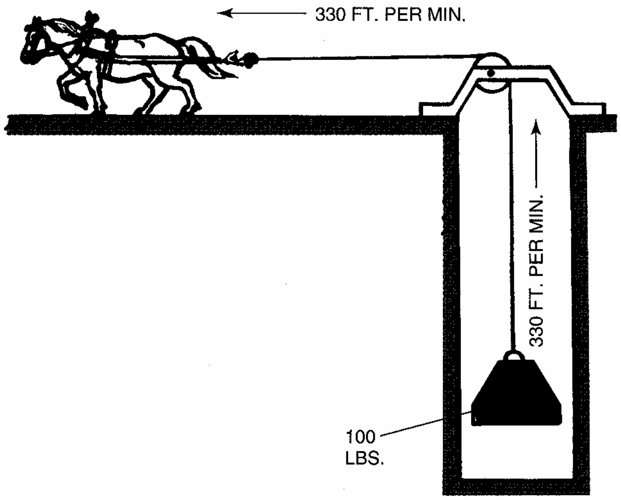
Force, Work, Power and Torque



Force, *F*, measures the strength with which one object pushes or pulls another object. For example, a 100 lb weight suspended from a cable exerts a force of 100 lbs on the cable. Work, *W*, is the application of a force through a distance, Δx. We express this as:

$$W = F\Delta x$$

For example, if you raise a 100 lb weight 10 ft, you perform 1000 ft-lb of work, or to drive a 2000 lb car to the top of a 100 ft hill requires 200,000 ft-lb of work (with no friction losses).

For automotive performance, we want to achieve maximum power. Power is the rate of performing work, i.e. the amount of work performed per unit of time, Δt. Power is represented by:

$$P = F\frac{\Delta x}{\Delta t} = Fv$$

The distance traveled per unit of time, $\Delta x/\Delta t$, is the speed of travel, *v*. For the example pictured, raising a weight of 100 lbs at a rate of 330 ft/min requires 33,000 ft-lb/min. 33,000 ft-lb/min or 550 ft-lb/sec is defined as one horsepower. For a 2,000 lb car to reach the top of a 100 ft hill in 30 sec (excluding friction) requires:

$$\frac{(2000lb)(100\,ft)}{(30\sec)} = 6{,}667\ ft - lb/\sec = 12.1hp$$

If we want to climb the hill in 15 sec, we need twice as much power.

When a twisting or rotational force is applied to an object, torque is the product of the force and the distance from the center of rotation. For the wheel of an automobile, the distance from the center of rotation is half the wheel diameter, *D*. However, the overall gear ratio, *G*, effectively reduces the wheel diameter, so the engine torque is given by:

$$T = F\frac{D}{2G}$$

When the engine turns one revolution, the car will travel a distance of $\pi D/G$. If the engine is turning at a rate R, then the speed is:

$$v = \frac{\pi DR}{G}$$

By comparing these relationships, we see that power and torque are related as follows:

$$P = 2\pi RT$$

For all of these equations, conversion factors must be used to make the units consistent. For example, if we use units of horsepower for P, ft-lb for T and revolutions per minute for R, this relationship becomes:

$$P = \frac{RT}{5252}$$

We hear people speak as if torque and horsepower are two separate and distinct quantities, but this is not the case. The two are related by the equation above. They provide two different ways to look at the same information.

Forces Acting on an Automobile

For an automobile traveling on a constant grade, the figure summarizes the active forces. The net force is given by (see reference 1):

$$F = F_e - F_d - F_f - F_r - F_g$$

where: F_e is the force produced by the engine, F_d is the force caused by wind resistance or drag, F_f is the force associated with drive train friction losses, F_r is the force due to rolling resistance, and F_g is the force due to gravity when the car is on a grade. If the net force, F, is known, the rate of acceleration can be determined from Newton's second law, i.e. when a force is applied to an object with mass, m, it will cause the object to accelerate at a rate a:

$$F = ma$$

If the forces are balanced so the net force is zero, the car will neither acceleration nor decelerate, but will travel at a constant rate of speed. If we can determine each of the forces, we can calculate how the car will perform.

The force produced by the engine, F_e, comes from the power and torque curves measured on a dyno. Drive train friction losses are difficult to correlate, so a simple factor is normally used to estimate this loss:

$$F_f = C_f F_e$$

where: C_f typically ranges from 0.05 to 0.15. However, for a Model T, we've found 0.2 to be reasonable.

The force associated with wind drag is determined by:

$$F_d = \frac{1}{2} C_d A \rho v^2$$

where: C_d is the drag coefficient, A is the frontal area, ρ is the density of air 0.0735 lb/cu ft at 80°F and atmospheric pressure and v is the speed of travel. For an automobile, drag coefficients typically range from about 0.2 to 0.7. We've found 0.8 to be a reasonable value for a Model T.

The force due to rolling resistance can be correlated by:

$$F_r = W C_r$$

where: W is the weight of the vehicle and C_r is the coefficient of rolling resistance, which typically ranges from 0.008 to 0.016.

The force due to gravity is:

$$F_g = \frac{Wp}{\sqrt{10000 + p^2}}$$

where: W is the weight of the car and p is the percent grade.

It is convenient to think of the values in terms of the force available at the rear wheels:

$$F_e(1 - C_f)$$

and the force required:

$$\frac{1}{2} C_d A \rho v^2 + W\left(C_r + \frac{p}{\sqrt{10000 + p^2}} \right)$$

The values can be represented in terms of power by multiplying each of the quantities by velocity, v. As explained above, gear ratio multiplies engine torque to give rear wheel torque, so the quantities above are multiplied by the wheel radius to get rear wheel torque:

$$TG = FD/2$$

In many cases, the values needed in the correlations (C_d, C_r, and C_f) will not be known or can only be roughly estimated. A coast down test can be used to estimate the drag coefficient and rolling resistance (see reference). A chassis dyno measures rear wheel power, so drive train friction losses are included.

Reference:

Bosch Automotive Handbook, 4th edition, pp 330-334, Robert Bosch GmbH, Stuttgart (1996).