TECHNICAL NOTE 21.
SOIL, DRAFT, AND TRACTION

21.0 BACKGROUND

The knowledge of soil, draft, and traction is very important in tillage. Unfortunately few soil science texts cover these subjects in a practical, integrated manner. In this technical note we shall examine these subjects, their practical significance to tillage, and to the power requirement in farming.

In simple terms, tillage involves the movement of soil from one place to another. The aim of tillage in agriculture is to improve soil physical conditions for seed germination and crop growth. In conventional plow-tillage farming, tillage may consume a major portion of the farm's energy budget. The *effectiveness* of tillage largely depends on the forward speed of the implement and the power unit used to pull it through the soil. Table 1 shows typical ground speeds for some common tillage tools.

Table 1.

Tillage Tool	Field Speed, mph	
	Range	Typical
Moldboard plow	3.0-5.5	4.5
Tandem disk, breaking	3.5-6.0	4.5
Tandem disk, harrowing	4.5-7.0	6.0
Chisel plow	4.0-6.5	6.0
Subsoiler	4.0-5.5	4.5
Spring-tooth harrow	5.0-8.0	7.0
Field cultivator	6.0-8.0	7.0
Rotary hoe	8.0-14.0	12.0
Row crop cultivator	3.0-7.0	5.0
Cultipacker	4.5-7.5	6.0
Rotary tiller	1.0-4.5	3.0

Source: *John Deere Service Publ. (1991)*

Data in Table 1 shows that optimum field speed varies according to the type of tillage being done. For example, lower ground speeds are typical of primary tillage tools such as moldboard plows and heavy disks. Higher ground speeds are required for harrows and cultivators that pulverize the soil and produce a finer tilth, and for mechanical weed control.

The power required to pull a tillage tool through the soil at a given ground speed depends on the: (1) *draft* of the tool, and (2) *traction* developed by the power unit. We'll consider these two factors separately, but the reader should keep in mind that they are related, each being greatly influenced by soil characteristics.

21.1 DRAFT

The force required to pull a tillage tool through the soil is called its ***draft***. The draft ***force*** is located at the point where the tool is attached to the power unit, called the ***hitch***. The power unit is usually a ***tractor,*** a name coined from the more ponderous word *traction engine* that translates the power developed by the internal combustion engine into forward motion (this definition is also applied to draft animals, such as oxen and horses). The direction of the draft force is in the direction of travel and the units to measure it are pounds force (lbf, English units) or kilo Newtons (kN, metric units). When using physical terms such as power, force, and work, we should understand that these words have different meanings, but are related to one another.

A *force* may be understood as the action of one body upon another that tends to produce motion, changes the rate of motion, or changes the direction of motion. A familiar example is gravity: it's the influence of earth, a body, upon another body that produces motion. A feather floats to earth under the influence of gravity and its motion is directed toward the earth's center. The rate of motion depends on the object's ***mass*** and its acceleration through a gravitational field, such as earth's atmosphere. The equation for force, or motion, is given by:

$$\text{Force (F)} = \text{mass (m)} \times \text{acceleration (a)}$$

where ***m*** is equal to the mass (not weight!) of an object in kilograms (kg), and ***a*** is equal to the acceleration of a body in units of meters (distance) per second squared (m/s^2). When a body is under the influence of earth's gravitational field, the term ***a*** becomes ***g*** which at sea level is considered to be 9.807 m/s^2, the term ***F*** becomes equal to the body's ***weight*** which is nothing more than the *force* on an object in a gravitational field. When we multiply **m** x **a** the units become kilograms per meter per second squared ($kg/m/s^2$). Since 1 Newton = 1 $kg/m/s^2$, we end up with the same units used to express draft force (1 kilo Newton = 1000 Newtons).

Work is defined as the *action* of a force through a distance, without regard to time (Figure 1). Work may be calculated by multiplying the force times the distance through which the force acts, or:

$$\text{Work} = \text{force} \times \text{distance}$$

For example, if a load requires 20 pounds of force to move it vertically a distance of three feet, the amount of work done is 20 pounds x 3 feet, or 60 foot- pounds (ft-lb, English units), or 81.4 joules (metric units).

Power is defined as the *rate* of doing work. This definition introduces the element of time and implies that a certain amount of work is being done in a given unit of time. The U.S. customary power unit is ***horsepower*** and is defined as 550 foot-pounds of work per second. The metric power unit is measured in kilowatts (kW).

$$\text{One horsepower} = \frac{33{,}000\,\mathit{foot-pounds}}{60\ \mathit{seconds}}$$

$$= 550\,\mathit{foot-pounds\ per\ second}$$

For example, if a 1,000 pound force (weight) is moved 33 feet in one minute, the rate of doing work is one horsepower, or 0.746 kilowatts (Figure 2).

In an engine, burning fuel inside the cylinder creates power. The force that is generated moves a piston up and down creating a twisting effort, or ***torque***, on the crankshaft. Each up and down cycle, or revolution, is repeated many times in one minute and so the amount of power developed at the ***flywheel*** can be calculated as follows:

$$\text{Engine horsepower (hp)} = \frac{\mathit{rpm\ x\ torque}}{252} \quad \frac{(\mathit{force\ x\ distance})}{(\mathit{a\ constant})}$$

$$\text{Engine power (kW)} = \frac{\mathit{rpm\ x\ torque}}{9549} \quad \frac{(\mathit{force\ x\ distance})}{(\mathit{a\ constant})}$$

where '*rpm'* is the number of *revolutions per minute*.

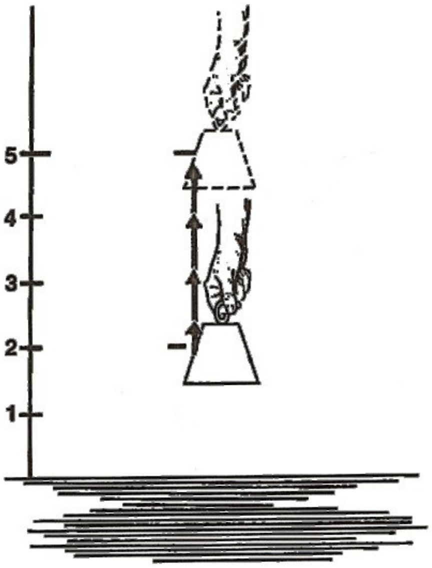


Figure 1. Work equals force x distance without a time factor. Source: *Finner and Straub, 1985.*

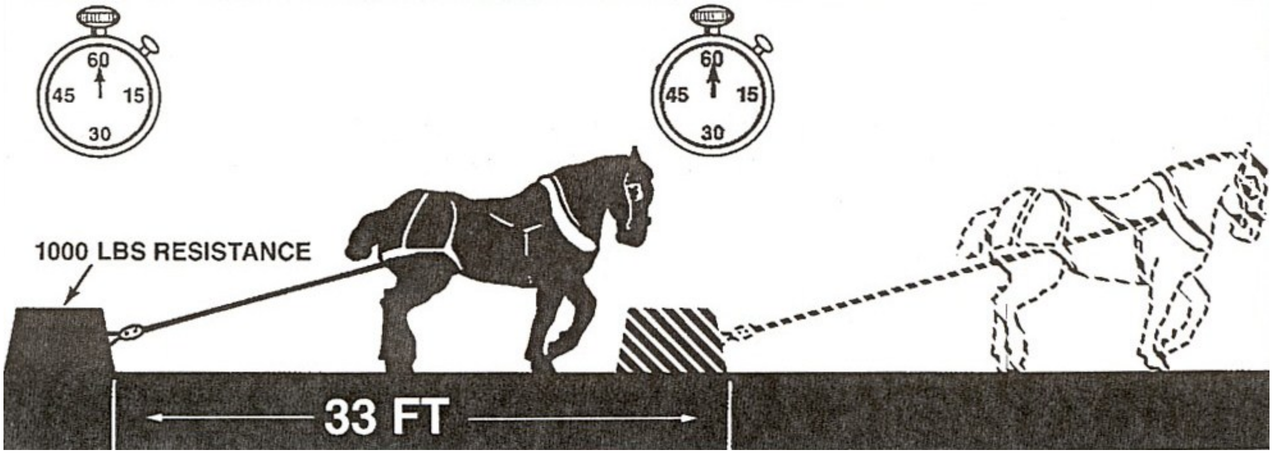


Figure 2. Horsepower is a measure of the rate at which work is done. Why horses? Because the idea of horsepower was first proposed by observing horses pulling weights out of mine shafts! Source: *Finner and Straub, 1985.*

It is useful to understand the different ways a tractor's power output is expressed. All tractors have three power ratings:

1. Brake
2. Power take-off (pto)
3. Drawbar

Brake horsepower is the maximum power the tractor's engine can develop. This is measured at the flywheel before installation using a ***dynamometer*** (Figure 3). A tractor's brake horsepower is not a particularly useful measurement because not all of the horsepower is available to do work. A more useful quantity is ***power take-off (PTO) horsepower***. PTO horsepower is the stationary power measured at the power take-off shaft (Figure 4) and is about 86% of brake horsepower (some of the power is lost in running accessories such as pumps, alternators, etc., and some power is lost as friction). ***Drawbar horsepower*** is a measure of the pulling power of the engine by way of tires, wheels, or tracks (Figure 5). As a percentage of the PTO power, the drawbar power varies, depending on soil surface characteristics and type of tractor (Table 2).

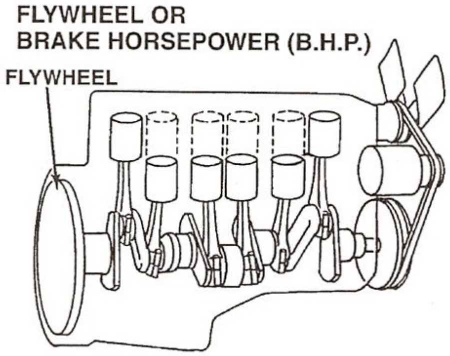


Figure 3. Brake horsepower

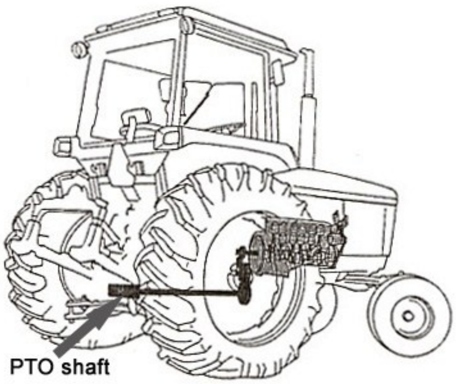


Figure 4. PTO horsepower

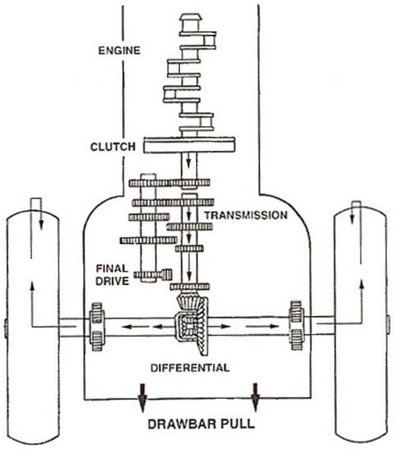


Figure 5. Drawbar horsepower

Tractor Type	Concrete	Firm Soil	Tilled Soil	Soft Soil
2-wheel drive	0.87	0.72	0.67	0.55
	(1.15)	(1.39)	(1.49)	(1.82)
Front wheel assist	0.87	0.77	0.73	0.65
	(1.15)	(1.30)	(1.37)	(1.54)
4-wheel drive	0.88	0.78	0.75	0.70
	(1.14)	(1.28)	(1.33)	(1.43)
Track	0.88	0.79	0.80	0.78
	(1.14)	(1.27)	(1.25)	(1.28)

Table 2. You can estimate a tractor's drawbar horsepower by multiplying the PTO power by the appropriate value in the table above. To estimate a tractor's PTO power if the drawbar horsepower is known, multiply drawbar horsepower by the value in parentheses. Source: *ASAE Standard D497.4 (2003).*

Note that, for a given tractor type, drawbar horsepower *decreases* as a percentage of the PTO power as the strength of the contact surface decreases, with a maximum for concrete and a minimum for fluffy tilled soil. On the other hand, for a given surface type, drawbar horsepower *increases* as the tractor contact surface area increases, as for example, by switching from 2-wheel drive to 4-wheel drive or tracks. This is due to differences in ***traction,*** a topic we'll consider later.

In tillage we are mostly concerned with a tractor's drawbar horsepower, though PTO horsepower is the most frequently quoted power rating. To pull a tillage tool at a given speed in the field, we must know the total amount of draft required. The *total draft* is the draft force required to pull a complete tillage tool in the field. The *unit draft*, or *specific draft*, is the draft force required to pull some unit of the tool. Total draft is therefore the sum of the specific drafts. Draft requirement for tillage tools may be obtained from engineering publications, equipment dealers or manufacturers, and is usually reported as draft *per foot of implement width* (Table 3).

To calculate the draft force of tillage tools, the following factors must be considered:

- ○ Width of the tool
- ○ Depth of tillage
- ○ Ground speed
- ○ Soil resistance

Draft force required to pull many seeding implements and tillage tools operated at shallow depths is mainly a function of the width of the implement and the speed at which it is pulled. In most draft tables, an 'average' working depth is assumed, and ground speeds are quoted within a range for optimum tillage performance. Soil resistance is based on texture, but may vary widely within a textural class depending on characteristics such as looseness (*i.e.* density), moisture content, and subtle changes in particle size distribution.

Consider this example: A 16 inch moldboard bottom plowing 7 inches deep has (7 x 16) a 112-square inch furrow cross-section (width of tool x depth). Moldboard-plow draft ranges from about 3 to 20 pounds per square inch; a moist sandy loam soil would have about 6.4 pounds of resistance per square inch. Unit draft would be (6.4 x 112) 717 pounds per bottom. A four bottom plow would have a total of (4 x 717) or 2868 pounds of resistance.

How much horsepower would it take to pull this particular plow at a depth of 7 inches and a speed of 5 mph? Table 3 shows a typical ground speed of 5 mph for a low draft, course soil type such as a sandy loam. Draft is given in *pounds per foot of implement width*, which for our moldboard plow, equals 2868 pounds divided by 5.3 ft, or 541 pounds per foot of width. This figure is less than the 600 pounds per foot quoted in the table. Because the relationship between soil texture and drawbar power is roughly proportional at the same ground speed, we can interpolate the drawbar horsepower per foot:

920-600 = 320 lbs/ft

12.3-8.0 = 4.3 hp/ft

$$\frac{320\ lbs\ /\ ft}{4.3\ hp\ /\ ft} = 74.4 \text{ pounds per horsepower}$$

Table 3. Soil Resistance

Tillage Tool/ Soil Type	Draft, lbs/ft	Typical Speed, mph	Drawbar power, hp/ft
Chisel Plow			
Fine	575	5	7.7
Medium	500	5.5	7.3
Coarse	400	6	6.4
Moldboard Plow			
Fine	1200	4.5	14.4
Medium	920	5	12.3
Coarse	600	5	8.0
Field Cultivator			
Fine	390	5	5.2
Medium	340	5.5	5.0
Coarse	270	6	4.3
Tandem Disk Harrow			
Fine	400	4.5	4.8
Medium	340	5	4.5
Coarse	300	5.5	4.4
Offset or Heavy Disk			
Fine	525	4.5	6.3
Medium	460	5	6.1
Coarse	430	5	5.7

Source: *Siemens, J.D. and W. Bowers. 1999. Machinery Management. John Deere Service Publication.*

The soil resistance data in Table 3 is plotted in Figure 6, so it is easy to compare the relationship between draft and drawbar power for different tillage implements operating in different soils. Figure 6 points up that, for all soil types, the moldboard plow has the largest draft and drawbar power requirement, and the field cultivator and tandem disk have the smallest. This makes sense because the operating depth of moldboard plow is deep and the field cultivator and disk are shallow. Bottom line: Moving the earth is expensive, so our tillage operations should be *directed* and *purposeful*.

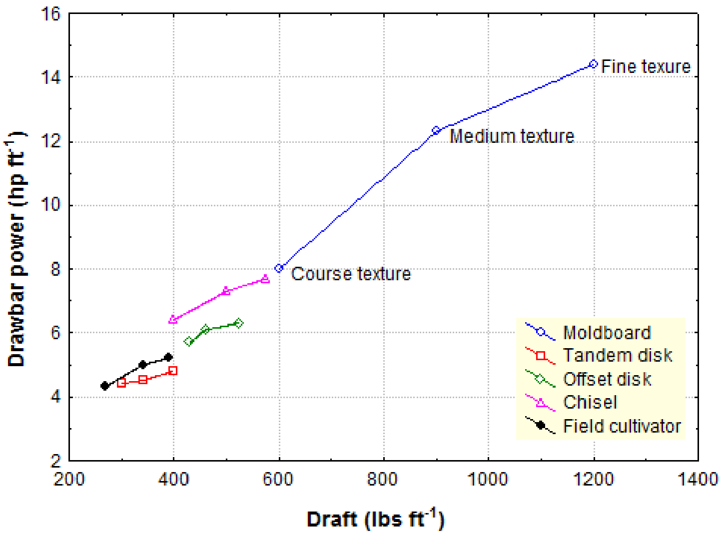


Figure 6. Plotting the soil resistance data in Table 3, it is easy to compare draft and power requirements for different tillage implements operating in different soils.

Since one horsepower is required for each 74.4 pounds of force, it will take (600 – 541) 59 divided by 74.4, or 0.79 horsepower per foot less than the published figure of 8 hp/ft which equals 7.2 hp/ft. At 5 mph, 7.2 horsepower per foot would be needed to pull the moldboard plow. Multiplying total width by horsepower per foot gives total horsepower required:

7.2 hp/ft x 5.3 ft = 38.2 *drawbar* hp

Another simpler formula yields the same answer:

$$\text{Drawbar hp} = \frac{draft\ (lbs)\ x\ speed\ (mph)}{375\ (a\ constant)}$$

$$\text{Drawbar hp} = \frac{2868\ lb\ x\ 5\ mph}{375}$$

Drawbar hp = 38.2

The answer to this problem can also be found by using the ***nomograph*** shown in Figure 7. Nomographs can be used to determine the required drawbar horsepower or to solve for *any value not known,* where all other values on the scale are either known or assumed.

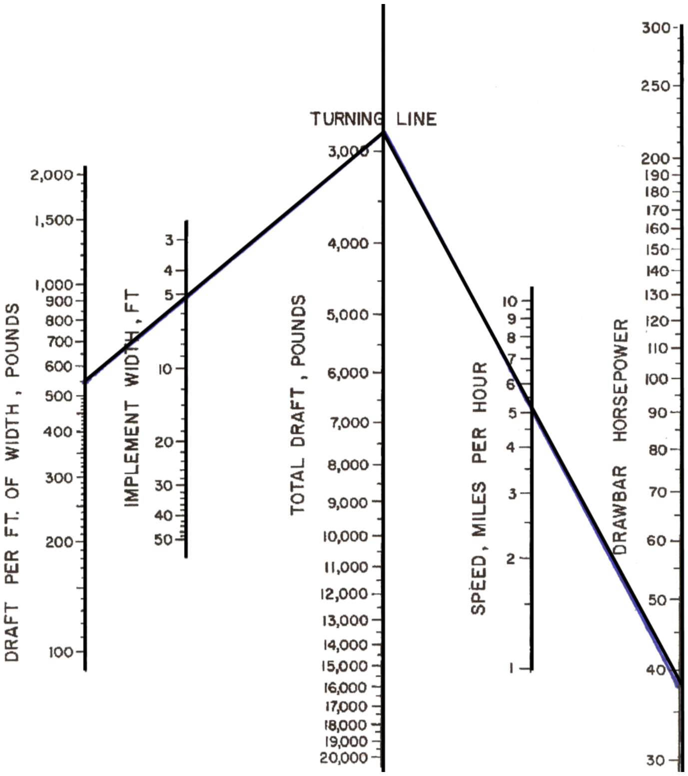


Figure 7. This nomograph can be used for sizing implements and tractors. Plotted above is the drawbar horsepower of a 16-inch four-bottom plow.

A dry sandy loam would have a much greater draft, and therefore require more power to plow, than a moist sandy loam. This is due to the lubricating effect of moisture films surrounding soil particles, and also due to a decrease in ***soil strength*** imparted by the moisture. On the other hand, fine textured soils require extra power to plow, and may be impossible to plow when moisture is too low. To save power, and maximize effectiveness, the timing of tillage should coincide with the time when soil is most ***friable***. Soils are usually in a most friable state when the moisture content is near ***field capacity***.

As plowing speed increases, draft also goes up, but usually varies as the square of ground speed. In practical terms this means that by doubling the ground speed, say from two to four miles per hour, the draft increases *four times*. This poses a problem for the farmer in choosing an economical balance between ground speed, tractor horsepower, and width of tillage implement. To find out how big a tractor we would need to pull the four-bottom plow in the example above, we need to refer back to Table 2. The drawbar horsepower required is 38.2. To covert this to PTO horsepower, multiply 38.2 x 1.39 = 53 PTO horsepower required for a 2WD tractor plowing firm soil. We would look for a tractor rated *at least* 53 PTO horsepower. In practice, it's best to size tractors for the *maximum* draft that might be encountered at a ground speed for optimum tillage performance. This means that if your fields are a mixture of soil types, the tractor must be sized according to the soil with the most resistance.

21.2 TRACTION

When a tillage tool is pulled through the soil, the power unit (tractor) must overcome draft forces created by soil resistance in order to move forward. This can be done because modern tractors are designed to transmit large amounts of power to the soil. Power is transmitted to the soil by way of the drive axle on which the wheels and tires are mounted. Transmitting that power requires large frictional forces, or ***traction***, at the soil surface which converts the torque, or rotary motion of the tractor's crankshaft, into forward motion. In other words, traction is the force of forward motion derived from contact between the tractor's tires and a medium such as soil, concrete, macadam, etc.

The main purpose of the tractor tire is to support the weight of the tractor while moving with a minimum amount of resistance over the soil surface. To do this, the wheel must rearrange the soil particles so as to give the soil enough ***shear strength*** to support the weight as well as generate forward motion. Shear strength is a measure of the force needed to deform the soil and is expressed as lbf/ft^2 (English units) or kN/m^2 (metric units).

Soil derives its shear strength from a combination of *internal friction*, which can be taken as the friction between soil particles in contact with one another, and *cohesion*, which can be taken as the resistance of a clod of soil to tearing apart. In both cases, the amount of moisture in the soil influences how much strength may be developed. For instance, saturated clay has no internal friction but has cohesion which does not depend on the load applied to it. Moist clay may have both internal friction and cohesion, depending on how much moisture is present. Pure dry sand derives its strength from internal friction, which increases with the load applied to it. Adding moisture to dry sand increases its cohesion due to the property of ***surface tension*** that exists within water molecules. It's more difficult to walk in dry sand because dry sand has internal friction but no cohesion. By adding water to the sand, traction becomes easier. Adding too much water to sand so diminishes its internal friction and cohesion as to lose all strength and become fluid. You would sink, like in quicksand.

Agricultural soils are a mixture of sand, silt, and clay, and therefore exhibit a mixed character of internal friction and cohesion. We observe sandy soils tending to increase their strength in response to loading whereas the strength of clay soils depends more on its cohesive properties. In practical terms this means traction on sandy soils is most likely to be obtained with ***ballast*** on the tractor tires; while on clay soils traction is obtained by means of increasing the contact area between the tire and soil, as for example, by switching from 2-wheel to 4-wheel drive or using tracks.

When a tractor tire passes over a field surface, it deforms the soil downward and leaves a wheel track. This is the tire's 'footprint'. The weight of the tire pressing on the soil results in compaction and increases its strength. Compaction can be understood as a rearrangement of soil particles that forces soil particles closer together at the expense of air (porosity). Since air has no internal friction or cohesive properties to impart strength, excluding air from the soil also increases its strength, other factors such as moisture being equal.

The amount of power that is actually delivered to the drawbar depends on two soil-related factors affecting the tractor's tires:

- ○ Rolling resistance
- ○ Wheel slippage

The tractor tire may be thought of as forever rolling up-hill or climbing out of its own track. The effort of counteracting this backward retarding force is ***rolling resistance***. In other words, a tractor that is constantly exerting effort climbing up-hill against the downward pull of gravity has less power available for forward motion. Loose, low-strength soils that have little weight bearing capacity leave deep wheel tracks. Under these conditions, much power is consumed simply counteracting the backward pull of gravity as the tractor struggles to move forward.

Just as the soil deforms vertically (downward) in response to the tractor's weight it must deform horizontally to generate traction. The amount the soil deforms horizontally is referred to as ***wheel slippage***. When there is zero wheel slippage, no soil deformation occurs and consequently there is no power. At 100% wheel slippage, all power is consumed in soil deformation, and no forward thrust is possible. A balance must be struck between the two extremes, and evidence suggests that maximum traction, and, consequently power, is transmitted to the drive wheels when slippage is in the range of 8-15%, depending on tractor type and soil surface characteristics (Table 4).

Wheel slippage on tractors can be managed by ballasting the tires. Usually this is achieved in two ways: (1) adding specially fabricated cast-iron weights to the drive axle, or front axle, and (2) filling the rear (drive) tires with a liquid such as **calcium chloride**. The amount of allowable ballast for a given tractor is usually specified by the manufacturer. Tractors are ballasted only enough to maximize ***tractive efficiency,*** which is the fraction of power available at the axle that is actually transmitted to an implement through the drawbar. If a tractor is over-ballasted, wheel slippage will be low, but rolling resistance will be excessive. Over-ballasting a tractor may also result in damage to the drive train. The effect of cast iron and liquid ballast is similar provided that the wheel load and tire inflation pressures are the same.

To sum up, here are some pointers to consider for improving tractive efficiency:

- ○ Follow the manufacturer's allowable weight limits when ballasting a tractor.
- ○ Operate within the allowable wheel slippage limits for the soil conditions and tractor type.
- ○ Use minimum allowable tire inflation pressures for the rated axle load as recommended by the manufacturer.

Select the largest diameter tire available that will support the tractor at the minimum tire pressure. Dual tires work best in firm soil conditions where increased traction is needed, or to support heavier axle loads. Duals may give increased pull of as much as 40% compared with a single tire at the same air pressure. On the other hand, duals have a higher rolling resistance and in some cases may actually reduce tractive efficiency.

Table 4. Recommended levels of wheel slip for different soil conditions (%). Source: *John Deere Service Publ., 1974.*

	2-Wheel Drive	Front-Wheel Assist	4-Wheel Drive	Tracks
Firm Surface	10	9	8	1
Tilled Soil	12	11	10	2
Soft Soil	15	13	12	3

We know a certain amount of wheel slippage is desirable, but the question arises: how do we measure wheel slippage? A fairly simple quantitative method may be used. First, determine the distance the tractor travels under load in ten wheel revolutions. Next count the number of turns the wheel makes without the load to travel the same distance.

Per cent wheel slippage =

$$\frac{(\#turns\ loaded - \#turns\ no\ load)\ x\ 100}{\#turns\ no\ load}$$

Example:

Number of wheel revolutions loaded: 10
Number of wheel revolutions no load: 9

Wheel slippage = $\frac{(10-9)\ x\ 100}{9}$ = 11 per cent

A visual inspection of a loaded tractor's footprint may also be used to assess wheel slippage. When there is too much ballast, a tire's footprint in the soil is sharp and distinct. Soil that is pinched between the cleats has a clear, undisturbed crown. In this instance, slippage is not evident. When there is too little ballast, the tread marks are nearly wiped out. Few undisturbed crowns are evident because they are obliterated as the tire spins. When the ballast is correct, a small amount of slippage occurs. Visually, this can be observed as a slight rearward disturbance of the soil crowns, yet the tire's footprint remains fairly distinct (**Figures 8A, B, C**).

We conclude this technical note with a few words about tractor tires. Most modern tractors use rubber tires, although in a few cases steel wheels are still employed. Under particularly difficult conditions, such as wet clay, tracks are often a necessity. Rubber tires have raised cleats that may be dimensioned and oriented in different ways to match different soil conditions.

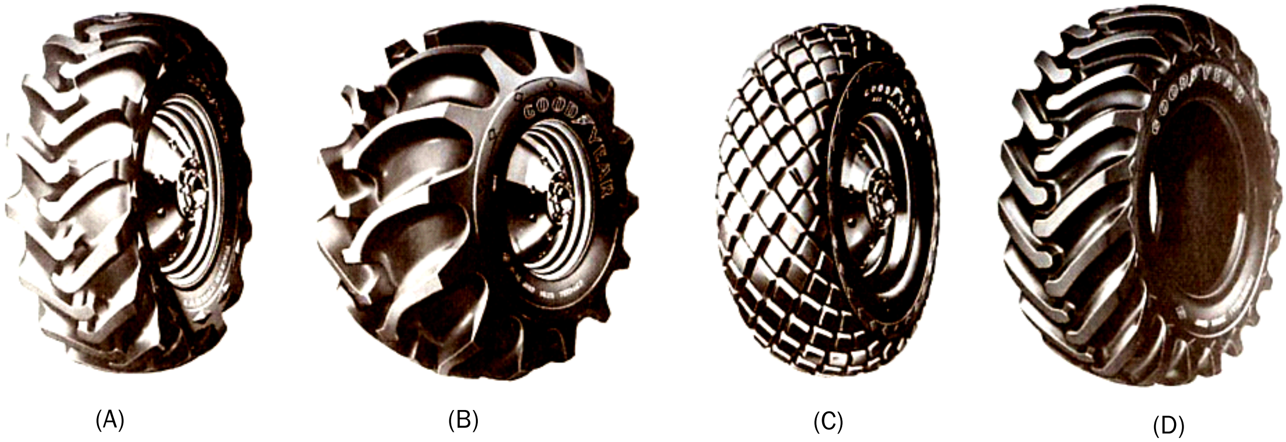
Figure 8. The footprint of a loaded tractor showing different amounts of wheel slippage. Reading footprints in the soil can tell us a lot about the object that made them. The wheels of other rolling implements like planters also have slippage, which must factored into their calibration. Source: *adapted from John Deere Service Publ., 1976.*

The functions of tire cleats are:

- To sweep away loose soil and trash while exposing firm soil underneath. Some wheel slippage is required to give this 'keying' action and therefore some loss of tractive efficiency is involved.
- To penetrate a water film on concrete or a slippery layer on firm, cohesive (clayey) soils.

Figure 9 shows some common types of tractor tires. The *general purpose* tire (**Figure 9-A**) has the familiar "V" tread and represents a compromise among traction, floatation, and tread life. The pitch and angle of the cleats are fixed to be self-cleaning. The cleats do not cross the entire width of the tire; this is the 'open center ' style universally used for land work. The *high cleat* tread (**Figure 9-B**) provides maximum traction in extremely muddy conditions. High cleats may wear rapidly if operated on hard or paved surfaces, but offer the promise of longer life because there's more rubber to wear. High cleat tread tires are commonly used in logging operations, and wherever mud is a problem. Diamond tread, or turf tread provides good traction while minimizing soil disturbance. Tractors used for turf service are mounted with diamond tread tires that leave no footprint to damage lawn surfaces (**Figure 9-C**). Diamond treads are also good for loose or sandy soils, and provide longer wear on paved surfaces. Industrial lug tread has cleats spaced more closely together thus giving more contact area for longer tread wear. It gives more traction than diamond tread, and has about double the life of general purpose tread on paved surfaces. Industrial lug tread is the best choice when equipment must be operated on and off paved surfaces (**Figure 9-D**).

Figure 9.


(A) (B) (C) (D)

21.3 CORE CONCEPTS

Ballast: Add-on weight used to increase safety, efficiency or performance of a device. Ballast is added to a tractor or implement to improve tractor traction and stability and/or improve penetration of soil-working tools.

Brake (flywheel) horsepower: Maximum power that an engine can develop. Measured at the flywheel and expressed as horsepower (Hp, English units) or kilowatts (kW, metric units). The term *brake* horsepower is given because it was originally measured using a device known as a *Prony brake* dynamometer.

Calcium Chloride ($CaCl_2$): A neutral salt that, when mixed with water, forms a liquid solution that is added to tractor tires to increase traction. This is sometimes referred to as 'hydro-ballasting'. Calcium chloride also lowers the freezing point of water, so providing degree of freeze protection similar to automotive antifreeze. The amount of freeze protection is determined by the $CaCl_2$ concentration of the water-$CaCl_2$ mixture. The freezing point of the water-$CaCl_2$ mixture can be increased or decreased relative to water (solid at +32° F/0° C) by adjusting the amount of $CaCl_2$ in the mixture. A typical water-$CaCl_2$ mixture has 3.5 lb $CaCl_2$ per gallon of water (0.42 kg/liter). This mixture is solid- (but not slush) free to -52° F/-47° C. The water-$CaCl_2$ mixture is injected into the tire with a special tool equipped with an air vent to allow the displaced air to escape. For maximum traction, the recommended fill level should reach *at least* the base of the valve stem when the tire is upright and the stem is in its highest position. The fill level will depend on the tire type. For tube type tires, the recommended fill level is 75%. For tubeless tires, a 90% fill level is recommended so that the rim is always completely covered ($CaCl_2$ is corrosive).

The amount of $CaCl_2$ and water to add to a tire to achieve a given level of ballast and freeze protection depends on the tire size and rim width. Many tire manufacturers and equipment dealers have charts to figure this. For the inquisitive, the general approach to calculating the amount of $CaCl_2$ and water follows.

Problem: Tire size XX26.5 R24 is fitted on a tractor and ballasted with $CaCl_2$ in the concentration of 0.42 kg per liter (3.5 lb per U.S. gallon) of water to withstand a temperature of -52°F/-47°C. From the manufacturer's table, an inner filling volume of 900 liters is specified for this tire type. Determine the volume of solution to be added and the ballast increase for each tire.

Solution: A standard fill level of 75% will be considered, so the amount of water-$CaCl_2$ solution needed is 0.75 x 900 = 675 liters. The total amount of water needed is calculated with the following formula:

$$\frac{675 \times 1000}{1000 + s} = \frac{675000}{1000 + 170} = 577 \text{ liters of water}$$

The 's' factor in the formula above is a 'swelling factor' used to account for the displacement of water by the added $CaCl_2$ (Archimedes' Principle). The swelling factor is given in terms of cubic centimeters per liter of water (cc/liter). The swelling factor for $CaCl_2$ is ~399 cc per kg $CaCl_2$, or 0.42 kg x 399 = 170 (rounded up). For $CaCl_2$ concentrations other than 0.42 kg/liter (3.5 lb/gal) of water, the appropriate 's' factor may be estimated by linear interpolation.

The quantity of $CaCl_2$ to add is calculated as:

$$\frac{0.42 \text{ kg}}{\text{liter } H_2O} \times \frac{577 \text{ liter } H_2O}{1} = 242 \text{ kg } CaCl_2$$

The amount of water to add is 577 liters and the amount of $CaCl_2$ is 242 kg. The increase in ballast per tire is 577 + 242 = 819 kg (1 liter H_20 weighs 1 kg). In English units the increase in ballast weight is 1,806 lb per tire.

Mixtures other than water-$CaCl_2$ can be used for ballast and and/or freeze protection. The above calculations apply only to $CaCl_2$. For mixtures other than water-$CaCl_2$, follow the manufacturer's recommendation. Of course, water itself can be used for ballasting where freezing never occurs. The increase in ballast per tire in the above example using water alone is 675 kg (1488 lb).

Draft: Horizontal force required to pull a soil-engaging implement (plow, drill, planter, etc) at a given ground speed. Expressed in units of pounds-force (lbf, English) or kiloNewtons (kN, metric). Draft force is measured with a dynamometer.

Drawbar horsepower: Measure of the pulling power of an engine by way of tires, wheels, or tracks. Drawbar horsepower is computed as a percentage of the tractor's rated PTO horsepower and varies depending on surface characteristics and tractor type.

Dynamometer: Instrument used to measure power output of an engine. The simplest (and crudest) dynamometer is the brake-type. More sophisticated devices are electrically or hydraulically actuated. Hitch-mounted strain gauges are typically used to measure implement draft in the field.

Field capacity: The amount of water remaining in the soil after free drainage. Water entering the soil from irrigation or natural precipitation initially moves downward due to the pull of gravity. The point at which drainage ceases (or becomes very small) is determined by soil particle shape and the packing density of the particles. Water remaining in the soil after free drainage is held by capillary forces (adhesion and the surface tension of water molecules), and represents its water content at 'field capacity'. A sandy loam soil reaches field capacity at a capillary suction of ~ -10 kPa but clay soils may have higher suctions. Field capacity is mainly used to infer some other soil physical condition like workability or available water capacity as related to water content. For most agricultural soils field capacity is reached within 24-48 h after wetting provided the soil is deep enough.

Flywheel: A spinning plate located at the end of the engine crankshaft on vehicles with manual transmissions that engages the clutch disc, causing the engine and the transmission to turn at the same rate of speed.

Force: Physical quantity defined as the action of one body upon another that tends to produce motion, change the rate of motion, or the direction of motion. Force is measured in units of newtons (N, metric units) or pounds force (lbf, English units). Arrowheads (also called *vectors*) are used to indicate the direction of the force, while length of the tail is proportional to the magnitude of the force.

Friable: Physical state of the soil when is easily worked with tillage tools. Soil clods are said to be friable when easily crumbled when a force is applied. Soil friability is influenced by both texture and moisture content.

Horsepower: English unit of power defined as 550 foot-pounds of work done per second, usually abbreviated HP. In the metric system, power is measured in units of kilowatts (kW). Power output of internal combustion engines is typically quoted in horsepower, although it is actually the amount of torque developed by the engine that permits conversion of horsepower into forward motion.

Hitch: Point of attachment of an implement to a tractor. Most modern tractors have three-point hitches, while some older types many have a single-point of attachment. The drawbar of a tractor is also considered to be a point of attachment. Tools hitched to a drawbar are referred to as *drawn* implements.

Mass: The amount of matter in an object that causes it to have weight in a gravitational field. Mass and weight are not the same properties (compare ***weight***). The unit of measure for mass is kilogram (metric units).

Nomograph: A graph consisting of three or more usually parallel straight lines of related variables. Each line is graduated for a different variable so that a straight line passing through all the lines intersects the related values of each variable. The center line is usually termed the pivotal line.

Power: Defined as the product of a force moving through a distance in some interval of time, or force x distance/time. Power is made available from tractors in at least four different ways: (1) pulling power from the drawbar and three-point hitch; (2) rotary power from the power take-off (PTO) shaft; (3) linear and rotary power from the hydraulic system; and (4) electrical power from the tractor electrical system. The unit of measure for power is horsepower (HP, English units) and kilowatt (kW, metric units).

Power take-off (PTO) horsepower: Stationary power measured at the tractor's power take-off shaft. The tractor PTO shaft permits direct transfer of power from the tractor to the implement through a series of shafts and universal joints. The standard 6-spline shaft on smaller tractors rotates at 540 RPM. Larger tractors may accept a 21-spline shaft that rotates at 1000 RPM.

Rolling resistance: A backward retarding force acting on a tractor's tires that tends to slow forward motion. Rolling resistance increases in direct proportion to an increase in weight on the tire. Rolling resistance also increases as soil strength decreases.

Shear strength: The ability of a soil to resist shearing, or movement of the soil mass at an angle to the applied force. An example would include the familiar landslide. Shear strength is measured in the field using a device known as a *torvane*. Units are pounds force/ft^2 (English) and kiloNewton/cm^2 (metric).

Soil strength: A fundamental physical property, soil strength is the degree of resistance of a soil mass to crushing or deformation when a force is applied. Also called *consistence*. Soil strength is determined by the degree of cohesion and internal friction existing between soil particles. Units are the same as for shear strength. Soil strength may be estimated from the pressure required to squeeze a soil sample between the fingers. Terms such as *brittle* (fails suddenly with little strain), *elastic* (rubbery), *friable* (crumbles easily), and *loose* (non-coherent) are commonly used to describe soil strength.

Surface tension: Physical property that exists at the interface of a liquid and gas, or a liquid and solid. In water, surface tension arises due to an imbalance in the cohesive forces between water molecules in contact with one another and water molecules in contact with the air, or a solid. The unbalanced force draws the water molecules together, creating a curved membrane-like interface of greater strength. It is surface tension that supports a steel needle on the surface of a glass of water, even though the density of steel is greater than water (of course, if the needle is pushed it will sink).

Torque: Force producing a turning or twisting effect about a pivot point. Torque is equal to the product of force x distance, where distance is given as the length of a perpendicular line between the pivot point and the line of force. Torque has the same units as work, foot-pound (ft-lb, English) and joules (metric); however, the concept of work and torque are quite different.

Traction: Effective force resulting from the thrust of tractor tires against the soil or other surface. Traction depends on such factors as type of surface, contact area between tires and surface, and tractor power and weight.

Tractive efficiency: Fraction of power available at the axle that is actually delivered to an implement through the hitch or drawbar. Tractive efficiency measures how well a tractor uses the power available at the axle to pull an implement through the soil. Power is transmitted most efficiently to surfaces that do not deform under pressure and where traction is great enough to prevent the wheels from slipping.

Tractor: A vehicle, powered by a gasoline or diesel engine, having large, deeply treaded tires, used in farming for pulling machinery. There are four main types of farm tractors: (1) *general purpose* (most popular for general crop production); *utility* (similar to general purpose but also may be used for earthwork such as loading, grading, excavation); (3) *row crop* (designed for tending crops in equally spaced rows, with front axle widely spaced or short); and (3) *orchard* (for tree crop production).

Weight: Force exerted on an object in a gravitational field. A body which is not restrained will accelerate rapidly toward the center of the earth (of course it hits the earth's surface first). If a body is restrained the restraining force is equal to or represents the *weight* of the object. The weight of a body will vary at different places on the earth because of differences in gravitation acceleration. On the other hand, the *mass* of an object is a fixed property and remains constant anywhere it may be measured.

Wheel slippage: The amount of soil that deforms horizontally as a wheel passes over it. Wheel slippage is a factor in computing *tractive efficiency*, amounting to a net loss of tractive power.

Work: Defined as the action of a force through a distance, without regard to time. The notion of *displacement* of an object through a distance is central to the definition of work. Work is computed as the product of force x distance, and is measured in units of foot-pounds (ft-lb, English) and joules (metric).

FURTHER READING

American Society of Agricultural Engineers Standards. 48th Ed. (2003). ASAE D497.4 St. Joseph, MI. Current standards for calculating tractor performance parameters including draft.

Borgman, D.E., Hainline, E., and M.E. Long. (1974). *Fundamentals of Machine Operation: Tractors*. John Deere Service Publication. Moline, IL.

Bowers, C.G. (1989). *Tillage draft and energy requirements for 12 southeastern soil series.* Transactions of the ASAE 32 (5):1492-1502.

Buckingham, F., Thorngren, H., and B. Johannsen. (1976). *Fundamentals of Machine Operation: Tillage*. John Deere Service Publication. Moline, IL. A classic nuts-and-bolts treatment of tillage machinery.

Davies, B., Finney, B., and D. Eagle. (2001). *Resource Management: Soil.* Farming Press, Tonbridge, United Kingdom. One of few soil science texts that covers traction. This excellent book also covers tillage, traffic and soil damage, power requirement, and other topics of interest to dirt hogs.

Finner, M.F., and R.J. Straub. (1985). *Farm Machinery Fundamentals*. 2nd. Ed. American Publishing Company. Madison, WI. Thorough and practical discussion of all aspects of farm machinery.

Harrigan, T.M. and C.A. Rotz. (1995). *Draft relationships for tillage and seeding equipment.* Applied Engineering in Agriculture. Vol. 11(6):773-783.

Siemens, J.C. and W. Bowers. (1999). *Farm Business Management: Machinery Management*. John Deere Service Publication. Moline, IL.

PREPARED BY:

Robert D. Walters
Department of Soil Science
North Carolina State University
101 Derieux St. CB 7619
Raleigh, NC 27695

robert_walters@ncsu.edu

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