Topic 2 | Automotive Power

A Case Study in Energy Relations

The power requirements of a gasoline-powered automobile are an important and practical example of the concepts in Chapter 6. If roads were flat and frictionless and air resistance didn't exist, there would be no need for an automobile to have an engine. All you'd need to go for a drive would be a few strong friends to give you a push to get started and a few other friends at your destination to stop you. (Steering on frictionless roads would be a problem, though.) In the real world, however, a moving car without an engine slows down because of forces that resist its motion. The engine's function is to continuously provide power to overcome this resistance. So to understand how much power is required from a car's engine, we must analyze the forces that act on the car.

Two forces oppose the motion of an automobile: rolling friction and air resistance. A typical value of μ_r for properly inflated tires on hard pavement is 0.015. A Porsche 911 Carrera has a mass of 1251 kg and a weight of (1251 kg) $\times$ (9.80 m/s^2) = 12,260 N, and so the resisting force of rolling friction on a level road (where the normal force $n = mg$) is

$$F_{\text{roll}} = \mu_r n = (0.015)(12{,}260\ \text{N}) = 180\ \text{N}$$

This force is nearly independent of car speed.

The air resistance force F_{air} is approximately proportional to the square of the speed and can be expressed by the equation

$$F_{\text{air}} = \frac{1}{2} C A \rho v^2 \qquad \text{(T2.1)}$$

where A is the silhouette area of the car (seen from the front), ρ is the density of air (about 1.2 kg/m^3 at sea level at ordinary temperatures), v is the car's speed, and C is a dimensionless constant called the *drag coefficient* that depends on the shape of the moving body. Typical values of C for cars range from 0.35 to 0.50; for the 911 Carrera, $C = 0.38$ and $A = 1.77$ m^2. For this car the air-resistance force is

$$F_{\text{air}} = \frac{1}{2}(0.38)(1.77\ \text{m}^2)(1.2\ \text{kg/m}^3)v^2 = (0.40\ \text{N}\cdot\text{s}^2/\text{m}^2)v^2$$

In a residential speed zone, where $v = 10$ m/s (36 km/h, or about 22 mi/h), the air-resistance force is about

$$F_{\text{air}} = (0.40\ \text{N}\cdot\text{s}^2/\text{m}^2)(10\ \text{m/s})^2 = 40\ \text{N}$$

At a moderate speed of 15 m/s (54 km/h or 34 mi/h), F_{air} is 90 N, and at a highway speed of 30 m/s (110 km/h or 67 mi/h) it is 360 N. Thus at slow speeds, air resistance is less important than rolling friction. At moderate speeds they are comparable, and at highway speeds air resistance dominates.

What does this mean in terms of the *power* needed from the engine? In constant-speed driving on a level road, the sum of F_{roll} and F_{air} must be just balanced by the forward force F_{forward} supplied by the drive wheels. (The drive wheels push backward on the pavement, and the pavement pushes forward on the drive wheels.) The power is just this forward force multiplied by the speed v. For the 911 Carrera the power needed for constant speed v is

$$P = F_{\text{forward}} v = (F_{\text{roll}} + F_{\text{air}})v = [180\ \text{N} + (0.40\ \text{N}\cdot\text{s}^2/\text{m}^2)v^2]v$$

For the three speeds mentioned above, you can do the arithmetic yourself to find the following results:

v (m/s)	F_{roll} (N)	F_{air} (N)	$F_{forward}$ (N)	P (kW)	P (hp)
10	180	40	220	2.2	2.9
15	180	90	270	4.1	5.5
30	180	360	540	16	22

How much fuel must be consumed in the engine to provide this power? Burning one liter (1 L) of gasoline releases about 3.5×10^7 J of energy. But not all of this is converted into useful work. The laws of thermodynamics, which we'll encounter in Chapters 19 and 20, impose fundamental limits on the efficiency of converting heat to work. In a typical car engine, about 65% of the heat released from gasoline combustion is wasted in the cooling system and the exhaust. Another 20% or so is converted to work that does nothing to propel the car; this includes work done to oppose friction in the drive train and to run accessories such as the air conditioner and power steering. This leaves only about 15% of the energy to do work against the rolling friction and air resistance we described above. The available energy per liter is then

$$(0.15)(3.5 \times 10^7 \text{ J/L}) = 5.3 \times 10^6 \text{ J/L} \qquad \text{(T2.2)}$$

Let's look at the fuel consumption in the 15-m/s case. The power required is 4.1 kW = 4100 J/s. In 1 hour (3600 s) the total energy required is

$$(4100 \text{ J/s})(3600 \text{ s}) = 1.5 \times 10^7 \text{ J}$$

and during that hour the car travels a distance of

$$(15 \text{ m/s})(3600 \text{ s}) = 5.4 \times 10^4 \text{ m} = 54 \text{ km}$$

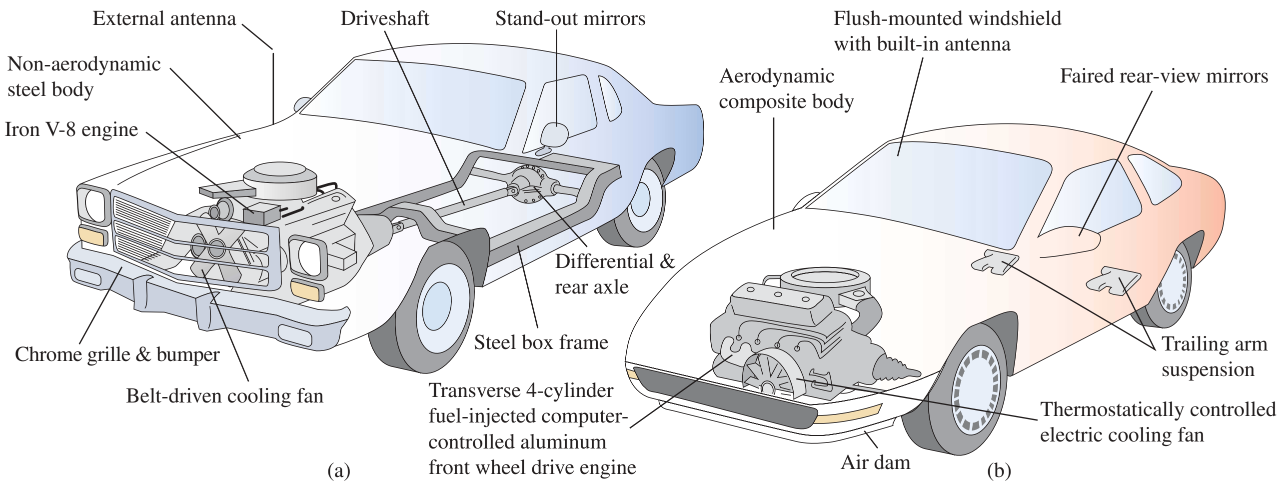
From Eq. (T2.2) the amount of fuel consumed in 1 hour, traveling 54 km at 15 m/s, is

$$\frac{1.5 \times 10^7 \text{ J}}{5.3 \times 10^6 \text{ J/L}} = 2.8 \text{ L}$$

That amount of gasoline moves the car 54 km, so the distance traveled per liter of fuel is (54 km)/(2.8 L) = 19 km/L, or about 45 miles per gallon. (Figure T2.1 shows some of the features of contemporary car design that have improved fuel efficiency.)

The power required for a steady 15 m/s on level ground is 4.1 kW, but the power required for acceleration and hill climbing may be much greater. The 911 Carrera is advertised as going from zero to 60 mi/h (27 m/s) in 6.1 s. The final kinetic energy is then

$$K = \frac{1}{2}mv^2 = \frac{1}{2}(1251 \text{ kg})(27 \text{ m/s})^2 = 4.6 \times 10^5 \text{ J}$$



T2.1 (a) Cars designed in the early 1970s did not feature aerodynamic styling and used heavy materials such as iron for engines and steel for body panels. Rear-wheel drive required a heavy drive train as well. (b) By the 1990s, economics forced new ideas in car designs. Body shapes had lower drag coefficients, engines were built of aluminum, and body panels were often made of plastic. These changes doubled the typical fuel efficiency of cars.

The average additional power required for the acceleration is

$$P_{av} = \frac{4.6 \times 10^5 \text{ J}}{61 \text{ s}} = 7.5 \times 10^4 \text{ W} = 75 \text{ kW} = 100 \text{ hp}$$

This rapid acceleration requires about 18 times as much power as cruising at a steady 15 m/s (not including the power to overcome friction in the drive train). For the record, the 911 Carrera advertises a maximum horsepower of 214 hp at an engine speed of 5900 rpm.

What about hill climbing? A 5% grade, about the maximum found on most interstate highways, rises 5 meters for every 100 meters of horizontal distance. A car moving at 30 m/s up a 5% grade is gaining elevation at the rate of (0.05) (30 m/s) = 1.5 m/s. The 911 Carrera weighs 12,260 N, so lifting it at this rate requires a power of

$$P = Fv = (12{,}260 \text{ N})(1.5 \text{ m/s}) = 1.8 \times 10^4 \text{ J/s} = 18 \text{ kW} = 24 \text{ hp}.$$

The total power required is this amount plus the 16 kW needed to maintain 30 m/s on a level road, that is,

$$P_{tot} = 18 \text{ kW} + 16 \text{ kW} = 34 \text{ kW} = 46 \text{ hp}.$$

Finally, let's compare the energy requirements of an automobile to your energy requirements while walking. A 70-kg man needs about 2.0×10^5 J of energy (released from food) to walk 1 km at 5 km/h = 1.4 m/s. If the 3.5×10^7 J obtained from 1 L of gasoline could somehow be made available to the man's body, he could travel a distance of $(3.5 \times 10^7 \text{ J})/(2.0 \times 10^5 \text{ J/km}) = 170$ km. Yet this same amount of energy can propel our car only 19 km. Of course, the car travels at more than ten times the speed of a walking man (15 m/s versus 1.4 m/s). But this example shows that the speed and convenience of traveling by automobile come only at the cost of greatly increased energy consumption.