Tractive Efficiency of the Farm Tractor

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SUMMARY

1. Of the total power used in agriculture, about one-half is used for field work and one-fifth for hauling.
2. Of the total primary power used in Iowa (1930) in farm operations, tractors comprise 39.4 percent and trucks 20 percent.
3. The maximum tractive efficiency of tractors tested under various conditions varied from 40 percent for soft field conditions to 84 percent for smooth hard sod.

CONCERNING STEEL TRACTOR WHEELS

4. The rolling resistance of tractors over the tractive surfaces was the principal cause for low efficiency.
5. Lugs or grousers of excessive length used to increase adhesion on a firm surface or turf may cause considerable loss in efficiency. With a wheel tractor weighing 5,620 pounds, the power required to overcome rolling resistance at a speed of 3 miles per hour varied from 2.45 horse power with drive wheels without lugs to 6.3 horse power with drive wheels equipped with 4-inch spade lugs. Because of the lugs, rolling resistance on oat stubble did not differ greatly from that on freshly plowed land.
6. On a loose soil of uniform texture, an increase in length of spade lugs from 4 to 7 inches increasingly lowered tractive efficiency.
7. On a loose soil of uniform texture, an increase in the width of the tire by use of an extension rim gave higher tractive efficiency.
8. On soil with a loose surface, but firm subsurface, a spade lug 9 inches long reaching firm soil resulted in a slightly increased efficiency over 6 and 7-inch lugs but was less than for 4 and 5-inch lugs.
9. Five-inch angle lugs mounted on a wheel 42 inches in diameter with a rim 12-inches wide gave higher tractive efficiency than spade lugs on freshly prepared loose soil.
10. Extension angle iron lugs increased tractive efficiency on loose soil materially, about one-fifth to one-fourth.
11. Angle iron lugs extending over wheel rims were advantageous on sticky soil, because the soil did not pack in between the lugs.
12. Increasing the weight from 1,750 to 2,250 pounds on a 12 x 42-inch traction wheel equipped with spade lugs increased the drawbar pull 75 to 100 pounds at maximum efficiency. The drawbar pull was increased approximately 200 pounds when the wheel was equipped with extension rims and angle lugs.
13. Angle iron lugs gave slightly better results with a 6-inch rim extension than without on freshly prepared loose soil.

14. Open type traction wheels performed practically the same as 12-inch rim wheels with lugs on firm traction surfaces of cinders or sod. The rim did not function, as the weight was carried entirely on the lugs.

15. On loose freshly prepared soil where the space between the lugs did not fill with soil, the rim wheel gave slightly higher tractive efficiency than open wheels.

16. The tractive efficiency of steel drive wheels was progressively raised by increasing the diameter from 38 to 58 inches by 4-inch increments.

17. The effect of wheel diameter is more marked on less firm traction surfaces.

CONCERNING LOW PRESSURE PNEUMATIC TIRES

18. The rolling resistance of a wheel tractor, defined herewith as drawbar pull or its equivalent required to move the tractor over a given surface, was materially reduced by low pressure pneumatic tires for all conditions observed.

19. On a smooth hard surface the maximum tractive efficiency of a tractor equipped with pneumatic tires was 84 percent.

20. The maximum drawbar pull of a tractor equipped with low pressure pneumatic tires was materially reduced on stubble and loose soil.

21. The maximum drawbar pull of tractors equipped with low pressure pneumatic tires can be increased by additional weight, chains or lugs.

22. The maximum tractive efficiency was increased progressively with a decrease of inflation pressure from 20 to 16, 12 and 8 pounds per square inch.

CONCERNING TRACKS

23. The tractive efficiency of a track tractor as observed is not materially influenced by normal variations of traction surfaces.

24. On freshly prepared loose soil maximum tractive efficiency of a track was lowered by increasing the height of hitch.
Tractive Efficiency of the Farm Tractor

By J. BROWNLEE DAVIDSON, EDGAR V. COLLINS and EUGENE G. McKIBBEN

This publication treats specifically the application of tractor power to a towed machine or to a load pulled by a drawbar, but farm power is treated briefly in a broad way to establish relationships. The investigational work reported has been directed toward the determination of tractive efficiency, or the ratio between power delivered for useful work at the tractor drawbar and power developed by a mechanical motor under the influence of such variable factors as traction equipment (steel wheels, pneumatic tires, tracks, etc.), weight, height of hitch and traction surface. In the tests reported in this publication the power was measured as it was delivered to the traction members; and the input so obtained was not actually the power supplied by the motor (see p. 266).

THE SOURCE OF POWER USED IN AGRICULTURE

The use of power in agriculture is a very important factor in present day crop production, and the increase in the size of the power units used has brought about many important changes. The substitution of power for muscular effort has greatly changed the character of labor and largely eliminated drudgery. The application of power to farm operations in general reduces the amount of labor required for each unit of production by increasing the labor output. The remarkable influence of the application of power is indicated by a reduction to one-half, during the last 30 years, of the labor required in growing several important crops. At present the cost of power is a large item in producing most agricultural crops. Although varying widely with

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2The authors wish to acknowledge valuable assistance in apparatus construction and the testing received from the following graduate students in Agricultural Engineering at Iowa State College: Ralph W. Baird, Harold T. Barr, M. W. Bloom, J. Fletcher Goss, F. R. Jones, Garland D. Kite, H. W. LeMert, D. W. Teare, Ben G. Van Zee, Byron T. Virtue, Ira L. Williams and A. L. Young. The following organizations and firms assisted with the investigation by furnishing apparatus and equipment: Bureau of Agricultural Engineering, U. S. Department of Agriculture, J. I. Case Company, Caterpillar Tractor Company, John Deere Tractor Works, Firestone Tire and Rubber Company, Goodyear Tire and Rubber Company, International Harvester Company and Oliver Farm Equipment Company. The Caterpillar Company contributed a research fellowship for one year.
the crop and conditions, the cost of power is usually from 25 to 40 percent of the operating costs (costs exclusive of fixed charges such as a charge for the use of land) of production. Efficiency and economy in the use of power, therefore, have an important influence upon the total production cost because of their influence upon the cost of the power itself and upon the cost of labor.

The table (page 263) indicates the source of power used in agriculture in terms of primary horse power for the United States and Iowa:

**THE USE OF POWER**

The principal uses of power in agricultural operations are for field work, road hauling, farm hauling and secondary work. Of the total about one-half is used for field work and about one-fifth for hauling. Preparing the seedbed by plowing or listing consumes much of the power used for field work, or about one-third of the total power so used.

In Iowa about one-third, or 11 million acres, of the cultivated land is planted to corn, a crop requiring intertillage while growing. The introduction of the general purpose tractor, with adequate clearance for cultivating corn plants up to the time they may be "laid by," greatly extended the use of mechanical power in Iowa agriculture. As long as the conventional type of tractor prevailed, it was necessary to use animals or a special motor cultivator for cultivation; and if a tractor were used at all, it represented, in part at least, a duplication of power plants.

**SOURCES OF MECHANICAL POWER**

The principal source of mechanical power in Iowa agriculture is the gas tractor of which there were, according to the 1930 Census, 66,285 in the state. The gas engine is also used extensively in the farm truck, totalling 32,699 in the state according to the 1930 Census. Over one-half the farms are equipped with small gas engines, numbering 114,977. Electric motors at present furnish only a small part of the farm power used, and the units are usually small. The use of steam traction engines, although extensive at one time for heavy stationary work, is being gradually discontinued. It is estimated that there are at present 1,000 steam traction engines still in use, averaging about 40 horse power

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7 The zero "gas tractor" as here used includes tractors equipped with internal combustion engines burning liquid fuel.
### Table 1. Sources of Power in Agriculture

**Primary Horse Power**

<table>
<thead>
<tr>
<th></th>
<th>United States</th>
<th></th>
<th>Iowa</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Average size</td>
<td>Total</td>
<td>Number</td>
</tr>
<tr>
<td></td>
<td>of units</td>
<td>of unit</td>
<td>Primary H. P.</td>
<td>units</td>
</tr>
<tr>
<td>Horses and mules</td>
<td>18161386</td>
<td>.95</td>
<td>17171322</td>
<td>25.</td>
</tr>
<tr>
<td>Gas tractors</td>
<td>920021</td>
<td>23.9</td>
<td>22000662</td>
<td>31.3</td>
</tr>
<tr>
<td>Stationary gas engines</td>
<td>1131108</td>
<td>2.68</td>
<td>3035891</td>
<td>4.4</td>
</tr>
<tr>
<td>Trucks</td>
<td>900385</td>
<td>25.</td>
<td>22509625</td>
<td>32.</td>
</tr>
<tr>
<td>Electric motors</td>
<td>386191</td>
<td>3.58</td>
<td>1383216</td>
<td>2.</td>
</tr>
<tr>
<td>Electric light plants</td>
<td>270303</td>
<td>3.</td>
<td>810909</td>
<td>.1</td>
</tr>
<tr>
<td>Combined harvester-thresher</td>
<td>60803</td>
<td>37.2</td>
<td>2260170</td>
<td>3.3</td>
</tr>
<tr>
<td>Steam engines and windmills</td>
<td>1.9</td>
<td>1330000</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>70501795</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* Estimated 50,000 windmills 1⁄3 H.P. each and 1000 steam tractors, 40 H.P. each.

each. The steam traction engine was impractical for field work except on the firmest soil surfaces or sod. At its highest state of development it weighed about 800 pounds per drawbar horse power, while the present gas tractor weighs from one-fourth to one-half as much.9

METHODS OF APPLYING MECHANICAL POWER

BY BELT

The simplest and customary way of applying power of a mechanical motor delivered to stationary machines from a shaft rotating at a relatively high speed is by pulleys and a belt (fig. 1). Under normal conditions the efficiency of a belt transmission should be from 90 to 95 percent depending upon internal resistance and belt slippage.10 A roller or silent chain is sometimes substituted for the belt to eliminate slippage but it is limited, however, to short drives and slower speeds. It is now customary with some field machines such as the combined harvester-thresher, and in some instances with the grain binder, to drive the machine with an engine mounted on the machine which may be particularly efficient in the application of power.

BY POWER TAKE-OFF

One of the later developments in the gas tractor is the use of a shaft with universal joints and a telescoping section to connect the driven machine to a power take-off shaft extending out conveniently from the tractor (fig. 2). The efficiency of this means of applying power may be as high as 95 percent depending upon the number of bearings, the number of gear reductions used in reducing the speed and the angularity of the universal joints.11 If the shaft can be used to form a straight line, very little energy is lost in the universal joints. The standard speed adopted by the American Society of Agricultural Engineers for the power take-off is 536 revolutions per minute. The power take-off not only provides for an efficient application of mechanical power but eliminates the serious loss of power which occurs in field machines driven from a master ground wheel. In the case of the binder, therefore, two sets of gears are required to increase the speed of the master wheel to that of the pitman shaft, resulting in a serious loss due to friction. The transmission of the motor power of a tractor to a draw-

Fig. 1. Power of a tractor transmitted by a belt.

Fig. 2. Power of a tractor transmitted by power take-off drive.

Fig. 3. Power of a tractor transmitted by drawbar.
bar and, in turn, from the ground wheel of a field machine to the mechanism of the driven machine, therefore, is particularly inefficient.

**BY DRAWBAR**

For most field uses a tractor delivers the power of its motor through a drawbar and is used as a direct substitute for the animal in drawing field machines. (Fig. 3.) This bulletin deals primarily with the application of power by this means. Various factors influencing efficiency will be treated in some detail.

**OTHER MEANS OF APPLYING MECHANICAL POWER**

Some mechanical power is applied to field work by means of cables and drums driven by a motor. Application of power by this means may be very efficient; but the equipment is inconvenient and requires much labor for handling. This method is used for plowing under unusually severe conditions.

Experiments have been conducted in applying mechanical power by electric transmission and electric motors. Such use has been very limited. The principal difficulty with electric transmission is in the handling of the cables and other parts of the electric transmission equipment.

**BY AUTOMATIC MEANS**

It has been suggested that power might be applied to field work under favorable conditions by automatic equipment largely eliminating labor. Experiments at Iowa State College with an automatically controlled plow, operating back and forth across the field, guided by the previous furrow and reversed by contact with the fences, gave some promise; but it appears such development will need to wait for some time.

**TRACTIVE EFFICIENCY**

Tractive efficiency may be defined as the ratio of power delivered from the drawbar to motor power. Thus, if \( P_1 \) equals motor power and \( P_2 \) the drawbar power, tractive efficiency equals \( \frac{P_2}{P_1} \). In measuring either drawbar power or the power supplied to traction members the forces acting and the distances through which the forces act in an interval of time must be determined. If, in determining the tractive efficiency of a traction member under certain conditions influencing its performance, the interval of time for observing distances is the same for output and input, the tractive efficiency becomes a relationship between work output and input for the specified interval or time. Since work is represented by the product of force times the dis-
tance through which the force acts, a tractive efficiency test for a certain interval of time becomes a relationship between the output and input forces and the distance through which they act. In the tests reported in this bulletin power delivered to the final drive of the tractor was measured, and losses in transmission between the motor and final drive and the losses from directional control were not included. It is convenient, therefore, in making tractive efficiency tests, to resolve tractive efficiency into two factors, a force ratio and a travel ratio, the tractive efficiency being the product of the two. The force ratio, \( F_r \), is the ratio of the force, \( F_2 \), delivered to the drawbar, to the force, \( F_1 \), which would be delivered to the drawbar if there were no losses. These losses are almost entirely those required to obtain adhesion and overcome rolling resistance. Stated in terms of the symbols used, \( F_r = F_2 / F_1 \).

The travel ratio is the ratio between the distance actually traveled and the distance which would be traveled if there were no slippage. In determining force and travel ratios, it is necessary to assume some normal circumference or length of the traction member.

In most of the tests reported in the bulletin the travel ratio was determined by using the circumference at the rim of the tractor drive wheels or the actual length of tracks as the base, for determining travel ratio. By adding lugs or grouters to the wheels, the effective circumference of the wheel is increased to the point where for light drawbar pulls a travel ratio greater than one is actually obtained. The assumption of a circumference of wheel or length of track does not introduce error in the tractive efficiency obtained, for the same assumption is used in determining the force ratio. Any error in travel ratio is compensated for in the force ratio when the two are multiplied together.

If \( T_1 \) equals the circumference (of the tractor drive wheel at the rim or the length of track, as the case may be, and \( T_d \) the actual distance traveled in one revolution, then

\[
\text{travel ratio} = \frac{T_r}{T_d / T_1}
\]

Furthermore,

\[
\text{tractive efficiency} = T_e = F_r \times T_r
\]

**FACTORS INFLUENCING TRACTIVE EFFICIENCY**

Part of the motor energy of a tractor is lost in many ways in delivery to the drawbar. These losses may be classified as follows:

**Transmission Losses**

To reduce the speed of the rotating shaft of the motor to a suitable linear speed for the tractor, three speed reduc-
tions are usually required which are obtained with gears or roller chain and sprockets. Four pairs of gears are sometimes required, while the use of a worm and gear may reduce the number to two pairs. Friction in the gears and bearings causes considerable loss of energy, although hardened steel gears running in oil have a fairly high transmission efficiency. An estimate of the overall transmission efficiency, that is, the ratio of power delivered to the drive wheel to that furnished by the motor, based on data from tests of gears, indicates an efficiency between 85 and 95 percent.\textsuperscript{12}

**Rolling Resistance**

Rolling resistance, in this bulletin, is represented by drawbar pull or its equivalent required to move the tractor over a given surface. The tractor in field work passes over soft traction surfaces. (Fig. 4.) The wheels or tracks, in sustaining the weight of the tractor, sink into the surface, therefore the tractor is virtually climbing an incline as it moves forward. In addition, rolling resistance as here used includes resistance due to friction in traction members and losses incurred in obtaining adhesion. (Fig. 5.)

**Energy Loss in Obtaining Adhesion**

Tractors with steel wheels are equipped with lugs to increase the adhesion between wheels and traction surface. On soft ground surfaces, for maximum adhesion, long and

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{fig4.png}
  \caption{Rolling resistance is due to the sinking of the wheel into the surface, compelling the wheel to roll up a virtual grade (G).}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{fig5.png}
  \caption{Energy is consumed by tractor lugs in compacting and disturbing the soil in securing traction.}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{fig6.png}
  \caption{The soil disturbance may vary with the shape of the lug.}
\end{figure}

sharp lugs are desirable to penetrate well into the soil. These long lugs cause considerable energy loss due to soil disturbance. (See fig. 6 and table 4.) Tractors with smooth faced steel wheels have little loss from adhesion which, however, depends wholly upon friction between the tractor wheel and the ground. Adhesion for field conditions is inadequate. With rimless traction wheels practically all the adhesion is obtained by the penetration of the lugs into the surface and compaction of the soil back of the lugs. Desired traction or adhesion without some compression of the soil below and back of the lugs is impossible in soft soils. Where adhesion is not good, slippage or failure of the tractor to travel a distance equal to the circumference of the drivers for each revolution may occasion serious loss.

**Losses Due to Steering**

In most types of tractors some of the power of the motor is used in providing directional control or in steering the tractor. The conventional four wheel tractor with two driving wheels and two front wheels requires some energy for pushing the front wheels. A tractor should be designed so that no more weight is carried upon the front wheels than necessary, but there should be enough adhesion between the front wheels and the ground to insure directional control. With tractors having two tracks for the driving members, losses are due to friction resulting from use of brakes in obtaining directional control and side shifting of tracks over the ground surface.

**Grade Resistance**

When a tractor is called upon to travel up an incline or grade, part of the motor power must be used in lifting the tractor. (Fig. 7.) The power required for lifting the tractor is in proportion to the steepness of the grade. Thus, for all practical purposes, a tractor ascending a grade having a rise of 10 feet in 100 is exerting the equivalent of a drawbar pull amounting to 10 percent of the weight of the tractor. When descending, the tractor is assisted similarly in proportion to steepness of grade.

**Relation Between Speed and Drawbar Pull**

The power delivered to the drawbar by a tractor is represented by the product of the drawbar pull times the rate of travel. An economic problem in design is at once introduced in regard to the relationship between rate of travel and drawbar pull. Because of the lightness of the internal combustion motor, a tractor may be constructed much too light to deliver its power at a normal field speed,
Fig. 7. Grade resistance. \( r \) is rise in distance \( R \). grade \( = \frac{r}{R} \). \( W \) equals weight of tractor. \( G \) equals grade resistance \( = W \times \frac{r}{R} \) (approximately since \( ac \) is approximately equal \( ab \)).

inasmuch as weight is a factor in determining adhesion or traction. Since the cost of building tractors varies somewhat with the weight, there is an economic advantage in increasing the speed as much as practicable. The normal rate of travel for the horse in performing field work is from 2 to 2½ miles per hour, averaging around 2½ miles per hour; and formerly all field machines were designed for such speeds. Owing to economy of higher speeds, tractor field speeds have been increasing generally during the past decade, until 3 miles per hour is recognized as normal speed, and 4 miles per hour and higher are possible, particularly with pneumatic tires.

**Height of Hitch**

When a tractor is exerting drawbar pull, the front of the tractor tends to be lifted owing to the moment of the force representing drawbar pull about the contact point of the tractor drivers with the ground. This transfers some of the weight from the front wheels to the drivers in the conventional wheel tractor; while with the track tractor, it is transferred to the rear portion of the tracks. The torque required to overcome rolling resistance also shifts some of the weight from the front to the rear of the tractor. (Fig. 8.) The standard height for the drawbar has been established at 14 inches by the American Society of Agricultural Engineers and the Society of Automotive Engineers. A vertical adjustment for the drawbar is commonly provided to facilitate hitching to certain implements and to partly control shifting of weight from front wheels to rear. The drawbar must extend to the rear of the rear axle so that, in case the front end of the tractor leaves the ground, the point of hitch
is automatically lowered to prevent overturning backward. The tractor design should distribute the weight so that the tractor when exerting its maximum pull, for normal conditions will still have sufficient weight on the front wheels to insure control.

**TYPES OF TRACTORS**

**CONVENTIONAL FOUR WHEEL TRACTOR**

Most tractors now manufactured have two rear traction wheels and two front wheels. (Fig. 9.) The purposes of the front wheels are to provide directional control and to furnish a mobile self-contained unit. The power used in pushing the front wheels represents, in a sense, a loss of energy. A good design so distributes the weight between the drivers and front wheels that with the length of wheel base and height of hitch used there will be sufficient weight on the front wheels to give good control under working conditions. On some tractors independent brakes are used on the drive wheels to assist in making short turns. A modification of this type of tractor consists of placing the front wheels so close together that the machine becomes virtually or in fact a three-wheel tractor.

**TWO-TRACK TRACTOR**

Most of the track tractors depend upon the tracks for traction and directional control. (Fig. 10.) The center of gravity is set well ahead to counteract the tendency of the
Fig. 9. Conventional four-wheel tractor with two traction or drive wheels and two front wheels.

Fig. 10. Conventional track laying tractor.

front end to rise. Directional control is obtained by varying the rate of travel of one track with respect to the other. This may be obtained either by independent clutches and brakes which may be applied to the drive for each track or by brakes acting upon drums attached to either side of a conventional differential or to a special planetary type of differential.

**FRONT WHEEL DRIVE TRACTOR**

A type of design with two drive wheels placed at the front was used extensively at one time but now is confined largely to small garden tractors. (Fig. 11.) In this type of
tractor a pivoted connection to the rear truck, or the drawn implement, provides directional control. In this type of tractor the torque required to overcome rolling resistance and the moment due to the drawbar pull tend to transfer some weight of the tractor to the rear truck, reducing the weight on the drivers.

Fig. 11 Front wheel drive tractor.

FOUR WHEEL DRIVE

The four wheel drive tractor overcomes some of the losses in the conventional tractor and makes possible a higher drawbar pull for a given weight by driving the front wheels. (Fig. 12.) To give the front wheels sufficient adhesion, the weight is placed well forward. This type of tractor is particularly resourceful on soft and uneven ground surfaces because of the traction provided by the four drive wheels.

Fig. 12. Four wheel drive tractor, front wheels used for guiding.
FACTORS IN THE DESIGN OF TRACTION MEMBERS

The design of the traction wheel or other traction member should obtain the greatest possible adhesion to the traction surface and also keep the expenditure of power to the surface as low as possible. The farm tractor operates over a soft surface much of the time, and the power expended in propelling the tractor itself over these surfaces is an important consideration.

To make clear the situation under which a tractor must operate, a comparison may be made with the traction conditions of a railroad locomotive. In the latter case rolling resistance is very low on account of the steel surface. Weight, therefore, in the locomotive has a minimum influence upon the loss due to rolling resistance but is needed for obtaining adequate adhesion between drive wheels and rail. With the tractor, on the other hand, weight greatly adds to the rolling resistance; and the traction member must be designed not only to reduce rolling resistance but to increase, as much as practicable, the adhesion between the traction wheel and the ground surface.

TRACTOR DRIVE WHEEL CHARACTERISTICS

Independent of facilities for increasing adhesion, the tractor wheel has three characteristics: Weight, or force supported by ground surface under the wheel; height, or diameter; and width of rim. The friction between a plain wheel and dry traction surface, for practical purposes, varies with the weight. Ground surfaces are often wet or covered with vegetative growth which may occasion a very low coefficient of friction. At present no dependence is placed upon friction solely for adhesion. Rubber tired traction wheels give high adhesion on dry surfaces, but the tire surface in contact with the ground is roughened to increase adhesion.

DIAMETER OF THE TRACTION WHEEL

Other factors being equal, the greater the diameter of a steel traction wheel the greater will be the area of the wheel rim surface in contact with the ground and the less the depth the wheel will sink. (Fig. 13.) This reduces rolling resistance and energy loss. At one time, particularly with large tractors, drive wheels of large diameter, 8 feet or more, were commonly provided. Extremely large drive wheels have practical disadvantages, however:

1. It is more difficult to change the direction of travel.
2. The height may be an objection in orchards where the wheel must pass under trees.
Fig. 13. A wheel of large diameter supports a given load with less sinking into the surface.

3. The expense is greater because the amount of material required for adequate strength increases faster than the diameter.
4. If rubber tires are used, the increased diameter means additional expense for tires.
5. The number of gear reductions increases.
6. The tractor is less stable in passing over obstructions.

**WIDTH OF RIM**

A wide rim is effective in reducing the rolling resistance of a traction wheel over a mellow ground surface such as is found in cultivated fields. (Fig. 14.) Tractor wheels are customarily equipped with extension rims for such conditions.

Fig. 14. An increase in width of wheel rim supports a given load with less sinking to the surface.
GENERAL CONDITIONS OF TRACTION SURFACES

As it is desirable to keep the weight of the farm tractor low, much attention has been given to the wheel equipment for increasing the adhesion. In general three classes of traction surface conditions have been observed in fields as follows:

1. With a deep layer of loose soil of a uniform texture, as freshly plowed soil or sand, and a sub surface soil for a considerable depth not much firmer nor of much greater resistance to disturbance, long lugs or grouters will accomplish little unless long enough to reach the firm soil under the loose layer. Rolling resistance, however, on such a surface is high and can best be reduced by using wheels of large diameter with wide rims. Figures 31 to 35 illustrate how, under such ground conditions, maximum tractive efficiency was lowered with an increase of length of lugs until the lugs were long enough to reach firm soil, as in fig. 36. Figures 41 and 49 show that highest tractive efficiency for the ground condition described is obtained by use of extension rims.

2. With a thin upper layer of loose, pliable or crumbly soil or a layer of soft vegetation with firm soil underneath, devices on the traction wheel to penetrate through the soft surface to the firmer soil are most practicable to obtain traction. Figures 36 and 46 illustrate this principle when compared with figs. 35 and 45.

3. With sticky soil (found often at certain seasons) satisfactory wheel equipment to obtain additional adhesion must be self cleaning. Sticky soil often fills in between the conventional tractor lugs on the rim of the traction wheel forming a smooth surface.

Studies reported herewith, as well as practical observations, indicate that wheel equipment suitable for one condition of ground surface may not be satisfactory for others.

TYPES OF DEVICES FOR OBTAINING ADHESION

LUGS

Devices applied to the face of traction wheel rims to increase adhesion to the traction surface vary widely and are unstandardized as to names. Cleats, lugs, grouters, grousers, spade lugs, spikes and spuds are terms used. These devices may be described as follows: Angle lugs or cleats are blunt or sharp ribs extending across the face of the drive wheel rim. To provide a smoother riding wheel for hard surfaces, angle lugs are given a helical shape or are placed diagonally across the face of the wheel rim. With sticky soils cleats may extend beyond the rim to remove support for soil filling in between lugs. (Fig. 15.) The spade
Fig. 15. Traction wheels equipped with cleats to increase adhesion to soil. Those at A are called extension cleats and have self-cleaning characteristics.

Fig. 16. Traction wheels equipped with spade lugs.

Fig. 17. Traction wheel equipped with spikes.

Fig. 18. Traction wheel of the open type which has self-cleaning characteristics.
lug is usually a wedge-shaped device on the face of the tractor wheel rim having a length or depth as great or greater than the width, varying in length from 4 to 8 inches. (Fig. 16.) Spikes are narrow lugs used where the soil is particularly firm beneath the surface or where there is a tough turf. Spikes usually do not disturb the surface as much as spade lugs or cleats. (Fig. 17.)

OPEN WHEELS

The open wheel of which the rimless wheel is a type, is used where it is necessary to penetrate several inches to reach firm soil for adequate adhesion or to prevent packing between lugs on sticky soil. (See figs. 18 and 55.) Observations in tests reported herewith indicate considerable wasted energy in soil disturbance by the lugs and other devices used to obtain adhesion, therefore, the type of lug giving the required adhesion with the least soil disturbance should be the most efficient. Figure 6 indicates how the shape of the lug may influence the amount of soil disturbance, as the soil is compacted by the lug.

PNEUMATIC TIRES

In recent years manufacturers have made pneumatic tires for tractors which may materially reduce rolling resistance. (Figs. 19 and 59.) They may not, however, provide the adhesion of steel wheels with suitable lugs, and, therefore, with pneumatic tires, the drawbar pull for a given weight on the tractor wheel may be reduced. The cushioning effect of the pneumatic tires permits higher speeds, thus, field speeds should be modified to take advantage of their special characteristics. Tire chains and special detachable lugs may add greatly to the adhesion of pneumatic tires under wet slippery conditions.

![Fig. 19. The pneumatic tire or air wheel used on tractors.](image)

TRACKS

For many years the track has been used to reduce rolling resistance and to increase adhesion. (Figs. 20 and 29.) This type of traction member may be looked upon either as a wheel with a flat side or as a rail made up of links and supported by pads over which the tractor carriage rolls.
The track provides a large area of contact with the ground and is eminently successful on soft ground surfaces. The advantages in reducing rolling resistance and obtaining additional adhesion are in part counterbalanced by internal track friction and greater first cost and maintenance.

SPECIAL APPARATUS

In making tractive efficiency studies special apparatus has necessarily been designed and constructed. The more important pieces will be described briefly. The pieces described have usually had several preliminary designs; and the designing, construction and testing has extended over several years beginning as early as 1922.
SINGLE WHEEL TRACTION APPARATUS

This apparatus, shown in figs. 21, 22 and 23, was designed to study the traction wheel as an isolated unit and was used in tests reported in figs. 31 to 49. A tractor wheel is mounted in a frame attached to a tractor by rocker arms. The power supplied to the wheel is furnished by the motor of the tractor to which the frame is attached. The power to the wheel is transmitted from the tractor motor through a variable speed drive and a shaft with universal joint to the final chain and sprocket drive on the frame. The wheel under test cannot have a forward speed greater than the tractor to which it is attached; but by means of interchangeable sprockets, a relative rotative speed provides for a predetermined amount of slip.

The torque delivered to the wheel under test is measured by the pressure developed in a cylinder in which a piston receives the force required to turn the wheel by a torque arm. The pressure produced in the cylinder is transmitted through suitable tubing to a recording device on the tractor. The output of the wheel under test is determined by measuring the pull which tends to cause the frame in which the wheel is mounted to pull away from the tractor. A standard recording and integrating traction dynamometer was used for measuring this pull, thus it was possible to measure the input of energy to the wheel under test and the output of energy from the wheel.

It is possible in this apparatus to vary the lug equipment, predetermine the amount of slip and vary the weight on the wheel by adding suitable weights to the frame. These weights were placed on the frame at a distance from the wheel axis equal to the distance from the wheel axis to the rocker arm. Thus, one pound added to the frame adds two pounds to the wheel. It was necessary to make a correction for the torque due to application of power to the frame. This apparatus was used in the tests reported in Figs. 31 to 49.

DYNAMOMETER CAR

In making drawbar tests, some form of resistance or drawbar load which could be varied and controlled to a constant magnitude was necessary. The dynamometer car illustrated in fig. 24 furnished a constant, automatically regulated resistance or load and consisted essentially of:

1. A chassis with tracks connected by suitable transmission to a hydraulic pump.

2. A hydraulic pump to furnish extra resistance in addition to the operating resistance of the apparatus.
Fig. 22. The torque arm and pressure cylinder used for measuring the force applied to the traction wheel and the instrument for measuring and recording the draw-bar pull of the wheel. (Details of the apparatus shown in fig. 21.)

Fig. 23. Plan and elevation of the apparatus shown in figs. 21 and 22, showing arrangement of parts.
3. A hydraulic cylinder equipped with a piston to which the pull of a tractor under test is applied.

4. A small pump with an adjustable relief valve for maintaining pressure in front of the piston at such a magnitude as to furnish the desired load.

In operation the relief valve is set to maintain a pressure which, acting over the area of the piston, will give the desired drawbar pull. The piston is connected through suitable linkage to the discharge valve on the main hydraulic pump controlling the resistance furnished by the pump. The forward movement of the piston gradually opening the discharge valve of the main pump and thereby reducing its resistance, or a backward movement gradually closing the discharge valve and increasing its resistance provides an automatic regulation of total resistance of the dynamometer car. A uniform resistance can be maintained at any magnitude within the limits of the apparatus or the resistance can be regulated manually by the discharge valve of the main pump.

A large test gauge indicates the pressure within the cylinder. The pressure unit to which the drawbar pull is applied has an area of 50 square inches. If a pressure of
40 pounds, for instance, is maintained in the pressure unit by the pressure regulating valve on the discharge side of small pump, the total resistance supplied by the apparatus is 50 x 40 or 2,000 pounds. The resistance furnished by the apparatus is independent of the road surface and grade when various parts are functioning properly.

**TRACTOR DRIVE INPUT APPARATUS**

The tractor drive input apparatus measures the torque delivered to the tractor drive wheel through the final drive in a conventional tractor. The principle used is the measurement of the tension in the driving side of the final roller chain drive and is illustrated in figs. 25 and 26. By mounting an additional sprocket on a suitable arm, it is possible to determine the pull in the driving side of the chain drive. This pull is measured by means of suitable linkage with a standard integrating and recording dynamometer. No means are provided for measuring the power delivered to the front wheels, and the tests made with this input dynamometer are necessarily of the tractor and not of the independent traction wheel.
REACTION APPARATUS FOR A TRACK TRACTOR

The torque delivered to the tracks was measured by determining the reaction or lifting moment developed in the tractor by the motor while exerting drawbar pull. (Fig. 27.) A type of tractor was selected which delivered the power to the rear sprocket of the tracks through a sleeve concentric with the axis on which the tracks were pivoted.
Fig. 27. Track laying tractor equipped with apparatus for measuring the force applied to the tracks. The apparatus as shown is being calibrated. Note that the drawbar is attached to the track frames and not to the tractor chassis.

Fig. 28. Drawing of the apparatus used in the tractor shown in fig. 27 for measuring the reaction or tendency of the front end of the tractor to rise when exerting a drawbar pull.
When the motor power is delivered to the tracks through such a sprocket, there is a tendency to lift the front end of the tractor independent of the tracks. In the testing apparatus suitable linkage was placed under the front end of the motor unit to measure the weight carried on the track support while at rest and under load (Fig. 28.) The weight supported by the tracks was measured by a standard integrating dynamometer. The drawbar was attached to a suitable frame attached to the tracks in such a manner that the drawbar pull did not affect the tendency of the driving sprocket torque to lift the front end of the tractor. In computing the power applied to the tracks, a correction for the shifting of the center of gravity of the tractor unit as the front end is raised must be made. The apparatus along with the dynamometer car previously described is shown in use in fig. 29.

RESULTS OF TESTS

The results of tests reported herewith represent a summary of the investigations made to date. So many important variables are involved in traction or the application of drawbar power that any one phase of the subject well justifies extended study. No one phase of the subject has been treated adequately or exhaustively. Additional and more extensive investigations are being planned.

To eliminate the effect of grade, all tests were either run on surfaces so nearly level as not to introduce any appreciable error or were made in opposite directions over the test plots and the results averaged.
The speed in all of the tests was 3 miles per hour or less.

The results of all tests are shown graphically; however, in table 2 data are given from which the graphs shown in fig. 31 were plotted. The individual observations are given on the charts for all series of tests and should be given preference over the graphs which represent the authors' estimate of the average of the individual observations.

**EFFECT OF LENGTH OF LUG**

The tests reported in figs. 31 to 36 were conducted to determine the effect of spade lug length upon tractive efficiency of a conventional tractor wheel operated on a freshly prepared field. The tractor wheel was 42 inches in diameter and had a rim 12 inches wide. The lugs shown in fig. 30 were of the spade type, 4 inches wide and from 4 to 9 inches long. The single wheel testing apparatus previously described on page 280 and shown in figs. 21 and 22 was used. To obtain uniform ground condition, test plots were prepared with a pulverator or plow with a power driven rotor for pulverizing the soil. The moisture content of the soil in all tests furnished a good condition for tilling. It was observed in the tests that slight variations in soil conditions materially influenced drawbar pull when a definite travel ratio was maintained. A comparison of the graphs in figs. 31 to 35 indicates that maximum tractive efficiency with a load of 1,750 pounds on the wheel was reduced as the length of the lug was increased from 4 to 7 inches. When a 9 inch lug was used, the maximum efficiency was increased over the efficiency obtained with 6 and 7 inch lugs and the drawbar pull was larger (fig. 36).
Fig. 31. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4-inch spade lugs; total weight of wheel and load, 1725 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.43 at 580 pounds drawbar pull.

Fig. 32. Efficiency test of traction wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 5-inch spade lugs; total weight of wheel and load, 1750 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.43 at 510 pounds drawbar pull.
### Table 2. Log of Tests Shown in Figure 31

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<tr>
<th>No.</th>
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<th>Output Integrator</th>
<th>Percent Efficiency</th>
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</table>

**Fig. 33. Efficiency test of traction wheel. Conditions:** Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 6-inch spade lugs; total weight of wheel and load, 1740 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverizer to a depth of 8 inches; maximum efficiency, 0.41 at 560 pounds drawbar pull.
Fig. 34. Wheel equipped with sixteen 6-inch spade lugs of the type used in the tests reported in figs. 31, 32, 33, 35 (2D) and 36 (2E).

Fig. 35. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 7-inch spade lugs; total weight of wheel and load, 1750 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface conditions, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.40 at 570 pounds drawbar pull.
Fig. 36. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 9-inch spade lugs; total weight of wheel and load, 1725 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.42 at 650 pounds drawbar pull.

EFFECT OF ANGLE LUGS AND EXTENSION RIMS

In figs. 38, 40 and 41 the test wheel was equipped with angle lugs, extension lugs and angle lugs with an extension rim. The soil conditions were the same as in tests reported in figs. 31 to 36. A comparison of the results of the tests with those of former tests shows that the tractive efficiency was definitely higher.

Fig. 37. Wheel equipped with twelve angle iron lugs 5 inches high and 14 inches long as used in the tests reported in fig. 38.
Fig. 38. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 5x12 inch angle lugs; total weight of wheel and load, 1750 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.505 at 525 pounds drawbar pull.

Fig. 39. Wheel equipped with 16 angle iron lugs, 4 inches high and 22 inches long. In the tests reported in fig. 40 the extension rim shown was not used but was used in the tests reported in fig. 41.
Fig. 40. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4x22 inch angle lugs extending beyond rim; total weight of wheel and load, 1745 pounds; apparatus used, single wheel, fig. 31; soil, Carrington silt loam; soil surface, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.48 at 550 pounds drawbar pull.

Fig. 41. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4x22 inch angle lugs with 6-inch rim extension; total weight of wheel and load, 1750 pounds; apparatus used, single wheel, fig. 31; soil, Carrington silt loam; soil surface, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.52 at 525 pounds drawbar pull.
EFFECT OF ADDITIONAL WEIGHT

In the tests reported in figs. 42 to 49, the tests of figs. 31 to 41 were repeated under similar conditions except the weight on the test wheel was increased from 1,750 to 2,250 pounds. A study of the test data when shown graphically indicates that the drawbar pull was definitely increased at the point of maximum efficiency 75 to 250 pounds by adding 500 pounds. Drawbar pull at maximum efficiency, however, cannot be accurately determined, and the above data are approximate. The tractive efficiency was not materially affected by adding weight.

Fig. 42. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4-inch spade lugs; total weight of wheel and load, 2250 pounds; apparatus used single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.42 at 600 pounds drawbar pull.
Fig. 43. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 5-inch spade lugs; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to depth of 8 inches; maximum efficiency, 0.42 at 650 pounds drawbar pull.

Fig. 44. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 6-inch spade lugs; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to depth of 8 inches; maximum efficiency, 0.38 at 675 pounds drawbar pull.
Fig. 45. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 7-inch spade lugs; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.37 at 725 pounds drawbar pull.

Fig. 46. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 9-inch spade lugs; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.41 at 775 pounds drawbar pull.
Fig. 47. Tractive efficiency of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 5-inch angle lugs; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 8 inches; maximum efficiency, 0.48 at 775 pounds drawbar pull.

Fig. 48. Tractive efficiency of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4x22 inch angle lugs extending over rim; total weight of wheel and load, 2250 pounds; soil, Carrington silt loam; soil surface condition, freshly prepared with pulverator to a depth of 3 inches maximum efficiency, 0.47 at 700 pounds drawbar pull.
Fig. 49. Tractive efficiency of tractor wheel. Conditions: Diameter of wheel, 42 inches; width of rim, 12 inches; wheel equipment, 12, 4x22 inch angle lugs with 6-inch extension rim; total weight of wheel and load, 2250 pounds; apparatus used, single wheel, fig. 21; soil Carrington silt loam; soil surface condition, freshly prepared with pulverator to depth of 8 inches; maximum efficiency, 0.48 at 725 pounds drawbar pull.

Fig. 50. Tractor drive wheel equipped with 5-inch spade lugs as used in tests reported in figs. 44, 45 and 46. In tests reported in fig. 47, the lugs were removed.
EFFECT OF TRACTION SURFACE

The effect of condition of ground or traction surface upon tractive efficiency was determined in tests reported in figs. 51, 52, 53 and 54. The apparatus used for measuring the energy input, figs. 25 and 26, consisted of a dynamometer applied to the final drive to the tractor. The output was measured by the dynamometer car shown in fig. 24. The traction surfaces were well packed cinders, blue grass sod, loose mellow soil freshly prepared with a pulverator and bare concrete pavement. Tractive efficiency obtained for firmer tractive surfaces was materially greater than for mellow field. The drawbar pull for the concrete floor was low. On the bluegrass sod the tractor motor was stalled with an increase in drawbar pull before the traction wheels slipped appreciably.

Fig. 51. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 46 inches; width of rim, 11¼ inches; wheel equipment, 24, 5-inch lugs (each wheel); total weight of wheel and load, 1555 pounds (each wheel); apparatus used, dynamometer attached final drive figs. 25 and 26; traction surface, cinders packed.
Fig. 52. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 46 inches; width of rim, 12½ inches; wheel equipment, 24, 5-inch lugs (each wheel); total weight of wheel and load, 1555 pounds (each wheel); apparatus used, dynamometer attached final drive figs. 25 and 26; traction surface, bluegrass sod.

Fig. 53. Same as above except traction surface.
Fig. 54. Efficiency test of tractor wheel. Conditions: Diameter of wheel, 46 inches; width of rim, 11 1/4 inches; wheel equipment, smooth rims; total weight of wheel and load, 1550 pounds (each wheel); apparatus used, dynamometer attached final drive, figs. 25 and 26; traction surface, concrete floor.

TESTS OF RIMLESS WHEEL

Tests reported in figs. 56, 57 and 58 were of a rimless wheel. The traction surfaces were the same as tests of figs. 51, 52 and 53, or, on well packed cinders, bluegrass sod and soil freshly prepared with a pulverator. The adhesion of the tractor wheel to the surface of bluegrass sod was sufficient to stall the tractor motor. Note that the tractive efficiencies obtained with the rimless wheel differ little from those of a conventional wheel and spade lugs.
Fig. 55. Tractor drive wheels equipped with a rimless wheel as used in tests reported in figs. 49, 50 and 51.

Fig. 56. Efficiency tests of tractor wheel. Conditions: Type of wheel, rimless, see fig. 55; diameter of wheel, 45 inches, wheel equipment, 20 spade lugs; total weight of wheel and load, 1550 pounds (each wheel); apparatus used, dynamometer attached to final drive, figs. 25 and 26; traction surface, cinders well packed.
Fig. 57. Efficiency tests of tractor wheel. Conditions: Type of wheel, rimless; diameter of wheel, 46 inches; wheel equipment, 20 spade lugs; total weight of wheel and load, 1550 pounds (each wheel); apparatus used, dynamometer attached to final drive, figs. 25 and 26; traction surface, bluegrass sod.

Fig. 58. Same as above except traction surface.
TESTS OF A TRACTOR EQUIPPED WITH PNEUMATIC TIRES

Figures 59 and 60 show a tractor equipped with 28 by 12.75-inch pneumatic tires for test under the same traction conditions reported by figs. 51 to 54 and figs. 56, 57 and 58. Tests reported in figs. 61, 63, 65 and 67 were made without chains on the tires, and tests reported in figs. 62, 64 and 66 were made with chains. The high tractive efficiency may be credited to reduced rolling resistance afforded by pneumatic tires. On firmer traction surfaces, much energy is evidently consumed by the lugs disturbing the surface. Chains on pneumatic tires very effectively increase adhesion on slippery surfaces, but on dry surfaces rolling resistance slightly increases.

Figures 68 and 69 report the effect of varying inflation pressure from 8 to 20 lbs. The lower pressure gives a decidedly higher tractive efficiency on a field prepared with the pulverator.

Figure 70 shows the effect on tractive efficiency of adding weight to a tractor with pneumatic tires. The tests indicated that the drawbar pull is materially increased; part of the increase is no doubt due to the shifting of weight to the drive wheels due to the increase in drawbar pull.

Fig. 59. Tractor equipped with 12.75X pneumatic tires as used in tests reported in figs. 53, 56, 58, 60, 61, 62 and 63.
Fig. 60. Tractor equipped with pneumatic tires as in fig. 52 but equipped with chains and used in tests reported in figs. 55, 57 and 59.

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Fig. 61. Efficiency test of tractor wheel. Conditions: Wheel equipment, 28 by 12.75 inch pneumatic tire; weight of wheel and load, 1518 pounds; inflation pressure, 12 pounds; apparatus used, dynamometer attached to final drive, figs. 25 and 26; traction surface, cinders well packed; maximum efficiency, 0.73 at 600 (1200 total) pounds drawbar pull.
Fig. 62. Conditions same as in fig. 61 except chains attached.

Fig. 63. Conditions same as fig. 61 except traction surface.

Graphs showing tractive efficiency, force ratio, and travel ratio as a function of drawbar load. Conditions, type of wheel, and traction surface are specified for each graph.
Fig. 64. Conditions same as in fig. 63 except chains attached.

Fig. 65. Conditions same as in fig. 61 except traction surface.
Fig. 66. Conditions same as in fig. 65 except chains attached.

Fig. 67. Conditions same as in fig. 61 except traction surface.
Fig. 68. Efficiency test of tractor wheel. Conditions: Wheel equipment, 28 by 12.75 inch pneumatic tire; weight of wheel and load, 1518 pounds (one wheel); inflation, 8 and 12 pounds; apparatus used, dynamometer attached to final drive, figs. 25 and 26; traction surface, silty loam soil, freshly prepared with pulverator 6½ inches in depth; maximum efficiency, 0.57 for 8 pounds inflation and 0.54 for 12 pounds.

Fig. 69. Efficiency tests of tractor wheels. Conditions: Wheel equipment, 28 by 12.75 inch pneumatic tire; weight of wheel and load, 1518 pounds (one wheel); inflation, 16 and 20 pounds; apparatus used, dynamometer attached to final drive, figs. 25 and 26; traction surface, silty loam soil, freshly prepared with pulverator 6½ inches in depth; maximum efficiency, 0.52 for 16 pounds inflation and 0.44 for 20 pounds.
INFLUENCE OF THE DIAMETER OF TRACTOR DRIVE WHEEL

A series of tests, fig. 73 to 90, were conducted on three traction surfaces to determine the influence of the diameter of tractor drive wheels upon tractive efficiency under uniform conditions except for tractive surfaces, as follows:

Apparatus used: The tractor equipped with apparatus for measuring the power delivered the final drive, fig. 25, was used for making the tests. The front wheels were equipped with 7.5 by 18-inch pneumatic tires. The weight on the front wheels at rest was 1,730 pounds; and on the rear wheels, 3,890 pounds including operator. These were maintained uniformly throughout the tests by adding or removing additional weights for individual tests. The dynamometer car in fig. 24 provided the drawbar load.

Test wheels: Six sets were used ranging by 4-inch increments from 38 to 58 inches in diameter. (See fig. 72.)

Wheel equipment: Four-inch spade lugs equally spaced were used on all wheels. The dimensions and lug spacing are given in table 3.

Drawbar: A special adjustable drawbar adjusted to a uniform height of 9 inches above the traction surface was used.
TABLE 3. WHEEL DIMENSIONS AND LUG EQUIPMENT

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<thead>
<tr>
<th>Diameter inches</th>
<th>Width Inches</th>
<th>Tread inches</th>
<th>Lugs Number</th>
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* Center to center of lugs in same row measured along rim.
** Center to center.
*** Nominal width 12 inches; actual width in parenthesis.

Fig. 71. Tractor of fig. 25 equipped with 58 inch wheels used in tests to determine influence of wheel diameter on tractive efficiency.

Traction surfaces: Tests were made on a silty clay loam under as uniform conditions as possible. Soil moisture was determined to check soil conditions. Tests were made under three soil conditions, namely: (1) oat stubble prepared with the pulverator to a depth of 8 inches, (2) oat stubble and (3) bluegrass sod.
Fig. 72. Wheels used in tests to determine the influence of wheel diameter. These wheels are 38, 42, 46, 50, 54 and 58 inches in diameter with 12-inch rims and equipped with 20, 22, 24, 26, 28 and 30 4-inch spade lugs, respectively.

Fig. 73. Efficiency of 38-inch tractor wheel on soil prepared with pulverizer. See p. 310 for conditions.
Travel ratio and force ratios: These factors were calculated on the basis of effective rolling diameter of each wheel for each soil condition as determined by rolling the wheel over the surface under no load and observing the distance traveled per revolution. This distance varied with the surface firmness.

Rolling Resistance

Rolling resistance or drawbar pull required to move the tractor was determined for soil prepared with the pulverator and oat stubble under the same conditions as for the tests reported in figs. 73 to 84.
The rolling resistance recorded in table 4 makes it possible to calculate the power required to move the tractor over the two ground surfaces. This was found to be from 2.45 to 6.3 horse power at 3 miles per hour. The above observations are the averages of four trials each. Variations in soil conditions were charged with the irregularities.

With bare wheels rolling resistance is markedly reduced on oat stubble compared with pulverated soil. When lugs are used, however, differences are slight and, with one exception, favor the softer ground surface. More power is required to force the lugs into the hard surface and remove them than into the softer surface.
Fig. 76. Efficiency of 50-inch tractor wheel on soil prepared with pulverator. See p. 310 for conditions.

<table>
<thead>
<tr>
<th>Wheel diameter (inches)</th>
<th>Pulverated soil</th>
<th>Oat stubble</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare wheels</td>
<td>4-inch lugs</td>
</tr>
<tr>
<td>38</td>
<td>655</td>
<td>739</td>
</tr>
<tr>
<td>42</td>
<td>610</td>
<td>734</td>
</tr>
<tr>
<td>46</td>
<td>615</td>
<td>690</td>
</tr>
<tr>
<td>50</td>
<td>585</td>
<td>658</td>
</tr>
<tr>
<td>54</td>
<td>528</td>
<td>642</td>
</tr>
<tr>
<td>58</td>
<td>561</td>
<td>628</td>
</tr>
</tbody>
</table>
Fig. 77. Efficiency of 54-inch tractor wheel on soil prepared with pulverator. See p. 310 for conditions.
Fig. 78. Efficiency of 58-inch tractor wheel on soil prepared with pulverator. See p. 310 for conditions.
Fig. 79. Efficiency of 38 inch tractor wheel on oat stubble. See p. 310 for conditions.
Fig. 80. Efficiency of 42-inch tractor wheel on oat stubble. See p. 310 for conditions.
Fig. 81. Efficiency of 46-inch tractor wheel on oat stubble. See p. 310 for conditions.
Fig. 82. Efficiency of 50-inch tractor wheel on oat stubble. See p. 319 for conditions.
Fig. 83. Efficiency of 54-inch tractor wheel on oat stubble. See p. 310 for conditions.
Fig. 84. Efficiency of 58-inch tractor wheel on oat stubble. See p. 319 for conditions.
Fig. 85. Efficiency of 38-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
Fig. 86. Efficiency of 42-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
Fig. 87. Efficiency of 46-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
Fig. 88. Efficiency of 50-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
Fig. 89. Efficiency of 54-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
Fig. 90. Efficiency of 58-inch tractor wheel on bluegrass sod. See p. 310 for conditions.
TESTS OF A TRACK TRACTOR

The main purpose of tests reported in figs. 91 to 95 was to determine tractive efficiency of a track-laying tractor on three conditions of traction surfaces, but additional tests were made to determine the influence of the height of hitch on tractive efficiency.

The tractor: The tractor shown in figs. 27, 28 and 29, used in the tests has been selected because of construction features partially described on p. 284. Partial specifications of the tractor are given in table 5.

The tractor was equipped with tracks that had been well worked in.

Drawbar: A special adjustable drawbar was bolted directly to the track members permitting the engine and transmission assembly to pivot freely about the center line of the drive sprockets. The points of attachment to the drawbar were 8, 12, 16 and 20 inches above a concrete floor and 233/4 inches to the rear of the center line of the sprockets.

An inclinometer was devised to measure the angle of rise of the tractor frame with the horizontal. Track slip was determined by comparing the distance the tractor traveled per revolution of track with the length of the track.

Traction surfaces: The tractor was tested under three traction surface conditions, namely: well-packed cinders, bluegrass sod and fallow silty loam soil freshly prepared with a pulverator to a depth of 8 inches. The moisture content of the last traction surface gave a good tillable condition.

Tests to determine the effect of height of hitch: Height of hitch had a pronounced influence upon tractive efficiency on soft ground surfaces. With a high hitch and heavy drawbar pull, the tractor was inclined backward so the tracks did not have full contact with the traction surfaces. To determine more accurately the effect of height of hitch on tractive efficiency, a series of tests, reported in figs. 94 and 95, were made on ground freshly prepared with a pulverator.
### TABLE 5. SPECIFICATIONS OF TRACK TRACTOR

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rated drawbar H. P.</td>
<td>20</td>
</tr>
<tr>
<td>Rated brake H. P.</td>
<td>25</td>
</tr>
<tr>
<td>Rated drawbar pull, pounds</td>
<td></td>
</tr>
<tr>
<td>first speed</td>
<td>4180</td>
</tr>
<tr>
<td>second speed</td>
<td>2900</td>
</tr>
<tr>
<td>third speed</td>
<td>2070</td>
</tr>
<tr>
<td>Speed in miles per hour</td>
<td></td>
</tr>
<tr>
<td>first</td>
<td>1.8</td>
</tr>
<tr>
<td>second</td>
<td>2.6</td>
</tr>
<tr>
<td>third</td>
<td>3.6</td>
</tr>
<tr>
<td>Tracks</td>
<td></td>
</tr>
<tr>
<td>links per track</td>
<td>29</td>
</tr>
<tr>
<td>link pitch inches</td>
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<tr>
<td>track length feet</td>
<td>16.275</td>
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<tr>
<td>track shoe width inches</td>
<td>11.1</td>
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<tr>
<td>lug length inches</td>
<td>1.9</td>
</tr>
<tr>
<td>area ground contact in square</td>
<td>2151</td>
</tr>
<tr>
<td>center to center of tractor inches</td>
<td>42</td>
</tr>
<tr>
<td>weight as tested</td>
<td>7700</td>
</tr>
</tbody>
</table>

**Fig. 91. Efficiency of track laying tractor. Conditions: Traction equipment, track; width of tracks, 11 inches; weight on tracks 7700 pounds; traction surface, cinders, well packed; maximum efficiency, 0.78 at 3400 pounds drawbar pull.**
Fig. 92. Efficiency of track laying tractor. Conditions: Traction equipment, track; width of tracks, 11 inches; weight on tracks, 7700 pounds; traction surface, bluegrass sod; maximum efficiency, 0.79 at 4000 pounds drawbar pull.

Fig. 93. Efficiency of track laying tractor. Conditions: Traction equipment, track; width of tracks, 11 inches; weight on tracks, 7700 pounds; traction surface, silty loam soil, freshly prepared with pulverator; maximum efficiency, 0.74 at 3700 pounds drawbar pull.
Fig. 94. Efficiency of track-laying tractor with varying height of hitch. Conditions: Traction equipment, track; width of tracks, 11 inches; weight on tracks, 7700 pounds; traction surface, silty loam soil, freshly prepared with pulverator; maximum efficiency, 0.77 at 3800 pounds drawbar pull for 8-inch height of hitch and 0.74 at 3700 pounds drawbar pull for 12-inch height of hitch.

Fig. 95. Efficiency of track-laying tractor with varying height of hitch. Conditions: Traction equipment, track; width of tracks, 11 inches; weight on tracks, 7700 pounds; traction surface, silty loam soil, freshly prepared with pulverator; maximum efficiency, 0.73 at 3600 pounds drawbar pull for 16-inch height of hitch and 0.70 at 3500 pounds for 20-inch height of hitch.