Selections from C. E. Goering and A. C. Hansen. 2014. Engine and Tractor Power. 4th ed. ASABE.

Chapter 2, fig. 2.3, Theoretical Diesel Cycle

The cycle shown in Figure 2.3 is Dr. Rudolph Diesel's original theoretical cycle for the diesel engine. The cycle is identical to the Otto cycle, except for the processes between points 2 and 4. Also, the pressure at point 2 is much higher in the diesel cycle than in the Otto cycle because of a higher compression ratio. Injecting and burning the fuel at constant volume in the diesel cycle would have caused very high engine pressures and stresses at point 3 because of the high compression pressure at point 2. The excessively high pressures were avoided in the theoretical diesel cycle by injecting and burning the fuel during the expansion stroke. Gas pressures tend to fall during an expansion stroke, but, by injecting the fuel energy at the right rate, pressures were kept constant between points 2 and 3 of the theoretical diesel cycle. Fuel input is stopped at point 3, and the pressures begin to fall, as in a normal expansion stroke. Point 3 is called the **fuel cutoff point**, and the ratio V_3/V_2 is called the **fuel cutoff ratio**.

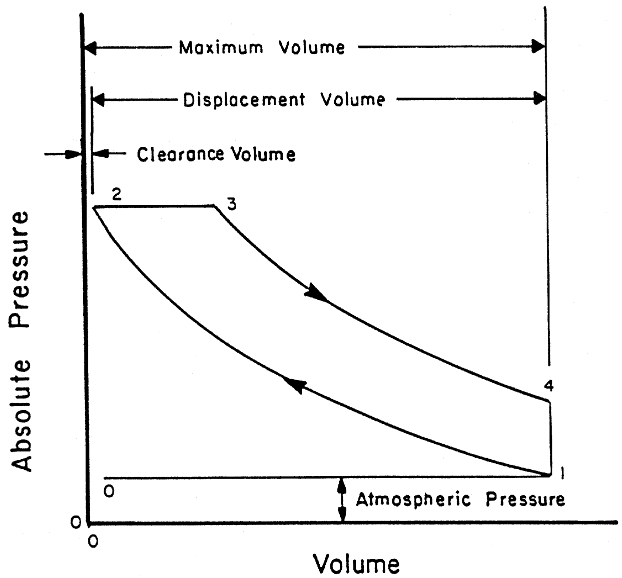

Figure 2.3 The theoretical diesel cycle

Chapter 5, eq. 5.1-5, Torque Equations

In Figure 5.1, the torque exerted on the nut is defined by the following equation:

$$T = F * L \quad (5.1)$$

where T = torque in N.m (Lb-ft)
F = force in N (Lb)
L = length in m (ft)

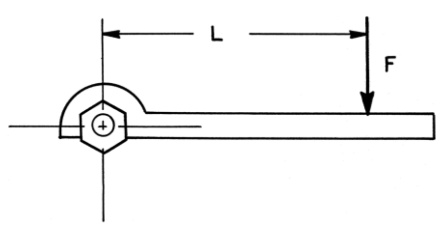

Figure 5.1-Torque being exerted by a wrench.

Notice that torque could be increased by exerting a larger force on the wrench or by exerting it further from the center of the bolt. Engines must produce torque in order to rotate the drive wheels when a tractor is pulling a load.

In Chapter 2, work was defined as a force acting through a distance. In contrast, torque is a force acting perpendicular to a distance, the distance being measured from a center of turning to the point of application of the force. In customary units, torque is given in Lb-ft to avoid confusion with work or energy, whose units are ft-Lbs. A torque does not necessarily do work. If the nut in Figure 5.1 resisted all movement, for example, a large torque could be exerted without accomplishing any work. Conversely, work would be done if the wrench moved. Suppose that a constant torque was exerted while the wrench traveled one revolution, as shown in Figure 5.2. Then, the force would have traveled a distance equal to the circumference of a circle of radius L. Thus, the work done per revolution (work/rev) would be:

$$\text{work}/\text{rev} = [2\pi L]*[F] = [2\pi]*[LF] = 2\pi * T \qquad (5.2)$$

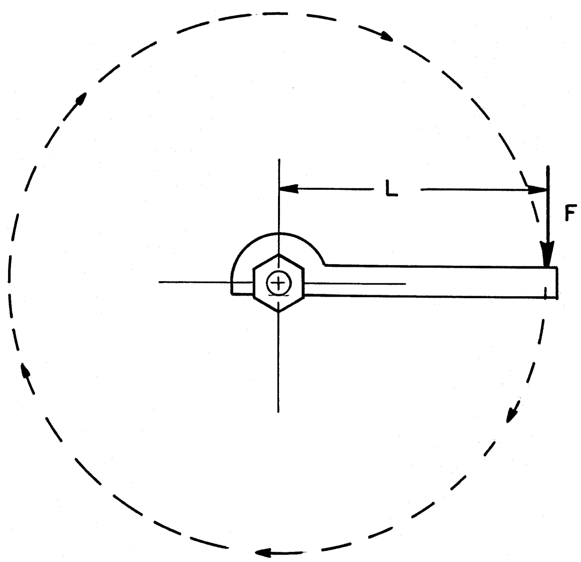

Figure 5.2-Work being done by a wrench.

That is, the work in joules (ft-Lbs) per revolution is 2π times the torque in N.m (Lb-ft).

Power is defined as the rate of doing work. That is, it is the amount of work accomplished per unit of time. In equation form, power (P) is defined as follows:

$$P = \frac{F * x}{t} = F * \left[\frac{x}{t}\right] \qquad (5.3)$$

where x = distance traveled by the force (F) in time (t)

A force of one newton (pound) moving a distance of one meter (foot) in one second would expend an amount of power equal to one N.m/s (ft-Lb/s). This combination of SI units has been given the name watt (W) in honor of James Watt. A watt is such a small unit that tractor power is more frequently measured in kilowatts (kW). In customary units, as was mentioned in Chapter 2, it was James Watt who defined one horsepower (hp) as being equal to 550 ft-Lbs/s.

In Chapter 2, linear speed was defined as distance traveled per unit of time. Therefore, Equation 5.3 can be interpreted as showing that linear power is the product of force times the speed with which the force is moving. Equation 5.4 computes linear power in typical units:

$$P = \frac{F * S}{K_{LP}} \quad (5.4)$$

where P = linear power in kW (hp)

F = force in kN (Lbs)

S = speed in km/h (mph)

K_{LP} = units constant = 3.6 (375)

Just as linear speed is defined as linear distance traveled per unit of time, **rotary speed** is defined as the amount of angular rotation per unit of time. The most common units for rotary speed are revolutions per minute (rev/min).

Rotary power is the product of work/rev (from Equation 5.2) and rotary speed. Equation 5.5 is used to compute rotary power in typical units:

$$P = \frac{2\pi * T * N}{K_{RP}} \quad (5.5)$$

where P_b = brake power in kW (hp)

T = engine torque in N.m (Lb-ft)

N = engine rotational speed in rev/min

K_{RP} = units constant = 60,000 (33,000)

The term **brake power** is used because the first devices for measuring engine power were called prony brakes. The term **flywheel power** is used interchangeably with brake power. Equation 5.5 can also be used to calculate power at the power take off (pto) if pto torque and speed are used instead of engine torque and speed.

Chapter 5, eq. 5.6, Power Adjectives

Power can be measured at various places on or in an engine or tractor. The amount of power varies greatly depending on where it is measured. Thus, various adjectives have been coined to describe measured power. The fuel is the source of all engine power (Figure 5.3). **Fuel equivalent power** can be computed from the product of fuel consumption rate and the heating value of the fuel:

$$P_{fe} = \frac{HV * \dot{M}_f}{K_{fe}} \quad (5.6)$$

where P_{fe} = fuel equivalent power in kW (hp)

HV = heating value of fuel in kJ/kg (BTU/Lb)

$\dot{M}_f$ = fuel consumption rate in kg/h (Lb/h)

K_{fe} = units constant = 3600 (2545)

In customary units, heat energy is measured in BTU, for British Thermal Units. The heating value of fuel is the amount of energy that would be released in burning a kilogram (pound) of fuel. Fuel heating values are listed in Table 6.5 and will be discussed in Chapter 6. The fuel consumption rate can be measured on a mass basis, as in Equation 5.6, or on a volume basis.

Chapter 5, eq. 5.15-18, Power Efficiencies

Several efficiency terms have been coined for describing how well engines convert fuel energy into useful power. **Indicated thermal efficiency** (e_{it}) is the fraction of fuel equivalent power that is converted to indicated power:

$$e_{it} = \frac{P_i}{P_{fe}} \quad (5.15)$$

Thus, indicated thermal efficiency is a measure of the combustion efficiency of the engine. For example, the indicated thermal efficiency of an engine could be increased by raising the compression ratio, but not by reducing the friction losses. The latter change would increase the mechanical efficiency.

Mechanical efficiency (e_m) is the fraction of the newly created indicated power that is delivered as useful power from the engine:

$$e_m = \frac{P_b}{P_i} \quad (5.16)$$

Brake thermal efficiency (e_{bt}) is the overall efficiency of the engine in converting fuel power into useful power:

$$e_{bt} = \frac{P_b}{P_{fe}} \quad (5.17)$$

The brake thermal efficiency, e_{bt}, is an indication of the fraction of the energy in the fuel that is converted to power at the flywheel. If the power was measured at the pto instead, Equation 5.17 would give the pto thermal efficiency, e_{pto}. Similarly, if the power was measured at the drawbar, the efficiency would be designated the drawbar thermal efficiency, e_{db}. The brake thermal efficiency can also be calculated using the following equation:

$$e_{bt} = e_{it} * e_m \quad (5.18)$$

Thus, for good overall efficiency, an engine must be mechanically efficient and have an efficient combustion process. Figure 5.6 summarizes the relationship of the various efficiencies to the power flow through an engine. Example Problem 5.4 illustrates the calculation of an example engine's efficiencies.

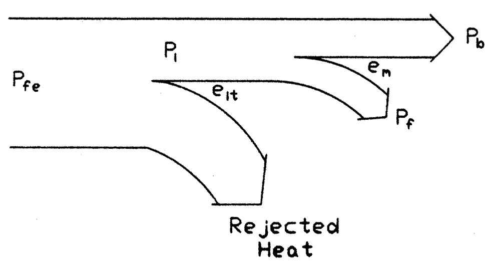

Figure 5.6- Energy flows through an engine.

Chapter 5, eq. 5.20, Specific Fuel Consumption

The rate at which an engine consumes fuel (in kg/h or Lb/h) varies with its efficiency but also with its size and load, that is, a large, heavily loaded engine will always consume more fuel than a small, lightly-loaded one. Thus, although engine efficiency affects fuel consumption, fuel consumption alone is not a good indicator of engine efficiency. The term **specific fuel consumption** (SFC), has been developed to indicate fuel consumption in relation to the amount of work that is being done by the engine. SFC is defined as follows:

$$SFC = \frac{\dot{M}_f}{P} \quad (5.20)$$

where: SFC = specific fuel consumption in kg/kW.h (Lb/hp-h)

$\dot{M}_f$ = fuel consumption rate in kg/h (Lb/h)

P = power, kW (hp)

Chapter 6, eq. 6.1, 6.2, table 6.6, Combustion Equation

The API has devised a special scale for gravities. It is expressed in API degrees and is calculated as follows:

$$API^{o} = \frac{141.5}{SG} - 131.5 \qquad (6.1)$$

where SG = specific gravity of fuel at 15.5 ^{o}C (60 ^{o}F)

Equations have been developed for estimating the heating value of petroleum fuels from their API gravity. The equations are:

$$HHV = K_{F1} + K_{F2}(API - 10) \qquad (6.2)$$

and $LHV = 0.7190HHV + K_{F3}$ (6.3)

where HHV = higher heating value in kJ/kg (BTU/Lb)

LHV = lower heating value in kJ/kg (BTU/Lb)

API = API gravity in degrees

K_{F1} = constant = 42,860 (18,440)

K_{F2} = constant = 93 (40)

K_{F3} = constant = 10,000 (4,310)

Table 6.6 Comparison of properties of several fuels

Fuel	**API Gravity Degrees**	**Density kg/L (Lb/gal)**	**Higher Heating Value kJ/kg (BTU/Lb)**	**Research Octane No.**	**Boiling Range ^{o}C (^{o}F)**	**Stoich Air-Fuel Ratio**
Hydrogen	---	0.09×10^{-3} [a] ($.751\times10^{-3}$)	142,000 (61,045)	130+	-253 (-423)	34.3
Butane	112	0.580 (4.835)	49,500 (21,280)	98	0 (32)	15.5
Propane	146	0.509 (4.244)	50,300 (21,625)	111	-44 (-42)	15.7
Gasoline	61	0.735 (6.128)	47,600 (20,464)	93	30-230 (86-446)	15.2
No. 1 diesel	40	0.823 (6.861)	45,700 (19,647)	40[b]	160-260 (320-500)	15.0
No. 2 diesel	38	0.834 (6.953)	45,500 (19,560)	40[b]	200-370 (392-700)	15.0
Methyl soyate	---	0.885 (7.378)	38,379 (16,500)	51[c]		12.5
Methanol	---	0.792 (6.603)	22,700 (9,759)	110	65 (149)	6.49
Ethanol	---	0.785 (6.545)	29,700 (12,769)	110	78 (172)	8.95
Butanol	---	0.805 (6.711)	36,100 (15,520)		118 (244)	11.2

[a]At a pressure of 100 kPa (14.5 psi) and temperature of 25°C (77°F)
[b]Minimum cetane rating for diesel fuel
[c]Measured cetane rating for methyl soyate (methyl ester of soybean oil)

Chapter 14, eq. 14.3-4, fig. 14.1, Hydraulic System Power

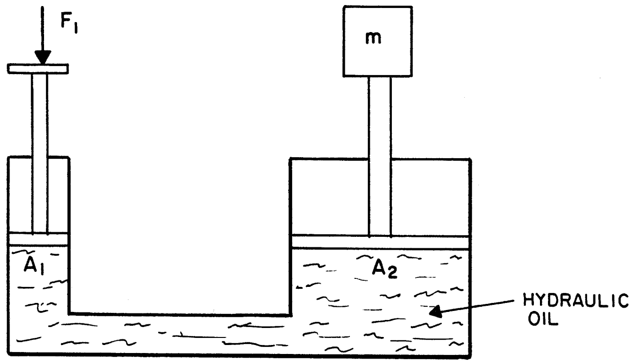

Figure 14.1 A positive displacement hydraulic system providing mechanical advantage.

Suppose the small piston in Figure 14.1 was pushed down a distance of 10 cm (4 in) in one second. Oil would be forced into the large chamber, and the large piston would be forced to raise the heavy mass. How fast would the large piston move, and how far would the mass be raised? The fundamental relationship needed to answer the question is that flow is the product of velocity and area. Equations 14.3 and 14.4 show this relationship with a constant inserted for more convenient units:

$$Q = K_v \, V \, A \qquad (14.3)$$

and $$V = \frac{Q}{K_v \, A} \qquad (14.4)$$

where: Q = oil flow rate in L/min (gpm)
V = piston speed in m/s (ft/s)
A = piston area in cm^2 (in^2)
K_v = units constant = 6 (3.12)

Chapter 14, eq. 14.11, Hydraulic Pump Power

The hydraulic power produced by a pump can be calculated by using Equation 14.11:

$$P_h = \frac{Q_A \, \Delta p}{K_p} \qquad (14.11)$$

where: P_h = hydraulic power in kw (hp)
Q_A = actual delivery in L/min (gpm)
Δp = pressure rise across the pump in MPa (psi)
K_P = units constant = 60 (1714)

Chapter 14, eq. 14.15, Hydraulic Cylinder Force

The load that can be moved by a hydraulic cylinder can be calculated from Equation 14.15:

$$F = \frac{p_1 A_1 - p_2 A_2}{K_p} \qquad (14.15)$$

where: F = force exerted by the cylinder rod in kN (Lbs)
A_1 = area of piston in cm^2 (in^2)
A_2 = area of piston minus area of rod in cm^2 (in^2)
p_1 = pressure acting on area A_1 in MPa (psi)
p_2 = pressure acting on area A_2 in MPa (psi)

K_p = units constant = 10 (1)

Chapter 14, eq. 14.17-18, Hydraulic Motor Power

The motor torque can be calculated as follows:

$$T = \frac{\Delta p\, D_m\, e_{Tm}}{K_{Tm}\, \pi} \qquad (14.17)$$

where: T = shaft torque in N.m (Lb-ft)

Δp = pressure drop across motor in MPa (psi)

D_m = motor displacement in cm^3/rev (in^3/rev)

e_{Tm} = torque efficiency in decimals

K_{Tm} = units constant = 2 (24)

The power available from a hydraulic motor is calculated with Equation 14.18:

$$P_S = \frac{Q_A\, \Delta p\, e_{pp}}{K_p} \qquad (14.18)$$

where: P_s = shaft power available from motor in kW (hp)

Q_A = oil delivery to motor in L/min (gpm)

Δp = pressure drop across motor in MPa (psi)

e_{Pm} = power efficiency in decimals

K_P = units constant = 60 (1714)

Chapter 14, figs. 14.23, 14.25, Open Center/Closed Center

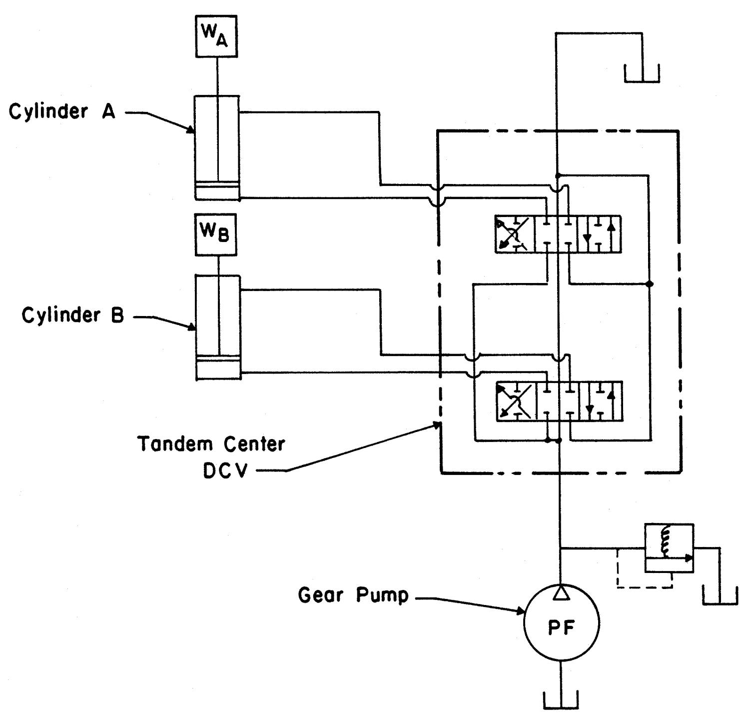

Figure 14.23 An open-center hydraulic system.

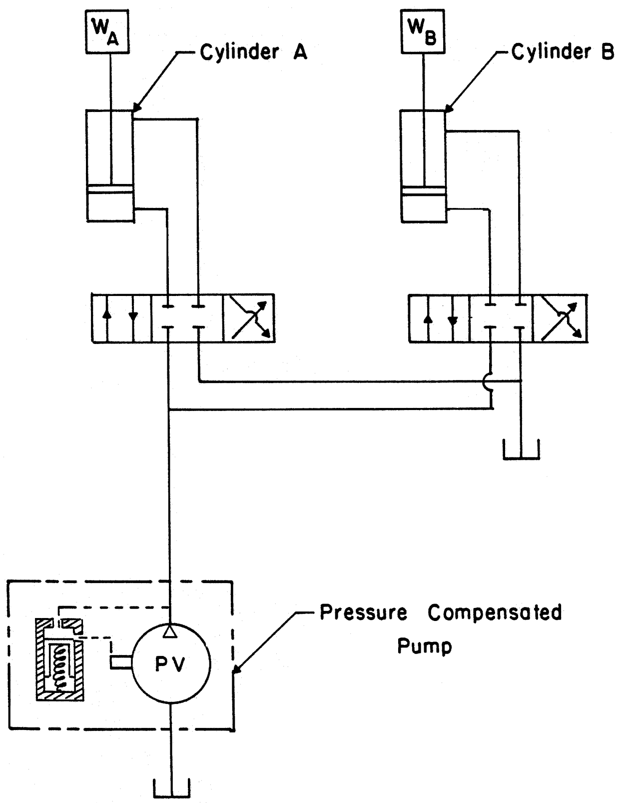

Figure 14.25 A pressure-compensated hydraulic system.

Chapter 15, eq. 15.1-2, Clutch

The torque-transmitting capacity of a clutch or brake can be calculated by using Equation 15.1:

$$T = F_c \, f \, r_m \, n \qquad (15.1)$$

where: T = torque in N.m (Lb-ft)

F_c = clamping force in kN (Lbs)

f = coefficient of friction

r_m = mean radius of the clutch or brake in mm (ft)

n = number of torque-transmitting surfaces

In the case of drum brakes, r_m is one half the inside diameter of the brake drum. For disk brakes, r_m is the radius from the axle centerline to the center of the brake pads. For clutches, the following equation can be used to calculate the mean radius:

$$r_m = \frac{d_o^3 - d_i^3}{3(d_o^2 - d_i^2)} \qquad (15.2)$$

where: d_o = outside diameter of clutch disk in mm (ft)

d_i = inside diameter of clutch disk in mm (ft)

Chapter 15, eq. 15.3-5, Gear Equations

Generally, several sets of gears are used to transmit power from the engine to the drive wheels of a vehicle. The gears are used to reduce speed and increase torque as power flows toward the drive wheels. When two gears are in mesh, the rotation of either gear can be calculated from the rotation of the other by using the following equation:

$$n_1 \theta_1 = n_2 \theta_2 \qquad (15.3)$$

where: n_1 and n_2 = number of teeth on gears 1 and 2, respectively

θ_1 and θ_2 = rotation of gears 1 and 2, respectively

Since the two rotations are accomplished within the same time period, the speed of either gear can be calculated from the other by using the following equation:

$$n_1 N_1 = n_2 N_2 \qquad (15.4)$$

where: N_1 and N_2 = rotational speeds of gears 1 and 2, respectively.

Usually, in a vehicle, gear sets are arranged so that the output speed is less than the input speed. The gear ratio is defined as the speed of the input shaft divided by the speed of the output shaft, as in the following equation:

$$R = \frac{N_{in}}{N_{out}} \qquad (15.5)$$

Where: R = gear ratio

N_{in}, N_{out} = rotational speeds of input and output shafts, respectively

Chapter 16, eq. 16.1-2, Weight Transfer

A tractor is shown resting on a smooth, horizontal surface in Figure 16.1. Three forces are applied to the tractor body. The tractor weight (W) is shown acting at the *center of gravity* of the tractor. The center of gravity can be considered a balance point. That is, if the tractor was lifted by a cable attached exactly at the center of gravity, the tractor would not tip in any direction. The weight of the tractor is supported by the ground through forces R_r and R_f applied at the rear and front wheels, respectively.

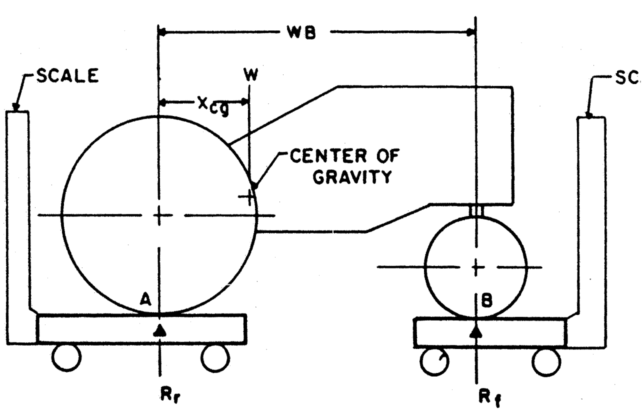

Figure 16.1 Tractor weight force and ground support forces.

Suppose that point A in Figure 16.1 is chosen as a center of moments. The perpendicular distance from point A to the weight force W is shown as X_{cg}, the distance from the rear axle centerline to the center of gravity. The weight W produces a clockwise (CW) moment, $(W)(X_{cg})$, about point A. The force R_r passes through point A and thus produces no moment. The force R_f produces a counterclockwise (CCW) moment, (R_f)(WB), about point A. The distance WB is the *wheelbase* of the tractor. For the tractor to be in equilibrium, the CW moment about point A must equal the CCW moments; therefore (using the quantities in Figure 16.1):

$$W\,X_{cg} = R_f\;WB \tag{16.1}$$

where: W = weight of tractor in kN (Lbs)

X_{cg} = distance from rear axle centerline to center of gravity in mm (in)

R_f = ground support force on front wheels in kN (Lbs)

WB = wheelbase of tractor in mm (in)

Dividing Equation 16.1 by the weight W provides a useful equation for calculating X_{cg}:

$$X_{cg} = \frac{R_f}{W}WB \tag{16.2}$$

We could place the front wheels of the tractor on a scale to measure R_f and then place the entire tractor on the scale to measure W. The wheelbase could be measured with a ruler, and Equation 16.2 could then be used to calculate X_{cg}.

The center of gravity of a tractor can be changed by adding ballast weight to the tractor. Adding ballast to the tractor ahead of the center of gravity increases X_{cg}; adding ballast behind the center of gravity decreases X_{cg}.

Chapter 16, eq. 16.10-11, Travel Reduction

Travel reduction refers to the reduction in forward speed that occurs when a tractor pulls a drawbar load. The term *slip* often is used interchangeably with travel reduction, even though the true slip is slightly greater than the travel reduction, i.e., there is some slip even when the tractor is not pulling a drawbar load. For example, although travel reduction is actually measured in Nebraska or OECD Tractor Tests, the results are reported as slip. Travel reduction can be calculated using the following equation:

$$TR = 100\left[1 - \frac{2\pi r}{2\pi r_o}\right] \tag{16.10}$$

where: TR = travel reduction in percent

r = effective rolling radius while pulling, in mm (in)

r_o = rolling radius on a specified surface in mm (in) when tractor pulls no load.

Measuring effective rolling radii is inconvenient. However, multiplying the rolling radius by the axle rotational speed gives the forward speed. If the engine is operating in the governor-controlled range (see Section 5.8.2) such that there is little change in axle speed due to the applied load, the approximate travel reduction can be calculated using the following equation:

$$TR = 100\left[1 - \frac{S_a}{S_o}\right] \tag{16.11}$$

where: S_a = actual speed in km/h (mph)

S_o = travel speed on a specified surface in km/h (mph) when tractor pulls no load

It is common practice to measure the no-load speed (S_o) when the tractor is running on a roadway or other rigid surface. The actual speed (S_a) must be measured in the field in which the tractor is working. Notice that the tractor cannot develop drawbar pull unless there is travel reduction. The tire lugs must move rearward and compress the soil to make it strong enough to support the tractive force F_t (Figure

16.2); the rearward movement of the lugs and the consequent shearing of the soil causes travel reduction.

Chapter 16, eq. 16.14-15, Tractive Efficiency

Tractive efficiency refers to the fraction of axle power that is converted to drawbar power by the drive wheels. Thus, tractive efficiency is defined as:

$$TE = \frac{P_{db}}{P_A} \tag{16.14}$$

where: TE = tractive efficiency in decimals

P_{db} = drawbar power in kW (hp)

P_A = axle power in kW (hp)

By making use of Equation 5.4 for drawbar power, the following equation for tractive efficiency can be developed:

$$TE = \frac{F_{db}\ S_a}{K_{LP}\ P_A} \tag{16.15}$$

where: K_{LP} = units constant = 3.6 (375)

The other variables in Equation 16.15 were previously defined. Equations 16.14 and 16.15 apply to tractors with 2WD, 4WD or crawler tractors.