170

THE IMPORTANCE OF WHEEL EQUIPMENT TO TRACTOR OPERATION

By

R. T. Stewart

124 Rush
80-16

A Thesis submitted for the Degree of

Bachelor of Science

Mechanical Engineering

J B Davidson
In Charge of Thesis

APPROVED:

W. H. Meeker
Head of Mech. Engr. Dept.

IOWA STATE COLLEGE

1928

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

History of the Tractor

The last twenty years has witnessed the development of the internal combustion engine, and along with this development has come the automobile, the truck, and tractor. Essentially the automobile and the truck are for the purpose of carrying loads while the tractor's primary function is to pull loads. In their component parts these three motorized machines are quite similar, but in design they are radically different.

In the early history of the tractor it was generally believed that weight played an important part in securing sufficient traction to pull loads and for that reason all of the early gas tractors were large and heavy machines. This large size made them clumsy to handle and limited their usefulness to a small class of work, that of pulling large loads at slow speed over a comparatively solid surface capable of supporting their heavy weight. In this large type tractor the lug equipment was of minor importance, as it depended almost entirely on weight and large sized wheels to furnish the traction. Oft times it was desired to use these large tractors on ground, which because of excessive moisture or looseness, would not provide either the necessary support or traction. As a consequence this type of tractor was easily mired. It is true that this condition is seldom met with in the large wheat fields of the Northwest and the more arid parts of the country. It was evident, however, that the large tractor was not adapted to the farms of the middle west, due to the variation in moisture and size of farms. It was easily demonstrated that a large unwieldly tractor was not economical on a quarter or half section farm with small fields.

In order to get into this field the manufacturers were faced with the situation of designing a tractor which would have the maximum work performing ability per pound of tractor weight. Thus with weight of tractor limited to the carrying capacity of the soil it was necessary to resort to other means of providing the necessary traction.

About 1919 the tractor manufacturers began to experiment with the lighter tractors with the result that in 1920 to 1922 a number of new model light weight tractors came on the market. These tractors weighed from 4000 to 5000 lbs. and had a draw bar rating of from 9 to 12 H. P. The primary use for which these tractors were intended was plowing, and they were successful in that field. They were light enough to be worked in the average midwest field, and small enough to be easily handled. Many models of large tractors were still manufactured, however, as there was an extensive use for them in the larger fields of the Northwest, and in foreign countries.

Even with this development of a lighter tractor the use of these machines in the corn belt did not expand as anticipated. In fact it was estimated in 1923 that only 6 per cent of the farms of Iowa, Illinois, Indiana, Ohio, Nebraska and Missouri were using tractors. The total number of tractors in these states was 82,000 representing one third of all the tractors in the United States. The other 94 per cent of the farms were still using horses extensively.

It is evident from these figures for 1923 that the possibility of the tractor in the corn belt had hardly begun. Tractor manufacturers began to investigate the reason for this lack of demand in the corn belt and the reason became apparent with a little study.

The average corn belt farm is comparatively small and it is not absolutely necessary on a small farm to do the work faster than horses can do it. The farmer, therefore, could not see the economy of buying a tractor to do the plowing when he had to keep enough horses to plant and cultivate his corn and to do other work on the farm. He reasoned that the investment in extra horses required for the plowing work would be less than the investment in a tractor. Thus the tractor manufacturer was faced with the problem of designing a tractor that would do cultivating, discing, dragging and other drawbar work in addition to plowing.

The design of such a tractor might seem simple on first thought, but when consideration is given to all the factors it is not so simple. In the first place the tractor must have considerable weight for stability. A two-bottom plow requires aproximately 8 to 9 drawbar horsepower. A three-bottom plow requires 12 to 13 drawbar horse power. To be adaptable to cultivating, a tractor must be comparatively light, to avoid packing the soil. It must handle quickly and easily and have a short turning radius. In addition a tractor for cultivating work must have at least a 24-inch clearance over the corn rows.

As the old adage puts it, "Necessity is the mother of invention"; so the need for this type of tractor has produced it and today such tractors are available for the farmer. While it is hardly to be expected that these tractors are the acme of perfection, it seems that the present all-purpose tractor has met the crying need of the corn belt farmer and has given him a single machine, weighing about 3000 lbs., which will do practically all the pulling work on the farm, and in addition afford him a unit power plant for threshing and similar work. With the situation which obtains in the tractor industry today it is well to look forward to the time when every midwest farmer will have an all-purpose tractor on his farm.

This discussion of tractor history has related entirely to the four-wheeled rear drive machine; It is well to keep in mind, however, that the need for lighter tractors developed two different types of machines, the four-wheel drive, and the so called caterpillar or track-laying type. The four-wheel drive machine, because of the extra mechanical parts and difficult controlling features, has been practically eliminated from the tractor industry. The track-laying type is being used extensively and has been a commercial success, tho its field of application appears to be more in industry and road building than on the farm. It can definitely be stated that the track-laying type is not applicable to cultivation and for that reason will not be considered in this paper.

Importance of the Problem.

It is indeed unfortunate with this rapid development of the tractor as a unit in the last few years, that design of tractive members has not had the attention it merits. Experience of manufacturers has demonstrated that many tractors as designed today are inefficient for farm use, as they are mechanically incapable of meeting the traction conditions of agricultural soils. This is not a new problem in tractor design but with the reduced weight of the present day tractor it becomes more and more important.

With the beginning of the trend for lighter tractors in 1919 it became evident that traction members were of major importance, and that lug equipment was the vital point of proper traction. Broadly stated the job facing the designer was to increase the work performing ability per pound of tractor weight. Experience, however, seems to indicate that too much attention has been paid to development of maximum possible engine power per unit displacement and other engine and mechanical developments. It is conceivable that 90 per cent of the operation of a tractor is at 50 to 80 per cent of maximum power and that the increase in tractive efficiency is far more important, especially in the light weight tractor.

It is quite generally realized that there is some loss of power in the tractive effort of a tractor wheel, but it is not fully appreciated that only 50 to 60 per cent of the power delivered to the wheel is available in tractive effort. Tests have shown that for every 10 horsepower put into the wheels of the average tractor under average conditions only 5 to 6 horsepower are available at the drawbar. The remainder is lost in work done on the soil.

A further example of the importance of the tractive members of a tractor is shown by the fact that for a given weight of tractor and wheel equipment there is a definite drawbar pull that may be attained and no more, even tho the tractor motor may have twice the power required. To state this in another way, assume a certain tractor, with weight and power of engine established. The problem then is to find the wheel and equipment that will give maximum drawbar horsepower under varying soil conditions. It is obvious that there is an unlimited source of information that can be derived from a scientific study of tractor wheel characteristics.

Some work has been done on this problem by the various agricultural colleges and experiment stations, but as yet, the results have not been conclusive, nor have they been carried to the point, where basic laws could be established.

It has been comparatively simple to determine the slippage of tractor wheels in different soils and to establish a more or less haphazard relative efficiency of different existing types of wheel equipment in this respect under definite local conditions. It is easily shown, however, that tractive efficiency of a tractor is influenced by a number of variable factors. In addition it has been determined that the principles of traction in soils are rather definitely related to the soil properties and the manner in which stresare imposed on the soil.

With the forgoing explanation of the importance of this problem as a basis, it is evident that it is of national importance. Therefore it behooves the agricultural engineers of the country as well as the tractor manufacturers to study the fundamental principles governing the traction of wheel tractors in soils and to provide a universally applicable basis for economical design of efficient tractors with reference to weight, power and drive wheel equipment.

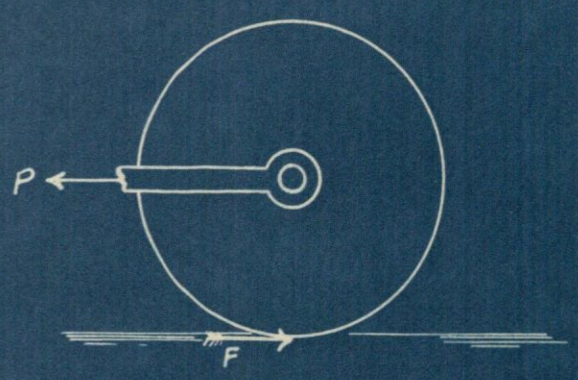


FIG. 1 APPLICATION OF A FORCE ON A WHEEl
(CASE ONE)

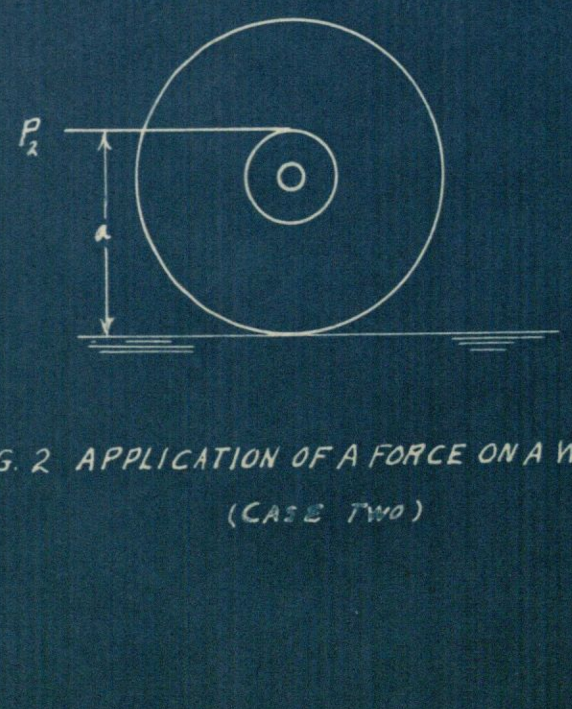


FIG. 2 APPLICATION OF A FORCE ON A WHEEL
(CASE TWO)

increases. With freshly tilled sandy loam soil the rolling resistance is comparatively large in proportion to weight on wheel, and becomes a factor for serious consideration in tractor wheel design.

Ordinarily in tractor operation there is considerable rolling resistance, and as the wheel is propelled thru a shaft or similar arrangement, some of the power delivered to the wheel is used in overcoming rolling resistance. Usually the rolling resistance is such that only a part of the frictional resistance is required to counter-act it. The rest of the frictional resistance is used for pulling the load. That is, the excess frictional resistance is transmitted thru hub of wheel to the frame of tractor and is available as Drawbar pull. These conditions exist in a tractor wheel as long as the drawbar pull is not large enough to cause slipping of the driver. Now then, when the drawbar pull plus rolling resistance is greater than the frictional resistance between the soil and wheel, slipping of the drive wheel ensues. In the extreme case of a large load on wet ground the slipping of the driver may be 100% and there will be no forward motion of the wheel over the surface. In the usual case of a moderate load on firm ground the slipping will increase until equilibrium of the forces obtains and the wheel will move forward. It is obvious then, in order to maintain forward movement the driver must continue to slip a certain amount, altho the amount of slipping will decrease slightly as soon as the wheel begins forward motion.

Slipping of a tractor wheel means loss of efficiency as part of the power put into the wheel is used up in work done on the soil. It is readily shown that excess slippage is a condition not desired in tractor operation; furthermore, slippage is to a limited extent a measure of efficiency. A good share of the work done to date has been concerned with slippage, probably because this element is more noticeable externally and for that reason is very interesting in tractor operation.

In this discussion slippage is considered as the relative motion between the surface of a wheel and the supporting surface. Thus when a wheel is pulling a load there will be a forward motion of the wheel equal to (D) at the same time the rotative motion of the wheel on the circumference will be π x diameter x revolutions. From these relations slippage in linear units is given by equation (1) below

$$(1) \quad \text{Slippage (in feet)} = 2\pi(d)(N) - D$$

Where D = Actual Forward Motion

d = Diameter of wheel (feet)

N = Revolutions of wheel

It is usually more useful to have the slippage expressed in terms of percent which is given by equation (2)

$$(2) \quad \%\ \text{slip} = \frac{2\pi(d)N - D \times 100}{2\pi dN}$$

When a wheel is propelled by a tangential force as shown in Fig. (2) there will always be a certain amount of slipping because there is a definite amount of rolling resistance, tho in the ideal case this is practically negligible. In tractor operation the rolling resistance is small as compared to the drawbar pull, hence, the slipping of the driver is usually considered as being entirely due to the pull on the wheel. While this may not be an exact consideration as to the cause of slipping the amount caused by rolling resistance is so small that it is not practicable to separate the values.

Formula (2) above gives the percent of slip which would be measured for a plain wheel without lugs. In this case the effective circumference is given by $2\pi d$, where (d) equals diameter at rim. It may easily be shown, however, that the effective circumference for a wheel with lugs is greater than the circumference at rim, but is less than the circumference at tip of the lug. This condition has led to considerable dispute as to the method that should be used in measuring the percent of slip. In this paper and in previous work at this and other colleges the percent of slip has been measured by means of rim circumference. However, when this basis is used with wheels having lugs the apparently erroneous result of negative slip is sometimes obtained. A negative result indicates that the wheel with lugs has moved forward in a given number of revolutions further than it would have moved on a smooth level surface without lugs. In other words the base circle of the wheel has shifted from the rim to some point midway between rim and the lug tip circle. An argument advanced for this method is, that a negative slip may indicate more lug equipment than is necessary. In the tractor tests at the University of Nebraska the base circle is taken at the tip of the lugs. Neither of these methods may be said to be strictly correct, but are used in lieu of a definitely established practice. Mr. E. S. Patch in his paper "Methods of Investigating Slippage of Traction Wheels on Tractors",(1) proposes that slippage be determined from a theoretical wheel circumference as determined by dividing the total number of wheel revolutions counted when tractor wheel is run without drawbar pull at a certain speed over a measured course into the length of the course. This method without question is the most accurate, but it is unwieldy in testing operations. It is also doubtful if the comparative results are more accurate by this method.

Having established these factors involved in tractor wheel operation it may be well to analyze their effect on efficiency and operation of the wheel. That slip of the tractor wheel is a loss, represented by work done on the soil has been shown. It is obvious that rolling resistance is a loss. Therefore, the input to wheel minus rolling resistance loss minus slippage loss equals the work that is available as output. To put this in the form of an equation

$$I = O + L_R + L_S$$

where

O = output

I = Input,

L_R = Loss due to Rolling Resistance

L_S = Loss due to slippage.

From this equation it is evident in order to increase

(1) Transactions Am. Soc. Agr. Engr. 1922 P 103-109.

the efficiency of a wheel for a given output or drawbar pull, that there are two points of attack. Rolling resistance loss must be reduced, slippage loss reduced or a combination of the two. Rolling resistance is more or less an established factor depending primarily on weight on wheel and soil factors. This is not entirely true as will be explained later; but at this time we may consider this fixed for a given soil and weight on wheel. The proposition then is to reduce the slipping and thereby increase the efficiency. With a plain wheel of a certain size, slippage for a given drawbar pull, may be reduced in only one way; that is, by increasing the frictional resistance between the soil and the wheel. In turn the frictional resistance may be increased by additional weight or by verying the soil texture or condition. The latter is impossible as tractors are called upon to work in all kinds of soil. The addition of weight to a certain degree is feasible, but beyond a certain point this only complicates the problem by increasing the rolling resistance. Thus the simple solution is to put projecting lugs on the wheel. When this is done slippage is not entirely dependent on the frictional resistance between wheel and surface, because these lugs penetrate the soil under the wheel rim, and act very similar to a gear and rack, where the rack is being continuously generated as the wheel moves forward. In this case in addition to the frictional resistance of soil and wheel, another factor enters, that of shearing value of the soil.

The action of a lug entering the soil is more or less an unsolved problem but experiments seem to indicate that as the lug penetrates the soil there is a compression of the soil directly behind it. This compression is probably due to the tendency of wheel to slip and to the pressure caused by the rim. As the wheel continues to slip the soil behind the lugs is further compressed and finally sheared from the adjacent soil to the side and below. Mr. Hewitt in his paper "The Principles of the Farm Wheeled Tractor"(2) states, "That the drawbar pull available from a cleated wheel depends entirely on the shearing strength of the soil at the ends of the cleats." "That the cleat carries a section of the top soil and slides it against the soil below the edge of the cleat. Experiments indicate that this was independent of the depth of the cleat, depending entirely on shearing strength of soil."

It becomes evident from these considerations that rolling resistance is affected by the addition of lugs to a wheel, because the wheel no longer merely rolls over the surface. Work must be expended when the lug penetrates the ground, hence, rolling resistance increases. Furthermore, the lug must leave the ground and further work is required. Hence, a lug should penetrate and leave the soil easily to reduce rolling resistance. It must be kept in mind, however, that the work of penetration is of minor importance as with a lug entering the soil, the main object of the lug is to reduce slipping; therefore, the lug must be of such a design as to reduce the

(2) Trans. Soc. Auto. Engr. 1919 Part 1 P 83-89.

shearing of the soil as much as possible on entering. It has been determined by experiments that a lug inclined forward gives the best results in reducing shearing. In this manner each lug acts very much like a step as it enters the soil.

The fact that there are so many variable conditions in this problem make thorough study difficult. A brief study of the conditions under which a tractor wheel operates reveals that tractor wheel slippage involves many factors, most of which vary with each other.

(1) Soil condition

(2) Weight on wheel

(3) Speed

(4) Drawbar load

(5) Height of tractor hitch

(6) Wheel

a- diameter

b- width

c- lug equipment

Of these six variables three have been more or less standardized by experience and manufacturing precedent. It is safe to say that weight on wheel is more nearly constant in different tractors today than ever before. The general trend seems to indicate that the ideal weight of the all-purpose tractor is between 3000 and 4000 lbs., although at present 4000 to 6000 lbs. is the average weight. The distribution of this weight between the front and rear wheels is a very complicated problem, involving the entire tractor design, but for purposes of this paper it may be assumed that two-thirds of the weight is carried on the rear wheels. Thus for a 4000 lb. tractor the weight on each rear wheel will be about 1300 lbs.

Speed of tractors is to a certain extent a function of the weight. That is slow moving tractors will involve greater weight, both for strength of parts and to obtain the necessary traction, to develop a large drawbar pull. High speeds on the other hand will permit a lighter construction. The other factor involving speed is the implements to be hauled by the tractor. The industry has in general established a speed for farm use of 2½ to 3½ miles per hour as a standard.

Height of tractor hitch has been standardized in practically all cases; so this variable is of minor importance. It is well to state, however, that with a given plow or other implement the method of hitching is a very great factor as to the amount of work required to pull the implement.

With the elimination of these three factors it is still necessary to study the interaction of the three remaining variables, namely (1) drawbar pull, (2) soil, (3) the wheel, or to put the question another way drawbar pull is a function of soil, wheel equipment and slippage.

REVIEW OF LITERATURE

A review of the literature on the traction of tractor wheels indicates that comparatively little work has been done in the study of this problem, or that manufacturers are reticent to contribute to the common cause the results of their experience. In view of the evident importance of this subject this situation seems strange, and possibly can only be explained by the fact that tractor manufacturers have been too engrossed in the design of the machine in general. This has been aptly stated by one tractor manufacturer who said "As a matter of fact, every manufacturer has gone about this largely with a yard stick, and I do not believe that there are any traction members designed for stock equipment, that are the result of careful study and experiment". While this remark was made in 1923 the precise data contributed by manufacturers since 1923 is conspicuous by its lack. To offset this apparent neglect of an important problem a few very good papers have been given on this subject. Abstracts from the most important of these papers are given below.

1. "THE PRINCIPLE OF THE FARM WHEELED TRACTOR"

   By E. R. Hewitt 1919

In his report Mr. Hewitt in a series of laboratory tests with full sized wheels has concluded that;

1. "The maximum drawbar pull is a definite function of the weight per inch of width. Weights used varied from 10 to 200 pounds per inch; the ratio of maximum possible drawbar pull to total weight on the

wheel was constant for that range. This was found to be true whether the ground was wet or dry.

2. "On sandy ground the drawbar pull available with a smooth metal wheel is about 30 per cent of the weight on the wheel.

3. "On damp, sandy ground, the maximum drawbar pull is greater, being about 43 per cent of the weight, and under some conditions even slightly higher.

4. "Cleats increase the maximum drawbar pull only insofar as the soil resists shearing; that is, the cleat carries a section of the top soil and slides it against the soil below the edge of the cleat. Experiments indicated that this was practically independent of the depth of the cleat, depending solely on the shearing strength of the soil at the depth of the cleat edge. In some cases the shallower cleat pulled more than the deeper cleat because the roots in the sod were not cut off and advantage was taken of their shearing strength. It was found that a cleat inclined forward at an angle would improve this condition somewhat. In going uphill the cleat enters the soil almost horrizontally, acting like a step and tending to lift the weight off the wheel. On leaving, the cleat stands almost vertical and causes less friction loss of power. An inclination of about 30 degrees was found to be the most satisfactory on a 6-foot wheel.

This arrangement tends to self cleaning to a certain extent. Setting the cleats at an angle of 30 degrees to the axis of the wheel also helps this cleaning effect by a slippage action. The shearing strength of the soils tested appeared to vary from 5 pounds in loam or sod. No doubt tough sod or gumbo may prove even stronger than this.

"From these facts it becomes evident that weight is the only means of obtaining a tractive effort of 40 per cent of the weight of the machine under bad conditions in dry ground or sand, as cleats will be of little use. Wheels 72 inches wide would give an added pull due to the use of cleats of only 360 pounds for loose ground. Weight is therefore practically the sole reliance for traction in sand or very dry loose ground. In sod or damp ground 72-inch wheels would ordinarily give 4000 to 5000 pounds pull from the cleats alone, and the light machine with only sufficient weight to hold the cleats down would show good results."

2. "METHODS OF INVESTIGATING SLIPPAGE OF TRACTION WHEELS ON TRACTORS"

By E.S. Patch 1922

Mr. E. S. Patch in his paper gives a comprehensive method of studying the soil factor in which a method of analysis of soils for following characteristics are explained:

(a) Specific gravity

(b) Moisture

(c) Gravel

(d) Sand

(e) Clay

(f) Humus

(g) Soil hardness

(h) Resistance to shear.

He also discusses the effect of speed on wheel slippage, and gives a method of measuring slip which is unique although cumbersome to determine.

The theoretical wheel circumference was determined by dividing the total number of wheel revolutions counted when tractor was run without load at a certain speed over a measured course into the length of the course. Slippage for each test thereafter was calculated by using this theoretical wheel circumference.

3. "TRACTOR LUG STUDIES ON SANDY SOIL"

By J.W. Randolph 1926

Mr. Randolph's study was made in the laboratory with a miniature tractor wheel. Apparently he has determined some accurate results for this small wheel. In his conclusions as given below he warns that these results are for a small wheel operating in sand., and are not applicable directly to full sized tractor wheels. The comclusions set forth in these tests are as follows:

1. "The entire study shows that the greatest factor in the transmission of force from any lug depends on

the tractor taking fullest advantage of the arch action of a soil. The resistance to shear determines the tractive value of a soil. If the soil is confined by a rim (an arch action), the shear area is increased by bringing the line of shear nearer parallel to the surface of the ground, the shear angle of unconfined soil being 45 degrees. The compressing action of the rim increases not only the arch action, but the shear value per square inch.

2."The characteristics of a tractor, discussed in this article, taken in the order of their importance, with reference to their tractive value, are as follows: (a) The weight distribution on the driving wheels; (b) the depth of lugs; (c) the width of lugs solid or broken (i.e., spade lugs); (d) the angle of the lugs across the rim.

3. "With a given width of rim, output will increase up to a maximum as the weight carried by the wheel is increased up to a certain point, in this case, up to 155 pounds. With further increase in weight, the output will decrease.

4. "With a given weight to be carried by a wheel, output will increase with the rim width where the weight is sufficient to force the lugs into the soil.

5. "Other factors remaining constant, output is in proportion to the depth of lug within the range of lugs studied.

6."Output varies but slightly with the width of lug.

7."With different soil conditions, different types of lugs have advantages. In loose soils having slight arch action, a solid angle iron lug is needed. When there is appreciable arch action, sharp spade lugs have an advantage as they have less resistance in entering and, due to this arch action in the soil, are able to produce the same or greater output than a solid lug. The spacing of spade lugs is dependent on the arch action of the soil, which in turn is governed by the confining and compressing action of the rim.

8."The angle of the lugs across the rim has little effect upon output.

9."The highest force ratio (efficiency) is produced with a weight carried by the wheel just sufficient to force the lug into the soil."

4."TRACTOR LUG STUDIES ON SANDY SOIL"

11--Field studies.

In the April 1927 issue of Agricultural Engineering Mr. Randolph published the results of his field tests. The primary object of these tests was to verify the laboratory findings and determine their practical value. These tests were made with McCormick-Deering and Fordson tractors using a General Motors Corp. dynamometer car. The following is a summary of data obtained in these field tests.

1."The laboratory findings previously reported were verified in the field.

6."Output varies but slightly with the width of lug.

7."With different soil conditions, different types of lugs have advantages. In loose soils having slight arch action, a solid angle iron lug is needed. When there is appreciable arch action, sharp spade lugs have an advantage as they have less resistance in entering and, due to this arch action in the soil, are able to produce the same or greater output than a solid lug. The spacing of spade lugs is dependent on the arch action of the soil, which in turn is governed by the confining and compressing action of the rim.

8."The angle of the lugs across the rim has little effect upon output.

9."The highest force ratio (efficiency) is produced with a weight carried by the wheel just sufficient to force the lug into the soil."

4."TRACTOR LUG STUDIES ON SANDY SOIL"

11--Field studies.

In the April 1927 issue of Agricultural Engineering Mr. Randolph published the results of his field tests. The primary object of these tests was to verify the laboratory findings and determine their practical value. These tests were made with McCormick-Deering and Fordson tractors using a General Motors Corp. dynamometer car. The following is a summary of data obtained in these field tests.

1."The laboratory findings previously reported were verified in the field.

2. The output-weight ratios were similar for the test wheel in the laboratory and for tractors in the field.

   (a) Weight per inch of rim width is proportional to the diameter of the wheel.

   (b) Depth of angle lugs is proportional to the square of the wheels diameter.

3. "Traction is influenced by the weight per inch of rim width, depending upon the lugs and the rim taking full benefit of the arch action of the soil.

4. "Drawbar pull, horsepower, and rolling resistance vary directly with the depth of lug.

5. "The tractors tested were found to require a wider rim or deeper lug than standard equipment to obtain their rated power in loose sand.

6. "Spade lugs are superior to angle lugs in loose sand when the wheel carries a relatively high unit weight. Easy penetrating lugs are superior on wheels that carry light loads.

7. "The proper spacings of lugs depends upon the arch action value of the soil, the laws of which have not as yet been determined.

8. "The relation of traction between two wheels can be expressed by the following formula, provided the weight per inch of rim width and the depth of lugs are in the ratios given in (2) above: $O_2 = O_1 \frac{L_2 + D_2 + W_2}{L_1 + D_1 + W_1}$ in which O is output, D is wheel diameter, L is

depth of lug, and W is weight per inch of rim width."

5."RELATION OF LUG EQUIPMENT TO TRACTION"

By R. V. Blasingame 1923

This paper is a report on work done at the Pensylvania State College. Various types of lugs were used on an I.H.C. tractor hauling various farm implements. The percent slip, speed and drawbar horsepower were observed for various farming operation. This work indicated that on level ground with clay loam sod, plowing required from 8 to 9 drawbar horsepower. Other data are given for Discing Rolling and Plowing, on other types of soil.

6."TRACTOR TRACTION"

By E. C. Sauve- 1923

This paper gives the results of some tests on an open or latticed tractor wheel. This wheel was fitted onto a Fordson tractor and tests were run on level ground, pulling a load of two plows. The percent slip of latticed wheel was 13.5% and for regular Fordson wheel 21.7 Some other tests were made on grades, in which the latticed wheel gave better results in every case than regular wheel.

7."NEBRASKA TRACTOR TESTS."

A study of the Nebraska Tractor Tests is of little value, as far as wheel equipment is concerned, as they are run on a cinder track and it cannot be said that these results will be duplicated in the field. The Force ratio, that is, drawbar pull to weight is interesting and shows a variation from 30 percent to 79 percent; it also shows that the small tractors have a higher force ratio. A comparison of the angle lug and spade lug equipment shows that the average slip of the angle to be 12.30% as against 9.90% for the spade. This seems to favor the spade lug, but it must be remembered that this is on a cinder track.

8. "TRACTOR WHEELS"

By A.W. Scarratt 1920

A summary of this article gives some conditions under which various lugs, namely pyramid, spade and angle iron cleats will operate effectively. Indications are that pyramid lugs are especially effective in sod, spade lugs for plowing, and angle cleats where soil is of light texture. The author concludes that no one type of lug is suitable for all conditions.

A review of the important literature on this subject would not be complete without the mention of the work by A. F. Moyer, Minneapolis, Minn. Mr. Moyer in his two articles "Tractor Weight and Drawbar Pull, and "Rolling Resistance of Tractor Wheels" has given a most interesting mathematical analysis of these two subjects, but too complete to be given in this paper.

A bibliography giving other references that were investigated is given on page (56) of this paper.

HISTORY OF DEVELOPMENT AT IOWA STATE COLLEGE

In line with the general interest in tractor development, the Agricultural Engineering Department of Iowa State College became interested in the development of a device to test tractor wheels, and thereby attempt to establish a relation between the various factors of traction, as applied to tractor wheels. Mr. Arthur L. Young in 1923 undertook the task of building such a machine as a thesis for the degree of Master of Science.

It was deemed advisable after careful analysis of the subject to make a testing machine that could be used in the field under actual operating conditions. It was further desired to have a machine that would measure by means of recording devices, drawbar pull, input, output, and slippage, from which efficiency might be calculated. The machine should be capable of using varying weights on the wheel and to be so constructed that the wheels might be readily removed.

With the above conditions as a start Mr. Young under the supervision of Prof. J. B. Davidson, in theory fulfilled these conditions. It was found, however, that in operation the results were not reliable because of the friction and lost motion in the apparatus itself.

In 1925 Messrs R. W. Baird and J. F. Goss rebuilt the machine preparatory to carrying on the experiments of Mr. A. L. Young. Anti-friction bearings were put in the machine for supporting the test wheel. The frame work was strengthened and a chain was substituted for the belt in the driving mechanism. With these changes practically all of the difficulties encountered in the original machine were overcome.

As it is the intent of this paper to make a thorough analysis of the work done at Iowa State College a complete description of this machine and method of making tests is given below.

Description of Testing Apparatus

The general plan of the apparatus is shown on Page (29). It consists of a tractor test wheel supported in a frame as shown. This frame is connected to a hitching point on the rear of a Heider tractor, thru an Iowa recording dynamometer. The shaft on which the drive wheel is mounted is connected to an extension of the tractor frame by means of flexible joint in the center of the large sprocket. In this manner the shaft, frame, and wheel are in reality separated from the driving mechanism, as considerable movement is allowed by these parts with respect to the rest of the apparatus. The tubular frame on which the driving mechanism is mounted is hinged at two points on the tractor and is allowed to move in a vertical arc with pivots at the two connection points but is held rigid from lateral movement. By the adoption of this method of drive no external forces are applied to the wheel except the reaction at the hitching point between frame and tractor. On the outer end of the frame carrying the driving mechanism is mounted a wheel on a sector and worm so that adjustment can be made to keep the test wheel in a horizontal position.

The frame surrounding the test wheel serves the dual pur-

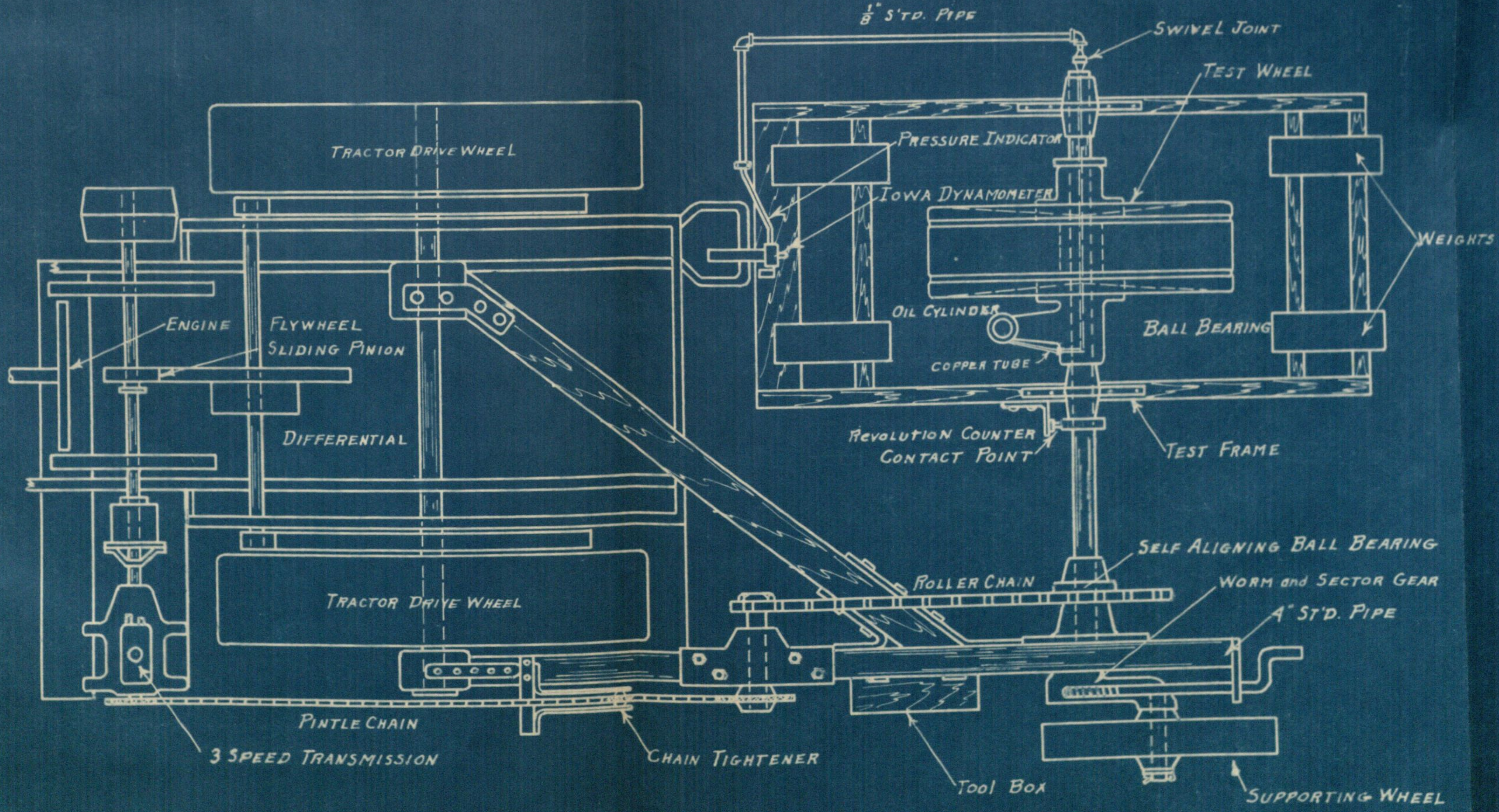


Fig.-3
TRACTOR WHEEL TESTING MACHINE
IOWA STATE COLLEGE JUNE, 1, 1927

pose of providing a hitching point between the tractor and the test wheel, and for supporting the cast iron weights by which the weight carried on the wheel is varied.

The test wheel is driven by means of chains from a power take off on the tractor. On the cross shaft of the tractor is mounted a three speed automobile transmission. Power is taken from the sprocket on the outer end of transmission and is transmitted by means of a chain and two sets of sprocket wheels to the shaft of the test wheel. The speed of the test wheel is determined by the various sized sprockets used.

The test wheel is not connected direct to the shaft on which it is mounted, but is driven by two arms as shown on page (31). One of these arms is fastened rigidly to the shaft and the other is connected to the test wheel by means of a casting bolted to the wheel flanges. This whole mechanism is mounted on ball bearings and is held in position on the shaft by means of collars. At the outer end of the driving arm which is connected to the shaft is mounted a cylinder, the axis of which is perpendicular to the shaft and aproximately one foot from the shaft. The arm connected to the wheel is curved, and allowed to enter this cylinder and press on a piston in the cylinder. The cylinder is filled with oil, and as the oil pressure builds up it causes the wheel to revolve with the shaft.

At the closed end of the cylinder a copper tube is connected and extended alongside the arm to the shaft, thence along the shaft in a keyway to a packing gland in the center of the shaft at the end. The packing gland connects with another

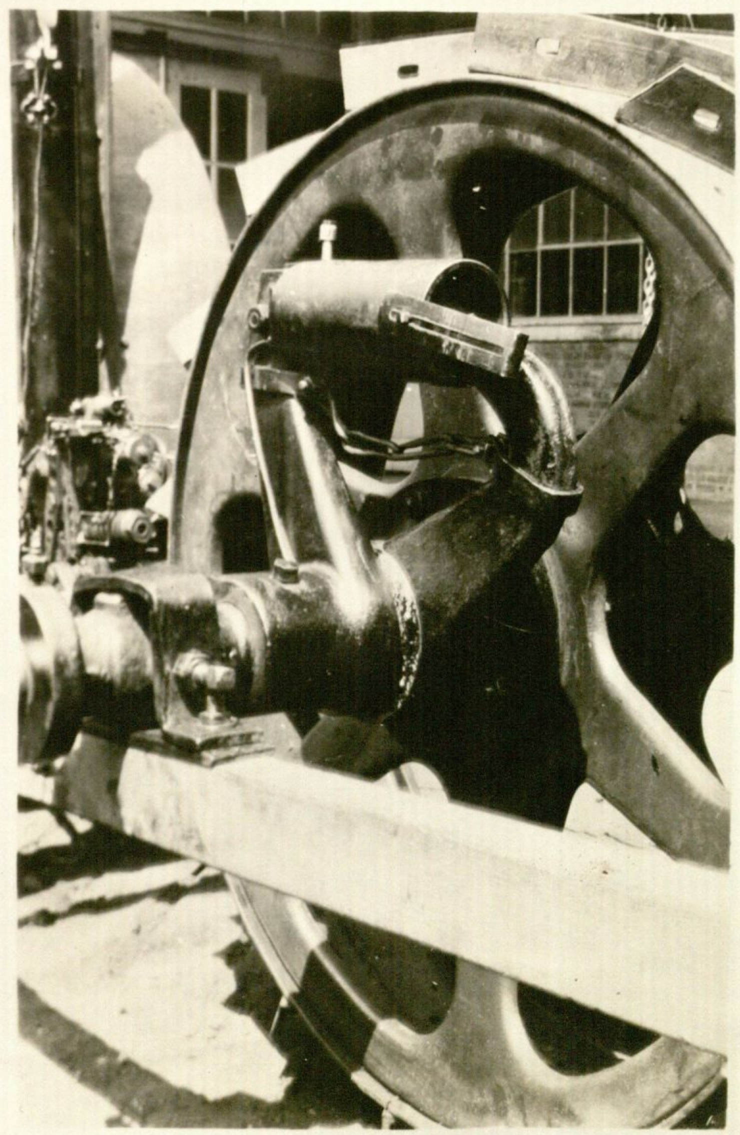


Fig.4 - Input Dynamometer

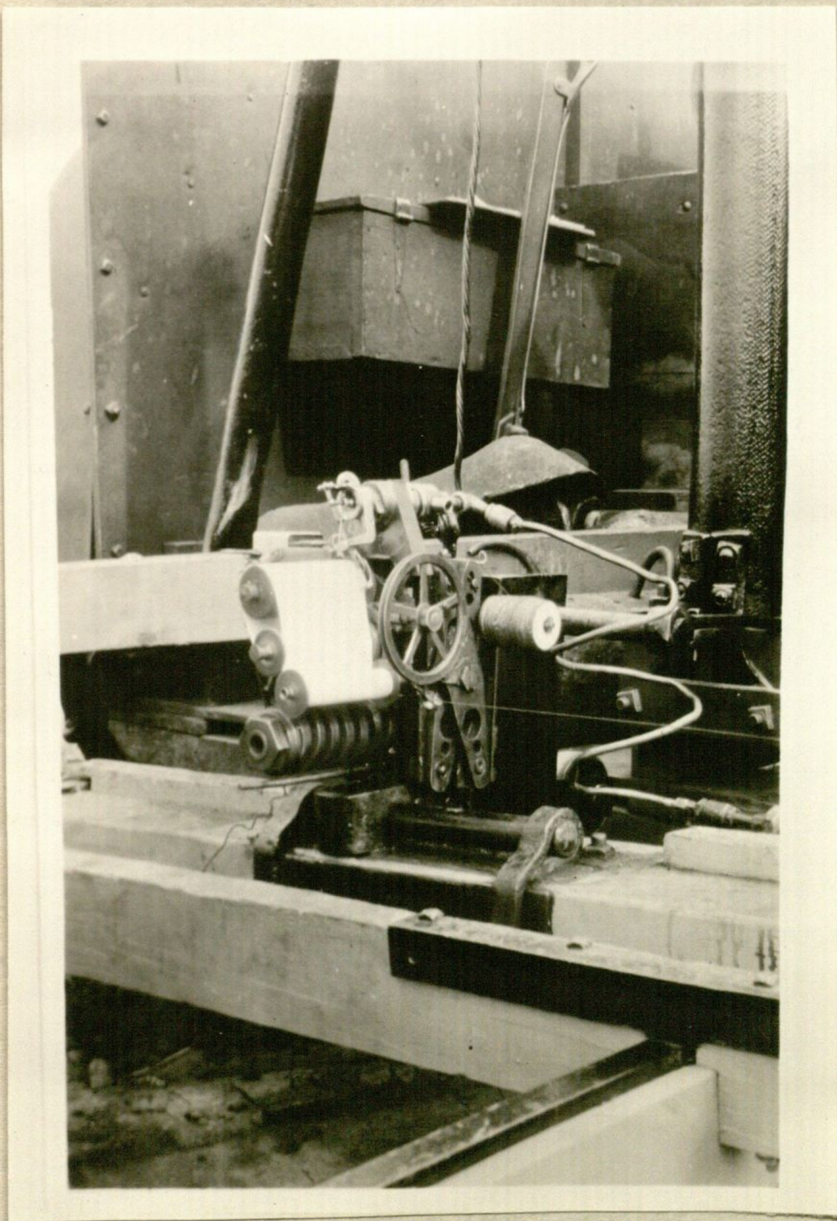


Fig. 5 - Iowa Dynamometer

the shaft and the bearings which hold the frame in place. Correction could be made for this, but the amount is so little that it is negligible.

The input to the wheel is measured by means of the oil cylinder already described and the pressure recorder on the dynamometer. The pressure recorder consists essentially of a steam engine indicator mounted on the top of the Iowa dynamometer. The pencil of the indicator is arranged so that it marks the pressure on the same paper used for the dynamometer.

In addition to the force pencil and pressure pencil a revolution counter is fitted on the indicator. This consists of an electric magnet having a pencil arm which is in contact with the paper at all times. This magnet is connected in an open circuit with batteries. The contact for closing circuit is made by a small contact point mounted on the shaft, so that at each revolution the circuit is closed and the pencil moves to the right about one-eigth inch, making an off set in the line. This mark made by the magnet pencil is so arranged that it may be used as a zero line for the pressure indicator. It is, however, more accurate to obtain the zero mark of pressure indicator from the stationary zero line of the force pencil. In operation this device gives a constant record of number of turns, drawbar pull and input to wheel. The paper is moved under the pencils by being held in contact with a cylinder which is rotated by a series of gears operated by a string passing around a pulley. The end of this string is anchored when a test is being run and unwinds from a spool around the pulley as the apparatus

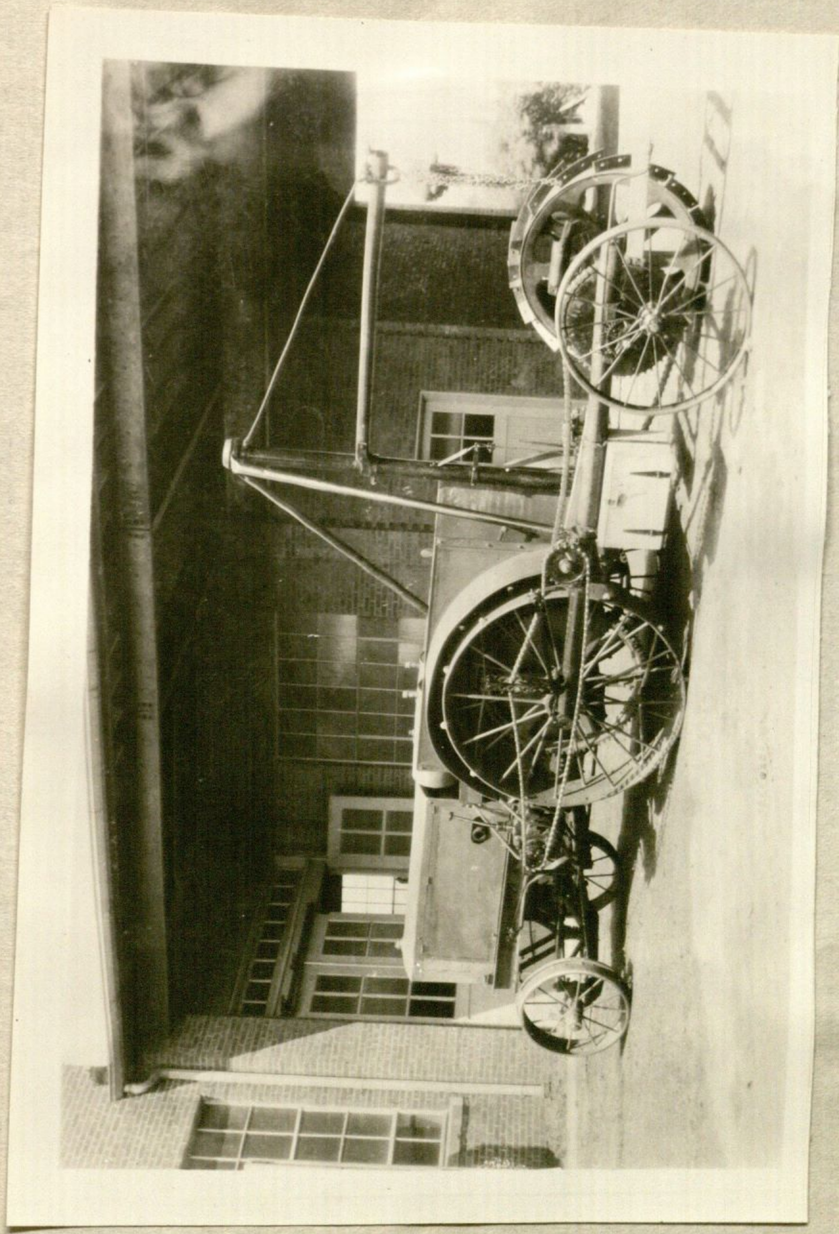


Fig. 6 - View of Testing Apparatus.

and the No. 1 sprocket (which is the sprocket for low percent slip) placed on the countershaft. The tractor is then started in reverse gear and run for three or four revolutions of the test wheel. The tractor is then stopped as quickly as possible. During the second or third revolution of the test wheel time can be taken with a stop watch by watching the revolution counter. No. 2 sprocket is then placed on the countershaft and the second test made. This is repeated using the eight sprockets. which represent 8 different different per cent of slip varying from 5 to 40 percent. The rolling resistance for the wheel is then determined by pulling the wheel about twenty or thirty feet over new ground.

The lug equipment size of wheel, width of wheel or weight on wheel may then be changed and the series of eight tests repeated with this new condition. After all the runs are made a sample of the soil should be taken and analysis made for moisture and grade.

Calculation of Recorded Data.

A short sample section of the recording tape is shown on page (39). This section is for one test. It is to be noted that the pressure pencil line is on one side of the paper and the force pencil line is on the other. In calculating the results the distance traveled in the second and third revolutions will be taken as the test. From the diagram measure the distance (d) with a scale. Determine the average ordinate of Pressure area X X'Y'Y and the average ordinate of force area a a'b'b.

Paper movement - - - - - - - (d) inches

Avg. Pressure ordinate = - - - - - - - (p) inches

Avg. Force ordinate = - - - - - - - - - -(F) inches

No of revolutions = - - - - - - - - - - -(N)

From this data the following may be calculated.

Distance traveled = (9.55)(d) = - - - - D Feet

Drawbar Pull = (F)(calibration factor) = - - F lbs.

Cylinder Press = (P)(calibration factor) = P lbs.

Input = 2 x π x length of arm x number of Revolutions x cylinder pressure

= $2 \pi L N P$

Output = (Drawbar Pull)(Distance)

= F D

Per cent of slip = $\frac{\text{(Cir. of wheel)(No of Rev)-Distance Traveled}}{\text{(Cir. of wheel)(No of Rev)}}$

This data may then be plotted as required. The curves drawn by Baird and Goss[1] were plotted with efficiency and Draw-bar pull as ordinates and percent slip as abscissa.

1. A study of Tractor Wheel Equipment. I.S.C. Library.

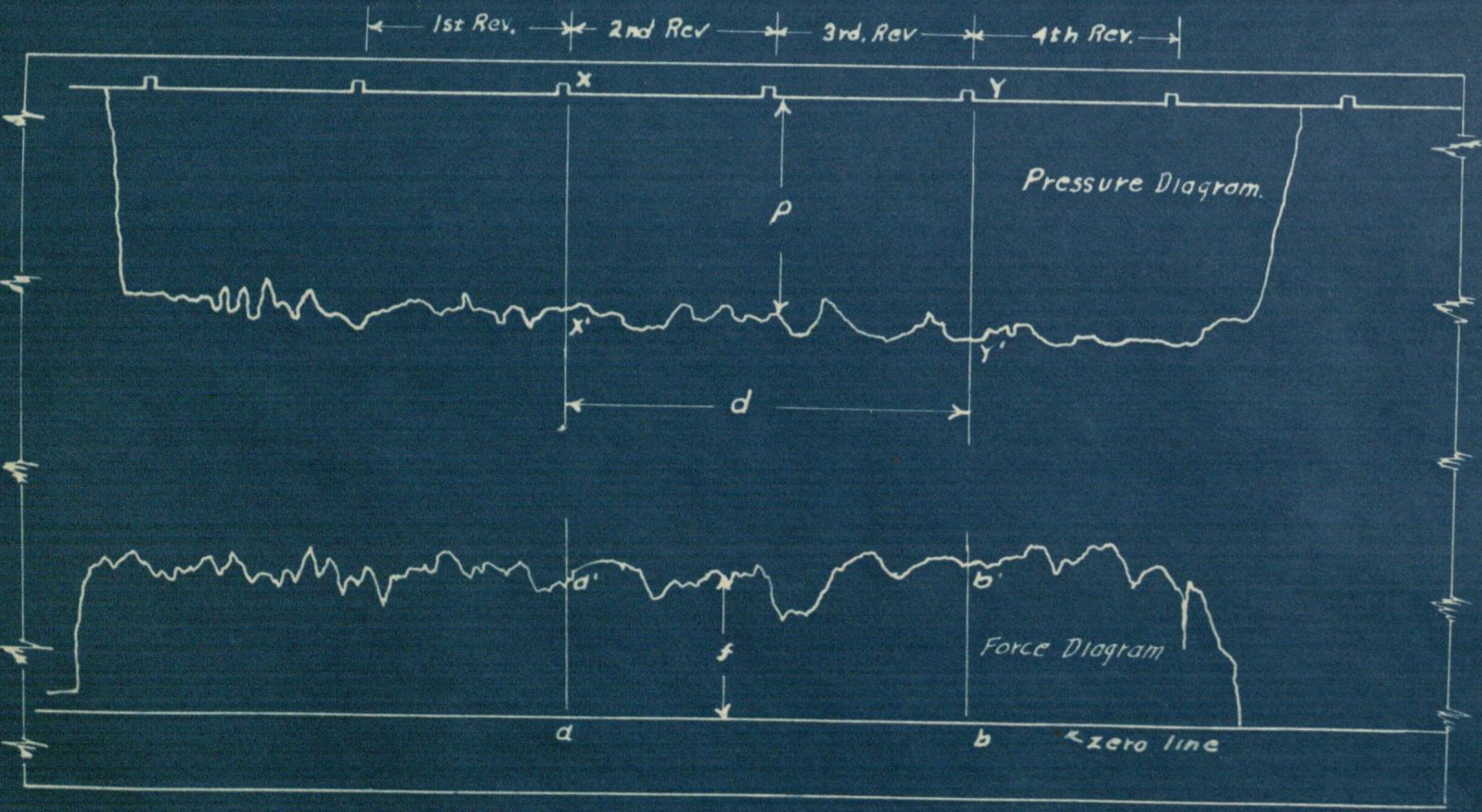


Fig.-7
Sample Section of Recording Chart

ANALYSIS OF RESULTS OBTAINED AT I.S.C.

Practically all of the results which have been obtained at Iowa State College on the subject are the results of the experiments carried on by Messers R.W. Baird and J.F. Goss. The primary intent of their experiments was to study the effect of weight on the wheel. To determine the effect of weight on drawbar pull and efficiency. The results of these tests, as set forth in the paper "A study of Tractor Wheel Equipment", seem consistant in every way and a summary of them is given below.

(1)"The efficiency of the wheel is low in all tests. It being lowest in loose soils, due to high rolling resistance, and that efficiency is lower for higher % of slip. With a given slip the efficiency is lower with high values of weight.

(2) That drawbar pull increases as slip increases, up to 40% (which was highest value of slip used) but that with sticky soil drawbar pull reduced after reaching a maximum at 15% slip. This was due to clogging of the lugs.

(3) That angle lugs and spade lugs on dry soil gave practically the same drawbar pull, but that spade lugs cleaned better and were more efficient in sticky soil.

(4) That the most efficient wheel will give high drawbar pull at low % of slip."

As a further analysis of the work accomplished to

date, the writer has plotted the curves shown on pages (43) to (52). Curves #1 to 5 inclusive are typical curves as plotted by Baird and Goss in their Thesis "A Study of Tractor wheel Equipment".
Curves #6 to # 10 inclusive are composite curves plotted from data obtained by Baird and Goss.

Curves #1 to #5 inclusive show that drawbar pull increases as slip increases but the rate of increase is greater for the heavier weight on wheel. These curves indicate that the maximum pull to be obtained is at 25% slip, however, at this point the efficiency was between 45% and 50% for all weights. It is obvious then a tractor wheel which would reach its maximum drawbar pull at say 10% slip would be an ideal wheel.

Curve #6 shows the effect of ground condition and to a limited extent moisture for a plain wheel with no lugs. It should be noted that with the weight of 660 lbs. on the wheel the maximum pull was reached at about 22% slip, and from then on the pull decreased as slip increased. Thus we would expect that the curve would return almost to zero pull at 100% slip if carried that far. It is interesting to note on these curves that with the same weight on the wheel the curves for 16.8% moisture had a greater maximum pull than for 12.8% moisture but with a low percent of slip, that is, less than 5 percent the 12.8% moisture was greater.

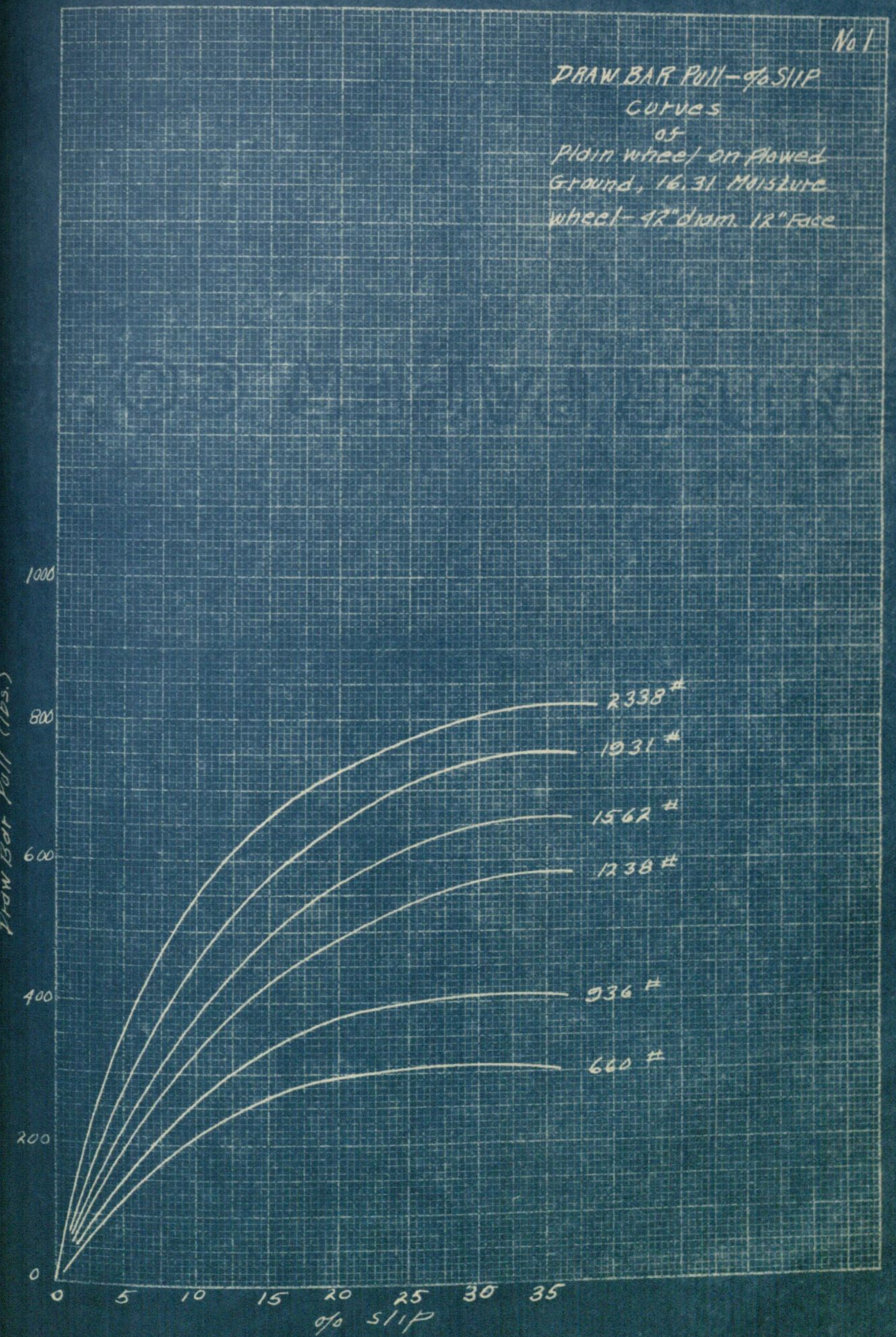
Curve #7 shows very markedly that a low percent of moisture on plowed ground is as undesireable for proper traction as too much moisture. The general trend of these tests indicate that about 14% moisture is the most efficient for tractor operation.

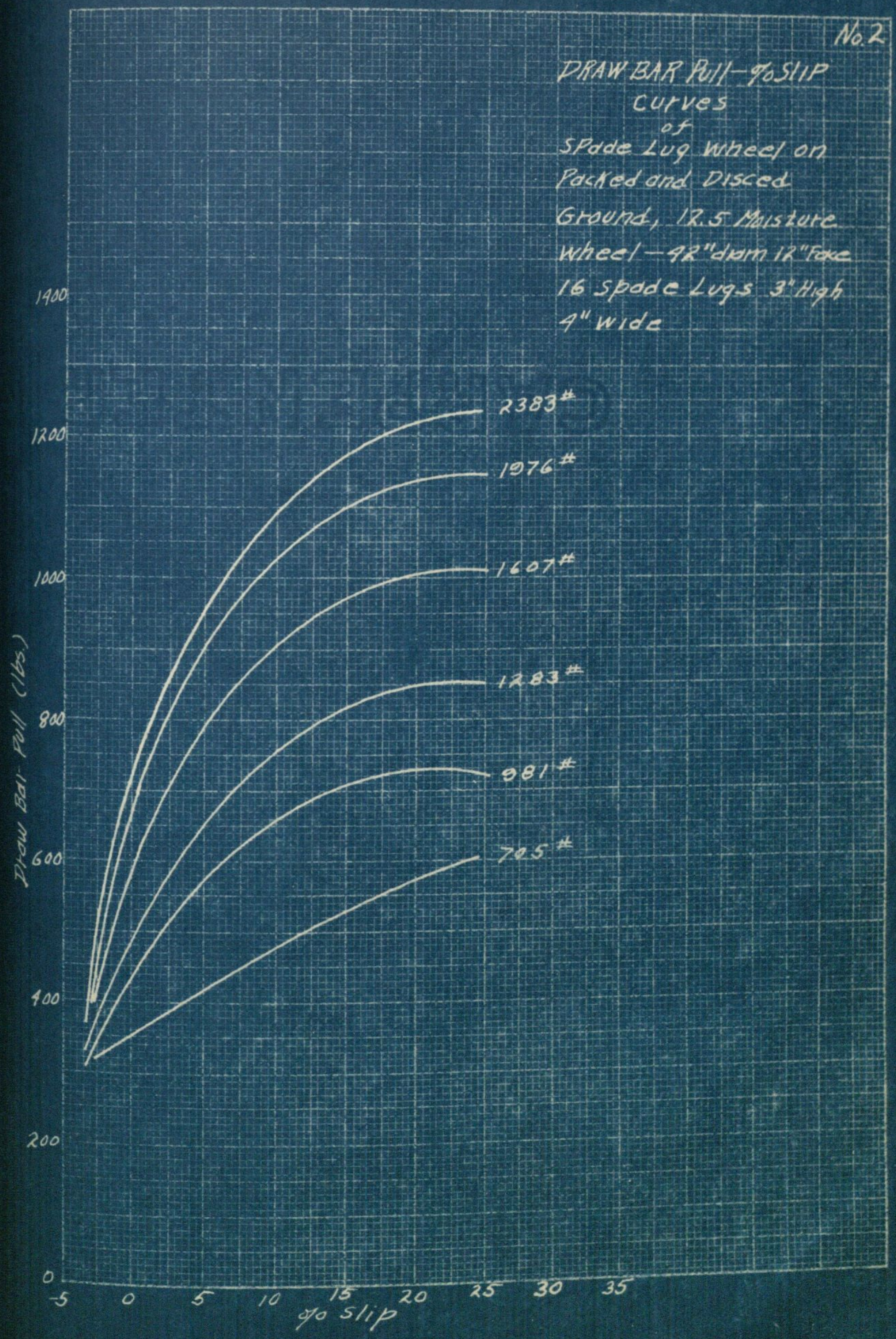
Curve #8 shows the effect of plowing and discing the ground against ground which has only been plowed. This condition is also shown by other curves plotted by Baird and Goss.

Curve #9 is a comparative curve between spade lugs and angle cleats. This curve indicates for the conditions shown that there is very little difference; however, it most be kept in mind that there were 16 angle lugs on this wheel that extended diagonally across the face of the wheel representing a projected area parallel to the axle of 499 square inches, whereas the (16) 3in. X 4in. spade lugs presented a projected area of only 182 square inches. In other words if the spade lugs were to have the same face area as the angle cleats they would have to be 10.4 inches high, or else there should be, 42 lugs instead of 16. In this case the curves might be entirely different in comparison. This point emphasises the necessity of making comparisons that are fair in all factors before arriving at conclusions.

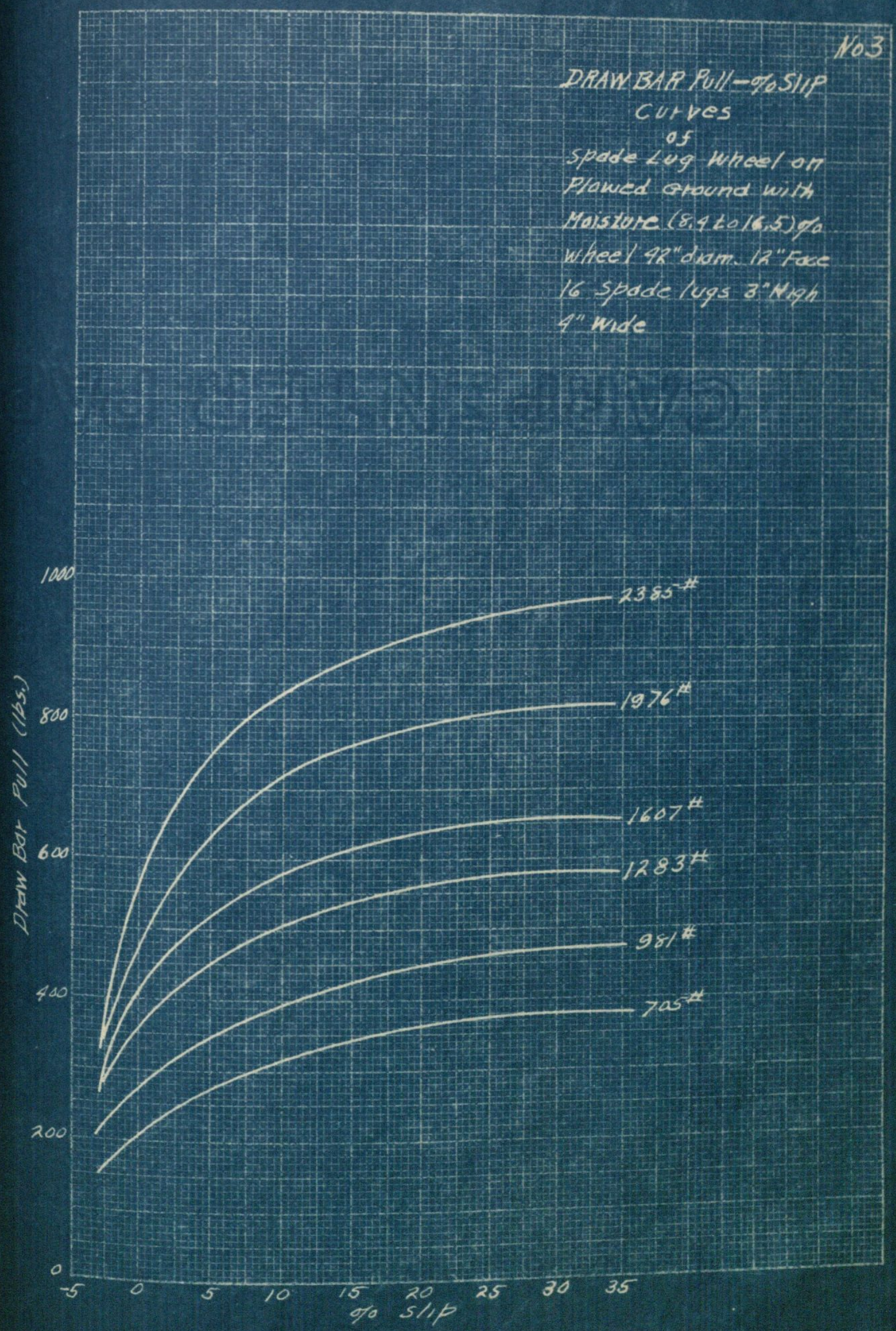
Curve #10 is plotted from different values of weight on wheel with a constant slip of 10 percent using 16 spade lugs. This shows very clearly that as weight on wheel decreased the rolling resistance becomes less important as a factor in determining drawbar pull, that is, at 700 pounds weight on wheel rolling resistance absorbs 16% of the force delivered to the ground, whereas with 2400 pounds on wheel 22% is required for rolling resistance.

Form E-5

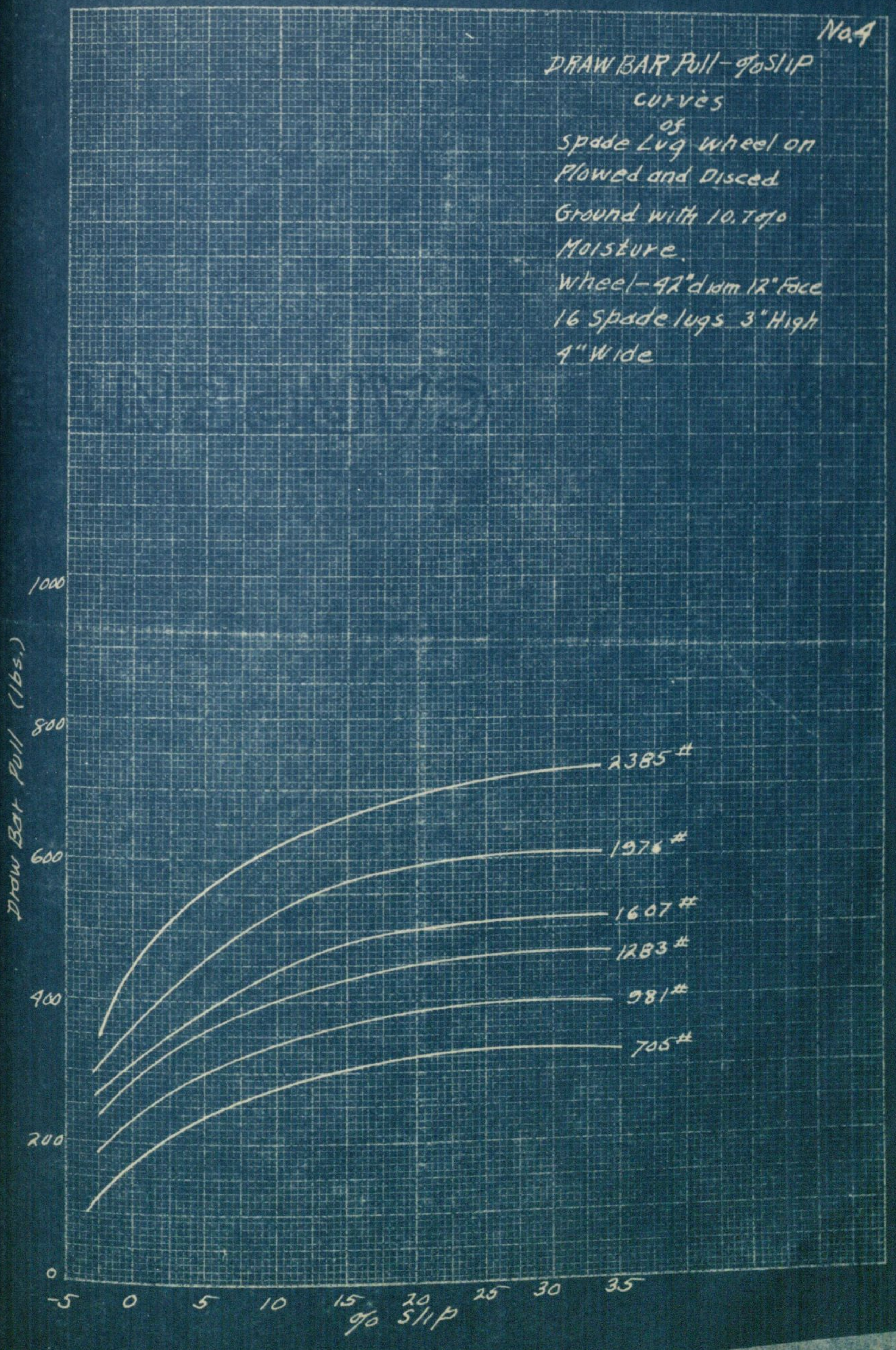

No 1
DRAW BAR Pull — % Slip
Curves
of
Plain wheel on Plowed Ground, 16.31 Moisture
wheel - 42" diam. 12" Face
2338 #
1931 #
1562 #
1238 #
936 #
660 #
Draw Bar Pull (lbs.)
0
200
400
600
800
1000
0 5 10 15 20 25 30 35
% Slip

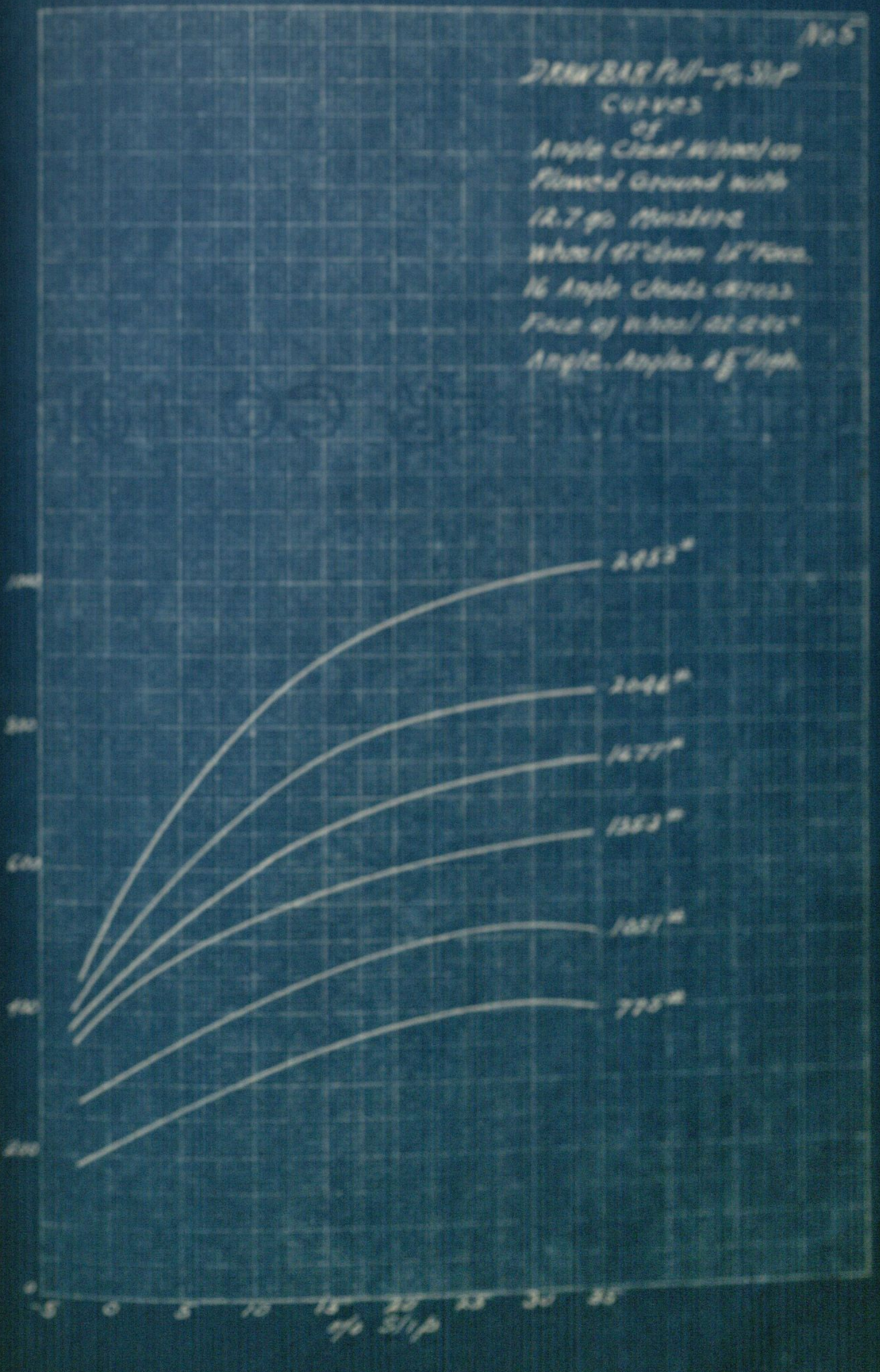

No. 2
DRAW BAR Pull – % Slip
Curves
of
Spade Lug Wheel on
Packed and Disced
Ground, 12.5 Moisture
Wheel – 42" diam 12" Face
16 Spade Lugs 3" High
4" wide
2383#
1976#
1607#
1283#
981#
705#
Draw Bar Pull (lbs.)
0
200
400
600
800
1000
1200
1400
-5
0
5
10
15
20
25
30
35
% slip

Form E-5

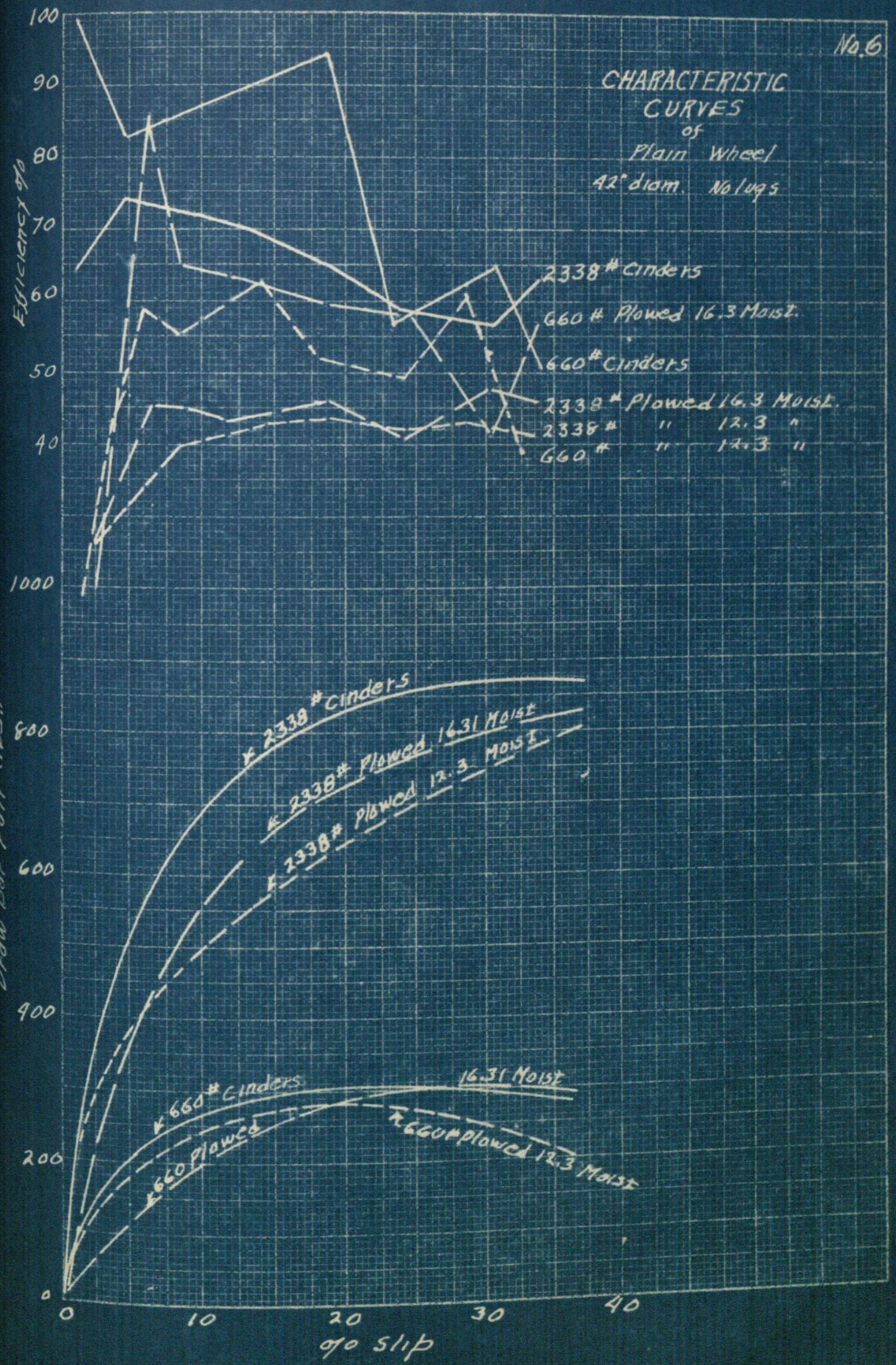

No3
DRAW BAR Pull—% Slip
Curves
of
Spade Lug Wheel on
Plowed Ground with
Moisture (8.4 to 16.5) %
Wheel 42" diam. 12" Face
16 Spade lugs 3" High
4" Wide
2385#
1976#
1607#
1283#
981#
705#
Draw Bar Pull (lbs.)
1000
800
600
400
200
0
-5
0
5
10
15
20
25
30
35
% Slip

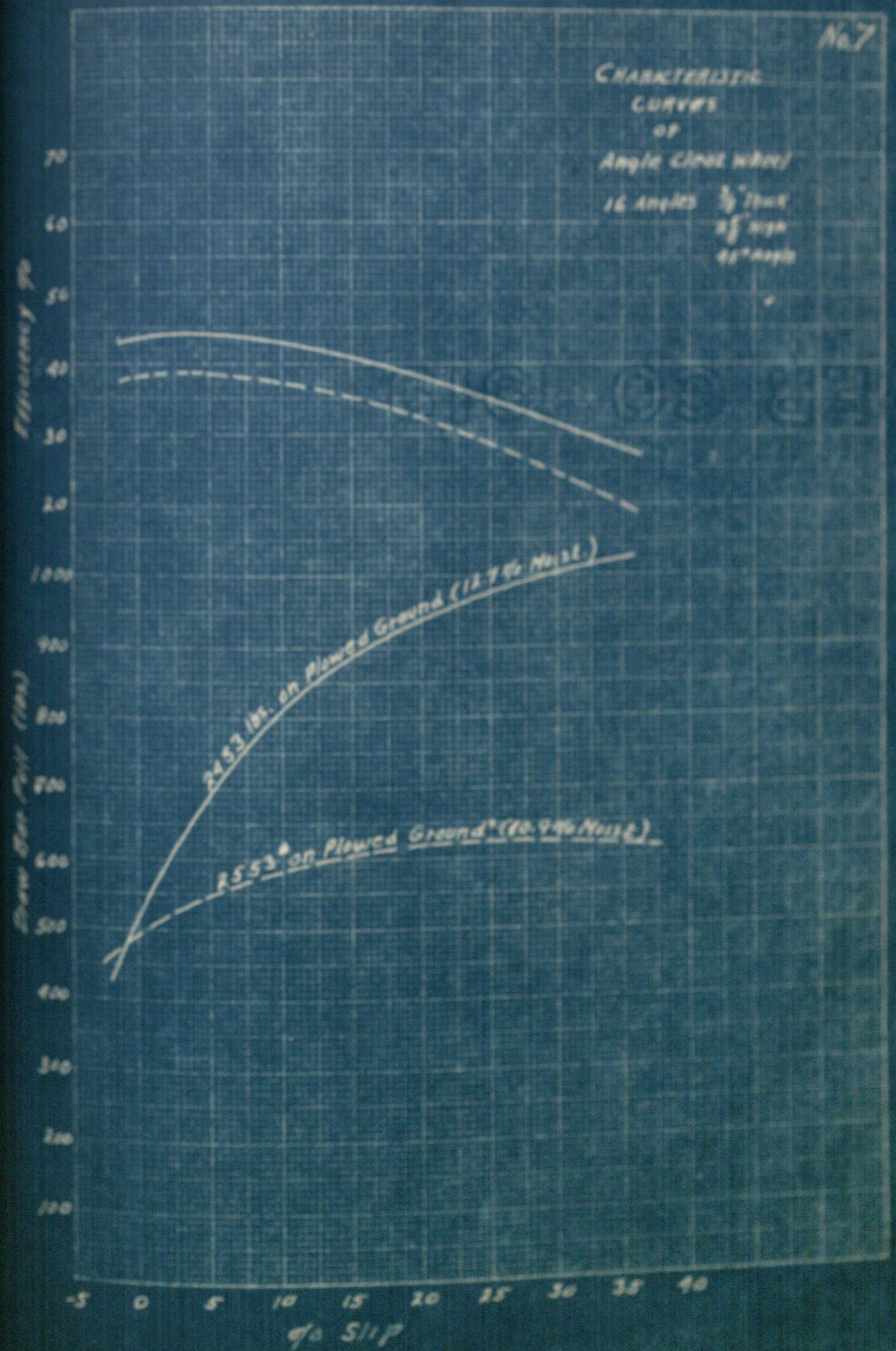
Form E-5


No. 4
DRAW BAR Pull - % Slip curves of Spade Lug wheel on Plowed and Disced Ground with 10.7% Moisture.
Wheel - 42" diam 12" Face
16 Spade lugs 3" High 4" Wide
2385#
1976#
1607#
1283#
981#
705#
Draw Bar Pull (lbs.)
1000
800
600
400
200
0
-5
0
5
10
15
20
25
30
35
% Slip

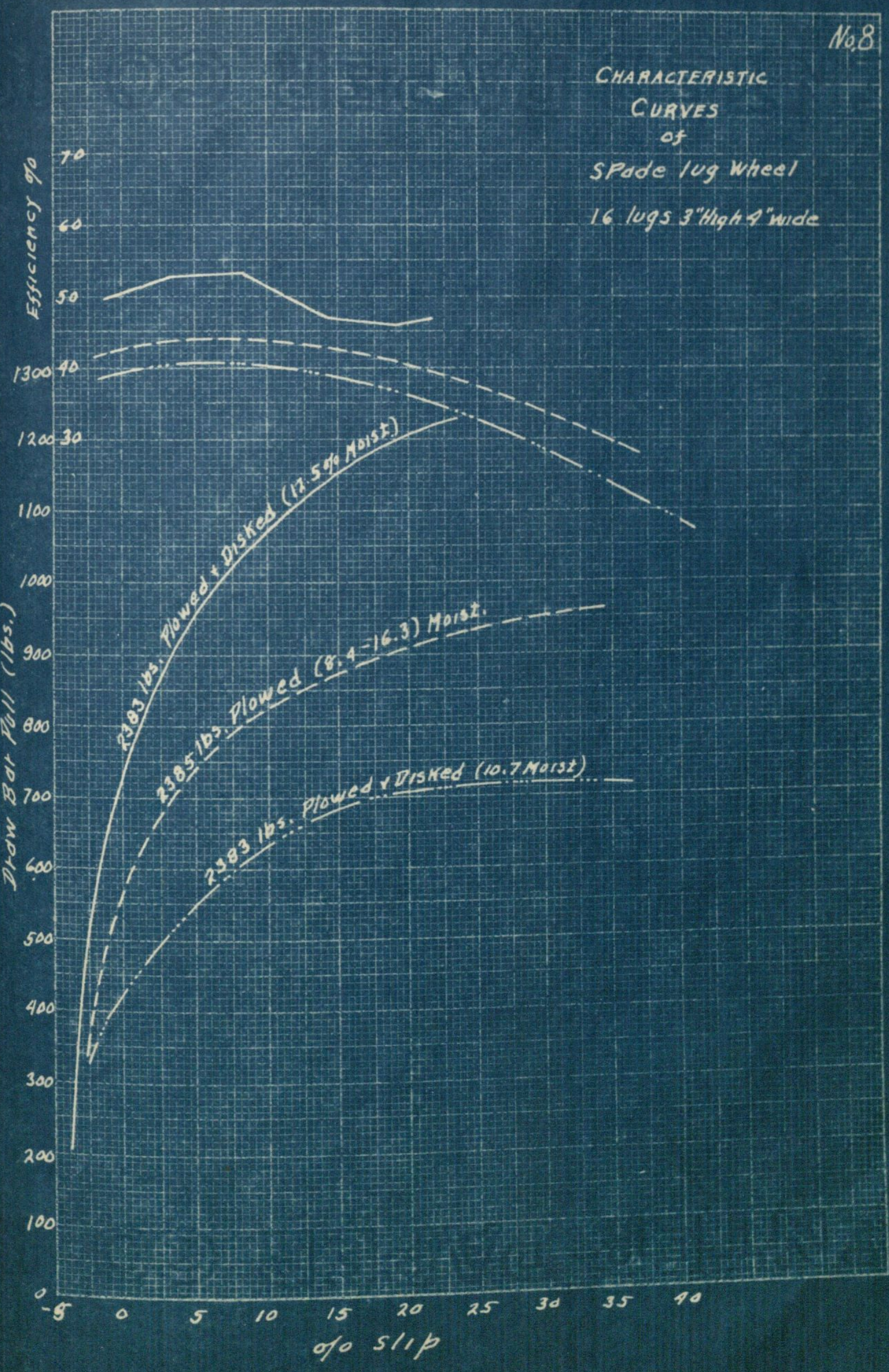

No 5
Draw Bar Pull-% Slip
Curves
of
Angle Cleat Wheel on
Plowed Ground with
12.7 % Moisture
2453#
2046#
1677#
1352#
1051#
775#
% Slip

Form E-5

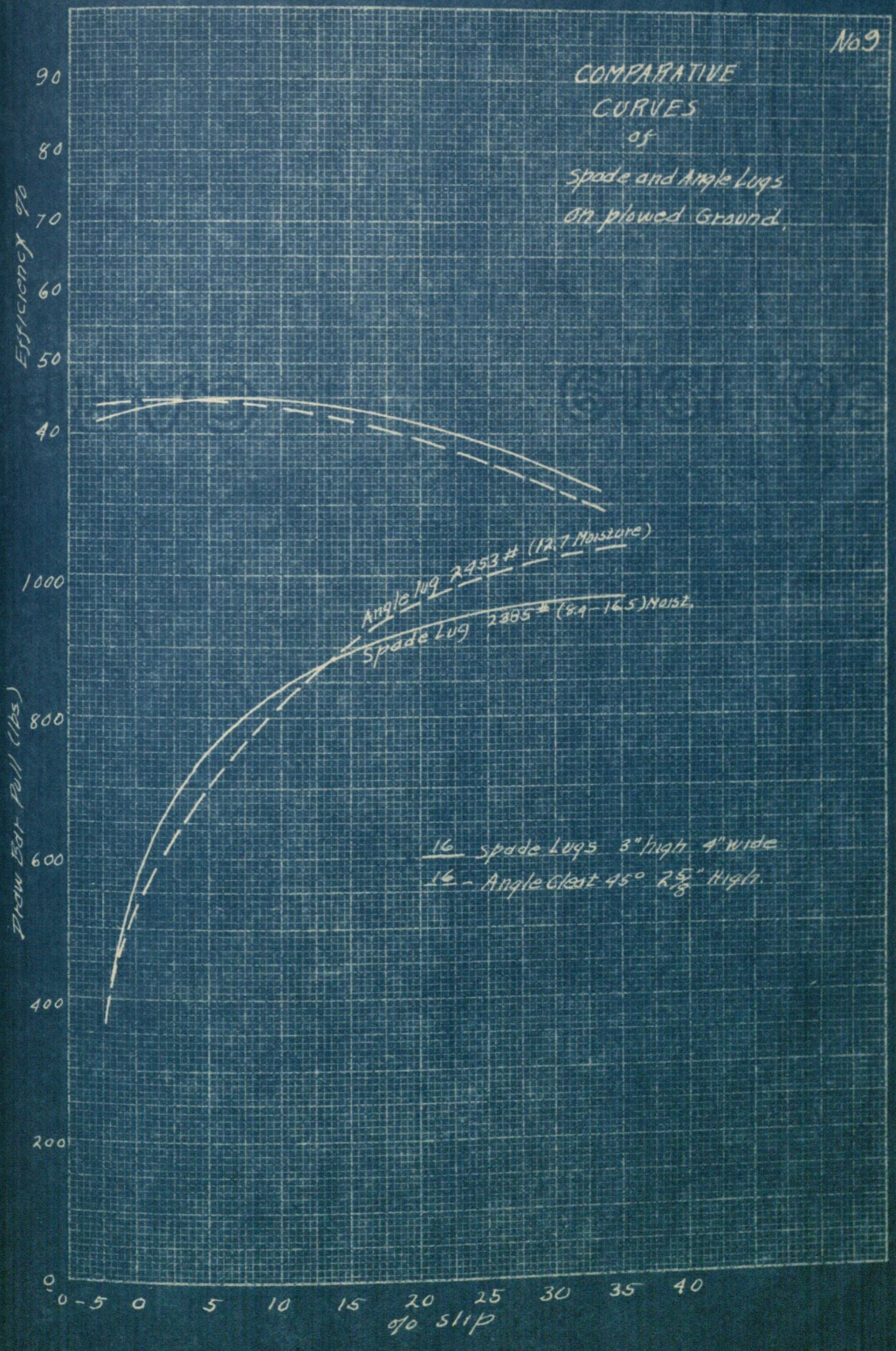

No. 6
CHARACTERISTIC CURVES of Plain Wheel 42" diam. No lugs
Efficiency %
100
90
80
70
60
50
40
2338# Cinders
660# Plowed 16.3 Moist.
660# Cinders
2338# Plowed 16.3 Moist.
2338# " 12.3 "
660# " 12.3 "
Draw Bar Pull (lbs.)
1000
800
600
400
200
0
2338# Cinders
2338# Plowed 16.31 Moist
2338# Plowed 12.3 Moist
660# Cinders
16.31 Moist
660 Plowed
660# Plowed 12.3 Moist
0
10
20
30
40
% Slip


No. 7
Characteristic Curves of Angle Cleat Wheel
16 Angles 3/8" Thick
2 5/8" High
45° Angle
Efficiency %
Draw Bar Pull (lbs.)
2453 lbs. on Plowed Ground (12.7% Moist.)
2553# on Plowed Ground (20.9% Moist.)
% Slip
70
60
50
40
30
20
1000
900
800
700
600
500
400
300
200
100
-5
0
5
10
15
20
25
30
35
40

Form E-5

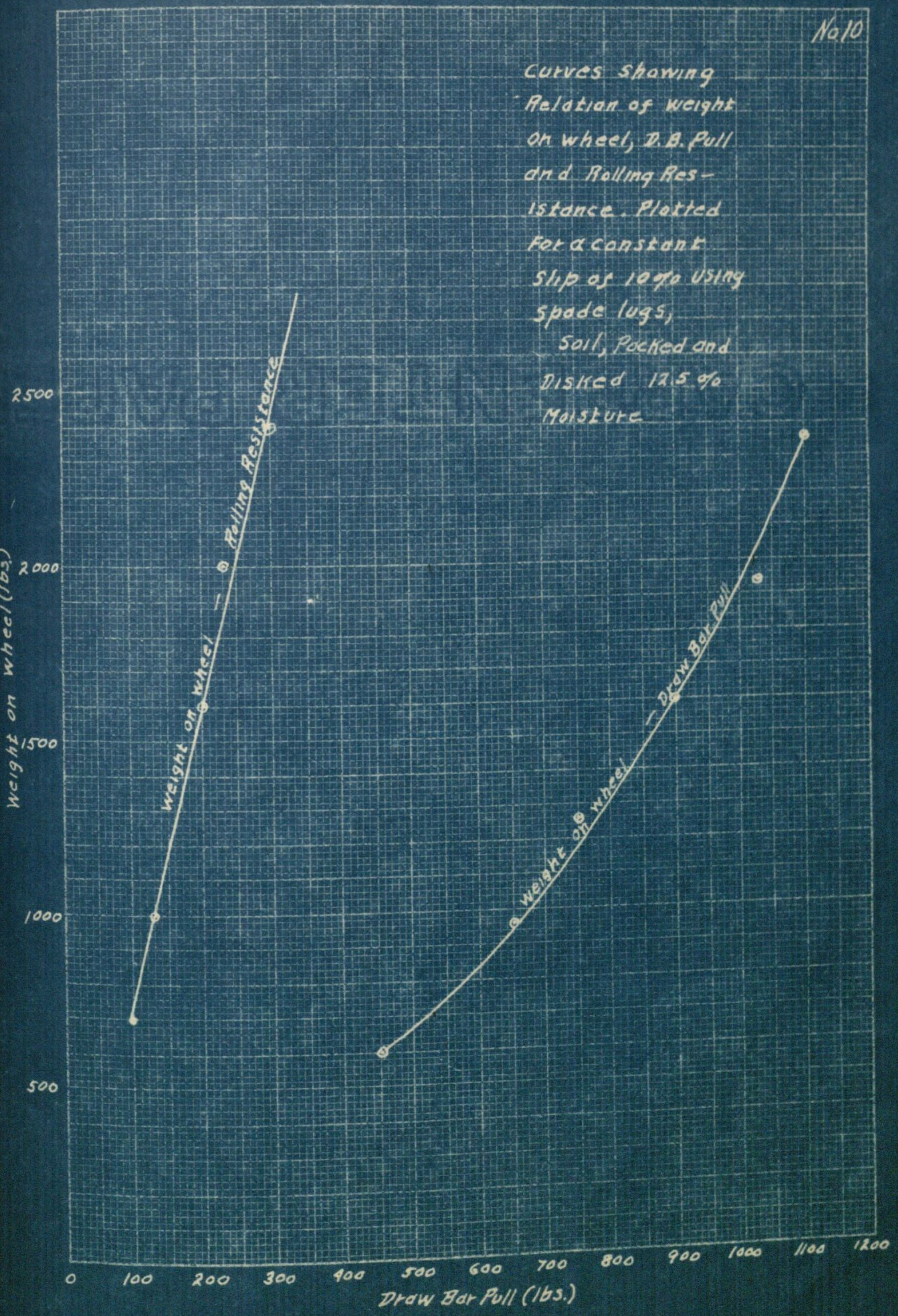

No.8
CHARACTERISTIC
CURVES
of
SPade lug Wheel
16 lugs 3" High 4" wide
Efficiency %
Draw Bar Pull (lbs.)
% slip
2383 lbs. Plowed + Disked (17.5% Moist.)
2385 lbs. Plowed (8.4-16.3) Moist.
2383 lbs. Plowed + Disked (10.7 Moist.)

Form E-5



No 9
COMPARATIVE
CURVES
of
Spade and Angle Lugs
on plowed Ground.
Efficiency %
90
80
70
60
50
40
Draw Bar Pull (lbs.)
1000
800
600
400
200
0
Angle lug 2453 # (12.7 Moisture)
Spade Lug 2385 # (8.4 - 16.5) Moist.
16 spade Lugs 3" high 4" wide
16 - Angle Cleat 45° 2 5/8" High.
-0 -5 0 5 10 15 20 25 30 35 40
% slip

Form E-5


No. 10
Curves Showing Relation of weight on wheel, D.B. Pull and Rolling Resistance. Plotted for a constant slip of 10% using spade lugs, Soil, Packed and Disked 12.5% Moisture
Weight on wheel — Rolling Resistance
Weight on wheel — Draw Bar Pull
Weight on wheel (lbs.)
2500
2000
1500
1000
500
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Draw Bar Pull (lbs.)

CONCLUSIONS

Much has been said, but little done in a scientific investigation of tractor wheel characteristics. That a great deal is yet to be learned is obvious, but the trend is in the right direction and real results may be expected. The solution of this problem has been attacked in at least three ways by different people. These three methods are (1) Operation of an actual tractor in the field (2) Laboratory work (3) Operation of a single wheel in the field. This latter method is the one adopted at Iowa State College and is, in the writers opinion, the most logical method of procedure. In the first place it gives efficiency of the wheel itself and second the testing is done under actual field conditions.

From the investigations of the writer it seems quite evident that with all things being equal the design of lugs and the number to be used is the problem yet to be solved. The writer makes the statement "Yet to be solved", simply on the fact that there exists today such a wide divergence of opinion as to proper lug design, that the truth of the statement seems self-evident. There is little agreement among tractor manufacturers as to whether a lug running across the rim of wheel is better than the non-continuous type of lug. Tractor manufacturers agree, however, "That no one type, size or shape of tractor lug is adaptable to all soils".

A general classification of lug equipment as applied to different types of soils seems to indicate that:

Sod or turf: the best lug is one that just penetrates the surface without cutting entirely thru the mass of roots.

Plowed ground dry on top, moist underneath: on this soil a long lug is required to penetrate to the moist ground where shearing resistance will be greater.

Freshly plowed, dry ground: Little is to be gained here by an extra long lug, the number will be more of a deciding factor. The continuous lug and noncontinuous lug seem to work equally well.

Loose dry Sand: In this condition the lug is of doubtful value. The best thing here is to increase width of wheel, thereby, increasing the bearing area.

Plowed ground with excessive moisture: The cleaning effect of the lugs is probably the most important in this condition, with just sufficient number to give proper traction. Too many lugs will prevent good cleaning and will be a detriment.

From the analysis of this problem as given it appears that the outstanding criterion by which tractor lugs should be judged is tractive efficiency. By tractive efficiency is meant the efficiency of the wheel to transmit the power delivered to hub into power available at the drawbar. When one considers the statement made in the introduction of this paper that only 50 to 60 per cent of the energy delivered to the average tractor wheel is available as work at the drawbar the extreme importance of tractive efficiency is realized. It is very likely true that there are times when efficiency must be sacrificed in order to get sufficient drawbar pull, but it is just as true that this sacrifice should not be made without knowing the extent of the reduction.

BIBLIOGRAPHY.

1. Hewitt, E.R. The Principles of the Farm Wheeled Tractor. Trans. Soc. Auto. Eng. 1919. Part 1, p.83-89.

2. Patch, E.S. Methods of Investigating Slippage of Traction wheels on Tractors. Trans. Amer. Soc. Agr. Eng. 1922. p.103-109.

3. Randolph, J.W. Tractor Lug Studies on Sandy Soil Agricultural Eng. Vol.7. May 1926. p-178.

4. Randolph, J.W. Tractor Lug Studies on Sandy Soil II Field Tests. Agricultural Eng. Vol.82. April 1927.

5. Blasingame, R.W. Relation of Lug Equipment to Traction Jour. Amer. Soc. Agr. Eng. 5:79-81, 1922.

6. Sauve, E.C. Tractor Traction. Mich. Agr. Exp. Sta. Quarterly Bul. Vol.5 No.3. Feb. 1923. p.135-137.

7. Scarrett, A.W. Tractor Wheels. Trans. Soc. Auto. Eng. 1920. p.732-734.

8. Moyer, E.F. Rolling Resistance of Tractor Wheels. Trans. Soc. Auto. Eng. 1918 Part I. p.405-421.

9. Moyer, A.F. Tractor Weight and Drawbar Pull. Trans. Soc. Auto. Eng. Part II. 1920. p. 726-732.

10. Collins, E.V. Apparatus for Testing Efficiency of Tractor Wheel Lugs. Trans. Amer. Soc. Agr. Eng. Vol. 19. 1925 p-221.

11. Moyer, A.F. Resistance to Rolling of Tractor in Soft Ground. Automotive Industries Vol.38. p.949-953.

12. Collins, E.V. Making Tractor Drawbar Tests Jour. Amer. Soc. Agr. Eng. Vol.2 No.1 Jan. 1921 p.19.

13. Lyon, L.T. Fippin, E.O. Buckman, H.O. Soils Their Properties and Management. The Macmillan Company, New York. p. 153-197. 1916.

14. Nohavec, F.R. Nebraska Tractor Tests. Neb. Agr. Exp. Sta. Bul. 177. 1921.

15. Brackett, E.E. Nebraska Tractor Tests. Neb. Agr. Exp. Sta. Bul. 200. 1924.

16. Sjogren, O.W. Nebraska Tractor Test Analysis. Trans. Soc. Auto. Engrs. 1923 Part I Vol. 18p.746.

17. Nichols, M.L. Methods of Studying Soil Stresses. Amer. Soc. Agr. Eng. Trans. 1925 p. 134-135.

18. Greer, E.R. Tractor Design Trans. Amer. Soc. Agr. Engr. Part II 1920 p.715-735.

19. Jandasek, Joseph. Farm Tractor Design. Automotive Industries June 12, 1919 p. 1265-1273.
June 19, 1917 p. 1406-1407.

20. Ellis, L.W. Tractive Efficiency. Vol.4 Dec. 1910 p.72.

21. Seaton, L.F. Compaction of Soil Due to Tractors. Trans. Amer. Soc. Agr. Engr. Vol. 10 No.1 Dec. 1916 p.68.

22. Zimmerman, O.B. Tractor and Plow Reactions to Various Hitches. Trans. Soc. Auto. Engr. 1922 Part I p.577-604.

23. Agg, T.R. Tractive Resistance and Related Characteristics of Roadway Surfaces. Ia. Eng. Expt. Sta. Bul. No.67 1924.

ANALYSIS OF PROBLEM

Before going further in this discussion of tractor wheels it is well to analyze the conditions that exist in tractor operation. In the first place when a wheel is rolled over a flat surface it is acted upon by a force at the point of contact called frictional resistance which is dependent on, the weight on the wheel and the surface being rolled over. This frictional resistance exerted at point of contact tends to prevent the wheel from slipping on the supporting surface. If the wheel is propelled by a force acting on its supporting shaft parallel to the surface and acting thru a bearing to the shaft as shown in Fig.(1) there is very little tendency to slip, especially if the bearing is of anti friction type. Now if the force be applied on the circumference of the wheel or shaft as shown in Fig. (2) the tendency of the wheel to slip is increased as the result of the force (P_2) acting thru the lever arm (a). The force tending to prevent slipping is the frictional resistance acting on the surface of the wheel. Now then as the wheel in Figure (1) moves forward it is acted on by a Force(F) or rolling friction which tends to prevent forward movement of the wheel. Rolling friction (or rolling resistance) is considered in application as the force required to pull the wheel over a surface. In the case of a smooth wheel being rolled over a smooth hard surface the rolling resistance is very little; however, as the surface becomes more pliable (ie capable of being molded to form) the rolling resistance