0.59	1.0	50	0.57	0.63	1.26	1.7
		Avg	2.26	-0.67	289	0.07	0	0.7	0.06	2.0	0.7	20	0.45	0.47	0.59	1.3	50	0.56	0.60	1.19	1.9
		Avg	2.25	-0.66	289	0.07	-0.1	0.5	0.06	2.4	0.7	20	0.43	0.46	0.57	1.2	50	0.57	0.60	1.17	1.8
A71-063-6	CPS*	1	2.98	-1.85	289	0.16	-7.0	1.4	0.21	1.5	1.1	20	0.39	0.44	0.55	1.4	50	0.42	0.49	0.98	2.4
-094-6	CPS*	1	2.90	-1.12	289	0.08	0	0.8	0.07	1.5	0.5	20	0.45	0.51	0.64	1.0	50	0.47	0.54	1.08	2.3
		Avg	2.94	-1.49	289	0.12	-3.5	1.1	0.14	1.5	0.8	20	0.42	0.48	0.60	1.2	50	0.45	0.52	1.03	2.4
-063-6		2	2.97	-1.91	289	0.12	-5.0	1.0	0.13	0	0.8	20	0.35	0.47	0.59	1.5	50	0.46	0.59	1.18	2.1
-094-6		2	2.81	-1.11	289	0.06	-2.5	1.0	0.07	0.5	1.4	20	0.46	0.47	0.59	2.3	50	0.56	0.57	1.14	2.3
		Avg	2.89	-1.51	289	0.09	-3.8	1.0	0.10	0.3	1.1	20	0.41	0.47	0.59	1.9	50	0.51	0.58	1.16	2.2
		Avg	2.92	-1.50	289	0.11	-3.6	1.1	0.12	0.9	1.0	20	0.41	0.48	0.59	1.6	50	0.48	0.55	1.10	2.3

(Continued)

Table 8 (Concluded)

Test No.	Type of Test	Pass No.	v_w or v_a (Constant) m/sec	Acceleration m/sec^2	Load N	Towed Point Data			Self-Propelled Point Data			Data for 20 and 50 Percent Slip									
						P_T/W	Slip %	Sinkage cm	PN_{sp}	Slip %	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm	Slip %	P/W	M/Wr_e	PN	Sinkage cm
A71-075-6	CPS*	1	1.45	-0.26	377	0.13	0	1.4	0.12	4.5	1.7	20	0.40	0.44	0.55	1.6	50	0.51	0.57	1.14	1.9
		2	-	-	377	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Avg	1.45	-0.26	377	0.13	0	1.4	0.12	4.5	1.7	20	0.40	0.44	0.55	1.6	50	0.51	0.57	1.14	1.9
A71-095-6	CPS*	1	2.08	-0.65	377	0.11	-2.5	0.8	0.10	1.0	0.7	20	0.39	0.45	0.56	1.4	50	0.47	0.53	1.06	1.7
		2	2.09	-0.65	377	0.05	-1.0	0.5	0.03	0	0.5	20	0.50	0.52	0.65	1.3	50	0.59	0.60	1.20	2.1
		Avg	2.09	-0.65	377	0.08	-1.8	0.7	0.07	0.5	0.6	20	0.45	0.49	0.61	1.4	50	0.53	0.57	1.13	1.9

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U. S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

PERFORMANCE OF THE BOEING LRV WHEELS IN A LUNAR SOIL SIMULANT; Report 2, EFFECTS OF SPEED, WHEEL LOAD, AND SOIL

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

Report 2 of a series

5. AUTHOR(S) *(First name, middle initial, last name)*

Klaus-Jurgen Melzer

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1971	89	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report M-71-10
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	George C. Marshall Space Flight Center National Aeronautics and Space Administration, Huntsville, Alabama

13. ABSTRACT

Two nearly identical Boeing-GM wire-mesh Lunar Roving Vehicle (LRV) wheels were laboratory tested in a lunar soil simulant to determine the influence of wheel speed and acceleration, wheel load, presence of a fender, travel direction, and soil strength on the wheel performance. Constant-slip and three types of programmed-slip tests were conducted with the U. S. Army Engineer Waterways Experiment Station single-wheel dynamometer system. Test results indicated that performance of single LRV wheels in terms of pull coefficient, power number, and efficiency were not influenced by wheel speed and acceleration, travel direction, the presence of a fender, or wheel load. Of these variables, only load influenced sinkage, which increased with increasing load. For a given slip, the pull coefficient and power number increased with increasing soil strength. However, for a given pull coefficient or slope, slip was less in firmer soil; thus, the power number decreased and efficiency increased with increasing soil strength.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dynamometers						
Lunar roving vehicles						
Lunar soils						
Simulation						
Soil strength						
Wheels						

Unclassified
Security Classification