Technical Note 21. Soil, Draft, and Traction

21.0 Background

Effective tillage requires an understanding of three interrelated topics: soil physical properties, draft (the horizontal force required to pull an implement through soil), and traction (the ability of drive wheels to transmit engine power to the soil surface). Although these subjects are treated individually in the soil science and agricultural engineering literature, they are rarely integrated in ways that are directly useful to practitioners. This technical note examines the principal types of soil-tool interaction, their practical significance for tillage operations, and the factors governing drawbar power requirements.

In simple terms, tillage involves moving the earth 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 implement's forward speed 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	Field Speed, mph 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)*

The data in Table 1 show that the optimum field speed varies with the type of tillage. 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 finer tilth, as well as for mechanical weed control.

The drawbar power required to pull a tillage tool through soil at a given speed is determined primarily by the draft force acting on the tool. Whether that power can be effectively delivered depends on the traction available at the drive wheels — the ability of the power unit to transmit force to the soil surface without excessive wheel slip. Although draft and traction are treated separately in the sections that follow, both are strongly governed by soil physical properties and conditions.

21.1 Draft

The ***force*** required to pull a tillage tool through the soil is called its ***draft***. Draft arises from the interaction between the tool and the soil and is measured at the ***hitch***, the point where the implement is attached to the ***tractor***. Although draft acts horizontally in the direction of travel, the full soil reaction force on a tillage tool has both horizontal and vertical components; draft refers specifically to the horizontal component. Draft force is expressed in pounds-force (lbf) in English units or kilonewtons (kN) in SI units.

When using physical terms such as force, work, and power, it is important to recognize that these words have precise, distinct meanings even though they are closely related. Each is defined in turn below.

A force is any interaction between two bodies that, when unopposed, changes the state of motion of an object — its speed, direction, or both. A familiar example is the ***weight*** of a tillage tool resting on the ground: Earth exerts a downward force on the tool proportional to its mass. Newton's second law relates force, mass, and acceleration:

$$F = m \times a$$

where F is force in Newtons (N), m is mass in kilograms (kg), and a is acceleration in meters per second squared (m/s^2). It is important to distinguish between mass and weight: mass is an intrinsic property of an object that does not change with location, whereas weight is the force exerted on that object by gravity and therefore depends on the local gravitational field. At Earth's surface, gravitational acceleration is approximately 9.807 m/s^2, so a tillage implement with a mass of 500 kg exerts a downward force, its weight of 500 × 9.807 = 4,904 N, or approximately 4.9 kN. Since one Newton equals one kg•m/s^2, draft forces expressed in kilonewtons are fully consistent with the SI unit system (1 kN = 1,000 N).

Work is defined as the product of a force and the distance through which it acts in the direction of the force (Figure 1). When force and displacement are parallel, work is calculated as:

$$W = F \times d$$

where work (W) is expressed in foot-pounds (ft•lb) in English units or Newton-meters (N•m)[1] in SI units, where 1 N•m = 1 Joule (J).

[1] Ft•lbs, Ft × lbs, and Ft-lbs all represent the same thing, as do N•m, N×m, and N-m. For consistency, we use the half-high center dot "•" multiplication symbol for abbreviated units, and reserve the hyphen "-" for spelled out units, e.g., "Newton-meters", "foot-pounds", etc. Variables in equations use the conventional "×" symbol for multiplication.

For example, if a force of 20 pounds is required to move a load vertically a distance of three feet, the work done is 20 pounds × 3 feet, or 60 foot-pounds (ft•lb, English units), or 81.3 Newton-meters (N•m, metric units). Note that time plays no role in this calculation — the same amount of work is done whether the task takes one second or one hour.

Power is defined as the *rate* at which work is done. This definition introduces the element of time and implies that a certain amount of work is being done per unit of time. The U.S. customary power unit is the ***horsepower,*** defined as 550 foot-pounds of work per second. The metric power unit is the watt (W), or 1,000 W (kilowatt, kW) in power systems.

$$\text{One horsepower (hp)} = \frac{\text{33,000 foot-pounds}}{\text{60 seconds}} = \text{550 ft-lb/sec}$$

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 746 watts (0.746 kilowatts) (Figure 2).

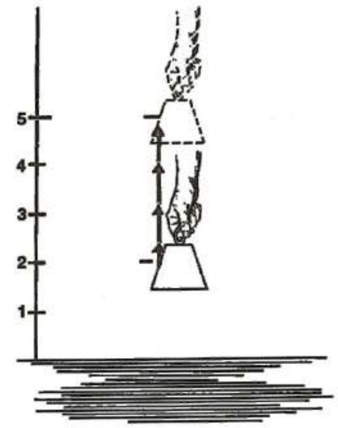

Figure 1 Work equals force × distance without a time factor where force and displacement are parallel. *Source: Finner and Straub, 1985.*

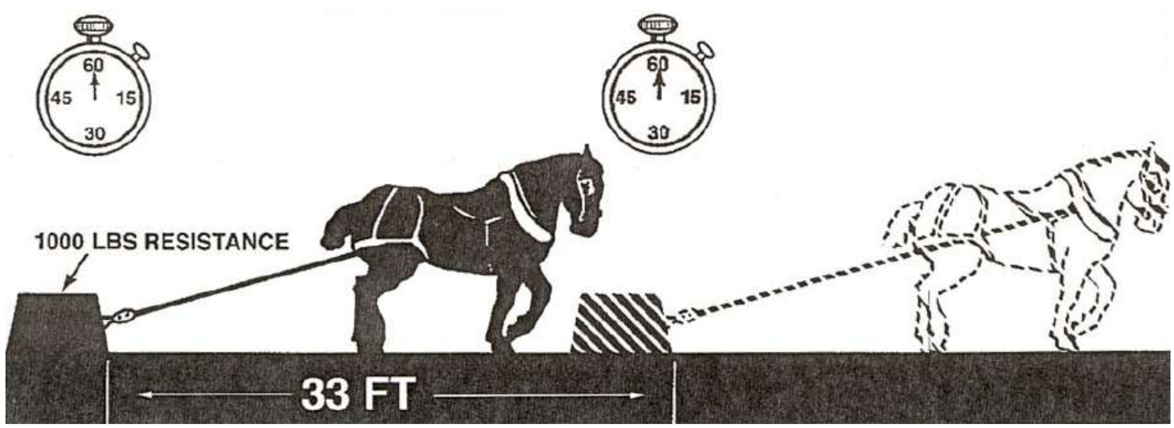

Figure 2 Horsepower is a measure of the rate at which work is done. Why horses? Because the idea of horsepower was first proposed by observing horses pulling weights out of mine shafts! *Source: Finner and Straub, 1985.*

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 complete cycle of the piston, representing one revolution of the crankshaft, is repeated many times in one minute, such that the amount of power developed at the ***flywheel*** can be calculated as follows:

$$[1]\ \text{Engine horsepower (hp)} = \frac{\text{rpm} \times \text{torque (force} \times \text{distance)}}{\text{5,252} \qquad \text{(a constant)}}$$

$$[2]\ \text{Engine power (kW)} = \frac{\text{rpm} \times \text{torque (force} \times \text{distance)}}{\text{9,549} \qquad \text{(a constant)}}$$

where 'rpm' is the number of revolutions per minute. The constant 5,252 in Equation [1] derives from the definition of horsepower (33,000 ft•lb per minute) divided by 2π, since each revolution involves a full circular path. The denominator 9,549 in Equation [2] derives from the definition of a watt (1 W = 1 N•m per second) combined with the conversion of rpm to radians per second.

The two equations can be combined to illustrate the relationship among engine speed, torque, and power in a way that is practical for students of tillage. Here's how they work in context:

If an engine develops 200 ft•lb of torque at 2,400 rpm, the power at the flywheel is:

$$\text{hp} = \frac{\text{2,400 rpm} \times \text{200 ft•lb}}{\text{5,252}} = \text{91.4 hp}$$

The same engine developing 271 N•m of torque (equivalent to 200 ft•lb) at 2,400 rpm produces:

$$\text{kW} = \frac{\text{2,400 rpm} \times \text{271 N•m}}{\text{9,549}} = \text{68.1 kW}$$

As a check, 91.4 hp × 0.746 = 68.2 kW, confirming the two results are consistent within rounding[2].

[2] The factor 0.746 is the conversion factor from horsepower to kilowatts, and it derives from reconciling the English and metric definitions of power.

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

- Brake horsepower
- Power take-off (PTO) horsepower
- Drawbar horsepower

Brake horsepower is the maximum power the tractor's engine can develop, measured on a ***dynamometer*** test stand before the engine is installed in the tractor (Figure 3). It is not a particularly useful field measurement because not all this power is available to do useful work. A more practical quantity is ***PTO horsepower***, which is the power measured at the power take-off shaft under stationary conditions (Figure 4). PTO horsepower is typically 83-90% of brake horsepower, with losses attributed to friction and engine accessories such as pumps and alternators. ***Drawbar horsepower*** measures the pulling power delivered to the hitch through the tractor's wheels or tracks (Figure 5). As a percentage of PTO horsepower, drawbar power varies with soil surface conditions and tractor type (Table 2). For a given tractor type,

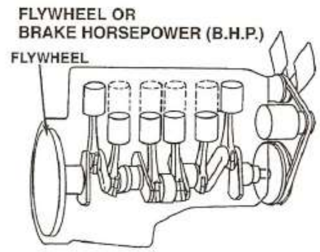

Figure 3 Brake horsepower

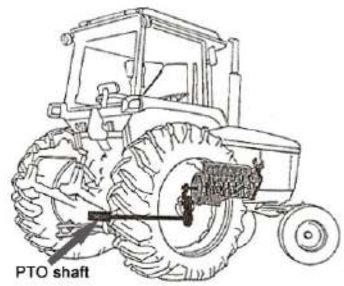

Figure 4 PTO horsepower

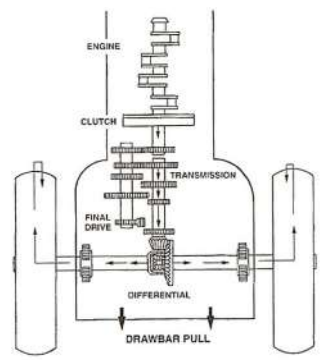

Figure 5 Drawbar horsepower

Tractor Type	Concrete	Firm Soil	Tilled Soil	Soft Soil
2-wheel drive	0.87 (1.15)	0.72 (1.39)	0.67 (1.49)	0.55 (1.82)
Front wheel assist	0.87 (1.15)	0.77 (1.30)	0.73 (1.37)	0.65 (1.54)
4-wheel drive	0.88 (1.14)	0.78 (1.28)	0.75 (1.33)	0.70 (1.43)
Track	0.88 (1.14)	0.79 (1.27)	0.80 (1.25)	0.78 (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 the drawbar horsepower by the value in parentheses. *Source: ASAE Standard D497.4 (2003)*

For a given tractor type, drawbar horsepower decreases as a percentage of PTO horsepower as the contact surface strength decreases, with a maximum on concrete and a minimum on freshly tilled soil. Conversely, for a given surface condition, drawbar horsepower increases as the number of drive wheels or the tire contact area increases, for example, by switching from 2-wheel drive to 4-wheel drive or to tracks. These differences are due to ***traction***, a topic considered in detail later.

In tillage, drawbar horsepower is the most relevant power rating, though PTO horsepower is the most frequently quoted. To pull a tillage tool at a given speed, the total draft must be known. Total draft is the force required to pull a complete implement through the soil, calculated by multiplying the unit draft (the draft force per foot or meter of implement width) by the total implement width. Draft values for common tillage tools are available from equipment manufacturers and engineering references and are usually reported as draft *per foot of implement width* (Table 3).

To calculate the draft force of a tillage tool, the following parameters must be specified:

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

For seeding implements and tillage tools operated at shallow, relatively uniform depths, draft force is primarily a function of implement width and ground speed. It is worth noting that draft generally increases with speed, which has direct implications for power requirements. In most draft tables, an average working depth is assumed, and ground speeds are given as a range consistent with optimum tillage performance. Soil resistance is strongly influenced by soil texture but can vary widely within a textural class depending on bulk density, moisture content, and the proportions of sand, silt, and clay. These factors can cause significant variation in draft requirements across fields that appear texturally similar.

Let's work a practical example:

:A 16-inch moldboard bottom plowing 7 inches deep has (7 × 16) a 112-square-inch furrow cross-section (width of tool × 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.

Calculate unit draft:

$$6.4 \text{ lbs} \times 112 \text{ in}^2 = 717 \text{ pounds of draft per bottom}$$

Calculate total resistance for a four-bottom plow:

4 bottoms × 717 lbs/bottom = 2,868 pounds

How much horsepower would it take to pull this 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, coarse soil type such as sandy loam. The draft is given in pounds per foot of implement width, which for our moldboard plow is:

2,868 lbs/5.3 ft = 541 lbs/ft

This figure is less than the 600 lbs/ft 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 lbs/ft–600 lbs/ft = 320 lbs/ft

12.3 hp/ft–8.0 hp/ft = 4.3 hp/ft

320 lbs/ft÷4.3 hp/ft=74.4 lbs/hp

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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 are plotted in Figure 6, providing a visual comparison of the relationship between draft and drawbar power across different tillage implements operating in different soils. Figure 6 shows that, across all soil types, the moldboard plow has the largest draft and drawbar power requirements, and the field cultivator and tandem disk have the smallest. This makes sense because the moldboard plow has a deep operating depth, while the field cultivator and disk are shallow. Bottom line: Moving the earth is expensive, so tillage operations should be *prescriptive* and *purposeful*.

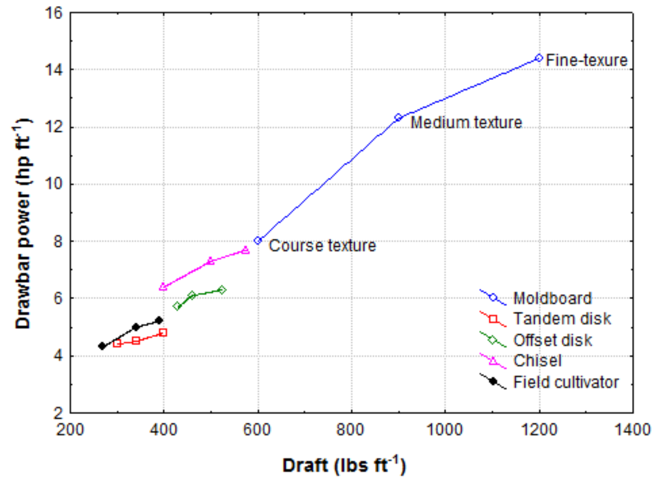

Figure 6 Plot of the soil resistance data in Table 3 visualizing comparative draft and power requirements for different tillage implements operating in different soils.

Since one horsepower is required for every 74.4 pounds of force, it will take:

600 lbs/ft – 541 lbs/ft = 59 lbs/ft

59 lbs/ft ÷ 74.4 lbs/hp = 0.79 hp/ft

less than the published figure of 8 hp/ft, which equals 7.2 hp/ft.

At 5 mph, 7.2 hp/ft would be needed to pull the moldboard plow. Multiplying the total width by horsepower per foot gives the total horsepower required:

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

A simple textbook formula yields the same answer:

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

$$\text{Drawbar hp} = \frac{2{,}868 \text{ lbs} \times 5 \text{ mph}}{375}$$

$$= 38.2 \text{ hp}$$

The constant 375 in the denominator represents the number of "mile-pounds per hour" required to equal 1 horsepower. It is derived by dividing the standard horsepower definition:

$$1 \text{ hp} = \frac{33{,}000 \text{ ft•lbs}}{\text{min•hp}}$$

by the number of feet per minute equal to 1 mph:

$$1 \text{ mph} = \frac{88 \text{ ft}}{\text{min•mph}}$$

$$\frac{\dfrac{33{,}000\text{ft•lbs}}{\text{min•hp}}}{\dfrac{88 \text{ ft}}{\text{min•mph}}} = \frac{375\text{mph•lbs}}{\text{hp}}$$

We derived this conversion factor to point out the importance of dimensional analysis following the rules of mathematics, which cannot be over-emphasized in science and engineering practice.

The answer to this problem can also be found using the ***nomograph*** shown in Figure 7. Nomographs can be used to determine the required drawbar horsepower or to solve for any unknown value, provided all other values on the scale are either known or assumed.

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 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 the moisture is too low. To save power and maximize effectiveness, tillage should be timed to coincide with the soil's greatest friability. Soils are usually in a most friable state when the moisture content is near ***field capacity***.

As plowing speed increases, draft also rises, but it usually varies with the square of ground speed. In practical terms, doubling the ground speed, say from two to four miles per hour, increases the draft by a factor of four. This poses a problem for the farmer in choosing an economical balance among ground speed, tractor horsepower, and the width of the tillage implement. To determine how big a tractor we would need to pull the four-bottom plow in the example above, we refer back to Table 2. The drawbar horsepower required is 38.2. To convert this to PTO horsepower, multiply 38.2 × 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 the ground speed for optimum tillage performance. This means that if your fields are a mixture of soil types, the tractor must be sized for the soil with the highest resistance.

21.2 Traction

When a tillage tool is pulled through the soil, the power unit (tractor) must overcome draft forces generated by soil resistance 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 minimal resistance on the soil surface. To do this, the wheel must rearrange the soil particles to provide the soil with enough shear strength to support the weight and 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).

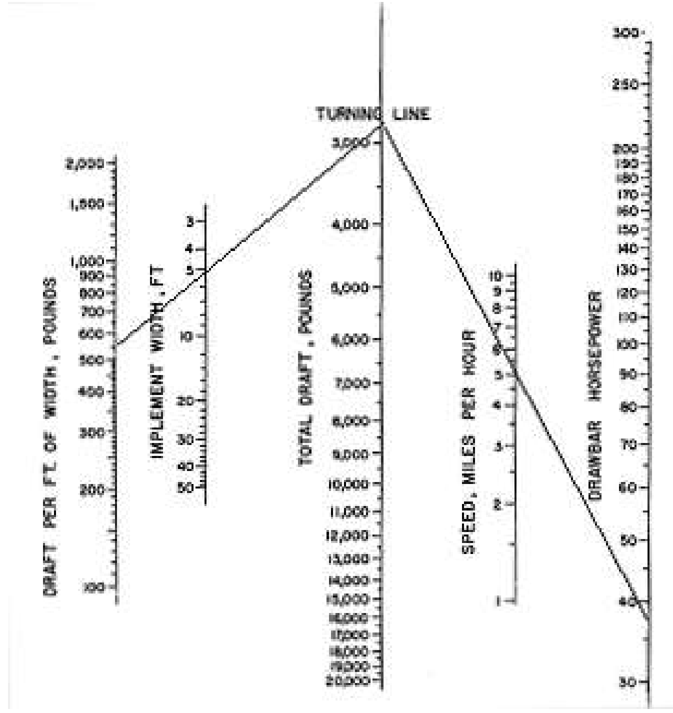

Figure 7 A nomograph used for sizing implements and tractors. Plotted above is the drawbar horsepower for a 16-inch four-bottom plow.

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

Agricultural soils are mixtures of sand, silt, and clay particles 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 their cohesive properties. In practical terms, this means traction on sandy soil is most likely to be achieved with ballast on the tractor tires, while on clay soils, traction is obtained by increasing the contact area between the tire and the soil, such as 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, leaving a wheel track. This is the tire's 'footprint'. The weight of the tire pressing into the soil compacts it and increases its strength. Compaction can be understood as the rearrangement of soil particles that forces them 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 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 required to counteract this backward retarding force is ***rolling resistance***. In other words, a tractor that is constantly exerting effort climbing uphill 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 of horizontal soil deformation 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).

Example:

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

$$\text{Wheel slippage} = \frac{10 - 9}{9} \times 100$$
$$= 11\% \text{ (rounded)}$$

Tractor wheel slippage 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 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 damage the transmission. 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 practical pointers 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.

	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

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

We know a certain amount of wheel slippage is desirable, but the question arises: how do we measure wheel slippage? A relatively simple method can be used to quantify this.

First, determine the distance the tractor travels under load in ten-wheel revolutions. Next, count the number of wheel turns required to travel the same distance without the load. Percent wheel slippage is given by:

$$\frac{\#\text{ turns loaded} - \#\text{ turns no load}}{\#\text{ turns no load}} \times 100$$

Duals may provide up to a 40% greater pull than a single tire at the same air pressure. On the other hand, duals have a higher rolling resistance and, in some cases, may reduce tractive efficiency.

A visual inspection of a loaded tractor's footprint may also be used to assess wheel slippage. When there is too much ballast, the 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

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

rearward disturbance of the soil crowns, yet the tire's footprint remains 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 differently to suit different soil conditions.

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 equipped with diamond-tread tires that leave no footprint on 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).

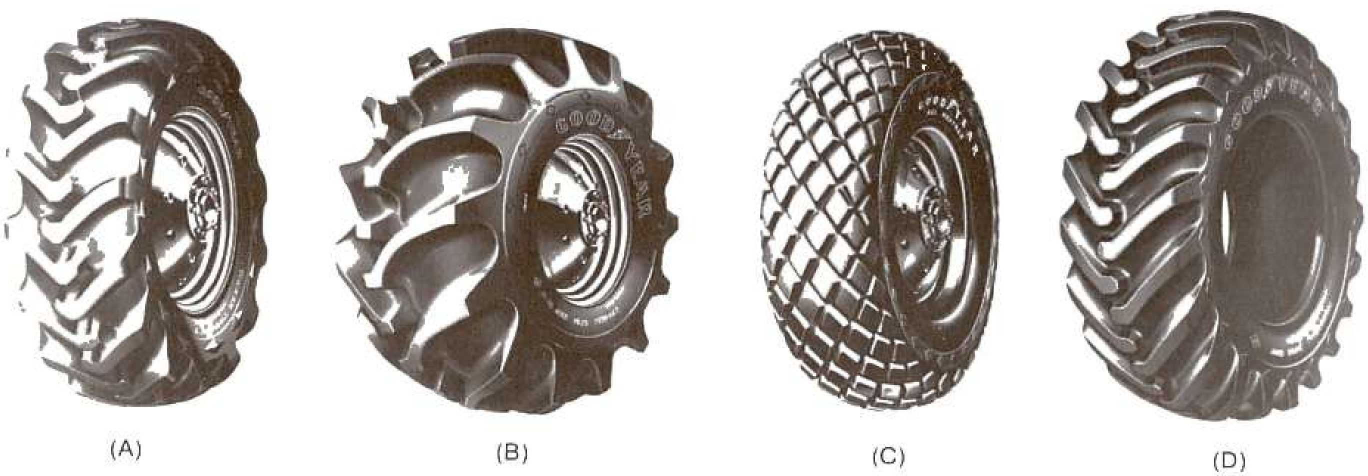

Figure 9 Tire tread designs for farming, logging, and construction machinery.

21.3 Core Concepts

Ballast: Supplemental weight added to a vehicle or implement to optimize traction, stability, and soil penetration. In tractors, proper ballasting reduces wheel slip and lowers fuel consumption by ensuring the engine's power is effectively transferred to the ground.

Brake (flywheel) horsepower: The total power output produced by an engine's crankshaft, measured at the flywheel before losses from the drivetrain, alternator, or hydraulic pumps. It is expressed in horsepower (hp) or kilowatts (kW). The term originates from the Prony brake, a friction-based measurement device.

Draft: The horizontal force required to pull a soil-engaging implement (e.g., plow, drill) through the ground. Draft is measured in pounds-force (lbf) or kilonewtons (kN). The relationship between draft and power is defined by the formula:

$$P = F \times v$$

Where P is power, F is draft force, and v is ground speed. To convert kilowatts to horsepower, use 1 hp = 0.746 kW.

Drawbar horsepower: The actual power available at the tractor's hitch for pulling a load. Unlike brake horsepower, drawbar horsepower accounts for frictional losses in the drivetrain and tractive efficiency (soil-tire interaction). It is typically measured as a percentage of the PTO (Power Take-Off) horsepower.

Dynamometer: A device used to measure torque and rotational speed (RPM) to calculate the power output of an engine or motor. While brake-type dynamometers use friction, modern versions use electrical or hydraulic resistance. Tractor-specific testing often uses a PTO dynamometer or hitch-mounted strain gauges to measure field draft.

Field capacity: Field capacity is the water content of a soil after the rate of downward drainage has become negligibly small following saturation. Following irrigation or rainfall, water moves downward under gravity; as larger, well-connected pores drain, hydraulic conductivity decreases sharply, and the remaining water is retained in smaller pores by capillary forces governed by adhesion, surface tension, and pore geometry. The matric potential at field capacity is conventionally approximated at −10 kPa for coarse-textured soils and −33 kPa for finer-textured soils. Most agricultural soils reach field capacity within 24–72 h after wetting, though this may be shorter in coarse sands or extended in fine-textured or layered profiles.

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 newtons (N, metric units) or pounds force (lbf, English units). The metric base units are 1 kg • m/s^2 derived from Newton's second law equation Force (F) = mass (m) × acceleration (a). Seconds are squared (s^2) because acceleration is calculated by dividing the change in velocity (meters per second) by time (also measured in seconds).

Friable: Physical state of the soil that is easily worked with tillage tools. Soil clods are said to be friable when they easily crumble 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 the torque developed by the engine that enables 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 attachment. The drawbar of a tractor is also considered to be a point of attachment. Tools hitched to a drawbar are called *drawn* implements.

Mass: The amount of matter in a body 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 the gram or 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's electrical system. The units of power are 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 implement through a series of shafts and universal joints. The standard 6-spline shaft on smaller tractors rotates at 540 RPM optimal. Larger tractors may accept a 21-spline shaft that rotates at 1,000 RPM optimal.

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 the weight on the tire. Rolling resistance also increases as soil strength decreases.

Shear strength: The ability of 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: Soil strength is the degree of resistance of a soil mass to crushing or deformation when a force is applied. Strength, along with friability, plasticity, and stickiness, are properties of soil consistency. Soil strength is determined by the degree of cohesion and internal friction existing between soil particles. Units are pounds force/ft^2 (English) and

Newton/m^2 (metric). Soil strength may be determined qualitatively from the pressure required to squeeze a fragment of air-dry soil 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: A physical property that exists at the interface of a liquid and a gas or a liquid and a solid. In water, surface tension arises from an imbalance in the cohesive forces between water molecules in contact with one another and those 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 that of 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 newton-meter (N•m, metric); however, the concepts 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 factors such as the type of surface, the contact area between the tires and the surface, and the tractor's power and weight.

***Tractive efficiency*:** Fraction of power available at the axle that is 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 to which traction is sufficient to prevent the wheels from slipping.

***Tractor*:** A high-torque vehicle, powered by a gasoline or diesel engine, having large, deeply treaded tires, used in farming and auxiliary power. There are four main types of farm tractors:

1. General Purpose: for standard crop production
2. Utility: For earthwork, loading, and grading
3. Row Crop: Featuring adjustable tread for driving between planted row
4. Orchard: Compact and shielded for maneuvering under trees

5. ***Weight:*** Force applied to a body in a gravitational field. Weight (W) is a body's mass (m) multiplied by the acceleration of gravity (g):

$$W = m \times g$$

In Earth's gravitational field, a body that is not restrained will accelerate toward the center. If a body is restrained, the restraining force is equal to or represents the weight of the body. For example, when a body is placed on a scale, the spring mechanism acts as the restraining force. The measured restraining force is the body's weight. The weight of the body will vary at different places on Earth's surface due to differences in gravitational acceleration. On the other hand, the mass of a body is fixed and remains constant anywhere it is measured. The following table compares the attributes of weight and mass.

Mass	Weight
Fixed property of matter	Depends on gravity
Can never be zero	Can be zero under no gravity
Does not vary with location	Varies according to location
Scalar quantity: has magnitude but no direction	Vector quantity: has magnitude and is directed toward the center of a gravity sink
Usually measured in grams or kilograms (SI).	Often measured in Newtons, a unit of force (SI).

***Wheel slippage*:** The amount of soil that deforms horizontally as a wheel passes over it. Wheel slippage is a factor in computing *tractive efficiency*, resulting in a net loss of tractive power. A slip of 8–15% is typically targeted for maximum efficiency in the field.

***Work*:** Defined as the action of a force through a distance, without regard to time. The idea of displacing an object over a distance is central to the definition of work. Work is the product of force x distance:

$$W = F \times d$$

Work is measured in units of foot-pounds (ft•lb, English) and Newton-meter (N•m, metric). 1 Newton-meter = 1 Joule (J).

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