THE EFFECT OF DRAWBAR LOAD AND TIRE INFLATION ON SOIL-TIRE INTERFACE PRESSURE

Thesis for the Degree of M. S.
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by

Gerald W. Trabbic

AN ABSTRACT

Submitted to the College of Agriculture of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the Degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

Year 1959

Approved by Wesley F. Buchele

ABSTRACT

The construction, mounting, calibration and testing of the diaphragm type pressure transducers in a rear tractor tire are described. The transducers were mounted in the undertread, lug face, leading lug side and trailing lug side. Ten cells were mounted in each position across the width of the tire. The tests were run at 5 different drawbar loads and 3 different tire inflation pressures. The method of varying and measuring the drawbar load is described.

The soil-tire interface pressure data collected were tabulated and plotted to show the effect of tire inflation pressure and drawbar load on the soil-tire interface pressure distribution across the width of the tire in each of the above positions. The plotted data show that as the drawbar load and tire inflation pressure were increased, the soil-tire interface pressure generally increased on the undertread and leading lug side. The soil-tire interface pressure decreased on the lug face and trailing lug side as the drawbar load was increased. The soil-tire interface pressure generally increased as the tire inflation pressure was increased.

Percent slip was calculated from measurements of actual and theoretical forward travel made with the use of microswitches. The method of measurement and calculation of percent slip are described. The effect of drawbar load on per-

cent slip at the 3 tire inflation pressures is shown in graphical form.

Rear axle torque was measured during the tests. The relationship of drawbar load and torque for the 3 tire inflation pressures is shown in graphical form. Data from the rear axle torque and percent slip tables are plotted for each tire inflation pressure to show their relationship. The plots show that as the percent slip increased, the rear axle torque increased.

An application of the soil-tire interface pressures on the undertread and lug face was made to determine the weight transfer. Theoretical equations for determining weight transfer, developed by Buchele (1959), were used to check the above mentioned calculations. The rear axle torque data and the dynamic weight on the soil (dead weight plus weight transfer) were used in another equation to determine the point of application of the resultant soil force against the rear tire.

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INTRODUCTION

The average horsepower of the tractors purchased by the American farmers doubled from 1947 to 1957. The use of fertilizers and pesticides (herbicides, fungicides and insecticides) has increased phenomenally during the past decade. Heavier tractors and more operations have contributed immeasurably to the soil compaction problem.

The mechanical consolidation of tillable soils has reduced crop yields and in extreme cases forced removal of the land from agricultural production. As the soil becomes consolidated, the mechanical strength of the soil is increased, the water holding capacity is lowered and the infiltration capacity is decreased.

One approach to the soil compaction problem would be to redesign the present tractors and tires in order to maintain or increase their ability to pull heavy drawbar loads and yet not compact the soil. Before this can be done, studies of the present tires must be made to determine how traction is developed and the magnitude of pressure at the surface of contact of the tire and soil.

The purpose of this investigation was to measure the soil-tire interface pressures on the undertread, lug face, leading lug side and trailing lug side of a rear tractor tire at several drawbar loads and tire inflation pressures.

The rear axle torque and slip of the rear tractor wheel were also measured. These tests were conducted on one tire operating in a sand box.

The above tests should be used on different tire designs and soil types to determine the relative merits of the design in the various soils. This information could lead to the development of more efficient tires than those now used and reduce the compaction of tillable soils.

LITERATURE REVIEW

Soil compaction caused by tractor wheel traffic has been a topic of discussion since the advent of the farm tractor. Aftér the introduction of the first pneumatic tractor tire in 1932, however, more emphasis was placed on the relative merits of lugged steel wheels versus pneumatic tires. Once the pneumatic tire became generally accepted for use on tractors, the emphasis was shifted to comparing tires weighted with liquid ballast to wheels weighted with cast iron weights. A literature survey on these early comparisons and later work has been done recently by Lask (1958).

Effects of Compaction

The problems of soil compaction were once again brought to the attention of investigators by Edminister (1956) as reported by Hovanesian (1958). He indicated that 2,000,000 acres of Class I land in California had been taken from production due to excessive compaction and that another 2,000,000 acres were destined to the same fate within a short period of time.

Since then, increased emphasis has been placed on the problem throughout the United States and Canada as evidenced by the ASAE Soil Compaction Committee Report (1958).

Tests conducted in Puerto Rico by Lugo-Lopez and Acevedo (1956) on the effect of heavy tractor traffic showed that in land areas compacted by tractors the water infiltration rate was considerably lower than in uncompacted areas. They also showed that bulk density was significantly higher in the compacted soil.

Buchele (1954) conducted experiments on the compaction of furrows between rows of contoured ridge-farmed corn plots in Iowa. He found that one hour after a rain the untraveled furrows were practically free of standing water while the traveled furrows were nearly full of standing water. He also noted that the only water lost from the field came from the traveled furrows. Tractor traffic increased the bulk density at the 6 to 8 inch level from 1.367 to 1.504.

During irrigation tests conducted in a field of sugar beets, Monson (1957), found in the rows traveled by the tractor wheels during cultivation, that the amount of water infiltrated into the soil during 5 1/2 hours was 1 1/8 inches while in the adjacent untraveled rows it was 5 5/16 inches.

Tire Traction

Other investigators have been concerned with the effects of tractors and tractor tire design on traction. McCuen (1933) found that the rolling resistance of a tractor when equipped with low pressure tires was on the average only 31.4 percent of that with steel wheels on sod and 54.1 percent of that with steel wheels on plowed ground.

Clyde (1936) realized the situation when he wrote "Our ideas about traction are not always correct. We really know little about the fundamentals of traction of a rubber tire."

Realizing this was so, Wileman (1939) proposed that tire engineers develop treads and tire profiles which would improve the efficiency of the rubber tire and that tractor engineers change the tractor to take full advantage of the newly developed tire.

After tests on pneumatic tires, McKibben and Davidson (1940) concluded that inflation pressure is one of the most important factors affecting the rolling resistance of pneumatic implement tires.

McKibben and Reed (1951) found that maximum drawbar load and efficiency when operating on dry sand was obtained with low inflation pressure.

Soehne (1957) showed that reducing tire pressure decreased the soil deformation. He believed that reducing the tire pressure minimized the rolling resistance.

Bekker (1956) stated that the main physical effect of grousers (lugs) is to increase the wheel diameter. He further stated: "If the soil is not homogenous, then the role of any grouser is similar to that of a cutter which helps the wheel dig through soft unstable layers and to reach the hard strata in which a sufficient tractive effort may be developed."

Vasey and Naylor (1958) conducted tests with 5 different tread designs and one smooth tire to show the relative tractive abilities on a variety of soil surfaces. They found that the maximum allowable slip varied with the surface and settled on 3 arbitrary values of slip for the 3 surfaces tested, as follows:

Bitumen road	32%
Stubble field	48%
Plowed soil	55%

The results showed that on the bitumen road the smooth tire and broad tread (road type) tire pulled the largest load at 32 percent slip. On the stubble field the smooth tire pulled the least load at 48 percent slip and the broad tread tire pulled the least load on plowed ground at 55 percent slip. Agricultural tires with chevron or diagonal lugs pulled the largest load on the stubble and plowed ground at the respective slips.

Reed and Shields (1950) found that in loose sand, tires with 1/2 inch lugs performed much better than those with higher lugs. In loam, the 1/2 inch lugs outperformed the higher lugs slightly but in clay, there was little difference. They recognized, however, that when operating on wet or muddy ground or on green cover crops, shallow lugs would slip while high lugs would tend to dig into a firmer layer of soil for improved traction.

Worthington (1957) proposed that tractor weight be reduced to avoid damaging soil compaction. To do this he stated the entire tractor weight should be used to develop the necessary draft.

Calculation and Measurement of Soil-Tire Interface Pressures

Soehne (1957) stated that the designers of tractors and tires should reduce the weight of tractors. He added that if any additional weight is needed for traction, the tractor should be weighted by detachable weights and water ballast in the tires. He conducted several tests with different tractor tires on a variety of soil conditions. By using the semi-empirical equations of Froelick, he found that inflation pressure was not identical with the soil-tire interface pressure. His calculations showed that the maximum and mean pressure under a wide tire with low inflation pressure were higher than the inflation pressure.

Although Soehne theoretically calculated the soil-tire interface pressures, the first recorded effort found by this literature survey to actually measure them was made by Lask (1958). Lask designed and built several small pressure transducers instrumented with resistance strain gages. These transducers were mounted in the tire so that the surfaces were flush with the surface of the tire. He found that the lower inflation pressures (10 and 14 psi) gave a more even pressure distribution across the tire and that the lugs carried a larger portion of the load than did the undertread.

These pressures were measured in a slightly different manner on a smooth tire by VandenBerg (1958). He placed 2 inch diaphragm cells flush with the surface in a densely packed sand. He then pulled a tractor equipped with a smooth tire over the cells. The results of these tests are shown in Figure 1. The curves show that the peak pressures occur just as the tire makes contact and then as the tire breaks contact with the soil. The curves also show the highest pressures at the center of the tire with a decreasing pressure toward the outside edge.

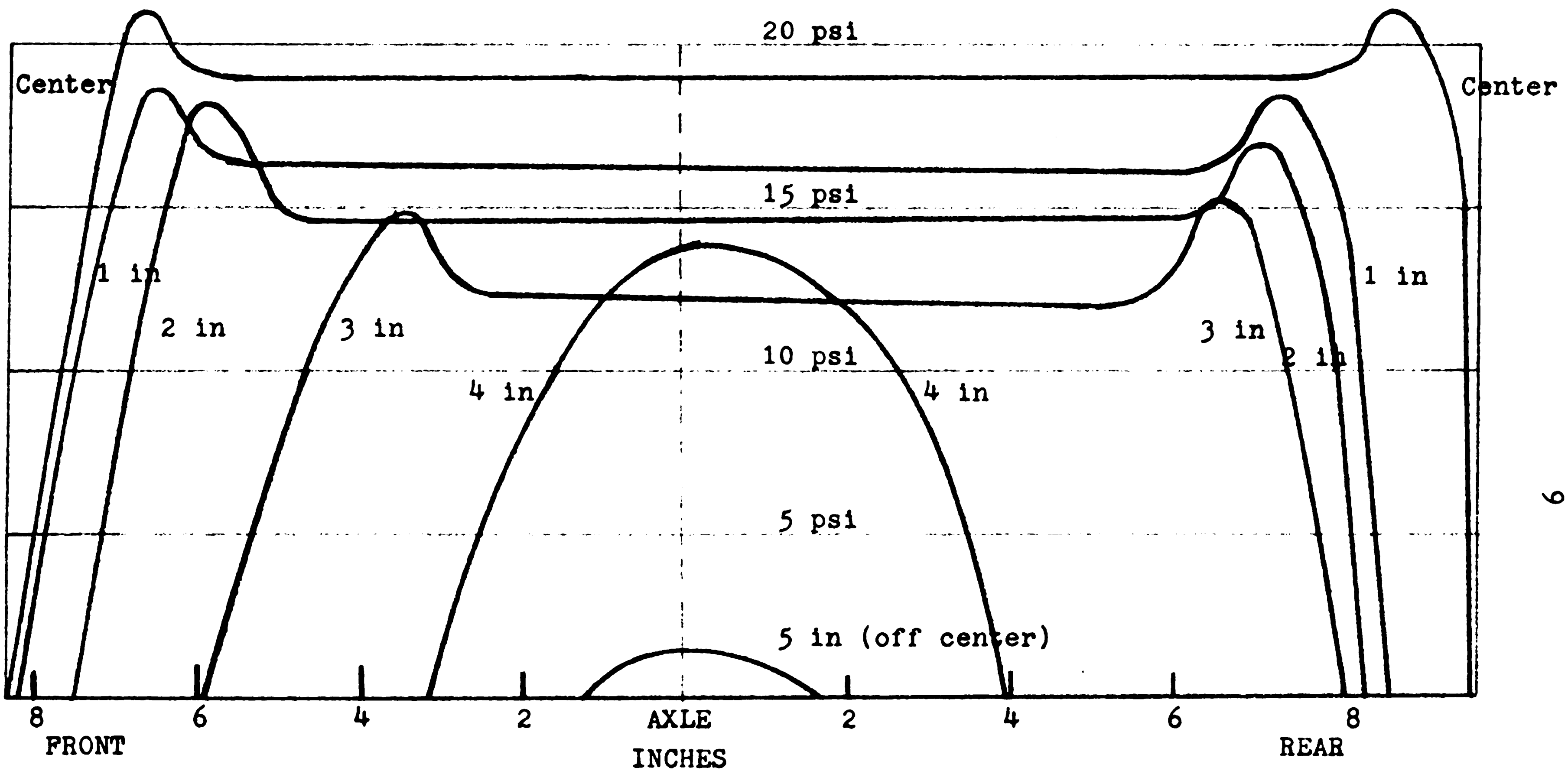

Fig. 1. Surface Pressures on Right Side of Fisk Carcass in Hard Sand.

NAMES OF TRACTOR TIRE TREAD PARTS

During the literature survey the need for standardized names of the parts of a tractor tire tread was observed. Good communication requires the use of names. The author's major professor, therefore, wrote to several large tire companies asking them to submit the names they used for the different tire parts. After receiving the replies, the author compiled the names and chose those most frequently used for standard names.

Figure 2 shows a chevron type tractor tire tread design and the end view of a lug with the proposed names. The names used here are used throughout the manuscript where applicable. This figure and definitions have been submitted to the Dictionary for Agricultural Engineering.

Interface pressure is that pressure existing at the point of contact of two different surfaces.

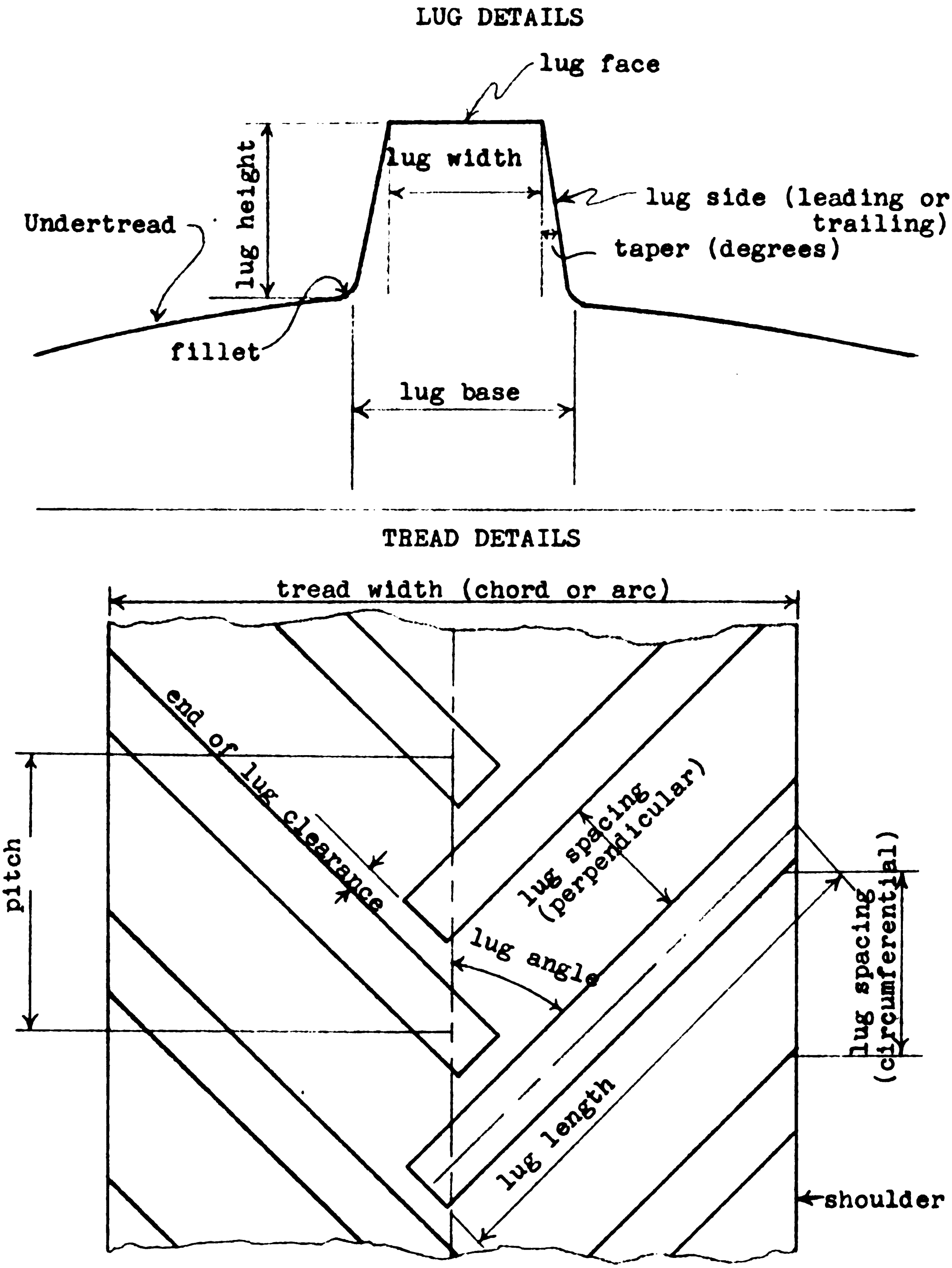

Figure 2. Diagram of lug (top) and tread showing names of lug and tread parts.

APPARATUS AND INSTRUMENTATION

Amplification and Recording

All measurement data in this investigation except slip were made by using SR-4 strain gages. Because the strains measured were of a dynamic nature, a system capable of amplifying and recording dynamic strains were necessary. The most readily available systems of this type were those made by Brush Electronics Corporation. Figure 3 shows the Brush amplifiers and 6 channel recorders.

Mechanical and Electrical Calibration of the Load, Torque, and Pressure Transducers.

The load, torque and pressure transducers were calibrated before any tests were conducted by the following method:

> The appropriate load (Figure 6), torque, (Figure 8) or pressure (Figure 15) was applied to the transducer and the attenuator and gain of the amplifier were adjusted so that the oscillograph pen deflected a predetermined number of lines (the actual operating deflection was considered when selecting the number of lines). This procedure was repeated at least 3

times. With the force removed, the calibration resistance was shunted into the bridge (pushed calibrate button) and the number of lines the pen deflected was noted.

When the actual test runs were made, all the calibration that was necessary was to set the attenuator to the calibration position, push the calibrate button and adjust the gain until the pen deflected the correct number of lines.

Tractor, Tire and Sand Box

The tractor used in these tests was a John Deere 1959 Model 630. The tractor weight with driver was 6760 pounds and the weight on the right rear wheel (the test tire was on this wheel) was 2400 pounds.

The test tire used was a 13.6 x 38, 4-ply Goodyear. The pressure transducers were installed in the tire in holes drilled into the rubber. The holes were drilled with a 3/4 inch wood bit (the centering screw was filed to a short, smooth point) operated by a 1/2 inch electric drill.

An analysis of the work conducted by Lask (1958) showed that at least 5 cells (Lask recommended this for future work) were necessary to form an accurate picture of the pressure distribution over a lug (one-half of the tire width). Thus,

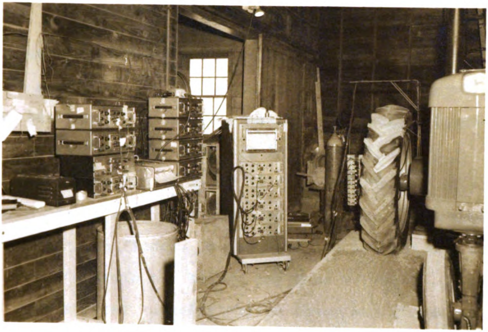

Figure 3. Overall view of test apparatus.

Figure 4. Arrangement of cells in the tire.

ten holes were drilled across each position on the tire. Cells were placed in the following position: undertread, lug face, leading lug side and trailing lug side. Figure 4 shows the arrangement of the cells in the tire.

The tests were run in a box (8 ft. x 16 ft. x 1 ft.) filled with mortar sand to a depth of 10 inches. The sand overlaid a concrete floor. The sand was wetted and the free water allowed to drain out before any runs were made. Once the runs were started, a polyethylene cover was placed over the sand at the end of each day to prevent a change in the moisture content. The moisture content of the sand was determined several times during the tests and found to vary from 7.8 percent to 12.7 percent (dry basis).

Drawbar Load

The drawbar load was varied between 40 and 1783 pounds in approximately 400 pound increments. The load remained constant during each run and each load value was reproduced accurately whenever needed.

This constant load was accomplished by using the loading frame designed by Lask (1958). A 3/8 inch cable was strung over pulleys on the frame at a 1:1 ratio and one end hooked to the tractor drawbar. Four weights of approximately 370 pounds each were assembled by stringing several Ford tractor wheel weights on short (8 ft.) pieces of 3/8 inch cable. Each weight had been previously weighed. Cable clamps were placed at each end of the cable to prevent the weights from sliding off the cable. The wheel weights were then evenly divided at each end of the cables. This left a length of bare cable in the middle; a cable loop was formed in the center with a cable clamp, making it easy to hook the weights to the lift cable (see Figures 5 and 6).

Since the lift cable passed over 3 pulleys, it could not be assumed that the drawbar load (on the tractor as the weights were lifted) was identical to that of the weights lifted. The load transducer shown in Figure 7 was used to measure the drawbar load while lifting the weights.

The load transducer was calibrated by hooking it between all the weights and the end of the cable and driving the tractor forward to lift them. The attenuator and gain of the amplifier, as outlined previously, were set so that the pen in the oscillograph deflected 40 lines. The weight which the 40 lines represented was recorded at this point on the chart paper. The load transducer was then checked at other weights to determine if the calibration was linear. With no weight on the transducer, the pen deflection for the electrical resistance calibration was noted.

With the transducer calibrated, it was then hooked between the drawbar and cable so the drawbar load could be determined when one, two, three, and four of the weights were being lifted. The drawbar loads thus determined are recorded in Table I. The transducer was then removed and laid aside as it was no longer needed.

Figure 5. Hooking a weight to the cable.

Figure 6. Three weights lifted by the tractor.

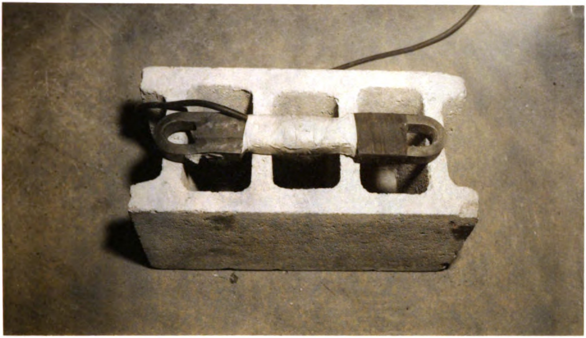

Figure 7. Load transducer.

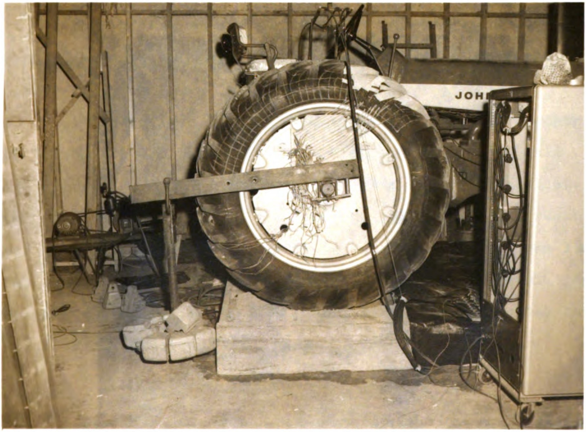

Figure 8. Calibration of rear axle torque.

TABLE I.

DRAWBAR LOAD WITH ONE, TWO, THREE AND FOUR WEIGHTS ON THE LIFT CABLE.

Number of weights	Drawbar load, pounds
1	446
2	928
3	1374
4	1783

Torque

Torque of the right rear axle was measured by applying strain gages to the axle in the manner shown in Perry and Lisner (1955).

Calibration was accomplished by bolting a 4 foot length of 3 inch x 1 1/2 inch x 1/8 inch channel iron to the axle and applying a load to the channel 3 feet from the axle center (see Figure 8). With the load applied and the attenuator set at 10, the gain was adjusted so the pen deflected one line for each 25 pound feet of torque. With the load removed, the pen deflection during resistance calibration was recorded for future recalibration.

Slip

It was suspected that slip would affect the gage readings and torque; therefore a method of measuring the slip was developed. In order to determine the percent slip it was necessary to know both the actual distance traveled, D_a, and the theoretical distance traveled, D_t, that is, the distance the tractor would have traveled had there been no slip. The calculation of percent slip was as follows:

$$\text{percent slip} = \frac{D_t - D_a}{D_t} \times 100 \qquad (1)$$

Measurement of the actual distance traveled was accomplished by welding 2 pieces of 1/4 inch steel rod, diametrically opposite each other, forming cams, on one side of the bottom pulley of the loading frame. Figure 9 shows a microswitch mounted on the frame in a position so that each time one of the cams passed the arm, the microswitch functioned and caused a pen on the oscillograph to blip. The distance a point on the cable traveled between two blips was measured to be 8 1/2 inches. The actual distance the tractor traveled in inches was determined by counting the spaces between blips on the chart paper and multiplying by 8 1/2. Although the tractor traveled approximately 12 feet, a test length of only 42 1/2 inches (spaces between 6 blips) was used to determine percent slip. This distance started just before the pressure transducers made contact with the soil and ended shortly after they broke contact with the soil.

The method of measuring theoretical forward travel was much the same manner except that the microswitch was mounted on a frame on the tractor so that the arm rode against the

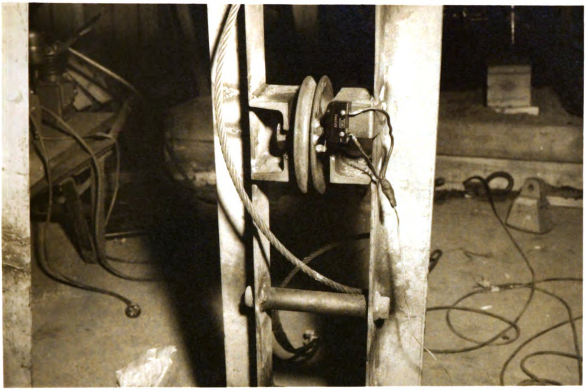

Figure 9. Microswitch mounted on the load frame to measure actual forward travel.

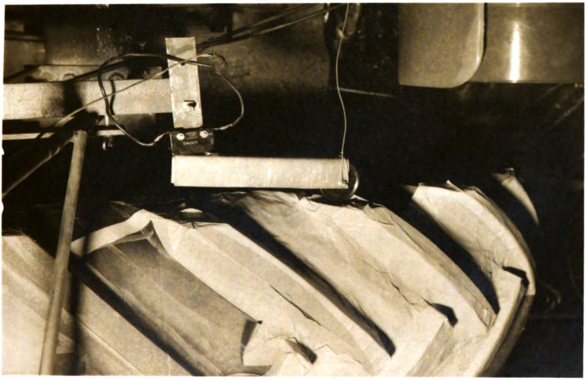

Figure 10. Microswitch mounted on the tractor to measure theoretical forward travel.

side of the tire (see Figure 10). The microswitch functioned and caused another pen on the oscillograph to blip every time the arm of the microswitch rolled over a lug.

The theoretical distance traveled between lugs was measured at inflation pressures of 10, 12, 14, 16, 18 and 20 psi by driving the tractor on a concrete floor without a drawbar load. The measurement was made by driving the tractor forward at the same speed traveled during the tests with the drawbar load until the tire had made 3 revolutions. The distance traveled was measured and divided by 69 (there were 23 lugs in the test tire) to obtain the distance traveled between lugs. Table II shows that as the inflation pressure was increased from 10 to 20 psi, the distance traveled increased.

TABLE II

THEORETICAL TRAVEL PER LUG WITH SEVERAL DIFFERENT INFLATION PRESSURES.

Inflation pressure	Theoretical travel per lug
psi	inches
10	7.8823
12	7.9137
14	7.9610
16	7.9942
18	8.0327
20	8.0613

Figure 11 shows that as the inflation pressure was increased from 10 to 20 psi the dimensionless ratio of theoretical distance traveled per revolution versus the unloaded circumference increased linearly.

The theoretical distance traveled during the test runs was then determined by multiplying the appropriate theoretical travel per lug times the number of spaces between blips on the chart paper as found by drawing lines directly across the chart paper from the 6 blips indicating actual travel.

Pressure Transducers

The pressure transducers (strain cells) used in the tire were constructed in the following manner. A length of 3/4 inch diameter cold-rolled-steel stock was chucked in a lathe and a 5/8 inch hole was drilled through the center of the piece. An 11/16 inch drill was used to enlarge the hole to a depth of 1/16 inch. A 3/8 inch long cylinder was then cut off the length, and a 1/8 inch hole was drilled through the side of the cylinder for the strain gage lead wires to pass through.

The diaphragms, made of 0.010, 0.020 and 0.025 inch thick stainless steel, were rough-cut to a 1 inch diameter with a metal clipper and soldered with stainless steel solder to the cylinder (hereafter called the cell wall) at the end with the 11/16 inch inside diameter hole. Finally the cell was chucked in a lathe and the outside diameter of the

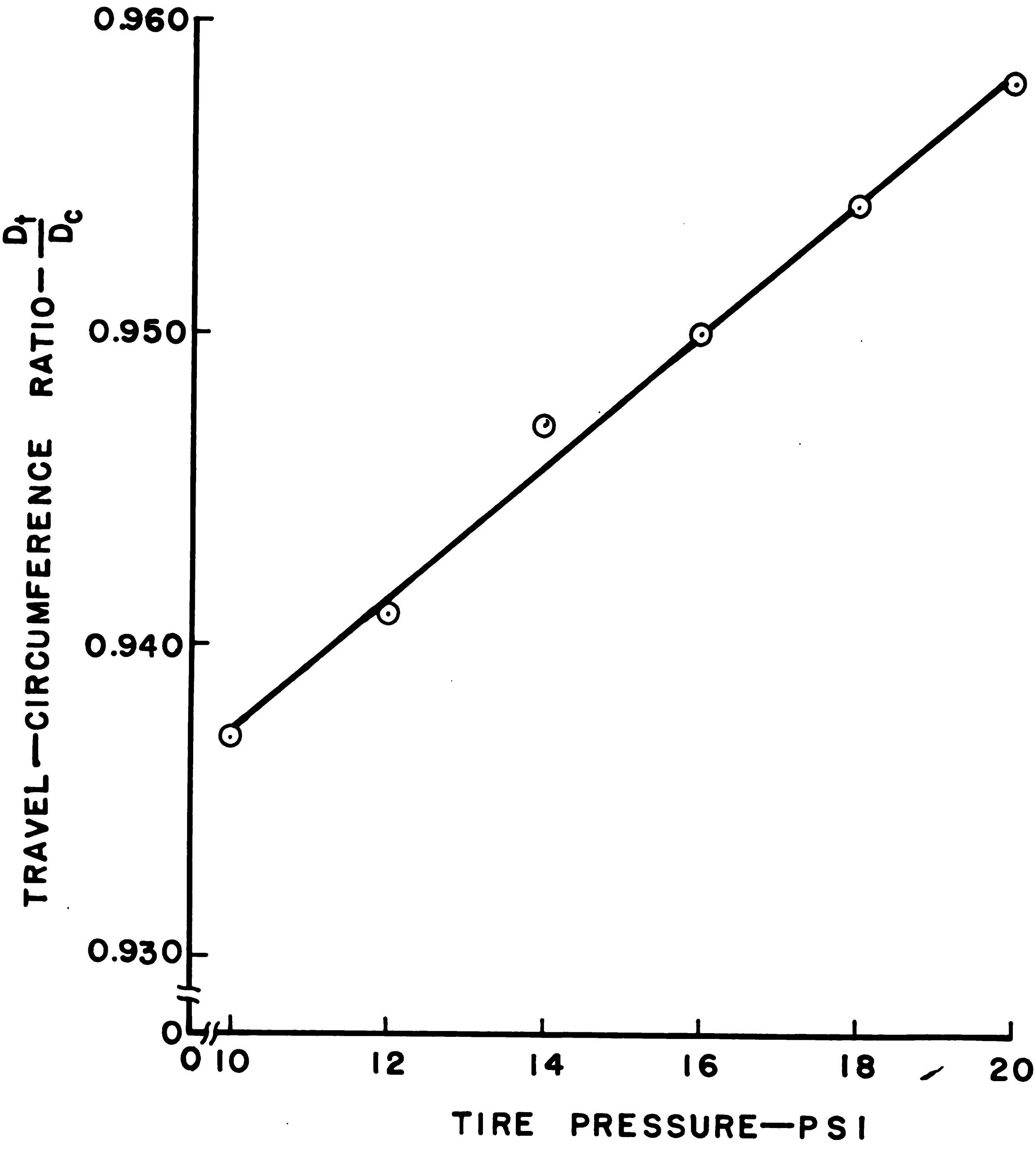

Figure 11. Effect of tire inflation pressure on the theoretical travel versus unloaded circumference ratio.

diaphragm was machined to the outside diameter of the cell wall.

After the cells were constructed, the strain gages (type A-18) were installed. Before installation the strain gages were trimmed to a 0.4 inch x 0.3 inch rectangle. After the glue had dried somewhat (to a plastic state) the cells were placed in the rack shown in Figure 12 and the one pound weights were set on top of the gages (one end of each weight was machined to 1/2 inch diameter and tipped with sponge rubber). The cells dried this way for one hour and then were placed in an electric oven at 120 degrees Fahrenheit for 24 hours.

Proving tests on the cells mounted in the lug side were conducted by rolling the tire on a board. It was found that the pressure on the lug face caused a deflection of the oscillograph pen. This was solved by construction of an outer protective shell in the same manner as the strain cells. This shell was made of 1 inch material with a 13/16 inch diameter hole. A slot was filed on the inside edge to provide room for the lead wire. A stainless steel diaphragm was soldered to one end to give the shell more strength.

Figure 13 shows the cell and the outside protective shell. Tests were again conducted by running the tire over the board and showed that with the outside shell in the lug side, the oscillograph pen did not deflect.

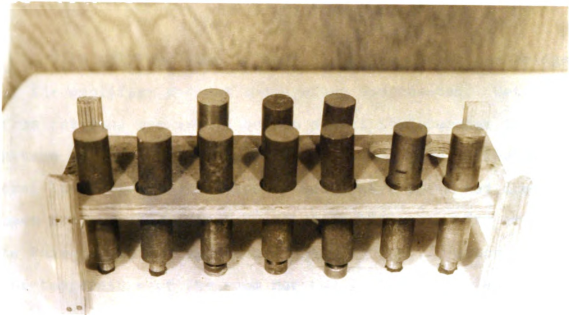

Figure 12. Rack and one pound weights for initial curing of strain gages after they were glued on the diaphragms.

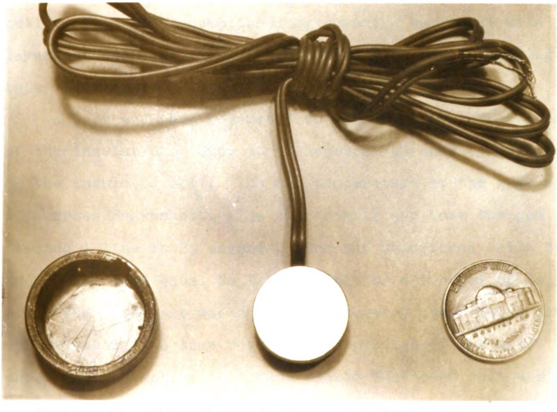

Figure 13. Outside protective shell and diaphragm pressure transducer.

With only one gage in each cell, the wheatstone bridge of the amplifier was not temperature compensated. Wet sand from the sand box was placed on a cell to determine the magnitude of pen deflection. The pen immediately deflected several lines in the direction it would have moved had there been a compressive strain applied to the gage. The error due to this change in temperature was 4 to 6 psi. Since neither the temperature of the room nor the soil could be kept constant, it was impossible to assign a definite error to each gage which could be used throughout the tests. Aside from adding another gage to each cell, the only practical method of eliminating the temperature effects was to insulate the cells. This was accomplished by covering each cell with 5 layers of cheesecloth and then covering them with masking tape (see Figure 14).

A test was then conducted to determine the effectiveness of the insulation. Snow at 32 degrees Fahrenheit was placed on the insulated cell. The air temperature at the gage was 82 degrees Fahrenheit. The test result was that the pen deflected 1 line in 25 seconds. For the undertread cells this would have been equal to 1/2 psi and for all other cells, 2 psi. The same test was applied to several other cells with approximately the same results. Inspection of the chart paper for the actual test runs showed that each cell was in contact with the sand for approximately 1 1/2 seconds.

Figure 14. View of tire with cells temperature insulated.

Figure 15. In-place calibration of pressure transducers.

Calibration of the cells was done before the insulation had been applied. Several of the insulated cells were recalibrated. The results showed that the insulation had no effect on the calibration of the cells.

Figure 15 shows the in-place calibration apparatus designed by Lask (1958). The cells were calibrated by holding the rubber diaphragm of the calibration device against the cell diaphragm and turning on the pressure. The pressure was raised to 60 psi (on the lug face, leading lug side and trailing lug side cells) and the attenuator and gain of the amplifier set to 30 lines pen deflection on the oscillograph. The pressure was released to check the zero pressure setting. The pressure cycle was repeated 3 times to check the 30 lines setting and the return to zero when the pressure was released. With the pressure off, pen deflection was noted during resistance calibrations so the amplifier could be recalibrated electrically before the actual test runs. Calibration of the undertread cells was the same except they were calibrated to 20 psi.

PROCEDURE

The controlled variables in this investigation were drawbar load and tire inflation pressure. Ten channels of amplifying and recording equipment were available for the pressure transducers. Since there were 10 transducers across each position in the tire and 4 positions, 4 series of tests were run.

After the lead wires were attached to the terminal board mounted on the axle, the amplifiers were warmed up, balanced and calibrated electrically.

Each series of tests was run by first adjusting the inflation pressure to 10 psi. With a 40 pound drawbar load, the tractor was driven forward approximately 3/4 of a wheel revolution in low gear and then backed up. This was repeated 3 times. One of the weights was then hooked to the cable and the tractor driven forward and back 3 more times. This was done until the 4 weights were tested on the cable.

After the runs were completed, the inflation pressure was increased to 14 psi. The same runs were made as at 10 psi except that this time the runs were started with the 1783 pound drawbar load and reduced to 40 pounds drawbar load. Finally the inflation pressure was increased to 18 psi and the same procedure was followed.

The lead wires for this set of cells were removed from the terminals, another set attached and the procedure stated above was repeated.

Before each run, the sand was thoroughly spaded and raked level.

Actual and theoretical forward travel and torque were measured during each run.

RESULTS AND DISCUSSION

Pressure Transducers

The data discussed in this thesis were obtained by reading the maximum pressure recorded on the chart by the oscillograph. Figure 16 shows the shape of the curves traced by the pen as the tire lug containing the cells pressed against the sand. The blips on the left side of the chart were made by the microswitch mounted on the tractor which measured theoretical travel while the blips on the right side indicated actual travel.

The 3 readings from each cell for each test condition were averaged and tabulated. The tabulated data are in Tables 7, 8, 9 and 10. The tables contain all the averaged data of the maximum pressure obtained with 40, 446, 928, 1374 and 1783 pound drawbar loads and 10, 14 and 18 psi tire inflation pressures.

The data from the pressure transducers with drawbar loads of 40 and 1783 pounds have been plotted to show the pressure distribution across the tire at both low and high drawbar loads. There are 3 separate plots of data for each set of transducers showing the effect of tire inflation pressure on the soil-tire interface pressure.

In all cases the cells are numbered from left to right (1 to 10) and the arrow points in the direction of slippage of the tire in the sand.

The next two sets of curves show the relationship of tire inflation pressure, soil-tire interface pressure and position of the cell in the tire.

Angle of Contact

The angle of contact is the angle subtended at the center of the tire by the portion of the tire in actual contact with the soil. The angle of contact is shown in Figure (36). The angle of contact for the lug face with a tire inflation pressure of 14 psi and 1374 pound drawbar load was read from the chart paper. On one side of the chart paper, the blips were drawn by the microswitch mounted on the tractor and indicated theoretical forward travel. The angle between lugs (blips on the chart paper) was 15.65 degrees. By counting the number of blips from the start to the end of pressure measurement, the angle of contact, measured electronically by the cell, was read. Table III gives the angle of contact for lug face cells 1 to 5.

TABLE III.

ANGLE OF CONTACT FOR LUG FACE CELLS 1 TO 5 WITH 14 PSI TIRE INFLATION PRESSURE AND 1374 POUND DRAWBAR LOAD.

Cell Number	Angle of Contact
	degrees
1	31.30
2	39.12
3	46.95
4	48.52
5	51.65

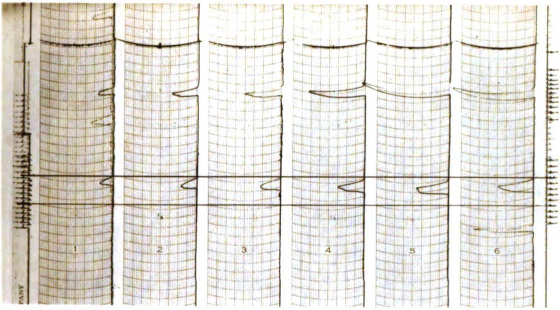

Figure 16. Chart section showing pressure curves from cells on the lug face with 1374 pound drawbar load and 14 psi tire pressure.

Figure 17. Measuring angle of contact.

The angle of contact was found difficult to measure with a protractor (see Figure 17). The point where the cell broke contact with the sand could not be accurately determined. The check showed the angle of contact for cell number 5 to be approximately 60 degrees. The reason for this measurement being larger than the angle determined from the chart was that the cell was removed from contact with the sand shortly after it had passed directly below the axle.

Undertread

Figures 18, 19 and 20 show that the pressure on the undertread increased with drawbar load and tire inflation pressure. A comparison of the 3 sets of curves shows that as the inflation pressure was increased from 10 to 18 psi, the pressure at cells 1, 2, 3, 8, 9 and 10 reduced slightly and the pressures at cells 4, 5, 6 and 7 increased considerably. As the inflation pressure was increased, the tire became more rigid. This prevented the tire from flattening and the center of the tire from buckling.

Lug Face

Figures 21, 22 and 23 show the contact pressures on the lug face at 10, 14 and 18 psi inflation pressures. As the inflation pressure was increased, the pressure on the lug face generally increased near the center and decreased near the outside edges of the lugs. In contrast with the undertread, however, the pressure on the lug face was higher with

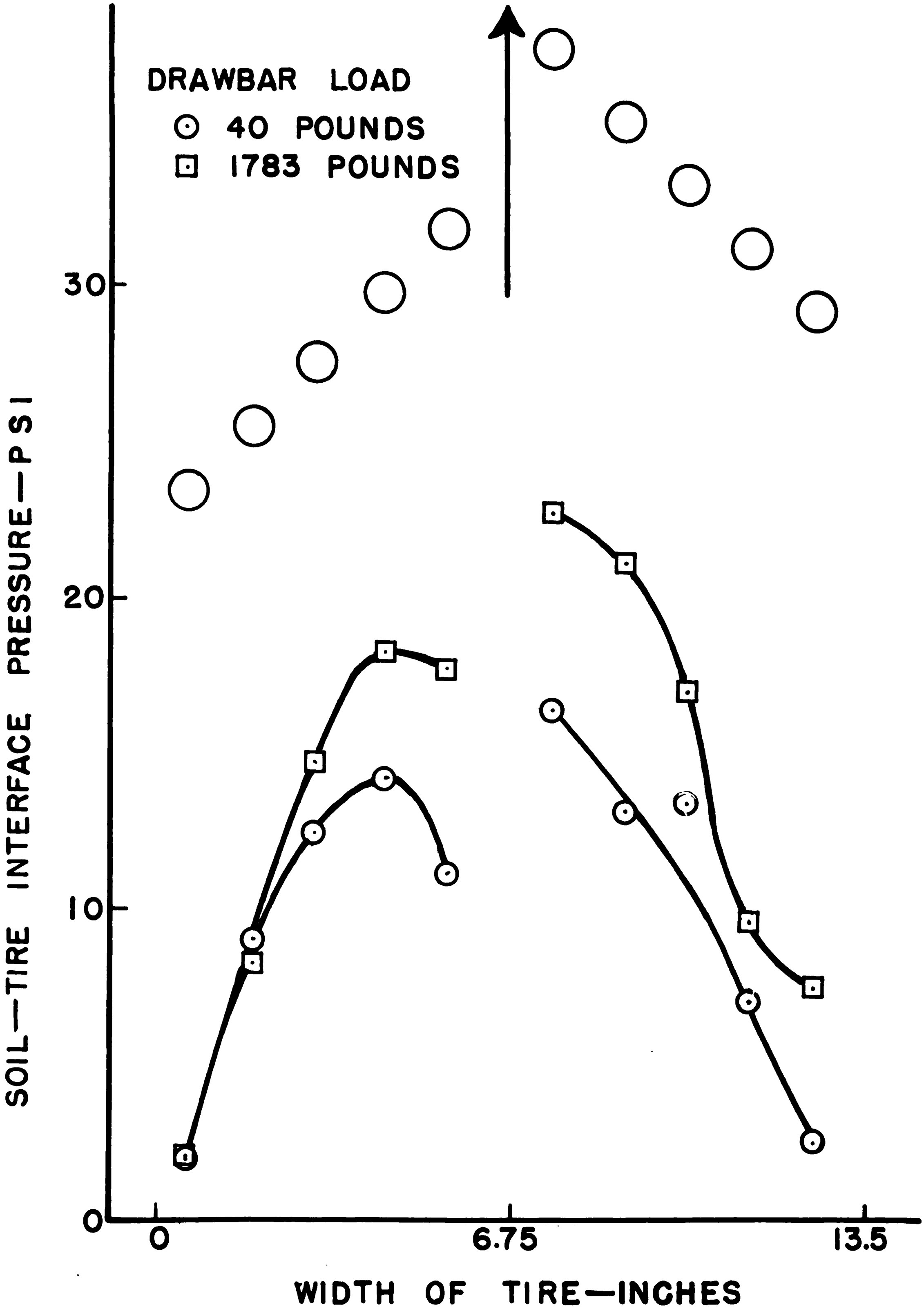

Figure 18. Soil-tire interface pressure distribution across undertread; 10 psi tire pressure; 40 and 1783 pound drawbar load.

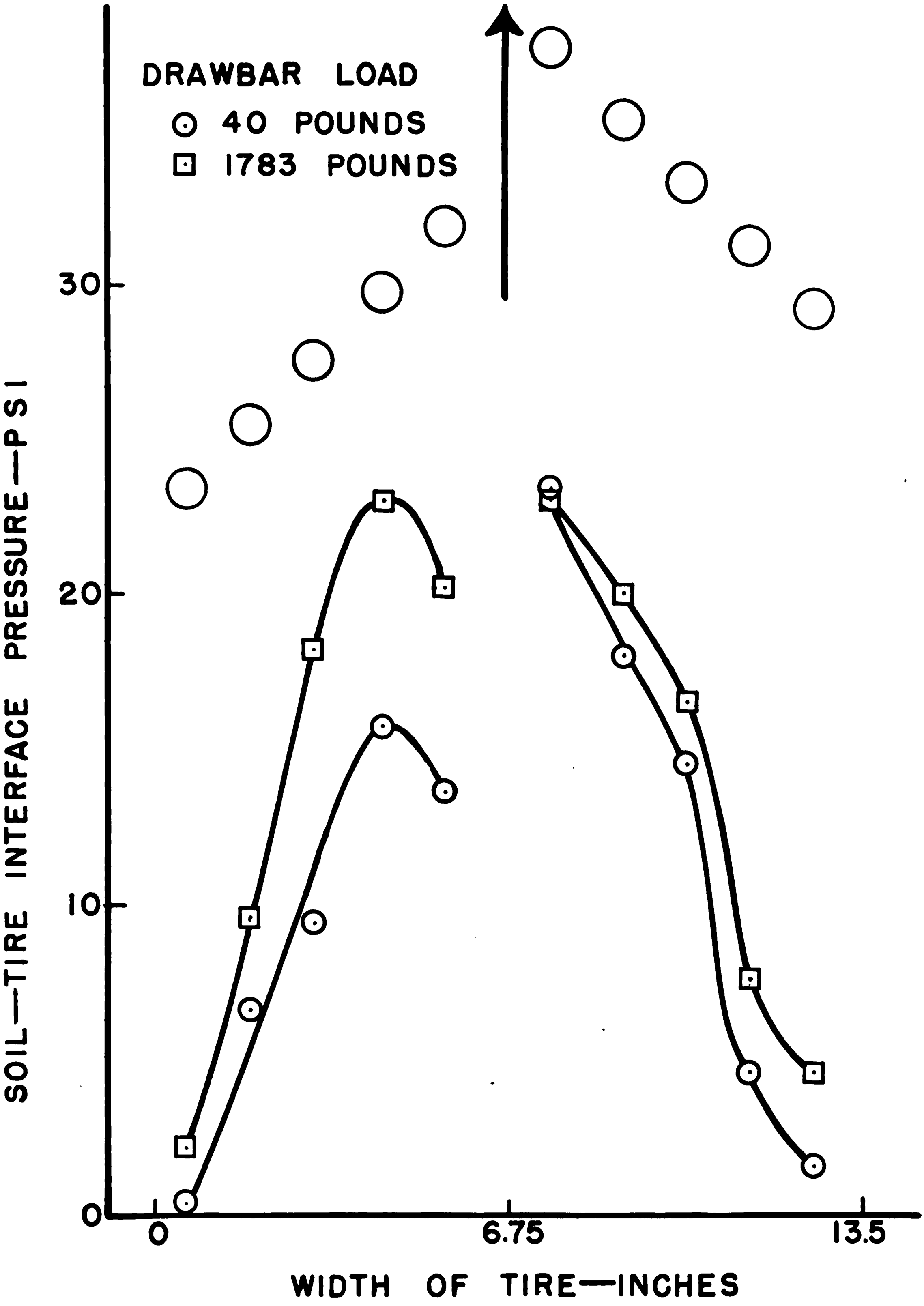

Figure 19. Soil-tire interface pressure distribution across undertread; 14 psi tire pressure; 40 and 1783 pound drawbar load.

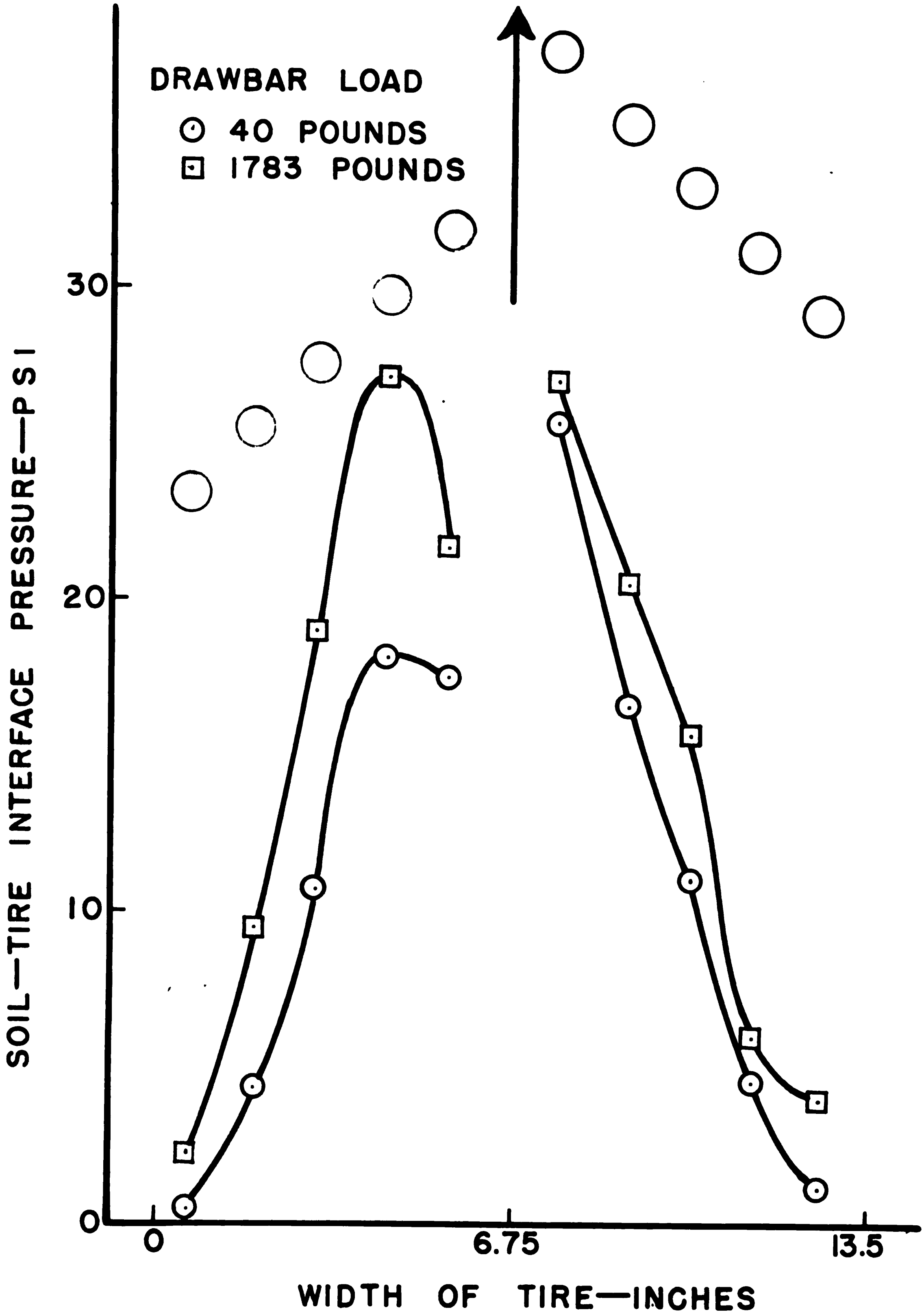

Figure 20. Soil-tire interface pressure distribution across undertread; 18 psi tire pressure; 40 and 1783 pound drawbar load.

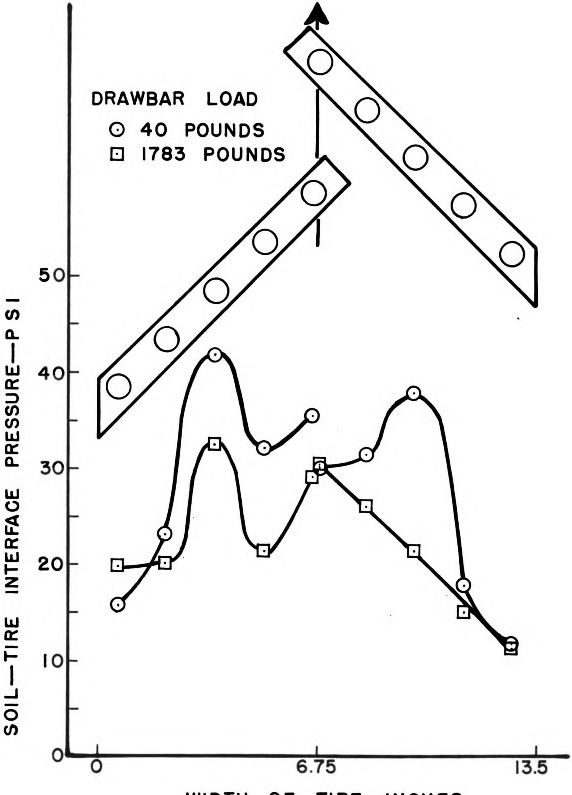

Figure 21. Soil-tire interface pressure distribution across lug face; 10 psi tire pressure; 40 and 1783 pound drawbar load.

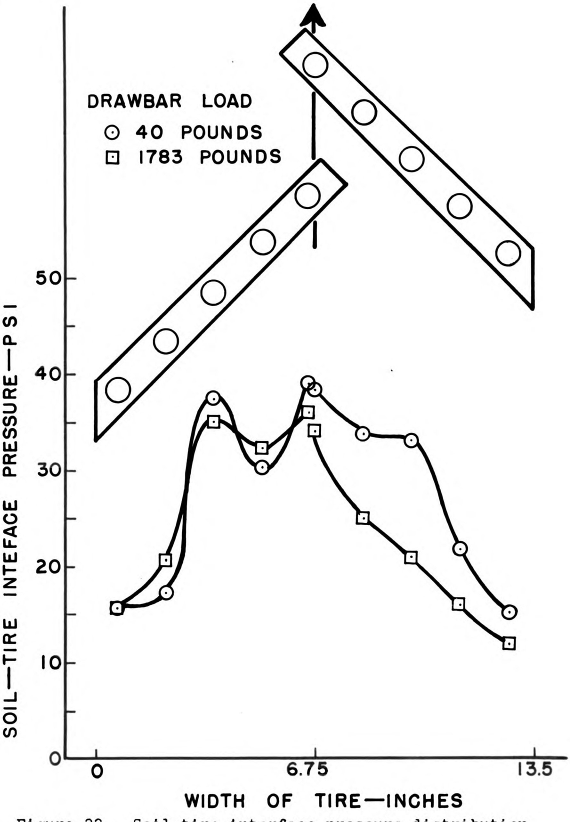

Figure 22. Soil-tire interface pressure distribution across lug face; 14 psi tire pressure; 40 and 1783 pound drawbar load.

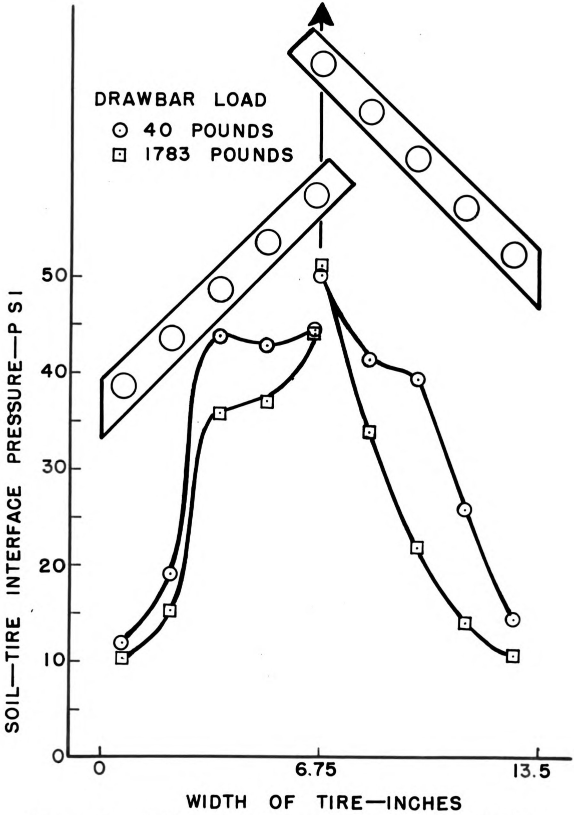

Figure 23. Soil-tire interface pressure distribution across lug face; 18 psi tire pressure; 40 and 1783 pound drawbar load.

the 40 pound drawbar load than with the 1783 pound drawbar load. A reason for this is that since the slip was considerably higher with the larger drawbar load (as evidenced in Figure 33) the lugs dug in and thus packed sand into the space between the lugs. Thus the undertread carried more of the weight at the higher drawbar load and relieved some of the weight from the lugs.

Another explanation may be as follows. The lug established a sand prism (sand packed in the shape of a prism) as the lug pressed against the sand. Because of the low slip with the 40 pound drawbar load, the lug remained on the prism and the prism carried the weight on the lug, producing high soil-lug interface pressures. In the case of the high drawbar loads, the lug slipped off the original prism and established another deeper in the sand as it dug deeper. Sand was thus packed into the undertread area and the undertread carried a larger share of the vertical load of the tire.

An explanation for the high pressures at cells 3 and 8 is that as the lug entered the soil it flattened out and twisted. When the lug twisted, there must have been a pivot point and this point would be expected to be near the center of the lug. While the lug was twisting, both ends dug in while at the pivot point the sand prism was built up thus causing a high pressure point. This high pressure point was not as noticeable at cell 8 as at cell 3. The reason for this could be that the tire was not exactly vertical and less weight was carried on this lug. As a result the right lug (as viewed in the figures) flattened less and twisted less than the other lug.

Leading Lug Side Cells

The leading lug side provided the traction for propelling the tractor forward. Figures 24, 25 and 26 show that as the tire inflation pressure was increased, the pressure on the leading lug side increased. An explanation for this is that with the higher inflation pressures there were fewer lugs in contact with the sand providing traction than with the low inflation pressure (see Table IV).

TABLE IV.

THE NUMBER OF LUGS IN CONTACT WITH THE SAND WITH 1374 POUND DRAWBAR LOAD AND INFLATION PRESSURES OF 10, 14 and 18 PSI.

Inflation pressure	Lugs in contact with sand	
	center	side
psi	number of lugs	
10	3	2
14	2 3/4	1 3/4
18	2 1/2	1 1/2

In all cases the pressure at the center of the tire was considerably higher than at the sides of the tire. The pressure on the leading lug side was higher with the 1783 pound draw-

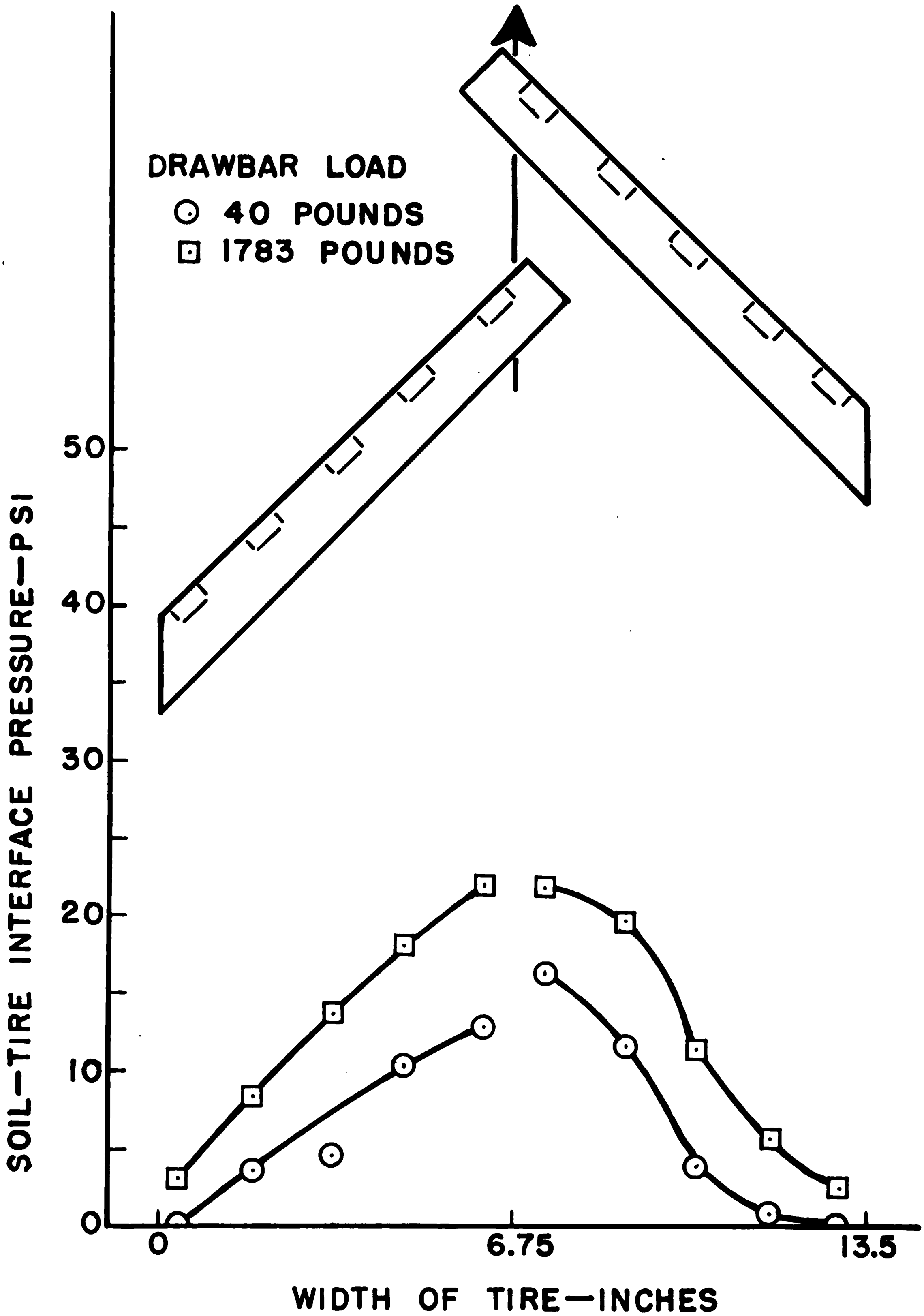

Figure 24. Soil-tire interface pressure distribution across leading lug side; 10 psi tire pressure; 40 and 1783 pound drawbar load.

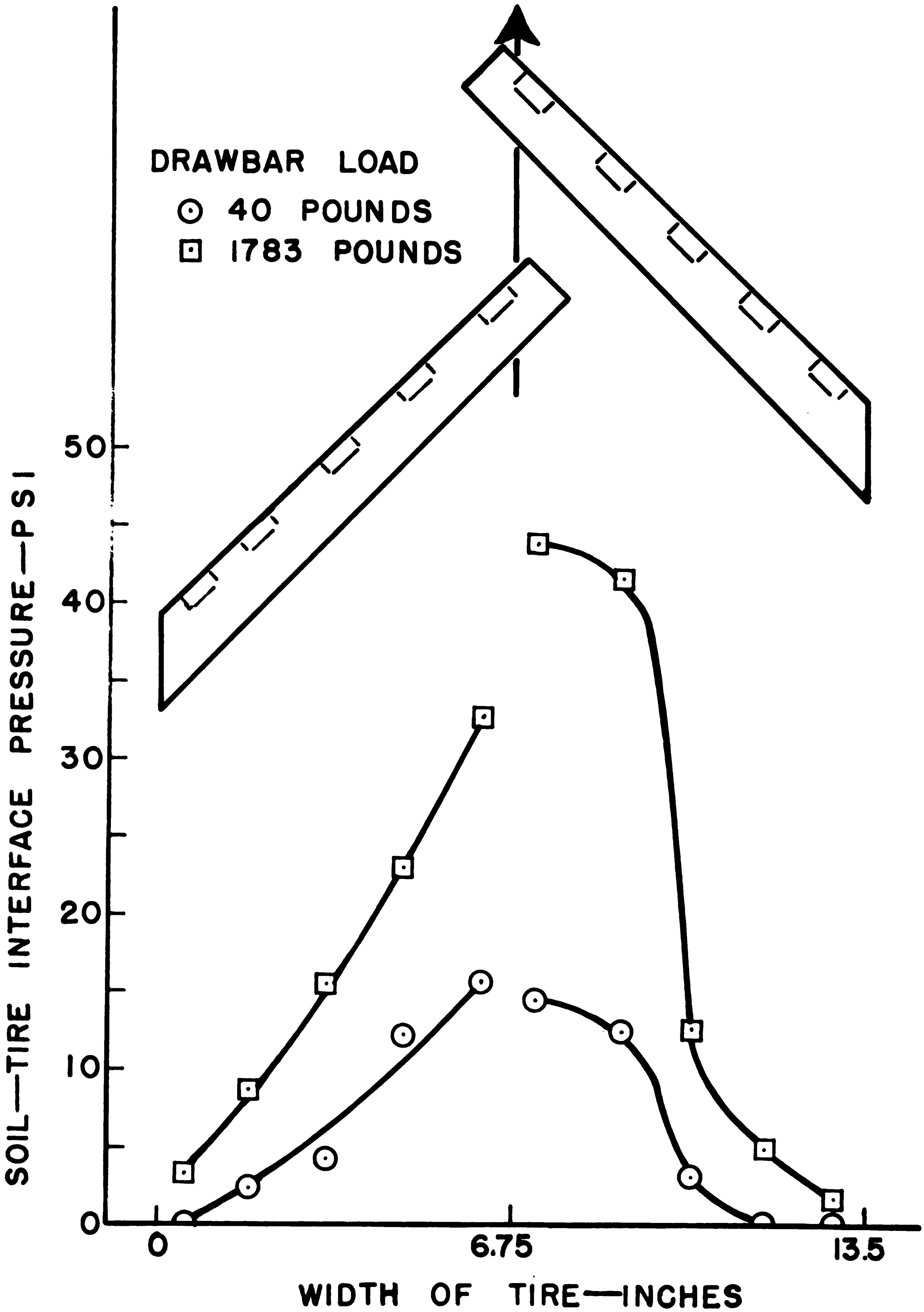

Figure 25. Soil-tire interface pressure distribution across leading lug side; 14 psi tire pressure; 40 and 1783 pound drawbar load.

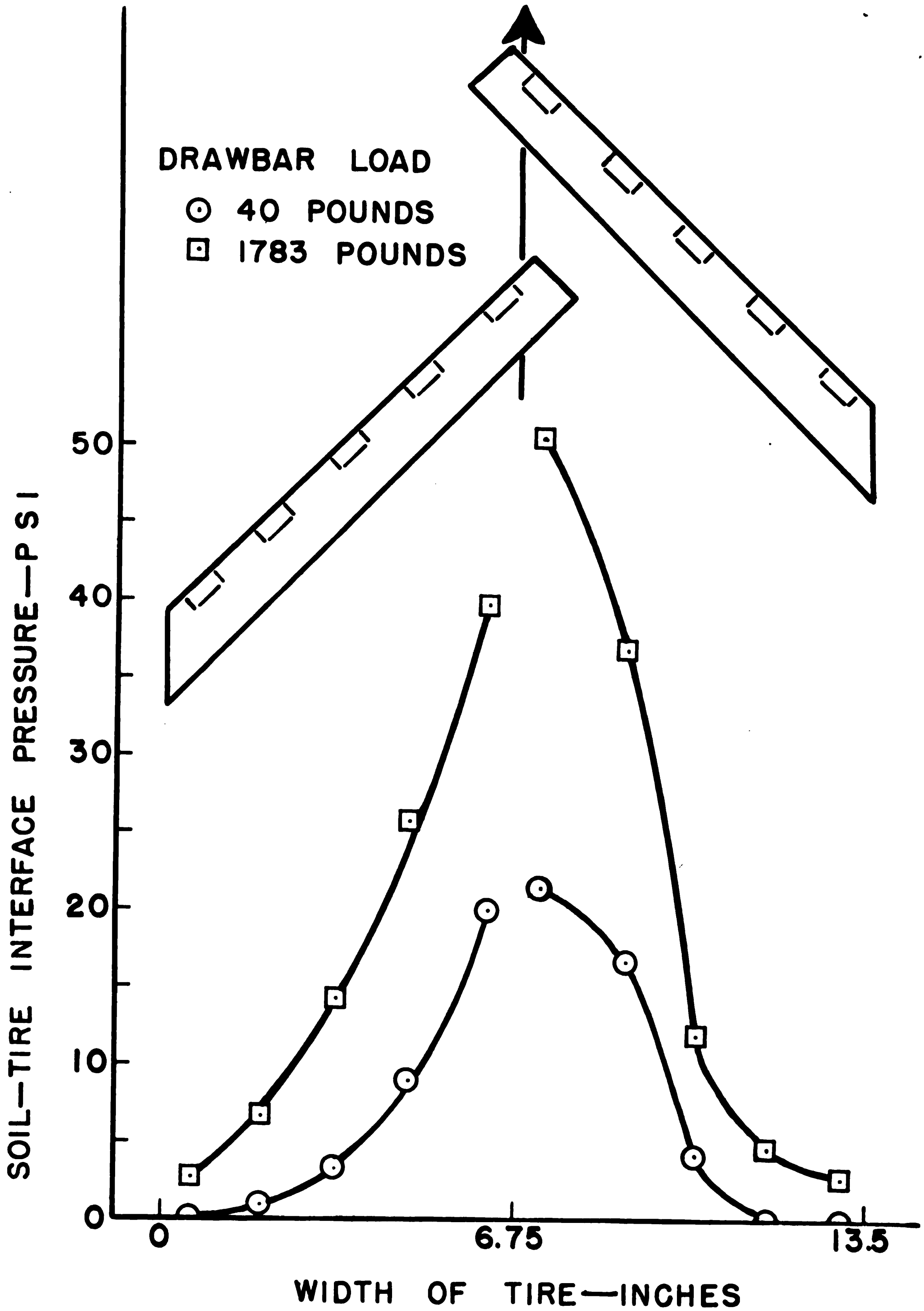

Figure 26. Soil-tire interface pressure distribution across leading lug side; 18 psi tire pressure; 40 and 1783 pound drawbar load.

bar load than with the 40 pound drawbar load. The outside cells apparently did not even touch the sand with the 40 pound drawbar load (at any tire pressure) as there was no pressure recorded.

Trailing Lug Side

Figures 27, 28 and 29 show that the pressure on the trailing lug side was generally greater with the 40 pound drawbar load than with the 1783 pound drawbar load. The reason for this was that with the larger drawbar load the slip was greater. The result of the greater slip was that the trailing lug side tended to move away from the sand in the space between the lugs.

The one noticeable exception to the above statement was at cell 4. At this point the pressure on the trailing lug side was higher with the 1783 pound drawbar load than with the 40 pound drawbar load. A possible reason for this was that the lug (not shown) perpendicular to the instrumented lug dug in and pushed the sand into this cell at the higher slip. At the same time the lug took some of the sand out from in front of cell number 3, thus lowering the pressure there. Another explanation might be that the sand flowed between the end of the lug and the side of the instrumented lug causing a build-up of pressure at this point as the lug was pulled through the sand.

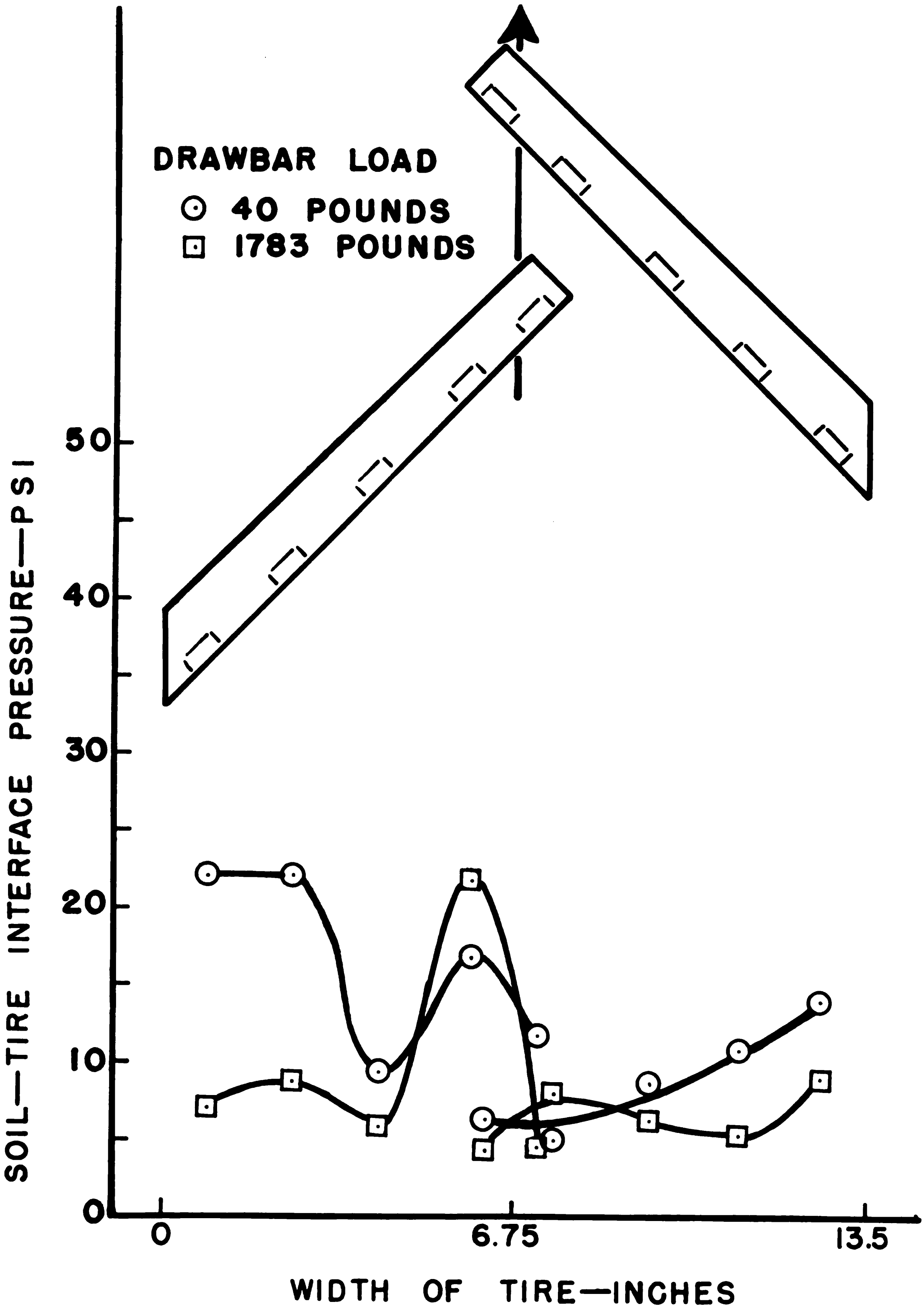

Figure 27. Soil-tire interface pressure distribution across trailing lug side; 10 psi tire pressure; 40 and 1783 pound drawbar load.

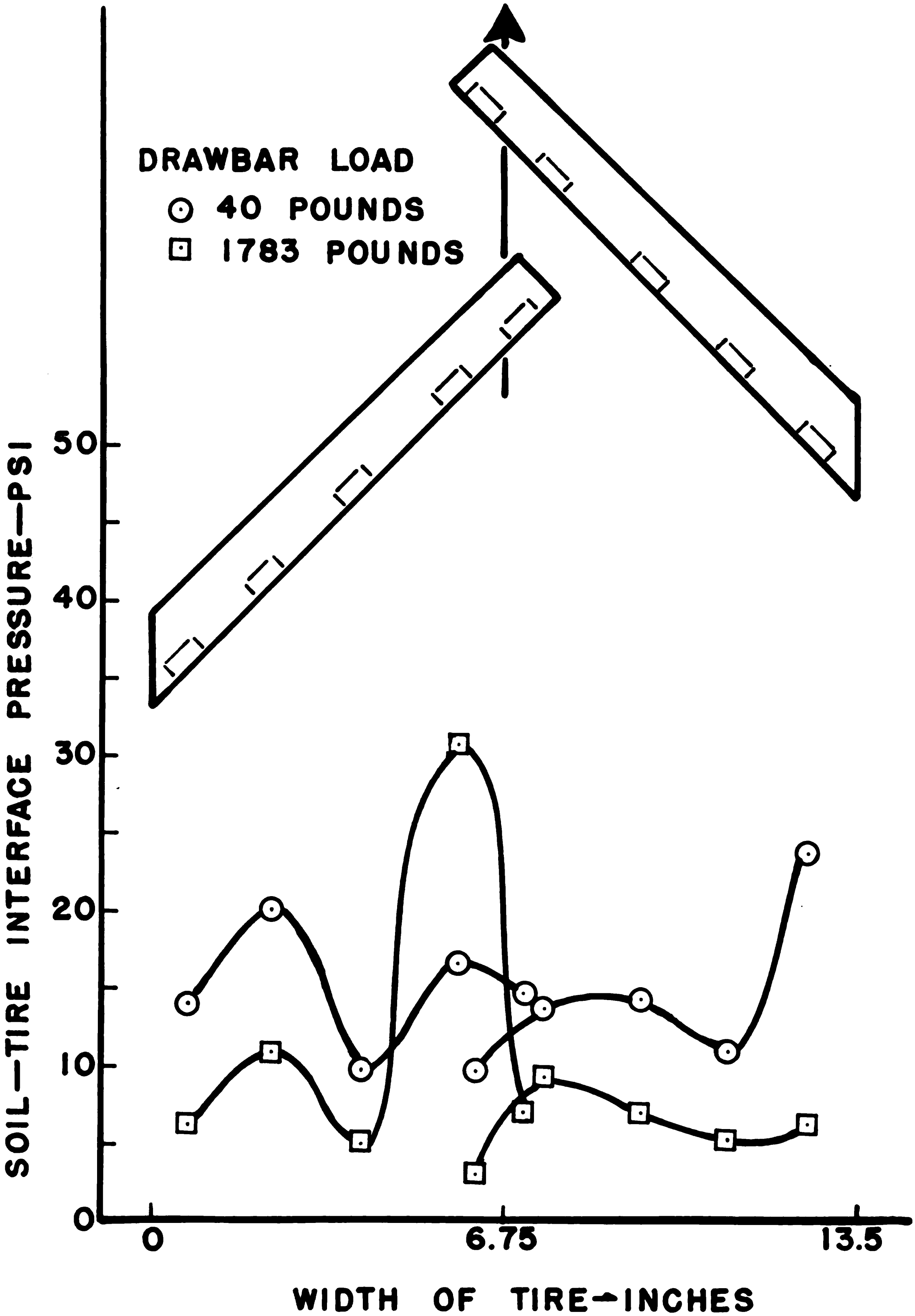

Figure 28. Soil-tire interface pressure distribution across trailing lug side; 14 psi tire pressure; 40 and 1783 pound drawbar load.

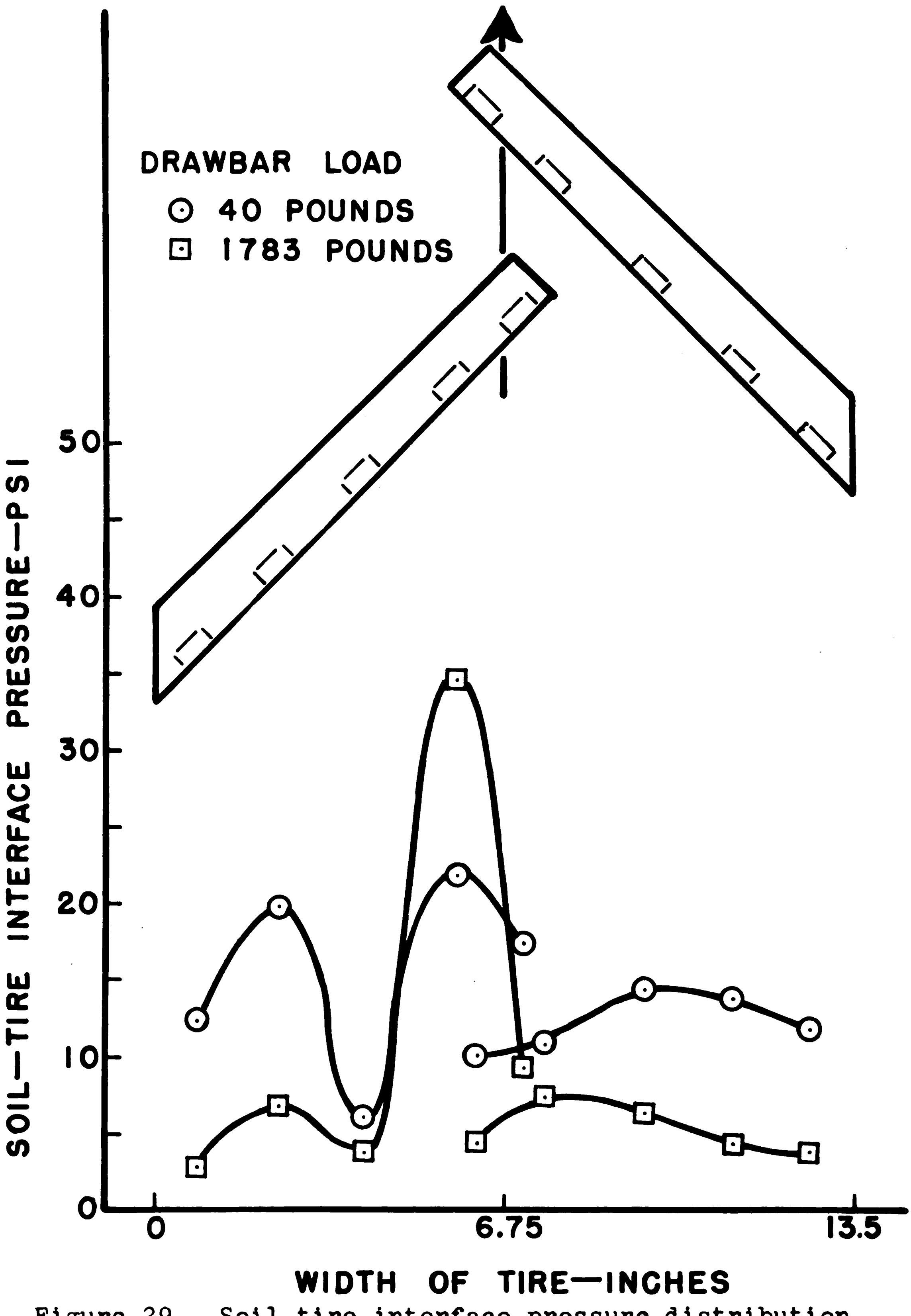

Figure 29. Soil-tire interface pressure distribution across trailing lug side; 18 psi tire pressure; 40 and 1783 pound drawbar load.

The reason for this not occurring at cells 7 and 8 is that the cells were not located in exactly comparable positions. It is possible the increase of pressure at one point and reduction of pressure at another point occurred but was not measured because no cell was in that position.

Effect of Tire Inflation Pressure on Station 3

The data set forth in Tables VII to X for station 3 in the 4 tire positions are shown in detail. These data could be presented in the same manner for the other 9 stations.

Figure 30 shows the effect of tire inflation pressure on station 3 in the 4 tire positions with the 1783 pound drawbar load. The curves show that as inflation pressure was increased, the soil-tire interface pressure increased in all positions except the trailing lug side. In this position, the soil-tire interface pressure decreased with increasing tire pressure.

Effect of Drawbar Load on Station 3

Figure 31 shows the effect of drawbar load on the soil-tire interface pressure at station 3 in the 4 tire positions with an inflation pressure of 14 psi. This plot shows that the pressure on the lug face increased with the first increment of drawbar load and then steadily decreased with increasing drawbar load. The reason for the initial increase of pressure on the lug face was that the tire did not slip enough to dig in and transfer some of the weight from the lug

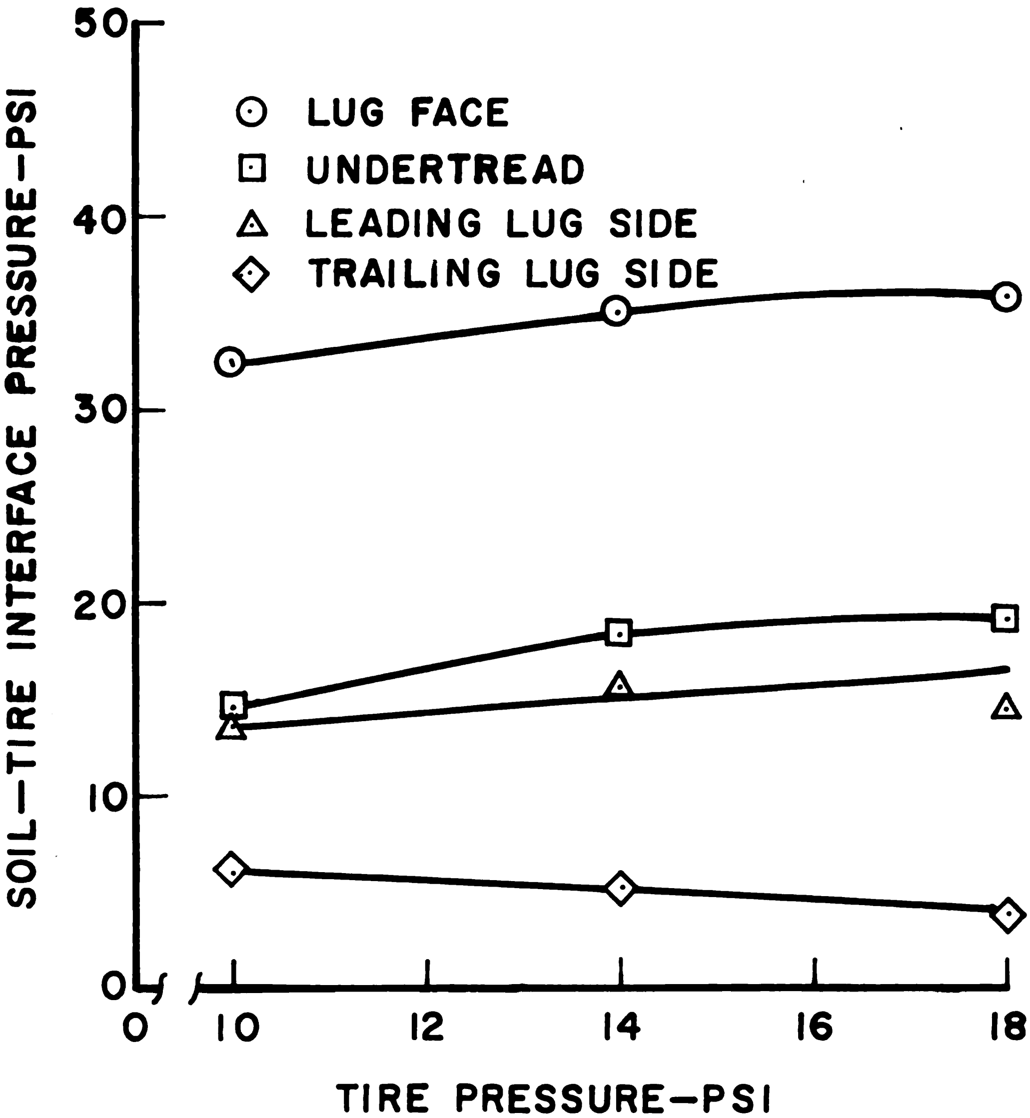

Figure 30. Effect of tire inflation pressure on the soil-tire interface pressure on station 3 in the 4 tire positions with a 1783 pound drawbar load.

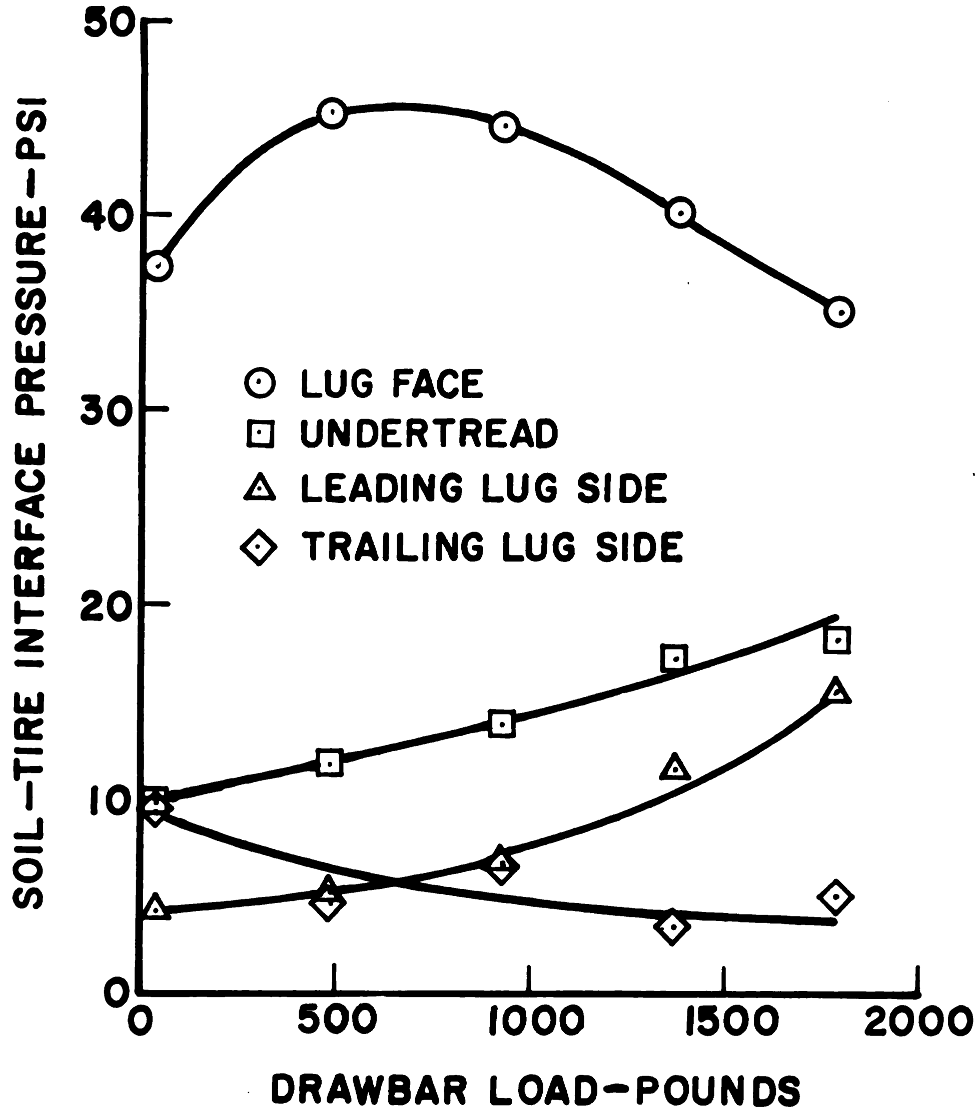

Figure 31. Effect of drawbar load on the soil-tire interface pressure on station 3 in the 4 tire positions with a tire inflation pressure of 14 psi.

to the undertread. The pressure on the undertread and leading lug side increased and the pressure on the trailing lug side decreased with increasing drawbar load. The increase in pressure on the leading lug side was due to the increase in drawbar load. The reason for the increase of pressure on the undertread was explained above under lug face. Another reason for the increase of pressure on the undertread is that the dynamic weight on the rear wheels increased due to dynamic weight transfer while the tractor pulled a load from the drawbar.

Torque

The torque data are tabulated in Table XI. Figure 32 shows that rear axle torque increased linearly with drawbar load with 10 psi tire inflation pressure up to the maximum load used in these tests. The torque increased linearly at a tire pressure of 14 psi up to 1374 pounds drawbar load and then increased at an increasing rate. The same was true at the 18 psi inflation pressure except that the linearity went only to the 928 pound drawbar load. The reason for the change in the slope of the rear axle torque versus drawbar load curve was due to the fact that the tire had dug itself into a rut at the higher percent slips (see Figures 33 and 34). The tire having dug a rut was virtually climbing an incline as it moved forward in the sand. This increased the torque required to pull a given drawbar load. At the same time the tire was slipping (digging in deeper), more of the traction side of the

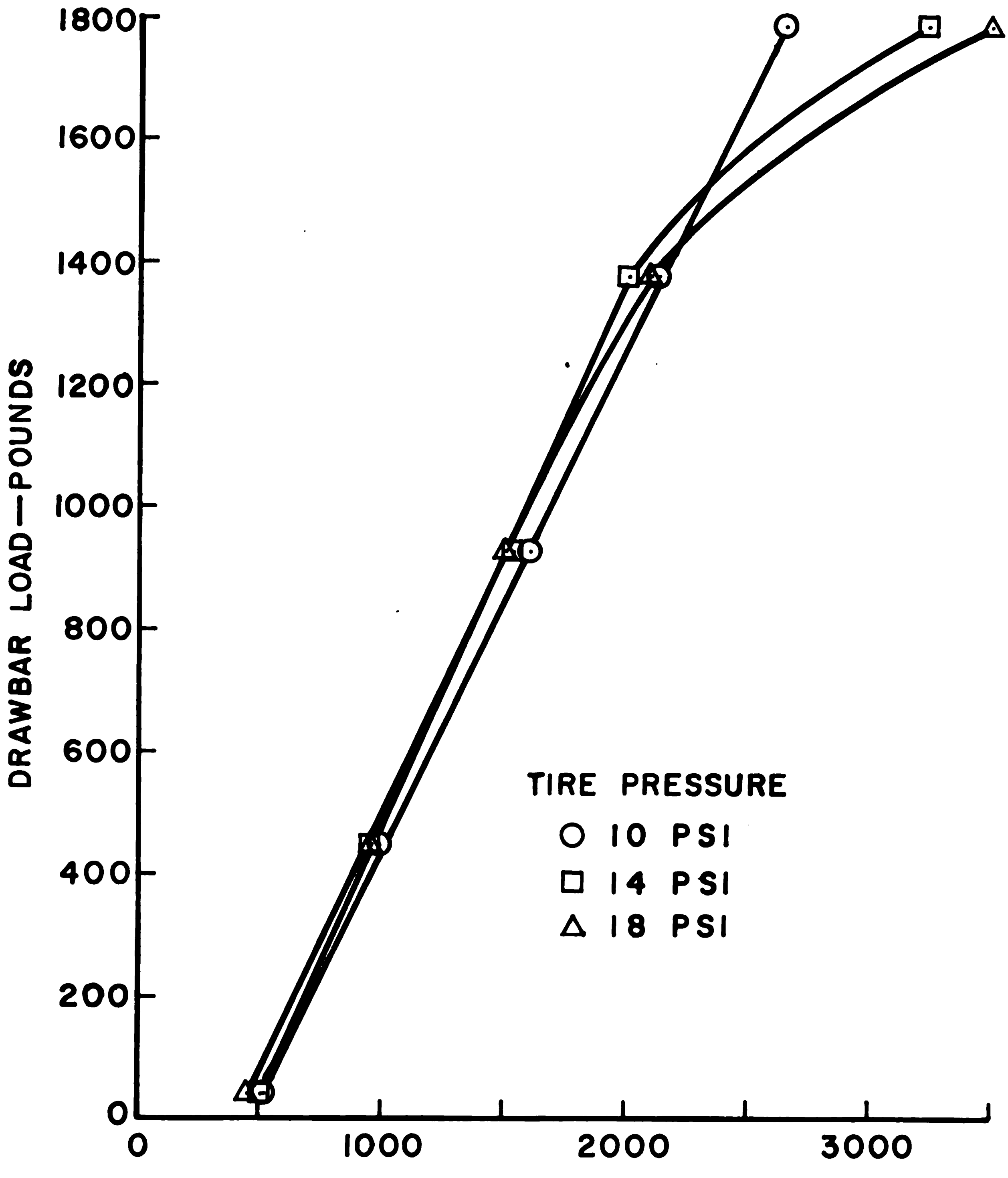

Figure 32. Relationship of drawbar load and rear axle torque with tire inflation pressures of 10, 14 and 18 psi.

lugs came in contact with the soil (greater angle of contact). With the increased angle of contact, the traction required to pull the drawbar load was developed.

Slip

Slip data are tabulated in Table XII. Figure 33 shows that with a tire inflation pressure of 10 psi, percent slip increased linearly with drawbar pull up to a load of 928 pounds. After that, slip increased at a slightly increasing rate. At the 14 psi inflation pressure, percent slip increased slightly to the 928 pound drawbar load and then increased rapidly. With the inflation pressure at 18 psi, percent slip increased rapidly from the 40 to 446 pound load, remained constant to the 928 pound load, and then increased at an increasing rate. The percent slip with a tire inflation pressure of 18 psi and 1783 pound drawbar load was nearly triple the percent slip with a tire inflation pressure of 10 psi and 1783 pound drawbar load.

A comparison of torque versus percent slip (Figure 34) shows that percent slip increased slowly at all tire inflation pressures up to a torque of 1500 pound feet. Above this torque value, percent slip, with 10 psi tire inflation pressure, increased only slightly more rapidly. With 14 and 18 psi inflation pressures, the curves increased rapidly and nearly converged. The torque required to develop a drawbar pull of 1783 pounds is shown by the top 3 points at the

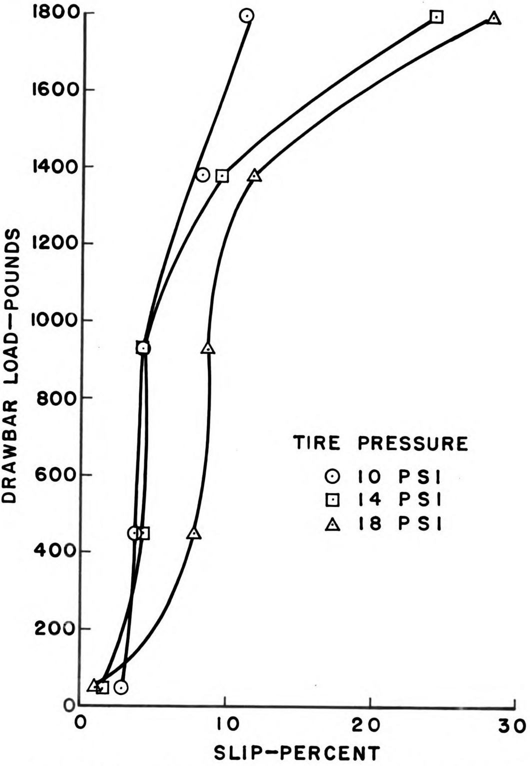

Figure 33. Relationship of drawbar load and percent slip with tire inflation pressures of 10, 14 and 18 psi.

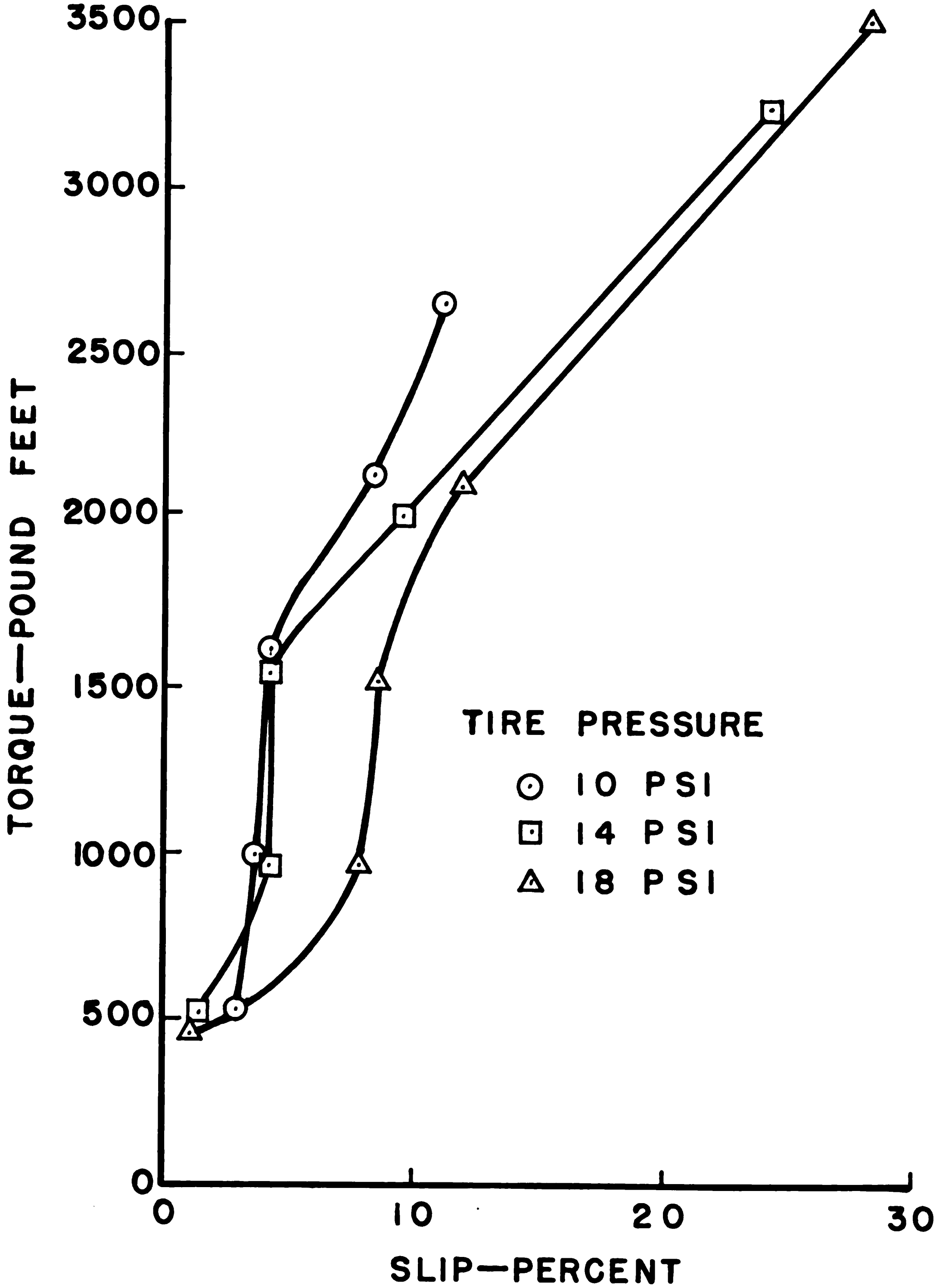

Figure 34. Relationship of torque and percent slip with tire inflation pressures of 10, 14 and 18 psi.

various pressures. To pull the 1783 pound drawbar load in sand, a 10 psi tire inflation pressure required 2,655 pound feet of torque, 14 psi required 3240 pound feet of torque, and 18 psi required 3506 pound feet of torque.

APPLICATION OF RESULTS

The following is one application which can be made of the results obtained in the study. The entire dynamic weight on the soil can be approximated from the pressure transducer readings in the undertread and lug face. The dynamic weight transfer is then determined by subtracting the dead weight from the dynamic weight. If the weight transfer had been measured, this would have constituted a proof of the reliability of the cells. The dynamic weight transfer cannot be calculated with the data as included in this thesis, but the necessary data can be obtained from the original oscillograph charts.

Since the data used in these calculations were distributed over 4 charts, a time zero line had to be established. It was noted that the undertread cell positions 3 and 10 and the lug face cell positions 4 and 9 were located on an approximately straight line across the width of the tire. The time zero line (reference line in the rotation of the tire) was fixed at the time when the pressures on the above mentioned cells were at a maximum (assuming they all reached a maximum at the same time). A line was drawn across the charts through the peaks of the pressure curves (located on four different charts) of the cells mentioned above and the pressures at the intersections of the line and the 10 pressure curves were read.

The angle of contact for the conditions of this test (14 psi tire inflation pressure and 1783 pound drawbar load) was approximately 55 degrees at the center of the tire and 33 degrees at the edges. A line was therefore drawn across the charts 15.65 degrees (the angle between lugs) before and 15.65 degrees after the zero line (as determined from the theoretical travel pen marks) and the pressures at the intersections were read and recorded. For the center of the tire there were still approximately 28 degrees of unaccounted angle of contact; therefore, the same procedure was followed for the 4 cell positions at the center of the tire. The pressures thus read were added for each cell position (undertread pressure, P_{ui}, i = 1 to 10 and lug face pressure, P_{fi}, i = 1 to 10) (see Table V).

TABLE V.

TOTAL PRESSURE OVER THE SURFACE OF CONTACT AT EACH CELL POSITION ON THE UNDERTREAD AND LUG FACE WITH A 1783 POUND DRAWBAR LOAD AND 14 PSI TIRE INFLATION PRESSURE.

	Cell number									
	1	2	3	4	5	6	7	8	9	10
	Pounds per square inch									
Undertread	2.0	5.0	12.0	46.0	37.5	43.0	39.5	25.0	10.5	8.5
Lug face	16.0	14.0	63.0	38.0	69.0	51.0	39.0	29.0	20.0	10.5

Both positions (lug face and undertread) on the tire were then divided into 10 sections (one for each cell) and the areas (A_{ui} and A_{fi}) were calculated (see Table VI).

TABLE VI.

CELL POSITION AREAS.

	Cell number									
	1	2	3	4	5	6	7	8	9	10
					square inches					
Undertread	6.88	7.92	8.01	8.46	9.70	10.67	7.99	8.01	7.48	6.88
Lug face	2.32	2.58	2.36	2.59	2.30	2.30	2.63	2.70	2.67	2.34

Calculation of the dynamic weight (W_d) on the tire was as follows:

$$W_d = \sum_{i=1}^{10} (P_{ui} A_{ui} + P_{fi} A_{fi}) \qquad (2)$$

$$W_d = 2.0 \times 6.88 + 5.0 \times 7.92 + ---- + 10.5 \times 2.34 = 2870 \text{ pounds.}$$

The dynamic weight transfer (WT) was calculated as follows:

$$(WT = 2870 - 2400 = 470 \text{ pounds}) \qquad (3)$$

where: dead weight = 2400 pounds.

It was realized that most of the cells were not measuring the true vertical force but were measuring the force at some angle from the vertical (see Figure 35). Assuming an average angle of 15 degrees from the vertical, forward of the rear axle centerline, the weight transfer was:

$$WT = 470 \times \cos 15^{\circ} = 454 \text{ pounds.} \qquad (4)$$

The total dynamic weight transfer was then twice this amount or 908 pounds. The dynamic weight transfer was calculated using an equation developed by Buchele (1959). The direction and point of application of the forces used in this equation are shown on the free body diagram of a tractor (Figure 35).

$$WT = \frac{TRE_2 - PY_2 - R_{12}Y_{12} + R_6Y_6}{X_1} \qquad (5)$$

Assuming R_{12} to be 40 pounds (the front wheels were rolling on a board) and R_6 to be zero, substitution of values gives:

$$WT = \frac{(3240 \times 12 \times 2)-(1783 \times 12.5)-(40 \times 31)}{90} =$$

602 pounds.

The dynamic weight transfer calculated from the pressure measurements was found to be 306 pounds higher than that calculated by the above equation. The error in measurement of the dynamic weight on the right rear wheel was calculated as follows:

$$\text{Error} = \frac{\text{Measured dynamic wt.} - \text{Calculated dynamic wt.}}{\text{Measured dynamic wt.}} \times 100$$

$$= \frac{2854 - 2701}{2854} \times 100 = 5.4 \text{ percent} \qquad (6)$$

The data may also be used to calculate the distance of the resultant soil reaction on the tire ahead of the center line of the rear axle. Making use of the moment equation about the rear axle developed by Buchele (1959) this distance was determined as follows:

$$\curvearrowright + \sum M_o = TRE_2 + R_{22}Y_{22} - R_{21}X_{21} - R_{23}X_{23} - R_{24}Y_{24} - R_{28}Y_{28} = 0 \qquad (7)$$

The direction and point of application of the forces used in this equation are shown on the free body diagram of a rear tractor wheel (Figure 36).

Rearrangement and solving for X_{21}:

$$X_{21} = \frac{TRE_2 + R_{22}Y_{22} - R_{23}X_{23} - R_{24}Y_{24} - R_{28}Y_{28}}{R_{21}} \qquad (8)$$

But: $Y_{22} = Y_{24}$ and $R_{24} = P + R_{22} + R_{12}$

and assuming: $R_{23} = R_{28} = 0$

then: $X_{21} = \dfrac{TRE_2 - Y_{22}(P + R_{12})}{R_{21}}$

Substitution of values gives:

$$X_{21} = \frac{77,760 - 28(1783 + 40)}{2854} = 9.3 \text{ inches.}$$

The second approximation of the angle of pressure measurement was:

$$\sin^{-1} \frac{9.3}{28} = 19.5^o$$

Dynamic weight transfer was:

$$Wt = 470 \times \cos 19.5^o = 443 \text{ lb.}$$

The second approximation value of X_{21} was:

$$X_{21} = \frac{77,760 - 28(1783 + 40)}{2843} = 9.38 \text{ inches}$$

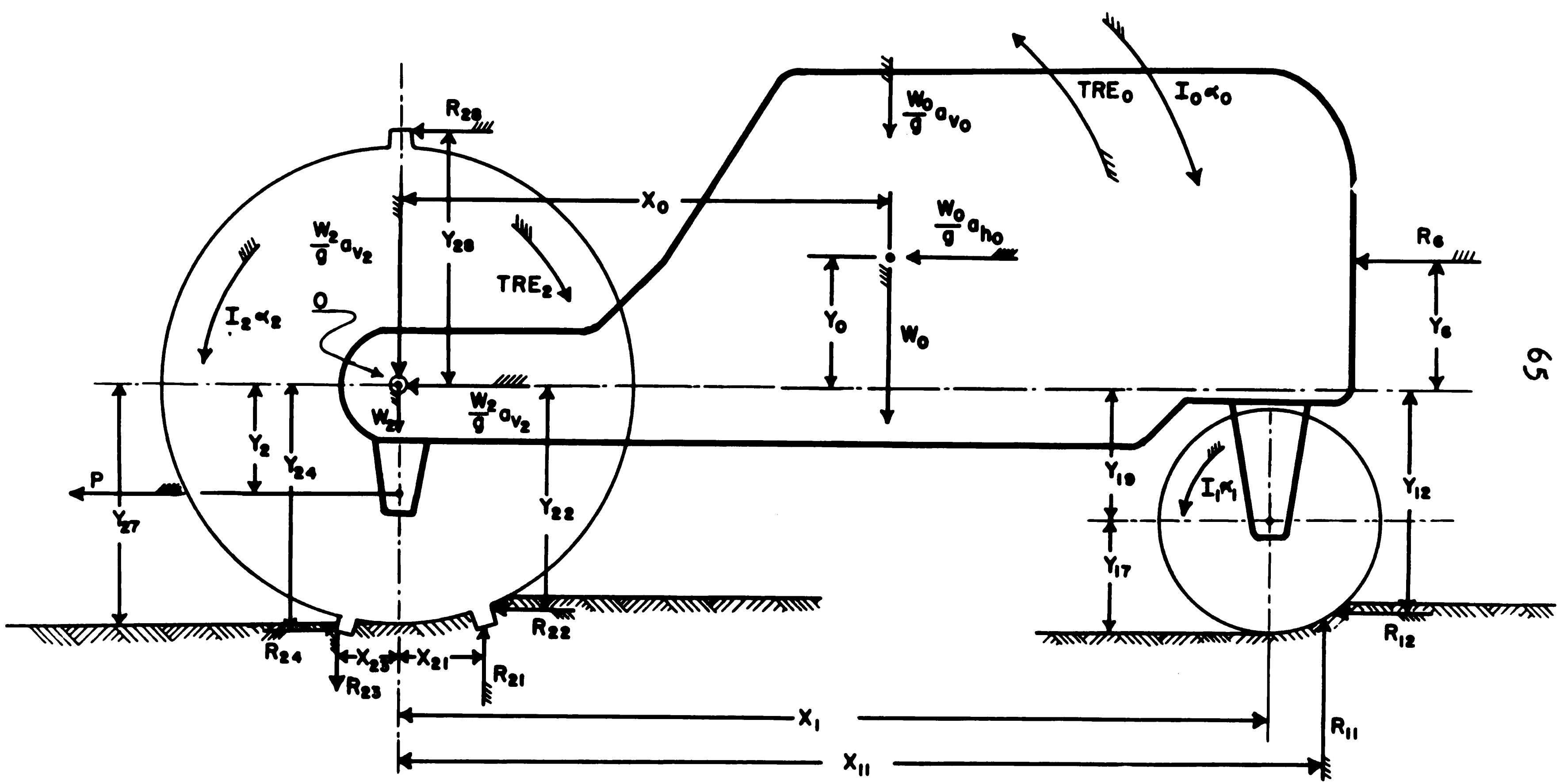

Figure 35. Free body diagram of a tractor.

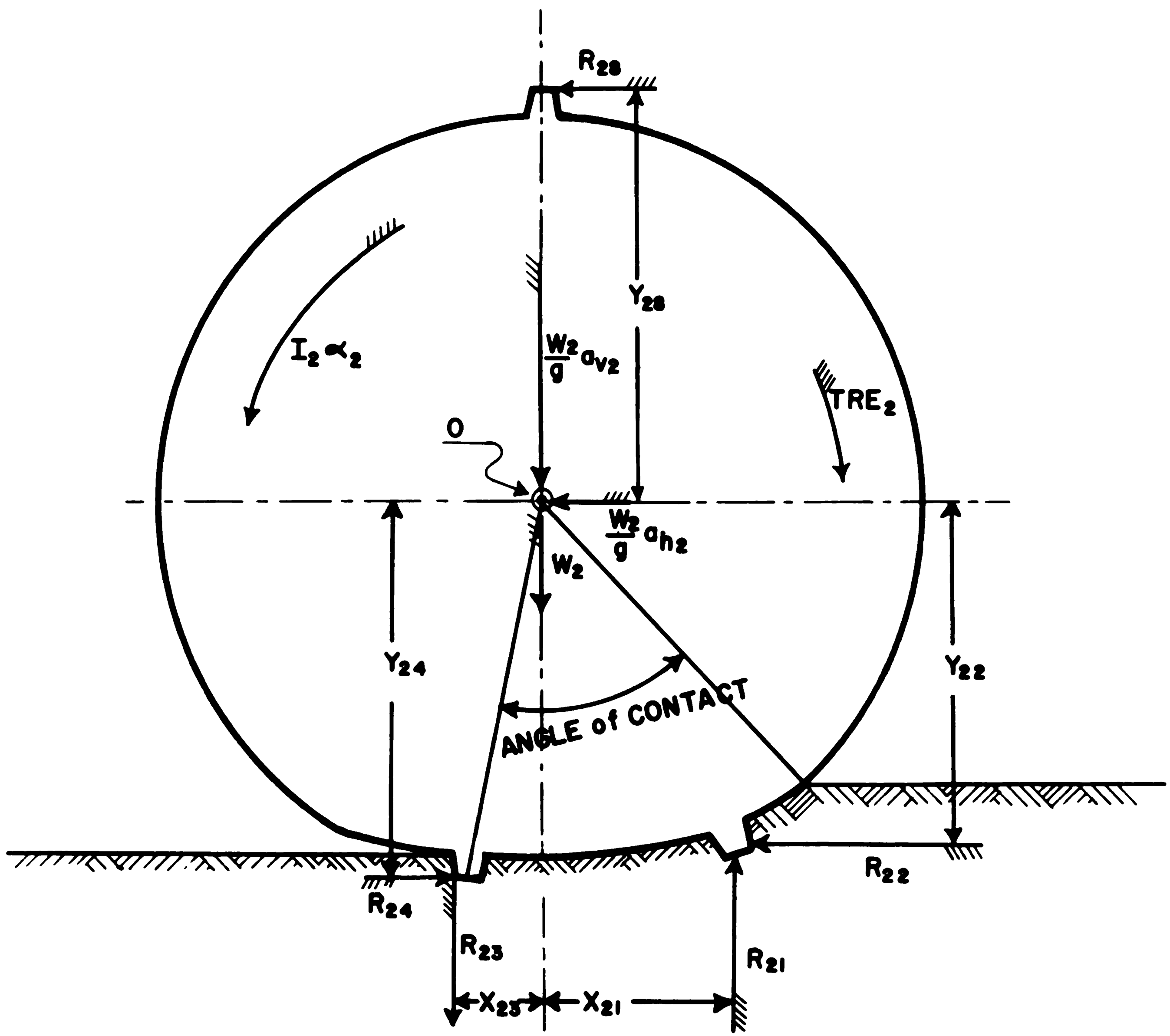

Figure 36. Free body diagram of a rear tractor wheel.

SUMMARY

The diaphragm pressure transducers designed by Lask were modified and used to measure soil-tire interface pressure on a rear tractor tire. These pressures were measured on the undertread, lug face, leading lug side and trailing lug side.

Drawbar load and tire inflation pressure were the controlled variables in this investigation. The tests were run with drawbar loads of 40, 446, 928, 1374 and 1783 pounds and tire inflation pressures of 10, 14 and 18 psi. Three replications were run for each condition. The results were averaged for each cell position, tabulated and plotted. The plotted data showed that high drawbar loads increased the soil-tire interface pressure on the undertread and leading lug side and reduced the pressure on the lug face and trailing lug side. These plots also showed that as tire inflation pressure was increased, the soil-tire interface pressure increased on the undertread, lug face, leading lug side and trailing lug side.

Slip was measured during each run with two microswitches electrically connected to event marker pens on the oscillograph. One of the microswitches measured actual forward travel and the other measured theoretical forward travel. Percent slip was calculated from the data thus obtained and

the results were tabulated and plotted against drawbar load for each tire inflation pressure.

The torque measured on the rear axle was averaged for each condition and tabulated. The tabulated torque data were plotted against drawbar load and percent slip for each tire inflation pressure. The plot of torque versus drawbar load showed that torque increased linearly with drawbar load with a tire inflation pressure of 10 psi. With tire inflation pressures of 14 and 18 psi, the torque increased linearly up to 1374 and 928 pound drawbar loads respectively and then increased at an increasing rate. The plot of torque versus percent slip showed that percent slip increased slowly up to a torque of approximately 1500 pound feet and then increased more rapidly, especially with the 14 and 18 psi tire inflation pressures. This plot also showed that with a tire inflation pressure of 10 psi, 1655 pound feet of torque in the right rear axle were required to develop a 1783 pound drawbar pull. With a tire inflation pressure of 18 psi, 3506 pound feet of torque in the right rear axle were required to develop the same pull.

An application of the results showed that it is possible to approximate the weight transfer and point of application of the resultant soil force against the tire.

CONCLUSIONS

The following conclusions are drawn based on the conditions of the test (damp mortar sand on concrete).

1. The pressure distribution across the width of a pneumatic tractor tire with lugs depended upon both drawbar load and tire inflation pressure.
2. As tire inflation pressure was increased, the soil-tire interface pressure increased, especially on the undertread, lug face and leading side.
3. The pressure data from the lug face and undertread could be used to approximate the weight transfer and point of application of the resultant soil reaction on the tire.
4. The total weight on the lugs was less than the total weight on the undertread.
5. The weight on the lugs was higher with a low drawbar load than with a heavier drawbar load.
6. With heavier drawbar load, some of the weight carried by the lug face was shifted to the undertread.
7. The angle of contact of a rear tire increased with decreasing tire inflation pressure.
8. The rear axle torque required to pull heavier drawbar loads increased as the tire inflation pressure increased.

9. For higher drawbar loads, rear axle torque increased as the slip increased.

10. As tire inflation pressure was increased from 10 to 20 psi, the effective circumference of the tire rolling on concrete was increased.

RECOMMENDATIONS FOR FURTHER STUDY

1. Repeat the tests conducted in this investigation under actual field conditions on various soil types.
2. Develop a direct method of measuring weight transfer and front wheel rolling resistance.
3. Mount pressure transducers in at least 3 sets of lugs and undertreads.
4. Instrument the diaphragm pressure transducers so the wheatstone bridge is temperature compensated.
5. Conduct tests of this type on different tread and tire designs.
6. Design new tread designs to provide more traction with less slippage.

APPENDIX

EXPERIMENTAL RESULTS

TABLE VII.

SOIL-TIRE INTERFACE PRESSURES ON THE LUG FACE.

Tire pressure	Drawbar load	Cell number 1	2	3	4	5	6	7	8	9	10
psi.	lb.	pounds per square inch									
10	40	15.7	23.0	41.7	32.0	35.3	30.0	31.3	37.7	17.7	11.7
	446	23.7	20.3	40.3	27.3	39.0	39.3	28.3	29.0	21.8	13.7
	928	18.0	20.3	40.7	26.0	31.3	30.8	29.1	30.3	19.8	17.0
	1374	12.3	13.0	30.3	22.3	29.2	30.5	28.0	26.7	21.7	14.8
	1783	19.7	20.0	32.3	21.3	29.0	30.3	26.0	21.3	15.0	11.3
14	40	15.7	17.3	37.3	30.3	39.0	38.3	33.7	33.2	21.7	15.3
	446	20.3	22.6	45.3	32.0	34.7	34.3	33.3	41.3	28.3	20.0
	928	10.3	14.7	44.7	32.3	35.0	36.7	35.7	28.3	23.0	18.3
	1374	22.7	28.5	40.3	31.7	36.8	33.6	29.0	26.0	20.3	14.7
	1783	15.7	20.7	35.0	32.3	36.0	34.0	25.0	21.0	16.0	12.0
18	40	11.8	19.0	43.7	42.7	44.3	50.0	41.3	39.3	25.7	14.3
	446	14.7	24.7	52.3	45.0	52.0	45.3	42.0	42.0	34.0	21.0
	928	10.7	19.0	44.0	44.0	48.7	54.3	48.3	42.7	24.0	14.7
	1374	11.0	16.3	39.0	38.0	60.3	54.7	41.3	33.0	20.7	10.3
	1783	10.2	15.2	35.7	37.0	44.0	51.0	33.7	21.7	14.0	10.6

TABLE VIII.
SOIL-TIRE INTERFACE PRESSURES ON THE UNDERTREAD.

Tire pressure	Drawbar load	Cell number 1	2	3	4	5	6	7	8	9	10
psi.	lb.	pounds per square inch									
	40	1.92	8.90	12.33	14.16	11.10	16.30	13.06	13.26	6.90	2.43
	446	1.17	6.83	11.58	17.50	14.00	17.00	15.83	15.83	7.23	1.66
10	928	0.58	7.16	15.66	13.66	-----	17.90	17.50	16.43	7.36	2.50
	1374	2.00	8.58	17.17	18.16	15.00	21.33	19.33	15.50	7.83	7.36
	1783	2.00	8.16	14.66	18.16	17.66	22.66	21.00	16.83	9.53	7.36
	40	0.33	6.58	9.33	15.75	13.66	23.35	18.00	14.50	4.60	1.60
	446	0.66	7.33	11.83	19.50	17.66	24.33	21.08	17.76	6.16	1.43
14	928	0.75	9.50	13.83	19.50	-----	22.83	16.66	17.23	4.50	2.06
	1374	1.75	7.75	17.33	22.66	19.66	25.83	20.00	16.90	7.50	3.43
	1783	2.16	9.58	18.16	23.00	20.16	23.00	20.00	16.50	7.58	4.60
	40	0.50	4.33	10.75	18.16	17.50	15.66	16.53	11.03	4.56	1.20
	446	0.58	7.66	13.66	22.66	17.20	22.68	22.16	17.76	6.93	2.16
18	928	0.50	7.58	16.08	25.00	20.33	25.00	22.66	18.26	6.26	1.66
	1374	0.58	7.83	20.33	27.16	20.16	26.50	23.16	19.50	7.23	2.13
	1783	2.25	9.50	19.00	27.16	21.66	27.00	20.50	15.66	6.00	4.00

TABLE IX.

SOIL-TIRE INTERFACE PRESSURES ON THE LEADING LUG SIDE.

Tire pressure	Drawbar load	Cell number 1	2	3	4	5	6	7	8	9	10
psi.	lb.	pounds per square inch									
	40	0.0	3.5	4.5	10.3	12.8	16.2	11.5	3.8	0.8	0.0
	446	0.0	3.0	6.3	10.0	8.3	18.3	14.0	5.3	3.0	0.3
10	928	0.0	5.0	9.0	13.6	16.2	16.7	17.6	7.5	2.8	1.0
	1374	1.5	5.2	11.6	15.6	15.5	20.2	20.6	10.7	4.2	1.0
	1783	3.0	8.3	13.6	18.0	22.0	21.7	19.6	11.3	5.7	2.5
	40	0.0	2.3	4.2	12.2	15.7	14.5	12.5	3.2	0.0	0.0
	446	0.0	2.2	5.2	14.2	23.7	21.0	16.0	5.2	0.7	0.0
14	928	0.0	3.0	6.7	14.7	21.0	20.8	19.0	6.3	1.0	0.3
	1374	0.5	4.3	11.5	18.7	26.0	37.2	30.0	11.0	2.5	1.3
	1783	3.3	8.7	15.5	23.0	32.7	44.0	41.5	12.7	5.0	1.8
	40	0.0	1.0	3.3	9.0	20.0	21.3	16.7	4.3	0.0	0.0
	446	0.0	2.7	4.7	10.0	22.7	32.0	19.3	4.8	0.0	0.0
18	928	0.0	1.5	7.2	14.3	23.8	32.0	25.5	6.8	0.0	0.0
	1374	0.0	2.3	8.5	16.2	33.8	37.8	26.3	8.2	1.3	0.0
	1783	2.7	6.7	14.3	25.7	39.7	50.5	36.8	12.0	4.7	2.7

TABLE X.
SOIL-TIRE INTERFACE PRESSURES ON THE TRAILING LUG SIDE.

Tire pressure	Drawbar load	Cell number 1	2	3	4	5	6	7	8	9	10
psi.	lb.	pounds per square inch									
	40	22.0	22.0	9.3	16.7	11.7	6.3	5.0	8.7	10.8	14.0
	446	11.3	13.3	4.7	21.7	15.3	5.3	4.7	12.0	9.7	17.0
10	928	17.0	15.7	6.0	17.0	7.0	3.2	3.8	4.3	5.3	15.3
	1374	5.8	10.5	5.0	30.8	7.3	3.2	4.3	6.0	4.0	9.7
	1783	7.0	8.7	5.8	21.7	4.5	4.3	8.0	6.3	5.3	9.0
	40	14.0	20.0	9.7	16.6	14.7	9.7	13.7	14.3	11.0	23.7
	446	14.3	18.7	4.7	17.0	8.5	4.7	15.0	7.0	7.7	19.3
14	928	12.8	14.2	6.7	22.7	7.3	3.7	9.7	7.0	8.3	14.5
	1374	9.3	10.8	3.5	28.7	10.0	3.0	2.7	8.0	8.0	11.7
	1783	6.2	10.8	5.0	30.7	7.0	3.0	9.3	7.0	5.3	6.3
	40	12.3	19.7	6.0	21.7	17.3	10.0	10.7	14.3	13.7	11.7
	446	13.7	20.7	8.7	21.3	11.0	8.3	9.7	11.3	9.3	11.0
18	928	13.0	17.0	7.3	24.0	13.7	6.0	8.3	10.3	10.3	11.3
	1374	8.0	10.7	3.3	27.3	8.7	3.7	9.0	8.7	8.2	8.0
	1783	2.7	6.7	3.7	34.5	9.3	4.3	7.3	6.3	4.2	3.7

TABLE XI.

REAR AXLE TORQUE AT VARIOUS TIRE INFLATION PRESSURES AND DRAWBAR LOADS.

Tire pressure	Drawbar load-pounds 40	446	928	1374	1783
psi	torque-pound feet				
10	525	995	1617	2136	2655
14	522	961	1540	2016	2655
18	457	966	1516	2104	3506

TABLE XII.

PERCENT SLIP AT VARIOUS TIRE INFLATION PRESSURES AND DRAWBAR LOADS.

Tire pressure	Drawbar load-pounds 40	446	928	1374	1783
psi	percent slip				
10	2.8	3.6	4.2	8.4	11.2
14	1.4	4.2	4.2	9.5	24.2
18	1.1	7.8	8.6	11.8	28.2

REFERENCES

ASAE Soil Compaction Committee Report (1958). Soil compaction research. Transactions of the ASAE. 1:58-64.

Bekker, M. G. (1956). Theory of Land Locomotion. University of Michigan Press. Ann Arbor, Michigan. 520 pp.

Brunner, E. F. (1933). Problems in the design of low-pressure tires for farm tractors. Agricultural Engineering. 14:2.

Buchele, W. F. (1954). Ridge farming and plant root environment. Thesis for degree of Ph.D., Iowa State College, Ames, Iowa. (Unpublished).

Buchele, W. F. (1959). The Dynamic Stability of Tractors, Agricultural Engineering (in press).

Clyde, A. W. (1936). The effect of tractor tire size on drawbar pull and travel reduction. Agricultural Engineering 17:255-256.

Edminster, T. W. (1956). Progress report of the committee on soil compaction. Paper presented at the winter meeting of ASAE. Chicago, Illinois. Dec., 1956.

Hovanesian, J. D. (1958). Development and use of a volumetric transducer for studies of parameters upon soil compaction. Thesis for the degree of Ph.D., Mich. State Univ., East Lansing, Michigan. (Unpublished).

Hurlbut, L. W. (1933). Comparative test results of rubber tires and steel wheels for tractors. Agricultural Engineering. 14:217-218.

Jones, W. B. (1934). Pneumatic rubber tires on farm equipment. Agricultural Engineering. 15:49-50.

Josephson, H. B. (1928). Tests of tractor wheel equipment. Agricultural Engineering. 9:313-315.

Lask, K. V. (1958). Instrumentation and measurement of soil-tire contact pressures. Thesis for the degree of M.S., Mich. State Univ., East Lansing, Michigan. (Unpublished).

Lugo-Lopez, and G. Acevedo. (1956). Effects of tractor traffic compaction on the physical properties of an irrigated soil in Southwestern Puerto Rico. The Journal of Agriculture of the University of Puerto Rico. XL:235-244.

Mayer, I. D. (1935). Application of rubber tires to combines. Agricultural Engineering. 16:53-54 and 60.

McCuen, G. W. (1933). Ohio tests of rubber tractor tires. Agricultural Engineering. 14:41-44.

McKibben, E. G. and J. B. Davidson. (1940). The effect of inflation pressure on the rolling resistance of pneumatic implement tires. Agricultural Engineering. 21:25-26.

McKibben, E. G. and I. F. Reed. (1951). Wider tire rims, no help in tractor operation on dry sand. Agricultural Engineering. 32:45-48.

Monson, O. W. (1957). Compaction caused by tractor wheels on the cultivation of sugar beets. Journal of the American Society of Sugar Beet Technologists. IX:289-294.

Moss, C. W. (1954). Off the road tires: A compromise in design. Agricultural Engineering. 35:26-29.

Perry, C. C. and H. R. Lissner. (1955). The Strain Gage Primer. McGraw-Hill Book Co., York, Pa. 281 pp.

Raney, W. A., T. W. Edminster and W. H. Allaway. (1955). Current status of research in soil compaction. Soil Science Proceedings. 19:423-428.

Reed, I. F. and J. W. Shields. (1950). Effect of lug height and of rim width on the performance of farm tractor tires. SAE Journal. Vol. 58.

Shields, J. W. (1933). Pneumatic tires for agricultural tractors. 14:39-40.

Smith, C. W. and L. W. Hurlbut. (1934). A comparative study of pneumatic tires and steel wheels on farm tractors. Agricultural Engineering. 15:35-48.

Soehne, W. (1957). The soil mechanic fundamentals of pressure distribution and soil compaction under tractor tires. Paper presented at the Golden Anniversary meeting of the American Society of Agricultural Engineers. 15 pp.

VandenBerg, G. E. (1956). Measurement and analysis of soil pressure distribution under tractor and implement traffic in an artificial field. Thesis for the degree of M.S., Mich. State Univ., East Lansing, Mich. (Unpublished).

VandenBerg, G. E. (1958). Personal letter sent to Dr. W. F. Buchele, October 9, 1958.

Vasey, G. H. and I. T. Naylor. (1958). Field tests on 14-30 tires. Journal of Agricultural Engineering Research. 3:1-8.

Wileman, R. H. (1939). Pneumatic Tractor Tire Profile Studies. Agricultural Engineering. 20:231-232.

Worthington, W. H. (1957). Proceedings of seminar on tillage and traction equipment research. Auburn, Alabama.

Zink, F. J. (1935). Pneumatic tractor tires on listed crop ridges. Agricultural Engineering. 16:57-60.