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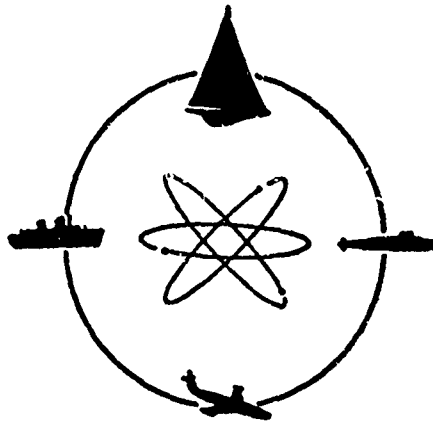
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June 1971

STUDIES OF DUAL AND TANDEM RIGID WHEEL
PERFORMANCE IN SAND

by

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**13. ABSTRACT**

Tests were conducted with five pair of wheels, three of which were geometrically similar. Four loads and three spacings were tested for each wheel pair. A dimensional analysis approach was utilized to develop general functional relationships for sinkage and motion resistance (tow force). Test data was analyzed and specific equations were developed for prediction of sinkage and resistance to motion for wheels in dual and tandem configuration. The resulting equations were compared with equations developed or discussed by Bekker. Single wheel tests were conducted and comparisons made between single wheel performance and dual or tandem wheel performance.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| DUAL WHEELS | | | | | | |
| LAND LOCOMOTION | | | | | | |
| OFF-ROAD MOBILITY | | | | | | |
| SOIL-VEHICLE RELATIONSHIPS | | | | | | |
| TANDEM WHEELS | | | | | | |

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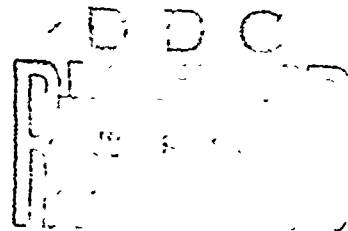Report SIT-DL-71-1536

June 1971

STUDIES OF DUAL AND TANDEM RIGID WHEEL
PERFORMANCE IN SAND

by

Gary D. Swanson

Prepared for
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Approved

I. Robert Ehrlich, Manager
Transportation Research Group

ABSTRACT

Studies of Dual and Tandem Rigid Wheel Performance in Sand

by

Gary D. Swanson

Advisor

I. Robert Ehrlich

January 1971

Tests were conducted with five pair of wheels, three of which were geometrically similar. Four loads and three spacings were tested for each wheel pair. A dimensional analysis approach was utilized to develop general functional relationships for sinkage and motion resistance (tow force). Test data was analyzed and specific equations were developed for prediction of sinkage and resistance to motion for wheels in dual and tandem configuration. The resulting equations were compared with equations developed or discussed by Bekker. Single wheel tests were conducted and comparisons made between single wheel performance and dual or tandem wheel performance.

KEYWORDS

Dual Wheels

Land Locomotion

Off-Road Mobility

Soil-Vehicle Relationships

Tandem Wheels

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## LIST OF SYMBOLS

| Symbol | | Dimensions |
|---|---|---|
| $a$ | Number of basic equations | -- |
| $b$ | Wheel width | -- |
| $B$ | Wheel skid (dual and single wheels) | -- |
| $B_F$ | Wheel skid (front tandem wheel) | -- |
| $B_R$ | Wheel skid (rear tandem wheel) | -- |
| $c$ | Vertical movement of tandem mounting plate | inches |
| $c_i$ | Exponent of prediction equation | -- |
| $D$ | Wheel diameter | inches |
| $k_c$ | Cohesive soil sinkage modulus | $lbs/in^{n+1}$ |
| $k_\varphi$ | Frictional soil sinkage modulus | $lbs/in^{n+2}$ |
| $K$ | Equation constant | -- |
| $\ell$ | Tandem wheel spacing (center-to-center) | inches |
| $m$ | Vertical movement of tandem wheel relative to pivot of the mounting plate | inches |
| $n$ | Soil sinkage exponent | -- |
| $N$ | Number of $\pi$ terms | -- |
| $p$ | Pressure | $lbs/in^2$ |
| $R$ | Motion resistance | pounds |
| $S$ | Dual wheel spacing (between adjacent faces) | inches |
| $u$ | Number of parameters | -- |
| $V_c$ | Carriage velocity | ft/sec |
| $V_w$ | Wheel peripheral velocity | ft/sec |

## List of Symbols
## (continued)

| Symbol | | Dimensions |
|--------|--|------------|
| $V_{wF}$ | Wheel peripheral velocity (front tandem wheel) | ft/sec |
| $V_{wR}$ | Wheel peripheral velocity (rear tandem wheel) | ft/sec |
| $W$ | Load | pounds |
| $x_i$ | Exponent of $\pi$ - equations | -- |
| $z$ | Wheel sinkage (dual and single wheels) | inches |
| $z_F$ | Wheel sinkage (front tandem wheel) | inches |
| $z_R$ | Wheel sinkage (rear tandem wheel) | inches |

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I. INTRODUCTION

A. Objective

Researchers involved with military, agricultural, construction and other off-road equipment have sought to increase the vehicle payload without substantial increases in motion resistance or sinkage. Designers of aircraft landing gear have also sougnt to find better methods of supporting larger aircraft on soil runways. A solution frequently employed is the utlization of many wheels mounted in dual tandem or dual-tandem configurations. The objective of this study was to determine the effects of spacing on the performance of towed rigid wheels mounted in dual and tandem configuration. This study is therefore applicable to aircraft landing gear, towed agricultural equipment, trailers, and unpowered wheels of self-propelled vehicles only.

Within this objective, it became appropriate also to study single wheels in order to simulate infinite spacing, to yield a comparison of single wheel performance, and to compare the results obtained here with those of other researchers.

B. Approach

The method chosen to study the effects of spacing on the performance of towed rigid wheels mounted in dual or tandem configuration was a dimensional analysis approach.[1] This approach was utilized to develop general functional relationships between significant parameters in this study (see Section III - RATIONALE). The general functional relationships were of the form:

$$\pi_1 = K\pi_2^{x_1} \; \pi_3^{x_2} \; \pi_4^{x_3} \qquad\qquad (1)$$

Experimental tests were then utilized to determine the values of K,
$x_1$, $x_2$ and $x_3$ for each general functional relationship. (See
Section V - TEST PROCEDURES and Section VII - ANALYSIS OF RESULTS.)

II.  BACKGROUND

Rouch and Liljedahl[2] tested driven 4.00 x 8 tires in an artificial soil.  Values of slip from zero to 20 percent were tested at dual spacings up to four inches.  They showed that, at close spacings, the wheel sinkage and motion resistance of dual wheels decreased because each wheel had a supporting effect on the other.

Roma and McGowan as referenced by Freitag,[3] utilizing a 4x4 vehicle with 6.00x16 tires in sand, showed that, if a given load must be carried by tires of a given size, two tires are better than one; however they are not twice as good.  This means that two tires operating side-by-side interact so that the individual performance of each tire is less than if it were operating independently.

Melzer and Knight[4] showed that at 20 percent slip two wheels in a close-spaced dual-wheel configuration performed proportionately better than a single wheel with the same characteristics as each wheel of the dual-wheel configuration.  Their tests were conducted in Yuma sand with 9.00-14 tires.  Their results were similar to those reported by Rouch and Liljedahl.[2]

Other studies,[5-10] relating to tandem wheels revealed that they were conducted by driving or towing a wheel with a dynamometer and then driving or towing the same wheel again in the rut left by the first pass.  The effect, therefore, was of infinite tandem spacing.

The studies reported in the previous paragraphs were concerned with performance of powered dual and tandem wheels.  Performance was defined in terms of the tractive coefficient, power efficiency,

pull coefficient, and overall efficiency. These studies also utilized
the same load for the single wheel configuration and the dual or
tandem configuration. This study was concerned with the performance
of towed dual and tandem wheels. The loads utilized for the single
wheel configuration were half those utilized for the dual or tandem
configuration.

III. RATIONALE

A. General

A dimensional analysis approach utilizing the Buckingham Pi Theorem[1] was used to develop general functional relationships between significant parameters in this study. The soil parameters utilized, $k_c$, $k_\varphi$ and n were those used by Bekker[11] in his pressure sinkage equation:

$$p = (k_\varphi + \frac{k_c}{b})z^n \qquad (2)$$

where

$p$ = pressure $(pounds/inch^2)$

$k_\varphi$ = frictional soil value $(pounds/inch^{n+2})$

$k_c$ = cohesive soil value $(pounds/inch^{n+1})$

$b$ = wheel width (inches)

$z$ = sinkage (inches)

$n$ = sinkage exponent (dimensionless)

In the conduct of a test there are certain primary and certain secondary parameters. The primary parameters are those established by the test setup; the secondary ones are those resulting from the test. In the tests conducted here, the secondary parameters studied were wheel motion resistance and wheel sinkage; wheel skid, also a secondary parameter was measured, but not analyzed. All other speci-fied parameters will be considered primary. Thus the analysis might properly be grouped into four categories:

Motion resistance of dual wheels,

Motion resistance of tandem wheels,

Sinkage of dual wheels, and

Sinkage of tandem wheels.

It might be noted here that the failure to control skid rate (as is necessary in towed wheels) destroyed some of the geometric simi-larity of the experiments, thus generating modeling distortion.

B. Motion Resistance of Dual Wheels

1. Significant Parameters

| Parameter | Symbol | Dimensions | Basic Quantity |
|---|---|---|---|
| Motion resistance | R | pounds | F |
| Wheel diameter | D | inches | L |
| Wheel width | b | inches | L |
| Load | W | pounds | F |
| Dual wheel spacing (between adjacent faces) | s | inches | L |
| Frictional soil sinkage modulus | $k_\varphi$ | pounds/inch$^{n+2}$ | $FL^{-n-2}$ |
| Cohesive soil sinkage modulus | $k_c$ | pounds/inch$^{n+1}$ | $FL^{-n-1}$ |
| Soil sinkage exponent | n | -- | -- |

2. Development of the Functional Relationship

Thus, the wheel resistance to motion may be expressed as:

$$R = f(D,b,W,s,k_\varphi,k_c,n) \tag{3}$$

Assuming that this function is in the form of a product of these variables:

$$C_\alpha R^{c_1} D^{c_2} b^{c_3} W^{c_4} s^{c_5} k_\varphi^{c_6} k_c^{c_7} = 1 \qquad (4)$$

Since n is dimensionless it may be assigned a separate $\pi$ term or may be in one or more of the exponents of Equation (4).

Equation (4) may now be expressed dimensionally as:

$$F^{c_1} L^{c_2} L^{c_3} F^{c_4} L^{c_5}(FL^{-n-2})^{c_6}(FL^{-n-1})^{c_7} = F^0 L^0 \qquad (5)$$

Solving Equation (5) for the various basic quantities:

Force:  $C_1 + C_4 + C_6 + C_7 = 0$ \qquad (6)

Length:  $C_2 + C_3 + C_5 -(n+2)C_c -(n+1)C_7 = 0$ \qquad (7)

Determining the number of $\pi$ terms:

$$N = u - a \qquad (8)$$

where:  N = number of $\pi$ terms

u = number of parameters

a = number of basic equations

$$N = 7 - 2 = 5 \qquad (9)$$

The exponents $C_2$ and $C_4$ may be determined in terms of $C_1$, $C_3$, $C_5$, $C_6$ and $C_7$. To determine that the exponents are independent, the determinant of the coefficients of $C_2$ and $C_4$ must be formed and shown to be non-zero. Thus:

$$\begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix} = 0 - 1 = -1$$

Since the value of this determinant is non-zero, the developed $\pi$ terms based on $C_2$ and $C_4$ will be independent.

The following procedure will be utilized to generate the five $\pi$ terms. Each of the exponents $C_1$, $C_3$, $C_5$, $C_6$ and $C_7$ in turn will assume a value of one while the others assume a value of zero. These values will be substituted into Equations (6) and (7). Simultaneous solution of the two resulting equations will generate one $\pi$ term.

$$C_1 = 1; \ C_3 = C_5 = C_6 = C_7 = 0$$

(6) $\quad 1 + C_4 = 0; \ C_4 = -1$

(7) $\quad C_2 = 0 \qquad\qquad \therefore \ \pi_1 = R/W \qquad\qquad (10)$

$$C_3 = 1; \ C_1 = C_5 = C_6 = C_7 = 0$$

(6) $\quad C_4 = 0$

(7) $\quad C_2 + 1 = 0; \ C_2 = -1 \quad \therefore \ \pi_2 = b/D \qquad\qquad (11)$

$$C_5 = 1; \ C_1 = C_3 = C_6 = C_7 = 0$$

(6) $\quad C_4 = 0$

(7) $\quad C_2 + 1 = 0; \ C_2 = -1 \quad \therefore \ \pi_3 = s/D \qquad\qquad (12)$

$$C_6 = 1; \ C_1 = C_3 = C_5 = C_7 = 0$$

(6) $\quad C_4 + 1 = 0; \ C_4 = -1$

(7) $\quad C_2 - (n+2) = 0; \ C_2 = n+2 \ \therefore \ \pi_4 = \dfrac{k_\varphi D^{n+2}}{W} \qquad (13)$

$$c_7 = 1; \quad c_1 = c_3 = c_5 = c_6 = 0$$

$$(6) \quad c_4 + 1 = 0; \quad c_4 = -1$$

$$(7) \quad c_2 - (n+1) = 0; \quad c_2 = n+1 \quad \therefore \quad \pi_5 = \frac{k_c D^{n+1}}{W} \qquad (14)$$

It was desired to utilize the wheel width rather than the wheel diameter in the $\pi_4$ and $\pi_5$ terms. Therefore, let:

$$\pi_4 = \pi_4 \cdot \pi_2^{n+2} = \frac{k_\varphi D^{n+2}}{W} \cdot \frac{b^{n+2}}{D^{n+2}} = \frac{k_\varphi b^{n+2}}{W} \qquad (15)$$

$$\pi_5 = \pi_5 \cdot \pi_2^{n+1} = \frac{k_c D^{n+1}}{W} \cdot \frac{b^{n+1}}{D^{n+1}} = \frac{k_c b^{n+1}}{W} \qquad (16)$$

The resulting functional relationship is:

$$\pi_1 = f(\pi_2, \ \pi_3, \ \pi_4, \ \pi_5) \qquad (17)$$

Substituting:

$$\frac{R}{W} = f\left(\frac{b}{D}, \ \frac{s}{D}, \ \frac{k_\varphi b^{n+2}}{W}, \ \frac{k_c b^{n+1}}{W}\right) \qquad (18)$$

The cohesive soil value, $k_c$ , for sand was determined to be zero (see par. IV, A, 1). Therefore, the term $\frac{k_c b^{n+1}}{W}$ may be eliminated from the functional relationship. The revised function relationship for the motion resistance of dual wheels is therefore:

$$\frac{R}{W} = f\left(\frac{b}{D}, \ \frac{s}{D}, \ \frac{k_\varphi b^{n+2}}{W}\right) \qquad (19)$$

## C. Motion Resistance of Tandem Wheels

The functional relationship which was developed previously for the motion resistance of dual wheels may also be applied to tandem wheels. This statement is true because of the fact that the wheel separation term for dual wheels, s , has the same basic dimension as the wheel separation term for tandem wheels ($\ell$).

Hence, the functional relationship for the motion resistance of tandem wheels may be written as:

$$\frac{R}{W} = f\left(\frac{b}{D}, \frac{\ell}{D}, \frac{k_\varphi b^{n+2}}{W}\right) \qquad (20)$$

## D. Sinkage of Dual and Tandem Wheels

The development of the sinkage functional relationships is almost identical to that of the motion resistance relationships. The major differences are the substitution of wheel sinkage, z , for motion resistance as the secondary parameter.

By a similar analysis, all $\pi$-terms are identical, with the exception of $\pi_1$. Here

$$\pi_1 = \frac{z}{D} \qquad (21)$$

and the functional relationship for the sinkage of dual wheels becomes

$$\frac{z}{D} = f\left(\frac{b}{D}, \frac{s}{D}, \frac{k_\varphi b^{n+2}}{W}\right) \qquad (22)$$

Likewise, the functional relationship for the sinkage of tandem wheels is

$$\frac{z}{D} = f\left(\frac{b}{D}, \frac{\ell}{D}, \frac{k_\varphi b^{n+2}}{W}\right) \qquad (23)$$

Since the two wheels of a tandem configuration may sink at different depths, the sinkage of the front wheels was designated $z_F$ ; that of rear wheel, $z_R$.

## IV. TEST FACILITY AND EQUIPMENT

### A. Test Facility

#### 1. Soil Bin

The tests were conducted in fine grain sand contained in a bin 37 feet long, 3 feet wide, and filled to a depth of 24 inches. The measured sand angle of internal friction was $31^{\circ}$; its coefficient of cohesion was zero; and its moisture content varied between 0.6% and 1.0%. The soil sinkage parameters for the sand, as determined by a series of Bevameter tests were: $k_{\varphi} = 4.7$; $k_c = 0$; $n = 1.15$.

#### 2. Tiller

The sand was tilled by means of a gyrotiller after each test to a depth of 17 to 18 inches, (see Figure 1). The sand was



FIGURE 1. GYROTILLER

tilled sufficiently prior to the tests to obtain a uniform air-dry
condition. To assure uniformity between tests, penetration readings
(standard 1/2" - 30° cone penetrometer[12]) and shear strength readings
(Cohron-Sheargraph[13]) were taken at three locations along the soil tank
in the path of the wheels.

B. Equipment

1. Wheels

Five pairs of wheels were constructed for use in this study.
Three of these (Pairs Ia, Ib, and Ic) were constructed with a width-to-
diameter ratio of approximately 0.26 in order to form a geometrically
similar set (see Figure 2). The other two (pairs II and III) were
of the same diameter as pair Ib and had width-to-diameter ratios of
0.297 and 0.225. They were formed by adding or removing sheets of
plywood from the wheels of that pair. The widths, diameters and width-
to-diameter ratios for each pair tested are shown in Table I.
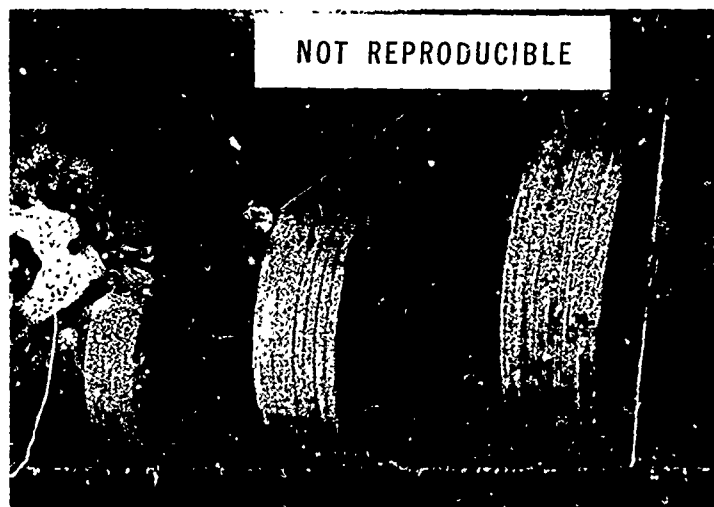


FIGURE 2. GEOMETRICALLY SIMILAR WHEELS

Table 1

Wheel Dimensions

| Wheel Pair No. | Diameter (D) (in) | Width (b) (in) | Width/Diameter (b/D) |
|---|---|---|---|
| I$_a$ | 14.75 | 3.88 | 0.263 |
| I$_b$ | 20.875 | 5.41 | 0.259 |
| I$_c$ | 27.0 | 6.98 | 0.259 |
| II | 20.875 | 4.70 | 0.225 |
| III | 20.875 | 6.20 | 0.297 |

2. Test Apparatus

   a. Sub-frame

     (1) Dual Configuration

In dual configuration the wheels were mounted on a one and one-quarter-inch steel axle. The ax'e was supported by a bearing holder which was bolted to the sub-frame. The wheels were prevented from slipping on the axle by two set screws which were mounted on the flange plate. Figure 3 shows the apparatus as utilized in the dual configuration.

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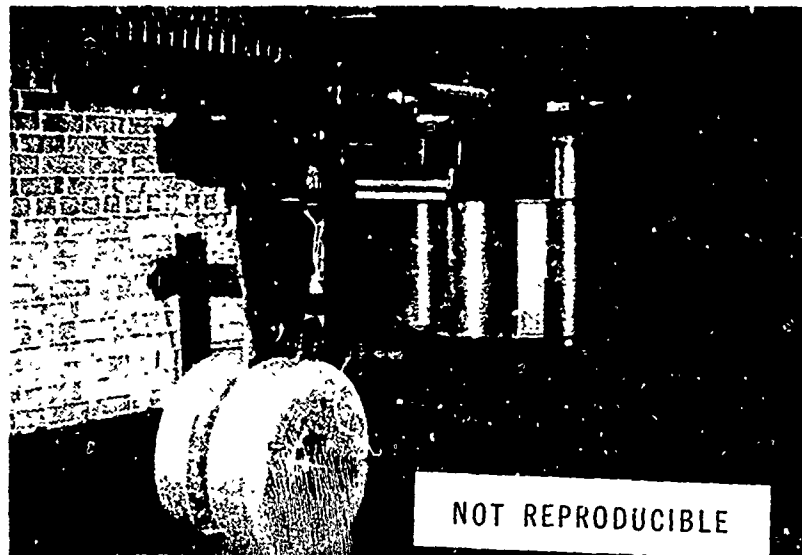
FIGURE 3.   TEST APPARATUS IN DUAL CONFIGURATION

(2) Tandem Configuration

In the tandem configuration the wheels were mounted on stub axles which were in turn mounted on a long steel mounting plate.  The center of the plate was bolted to another stub axle which was bolted to the sub-frame.  Figure 4 shows the apparatus as utilized in the tandem configuration.

(3) Single Wheel Configuration

In the single wheel configuration the wheel was mounted on a stub axle which was bolted to the sub-frame.  Figure 5 shows the apparatus as utilized in the single wheel configuration.

b. Main-frame

The sub-frame was attached to a wheel dynamometer main-frame which included a parallelogram type force transducer (see Section C, Instrumentation).  The main frame was fastened to two linear bearings permitting a near-frictionless vertical movement of

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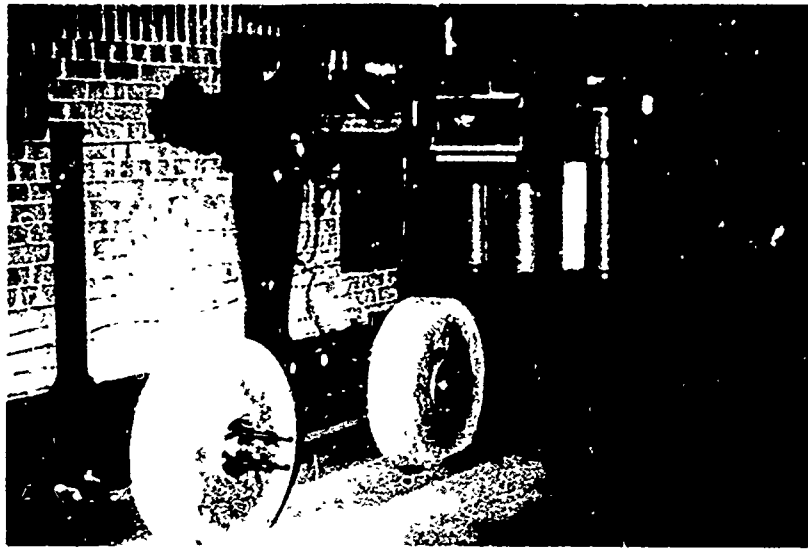


FIGURE 4.  TEST APPARATUS IN TANDEM CONFIGURATION



FIGURE 5.  TEST APPARATUS IN SINGLE
WHEEL CONFIGURATION

the whole assembly.  The main-frame may be seen in Figures 3, 4 and 5.

c. Counterbalance

A counterbalance (Figure 6) was constructed to permit operation of the wheels at loads below the total weight of the main-frame, sub-frame, wheels and other auxilliary equipment.



FIGURE 6.  COUNTERBALANCE

C. Instrumentation

1. Velocity

a. Carriage Velocity

The velocity of the carriage was measured utilizing a series of event markers spaced at one and one-half foot intervals along the test bin.  As the carriage was driven down the test bin a

microswitch was closed by each of the event markers. When the micro-
switch was closed, it briefly shorted out the channel of the recorder
on which the sinkage of the wheels was recorded causing a large de-
flection of the pen. Calculation of the carriage velocity is shown
in Appendix I. Figure 7 shows the microswitch and several of the
event markers.



FIGURE 7. MICROSWITCH AND EVENT MARKERS USED
TO MEASURE CARRIAGE VELOCITY

b. Wheel Velocity

The velocity of the wheels was measured utlizing a
microswitch triggered by the four bolts with which the wheel was held
to the flange plate. In the tandem configuration two microswitches
were utilized so that the velocity of each wheel could be measured
independently. A one and one-half volt battery was wired into the
circuit to give a voltage pulse when the microswitch was closed. The

signal from this microswitch was fed into a DC amplifier in the re-
corder. Calculation of the wheel velocity is shown in Appendix I.
Figure 8 shows the microswitch and the mounting apparatus as utilized
in the dual configuration.
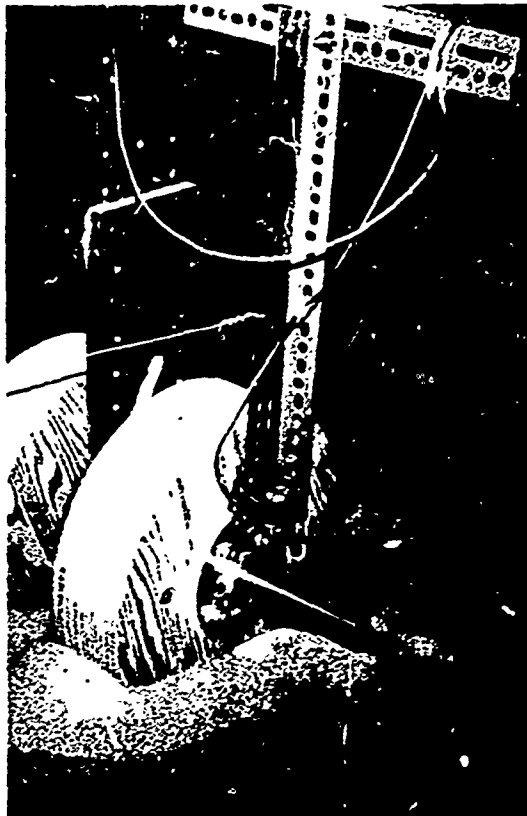


FIGURE 8. MICROSWITCH USED TO MEASURE WHEEL VELOCITY

2. Wheel Sinkage Measurement

a. Dual Wheels and Single Wheel

The sinkage of the dual and single wheels was measured
by means of a chain-driven multiple turn potentiometer (Figure 9).
The potentiometer was mounted on the rigid part of the carriage while
the chain was fastened to the main-frame of the test apparatus. As
the wheels sank into the sand, the potentiometer was turned as the

FIGURE 9. SINKAGE MEASUREMENT DEVICE

chain moved downward.

  b. Tandem Wheels

    In the tandem configuration the same potentiometer measured the vertical motion of the center of the mounting plate. A second multiple turn potentiometer was utilized to determine the difference in sinkage between the front and rear wheels. This second potentiometer was operated by a string which was attached to the end of the mounting plate. By determining the distance that the plate moved from a level position, it was possible to determine the front and rear wheel sinkage. Sample calculations of wheel sinkage are shown in Appendix II. Figure 10 shows this second potentiometer and

the string by which it was turned.



FIGURE 10.   TANDEM WHEE   SINKAGE MEASUREMENT DEVICE

3. Motion Resistance Measurement

It was determined that frictional losses in the system were negligible. Therefore, the force measured at the dynamometer was considered to be the motion resistance. It was measured by means of a Linear Differential Transformer (LVDT) type transducer. The transducer was mounted in an aluminum frame as shown in Figure 11.

4. Recording Data

A four-channel Sanborn recorder was utilized to record the data taken for each test. Only three channels were utilized to record motion resistance, wheel velocity, sinkage and carriage velocity
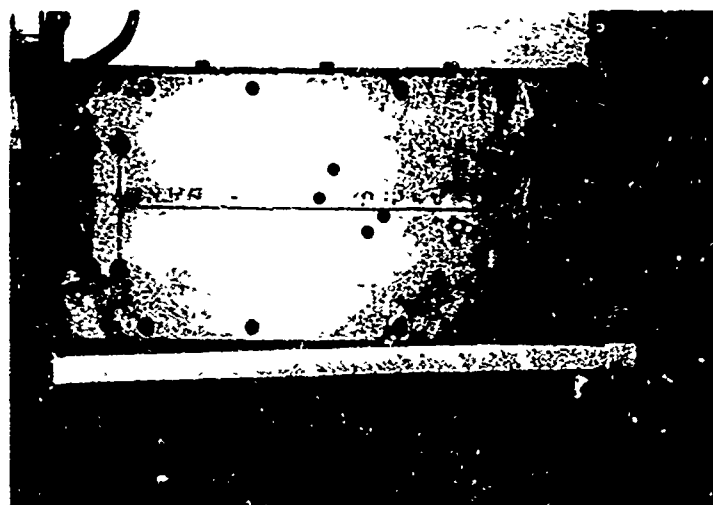
FIGURE 11. SOIL BIN DYNAMOMETER

since carriage velocity was recorded by means of an interruption in
the sinkage trace. Figure 12 shows a copy of the recorded data for one
test run.

5. Calibration

a. General

All potentiometers were calibrated prior to testing
each different set of wheels. If tests for a set of wheels extended
to a second day, calibration checks were made prior to the second
day's tests.

b. Sinkage

(1) Dual Wheels and Single Wheel

The chain-driven multiple turn potentiometer was
calibrated by establishing the "zero" sinkage level (that level at
which the bottom of the wheel touched the top surface of the soil)
and then physically lowering the wheel into a hole in the sand. The
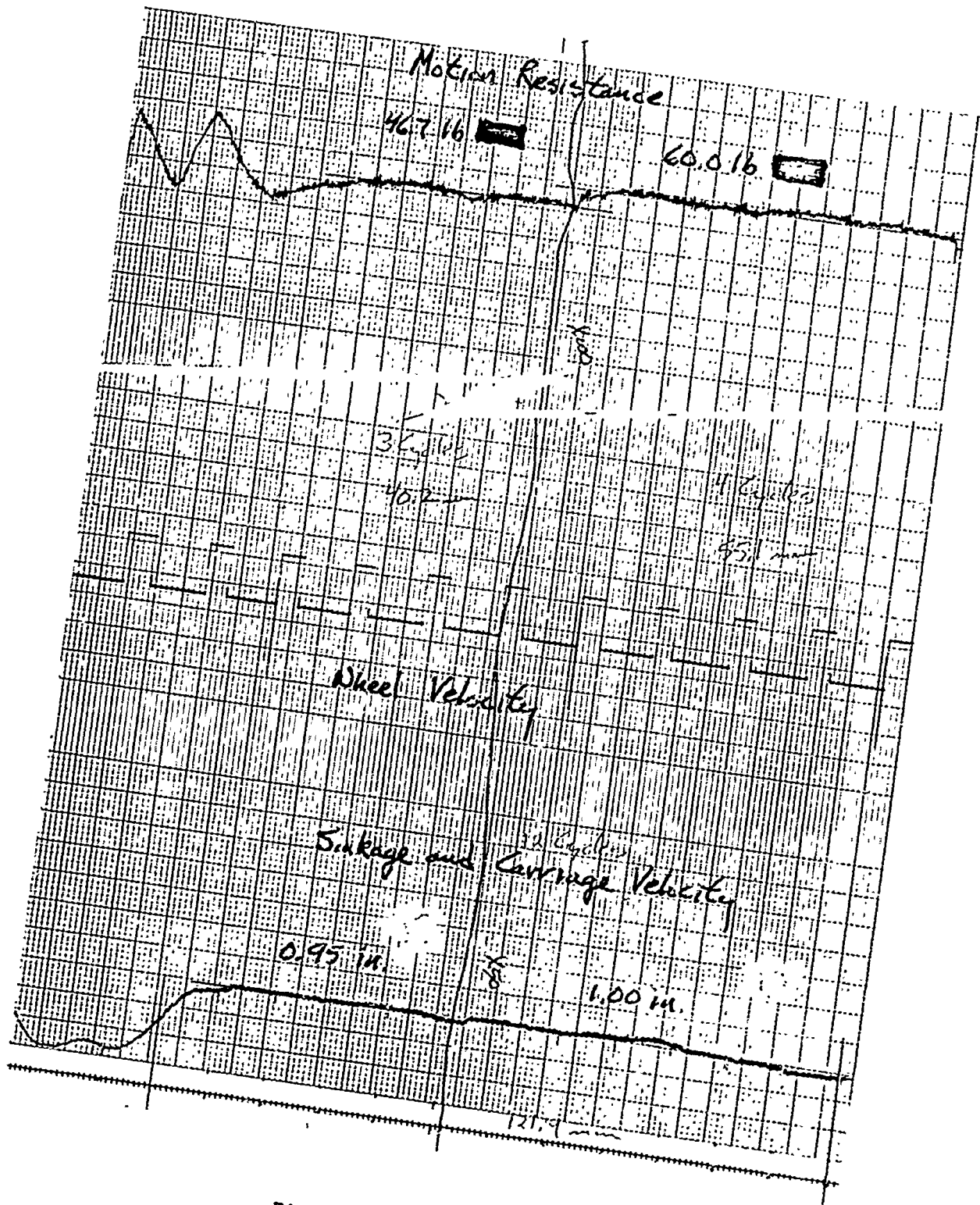
FIGURE 12. DATA RECORD

recording was marked each time the wheel was lowered an inch (as measured by a ruler) and a calibration curve was generated in this manner.

(2) Tandem Wheels

In addition to the steps in the preceding paragraph, it was required that the second multiple turn potentiometer be calibrated. This potentiometer was calibrated by first leveling the mounting plate (see Figure 4), thus establishing a zero point. The recording was marked each time the plate was moved up or down one-half inch.

c. Motion Resistance

Since it was determined that loadings on the sub-frame gave the same readings as loadings at the bottom of the wheel, the motion resistance dynamometer was calibrated by loading known weights on a weight pan which was attached to the sub-frame over a pulley by a rope.

## V. TEST PROCEDURES

Prior to each day of testing a calibration check was made of all instrumentation. If this was a new configuration, it was calibrated completely. The soil was tilled prior to each test, and penetration, and shear strength readings were taken at the beginning of each day. The wheels were loaded by means of dead weights placed on the load pan or on the counterbalance system. All tests were run at a constant carriage speed of approximately 0.167 feet/second.

For dual wheel tests, the wheels were placed at a given spacing. Since both the sinkage and the motion resistance stabilized quite rapidly, it was found that we could add weights during the test so that two loads would be tested during each run. Three tests were made for each condition to be studied. Four loads and three spacings were used for each wheel size tested.

The tandem wheel tests were conducted in generally the same manner as the dual wheel tests. However, an additional preliminary step was necessary to allow for measurement of individual sinkages of the front and rear wheels. This additional step was to insure that, prior to each test, the pen measuring output of the string-driven multiple turn potentiometer was set to the midpoint when the mounting plate was level. The plate was leveled utilizing a carpenter's level.

The test procedures for the single wheel tests were somewhat different from those for the dual and tandem wheels. Two loadings could be tested in each test run but the soil was not processed after each run. The wheel was blocked above the sand level as the carriage

was returned to the starting position. A second pass was then made in the rut formed by the wheel in the first pass. The soil was tilled after every other run. Single wheel tests were conducted only with pairs Ia, Ib and Ic and were conducted with loadings one-half of that for the dual and tandem configurations.

Tables II, III and IV show a summary of the test configurations of all tests which were conducted.

## Table II

### Summary of Dual Wheel Tests

| Test No. | Wheel Pair | Load (W) (lb) | Wheel Separation (s) (in.) |
|---|---|---|---|
| 1-3 | $I_a$ | 150 | 1.5 |
| 4-6 | $I_a$ | 150 | 2.5 |
| 7-9 | $I_a$ | 150 | 3.8 |
| 10-12 | $I_a$ | 220 | 1.5 |
| 13-15 | $I_a$ | 220 | 2.5 |
| 16-18 | $I_a$ | 220 | 3.8 |
| 19-21 | $I_a$ | 300 | 1.5 |
| 22-24 | $I_a$ | 300 | 2.5 |
| 25-27 | $I_a$ | 300 | 3.8 |
| 28-30 | $I_a$ | 350 | 1.5 |
| 31-33 | $I_a$ | 350 | 2.5 |
| 34-36 | $I_a$ | 350 | 3.8 |
| 37-39 | $I_b$ | 150 | 2.625 |
| 40-42 | $I_b$ | 150 | 3.56 |
| 43-45 | $I_b$ | 150 | 5.41 |
| 46-48 | $I_b$ | 220 | 2.625 |
| 49-51 | $I_b$ | 220 | 3.56 |
| 52-54 | $I_b$ | 220 | 5.41 |
| 55-57 | $I_b$ | 300 | 2.625 |
| 58-60 | $I_b$ | 300 | 3.56 |
| 61-63 | $I_b$ | 300 | 5.41 |
| 64-66 | $I_b$ | 350 | 2.625 |
| 67-69 | $I_b$ | 350 | 3.56 |
| 70-72 | $I_b$ | 350 | 5.41 |
| 73-75 | $I_c$ | 150 | 2.75 |
| 76-78 | $I_c$ | 150 | 4.56 |
| 79-81 | $I_c$ | 150 | 7.00 |
| 82-84 | $I_c$ | 220 | 2.75 |
| 85-87 | $I_c$ | 220 | 4.56 |
| 88-90 | $I_c$ | 220 | 7.00 |
| 91-93 | $I_c$ | 300 | 2.75 |
| 94-96 | $I_c$ | 300 | 4.56 |
| 97-99 | $I_c$ | 300 | 7.00 |
| 100-102 | $I_c$ | 350 | 2.75 |
| 103-105 | $I_c$ | 350 | 4.56 |
| 106-108 | $I_c$ | 350 | 7.00 |

Table II (continued)

| Test No | Wheel Pair | Load (W) (lb) | Wheel Separation (s) (in.) |
|---------|-----------|---------------|----------------------------|
| 109-111 | II | 150 | 2.625 |
| 112-114 | II | 150 | 3.56 |
| 1;5-117 | II | 150 | 5.41 |
| 118-120 | II | 220 | 2.625 |
| 121-123 | II | 220 | 3.56 |
| 124-126 | II | 220 | 5.41 |
| 127-129 | II | 300 | 2.625 |
| 130-132 | II | 300 | 3.56 |
| 133-135 | II | 300 | 5.41 |
| 136-138 | II | 350 | 2.625 |
| 139-141 | II | 350 | 3.56 |
| 142-144 | II | 350 | 5.41 |
| 145-147 | III | 150 | 2.625 |
| 148-150 | III | 150 | 3.56 |
| 151-153 | III | 150 | 5.41 |
| 154-156 | III | 220 | 2.625 |
| 157-159 | III | 220 | 3.56 |
| 160-162 | III | 220 | 5.41 |
| 163-165 | III | 300 | 2.625 |
| 166-168 | III | 300 | 3.56 |
| 169-171 | III | 300 | 5.41 |
| 172-174 | III | 350 | 2.625 |
| 175-177 | III | 350 | 3.56 |
| 178-180 | III | 350 | 5.41 |

Table III

Summary of Tandem Wheel Tests

| Test No | Wheel Pair | Load (W) (lb) | Wheel Separation ($\ell$) (in.) |
|---|---|---|---|
| 181-183 | $I_a$ | 150 | 16.125 |
| 184-186 | $I_a$ | 150 | 21.80 |
| 187-189 | $I_a$ | 150 | 29.50 |
| 190-192 | $I_a$ | 220 | 16.125 |
| 193-195 | $I_a$ | 220 | 21.80 |
| 196-198 | $I_a$ | 220 | 29.50 |
| 199-201 | $I_a$ | 300 | 16.125 |
| 202-204 | $I_a$ | 300 | 21.80 |
| 205-207 | $I_a$ | 300 | 29.50 |
| 208-210 | $I_a$ | 350 | 16.125 |
| 211-213 | $I_a$ | 350 | 21.80 |
| 214-216 | $I_a$ | 350 | 29.50 |
| 217-219 | $I_b$ | 150 | 21.80 |
| 220-222 | $I_b$ | 150 | 29.50 |
| 223-225 | $I_b$ | 150 | 41.75 |
| 226-228 | $I_b$ | 220 | 21.80 |
| 229-231 | $I_b$ | 220 | 29.50 |
| 232-234 | $I_b$ | 220 | 41.75 |
| 235-237 | $I_b$ | 300 | 21.80 |
| 238-240 | $I_b$ | 300 | 29.50 |
| 241-243 | $I_b$ | 300 | 41.75 |
| 244-246 | $I_b$ | 350 | 21.80 |
| 247-249 | $I_b$ | 350 | 29.50 |
| 250-252 | $I_b$ | 350 | 41.75 |
| 253-255 | $I_c$ | 150 | 29.50 |
| 256-258 | $I_c$ | 150 | 41.75 |
| 259-261 | $I_c$ | 150 | 54.0 |
| 262-264 | $I_c$ | 220 | 29.50 |
| 265-267 | $I_c$ | 220 | 41.75 |
| 268-270 | $I_c$ | 220 | 54.0 |
| 271-273 | $I_c$ | 300 | 29.50 |
| 274-276 | $I_c$ | 300 | 41.75 |
| 277-279 | $I_c$ | 300 | 54.0 |
| 280-282 | $I_c$ | 350 | 29.50 |
| 283-285 | $I_c$ | 350 | 41.75 |
| 286-288 | $I_c$ | 350 | 54.0 |

Table ill (continued)

| Test No. | Wheel Pair | Load (W) (lb) | Wheel Separation (ℓ) (in.) |
|---|---|---|---|
| 289-291 | II | 150 | 21.80 |
| 292-294 | II | 150 | 29.50 |
| 295-297 | II | 150 | 41.75 |
| 298-300 | II | 220 | 21.80 |
| 301-303 | II | 220 | 29.50 |
| 304-306 | II | 220 | 41.75 |
| 307-309 | II | 300 | 21.80 |
| 310-312 | II | 300 | 29.50 |
| 313-315 | II | 300 | 41.75 |
| 316-318 | II | 350 | 21.80 |
| 319-321 | II | 350 | 29.50 |
| 322-324 | II | 350 | 41.75 |
| 325-327 | III | 150 | 21.80 |
| 328-330 | III | 150 | 29.50 |
| 331-333 | III | 150 | 41.75 |
| 334-336 | III | 220 | 21.80 |
| 337-339 | III | 220 | 29.50 |
| 340-342 | III | 220 | 41.75 |
| 343-345 | III | 300 | 21.80 |
| 346-348 | III | 300 | 29.50 |
| 349-351 | III | 300 | 41.75 |
| 352-354 | III | 350 | 21.80 |
| 355-357 | III | 350 | 29.50 |
| 358-360 | III | 350 | 41.75 |

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## TABLE IV

### Summary of Single Wheel Tests

| Test No. | Wheel Pair (one wheel only) | Load (W) (lb) | Pass No. |
|---|---|---|---|
| 361-362 | $l_a$ | 75 | 1 |
| 363-364 | $l_a$ | 75 | 2 |
| 365-366 | $l_a$ | 110 | 1 |
| 367-368 | $l_a$ | 110 | 2 |
| 369-370 | $l_a$ | 150 | 1 |
| 371-372 | $l_a$ | 150 | 2 |
| 373-374 | $l_a$ | 175 | 1 |
| 375-376 | $l_a$ | 175 | 2 |
| 377-378 | $l_b$ | 75 | 1 |
| 379-380 | $l_b$ | 75 | 2 |
| 381-382 | $l_b$ | 110 | 1 |
| 383-384 | $l_b$ | 110 | 2 |
| 385-386 | $l_b$ | 150 | 1 |
| 387-388 | $l_b$ | 150 | 2 |
| 389-390 | $l_b$ | 175 | 1 |
| 391-392 | $l_b$ | 175 | 2 |
| 393-394 | $l_c$ | 75 | 1 |
| 395-396 | $l_c$ | 75 | 2 |
| 397-398 | $l_c$ | 110 | 1 |
| 399-400 | $l_c$ | 110 | 2 |
| 401-402 | $l_c$ | 150 | 1 |
| 403-404 | $l_c$ | 150 | 2 |
| 405-406 | $l_c$ | 175 | 1 |
| 407-408 | $l_c$ | 175 | 2 |

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## VI. RESULTS

The results were tabulated and will be found in Appendix IV. The linear average of the three test values were used in computing the $\pi$ terms presented.

VII.  ANALYSIS OF RESULTS

   A. General

        Each of the general functional relationships previously de-

veloped contained an unknown equation constant and unknown exponents

for each  $\pi$  term.  The results of the tests were evaluated to deter-

mine these unknown quantities for each relationship.  Only the dual

and tandem wheel motion resistance relationships will be discussed in

detail.  The dual and tandem wheel sinkage relationships will only be

outlined as they were determined in much the same manner.

   B. Motion Resistance of Dual Wheels

        1. $\pi_1$ (R/W) and  $\pi_3$ (s/D) Relationship

        The tests were designed to be conducted with five sets

of wheels, three of which had an aspect ratio (b/D) of 0.26.  The

aspect ratios of the other sets of wheels were 0.225 and 0.297 (see

Table 1).  A plot was made of log  $\pi_1$  vs.  log $\pi_3$  for various aspect

ratios and weights  (Figure 13).  A close examination of the plots in

Figure 13 reveal that, in the case of wheel pairs Ic, III and the

lighter loads of wheel pair Ib, a line connecting the data points

would be concave downward.  On the other hand, the data from pair II,

and the lightest load of pair Ia are concave upwards.  Other configura-

tions appear to lie in an almost horizontal straight line.  Further

examination of the plots of the other configurations tested (Figures

19, 23, 27 and 31) reveal a horizontal straight line will yield the

best overall fit to the data.  Thus, though there may be a somewhat

more complex relationship, for the rest of this study  it was assumed
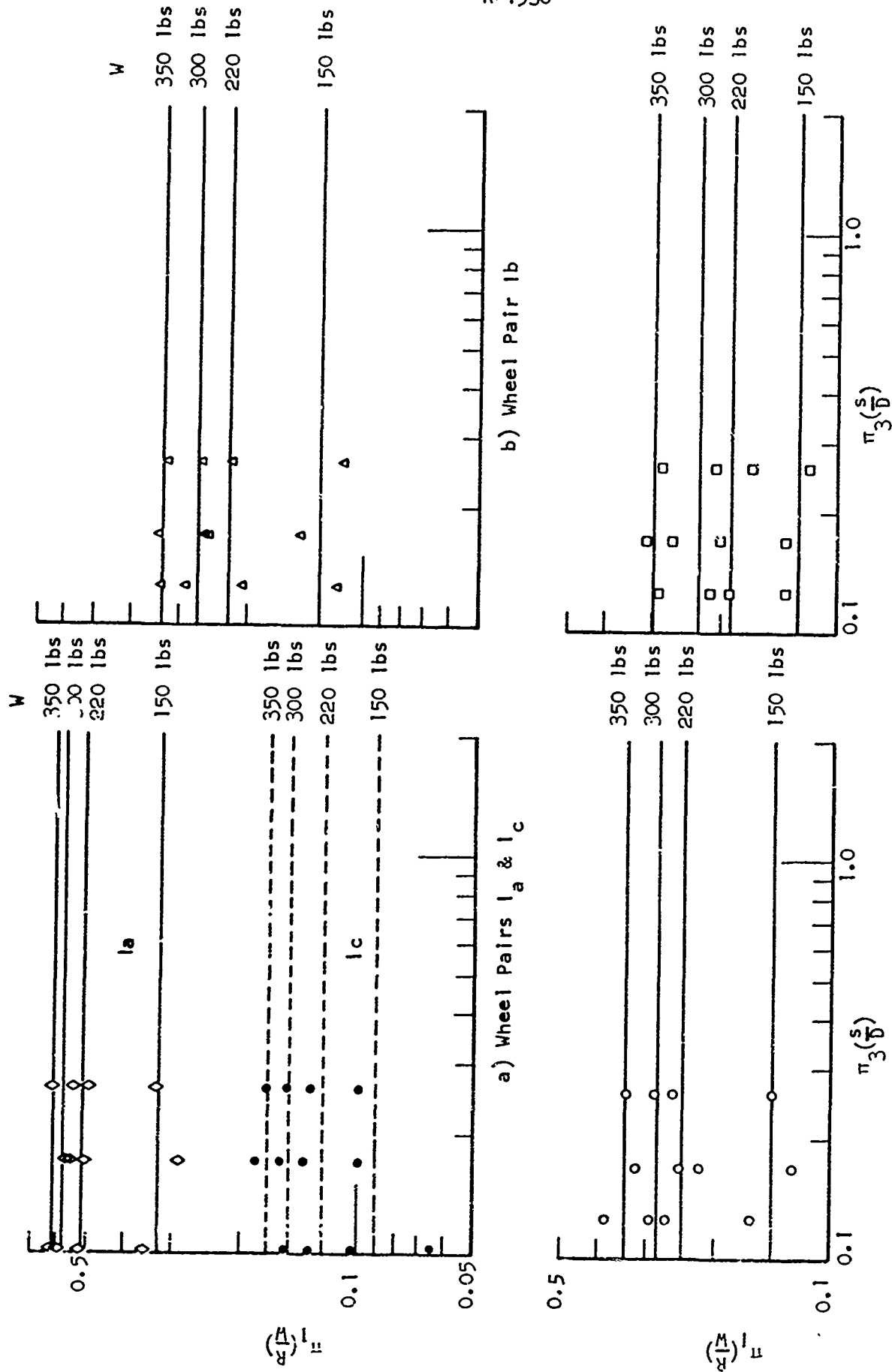
FIGURE 13. PLOTS SHOWING THE INFLUENCE OF DUAL WHEEL SPACING ON MOTION RESISTANCE

that the data could best be represented by a horizontal straight line. Thus the $\frac{R}{W}$ ratio did not vary with wheel spacing, or it varied so little, within the range tested, that its effect was within the data scatter. For this reason the exponent of the $\pi_3$ term could be set to zero and removed from the functional relationship of Equation (19). The plots in Figure 13 do not overlie because, for the various weights tested, the $\pi_4$-terms have different values. To collapse these curves we must therefore examine the relationships between $\pi_1$ and $\pi_4$.

  2. $\pi_1$ (R/W) and $\pi_4$ ($k_\varphi b^{n+2}/W$)

  In order to generate a relationship between $\pi_1$ and $\pi_4$, we took the intersection of the horizontal fitting line of Figure 13 with the $\pi_1$ axis to be the representative $\pi_1$ value for the wheel pair and load under consideration. This representative value was then called $\bar{\pi}_1$. A plot was then made of log $\bar{\pi}_1$ vs. log $\pi_4$ for each set of wheels, (Table V and Figure 14). In Figure 14, since all π-terms for wheel pairs Ia, Ib and Ic are equal, the three lines should overlap. This they clearly do not do, thus indicating model distortion either to the effects of dissimilar slip or to other reasons.

  From the measured slope of these lines and each line's intercept at log 1, the following relationships were generated:

$$\text{Wheel Pair Ia; } \bar{\pi}_1 = 0.66 \; \pi_4^{-0.9} \tag{24}$$

$$\text{Wheel Pair Ib; } \bar{\pi}_1 = 0.81 \; \pi_4^{-0.9} \tag{25}$$

$$\text{Wheel Pair Ic; } \bar{\pi}_1 = 0.91 \; \pi_4^{-0.9} \tag{26}$$

$$\text{Wheel Pair II; } \bar{\pi}_1 = 0.54 \; \pi_4^{-0.9} \tag{27}$$

$$\text{Wheel Pair III; } \bar{\pi}_1 = 1.01 \; \pi_4^{-0.9} \tag{28}$$

## Table V

$\bar{\pi}_1$ and $\pi_4$ Values for Motion Resistance of Dual Wheels

Wheel Pair No.

| Load (lb) | $I_a$ | | $I_b$ | | $I_c$ | | II | | III | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ |
| 150 | 0.325 | 2.241 | 0.129 | 6.348 | 0.098 | 14.248 | 0.142 | 4.10 | 0.126 | 9.806 |
| 220 | 0.510 | 1.532 | 0.223 | 4.34 | 0.135 | 9.741 | 0.242 | 2.803 | 0.187 | 6.705 |
| 300 | 0.573 | 1.124 | 0.268 | 3.184 | 0.150 | 7.147 | 0.280 | 2.057 | 0.227 | 4.919 |
| 350 | 0.605 | 0.959 | 0.331 | 2.718 | 0.170 | 6.100 | 0.340 | 1.755 | 0.297 | 4.198 |
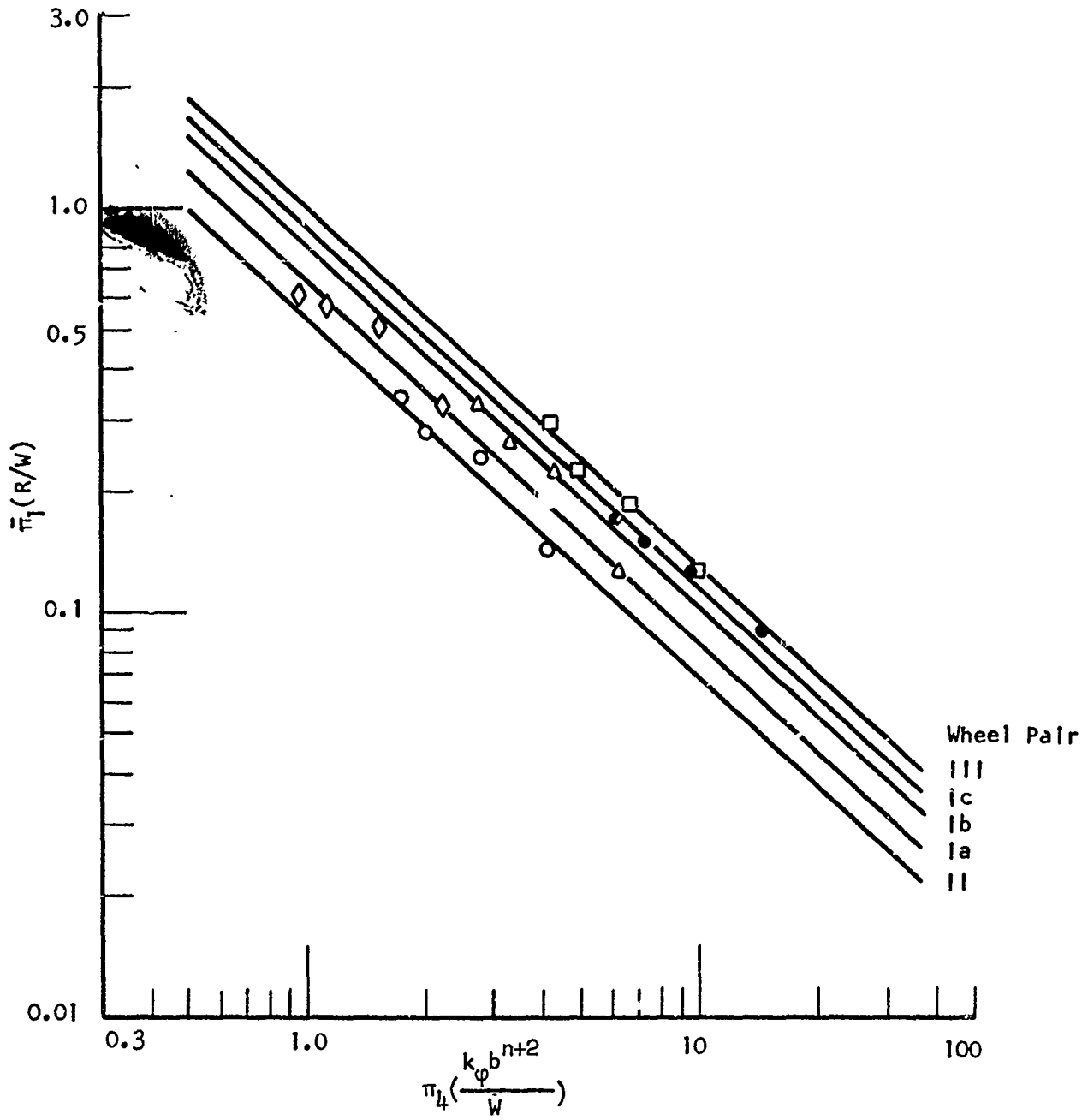
FIGURE 14. PLOTS SHOWING THE RELATIONSHIP BETWEEN
WHEEL WIDTH AND MOTION RESISTANCE OF DUAL WHEEL~

To continue the solution of this problem the relationships for the three wheel pairs with the same aspect ratio must be collapsed. This was accomplished by plotting the coefficients of Equations (24), (25) and (26) (called $c_\alpha$) vs. the wheel width (see Figure 15). From Figure 15, the following relationship was generated:

$$c_\alpha = 0.32 \, b^{0.54} \tag{29}$$

When equations (24) to (26) are divided by this relationship they collapse to the relationship:

$$\pi_1' = \frac{\bar{\pi}_1}{c_\alpha} = \frac{(\text{intercept}) \, \pi_4^{-0.9}}{0.32 \, b^{0.54}} \approx 1 \, \pi_4^{-0.9} \tag{30}$$

Note that the new relationship was designated $\pi_1'$. Now, since Equations (24) to (26) were divided by $0.32 \, b^{0.54}$, Equations (27) and (28) must also be divided likewise:

$$\pi_1' = \frac{\bar{\pi}_1}{c_\alpha} = \frac{0.54 \, \pi_4^{-0.9}}{0.32 \, b^{0.54}} \cdot = \frac{0.54 \pi_4^{-0.9}}{0.32(4.7)^{0.54}} = 0.73 \, \pi_4^{-0.9} \tag{31}$$

$$\pi_1' = \frac{\bar{\pi}_1}{c_\alpha} = \frac{1.01 \, \pi_4^{-0.9}}{0.32 \, b^{0.54}} = \frac{1.01 \, \pi_4^{-0.9}}{0.32(6.2)^{0.54}} = 1.18 \, \pi_4^{-0.9} \tag{32}$$

Equations (30) to (32) are plotted in Figure 16.

3. $\pi_1'$ (R/W) and $\pi_2$ (b/D) Relationship

To complete the functional relationship, a plot was next made of $\log \pi_1'$ vs. $\log \pi_2$ at a constant value of $\pi_4$ equal to one (Figure 17). From Figure 17 the following relationship was determined:
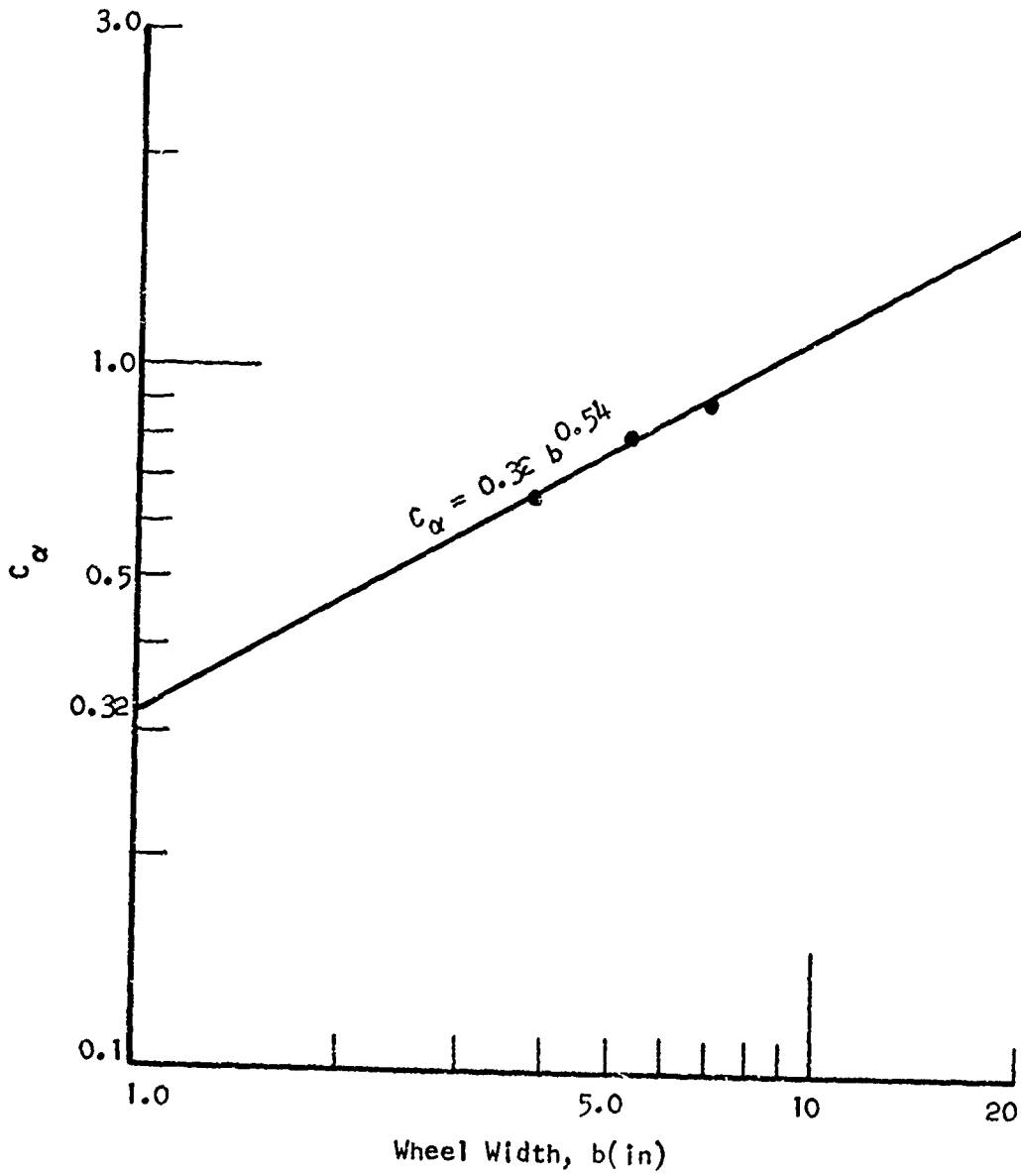
FIGURE 15.  $C_\alpha$ vs b for MOTION RESISTANCE
OF DUAL WHEELS
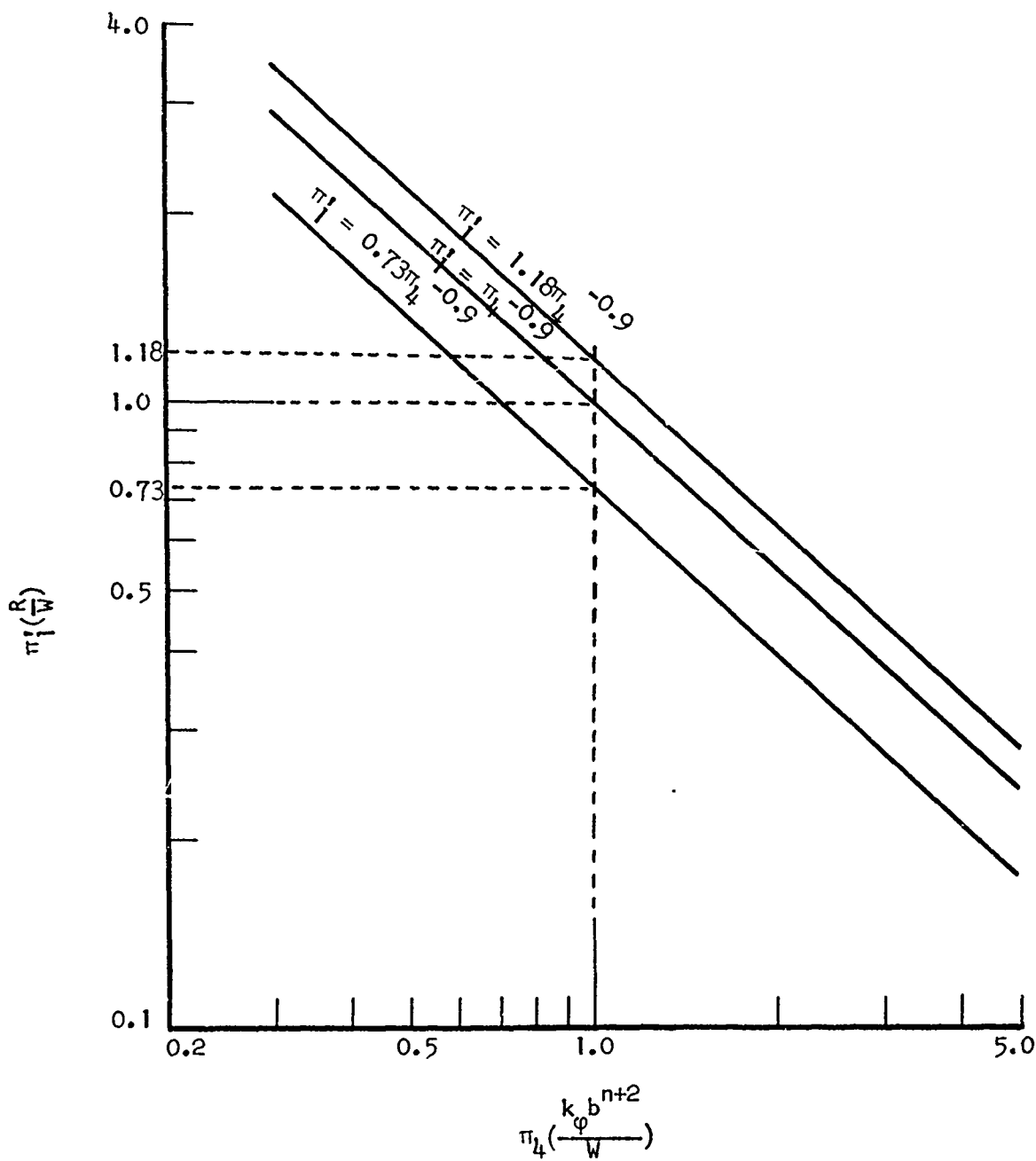
FIGURE 16. $\pi'_1$ vs $\pi_4$ AFTER COLLAPSING LINES
FOR SIMILAR WHEELS
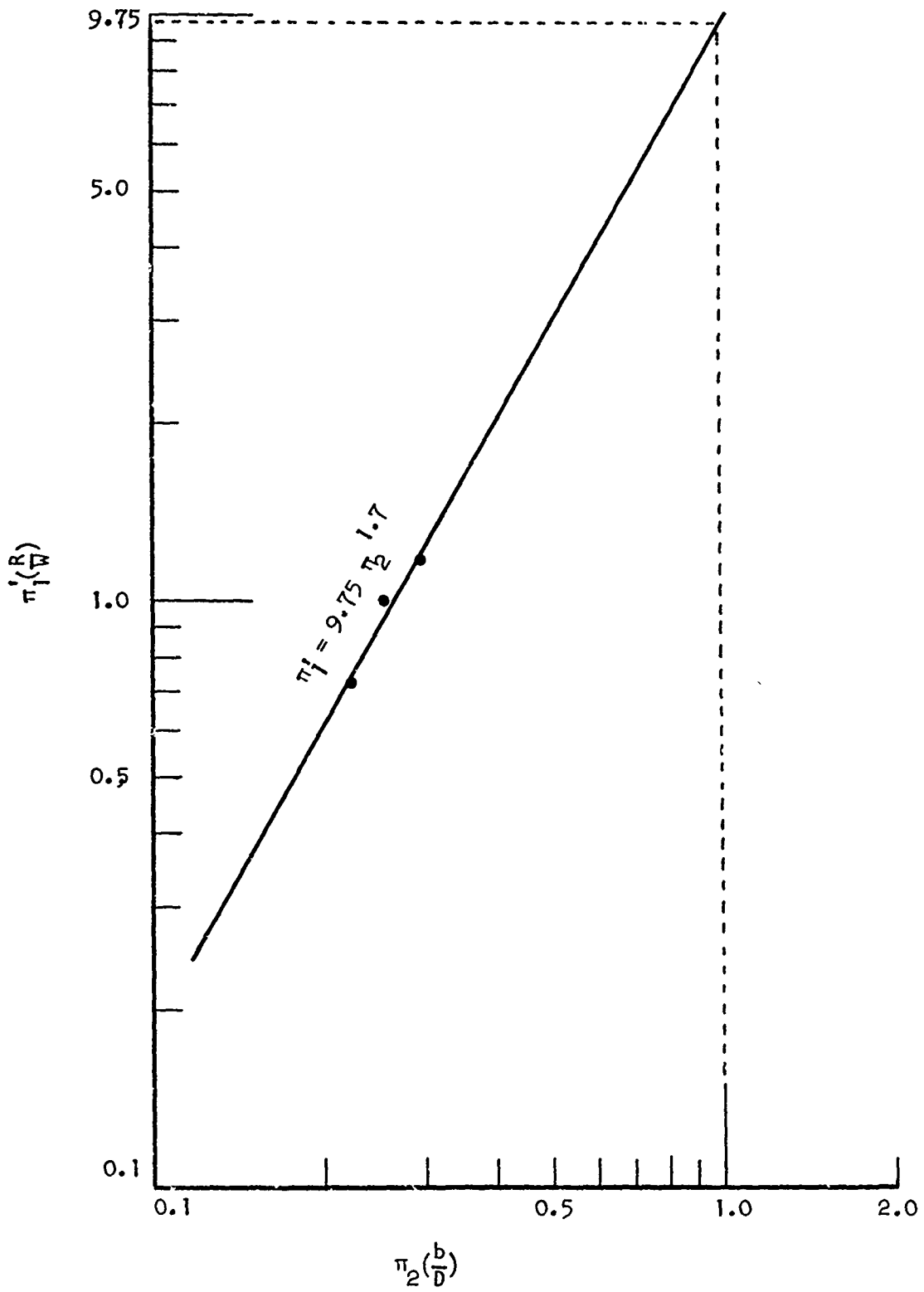
FIGURE 17. $\pi'_1$ vs $\pi_2$ for MOTION RESISTANCE OF DUAL WHEELS

$$\pi_1' = 9.75 \; \pi_2^{1.7} \tag{33}$$

## 4. Complete Functional Relationship

Since two relationships were known for $\pi_1'$, they could be combined by the technique presented by Murphy.[1] (See Appendix III).

$$\pi_1' = F(\pi_2, \pi_4) = \frac{F(\bar{\pi}_2, \pi_4) F(\pi_2, \bar{\pi}_4)}{F(\bar{\pi}_2, \bar{\pi}_4)} = \frac{(1 \; \pi_4^{-0.9})(9.75 \; \pi_2^{1.7})}{1}$$

$$\pi_1' = 9.75 \; \pi_2^{1.7} \; \pi_4^{-0.9} \tag{34}$$

but, from Equation (30)

$$\bar{\pi}_1 = c_\alpha \; \pi_1' \tag{30}$$

Therefore:

$$\bar{\pi}_1 = 0.32 \; b^{0.54}(9.75 \; \pi_2^{1.7} \; \pi_4^{-0.9})$$

$$\bar{\pi}_1 = 3.12 \; b^{0.54} \pi_2^{1.7} \; \pi_4^{-0.9} \tag{35}$$

## 5. Modification of Functional Relationship

It was noted that the constant and exponents of Equation (35) were decimal fractions. These numbers are probably subject to experimental error. Therefore, for simplification, without probable loss of accuracy, the equation was modified as seen below:

$$\bar{\pi}_1 = 3 \; \frac{\sqrt{b} \; \pi_2^{1.5}}{\pi_4} \tag{36}$$

Expressed in terms of the problem variables, Equation (36) be-
comes:*

$$R = 3 \frac{w^2}{b^n k_\varphi D^{1.5}} \qquad (37)$$

To determine how accurately Equation (36) was, the corresponding
values of b, $\pi_2$ and $\pi_4$ were substituted into it and plotted in
Figure 18. It will be noted that two points for wheel pair la were
very poorly predicted. These points were for the 300 and 350 pound
loads and each had a very high skid rate.

6. Comparison with Bekker's Equation

Bekker derived an equation[11] to predict towing resistance
of any rigid wheel in homogeneous soils of any type. His equation,
with n = 1.15 and k = 4.7 is

$$R = 0.55 \frac{w^{1.3}}{b^{.3} D^{.65}} \qquad (38)$$

For similar data, Equation (37) becomes

$$R = 0.64 \frac{w^2}{b^{1.15} D^{1.5}} \qquad (39)$$

It will be noted that the Equations (37) and (38) are of the
same form, however, the constants and exponents differ greatly. This
difference is probably due to the fact that Bekker's Equation was
derived from theoretical considerations only, and was not well vali-
dated with experiments.

─────────────
*It should be noted that, in our experiments, $k_\varphi$ was not varied;
hence there is some uncertainty regarding its exponent in the
above equation
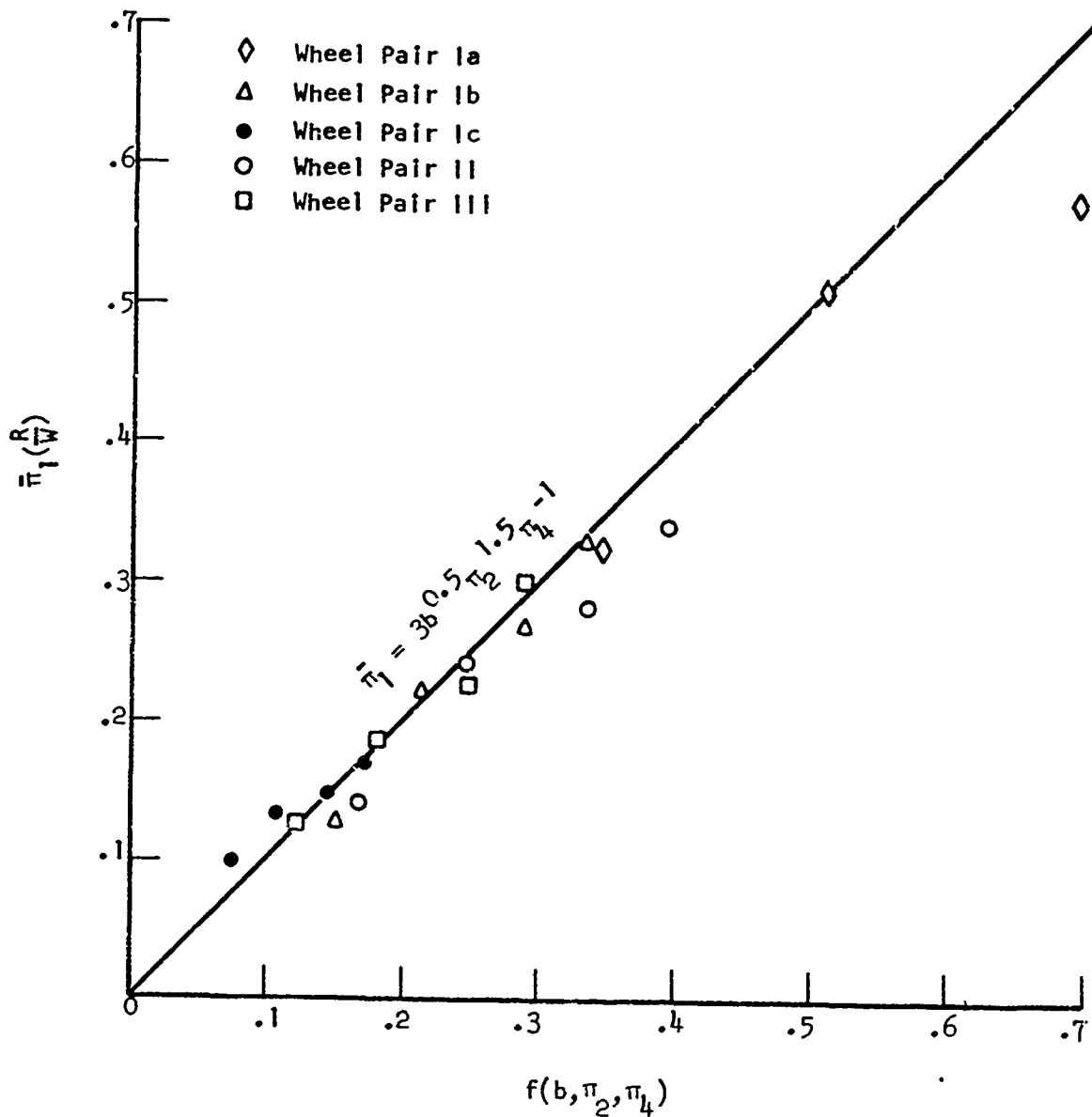
FIGURE 18. COMPARISON OF EQUATION (36)
WITH MEASURED DATA

## C. Motion Resistance of Tandem Wheels

### 1. $\pi_1$ (R/W) and $\pi_3$ ($\ell$/D)

As described above, log plots were made of $\pi_1$ vs. $\pi_3$ for various aspect ratios and weights (see Figure 19). It was determined, as in the previous case, that the R/W ratio did not vary with spacing or varied so little that it was negligible. For this reason the exponent of the $\pi_3$ term for tandem wheels was also set to zero and removed from the functional relationship of Equation (20). Similarly, a representative value of $\pi_1$ (designated $\bar{\pi}_1$) was read from the plot at the intersection of the horizontal fitting line with the $\pi_1$ axis.

### 2. $\bar{\pi}_1$ (R/W) and $\pi_4$ ($k_\varphi b^{n+2}$/W) Relationship

A plot was then made of $\log \bar{\pi}_1$ vs. $\log \pi_4$ for each set of wheels. (Table VI and Figure 20). Once again the lines connecting all of the points for each wheel were drawn parallel to one another. From the measured slope of the lines and each line's intercept at $\log$ 1, the following relationships were generated:

Wheel Pair $I_a$

Wheel Pair $I_b$
$$\bar{\pi}_1 = 0.42 \, \pi_4^{-0.39} \tag{40}$$

Wheel Pair II
$$\bar{\pi}_1 = 0.388 \, \pi_4^{-0.39} \tag{41}$$

Wheel Pair III
$$\bar{\pi}_1 = 0.469 \, \pi_4^{-0.39} \tag{42}$$

It will be noted in Figure 20 that the data for wheel pair Ic falls far away from that of Ia and Ib. These points were determined to erroneous upon comparing them with single wheel resistance readings
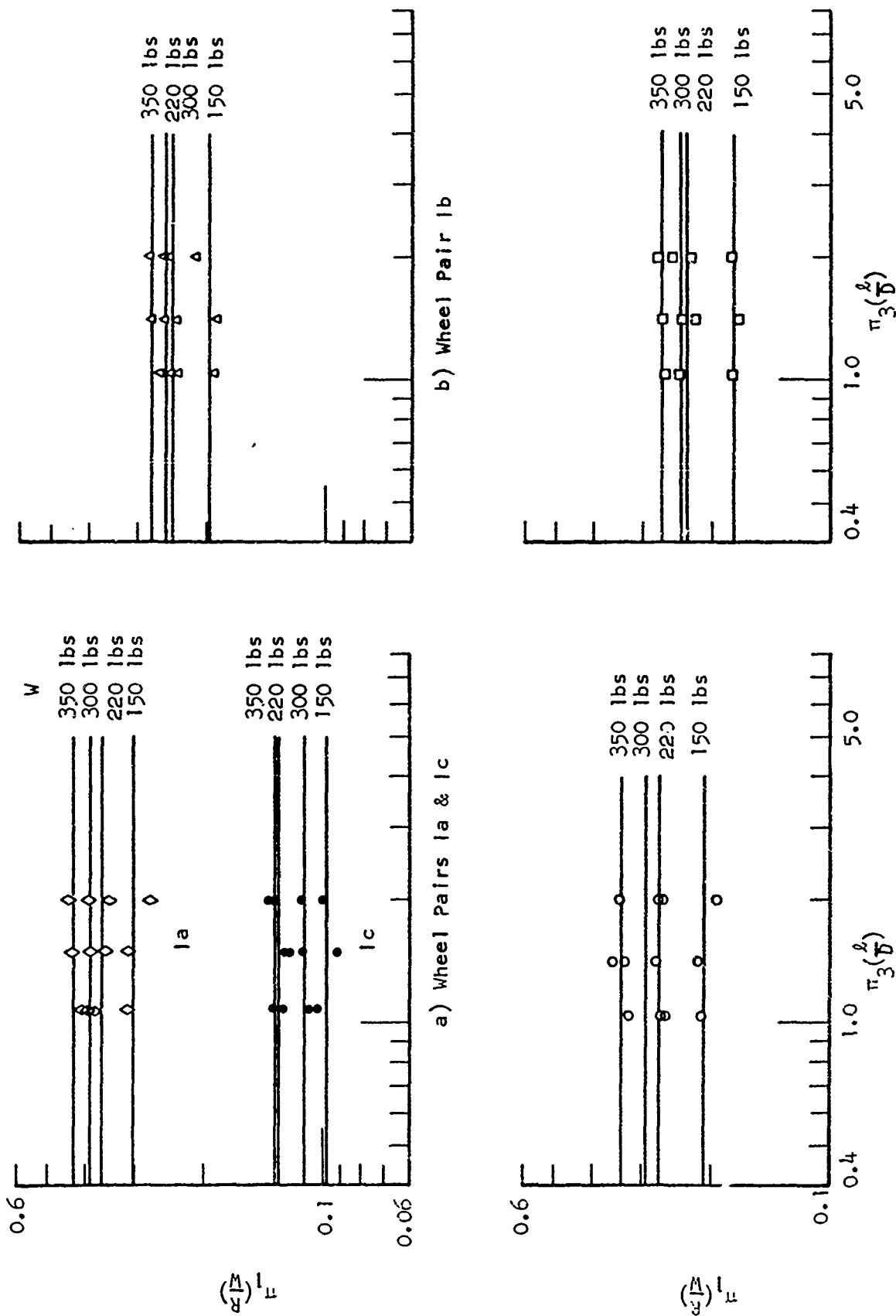
FIGURE 19. PLOTS SHOWING THE INFLUENCE OF TANDEM WHEEL
SPACING ON MOTION RESISTANCE

Table VI

$\bar{\pi}_1$ and $\pi_4$ Values for Motion Resistance of Tandem Wheels

Wheel Pair No.

| Load (lb) | $I_a$ | | $I_b$ | | $I_c$ | | II | | III | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ |
| 150 | 0.302 | 2.241 | 0.197 | 6.348 | 0.098 | 14.248 | 0.208 | 4.10 | 0.176 | 9.806 |
| 220 | 0.364 | 1.532 | 0.254 | 4.34 | 0.128 | 9.741 | 0.270 | 2.803 | 0.231 | 6.706 |
| 300 | 0.390 | 1.124 | 0.245 | 3.184 | 0.111 | 7.147 | 0.293 | 2.057 | 0.240 | 4.919 |
| 350 | 0.430 | 0.959 | 0.276 | 2.718 | 0.132 | 6.10 | 0.338 | 1.755 | 0.268 | 4.198 |
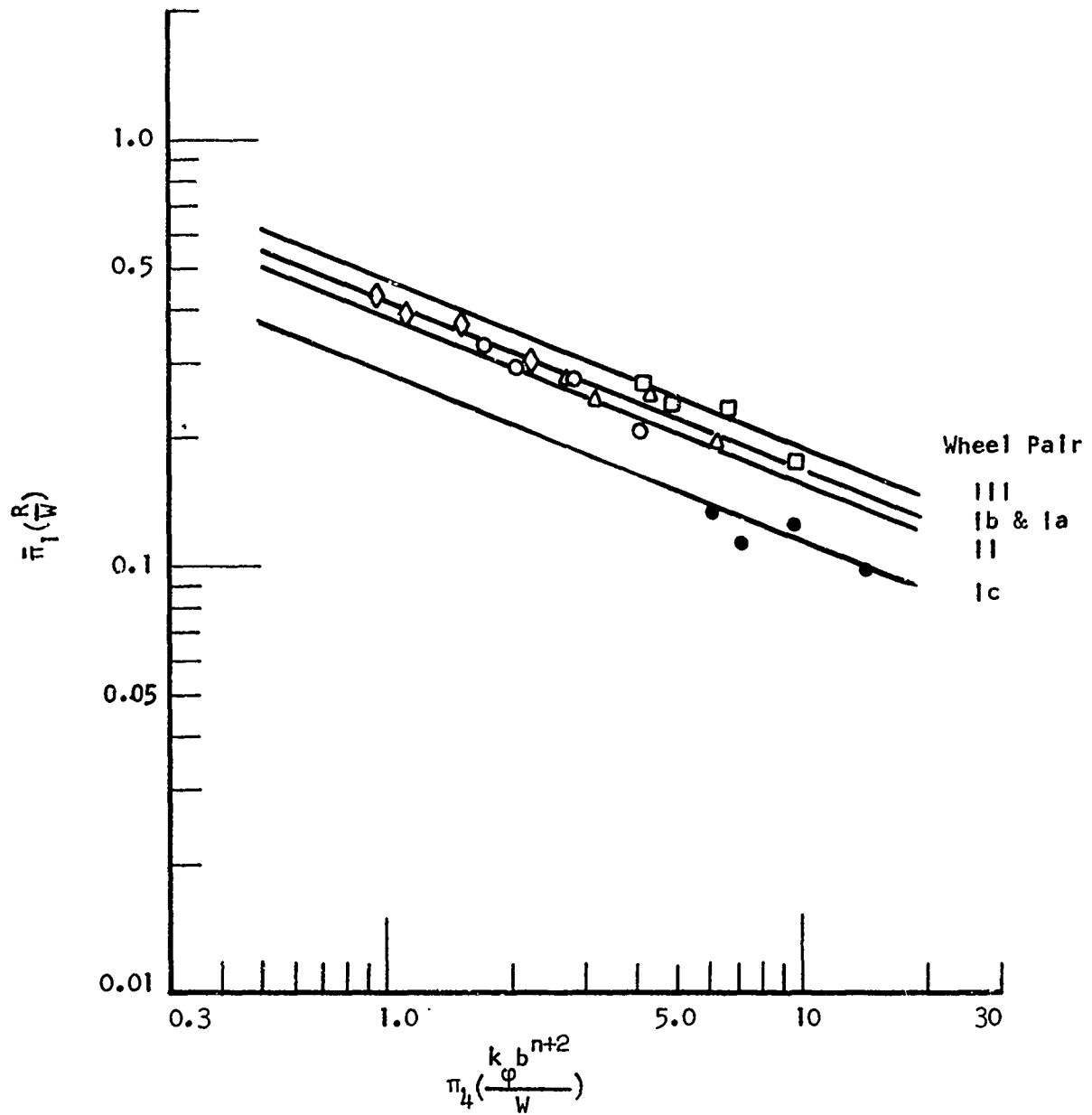
FIGURE 20. PLOTS SHOWING THE RELATIONSHIP BETWEEN
WHEEL WIDTH AND MOTION RESISTANCE OF TANDEM WHEELS

for the three similar wheels. The tandem resistance readings for the large wheel were 25% to 40% lower than those for the other wheels. These points were therefore neglected in the calculations which follow.

Since the points for the two remaining similar wheels fell in a single line, there appeared to be no distortion of motion resistance due to scale effects.

### 3. $\bar{\pi}_1$ (R/W) and $\pi_2$ (b/D) Relationship

To complete the functional relationship, a plot was next made of log $\bar{\pi}_1$ vs. log $\pi_2$ at a constant value of $\pi_4$ equal to one. From Figure 21

$$\bar{\pi}_1 = 1.02\pi_2^{0.66} \tag{43}$$

### 4. Complete Function Relationship

The complete functional relationship then becomes:

$$\bar{\pi}_1 = F(\pi_2,\pi_4) = \frac{F(\bar{\pi}_2,\pi_4)F(\pi_2,\bar{\pi}_4)}{F(\bar{\pi}_2,\bar{\pi}_4)} = \frac{(0.42\pi_4^{-0.39})(1.02\pi_2^{0.66})}{0.42}$$

$$\bar{\pi}_1 = 1.02\pi_2^{0.66}\,\pi_4^{-0.39} \tag{44}$$

A simplified version of Equation (44) would be

$$\bar{\pi}_1 = \pi_2^{2/3}\,\pi_4^{-1/3} \tag{45}$$

Expressed in terms of the problem variables, Equation (45) becomes:
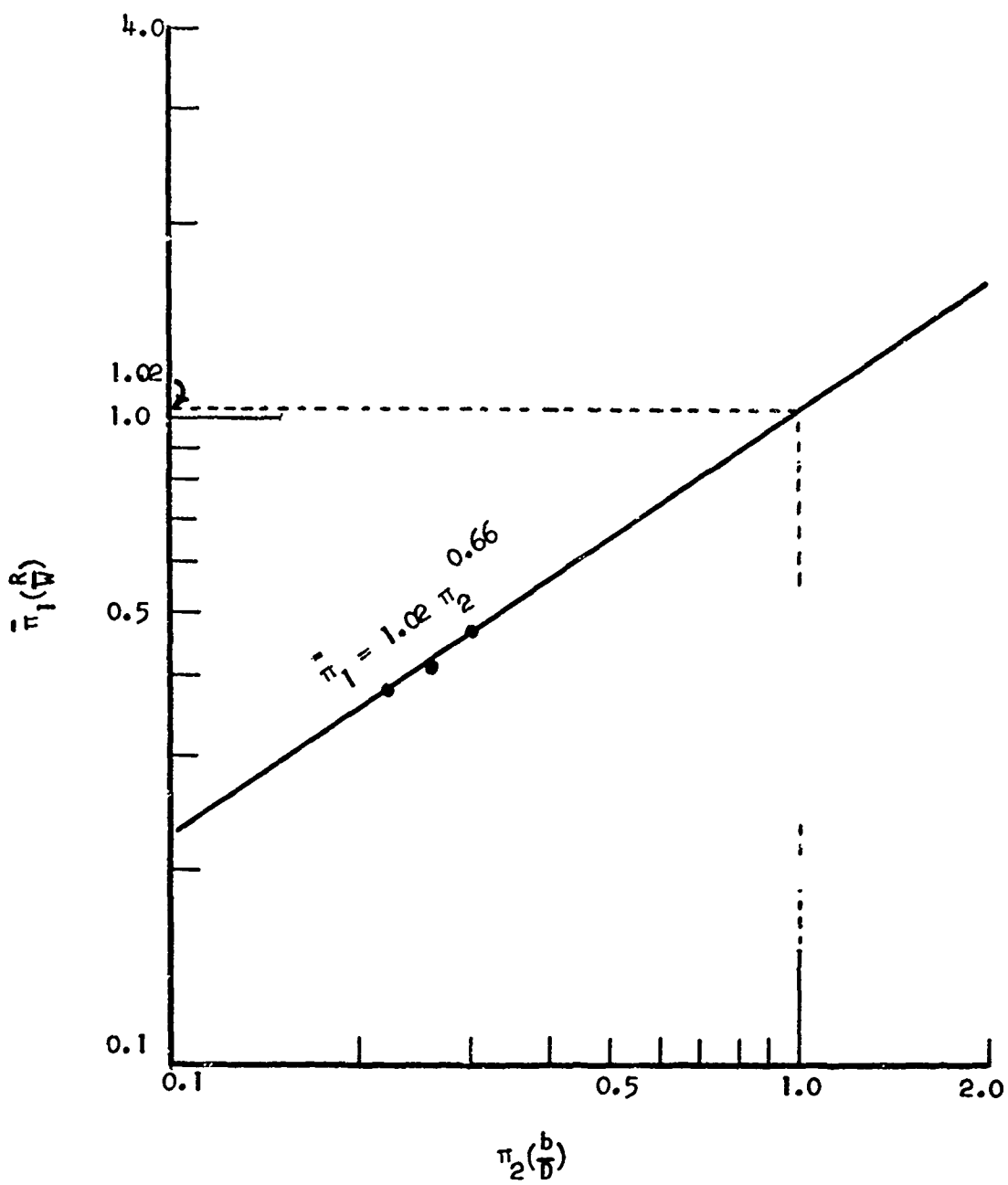
FIGURE 21.  $\bar{\bar{\pi}}_1$ vs $\pi_2$ FOR MOTION RESISTANCE
OF TANDEM WHEELS

$$F = \frac{W^{4/3}}{D^{2/3} \, k_\varphi^{1/3} \, b^{n/3}} \tag{46}$$

Figure 22 shows a plot of the measured values of $\bar{\pi}_1$ compared with calculated value utilizing Equation (45).

5. Comparison with Letoshnev's Equation

Bekker presented an equation[11] introduced by Letoshnev for motion resistance of tandem, towed wheels of the same width. The equation based on a value of $n$ equal to one-half is:

$$R \approx 1.6 \, \frac{W^{3/2}}{b^{.5} \, k^{1/2} \, D^{3/4}} \tag{47}$$

Equation (46) was expressed in similar terms and $n = 1.15$ becomes:

$$R = \frac{W^{4/3}}{b^{0.38} \, k_\varphi^{1/3} \, D^{2/3}} \tag{48}$$

D. Sinkage of Dual Wheels

An analysis of $\pi_1(\frac{z}{D})$ vs. $\pi_3(\frac{s}{D})$ shown in Figure 23 also indicates that the exponent of $\pi_3$ is zero. Then a comparison of $\bar{\pi}_1$ vs. $\pi_4$, shown in Table VII and Figure 24 yields the following relationships:

Wheel Pair $I_a$

Wheel Pair $I_b$    ;    $\bar{\pi}_1 = 0.218 \, \pi_4^{-1.11}$ $\qquad$ (49)
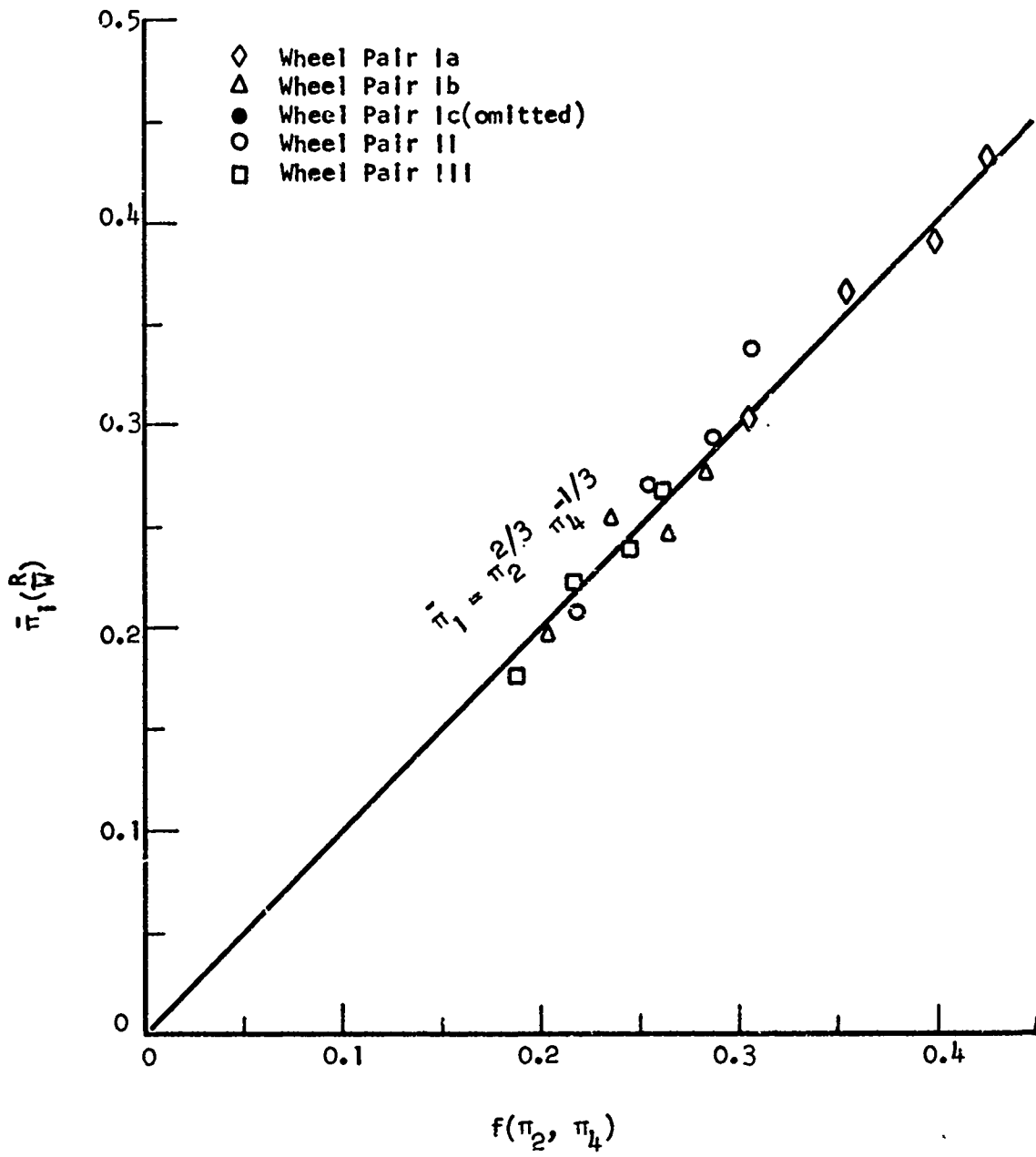
Wheel Pair $I_c$

FIGURE 22.  COMPARISON OF EQUATION (45)
WITH MEASURED DATA
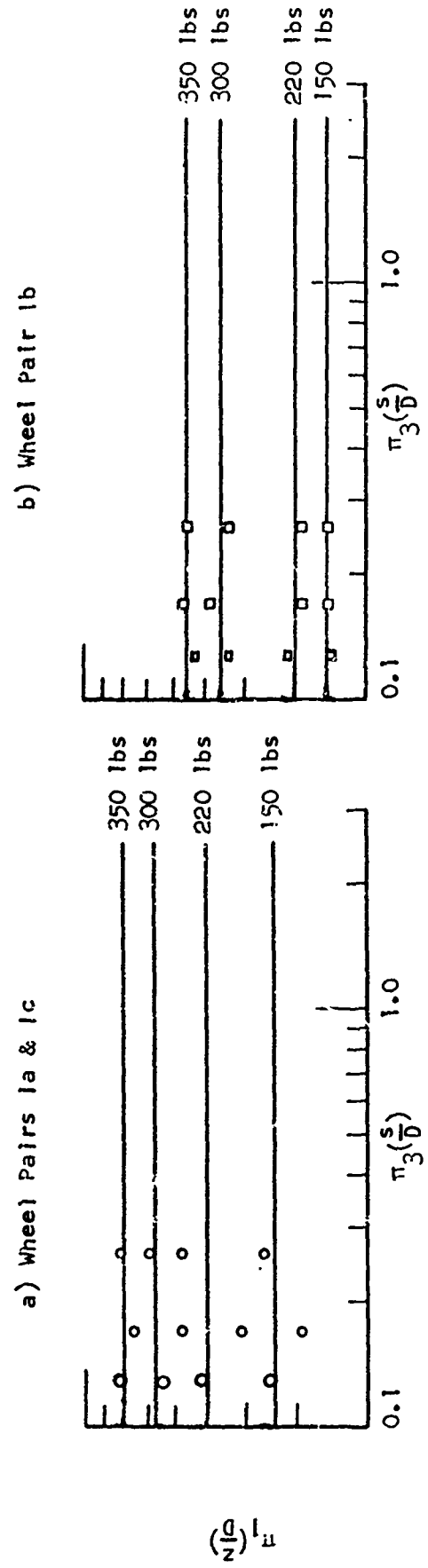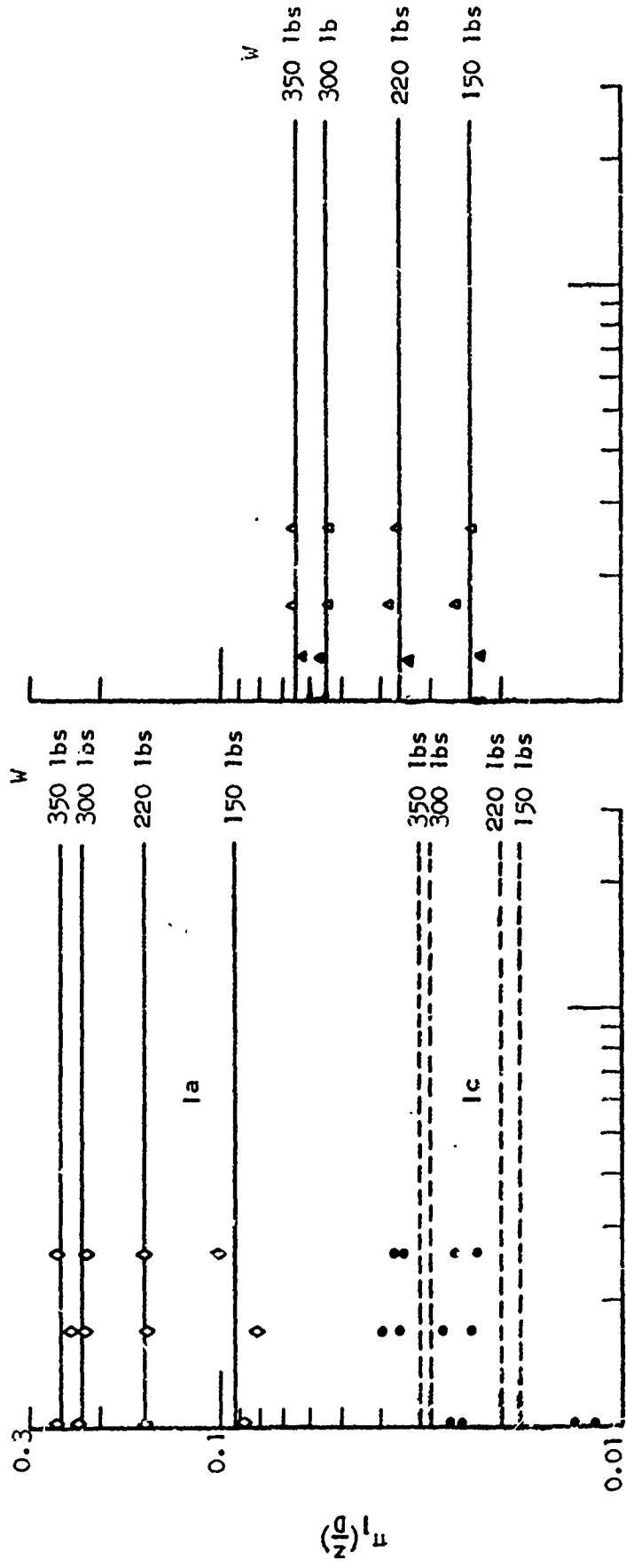
FIGURE 23. PLOTS SHOWING THE INFLUENCE OF DUAL WHEEL SPACING ON SINKAGE

53

Table VII

$\bar{\pi}_1$ and $\pi_4$ Values for Sinkage of Dual Wheels

Wheel Pair No.

| Load (lb) | $I_a$ | | $I_b$ | | $I_c$ | | II | | III | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ |
| 150 | 0.092 | 2.241 | 0.024 | 6.348 | 0.018 | 14.248 | 0.034 | 4.100 | 0.025 | 9.806 |
| 220 | 0.155 | 1.532 | 0.036 | 4.340 | 0.020 | 9.741 | 0.050 | 2.303 | 0.030 | 6.706 |
| 300 | 0.222 | 1.124 | 0.055 | 3.184 | 0.030 | 7.147 | 0.064 | 2.057 | 0.055 | 4.919 |
| 350 | 0.250 | 0.959 | 0.066 | 2.718 | 0.032 | 6.100 | 0.080 | 1.755 | 0.055 | 4.198 |
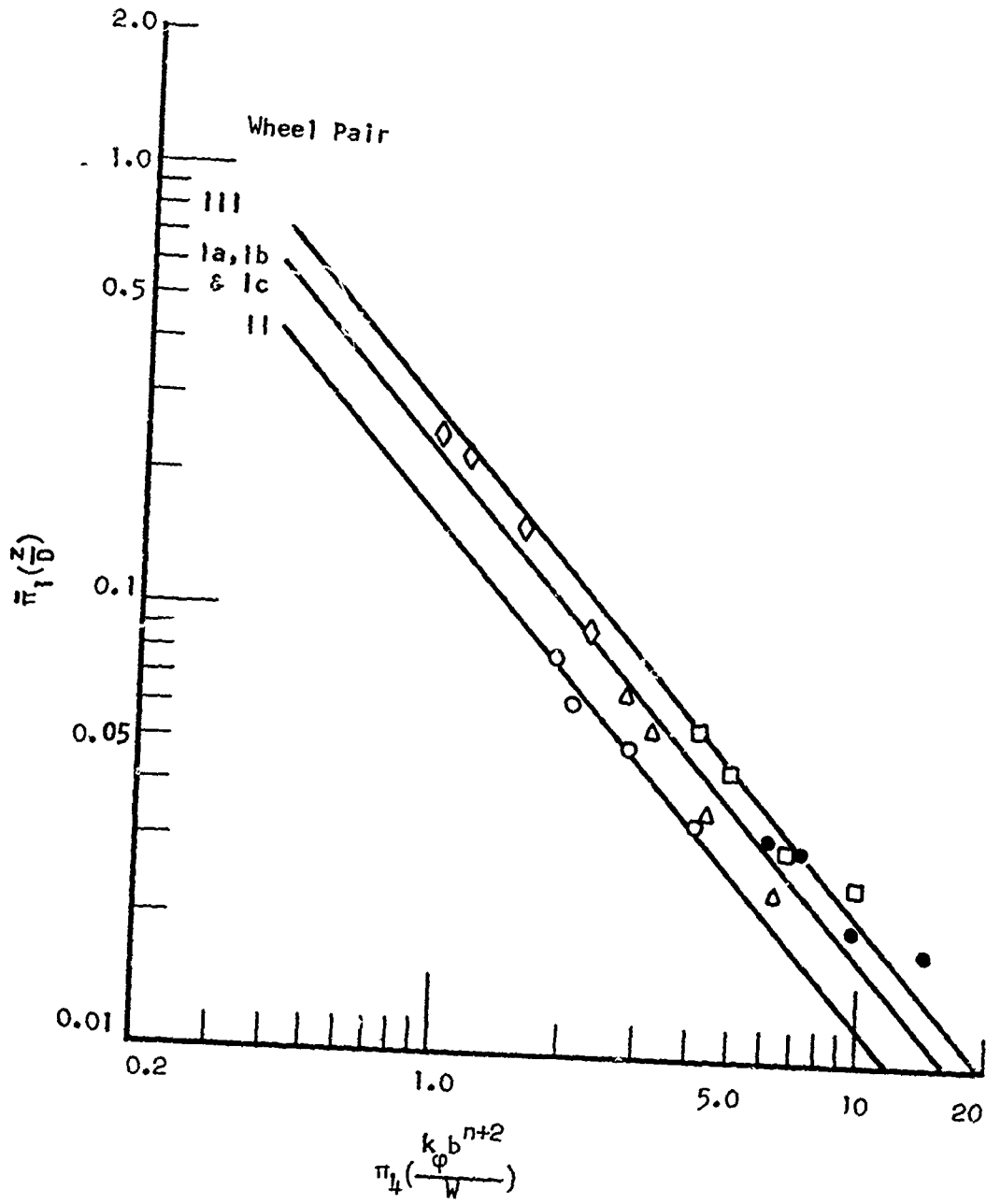
FIGURE 24. PLOTS SHOWING THE RELATIONSHIP OF
SINKAGE TO WHEEL WIDTH FOR DUAL WHEELS

$$\text{Wheel Pair II} \quad ; \quad \bar{\pi}_1 = 0.155 \, \pi_4^{-1.11} \tag{50}$$

$$\text{Wheel Pair III} \quad ; \quad \bar{\pi}_1 = 0.269 \, \pi_4^{-1.11} \tag{51}$$

Figure 25 then develops the relationship between $\bar{\pi}_1$ and $\pi_2$:

$$\bar{\pi}_1 = 2.73 \, \pi_2^{1.9} \tag{52}$$

Hence, the final relationship becomes

$$\bar{\pi}_1 = F(\pi_2, \pi_4) = \frac{F(\bar{\pi}_2, \pi_4) F(\pi_2, \bar{\pi}_4)}{F(\bar{\pi}_2, \bar{\pi}_4)} = \frac{(0.218\pi_4^{-1.11})(2.73\pi_2^{1.9})}{0.215}$$

$$\bar{\pi} = 2.77\pi_2^{1.9} \, \pi_4^{-1.11} \tag{53}$$

which can be simplified to

$$\bar{\pi}_1 = 3\pi_2^2 \, \pi_4^{-1} \tag{54}$$

or, in the problem variables, to:

$$z = \frac{3W}{b^n \, k_\varphi D} \tag{55}$$

Figure 26 shows the accuracy of Equation (54). It should be noted that two points for wheel pair $I_a$ were very poorly predicted. These points were for the 300 and 350 pound loads which had a very high skid rate.

Bekker's prediction for rigid wheel sinkage, for $k_\varphi = 4.7$ and $n = 1.15$ is
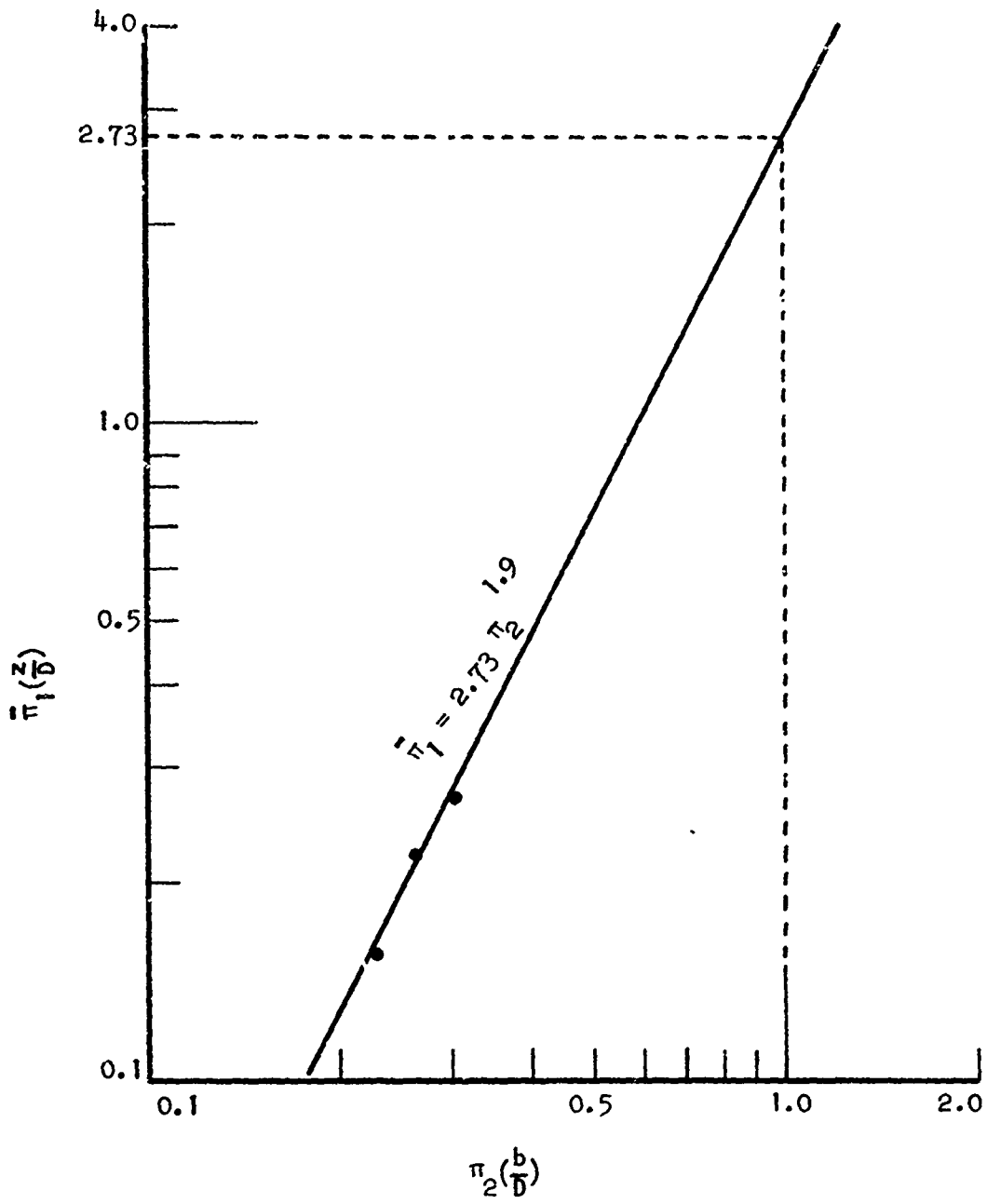
FIGURE 25. $\bar{\pi}_1$ vs $\pi_2$ FOR DUAL WHEEL SINKAGE
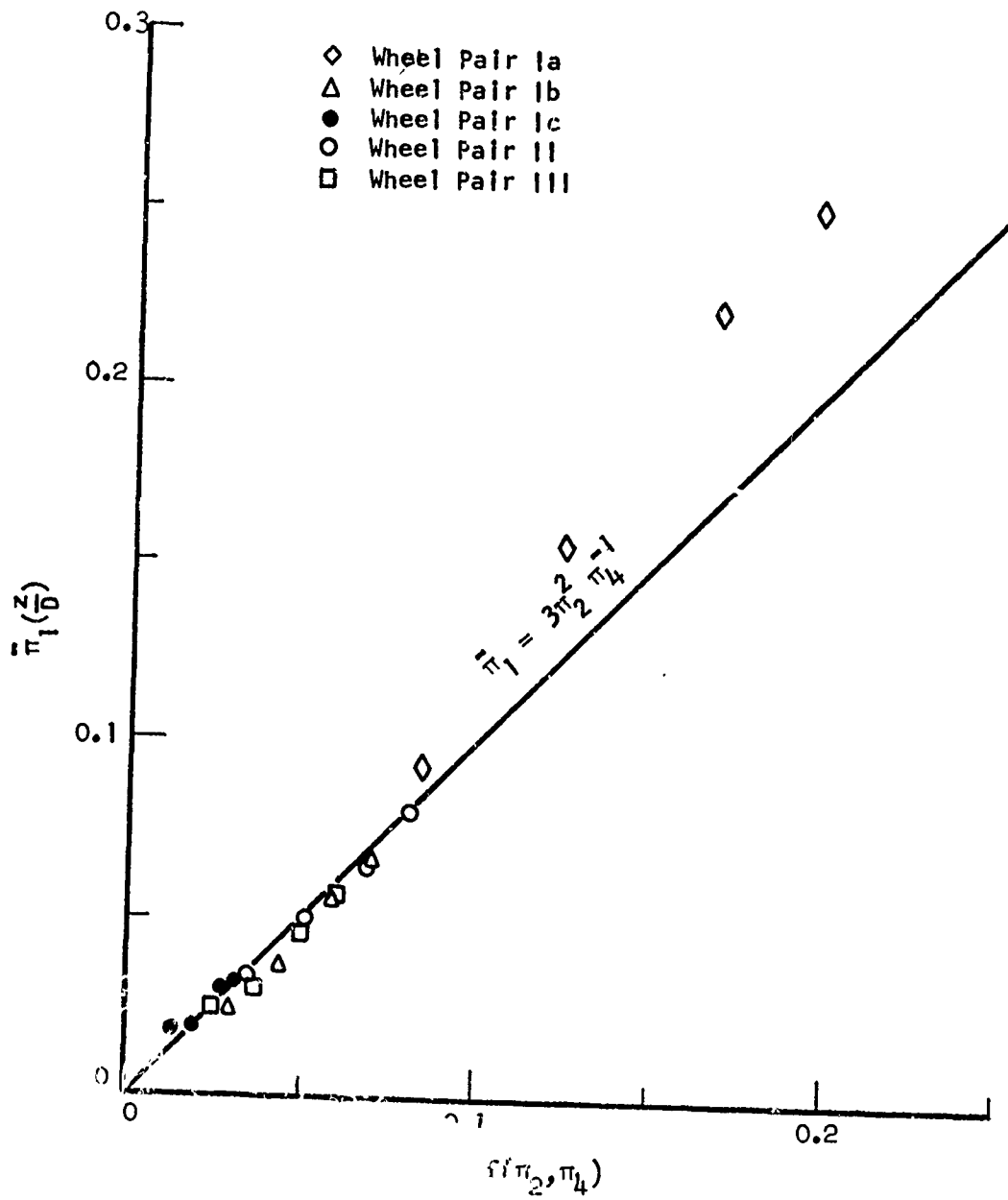
FIGURE 26. COMPARISON OF EQUATION (54) WITH MEASURED DATA

$$z = \frac{0.53W^{.6}}{b^{.6}D^{.3}} \qquad (56)$$

but cautions that, for dry sandy soils it would not be accurate at high slip rates. For similar values, Equation (55) becomes

$$z = \frac{0.64\ W}{b^{1.15}D} \qquad (57)$$

### E. Sinkage of Tandem Wheels

Since the front and rear wheels of a tandem combination may sink to different depths, the analysis of the front and rear wheels were conducted separately.

For the front wheels, a log plot of $\pi_1 (\frac{z}{D})$ vs. $\pi_3 (\frac{\ell}{D})$ again demonstrated (Figure 27) that $\pi_1$ was independent of $\pi_3$ and that the exponent of $\pi_3$ should be zero. The data of $\bar{\pi}_1$ vs. $\pi_4$ (Table VIII and Figure 28) show the following relationships:

Wheel Pair I$_a$

Wheel Pair I$_b$ ; $\bar{\pi}_1 = 0.3\ \pi_4^{-0.772}$ $\qquad (58)$

Wheel Pair I$_c$

Wheel Pair II ; $\bar{\pi}_1 = 0.244\ \pi_4^{-0.772}$ $\qquad (59)$

Wheel Pair III ; $\bar{\pi}_1 = 0.378\ \pi_4^{-0.772}$ $\qquad (60)$

From these equations and Figure 29, was generated

$$\bar{\pi}_1 = 2.36\ \pi_2^{1.53} \qquad (61)$$

Finally, the complete functional relationship becomes
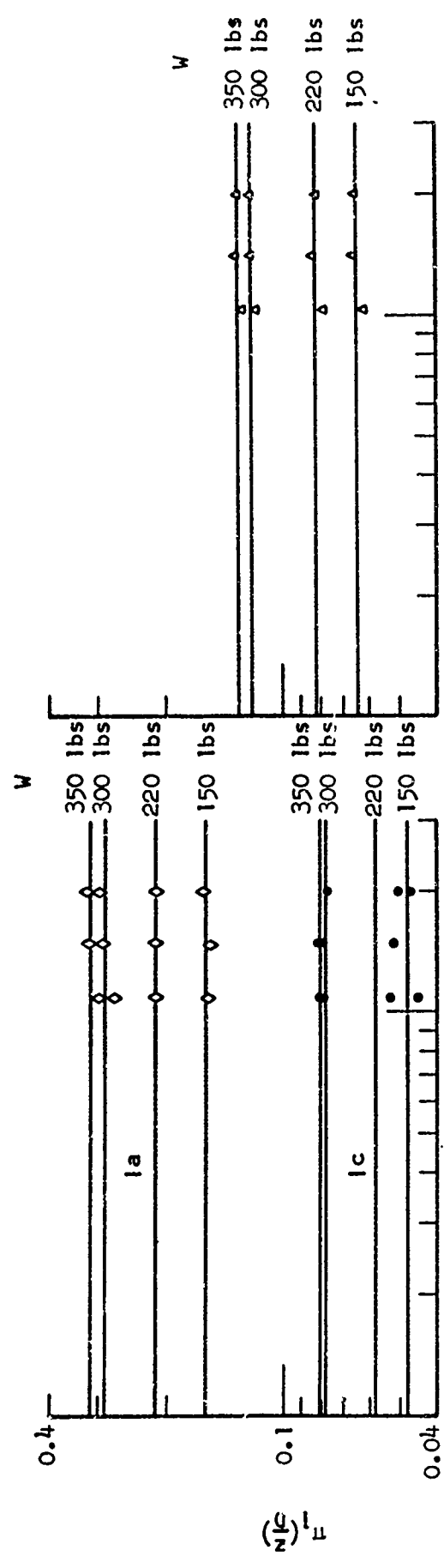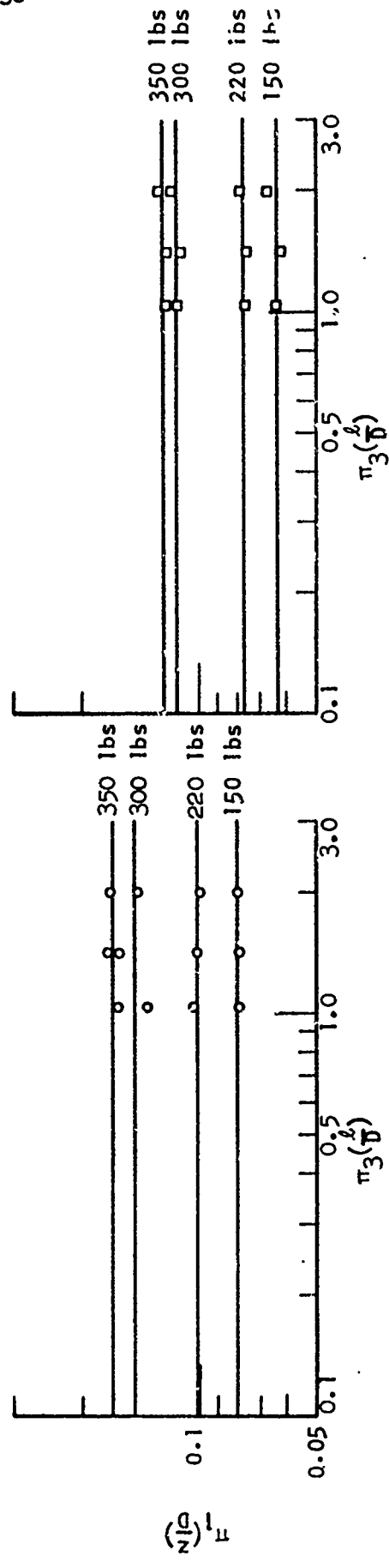
FIGURE 27. PLOTS SHOWING THE INFLUENCE OF TANDEM WHEEL SPACING
ON THE SINKAGE OF THE FRONT WHEEL

Table VIII

$\bar{\pi}_1$ and $\pi_4$ Values for Sinkage of the Front Tandem Wheel

Wheel Pair No.

| Load (lb) | I$_a$ | | I$_b$ | | I$_c$ | | II | | III | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ |
| 150 | 0.159 | 2.241 | 0.064 | 6.348 | 0.048 | 14.248 | 0.080 | 4.100 | 0.063 | 9.806 |
| 220 | 0.213 | 1.532 | 0.082 | 4.340 | 0.058 | 9.741 | 0.102 | 2.803 | 0.077 | 6.706 |
| 300 | 0.286 | 1.124 | 0.120 | 3.184 | 0.078 | 7.147 | 0.148 | 2.057 | 0.114 | 4.919 |
| 350 | 0.312 | 0.959 | 0.130 | 2.718 | 0.080 | 6.100 | 0.168 | 1.755 | 0.124 | 4.198 |

FIGURE 28. PLOTS SHOWING THE RELATIONSHIP BETWEEN
WHEEL WIDTH AND THE SINKAGE OF THE FRONT TANDEM WHEEL
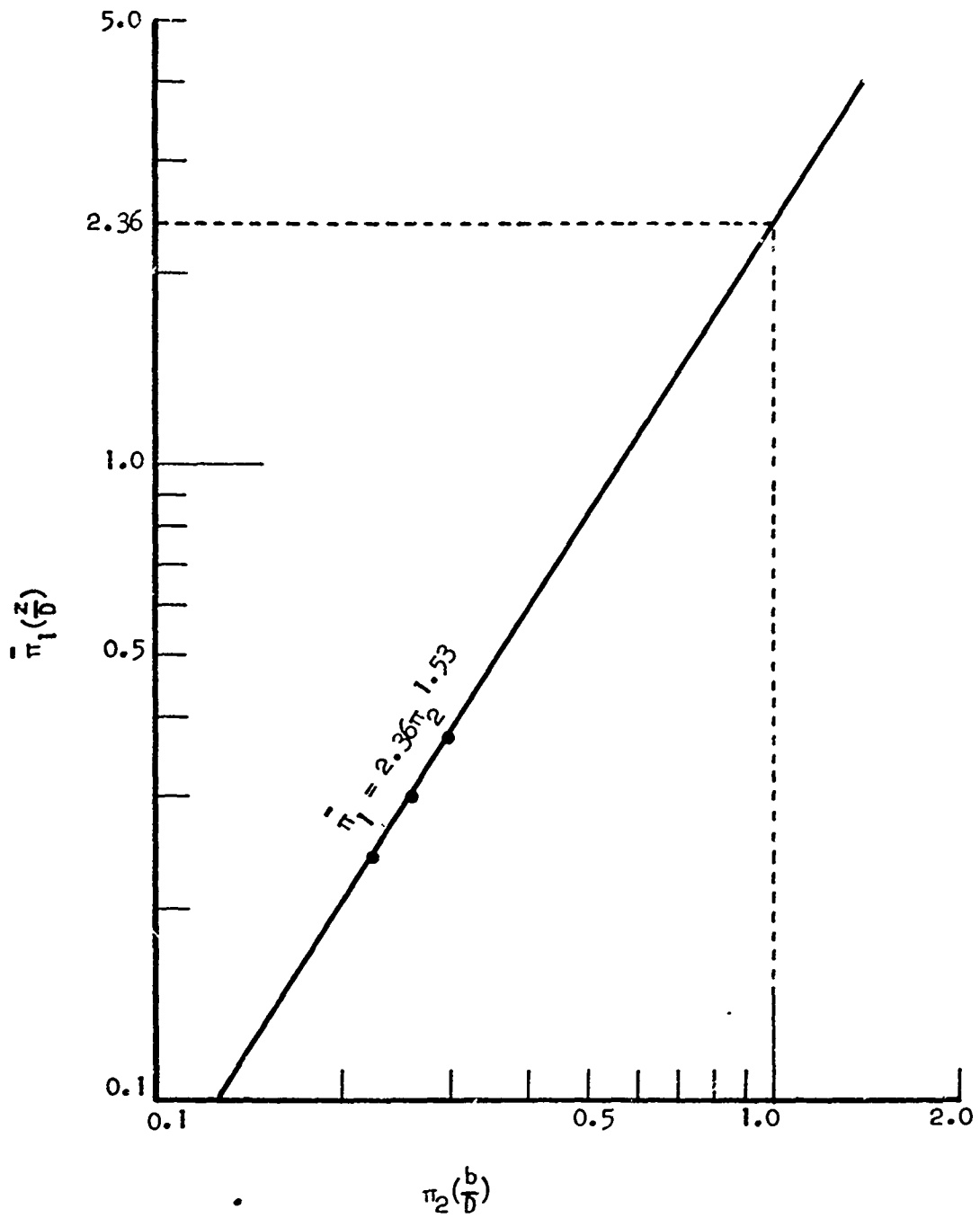
FIGURE 29. $\bar{\pi}_1$ vs $\pi_2$ FOR FRONT TANDEM WHEEL SINKAGE

$$\bar{\bar{\pi}}_1 = F(\pi_2, \pi_4) = \frac{F(\bar{\pi}_2, \pi_4)F(\pi_2, \bar{\pi}_4)}{F(\bar{\pi}_2, \bar{\pi}_4)} = \frac{(0.3\pi_4^{-0.772})(2.36\pi_2^{1.53})}{0.3}$$

$$\bar{\bar{\pi}}_1 = 2.36\ \pi_2^{1.53}\ \pi_4^{-0.772} \tag{62}$$

Equation (62) may be approximated by

$$\bar{\pi}_1 = 2.5\pi_2^{3/2}\ \pi_4^{-3/4} \tag{63}$$

Or, in the problem variables, Equation (63) becomes

$$z_F = \frac{2.5W^{0.75}}{D^{0.5}b^{0.75}n_{k_\varphi}^{0.75}} \tag{64}$$

A comparison of Equation (63) with the measured data is pre-sented in Figure 30.

Bekker's prediction for rigid wheels with $k_\varphi = 4.7$ and $n = 1.15$ is

$$z = \frac{0.53W^{0.6}}{b^{0.6}D^{0.3}} \tag{56}$$

For the same parameters, Equation (64) becomes

$$z_F = \frac{0.78W^{0.75}}{b^{0.86}D^{0.5}} \tag{65}$$

For the rear wheels of a tandem pair, a log plot of $\pi_1$ vs. $\pi_3$ also predicts that the exponent of $\pi_3$ should be zero (see Figure 31). Table IX and the corresponding plot (Figure 32) yields the following relationship:
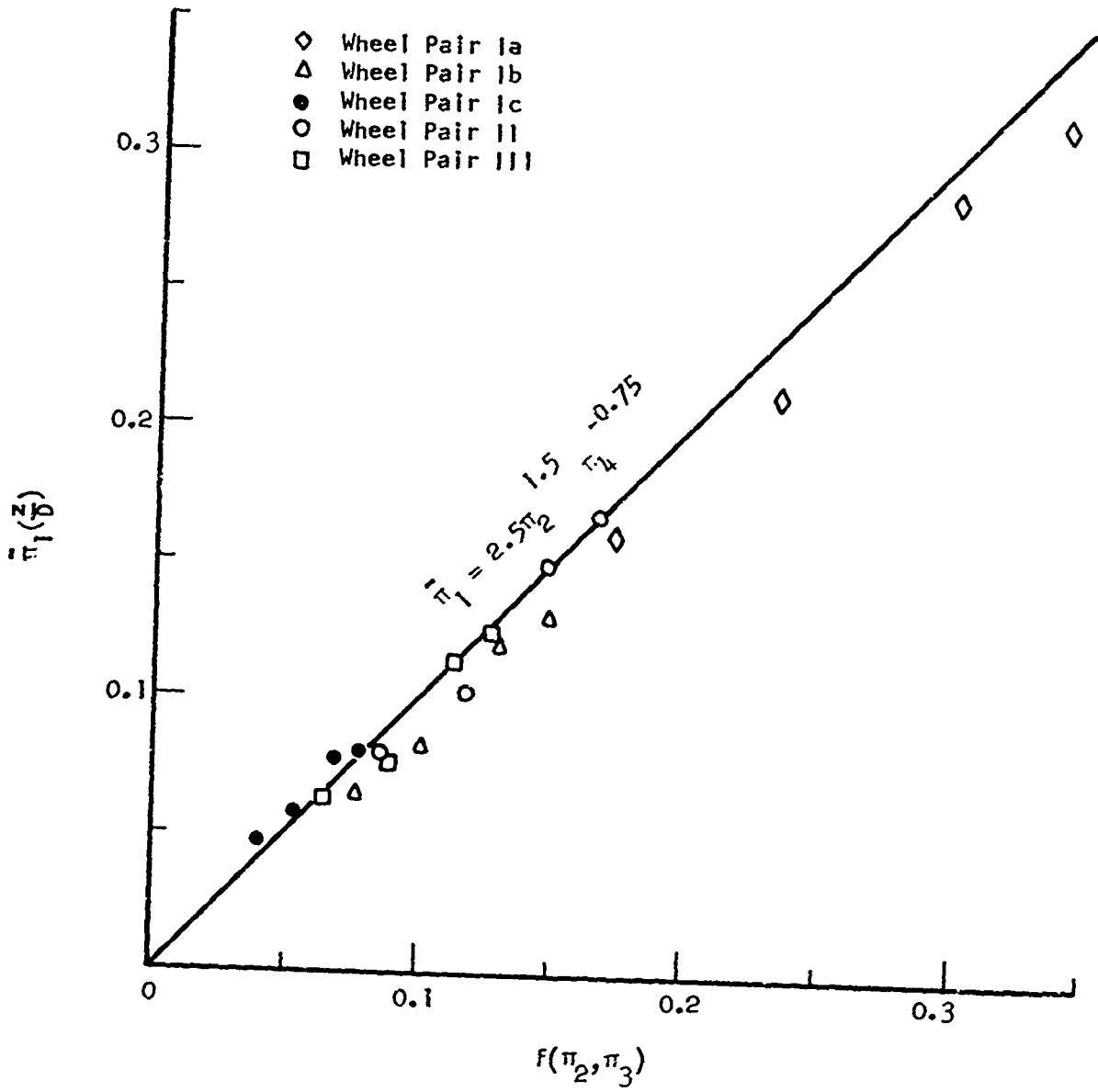
FIGURE 30. COMPARISON OF EQUATION (63)
WITH MEASURED DATA

66
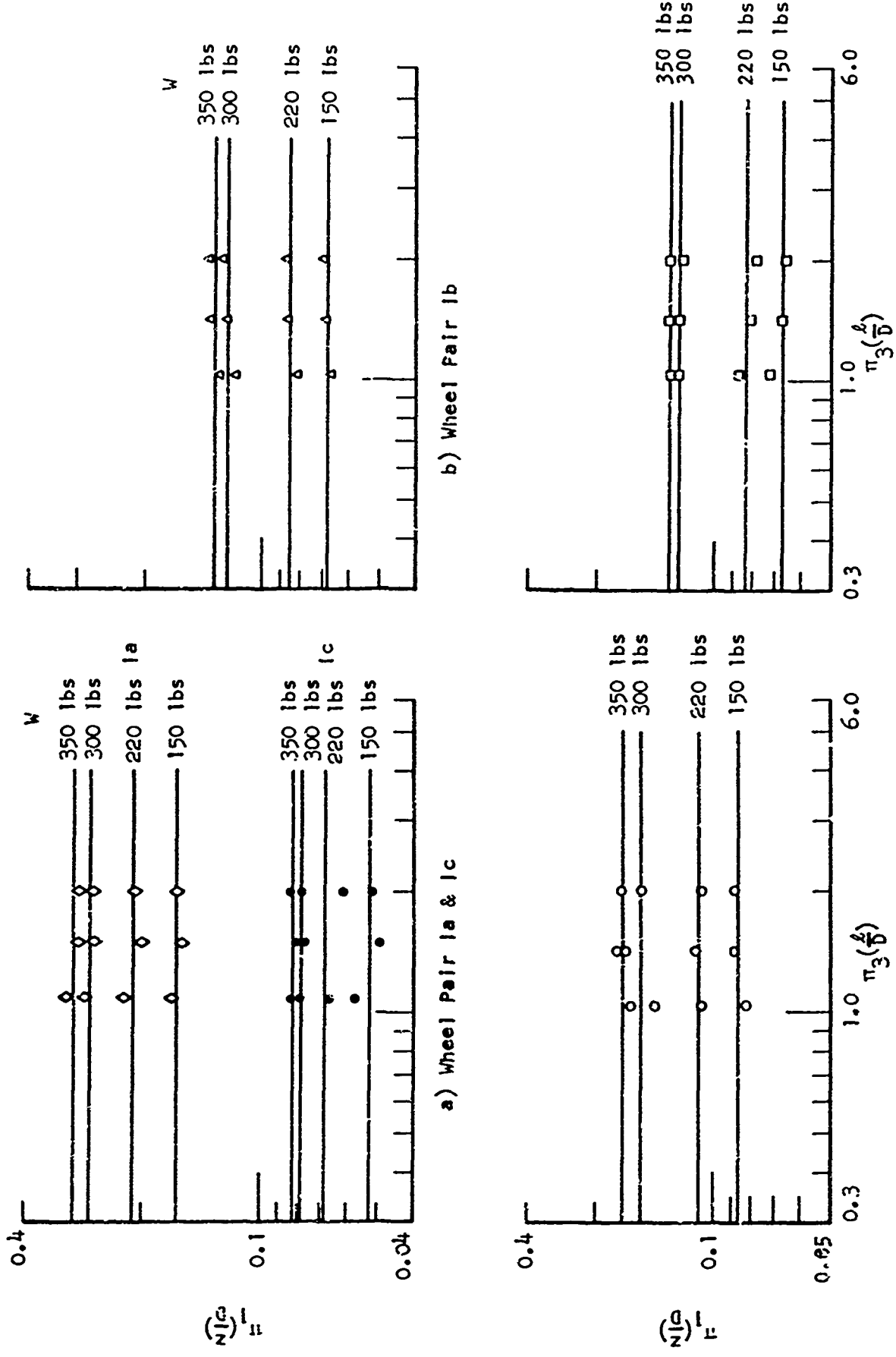


FIGURE 31. PLOTS SHOWING THE INFLUENCE OF TANDEM WHEEL SPACING
ON THE SINKAGE OF THE REAR WHEEL

Table IX

$\bar{\pi}_1$ and $\pi_4$ Values for Sinkage of the Rear Tandem Wheel

Wheel Pair No.

| Load (lb) | $I_a$ | | $I_b$ | | $I_c$ | | II | | III | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ | $\bar{\pi}_1$ | $\pi_4$ |
| 150 | 0.163 | 2.241 | 0.068 | 6.348 | 0.052 | 14.248 | 0.086 | 4.100 | 0.067 | 9.806 |
| 220 | 0.210 | 1.532 | 0.085 | 4.340 | 0.068 | 9.741 | 0.108 | 2.803 | 0.083 | 6.706 |
| 300 | 0.271 | 1.124 | 0.123 | 3.184 | 0.078 | 7.147 | 0.153 | 2.057 | 0.122 | 4.919 |
| 350 | 0.299 | 0.959 | 0.133 | 2.718 | 0.082 | 6.100 | 0.170 | 1.755 | 0.130 | 4.198 |
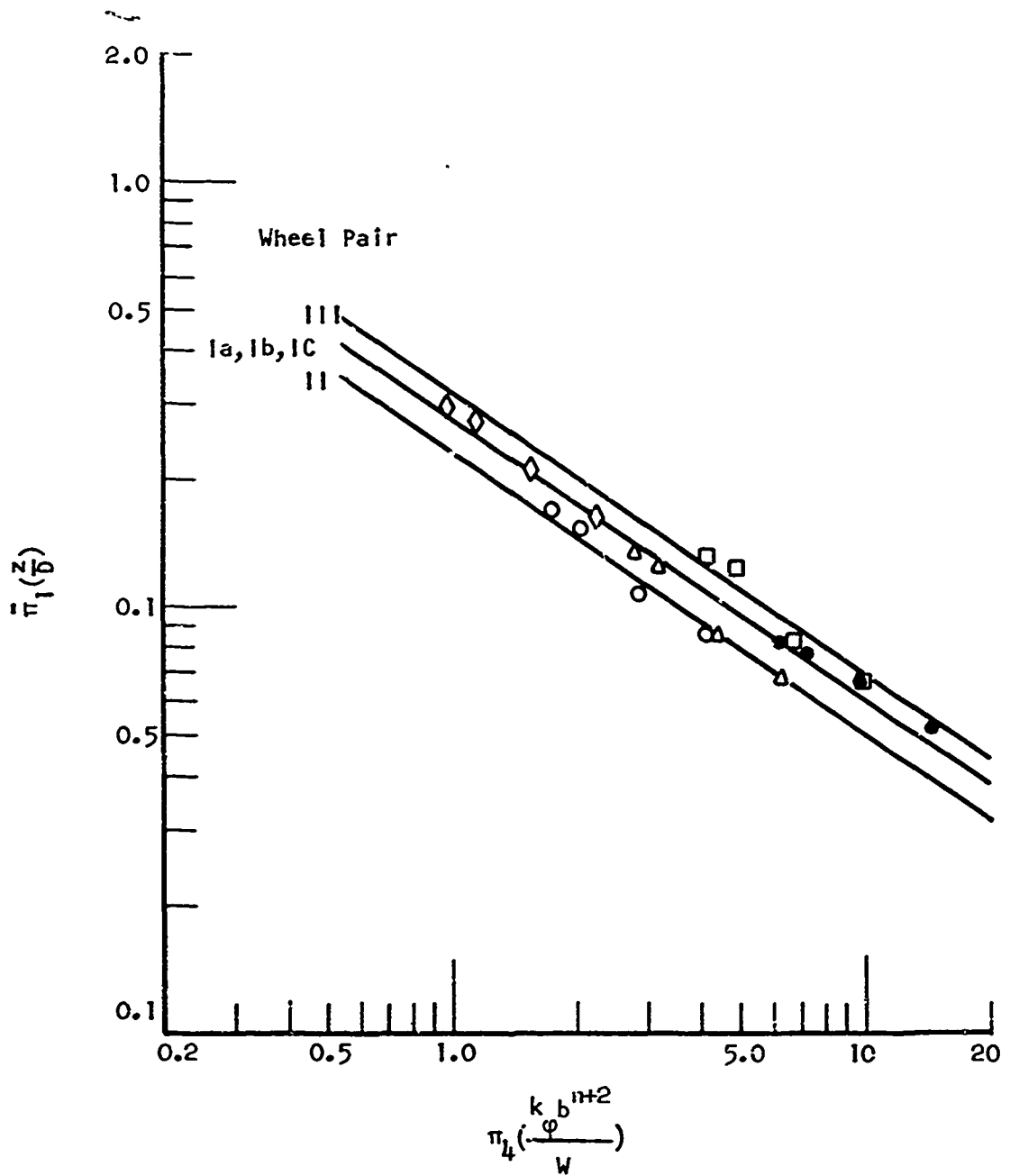
FIGURE 32. PLOTS SHOWING THE RELATIONSHIP BETWEEN
WHEEL WIDTH AND THE SINKAGE OF THE
REAR TANDEM WHEEL

Wheel Pair $I_a$

Wheel Pair $I_b$ ; $\bar{\pi}_1 \approx 0.275 \, \pi_4^{-0.662}$ (66)

Wheel Pair $I_c$

Wheel Pair $II$ ; $\bar{\pi}_1 = 0.23 \, \pi_4^{-0.662}$ (67)

Wheel Pair $III$ ; $\bar{\pi}_1 = 0.318 \, \pi_4^{-0.662}$ (68)

From these equations, Figure 33 may be generated, yielding

$$\bar{\pi}_1 = 1.2 \, \pi_2^{1.1} \tag{69}$$

Finally, the complete functional relationship is:

$$\bar{\pi}_1 = F(\pi_2, \pi_4) = \frac{F(\bar{\pi}_2, \pi_4) F(\pi_2, \bar{\pi}_4)}{F(\bar{\pi}_2, \bar{\pi}_4)} = \frac{(0.275 \, \pi_4^{-0.662})(1.2 \, \pi_2^{1.1})}{0.274}$$

$$\bar{\pi}_1 = 1.2 \pi_2^{1.1} \, \pi_4^{-0.662} \tag{70}$$

which can be simplified to

$$\bar{\pi}_1 = 1.2 \, \pi_2 \, \pi_4^{-2/3} \tag{71}$$

In the problem variables, Equation (71) becomes

$$z_R = \frac{1.2 \, W^{2/3}}{k_\varphi^{2/3}(b^{2n+1})^{1/3}} \tag{72}$$

Interestingly, the parameter $D$ is missing from Equation (72).

Equation (71) is compared with the measured data in Figure 34. Agreement is relatively good, but all the data appear to be a little higher than the fitting curve.
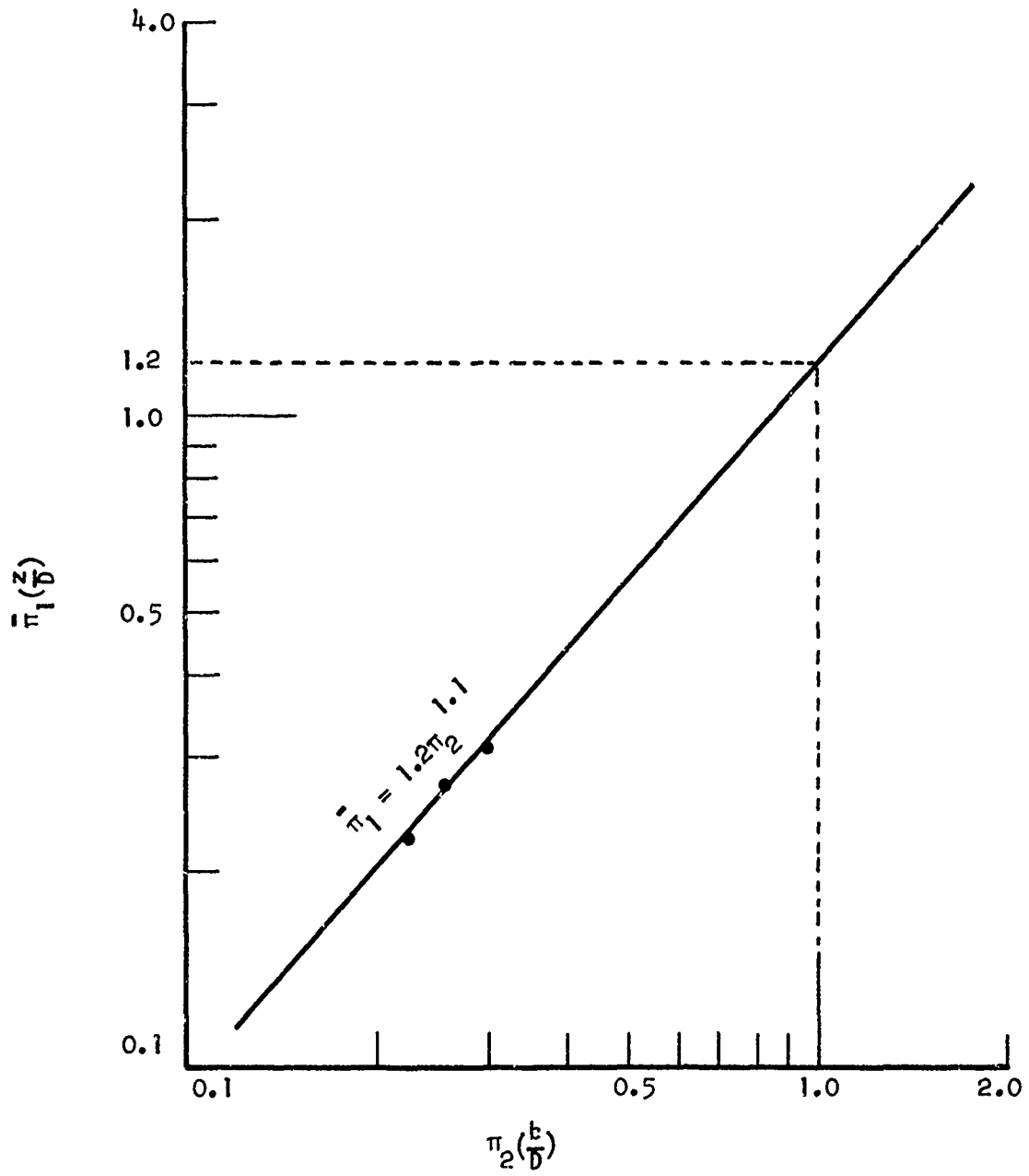
FIGURE 33. $\bar{\pi}_1$ vs $\pi_2$ FOR REAR TANDEM WHEEL SINKAGE
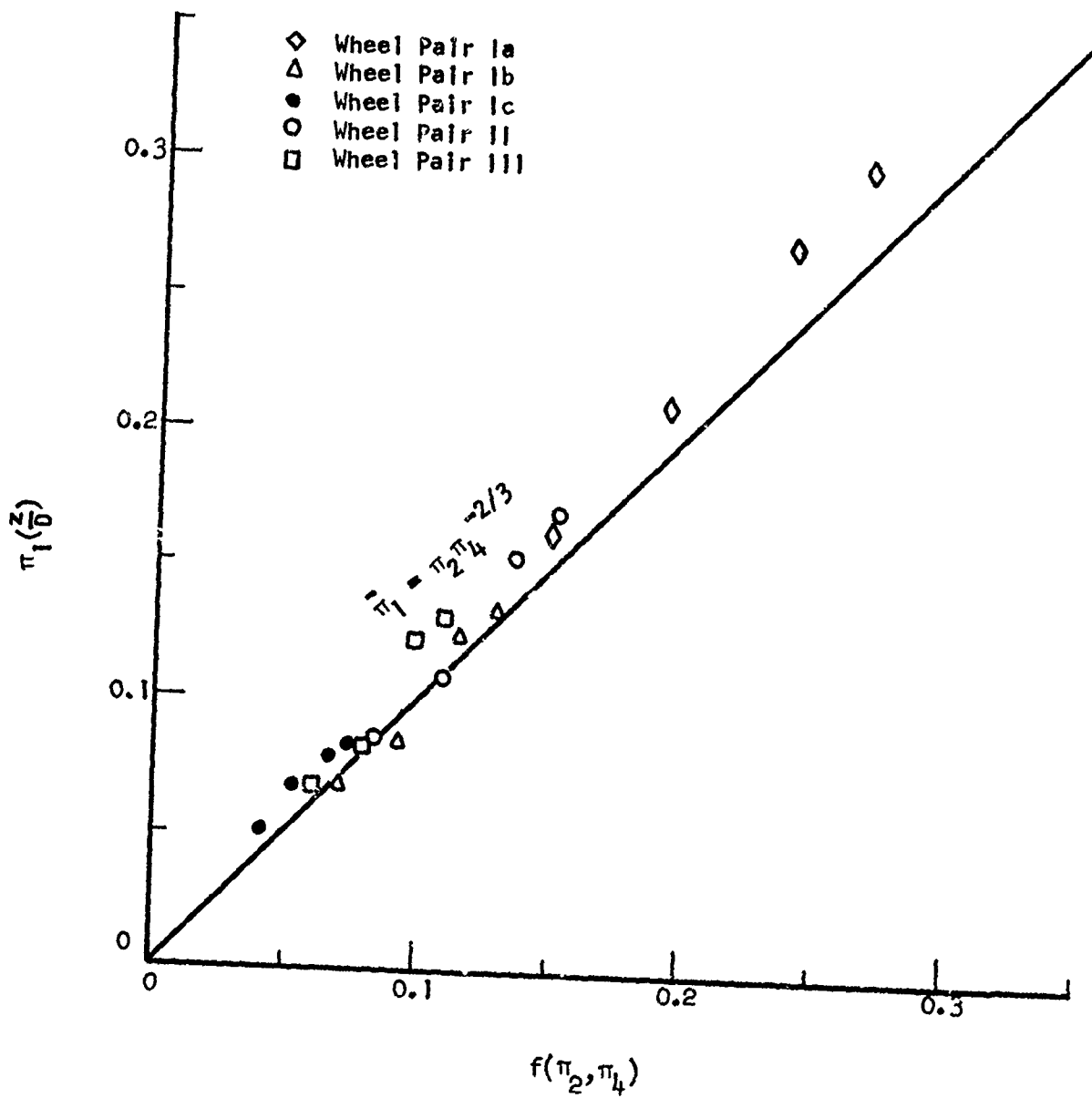
FIGURE 34. COMPARISON OF EQUATION (71) WITH MEASURED DATA

Again, comparing Equation (72) with Bekker's Equation (56),

$$z = \frac{0.53 \ W^{0.6}}{b^{0.6} \ D^{0.3}} \tag{56}$$

for the same parameters, Equation (72) becomes

$$z_R = \frac{0.427 \ W^{0.66}}{b^{1.1}} \tag{73}$$

This equation is quite different from Bekker's. However, Bekker was not attempting to predict the sinkage of the following wheel of a tandem wheel configuration; hence no rational agreement was expected.

F. Single Wheel Tests

1. Comparison of Dual and Single Wheels

Tables X, XI and XII show averaged data for wheel sinkage and motion resistance for Wheel Pairs $I_a$, $I_b$ and $I_c$, respectively. The dual wheel results are an average of all tests for a given weight as it has been demonstrated that the wheel spacing had little or no effect on the results.

Data contained in Tables X, XI and XII show that the sinkage of dual wheels was generally less than that of a single wheel. For Wheel Pair $I_b$, dual wheel sinkage was approximately 30% less than single wheel sinkage and, for Wheel Pairs $I_c$, it was approximately 14% less. However, for Wheel Pair $I_a$, dual wheel sinkage was greater than single wheel sinkage except at the smallest load. A probable cause for this occurrence was that the skid rate for the dual wheels was approximately 10% higher than that for the single wheels. The skid rate for Wheel Pairs $I_b$ and $I_c$ was approximately the same for both dual wheels and

## Table X

Comparison of Dual and Single Wheel Performance for Wheel Pair $I_a$

Dual Wheel Sinkage (in)*

| Load (lb) | |
|---|---|
| 150 | 1.31 |
| 220 | 2.29 |
| 300 | 3.26 |
| 350 | 3.69 |

Single Wheel Sinkage (in)*

| Load (lb) | First Pass |
|---|---|
| 75 | 1.79 |
| 110 | 2.23 |
| 150 | 3.15 |
| 175 | 3.58 |

Dual Wheel Resistance (lb)*

| Load (lb) | |
|---|---|
| 150 | 49.1 |
| 220 | 111.9 |
| 300 | 171.1 |
| 350 | 209.3 |

Single Wheel Resistance (lb)*

| Load (lb) | First Pass |
|---|---|
| 75 | 35.8 |
| 110 | 50.6 |
| 150 | 80.0 |
| 175 | 100.0 |

* Note: Data is an average of all tests at each weight.

Table XI

Comparison of Dual and Single Wheel Performance for Wheel Pair $I_b$

| Dual Wheel Sinkage (in)* | | Single Wheel Sinkage (in)* | |
| --- | --- | --- | --- |
| Load (lb) | | Load (lb) | First Pass |
| 150 | 0.52 | 75 | 0.94 |
| 220 | 0.75 | 110 | 1.14 |
| 300 | 1.14 | 150 | 1.46 |
| 350 | 1.37 | 175 | 1.67 |

| Dual Wheel Resistance (lb)* | | Single Wheel Resistance (lb)* | |
| --- | --- | --- | --- |
| Load (lb) | | Load (lb) | First Pass |
| 150 | 18.8 | 75 | 15.8 |
| 220 | 49.5 | 110 | 28.7 |
| 300 | 80.5 | 150 | 41.4 |
| 350 | 115.9 | 175 | 55.6 |

* Note: Data is an average of all tests at each weight.

Table XII

Comparison of Dual and Single Wheel Performance for Wheel Pair $I_c$

**Dual Wheel Sinkage (in)***

| Load (lb) | |
|---|---|
| 150 | 0.54 |
| 220 | 0.61 |
| 300 | 0.87 |
| 350 | 0.94 |

**Single Wheel Sinkage (in)***

| Load (lb) | First Pass |
|---|---|
| 75 | 0.60 |
| 110 | 0.79 |
| 150 | 0.96 |
| 175 | 1.08 |

**Dual Wheel Resistance (lb)***

| Load (lb) | |
|---|---|
| 150 | 12.9 |
| 220 | 27.1 |
| 300 | 44.3 |
| 350 | 59.3 |

**Single Wheel Resistance (lb)***

| Load (lb) | First Pass |
|---|---|
| 75 | 14.65 |
| 110 | 18.85 |
| 150 | 33.90 |
| 175 | 37.55 |

* Note: Data is an average of all tests at each weight.

the single wheel.

Data contained in Tables X, XI and XII show that the motion resistance of dual wheels was greater than that of a single wheel. The motion resistance of dual wheels for Wheel Pair $I_a$ was approximately 47% greater than for the single wheel. The percentages for Wheel Pairs $I_b$ and $I_c$ were 40% and 23%, respectively.

2. Comparison of Tandem and Single Wheels

Tables XIII, XIV and XV show averaged data for wheel sinkage and motion resistance for Wheel Pairs $I_a$, $I_b$ and $I_c$, respectively when connected in tandem. These tables show that for Wheel Pairs $I_b$ and $I_c$ the rear tandem wheel sank slightly deeper than the front tandem wheel. The second pass of the single wheel also sank deeper than the first pass for these wheel pairs. The front tandem wheel sank slightly deeper than the rear tandem wheel for the three highest weights for Wheel Pair $I_a$. The first pass of the single wheel also sank deeper than the second pass for all weights for this wheel pair. The probable cause of the greater front wheel and first pass sinkage for Wheel Pair No. $I_a$ was determined to be due to a greater amount of rut refill from the loose flowing sand. A comparison of Figures 35 and 36 will demonstrate the difference in rut refill. Figure 36 shows one wheel of Wheel Pair $I_a$ making a second pass while carrying a load of 175 pounds. It will be noted that the sand had filled in to the center from both sides after the first pass. Figure 35 shows one wheel of Wheel Pair $I_c$ making a second pass while carrying a load of 175 pounds. In this case, it will be noted that very little rut refill

Table XIII

Comparison of Tandem and Single Wheel Performance for Wheel Pair $I_a$

Tandem Wheel Sinkage (in)*

| Load (lb) | Front | Rear |
|---|---|---|
| 150 | 2.35 | 2.40 |
| 220 | 3.15 | 3.09 |
| 300 | 4.24 | 4.00 |
| 350 | 4.60 | 4.41 |

Single Wheel Sinkage (in)*

| Load (lb) | First Pass | Second Pass |
|---|---|---|
| 75 | 1.79 | 1.7 |
| 110 | 2.23 | 2.15 |
| 150 | 3.15 | 2.75 |
| 175 | 3.58 | 3.2 |

Tandem Wheel Resistance (lb)*

| Load (lb) | |
|---|---|
| 150 | 45.1 |
| 220 | 80.6 |
| 300 | 117.0 |
| 350 | 150.1 |

Single Wheel Resistance (lb)*

| Load (lb) | First Pass | Second Pass | Total |
|---|---|---|---|
| 75 | 35.8 | 23.8 | 59.6 |
| 110 | 50.6 | 40.3 | 90.9 |
| 150 | 80.0 | 60.0 | 140.0 |
| 175 | 100.0 | 76.0 | 176.0 |

* Note: Data is an average of all tests at each weight.

Table XIV

Comparison of Tandem and Single Wheel Performance for Wheel Pair Ib

Tandem Wheel Sinkage (in)*

| Load (lb) | Front | Rea |
|---|---|---|
| 150 | 1.34 | 1.42 |
| 220 | 1.69 | 1.78 |
| 300 | 2.51 | 2.56 |
| 350 | 2.74 | 2.79 |

Single Wheel Sinkage (in)*

| Load (lb) | First Pass | Second Pass |
|---|---|---|
| 75 | 0.94 | 1.1 |
| 110 | 1.14 | 1.33 |
| 150 | 1.46 | 1.73 |
| 175 | 1.67 | 1.97 |

Tandem Wheel Resistance (lb)*

| Load (lb) | |
|---|---|
| 150 | 29.7 |
| 220 | 56.0 |
| 300 | 73.8 |
| 350 | 96.3 |

Single Wheel Resistance (lb)*

| Load (lb) | First Pass | Second Pass | Total |
|---|---|---|---|
| 75 | 15.8 | 8.3 | 24.1 |
| 110 | 28.7 | 12.5 | 41.2 |
| 150 | 41.4 | 31.3 | 72.7 |
| 175 | 55.6 | 43.8 | 98.4 |

* Note: Data is an average of all tests at each weight.

## Table XV

Comparison of Tandem and Single Wheel Performance for Wheel Pair $I_c$

**Tandem Wheel Sinkage (in)\***

| Load (lb) | Front | Rear |
|---|---|---|
| 150 | 1.29 | 1.42 |
| 220 | 1.45 | 1.65 |
| 300 | 2.11 | 2.11 |
| 350 | 2.16 | 2.22 |

**Single Wheel Sinkage (in)\***

| Load (lb) | First Pass | Second Pass |
|---|---|---|
| 75 | 0.60 | 0.73 |
| 110 | 0.79 | 0.90 |
| 150 | 0.96 | 1.17 |
| 175 | 1.08 | 1.27 |

**Tandem Wheel Resistance (lb)\*\***

| Load (lb) | |
|---|---|
| 150 | 14.6 |
| 220 | 28.2 |
| 300 | 33.3 |
| 350 | 46.2 |

**Single Wheel Resistance (lb)\***

| Load (lb) | First Pass | Second Pass | Total |
|---|---|---|---|
| 75 | 14.65 | 6.95 | 21.6 |
| 110 | 18.85 | 16.55 | 35.4 |
| 150 | 33.9 | 13.2 | 47.1 |
| 175 | 37.55 | 20.6 | 48.2 |

\* Note: Data is an average of all tests at each weight.

\*\* Note: Data was neglected as erroneous (explained in para VII,c,2).
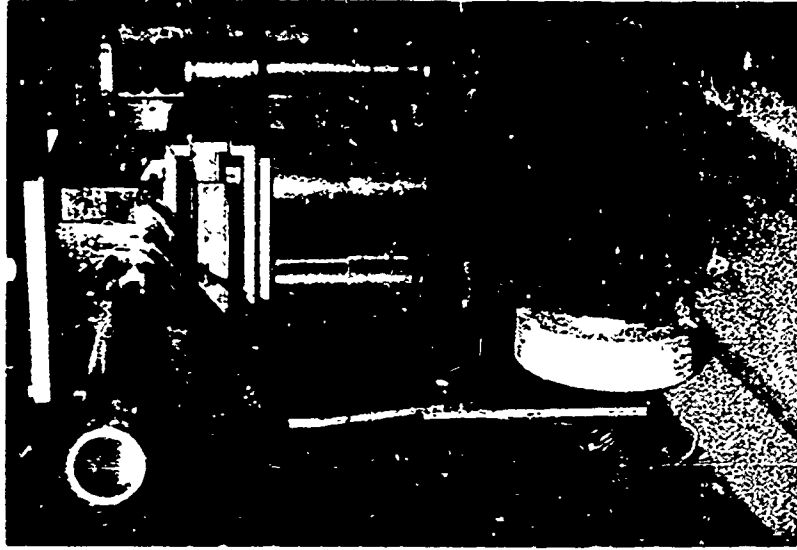
FIGURE 36. SECOND PASS OF SINGLE WHEEL OF WHEEL PAIR I$_a$

NOT REPRODUCIBLE
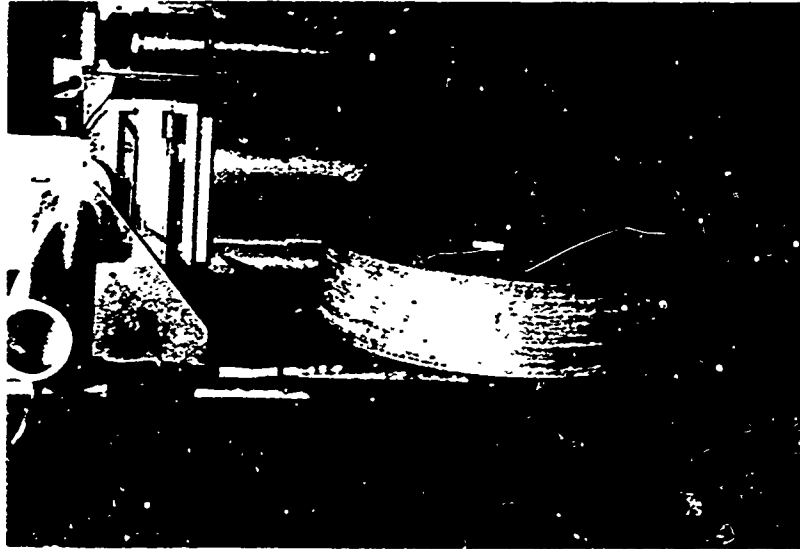


FIGURE 35. SECOND PASS OF SINGLE WHEEL OF WHEEL PAIR I$_c$

had taken place after the first pass due mainly to the greater wheel
sinkage. It was felt that the second pass of the wheel from Wheel
Pair $I_a$ did not sink as far as the first pass because of the excessive
amount of rut refill and the soil compaction created by the first pass.

These Tables also show that the single wheel sinkage was 25% to
45% less than either the front or rear sinkage of the tandem wheels.
Since the load for the tandem wheels was exactly twice that for the
single wheel, it was concluded that the difference in sinkage was
caused by an unbalance in the distribution of the load on the two
wheels caused by the moment of the motion resistance on the two wheels
about the mounting plate pivot. Instead of the load being divided
evenly between the two wheels, the front wheel was loaded with more
than half of the load. This meant that the front tandem wheel was
subjected to a greater load than the single wheel; hence the front
tandem wheel sank deeper than the first pass of the single wheel.

The data contained in tables XIII, XIV and XV show that the
motion resistance of both passes for the single wheel was approxi-
mately 17% greater than that for the tandem wheels for Wheel Pair No.
$I_a$. This was caused by the large amount of rut refill coupled with
the fact that the single wheel was subjected to a greater load during
the second pass than was the rear tandem wheel thus causing more
motion resistance. For Wheel Pair $I_b$, the motion resistance
of the tandem wheels was greater than that for both passes of the
single wheel for the two lowest weights. For the two higher weights
the resistance to motion was approximately equal for the tandem wheels

and both passes of the single wheel. The tandem wheel motion re-
sistance for Wheel Pair $I_c$ will not be discussed because the data
was neglected as erroneous (. . par. VII,c,2).

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

It may be concluded from the results of this study that a similitude approach may be utilized to develop functional relationships with which wheel performance in dual and tandem configuration may be predicted. The study demonstrated that spacing of the wheels had a negligible effect on sinkage and resistance to motion for both dual and tandem towed wheels in sand. A comparison of the prediction equations from this study with those developed by Bekker showed that the equations were all of the same general form but the constants and exponents were frequently quite different.

A comparison of single wheel tests with dual wheel tests showed that the results of this study generally agreed with those of Roma and McGowan.

Comparison of the single wheel test results with tandem wheel test results was difficult because of the uneven load distribution on the wheels in tandem configuration. This study showed that it would be difficult to predict the performance of tandem wheels mounted in a bogie type suspension with multiple passes of single wheels, because the load distribution on the wheels would be different.

. Recommendations

It is recommended that no further tests of this type be conducted utilizing towed wheels. Tests should be conducted, however, utilizing driven dual and tandem wheels. The tests should be conducted in at least two different soils to determine whether the similitude approach can be utilized under conditions where $k_c$ and c are not zero.

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## X. ACKNOWLEDGEMENTS

XI.   VITA

Gary D. Swanson was born in New Castle, Pennsylvania on May 2, 1939.  He graduated from Youngstown University in May 1962. At Youngstown University he majored in Mechanical Engineering and was commissioned as a Second Lieutenant in the United States Army upon graduation.

He has served at Sandia Base, Albuquerque, New Mexico, Cha Rang Valley, Qui Nhon, RVN, and Aberdeen Proving Grounds, Maryland prior to attending Stevens Institute of Technology.  He currently holds the rank of Major, U.S. Army Ordnance Corps.

He is married to the former Rosalie Kay McRae of Albuquerque, New Mexico and has a son, David.

APPENDIX I

Carriage Velocity, Wheel Velocity and Skid Rate Calculations

A. Carriage Velocity:

$$V_c = \frac{(\text{Number of event markers passed}) \times (1.5 \text{ feet})}{(\text{time elapsed in seconds})}$$

B. Wheel Velocity

1. Dual and Tandem Wheels

$$V_w = \frac{(\text{Number of wheel bolts passed}) \times (\text{Circumference of wheel in ft})}{(\text{time elapsed in seconds}) \times 4}$$

2. Single Wheel

$$V_w = \frac{(\text{Number of wheel bolts passed}) \times (\text{Circumference of wheel in ft})}{(\text{time elapsed in seconds}) \times 5}$$

C. Skid Rate

$$B = 100 \times \frac{V_c - V_w}{V_c}$$

## Appendix II

### Calculation of Tandem Front and Rear Wheel Sinkage

In tandem configuration the two wheels were mounted on stub axles which were then bolted to a 61 inch long steel plate. The sinkage at the center of the plate was the sinkage measured by the recorder. To determine the sinkage of the front and rear wheels the movement of one of the ends of the steel plate was measured. By utilizing similar triangles it was possible to determine the sinkage of the front and rear wheels
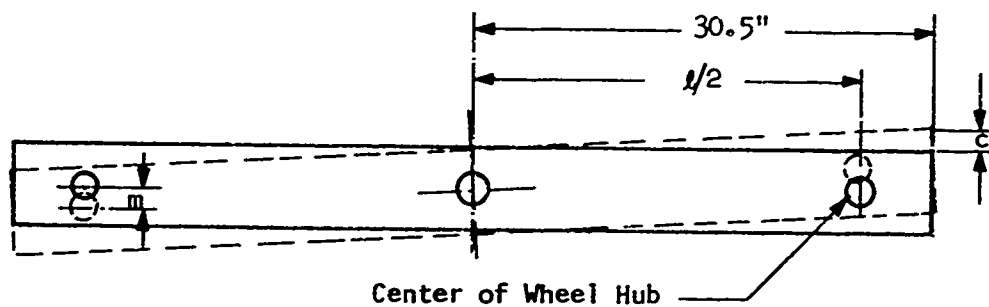


Figure 37. Sinkage Calculation Diagram

By similar triangles:

$$\frac{c}{30.5} = \frac{m}{\ell/2} \quad \therefore \quad m = \frac{c\ell}{61}$$

Sample calculation:
$$\ell = 16.125$$
$$c = +.16$$
$$z_c = 4.1$$

$$m = \frac{c\ell}{61} = \frac{(0.16)\cdot(16.125)}{61} = 0.0423$$

$$\therefore z_F = z_c - m = 4.1 - 0.0423 = 4.0577 \approx 4.06$$

$$z_R = z_c + m = 4.1 + 0.0423 = 4.1423 \approx 4.14$$

## APPENDIX III

### Procedure for Combining $\pi_1$ Terms by Multiplication[1]

General Equation

$$\pi_1 = F(\pi_2, \pi_4) = \frac{F(\bar{\pi}_2, \pi_4)F(\pi_2, \bar{\pi}_4)}{F(\bar{\pi}_2, \bar{\pi}_4)}$$

where:

$F(\bar{\pi}_2, \pi_4) = $ (relationship generated in terms of $\pi_4$ with $\pi_2$ held constant)

$F(\pi_2, \bar{\pi}_4) = $ (relationship generated in terms of $\pi_2$ with $\pi_4$ held constant)

$F(\bar{\pi}_2, \bar{\pi}_4)^* = $ (constant determined by substituting constant values of $\pi_2$ and $\pi_4$ into the appropriate equation)

Sample Calculation: (From Dε : Wheels – Sinkage)

$$F(\bar{\pi}_2, \pi_4) = 0.218\ \pi_4^{-1.11} \quad (\bar{\pi}_2 = 0.26)$$

$$F(\pi_2, \bar{\pi}_4) = 2.73\ \pi_2^{1.9} \quad (\bar{\pi}_4 = 1)$$

$$F(\bar{\pi}_2, \bar{\pi}_4) = 0.218(1)^{-1.11} = 0.218(1) = 0.218$$

$$F(\bar{\pi}_2, \bar{\pi}_4) = 2.73(0.26)^{1.9} = 2.73(0.0775) = 0.212$$

$$\therefore\ F(\bar{\pi}_2, \bar{\pi}_4) = \frac{0.218 + 0.212}{2} = 0.215$$

---

*The $F(\bar{\pi}_2, \bar{\pi}_4)$ terms should be equal when calculated with each of the two relationships. If they are not, their average value should be utilized.

APPENDIX III (continued)

$$\pi_1 = F(\pi_2, \pi_4) = \frac{(0.218 \; \pi_4^{-1.11})(2.73 \; \pi_2^{1.9})}{0.215}$$

$$\pi_1 = 2.77 \; \pi_2^{1.9} \; \pi_4^{-1.11}$$

APPENDIX IV

Tables of Test Data

Test Data is Contained in Tables XVI through XLIII

Table XVI:  Dual Wheel Performance of Wheel Pair No. $I_a$

Wheel Parameters:  $D = 14.75$ in., $b = 3.88$ in.; Tests 1-9:  $W = 150$ lb, Tests 10-18:  $W = 220$ lb

| | Measured Parameters | | | | | Calculated Values | | | | | |
| Test No. | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\dfrac{k_\varphi b^{n+2}}{W}$ | B (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 1.36 | 58.6 | 0.154 | 0.093 | | | | | | 39.4 |
| 2 | 1.5 | 1.53 | 66.7 | 0.178 | 0.097 | | | | | | 45.6 |
| 3 | 1.5 | 1.00 | 35.4 | 0.151 | 0.099 | | | | | | 34.3 |
| Avg. | 1.5 | 1.29 | 53.6 | -- | -- | 0.358 | 0.088 | 0.102 | 0.263 | 2.241 | 39.7 |
| 4 | 2.5 | 1.18 | 44.3 | 0.171 | 0.111 | | | | | | 34.9 |
| 5 | 2.5 | 1.26 | 44.3 | 0.160 | 0.106 | | | | | | 33.9 |
| 6 | 2.5 | 1.18 | 42.6 | 0.168 | 0.109 | | | | | | 35.1 |
| Avg. | 2.5 | 1.21 | 43.7 | -- | -- | 0.292 | 0.082 | 0.17 | 0.263 | 2.241 | 34.6 |
| 7 | 3.8 | 1.18 | 33.2 | 0.166 | 0.114 | | | | | | 31.1 |
| 8 | 3.8 | 1.54 | 57.1 | 0.183 | 0.121 | | | | | | 34.1 |
| 9 | 3.8 | 1.59 | 60.0 | 0.170 | 0.103 | | | | | | 39.3 |
| Avg. | 3.8 | 1.49 | 50.1 | -- | -- | 0.334 | 0.101 | 0.258 | 0.263 | 2.241 | 34.8 |
| 10 | 1.5 | 2.3 | 115 | 0.178 | 0.093 | | | | | | -- |
| 11 | 1.5 | 2.2 | 113 | 0.151 | 0.071 | | | | | | 47.6 |
| 12 | 1.5 | 2.4 | 119 | | | | | | | | 52.5 |
| Avg. | 1.5 | 2.3 | 115.7 | -- | -- | 0.525 | 0.156 | 0.102 | 0.263 | 1.532 | 50.1 |
| 13 | 2.5 | 2.1 | 110 | 0.171 | 0.089 | | | | | | 47.9 |
| 14 | 2.5 | 2.28 | 113 | 0.160 | 0.082 | | | | | | 49.0 |
| 15 | 2.5 | 2.36 | 119 | 0.168 | 0.085 | | | | | | 49.3 |
| Avg. | 2.5 | 2.25 | 110.6 | -- | -- | 0.503 | 0.153 | 0.17 | 0.263 | 1.532 | 48.7 |
| 16 | 3.8 | 2.5 | 116 | 0.166 | 0.088 | | | | | | 47.1 |
| 17 | 3.8 | 2.4 | 116 | 0.183 | 0.097 | | | | | | 47.3 |
| 18 | 3.8 | 2.05 | 96 | 0.170 | 0.095 | | | | | | 44.0 |
| Avg. | 3.8 | 2.32 | 109.3 | -- | -- | 0.497 | 0.157 | 0.258 | 0.263 | 1.532 | 46.1 |

Table XVII: Dual Wheel Performance of Wheel Pair No. $I_a$

Wheel Parameters: D = 14.75 in., b = 3.88 in.; Tests 19-27: W = 300 lb, Tests 28-36: W = 350 lb

| | Measured Parameters | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | S (in) | z (in) | R (lb) | $v_c$ (ft/sec) | $v_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\frac{k_\phi b^{n+2}}{W}$ | B (%) |
| 19 | 1.5 | 3.3 | 169 | 0.160 | 0.069 | | | | | | 57.0 |
| 20 | 1.5 | 3.4 | 180 | 0.159 | 0.069 | | | | | | 56.4 |
| 21 | 1.5 | 3.4 | 190 | 0.162 | 0.067 | | | | | | 58.6 |
| Avg. | 1.5 | 3.37 | 179.7 | -- | -- | 0.598 | 0.228 | 0.102 | 0.263 | 1.124 | 57.3 |
| 22 | 2.5 | 3.6 | 190 | 0.163 | 0.071 | | | | | | 52.5 |
| 23 | 2.5 | 3.0 | 155 | 0.167 | 0.080 | | | | | | 52.1 |
| 24 | 2.5 | 3.15 | 165 | 0.169 | 0.079 | | | | | | 53.0 |
| Avg. | 2.5 | 3.25 | 170 | -- | -- | 0.566 | 0.220 | 0.170 | 0.263 | 1.124 | 52.5 |
| 25 | 3.8 | 3.22 | 170 | 0.176 | 0.090 | | | | | | 48.9 |
| 26 | 3.8 | 3.16 | 161 | 0.184 | 0.094 | | | | | | 48.8 |
| 27 | 3.8 | 3.15 | 160 | 0.181 | 0.091 | | | | | | 49.1 |
| Avg. | 3.8 | 3.17 | 163.7 | -- | -- | 0.545 | 0.215 | 0.258 | 0.263 | 1.124 | 48.9 |
| 28 | 1.5 | 3.6 | 200 | 0.160 | 0.069 | | | | | | 56.8 |
| 29 | 1.5 | 3.9 | 230 | 0.159 | 0.063 | | | | | | 60.1 |
| 30 | 1.5 | 3.9 | 220 | 0.162 | 0.070 | | | | | | 57.0 |
| Avg. | 1.5 | 3.8 | 216.7 | -- | -- | 0.620 | 0.258 | 0.102 | 0.263 | 0.959 | 58.0 |
| 31 | 2.5 | 3.89 | 222 | 0.163 | 0.072 | | | | | | 55.5 |
| 32 | 2.5 | 3.10 | 175 | 0.167 | 0.077 | | | | | | 53.9 |
| 33 | 2.5 | 3.45 | 190 | 0.169 | 0.076 | | | | | | 54.9 |
| Avg. | 2.5 | 3.48 | 195.7 | -- | -- | 0.560 | 0.236 | 0.170 | 0.263 | 0.959 | 55.1 |
| 34 | 3.8 | 3.78 | 215 | 0.176 | 0.081 | | | | | | 54.0 |
| 35 | 3.8 | 3.80 | 216 | 0.184 | 0.085 | | | | | | 53.3 |
| 36 | 3.8 | 3.80 | 216 | 0.181 | 0.083 | | | | | | 54.2 |
| Avg. | 3.8 | 3.79 | 215.7 | -- | -- | 0.615 | 0.257 | 0.258 | 0.263 | 0.959 | 53.8 |

Table XVIII: Dual Wheel Performance of Wheel Pair No. 1

Wheel Parameters: D = 20.875 in., b = 5.41 in.; Tests 37-45: W = 150 lb, Tests 46-54: W = 220 lb

| | Measured Parameters | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\frac{k_\phi b^{n+2}}{W}$ | B (%) |
| 37 | 2.625 | 0.49 | 18.5 | 0.167 | 0.149 | | | | | | 10.6 |
| 38 | 2.625 | 0.46 | 14.0 | 0.178 | 0.156 | | | | | | 12.3 |
| 39 | 2.625 | 0.50 | 20.0 | 0.175 | 0.148 | | | | | | 15.6 |
| Avg. | 2.625 | 0.48 | 17.5 | -- | -- | 0.117 | 0.023 | 0.126 | 0.259 | 6.348 | 12.8 |
| 40 | 3.56 | 0.51 | 21.1 | 0.166 | 0.144 | | | | | | 13.1 |
| 41 | 3.56 | 0.55 | 21.3 | 0.160 | -- | | | | | | -- |
| 42 | 3.56 | 0.60 | 23.3 | 0.163 | 0.141 | | | | | | 13.4 |
| Avg. | 3.56 | 0.55 | 21.9 | -- | -- | 0.146 | 0.026 | 0.170 | 0.259 | 6.348 | 13.3 |
| 43 | 5.41 | 0.58 | 21.1 | 0.166 | 0.146 | | | | | | 11.6 |
| 44 | 5.41 | 0.51 | 16.0 | 0.165 | 0.144 | | | | | | 12.6 |
| 45 | 5.41 | 0.45 | 13.3 | 0.175 | 0.158 | | | | | | 9.9 |
| Avg. | 5.41 | 0.51 | 16.8 | -- | -- | 0.112 | 0.024 | 0.259 | 0.259 | 6.348 | 11.4 |
| 46 | 2.625 | 0.80 | 58.6 | 0.167 | 0.128 | | | | | | 23.1 |
| 47 | 2.625 | 0.60 | 34.0 | 0.178 | 0.140 | | | | | | 21.3 |
| 48 | 2.625 | 0.65 | 43.0 | 0.175 | 0.140 | | | | | | 19.9 |
| Avg. | 2.625 | 0.68 | 42.5 | -- | -- | 0.206 | 0.034 | 0.126 | 0.259 | 4.34 | 21.4 |
| 49 | 3.56 | 0.80 | 55.7 | 0.166 | 0.129 | | | | | | 22.3 |
| 50 | 3.56 | 0.78 | 54.3 | 0.160 | 0.124 | | | | | | 22.3 |
| 51 | 3.56 | 0.80 | 55.7 | 0.163 | 0.127 | | | | | | 22.0 |
| Avg. | 3.56 | 0.79 | 55.2 | -- | -- | 0.25 | 0.038 | 0.170 | 0.259 | 4.34 | 22.2 |
| 52 | 5.41 | 0.89 | 53.7 | 0.166 | 0.127 | | | | | | 23.2 |
| 53 | 5.41 | 0.61 | 38.0 | 0.165 | 0.135 | | | | | | 18.0 |
| 54 | 5.41 | 0.81 | 52.3 | 0.175 | 0.130 | | | | | | 25.6 |
| Avg. | 5.41 | 0.77 | 48.0 | -- | -- | 0.218 | 0.037 | 0.259 | 0.259 | 4.34 | 22.3 |

Table XIX:  Dual Wheel Performance of Wheel Pair No. 1$_b$

Wheel Parameters:  D = 20.815 in., b = 5.41 in.; Tests 55-63; W = 300 lb, Tests 64-72:  W = 350 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | | R/W | z/D | S/D | b/D | $\dfrac{k_\varphi b^{n+2}}{W}$ | B (%) |
| 55 | 2.625 | 1.19 | 88.6 | 0.165 | 0.119 | | | | | | | 28.0 |
| 56 | 2.625 | 1.19 | 85.7 | 0.135 | 0.108 | | | | | | | 29.4 |
| 57 | 2.625 | 1.10 | 85.2 | 0.170 | 0.121 | | | | | | | 28.4 |
| Avg. | 2.625 | 1.16 | 86.5 | -- | -- | | 0.288 | 0.056 | 0.126 | 0.259 | 3.184 | 28.6 |
| 58 | 3.56 | 1.24 | 88.0 | 0.162 | 0.115 | | | | | | | 29.1 |
| 59 | 3.56 | 0.99 | 63.0 | 0.161 | 0.121 | | | | | | | 24.7 |
| 60 | 3.56 | 1.14 | 80.0 | -- | -- | | | | | | | -- |
| Avg. | 3.56 | 1.12 | 77.0 | -- | -- | | 0.256 | 0.054 | 0.170 | 0.259 | 3.184 | 26.9 |
| 61 | 5.41 | 1.04 | 70.0 | 0.168 | 0.127 | | | | | | | 24.4 |
| 62 | 5.41 | 1.26 | 88.0 | 0.169 | 0.122 | | | | | | | 27.3 |
| 63 | 5.41 | 1.10 | 76.0 | 0.166 | 0.124 | | | | | | | 25.3 |
| Avg. | 5.41 | 1.13 | 78.0 | -- | -- | | 0.260 | 0.054 | 0.259 | 0.259 | 3.184 | 25.7 |
| 64 | 2.625 | 1.36 | 124.0 | 0.165 | 0.106 | | | | | | | 35.5 |
| 65 | 2.625 | 1.25 | 110.0 | 0.153 | 0.101 | | | | | | | 33.8 |
| 66 | 2.625 | 1.30 | 116.7 | 0.170 | 0.111 | | | | | | | 34.7 |
| Avg. | 2.625 | 1.30 | 116.9 | -- | -- | | 0.334 | 0.062 | 0.126 | 0.259 | 2.718 | 34.7 |
| 67 | 3.56 | 1.40 | 120.0 | 0.162 | 0.106 | | | | | | | 34.7 |
| 68 | 3.56 | 1.40 | 117.0 | 0.161 | 0.108 | | | | | | | 33.3 |
| 69 | 3.56 | 1.40 | 119.0 | -- | -- | | | | | | | -- |
| Avg. | 3.56 | 1.40 | 118.7 | -- | -- | | 0.339 | 0.067 | 0.170 | 0.259 | 2.718 | 34.0 |
| 70 | 5.41 | 1.35 | 107.0 | 0.168 | 0.114 | | | | | | | 32.6 |
| 71 | 5.41 | 1.49 | 120.0 | 0.169 | 0.114 | | | | | | | 32.6 |
| 72 | 5.41 | 1.34 | 109.0 | 0.166 | 0.114 | | | | | | | 31.2 |
| Avg. | 5.41 | 1.39 | 112.0 | -- | -- | | 0.320 | 0.067 | 0.259 | 0.259 | 2.718 | 32.1 |

Table XX: Dual Wheel Performance of Wheel Pair No. $1_c$

Wheel Parameters: $D = 27.0$ in., $b = 6.98$ in.; Tests 73-81: $W = 150$ lb, Tests 82-90: $W = 220$ lb

| | Measured Parameters | | | | | Calculated Values | | | | | |
| Test No. | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\dfrac{k_\varphi b^{n+2}}{W}$ | B (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 73 | 2.75 | 0.32 | 9.7 | 0.146 | 0.136 | | | | | | 7.0 |
| 74 | 2.75 | 0.29 | 8.8 | 0.145 | 0.135 | | | | | | 7.5 |
| 75 | 2.74 | 0.35 | 9.9 | 0.146 | 0.141 | | | | | | 3.9 |
| Avg | 2.75 | 0.32 | 9.5 | -- | -- | 0.063 | 0.0118 | 0.102 | 0.259 | 14.248 | 6.1 |
| 76 | 4.56 | 0.62 | 13.2 | 0.152 | 0.143 | | | | | | 5.8 |
| 77 | 4.56 | 0.70 | 15.4 | 0.143 | 0.133 | | | | | | 7.1 |
| 78 | 4.56 | 0.66 | 15.4 | 0.142 | 0.131 | | | | | | 7.9 |
| Avg. | 4.56 | 0.66 | 14.6 | -- | -- | 0.099 | 0.024 | 0.170 | 0.259 | 14.248 | 6.9 |
| 79 | 7.0 | 0.62 | 14.1 | 0.141 | 0.131 | | | | | | 6.9 |
| 80 | 7.0 | 0.65 | 15.4 | 0.156 | -- | | | | | | -- |
| 81 | 7.0 | 0.62 | 14.3 | 0.159 | 0.143 | | | | | | |
| Avg. | 7.0 | 0.63 | 14.6 | -- | -- | 0.099 | 0.023 | 0.259 | 0.259 | 14.248 | |
| 82 | 2.75 | 0.38 | 23.5 | 0.146 | 0.130 | | | | | | 10.4 |
| 83 | 2.75 | 0.32 | 22.4 | 0.145 | 0.130 | | | | | | 8.7 |
| 84 | 2.75 | 0.39 | 23.5 | 0.146 | 0.133 | | | | | | 10.7 |
| Avg. | 2.75 | 0.36 | 23.1 | -- | -- | 0.105 | 0.0133 | 0.102 | 0.259 | 9.741 | 10.0 |
| 85 | 4.56 | 0.71 | 28.3 | 0.152 | 0.137 | | | | | | 9.8 |
| 86 | 4.56 | 0.80 | 29.5 | 0.143 | 0.128 | | | | | | 10.2 |
| 87 | 4.56 | 0.75 | 30.6 | 0.142 | 0.129 | | | | | | 9.3 |
| Avg. | 4.56 | 0.75 | 29.4 | -- | -- | 0.136 | 0.028 | 0.170 | 0.259 | 9.741 | 9.7 |
| 88 | 7.0 | 0.70 | 28.3 | 0.141 | 0.129 | | | | | | 8.8 |
| 89 | 7.0 | 0.70 | 28.3 | 0.156 | 0.142 | | | | | | 9.4 |
| 90 | 7.0 | 0.70 | 29.5 | 0.159 | 0.145 | | | | | | 8.9 |
| Avg. | 7.0 | 0.70 | 28.7 | -- | -- | 0.132 | 0.026 | 0.259 | 0.259 | 9.741 | 9.0 |

Table XXI: Dual Wheel Performance of Wheel Pair No. $1_c$

Wheel Parameters:  D = 27.0 in., b = 6.98 in.; Tests 91-99:  W = 300 lb, Tests 100-108:  W = 350 lb

| | Measured Parameters | | | | | | Calculated Values | | | | | |
| | S | z | R | $V_c$ | $V_w$ | | $R/W$ | $z/D$ | $S/D$ | $b/D$ | $\dfrac{k_\varphi b^{n+2}}{W}$ | B |
| Test No. | (in) | (in) | (lb) | (ft/sec) | (ft/sec) | | | | | | | (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 91 | 2.75 | 0.65 | 38.8 | 0.160 | 0.142 | | | | | | | 11.2 |
| 92 | 2.75 | 0.69 | 40.0 | 0.174 | 0.157 | | | | | | | 9.7 |
| 93 | 2.75 | 0.69 | 40.0 | 0.159 | 0.145 | | | | | | | 8.5 |
| Avg. | 2.75 | 0.68 | 39.6 | -- | -- | | 0.132 | 0.025 | 0.102 | 0.259 | 7.147 | 9.8 |
| 94 | 4.56 | 0.99 | 48.3 | 0.144 | 0.128 | | | | | | | 10.7 |
| 95 | 4.56 | 0.99 | 46.7 | 0.144 | 0.133 | | | | | | | 7.7 |
| 96 | 4.56 | 0.98 | 46.7 | 0.152 | 0.134 | | | | | | | 11.7 |
| Avg. | 4.56 | 0.98 | 47.2 | -- | -- | | 0.157 | 0.036 | 0.170 | 0.259 | 7.147 | 10.0 |
| 97 | 7.0 | 0.95 | 46.7 | 0.170 | 0.153 | | | | | | | 9.9 |
| 98 | 7.0 | 0.95 | 44.5 | 0.158 | 0.143 | | | | | | | 9.3 |
| 99 | 7.0 | 0.95 | 46.7 | 0.148 | 0.132 | | | | | | | 10.7 |
| Avg. | 7.0 | 0.95 | 45.9 | -- | -- | | 0.153 | 0.035 | 0.259 | 0.259 | 7.147 | 10.0 |
| 100 | 2.75 | 0.70 | 51.5 | 0.160 | 0.138 | | | | | | | 13.8 |
| 101 | 2.75 | 0.79 | 54.5 | 0.174 | 0.147 | | | | | | | 15.3 |
| 102 | 2.75 | 0.75 | 54.8 | 0.159 | 0.136 | | | | | | | 14.5 |
| Avg. | 2.75 | 0.74 | 53.6 | -- | -- | | 0.153 | 0.027 | 0.102 | 0.259 | 6.10 | 14.5 |
| 103 | 4.56 | 1.10 | 65.0 | 0.144 | 0.122 | | | | | | | 15.3 |
| 104 | 4.56 | 1.00 | 62.5 | 0.144 | 0.120 | | | | | | | 16.7 |
| 105 | 4.56 | 1.10 | 65.0 | 0.152 | 0.130 | | | | | | | 13.9 |
| Avg. | 4.56 | 1.07 | 64.1 | -- | -- | | 0.183 | 0.040 | 0.170 | 0.259 | 6.10 | 15.3 |
| 106 | 7.0 | 1.00 | 60.0 | 0.170 | 0.147 | | | | | | | 13.7 |
| 107 | 7.0 | 1.00 | 60.0 | 0.158 | 0.135 | | | | | | | 14.6 |
| 108 | 7.0 | 1.00 | 60.0 | 0.148 | 0.128 | | | | | | | 13.1 |
| Avg. | 7.0 | 1.00 | 60.0 | -- | -- | | 0.171 | 0.037 | 0.259 | 0.259 | 6.10 | 13.8 |

Table XXII: Dual Wheel Performance of Wheel Pair No. 11

Wheel Parameters: D = 20.875 in., b = 4.7 in.; Tests 109-117: W = 150 lb, Tests 118-126: W = 220 lb

| Test No. | Measured Parameters | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\dfrac{k_\phi b^{n+2}}{W}$ | B (%) |
| 109 | 2.625 | 0.70 | 18.9 | 0.167 | 0.150 | | | | | | 9.9 |
| 110 | 2.625 | 0.80 | 26.6 | 0.164 | 0.137 | | | | | | 16.7 |
| 111 | -- | -- | -- | -- | -- | | | | | | -- |
| Avg. | 2.625 | 0.75 | 22.7 | -- | -- | 0.162 | 0.036 | 0.126 | 0.225 | 4.10 | 12.3 |
| 112 | 3.56 | 0.66 | 20.0 | 0.182 | 0.152 | | | | | | 16.6 |
| 113 | 3.56 | 0.62 | 19.0 | 0.176 | 0.152 | | | | | | 13.6 |
| 114 | 3.56 | 0.52 | 14.6 | 0.176 | 0.152 | | | | | | 13.6 |
| Avg. | 3.56 | 0.60 | 17.8 | -- | -- | 0.127 | 0.029 | 0.170 | 0.225 | 4.10 | 14.6 |
| 115 | 5.4 | 0.70 | 17.6 | 0.170 | 0.145 | | | | | | 14.2 |
| 116 | 5.4 | 0.80 | 22.6 | 0.168 | 0.143 | | | | | | 15.1 |
| 117 | -- | -- | -- | -- | -- | | | | | | -- |
| Avg. | 5.4 | 0.75 | 20.1 | -- | -- | 0.143 | 0.036 | 0.259 | 0.225 | 4.10 | 14.7 |
| 118 | 2.625 | 1.07 | 54.9 | -- | -- | | | | | | -- |
| 119 | 2.625 | 1.08 | 56.7 | 0.164 | 0.121 | | | | | | 30.0 |
| 120 | -- | -- | -- | -- | -- | | | | | | -- |
| Avg. | 2.625 | 1.08 | 55.8 | -- | -- | 0.266 | 0.052 | 0.126 | 0.225 | 2.803 | 30.0 |
| 121 | 3.56 | 0.87 | 44.3 | 0.182 | 0.135 | | | | | | 25.8 |
| 122 | 3.56 | 0.82 | 44.0 | 0.176 | 0.140 | | | | | | 20.2 |
| 123 | 3.56 | 0.90 | 47.7 | 0.176 | 0.137 | | | | | | 22.2 |
| Avg. | 3.56 | 0.86 | 45.3 | -- | -- | 0.216 | 0.041 | 0.170 | 0.225 | 2.803 | 22.7 |
| 124 | 5.4 | 1.20 | 53.2 | -- | -- | | | | | | -- |
| 125 | 5.4 | 1.20 | 55.8 | 0.168 | 0.128 | | | | | | 23.8 |
| 126 | -- | -- | -- | -- | -- | | | | | | -- |
| Avg. | 5.4 | 1.20 | 54.5 | -- | -- | 0.260 | 0.058 | 0.259 | 0.225 | 2.803 | 23.8 |

Table XXIII: Dual Wheel Performance of Wheel Pair No. 11

Wheel Parameters:  D = 20.875 In., b = 4.7 In.; Tests 127-135:  W = 300 lb, Tests 136-144:  W = 350 lb

| Tests | Measured Parameters | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/n | b/D | $\dfrac{k_\rho b^{n+2}}{W}$ | B (%) |
| 127 | 2.625 | 1.40 | 88.0 | -- | -- | | | | | | -- |
| 128 | 2.625 | 1.35 | 96.0 | 0.157 | 0.114 | | | | | | 27.3 |
| 129 | 2.625 | 1.30 | 81.0 | -- | -- | | | | | | -- |
| Avg. | 2.625 | 1.35 | 85.0 | -- | -- | 0.293 | 0.065 | 0.126 | 0.225 | 2.057 | 27.3 |
| 130 | 3.56 | 1.26 | 70.0 | 0.180 | 0.134 | | | | | | 25.4 |
| 131 | 3.56 | 1.22 | 75.0 | 0.171 | 0.126 | | | | | | 26.7 |
| 132 | 3.56 | 1.14 | 70.0 | 0.175 | 0.130 | | | | | | 25.6 |
| Avg. | 3.56 | 1.21 | 71.6 | -- | -- | 0.247 | 0.058 | 0.170 | 0.225 | 2.057 | 25.9 |
| 133 | 5.4 | 1.40 | 77.0 | 0.173 | 0.126 | | | | | | 27.0 |
| 134 | 5.4 | 1.40 | 80.0 | 0.176 | 0.129 | | | | | | 26.6 |
| 135 | 5.4 | 1.52 | 94.0 | 0.176 | 0.126 | | | | | | 28.0 |
| Avg. | 5.4 | 1.44 | 83.6 | -- | -- | 0.288 | 0.069 | 0.259 | 0.225 | 2.057 | 27.2 |
| 136 | 2.625 | 1.68 | 128.0 | -- | -- | | | | | | -- |
| 137 | 2.625 | 1.74 | 132.0 | 0.157 | 0.101 | | | | | | 35.4 |
| 138 | 2.625 | 1.72 | 122.0 | -- | -- | | | | | | -- |
| Avg. | 21625 | 1.71 | 130.6 | -- | -- | 0.384 | 0.082 | 0.126 | 0.225 | 1.755 | 35.4 |
| 139 | 3.56 | 1.70 | 117.0 | 0.180 | 0.117 | | | | | | 34.9 |
| 140 | 3.56 | 1.76 | 124.0 | 0.171 | 0.112 | | | | | | 34.7 |
| 141 | 3.56 | 1.30 | 85.7 | 0.175 | 0.124 | | | | | | 29.0 |
| Avg. | 3.56 | 1.58 | 108.9 | -- | -- | 0.320 | 0.076 | 0.170 | 0.225 | 1.755 | 32.8 |
| 142 | 5.4 | 1.70 | 113.0 | 0.173 | 0.117 | | | | | | 32.5 |
| 143 | 5.4 | 1.65 | 110.0 | 0.176 | 0.120 | | | | | | 32.1 |
| 144 | 5.4 | 1.75 | 120.0 | 0.176 | 0.120 | | | | | | 31.6 |
| Avg. | 5.4 | 1.70 | 114.3 | -- | -- | 0.337 | 0.082 | 0.259 | 0.225 | 1.755 | 32.1 |

Table XXIV: Dual Wheel Performance of Wheel Pair No. III

Wheel Parameters: D = 20.875 In., b = 6.2 In.; Tests 145-153: W = 150 lb, Tests 154-162: W = 220 lb

| | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | | R/W | z/D | S/D | b/D | $\dfrac{k_\varphi b^{n+2}}{W}$ | B (%) |
| 145 | 2.625 | 0.50 | 15.9 | 0.167 | 0.148 | | | | | | | 11.4 |
| 146 | 2.625 | 0.55 | 23.3 | 0.168 | 0.149 | | | | | | | 11.4 |
| 147 | 2.625 | 0.50 | 22.0 | 0.170 | 0.152 | | | | | | | 10.5 |
| Avg. | 2.625 | 0.52 | 20.4 | -- | -- | | 0.136 | 0.025 | 0.126 | 0.297 | 9.806 | 11.1 |
| 148 | 3.56 | 0.50 | 18.6 | 0.167 | 0.152 | | | | | | | 9.1 |
| 149 | 3.56 | 0.50 | 20.0 | 0.165 | 0.146 | | | | | | | 11.8 |
| 150 | 3.56 | 0.55 | 23.3 | 0.174 | 0.152 | | | | | | | 12.5 |
| Avg. | 3.56 | 0.52 | 20.6 | -- | -- | | 0.137 | 0.025 | 0.170 | 0.297 | 9.806 | 11.1 |
| 151 | 5.4 | 0.50 | 14.6 | 0.165 | 0.148 | | | | | | | 10.6 |
| 152 | 5.4 | 0.50 | 16.0 | 0.170 | 0.152 | | | | | | | 10.4 |
| 153 | 5.4 | 0.59 | 22.5 | 0.165 | 0.144 | | | | | | | 13.0 |
| Avg. | 5.4 | 0.53 | 17.7 | -- | -- | | 0.118 | 0.025 | 0.259 | 0.297 | 9.806 | 11.3 |
| 154 | 2.625 | 0.67 | 40.0 | 0.167 | 0.138 | | | | | | | 17.0 |
| 155 | 2.625 | 0.65 | 44.3 | 0.168 | 0.135 | | | | | | | 19.7 |
| 156 | 2.625 | 0.65 | 41.0 | 0.170 | 0.138 | | | | | | | 18.6 |
| Avg. | 2.625 | 0.66 | 41.7 | -- | -- | | 0.190 | 0.032 | 0.126 | 0.297 | 6.705 | 18.4 |
| 157 | 3.56 | 0.60 | 42.0 | 0.167 | 0.137 | | | | | | | 18.2 |
| 158 | 3.56 | 0.62 | 44.3 | 0.165 | 0.133 | | | | | | | 19.4 |
| 159 | 3.56 | 0.62 | 46.3 | 0.174 | 0.142 | | | | | | | 18.8 |
| Avg. | 3.56 | 0.61 | 44.2 | -- | -- | | 0.201 | 0.029 | 0.170 | 0.297 | 6.705 | 18.8 |
| 160 | 5.4 | 0.58 | 30.0 | 0.165 | 0.140 | | | | | | | 15.2 |
| 161 | 5.4 | 0.60 | 36.5 | 0.170 | 0.142 | | | | | | | 16.3 |
| 162 | 5.4 | 0.63 | 43.0 | 0.165 | 0.137 | | | | | | | 17.3 |
| Avg. | 5.4 | 0.60 | 36.5 | -- | -- | | 0.166 | 0.029 | 0.259 | 0.297 | 6.705 | 16.3 |

Table XXV: Dual Wheel Performance of Wheel Pair No. 111

Wheel Parameters: D = 20.875 in., b = 6.2 in.; Tests 163-171: W = 300 lb, Tests 172-180: W = 350 lb

| Test No. | Measured Parameters | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S (in) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | R/W | z/D | S/D | b/D | $\dfrac{k_\phi b^{n+2}}{W}$ | B (%) |
| 163 | 2.625 | 1.00 | 72.0 | 1.067 | 0.124 | | | | | | 25.5 |
| 164 | 2.625 | 0.90 | 62.0 | 0.168 | 0.128 | | | | | | 23.8 |
| 165 | 2.625 | 0.82 | 58.0 | 0.168 | 0.131 | | | | | | 21.7 |
| Avg. | 2.625 | 0.91 | 64.0 | -- | -- | 0.213 | 0.044 | 0.126 | 0.297 | 4.919 | 23.7 |
| 166 | 3.56 | 1.05 | 81.0 | 0.161 | 0.119 | | | | | | 26.3 |
| 167 | 3.56 | 1.02 | 80.0 | 0.169 | 0.124 | | | | | | 26.6 |
| 168 | 3.56 | 1.03 | 80.0 | 0.171 | 0.121 | | | | | | 29.0 |
| Avg. | 3.56 | 1.03 | 80.3 | -- | -- | 0.268 | 0.049 | 0.170 | 0.297 | 4.919 | 27.3 |
| 169 | 5.40 | 0.90 | 58.0 | 0.163 | 0.130 | | | | | | 19.9 |
| 170 | 5.40 | 0.90 | 63.0 | 0.168 | 0.131 | | | | | | 21.9 |
| 171 | 5.40 | 0.95 | 64.0 | 0.156 | 0.123 | | | | | | 21.3 |
| Avg. | 5.40 | 0.92 | 61.6 | -- | -- | 0.206 | 0.044 | 0.259 | 0.297 | 4.919 | 21.0 |
| 172 | 2.625 | 1.14 | 103.0 | 0.167 | 0.114 | | | | | | 31.7 |
| 173 | 2.625 | 1.14 | 103.0 | 0.168 | 0.113 | | | | | | 32.8 |
| 174 | 2.625 | 1.10 | 99.0 | 0.168 | 0.117 | | | | | | 30.4 |
| Avg. | 2.625 | 1.12 | 101.6 | -- | -- | 0.290 | 0.054 | 0.126 | 0.297 | 4.198 | 31.6 |
| 175 | 3.56 | 1.20 | 107.0 | 0.161 | 0.111 | | | | | | 31.3 |
| 176 | 3.56 | 1.19 | 107.0 | 0.169 | 0.115 | | | | | | 31.8 |
| 177 | 3.56 | 1.21 | 113.0 | 0.171 | 0.113 | | | | | | 33.5 |
| Avg. | 3.56 | 1.20 | 109.0 | -- | -- | 0.312 | 0.057 | 0.170 | 0.297 | 4.198 | 32.2 |
| 178 | 5.4 | 1.20 | 101.0 | 0.163 | 0.114 | | | | | | 29.9 |
| 179 | 5.4 | 1.16 | 99.0 | 0.168 | 0.120 | | | | | | 28.7 |
| 180 | 5.4 | 1.15 | 99.0 | 0.156 | 0.110 | | | | | | 29.2 |
| Avg. | 5.4 | 1.17 | 99.6 | -- | -- | 0.285 | 0.056 | 0.259 | 0.297 | 4.198 | 29.3 |

Table XXVI: Tandem Wheel Performance of Wheel Pair No. I$_a$

Wheel Parameters: D = 14.75 in., b = 3.88 in.; Tests 181-189: W = 150 lb, Tests 190-198: W=220 lb

| Test No. | ℓ (in) | Measured Parameters z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | Calculated Values R/W | $z_F/D$ | $z_R/D$ | ℓ/D | b/D | $\dfrac{k_\phi b^{n+2}}{W}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 181 | 16.125 | 2.4 | 0.25 | 2.33 | 2.47 | 45.0 | | | | | | |
| 182 | 16.125 | 2.4 | 0.33 | 2.31 | 2.49 | 52.5 | | | | | | |
| 183 | 16.125 | 2.3 | 0.26 | 2.33 | 2.47 | 45.0 | | | | | | |
| Avg. | 16.125 | - | -- | 2.32 | 2.48 | 47.5 | 0.317 | 0.157 | 0.168 | 1.09 | 0.263 | 2.241 |
| 184 | 21.80 | 2.31 | 0 | 2.31 | 2.31 | 46.0 | | | | | | |
| 185 | 21.80 | 2.34 | 0 | 2.34 | 2.34 | 48.0 | | | | | | |
| 186 | 21.80 | 2.30 | .09 | 2.27 | 2.33 | 46.0 | | | | | | |
| Avg. | 21.80 | - | -- | 2.31 | 2.33 | 46.7 | 0.311 | 0.157 | 0.158 | 1.48 | 0.263 | 2.241 |
| 187 | 29.50 | 2.40 | 0 | 2.40 | 2.40 | 40.0 | | | | | | |
| 188 | 29.50 | 2.40 | .09 | 2.36 | 2.44 | 40.0 | | | | | | |
| 189 | 29.50 | 2.39 | 0 | 2.39 | 2.39 | 43.0 | | | | | | |
| Avg. | 29.50 | - | -- | 2.38 | 2.41 | 41.0 | 0.273 | 0.161 | 0.163 | 2.0 | 0.263 | 2.241 |
| 190 | 16.125 | 3.20 | 0.25 | 3.13 | 3.27 | 95.0 | | | | | | |
| 191 | 16.125 | 3.05 | 0.29 | 3.12 | 3.28 | 82.0 | | | | | | |
| 192 | 16.125 | 3.05 | 0.25 | 3.13 | 3.27 | 83.5 | | | | | | |
| Avg. | 16.125 | - | -- | 3.13 | 3.27 | 86.8 | 0.395 | 0.212 | 0.222 | 1.09 | 0.263 | 1.532 |
| 193 | 21.80 | 3.10 | -0.42 | 3.25 | 2.95 | 80.0 | | | | | | |
| 194 | 21.80 | 2.90 | -0.24 | 2.99 | 2.81 | 75.0 | | | | | | |
| 195 | 21.80 | 3.17 | -0.23 | 3.25 | 3.09 | 80.0 | | | | | | |
| Avg. | 21.80 | - | -- | 3.16 | 2.95 | 78.3 | 0.356 | 0.214 | 0.200 | 1.48 | 0.263 | 1.532 |
| 196 | 29.50 | 3.10 | 0 | 3.10 | 3.10 | 75.0 | | | | | | |
| 197 | 29.50 | 3.12 | -0.08 | 3.16 | 3.08 | 80.0 | | | | | | |
| 198 | 29.50 | 3.10 | -0.26 | 3.23 | 2.97 | 75.0 | | | | | | |
| Avg. | 29.50 | - | -- | 3.16 | 3.05 | 76.7 | 0.348 | 0.214 | 0.207 | 2.0 | 0.263 | 1.532 |

Table XXVII: Tandem Wheel Performance of Wheel Pair No. $I_a$

Wheel Parameters: D = 14.75 in., b = 3.88 in.; Tests 199-207: W = 300 lb, Tests 208-216: W = 350 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\ell$ (in) | z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | R/W | $z_F/D$ | $z_R/D$ | $\ell/D$ | b/D | $\dfrac{k_\varphi b^{n+2}}{W}$ |
| 199 | 16.125 | 4.20 | 0.30 | 4.12 | 4.28 | 119.0 | | | | | | |
| 200 | 16.125 | 4.10 | 0.16 | 4.06 | 4.14 | 115.0 | | | | | | |
| 201 | 16.125 | 4.00 | 0.14 | 3.96 | 4.04 | 109.0 | | | | | | |
| Avg. | 16.125 | -- | -- | 4.04 | 4.15 | 114.3 | 0.382 | 0.274 | 0.281 | 1.09 | 0.263 | 1.124 |
| 202 | 21.80 | 4.10 | -0.37 | 4.23 | 3.97 | 120.0 | | | | | | |
| 203 | 21.80 | 4.05 | -0.61 | 4.27 | 3.83 | 117.0 | | | | | | |
| 204 | 21.80 | 4.08 | -0.64 | 4.31 | 3.85 | 118.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 4.30 | 3.91 | 118.3 | 0.395 | 0.292 | 0.265 | 1.48 | 0.263 | 1.124 |
| 205 | 29.50 | 4.20 | -0.5 | 4.44 | 3.96 | 120.0 | | | | | | |
| 206 | 29.50 | 4.20 | -0.33 | 4.36 | 4.04 | 121.0 | | | | | | |
| 207 | 29.50 | 4.15 | -0.5 | 4.39 | 3.91 | 115.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 4.40 | 3.97 | 118.6 | 0.395 | 0.298 | 0.269 | 2.0 | 0.263 | 1.124 |
| 208 | 16.125 | 4.55 | 0.43 | 4.44 | 4.66 | 145.0 | | | | | | |
| 209 | 16.125 | 4.50 | 0.44 | 4.38 | 4.62 | 140.0 | | | | | | |
| 210 | 16.125 | 4.50 | 0.50 | 4.37 | 4.63 | 140.0 | | | | | | |
| Avg. | 16.125 | -- | -- | 4.39 | 4.64 | 141.6 | 0.405 | 0.297 | 0.314 | 1.09 | 0.263 | 0.959 |
| 211 | 21.80 | 4.50 | -0.43 | 4.65 | 4.35 | 155.0 | | | | | | |
| 212 | 21.80 | 4.50 | -0.46 | 4.66 | 4.34 | 152.0 | | | | | | |
| 213 | 21.80 | 4.50 | -0.68 | 4.74 | 4.26 | 150.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 4.68 | 4.31 | 152.3 | 0.435 | 0.317 | 0.292 | 1.48 | 0.263 | 0.959 |
| 214 | 29.50 | 4.50 | -0.42 | 4.70 | 4.30 | 159.0 | | | | | | |
| 215 | 29.50 | 4.50 | -0.42 | 4.70 | 4.30 | 155.0 | | | | | | |
| 216 | 29.50 | 4.55 | -0.50 | 4.74 | 4.26 | 155.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 4.71 | 4.29 | 156.3 | 0.446 | 6.320 | 0.290 | 2.0 | 0.263 | 0.959 |

Table XXVIII: Tandem Wheel Performance of Wheel Pair No. 1b

Wheel Parameters: D = 20.875 in., b = 5.41 in.; Tests 217-225; W = 150 lb, Tests 226-234; W = 220 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\ell$ (in) | $z$ (in) | $c$ (in) | $z_F$ (in) | $z_R$ (in) | $R$ (lb) | $R/W$ | $z_F/D$ | $z_R/D$ | $\ell/D$ | $b/D$ | $\dfrac{k_\phi b^{n+2}}{W}$ |
| 217 | 21.80 | 1.32 | 0.18 | 1.25 | 1.39 | 32.9 | | | | | | |
| 218 | 21.80 | 1.36 | 0.07 | 1.33 | 1.39 | 26.8 | | | | | | |
| 219 | 21.80 | 1.30 | 0.07 | 1.27 | 1.33 | 26.2 | | | | | | |
| Avg. | 21.80 | -- | -- | 1.28 | 1.37 | 28.6 | 0.191 | 0.062 | 0.066 | 1.04 | 0.259 | 6.348 |
| 220 | 29.50 | 1.40 | 0.07 | 1.37 | 1.43 | 25.0 | | | | | | |
| 221 | 29.50 | 1.40 | 0.07 | 1.37 | 1.43 | 30.6 | | | | | | |
| 222 | 29.50 | 1.40 | 0.07 | 1.37 | 1.43 | 29.2 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.37 | 1.43 | 28.3 | 0.189 | 0.066 | 0.069 | 1.41 | 0.259 | 6.348 |
| 223 | 41.75 | 1.40 | 0.07 | 1.35 | 1.45 | 30.5 | | | | | | |
| 224 | 41.75 | 1.42 | 0.07 | 1.37 | 1.47 | 32.7 | | | | | | |
| 225 | 41.75 | 1.40 | 0.07 | 1.35 | 1.45 | 33.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.36 | 1.46 | 32.1 | 0.214 | 0.065 | 0.070 | 2.0 | 0.259 | 6.348 |
| 226 | 21.80 | 1.60 | 0.11 | 1.56 | 1.64 | 53.0 | | | | | | |
| 227 | 21.80 | 1.70 | 0.07 | 1.67 | 1.73 | 55.0 | | | | | | |
| 228 | 21.80 | 1.70 | 0.07 | 1.67 | 1.73 | 55.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 1.63 | 1.70 | 54.7 | 0.248 | 0.078 | 0.082 | 1.04 | 0.259 | 4.340 |
| 229 | 29.50 | 1.81 | 0.07 | 1.78 | 1.84 | 54.0 | | | | | | |
| 230 | 29.50 | 1.81 | 0.07 | 1.78 | 1.34 | 60.0 | | | | | | |
| 231 | 29.50 | 1.71 | 0.07 | 1.68 | 1.74 | 56.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.74 | 1.81 | 56.7 | 0.258 | 0.084 | 0.087 | 1.41 | 0.259 | 4.340 |
| 232 | 41.75 | 1.77 | 0.07 | 1.72 | 1.82 | 57.0 | | | | | | |
| 233 | 41.75 | 1.76 | 0.11 | 1.68 | 1.84 | 57.0 | | | | | | |
| 234 | 41.75 | 1.76 | 0.07 | 1.71 | 1.81 | 56.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.70 | 1.82 | 56.7 | 0.258 | 0.082 | 0.087 | 2.0 | 0.259 | 4.340 |

Table XXIX: Tandem Wheel Performance of Wheel Pair No. ...

Wheel Parameters: D = 20.875 in., b = 5.41 in.; Tests 235-243: W = 300 lb, Tests 244-252: W=350 lb

| | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | $\ell$ (in) | z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | R/W | $z_F/D$ | $z_R/D$ | $\ell/D$ | b/D | $\dfrac{k_\phi b^2}{W}$ |
| 235 | 21.80 | 2.50 | 0.04 | 2.49 | 2.51 | 73.0 | | | | | | |
| 236 | 21.80 | 2.42 | 0.00 | 2.42 | 2.42 | 75.0 | | | | | | |
| 237 | 21.80 | 2.44 | 0.00 | 2.44 | 2.44 | 68.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 2.45 | 2.46 | 72.0 | 0.240 | 0.117 | 0.118 | 1.04 | 0.259 | 3. . |
| 238 | 29.50 | 2.50 | 0.00 | 2.50 | 2.50 | 70.0 | | | | | | |
| 239 | 29.50 | 2.60 | 0.10 | 2.55 | 2.65 | 74.0 | | | | | | |
| 240 | 29.50 | 2.60 | 0.07 | 2.57 | 2.63 | 70.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.54 | 2.59 | 71.3 | 0.238 | 0.122 | 0.124 | 1.41 | 0.259 | 3.184 |
| 241 | 41.75 | 2.58 | 0.07 | 2.53 | 2.63 | 77.0 | | | | | | |
| 242 | 41.75 | 2.60 | 0.11 | 2.52 | 2.68 | 74.0 | | | | | | |
| 243 | 41.75 | 2.60 | 0.07 | 2.55 | 2.65 | 74.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.53 | 2.65 | 75.0 | 0.250 | 0.121 | 0.127 | 2.0 | 0.259 | 3.184 |
| 244 | 21.80 | 2.70 | 0.07 | 2.67 | 2.73 | 96.0 | | | | | | |
| 245 | 21.80 | 2.70 | 0.00 | 2.70 | 2.70 | 96.0 | | | | | | |
| 246 | 21.80 | 2.62 | 0.00 | 2.62 | 2.62 | 88.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 2.66 | 2.68 | 93.3 | 0.266 | 0.127 | 0.128 | 1.04 | 0.259 | 2.718 |
| 247 | 29.50 | 2.75 | 0.00 | 2.75 | 2.75 | 96.0 | | | | | | |
| 248 | 29.50 | 2.88 | 0.10 | 2.83 | 2.93 | 99.0 | | | | | | |
| 249 | 29.50 | 2.82 | 0.07 | 2.79 | 2.85 | 97.6 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.79 | 2.84 | 97.5 | 0.279 | 0.134 | 0.136 | 1.41 | 0.259 | 2.718 |
| 250 | 41.75 | 2.80 | 0.07 | 2.75 | 2.85 | 99.0 | | | | | | |
| 251 | 41.75 | 2.80 | 0.07 | 2.75 | 2.85 | 98.0 | | | | | | |
| 252 | 41.75 | 2.78 | 0.07 | 2.73 | 2.83 | 97.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.74 | 2.84 | 98.0 | 0.280 | 0.131 | 0.136 | 2.0 | 0.259 | 2.718 |

Table XXX: Tandem Wheel Performance of Wheel Pair No. 1$_c$

Wheel Parameters: D = 27.0 in., b = 6.98 in.; Tests 253-261: W = 150 lb, Tests 262-270: W = 220 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\ell$ (in) | z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | R/W | $z_F/D$ | $z_R/D$ | $\ell/D$ | b/D | $\frac{k_\varphi b^{n+2}}{W}$ |
| 253 | 29.50 | 1.35 | 0.30 | 1.20 | 1.50 | 16.3 | | | | | | |
| 254 | 29.50 | 1.40 | 0.40 | 1.21 | 1.5 | 15.0 | | | | | | |
| 255 | 29.50 | 1.39 | 0.40 | 1.20 | 1.58 | 15.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.20 | 1.55 | 15.4 | 0.103 | 0.045 | 0.057 | 1.09 | 0.259 | 14.248 |
| 256 | 41.75 | 1.35 | -0.05 | 1.38 | 1.32 | -- | | | | | | |
| 257 | 41.75 | 1.35 | -0.04 | 1.38 | 1.32 | 13.8 | | | | | | |
| 258 | 41.75 | 1.38 | -0.05 | 1.41 | 1.35 | 13.8 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.39 | 1.33 | 13.8 | 0.092 | 0.052 | 0.049 | 1.55 | 0.259 | 14.248 |
| 259 | 54.0 | 1.35 | 0.05 | 1.31 | 1.39 | 15.0 | | | | | | |
| 260 | 54.0 | 1.30 | 0.10 | 1.21 | 1.39 | 15.0 | | | | | | |
| 261 | 54.0 | 1.35 | 0.05 | 1.31 | 1.39 | 15.0 | | | | | | |
| Avg. | 54.0 | -- | -- | 1.28 | 1.39 | 15.0 | 0.100 | 0.047 | 0.051 | 2.0 | 0.259 | 14.248 |
| 262 | 29.50 | 1.58 | 0.20 | 1.48 | 1.68 | 30.4 | | | | | | |
| 263 | 29.50 | 1.62 | 0.50 | 1.38 | 1.86 | 29.5 | | | | | | |
| 264 | 29.50 | 1.60 | 0.40 | 1.41 | 1.79 | 27.8 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.42 | 1.77 | 29.2 | 0.133 | 0.053 | 0.066 | 1.09 | 0.259 | 9.741 |
| 265 | 41.75 | 1.49 | -0.05 | 1.52 | 1.46 | 23.0 | | | | | | |
| 266 | 41.75 | 1.60 | 0.00 | 1.60 | 1.60 | 29.9 | | | | | | |
| 267 | 41.75 | 1.59 | -0.04 | 1.62 | 1.56 | 26.8 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.58 | 1.54 | 26.6 | 0.121 | 0.079 | 0.077 | 1.55 | 0.259 | 9.741 |
| 268 | 54.0 | 1.50 | 0.10 | 1.41 | 1.59 | 31.0 | | | | | | |
| 269 | 54.0 | 1.50 | 0.19 | 1.33 | 1.67 | 29.5 | | | | | | |
| 270 | 54.0 | 1.50 | 0.19 | 1.33 | 1.67 | 29.5 | | | | | | |
| Avg. | 54.0 | -- | -- | 1.36 | 1.64 | 30.0 | 0.136 | 0.050 | 0.061 | 2.0 | 0.259 | 9.741 |

Table XXXI: Tandem Wheel Performance of Wheel Pair No. $1_c$

Wheel Parameters: D = 27.0 in., b = 6.98 in.; Tests 271-279: W = 300 lb, Tests 280-288: W = 350 lb

| Test No. | $\ell$ (in) | z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | R/W | $z_F/D$ | $z_R/D$ | $\ell/D$ | b/D | $\dfrac{k_\phi b^{n+2}}{W}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 271 | 29.50 | 2.10 | 0.10 | 2.05 | 2.15 | 33.0 | | | | | | |
| 272 | 29.50 | 2.15 | -0.04 | 2.17 | 2.13 | 33.0 | | | | | | |
| 273 | 29.50 | 2.12 | -0.04 | 2.14 | 2.10 | 32.5 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.12 | 2.13 | 32.8 | 0.109 | 0.079 | 0.079 | 1.09 | 0.259 | 7.147 |
| 274 | 41.75 | 2.12 | -0.07 | 2.17 | 2.07 | 36.0 | | | | | | |
| 275 | 41.75 | 2.12 | 0.00 | 2.12 | 2.12 | 32.9 | | | | | | |
| 276 | 41.75 | 2.10 | -0.04 | 2.13 | 2.07 | 32.9 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.14 | 2.09 | 33.9 | 0.113 | 0.079 | 0.077 | 1.55 | 0.259 | 7.147 |
| 277 | 54.0 | 1.99 | 0.00 | 1.99 | 1.99 | 34.0 | | | | | | |
| 278 | 54.0 | 2.20 | 0.05 | 2.16 | 2.24 | 35.0 | | | | | | |
| 279 | 54.0 | 2.10 | 0.00 | 2.10 | 2.10 | 35.0 | | | | | | |
| Avg. | 54.0 | -- | -- | 2.08 | 2.11 | 34.6 | 0.113 | 0.077 | 0.078 | 2.0 | 0.259 | 7.147 |
| 280 | 29.50 | 2.20 | 0.10 | 2.15 | 2.25 | 46.0 | | | | | | |
| 281 | 29.50 | 2.25 | 0.00 | 2.25 | 2.25 | 45.0 | | | | | | |
| 282 | 29.50 | 2.25 | 0.10 | 2.18 | 2.25 | 46.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.18 | 2.25 | 45.7 | 0.131 | 0.081 | 0.083 | 1.09 | 0.259 | 6.100 |
| 283 | 41.75 | 2.20 | -0.07 | 2.25 | 2.15 | 46.0 | | | | | | |
| 284 | 41.75 | 2.18 | 0.00 | 2.18 | 2.18 | 47.0 | | | | | | |
| 285 | 41.75 | 2.18 | -0.04 | 2.21 | 2.15 | 43.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.21 | 2.16 | 45.3 | 0.130 | 0.082 | 0.080 | 1.55 | 0.259 | 6.100 |
| 286 | 54.0 | 2.10 | 0.05 | 2.06 | 2.14 | 50.0 | | | | | | |
| 287 | 54.0 | 2.25 | 0.10 | 2.16 | 2.34 | 46.0 | | | | | | |
| 288 | 54.0 | 2.15 | 0.15 | 2.02 | 2.28 | 44.0 | | | | | | |
| Avg. | 54.0 | -- | -- | 2.08 | 2.25 | 46.7 | 0.133 | 0.077 | 0.083 | 2.0 | 0.259 | 6.100 |

Measured Parameters | Calculated Values

Table XXXII: Tandem Wheel Performance of Wheel Pair No. 11

Wheel Parameters: D = 20.875 in., b = 4.7 in., Tests 289-297: W = 150 lb, Tests 298-306: W = 220 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | $\ell$ (in) | $z$ (in) | $c$ (in) | $z_F$ (in) | $z_R$ (in) | $R$ (lb) | $R/W$ | $z_F/D$ | $z_R/D$ | $\ell/D$ | $b/D$ | $\dfrac{k_\varphi b^{n+2}}{W}$ |
| 289 | 21.80 | 1.68 | 0.12 | 1.64 | 1.72 | 31.4 | | | | | | |
| 290 | 21.80 | 1.70 | 0.12 | 1.66 | 1.74 | 31.4 | | | | | | |
| 291 | 21.80 | 1.70 | 0.12 | 1.66 | 1.74 | 33.2 | | | | | | |
| Avg. | 21.80 | -- | -- | 1.65 | 1.73 | 32.0 | 0.213 | 0.079 | 0.083 | 1.04 | 0.225 | 4.100 |
| 292 | 29.50 | 1.77 | 0.21 | 1.67 | 1.77 | 34.3 | | | | | | |
| 293 | 29.50 | 1.74 | 0.24 | 1.62 | 1.86 | 32.0 | | | | | | |
| 294 | 29.50 | 1.72 | 0.17 | 1.64 | 1.80 | 31.4 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.64 | 1.84 | 32.6 | 0.217 | 0.079 | 0.088 | 1.41 | 0.225 | 4.100 |
| 295 | 41.75 | 1.80 | 0.09 | 1.74 | 1.86 | 24.3 | | | | | | |
| 296 | 41.75 | 1.76 | 0.08 | 1.71 | 1.81 | 31.7 | | | | | | |
| 297 | 41.75 | 1.68 | 0.21 | 1.54 | 1.82 | 31.4 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.66 | 1.83 | 29.1 | 0.194 | 0.080 | 0.088 | 2.0 | 0.225 | 4.100 |
| 298 | 21.80 | 2.19 | 0.04 | 2.18 | 2.20 | 58.0 | | | | | | |
| 299 | 21.80 | 2.20 | 0.08 | 2.17 | 2.23 | 59.0 | | | | | | |
| 300 | 21.80 | 2.20 | 0.08 | 2.17 | 2.23 | 60.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 2.17 | 2.22 | 59.0 | 0.268 | 0.104 | 0.106 | 1.04 | 0.225 | 2.803 |
| 301 | 29.50 | 2.16 | 0.21 | 2.06 | 2.26 | 64.0 | | | | | | |
| 302 | 29.50 | 2.22 | 0.21 | 2.12 | 2.32 | 60.0 | | | | | | |
| 303 | 29.50 | 2.26 | 0.17 | 2.18 | 2.34 | 60.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.12 | 2.31 | 61.3 | 0.279 | 0.102 | 0.111 | 1.41 | 0.225 | 2.803 |
| 304 | 41.75 | 2.22 | 0.02 | 2.21 | 2.23 | 58.0 | | | | | | |
| 305 | 41.75 | 2.16 | 0.04 | 2.13 | 2.19 | 60.0 | | | | | | |
| 306 | 41.75 | 2.12 | 0.25 | 1.95 | 2.29 | 60.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.10 | 2.24 | 59.3 | 0.269 | 0.100 | 0.107 | 2.0 | 0.225 | 2.803 |

Table XXXIII:  Tandem Wheel Performance of Wheel Pair No. 11

Wheel Parameters:  D = 20.875 in., b = 4.7 in.; Tests 307-315: W = 300 lb, Tests 316-324: W = 350 lb

| | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | ℓ (in) | z (in) | c (in) | $z_F$ (in) | $z_R$ (in) | R (lb) | R/W | $z_F/D$ | $z_R/D$ | ℓ/D | b/D | $\dfrac{k_\phi b^{n+2}}{W}$ |
| 307 | 21.80 | 2.90 | 0.00 | 2.90 | 2.90 | 77.1 | | | | | | |
| 308 | 21.80 | 2.90 | 0.21 | 2.82 | 2.98 | 77.1 | | | | | | |
| 309 | 21.80 | -- | -- | -- | -- | -- | | | | | | |
| Avg. | 21.80 | -- | -- | 2.86 | 2.94 | 77.1 | 0.257 | 0.137 | 0.141 | 1.04 | 0.225 | 2.057 |
| 310 | 29.50 | 3.40 | 0.12 | 3.34 | 3.46 | 93.3 | | | | | | |
| 311 | 29.50 | 3.45 | 0.12 | 3.39 | 3.51 | 99.0 | | | | | | |
| 312 | 29.50 | 3.42 | 0.12 | 3.36 | 3.48 | 100.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 3.36 | 3.48 | 99.4 | 0.331 | 0.161 | 0.167 | 1.41 | 0.225 | 2.057 |
| 313 | 41.75 | 2.90 | 0.08 | 2.85 | 2.95 | 71.4 | | | | | | |
| 314 | 41.75 | 3.00 | 0.00 | 3.00 | 3.00 | 80.0 | | | | | | |
| 315 | 41.75 | 3.36 | 0.17 | 3.24 | 3.48 | 94.1 | | | | | | |
| Avg. | 41.75 | -- | -- | 3.03 | 3.14 | 81.8 | 0.272 | 0.145 | 0.151 | 2.0 | 0.225 | 2.057 |
| 316 | 21.80 | 3.13 | 0.08 | 3.10 | 3.16 | 100.0 | | | | | | |
| 317 | 21.80 | 3.56 | 0.12 | 3.52 | 3.60 | 120.0 | | | | | | |
| 318 | 21.80 | 3.54 | 0.04 | 3.53 | 3.55 | 119.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 3.38 | 3.43 | 113.0 | 0.323 | 0.162 | 0.164 | 1.04 | 0.225 | 1.755 |
| 319 | 29.50 | 3.63 | 0.08 | 3.59 | 3.67 | 119.0 | | | | | | |
| 320 | 29.50 | 3.64 | 0.08 | 3.60 | 3.68 | 124.0 | | | | | | |
| 321 | 29.50 | 3.69 | 0.00 | 3.69 | 3.69 | 128.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 3.63 | 3.68 | 123.6 | 0.353 | 0.174 | 0.176 | 1.41 | 0.225 | 1.755 |
| 322 | 41.75 | 3.55 | -0.10 | 3.62 | 3.48 | 119.0 | | | | | | |
| 323 | 41.75 | 3.52 | 0.04 | 3.49 | 3.55 | 119.0 | | | | | | |
| 324 | 41.75 | 3.61 | 0.08 | 3.56 | 3.66 | 119.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 3.56 | 3.56 | 119.0 | 0.340 | 0.170 | 0.170 | 2.0 | 0.225 | 1.755 |

Table XXXIV:   Tandem Wheel Performance of Wheel Pair No. 111

Wheel Parameters: D = 20.875 in., b = 6.2 in., Tests 325-333: W = 150 lb, Tests 334-342: W = 220 lb

| Test No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\ell$ (in) | $z$ (in) | $c$ (in) | $z_F$ (in) | $z_R$ (in) | $R$ (lb) | $R/W$ | $z_F/D$ | $z_R/D$ | $\ell/D$ | $b/D$ | $\dfrac{k_\phi b^{n+2}}{W}$ |
| 325 | 21.80 | 1.40 | 0.25 | 1.31 | 1.49 | 25.7 | | | | | | |
| 326 | 21.80 | 1.42 | 0.33 | 1.30 | 1.54 | 27.2 | | | | | | |
| 327 | 21.80 | 1.42 | 0.25 | 1.33 | 1.51 | 28.6 | | | | | | |
| Avg. | 21.80 | -- | -- | 1.31 | 1.51 | 27.1 | 0.180 | 0.063 | 0.072 | 1.04 | 0.297 | 9.806 |
| 328 | 29.50 | 1.35 | 0.00 | 1.35 | 1.35 | 24.6 | | | | | | |
| 329 | 29.50 | 1.35 | 0.08 | 1.31 | 1.39 | 26.3 | | | | | | |
| 330 | 29.50 | 1.35 | 0.25 | 1.23 | 1.47 | 26.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.29 | 1.40 | 25.6 | 0.171 | 0.062 | 0.067 | 1.41 | 0.297 | 9.806 |
| 331 | 41.75 | 1.38 | -0.04 | 1.41 | 1.35 | 24.3 | | | | | | |
| 332 | 41.75 | 1.39 | -0.02 | 1.40 | 1.38 | 28.6 | | | | | | |
| 333 | 41.75 | 1.39 | 0.00 | 1.39 | 1.39 | 28.6 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.40 | 1.37 | 27.2 | 0.181 | 0.067 | 0.066 | 2.0 | 0.297 | 9.806 |
| 334 | 21.30 | 1.70 | 0.33 | 1.58 | 1.82 | 50.0 | | | | | | |
| 335 | 21.80 | 1.70 | 0.33 | 1.58 | 1.82 | 57.0 | | | | | | |
| 336 | 21.80 | 1.70 | 0.33 | 1.58 | 1.82 | 53.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 1.58 | 1.82 | 53.3 | 0.242 | 0.076 | 0.087 | 1.04 | 0.297 | 6.705 |
| 337 | 29.50 | 1.62 | 0.00 | 1.62 | 1.62 | 48.0 | | | | | | |
| 338 | 29.50 | 1.62 | 0.04 | 1.60 | 1.64 | 50.0 | | | | | | |
| 339 | 29.50 | 1.63 | 0.25 | 1.51 | 1.75 | 48.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 1.58 | 1.67 | 48.7 | 0.221 | 0.076 | 0.081 | 1.41 | 0.297 | 6.705 |
| 340 | 41.75 | 1.62 | -0.04 | 1.65 | 1.59 | 49.0 | | | | | | |
| 341 | 41.75 | 1.66 | 0.00 | 1.66 | 1.66 | 50.0 | | | | | | |
| 342 | 41.75 | 1.65 | 0.00 | 1.65 | 1.65 | 52.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 1.65 | 1.63 | 50.3 | 0.228 | 0.079 | 0.078 | 2.0 | 0.297 | 6.705 |

Table XXXV: Tandem Wheel Performance of Wheel Pair No. III

Wheel Parameters: D = 20.875 in., b = 6.2 in.; Tests 343-351: W = 300 lb, Tests 352-360: W = 350 lb

| Tests No. | Measured Parameters | | | | | | Calculated Values | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\ell$ (in) | $z$ (in) | $c$ (in) | $z_F$ (in) | $z_\delta$ (in) | $R$ (lb) | $R/W$ | $z_F/D$ | $z_R/D$ | $\ell/D$ | $b/D$ | $\dfrac{k_\varphi b^{n+2}}{W}$ |
| 343 | 21.80 | 2.50 | 0.33 | 2.38 | 2.62 | 78.0 | | | | | | |
| 344 | 21.80 | 2.45 | 0.25 | 2.36 | 2.54 | 70.0 | | | | | | |
| 345 | 21.80 | 2.45 | 0.25 | 2.36 | 2.54 | 70.0 | | | | | | |
| Avg. | 21.80 | -- | -- | 2.37 | 2.57 | 72.6 | 0.242 | 0.114 | 0.123 | 1.04 | 0.297 | 4.919 |
| 346 | 29.50 | 2.42 | 0.00 | 2.42 | 2.42 | 75.0 | | | | | | |
| 347 | 29.50 | 2.50 | 0.50 | 2.26 | 2.74 | 70.0 | | | | | | |
| 348 | 29.50 | 2.45 | 0.25 | 2.33 | 2.51 | 70.0 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.33 | 2.57 | 71.6 | 0.239 | 0.112 | 0.123 | 1.41 | 0.297 | 4.919 |
| 349 | 41.75 | 2.50 | 0.05 | 2.47 | 2.53 | 76.0 | | | | | | |
| 350 | 41.75 | 2.50 | 0.00 | 2.50 | 2.50 | 76.0 | | | | | | |
| 351 | 41.75 | 2.50 | 0.00 | 2.50 | 2.50 | 75.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.49 | 2.51 | 75.6 | 0.252 | 0.119 | 0.120 | 2.0 | 0.297 | 4.919 |
| 352 | 21.80 | 2.67 | 0.25 | 2.58 | 2.76 | 93.3 | | | | | | |
| 353 | 21.80 | 2.60 | 0.17 | 2.54 | 2.66 | 90.0 | | | | | | |
| 354 | 21.80 | 2.60 | 0.17 | 2.54 | 2.66 | 93.3 | | | | | | |
| Avg. | 21.80 | -- | -- | 2.55 | 2.69 | 92.2 | 0.263 | 0.122 | 0.129 | 1.04 | 0.297 | 4.198 |
| 355 | 29.50 | 2.65 | 0.00 | 2.65 | 2.65 | 93.4 | | | | | | |
| 356 | 29.50 | 2.62 | 0.42 | 2.42 | 2.82 | 93.4 | | | | | | |
| 357 | 29.50 | 2.64 | 0.17 | 2.56 | 2.72 | 93.4 | | | | | | |
| Avg. | 29.50 | -- | -- | 2.54 | 2.73 | 93.4 | 0.266 | 0.121 | 0.131 | 1.41 | 0.297 | 4.198 |
| 358 | 41.75 | 2.70 | 0.08 | 2.65 | 2.75 | 98.0 | | | | | | |
| 359 | 41.75 | 2.69 | 0.00 | 2.69 | 2.69 | 96.0 | | | | | | |
| 360 | 41.75 | 2.69 | 0.00 | 2.69 | 2.69 | 98.0 | | | | | | |
| Avg. | 41.75 | -- | -- | 2.68 | 2.71 | 97.3 | 0.278 | 0.128 | 0.130 | 2.0 | 0.297 | 4.198 |

Table XXXVI: Tandem Wheel Test Carriage Velocities, Wheel Velocities and Skid Rates

Wheel Pair No. I$_a$

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 181 | 0.162 | 0.102 | 0.116 | 37.1 | 28.3 |
| 182 | 0.168 | -- | -- | -- | -- |
| 183 | 0.170 | 0.108 | 0.130 | 36.8 | 23.9 |
| Avg. | -- | -- | -- | 37.0 | 26.1 |
| 184 | 0.158 | 0.103 | 0.124 | 35.0 | 21.9 |
| 185 | 0.167 | 0.103 | 0.128 | 38.5 | 23.2 |
| 186 | 0.173 | 0.110 | -- | 36.5 | -- |
| Avg. | -- | -- | -- | 36.7 | 22.6 |
| 187 | 0.206 | 0.145 | 0.166 | 29.7 | 19.4 |
| 188 | 0.194 | 0.129 | 0.160 | 33.5 | 17.2 |
| 189 | 0.172 | 0.111 | 0.131 | 35.4 | 23.8 |
| Avg. | -- | -- | -- | 32.9 | 20.1 |
| 190 | 0.162 | 0.094 | 0.098 | 42.3 | 39.3 |
| 191 | 0.168 | -- | -- | -- | -- |
| 192 | 0.170 | 0.095 | 0.111 | 44.2 | 34.6 |
| Avg. | -- | -- | -- | 43.3 | 37.0 |
| 193 | 0.158 | 0.097 | 0.106 | 38.8 | 33.1 |
| 194 | 0.167 | 0.097 | 0.117 | 42.0 | 30.0 |
| 195 | 0.173 | 0.108 | 0.116 | 37.7 | 32.9 |
| Avg. | -- | -- | -- | 39.5 | 32.0 |
| 196 | 0.206 | 0.116 | -- | 43.7 | -- |
| 197 | 0.194 | 0.111 | 0.129 | 42.7 | 33.5 |
| 198 | 0.172 | 0.099 | 0.120 | 42.0 | 29.9 |
| Avg. | -- | -- | -- | 42.8 | 31.7 |

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 199 | -- | -- | -- | -- | -- |
| 200 | 0.165 | 0.095 | 0.105 | 42.8 | 36.3 |
| 201 | 0.169 | 0.098 | 0.105 | 42.1 | 37.9 |
| Avg. | -- | -- | -- | 42.4 | 37.1 |
| 202 | 0.184 | 0.104 | 0.118 | 43.4 | 35.7 |
| 203 | 0.183 | 0.099 | -- | 45.6 | -- |
| 204 | 0.171 | 0.097 | 0.110 | 43.7 | 35.6 |
| Avg | -- | -- | -- | 44.2 | 35.7 |
| 205 | 0.169 | -- | 0.097 | -- | 42.9 |
| 206 | 0.169 | -- | 0.086 | -- | 43.2 |
| 207 | 0.183 | -- | 0.117 | -- | 36.7 |
| Avg. | -- | -- | -- | -- | 40.7 |
| 208 | -- | -- | -- | -- | -- |
| 209 | 0.165 | 0.095 | 0.103 | 42.8 | 37.7 |
| 210 | 0.169 | 0.087 | 0.103 | 48.5 | 38.8 |
| Avg. | -- | -- | -- | 45.7 | 38.3 |
| 211 | 0.184 | 0.097 | 0.111 | 47.3 | 39.7 |
| 212 | 0.183 | 0.097 | 0.103 | 46.7 | 43.8 |
| 213 | 0.171 | 0.089 | 0.104 | 47.8 | 39.4 |
| Avg. | -- | -- | -- | 47.3 | 41.0 |
| 214 | 0.169 | -- | 0.092 | -- | 45.6 |
| 215 | 0.169 | -- | 0.090 | -- | 46.4 |
| 216 | 0.183 | -- | 0.116 | -- | 36.6 |
| Avg. | -- | -- | -- | -- | 42.9 |

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Table XXXVII: Tandem Wheel Test Carriage Velocities, Wheel Velocities and Skid Rates

Wheel P; No. $I_b$

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 217 | -- | -- | -- | -- | -- |
| 218 | 0.173 | 0.143 | 0.159 | 17.4 | 8.1 |
| 219 | 0.168 | 0.138 | 0.158 | 17.9 | 6.2 |
| Avg. | -- | -- | -- | 17.7 | 7.1 |
| 220 | 0.200 | -- | 0.186 | -- | 7.1 |
| 221 | 0.176 | -- | 0.158 | -- | 10.7 |
| 222 | 0.168 | 0.139 | 0.161 | 17.2 | 4.5 |
| Avg. | -- | -- | -- | 17.2 | 11.1 |
| 223 | 0.165 | 0.133 | 0.152 | 19.6 | 8.0 |
| 224 | 0.172 | 0.137 | 0.153 | 20.8 | 11.0 |
| 225 | 0.166 | 0.135 | 0.153 | 19.1 | 8.2 |
| Avg. | -- | -- | -- | 19.8 | 9.1 |
| 226 | -- | -- | -- | -- | -- |
| 227 | 0.173 | 0.125 | 0.158 | 27.5 | 8.4 |
| 228 | 0.168 | 0.122 | 0.146 | 27.1 | 12.9 |
| Avg. | -- | -- | -- | 27.3 | 10.6 |
| 229 | 0.200 | -- | 0.165 | -- | 17.7 |
| 230 | 0.176 | 0.119 | 0.146 | 32.7 | 17.1 |
| 231 | 0.168 | 0.124 | 0.148 | 26.2 | 11.8 |
| Avg. | -- | -- | -- | 29.4 | 15.5 |
| 232 | 0.165 | 0.121 | 0.144 | 26.7 | 12.6 |
| 233 | 0.172 | 0.128 | 0.154 | 25.5 | 11.0 |
| 234 | 0.166 | 0.121 | 0.146 | 27.3 | 12.3 |
| Avg. | -- | -- | -- | 26.7 | 11.9 |
| 235 | 0.173 | -- | 0.148 | -- | 14.5 |
| 236 | 0.175 | -- | -- | -- | -- |
| 237 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | -- | 14.5 |
| 238 | -- | -- | -- | -- | -- |
| 239 | 0.165 | -- | 0.139 | -- | 15.4 |
| 240 | 0.176 | 0.136 | -- | 22.6 | -- |
| Avg. | -- | -- | -- | 22.6 | 15.4 |
| 241 | 0.164 | 0.119 | 0.142 | 27.6 | 13.7 |
| 242 | 0.167 | 0.115 | 0.145 | 31.1 | 12.8 |
| 243 | -- | -- | -- | -- | 13.3 |
| Avg. | -- | -- | -- | 29.3 | 13.3 |
| 244 | 0.173 | 0.114 | 0.140 | 34.1 | 18.9 |
| 245 | 0.175 | 0.116 | 0.141 | 33.7 | 19.1 |
| 246 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | 33.9 | 19.0 |
| 247 | -- | -- | -- | -- | -- |
| 248 | 0.165 | -- | 0.133 | -- | 19.5 |
| 249 | 0.176 | 0.124 | 0.148 | 29.3 | 15.4 |
| Avg. | -- | -- | -- | 29.3 | 17.4 |
| 250 | 0.164 | 0.112 | 0.135 | 31.7 | 17.8 |
| 251 | 0.167 | 0.111 | 0.135 | 33.5 | 18.9 |
| 252 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | 32.6 | 19.3 |

Table XXXVIII: Tandem Wheel Test Carriage Velocities, Wheel Velocities and Skid Rates

Wheel Pair No. $I_c$

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 253 | 0.152 | 0.139 | 0.148 | 8.3 | 2.1 |
| 254 | 0.151 | 0.137 | 0.147 | 9.6 | 2.9 |
| 255 | 0.149 | 0.135 | 0.144 | 9.4 | 3.3 |
| Avg. | -- | -- | -- | 9.1 | 2.7 |
| 256 | 0.154 | 0.141 | 0.150 | 8.0 | 2.6 |
| 257 | 0.152 | 0.142 | -- | 6.3 | -- |
| 258 | 0.163 | 0.154 | -- | 5.7 | -- |
| Avg. | -- | -- | -- | 6.7 | 2.6 |
| 259 | 0.143 | 0.129 | 0.141 | 9.7 | 1.4 |
| 260 | 0.143 | 0.132 | 0.141 | 7.9 | 1.2 |
| 261 | 0.142 | 0.125 | 0.136 | 11.4 | 3.9 |
| Avg. | -- | -- | -- | 9.6 | 2.2 |
| 262 | 0.152 | 0.132 | 0.147 | 13.1 | 2.9 |
| 263 | 0.151 | 0.135 | 0.147 | 11.0 | 2.6 |
| 264 | 0.149 | 0.130 | 0.140 | 12.5 | 5.6 |
| Avg. | -- | -- | -- | 12.2 | 3.7 |
| 265 | 0.154 | 0.136 | 0.147 | 11.6 | 4.2 |
| 266 | 0.152 | 0.136 | 0.148 | 10.2 | 2.3 |
| 267 | 0.163 | 0.145 | 0.154 | 10.7 | 5.3 |
| Avg. | -- | -- | -- | 10.8 | 3.9 |
| 268 | 0.143 | 0.126 | 0.136 | 11.6 | 4.9 |
| 269 | 0.143 | 0.126 | 0.138 | 11.8 | 3.6 |
| 270 | 0.142 | 0.124 | 0.132 | 12.1 | 6.5 |
| Avg. | -- | -- | -- | 11.8 | 5.0 |

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 271 | 0.145 | 0.125 | 0.138 | 13.7 | 4.6 |
| 272 | 0.141 | 0.121 | 0.129 | 14.1 | 8.3 |
| 273 | 0.143 | 0.123 | 0.132 | 14.1 | 7.3 |
| Avg. | -- | -- | -- | 13.9 | 6.7 |
| 274 | 0.145 | 0.127 | 0.141 | 12.9 | 3.1 |
| 275 | 0.144 | 0.122 | 0.130 | 15.2 | 10.0 |
| 276 | 0.148 | 0.137 | 0.143 | 7.6 | 3.9 |
| Avg. | -- | -- | -- | 11.9 | 5.6 |
| 277 | 0.176 | 0.131 | 0.148 | 25.5 | 15.5 |
| 278 | 0.158 | 0.134 | 0.145 | 14.9 | 8.3 |
| 279 | 0.140 | 0.119 | 0.131 | 14.8 | 6.6 |
| Avg. | -- | -- | -- | 18.4 | 10.1 |
| 280 | 0.145 | 0.121 | 0.134 | 16.0 | 7.1 |
| 281 | 0.141 | 0.116 | 0.130 | 17.9 | 8.0 |
| 282 | 0.143 | 0.118 | 0.131 | 17.5 | 8.4 |
| Avg. | -- | -- | -- | 17.0 | 7.8 |
| 283 | 0.145 | 0.121 | 0.127 | 16.4 | 12.5 |
| 284 | 0.144 | 0.126 | 0.135 | 12.5 | 6.2 |
| 285 | 0.148 | 0.119 | 0.131 | 19.5 | 11.4 |
| Avg. | -- | -- | -- | 16.1 | 10.0 |
| 286 | 0.176 | 0.151 | 0.167 | 14.1 | 5.1 |
| 287 | 0.158 | 0.128 | 0.143 | 18.9 | 9.4 |
| 288 | 0.140 | 0.118 | 0.131 | 15.0 | 6.6 |
| Avg. | -- | -- | -- | 16.0 | 7.0 |

Table XXXIX: Tandem Wheel Test Carriage Velocities, Wheel Velocities and Skid Rates

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 289 | 0.176 | 0.137 | 0.142 | 22.2 | 15.4 |
| 290 | 0.175 | 0.137 | 0.156 | 21.8 | 10.6 |
| 291 | 0.193 | 0.167 | -- | 12.7 | -- |
| Avg. | -- | -- | -- | 19.2 | 13.0 |
| 292 | -- | -- | -- | -- | -- |
| 293 | -- | -- | -- | -- | -- |
| 294 | 0.179 | 0.152 | 0.171 | 15.3 | 4.7 |
| Avg. | -- | -- | -- | 15.3 | 4.7 |
| 295 | -- | -- | -- | -- | -- |
| 296 | 0.187 | 0.145 | 0.171 | 22.8 | 8.8 |
| 297 | 0.168 | 0.137 | 0.152 | 18.8 | 9.5 |
| Avg. | -- | -- | -- | 20.7 | 9.2 |
| 298 | 0.176 | 0.124 | 0.159 | 29.6 | 9.5 |
| 299 | 0.175 | 0.124 | 0.153 | 29.0 | 12.7 |
| 300 | 0.193 | 0.130 | 0.154 | 32.6 | 20.0 |
| Avg. | -- | -- | -- | 30.4 | 14.1 |
| 301 | -- | -- | -- | -- | -- |
| 302 | -- | -- | -- | -- | -- |
| 303 | 0.179 | 0.129 | 0.161 | 28.0 | 10.3 |
| Avg. | -- | -- | -- | 28.0 | 10.3 |
| 304 | -- | -- | -- | -- | -- |
| 305 | 0.187 | 0.134 | 0.161 | 28.4 | 14.1 |
| 306 | 0.168 | 0.110 | 0.136 | 34.3 | 19.0 |
| Avg. | -- | -- | -- | 31.3 | 16.5 |

Wheel Pair No. II

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 307 | -- | -- | -- | -- | -- |
| 308 | 0.175 | 0.130 | 0.157 | 25.6 | 10.2 |
| 309 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | 25.6 | 10.2 |
| 310 | 0.160 | 0.106 | 0.126 | 34.0 | 21.2 |
| 311 | 0.154 | 0.105 | 0.125 | 31.9 | 18.8 |
| 312 | 0.160 | 0.108 | 0.135 | 32.4 | 15.7 |
| Avg. | -- | -- | -- | 32.7 | 18.5 |
| 313 | -- | -- | -- | -- | -- |
| 314 | 0.182 | 0.102 | 0.147 | 44.0 | 19.4 |
| 315 | 0.165 | 0.111 | 0.145 | 32.7 | 12.0 |
| Avg. | -- | -- | -- | 38.3 | 15.7 |
| 316 | -- | -- | -- | -- | -- |
| 317 | 0.175 | 0.114 | 0.137 | 34.9 | 21.9 |
| 318 | 0.170 | 0.106 | 0.117 | 37.6 | 30.9 |
| Avg. | -- | -- | -- | 36.2 | 26.4 |
| 319 | 0.160 | 0.105 | 0.124 | 34.5 | 23.0 |
| 320 | 0.154 | 0.099 | 0.112 | 35.9 | 23.4 |
| 321 | 0.160 | 0.105 | 0.124 | 34.3 | 22.3 |
| Avg. | -- | -- | -- | 34.7 | 22.9 |
| 322 | -- | -- | -- | -- | -- |
| 323 | 0.182 | 0.114 | 0.137 | 37.5 | 25.0 |
| 324 | 0.165 | 0.108 | 0.127 | 34.4 | 23.1 |
| Avg. | -- | -- | -- | 35.9 | 24.0 |

Table XL: Tandem Wheel Test Carriage Velocities, Wheel Velocities and Skid Rates

Wheel Pair No. III

| Test No. | $V_c$ (ft/sec) | $V_{wF}$ (ft/sec) | $V_{wR}$ (ft/sec) | $B_F$ (%) | $B_R$ (%) |
|---|---|---|---|---|---|
| 325 | 0.153 | 0.128 | -- | 16.4 | -- |
| 326 | -- | -- | -- | -- | -- |
| 327 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | 16.4 | -- |
| 328 | 0.170 | 0.146 | 0.165 | 13.7 | 2.6 |
| 329 | -- | -- | -- | -- | -- |
| 330 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | 13.7 | 2.6 |
| 331 | 0.162 | 0.144 | 0.153 | 11.1 | 5.1 |
| 332 | 0.154 | 0.129 | -- | 16.0 | -- |
| 333 | 0.160 | 0.135 | 0.148 | 15.6 | 7.8 |
| Avg. | -- | -- | -- | 14.2 | 6.5 |
| 334 | 0.153 | 0.115 | 0.135 | 24.6 | 11.7 |
| 335 | -- | -- | -- | -- | -- |
| 336 | 0.164 | 0.119 | 0.139 | 27.6 | 15.0 |
| Avg. | -- | -- | -- | 26.1 | 13.3 |
| 337 | -- | -- | -- | -- | -- |
| 338 | -- | -- | -- | -- | -- |
| 339 | -- | -- | -- | -- | -- |
| Avg. | -- | -- | -- | -- | -- |
| 340 | 0.162 | 0.125 | 0.148 | 22.8 | 8.7 |
| 341 | 0.154 | 0.119 | 0.138 | 22.9 | 10.5 |
| 342 | 0.160 | 0.119 | 0.141 | 25.5 | 12.1 |
| Avg. | -- | -- | -- | 23.7 | 10.4 |
| 343 | 0.160 | -- | 0.143 | -- | 10.8 |
| 344 | 0.157 | 0.112 | 0.136 | 28.7 | 13.5 |
| 345 | 0.155 | 0.110 | 0.141 | 29.0 | 9.2 |
| Avg. | -- | -- | -- | 28.9 | 11.1 |
| 346 | -- | -- | -- | -- | -- |
| 347 | -- | -- | -- | -- | -- |
| 348 | 0.167 | 0.119 | 0.152 | 28.9 | 9.1 |
| Avg. | -- | -- | -- | 28.9 | 9.1 |
| 349 | 0.146 | 0.108 | 0.133 | 30.4 | 14.5 |
| 350 | -- | -- | -- | -- | -- |
| 351 | 0.164 | -- | 0.138 | -- | 15.6 |
| Avg. | -- | -- | -- | 30.4 | 15.0 |
| 352 | 0.160 | -- | 0.137 | -- | 14.8 |
| 353 | 0.157 | 0.107 | 0.127 | 32.0 | 19.2 |
| 354 | 0.155 | 0.105 | 0.123 | 32.2 | 20.9 |
| Avg. | -- | -- | -- | 32.1 | 18.3 |
| 355 | -- | -- | -- | -- | -- |
| 356 | -- | -- | -- | -- | -- |
| 357 | 0.167 | 0.116 | 0.137 | 30.6 | 17.9 |
| Avg. | -- | -- | -- | 30.6 | 17.9 |
| 358 | 0.156 | 0.108 | 0.125 | 30.4 | 19.6 |
| 359 | -- | -- | -- | -- | -- |
| 360 | 0.164 | -- | 0.132 | -- | 19.2 |
| Avg. | -- | -- | -- | 30.4 | 19.4 |

Table XLI

Single Wheel Performance of Wheel Pair No. $1_a$

| Test No. | W (lb) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | B (%) | Remarks |
|---|---|---|---|---|---|---|---|
| 361 | 75 | 1.78 | 36.5 | 0.157 | 0.099 | 36.9 | |
| 362 | 75 | 1.79 | 35.0 | 0.174 | 0.144 | 34.5 | First Pass |
| Avg. | 75 | 1.79 | 35.8 | -- | -- | 35.7 | |
| 363 | 75 | -- | -- | -- | -- | -- | |
| 364 | 75 | 1.70 | 23.8 | 0.161 | 0.121 | 24.8 | Second Pass |
| Avg. | 75 | 1.70 | 23.8 | -- | -- | 24.8 | |
| 365 | 110 | 2.20 | 50.3 | 0.157 | 0.097 | 38.2 | |
| 366 | 110 | 2.25 | 51.0 | 0.174 | 0.118 | 32.2 | First Pass |
| Avg. | 110 | 2.23 | 50.6 | -- | -- | 35.2 | |
| 367 | 110 | 2.19 | 41.7 | 0.180 | 0.114 | 36.7 | |
| 368 | 110 | 2.10 | 38.8 | 0.161 | 0.111 | 31.0 | Second Pass |
| Avg. | 110 | 2.15 | 40.3 | -- | -- | 33.8 | |
| 369 | 150 | 3.10 | 80.0 | 0.158 | 0.088 | 44.3 | |
| 370 | 150 | 3.20 | 80.0 | 0.160 | 0.092 | 42.5 | First Pass |
| Avg. | 150 | 3.15 | 80.0 | -- | -- | 43.4 | |
| 371 | 150 | 2.77 | 60.0 | 0.159 | 0.103 | 35.2 | |
| 372 | 150 | 2.73 | 60.0 | 0.154 | 0.099 | 35.7 | Second Pass |
| Avg. | 150 | 2.75 | 60.0 | -- | -- | 35.5 | |
| 373 | 175 | 3.55 | 101.0 | 0.158 | 0.086 | 45.5 | |
| 374 | 175 | 3.60 | 99.0 | 0.160 | -- | -- | First Pass |
| Avg. | 175 | 3.58 | 100.0 | -- | -- | 45.5 | |
| 375 | 175 | 3.20 | 76.0 | 0.159 | 0.100 | 37.1 | |
| 376 | 175 | 3.20 | 76.0 | 0.154 | 0.095 | 38.3 | Second Pass |
| Avg. | 175 | 3.20 | 76.0 | -- | -- | 37.7 | |

## Table XLII

Single Wheel Performance of Wheel Pair No. $I_b$

| Test No. | W (lb) | z (in) | R (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | B (%) | Remarks |
|---|---|---|---|---|---|---|---|
| 377 | 75 | 0.96 | 15.3 | 0.151 | 0.124 | 17.9 | |
| 378 | 75 | 0.92 | 16.3 | 0.154 | 0.129 | 16.2 | First Pass |
| Avg. | 75 | 0.94 | 15.8 | -- | -- | 17.1 | |
| 379 | 75 | 1.10 | 6.5 | 0.154 | 0.143 | 7.2 | |
| 380 | 75 | 1.10 | 10.0 | 0.163 | 0.152 | 6.8 | Second Pass |
| Avg. | 75 | 1.10 | 8.25 | -- | -- | 7.0 | |
| 381 | 110 | 1.16 | 28.8 | 0.151 | 0.117 | 22.5 | |
| 382 | 110 | 1.12 | 28.5 | 0.154 | 0.125 | 18.8 | First Pass |
| Avg. | 110 | 1.14 | 28.7 | -- | -- | 20.6 | |
| 383 | 110 | 1.35 | 12.5 | 0.154 | 0.145 | 5.9 | |
| 384 | 110 | 1.30 | 12.5 | 0.163 | 0.155 | 4.9 | Second Pass |
| Avg. | 110 | 1.33 | 12.5 | -- | -- | 5.4 | |
| 385 | 150 | 1.28 | 32.8 | 0.164 | 0.132 | 19.5 | |
| 386 | 150 | 1.65 | 50.0 | 0.175 | 0.119 | 32.0 | First Pass |
| Avg. | 150 | 1.46 | 41.4 | -- | -- | 25.8 | |
| 387 | 150 | 1.65 | 33.8 | 0.168 | 0.145 | 13.7 | |
| 388 | 150 | 1.82 | 28.9 | 0.200 | 0.175 | 12.5 | Second Pass |
| Avg. | 150 | 1.73 | 31.3 | -- | -- | 13.1 | |
| 389 | 175 | 1.53 | 48.3 | 0.154 | 0.115 | 29.9 | |
| 390 | 175 | 1.80 | 62.9 | 0.175 | 0.126 | 28.0 | First Pass |
| Avg. | 175 | 1.67 | 55.6 | -- | -- | 28.9 | |
| 391 | 175 | 1.90 | 44.7 | 0.168 | 0.133 | 20.8 | |
| 392 | 175 | 2.05 | 43.0 | 0.200 | 0.156 | 22.0 | Second Pass |
| Avg. | 175 | 1.97 | 43.8 | -- | -- | 21.4 | |

Table XLIII

Sing's Wheel Performance of Wheel Pair No. 1$_c$

| Test No. | W (lb) | z (in) | $\dot{n}$ (lb) | $V_c$ (ft/sec) | $V_w$ (ft/sec) | B (%) | Remarks |
|---|---|---|---|---|---|---|---|
| 393 | 75 | 0.60 | 15.5 | 0.136 | 0.124 | 8.9 | |
| 394 | 75 | 0.60 | 13.8 | 0.139 | 0.127 | 8.6 | First Pass |
| Avg. | 75 | 0.60 | 14.65 | -- | -- | 8.7 | |
| 395 | 75 | 0.70 | 6.0 | 0.135 | 0.132 | 2.2 | |
| 396 | 75 | 0.75 | 7.9 | 0.140 | 0.137 | 2.2 | Second Pass |
| Avg. | 75 | 0.73 | 6.95 | -- | -- | 2.2 | |
| 397 | 110 | 0.80 | 19.7 | 0.136 | 0.119 | 12.5 | |
| 398 | 110 | 0.78 | 18.0 | 0.139 | 0.123 | 11.5 | First Pass |
| Avg. | 110 | 0.79 | 18.85 | -- | -- | 12.0 | |
| 399 | 110 | 0.90 | 13.2 | 0.135 | 0.128 | 5.2 | |
| 400 | 110 | 0.90 | 12.9 | 0.140 | 0.129 | 7.9 | Second Pass |
| Avg. | 110 | 0.90 | 16.55 | -- | -- | 6.5 | |
| 401 | 150 | 0.97 | 35.1 | 0.148 | 0.124 | 16.2 | |
| 402 | 150 | 0.95 | 32.7 | 0.138 | 0.113 | 18.1 | First Pass |
| Avg. | 110 | 0.96 | 33.9 | -- | -- | 17.1 | |
| 403 | 150 | 1.18 | 12.5 | 0.138 | 0.131 | 5.1 | |
| 404 | 150 | 1.15 | 13.8 | 0.152 | 0.141 | 7.3 | Second Pass |
| Avg. | 150 | 1.17 | 13.2 | -- | -- | 6.2 | |
| 405 | 175 | 1.10 | 39.4 | 0.148 | 0.122 | 17.6 | |
| 406 | 175 | 1.05 | 35.7 | 0.138 | 0.111 | 19.5 | First Pass |
| Avg. | 175 | 1.08 | 37.6 | -- | -- | 18.5 | |
| 407 | 175 | 1.28 | 20.6 | 0.138 | 0.128 | 7.3 | |
| 408 | 175 | 1.26 | 20.6 | -- | -- | -- | Second Pass |
| Avg. | 175 | 1.27 | 20.6 | -- | -- | 7.3 | |