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ELEMENTARY PHYSICS APPLIED TO AUTOMOBILE FUEL ECONOMY

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Introduction

Science educators, especially physics teachers, are frequently confronted with stories about devices and carburetors that permit ordinary cars to get spectacular fuel economy. The claims often exceed 46 kilometers per liter (110mpg). By applying basic physics as taught at the high school or college freshman level, one can measure the average power output of an automobile at any speed and calculate the maximum possible fuel economy that can be expected.

Power Measurement

An automobile's average power output to overcome wind and rolling friction at any speed can be measured with a stopwatch and the automobile's speedometer. The automobile is driven on a level roadway at a speed V_0. The car is shifted into neutral and allowed to coast to the final speed V_f. A stopwatch measures the time for this change in speed. This is then repeated on the same road in the opposite direction and the times are averaged to account for prevailing winds. Let the average time be *t* and the total mass of the automobile be *m*.

The power can be calculated from the time rate of change of the automobile's kinetic energy (KE) as it slows over the coasting interval.

$$P = -\frac{d(KE)}{dt} \qquad \text{(Eqn. 1)}$$

An average power is obtained by assuming that the power varies linearly with speed over the coasting interval. This assumption represents an approximation and its effect on the result will be discussed later.

Let,

$\overline{P}$ = average power required to overcome wind and rolling friction (watts)

$$\overline{P} = -\frac{\Delta KE}{t} = -\frac{(\frac{1}{2} m v_f^2 - \frac{1}{2} m V_0^2)}{t}$$

$$\overline{P} = \frac{m}{2t} \times (V_0^2 - V_f^2) \qquad \text{(Eqn. 2)}$$

Example

A 1973 Volkswagen Sedan (Type I) was allowed to coast from 97 km/h (60 mph) to 81 km/h (50 mph) and the average coasting time, t, was measured to be 12.4 seconds. According to the license registration form, the vehicle had a mass of 910 kilograms plus an additional 340 kilograms for four adult passengers to make a total mass of 1250 kilograms.

The average power developed to overcome rolling and wind friction is given by Eqn. 2.

$$\bar{P} = \frac{m}{2t} (V_o^2 - V_f^2)$$

$$\bar{P} = \frac{1250 \text{ kg}}{2 \times 12.4 \text{ s}} [(27.0 \frac{m}{s})^2 - (23.0 \frac{m}{s})^2]$$

$$\bar{P} = 10.0 \text{ kilowatts} \quad (14 \text{ horsepower})$$

Maximum Fuel Economy

Whenever it is necessary to make assumptions about the processes involved, these assumptions will tend to favor higher fuel economy. Therefore, the results will indicate the maximum or upper limit to fuel economy.

Let:

e = engine efficiency
$\bar{V}$ = average speed (kilometers per hour)
f = fuel economy (kilometers per liter)
d = energy density of the fuel (joules per liter)
$\bar{R}$ = average rate of energy consumption (watts)

then,

$$\bar{R} = \frac{\bar{V}}{f} \cdot d \times \left(\frac{1}{3600} \text{ h/s}\right) \qquad \text{(Eqn. 3)}$$

but,

$$\bar{P} = e \bar{R} \qquad \text{(Eqn. 4)}$$

or,

$$\bar{P} = e \frac{\bar{V}}{f} d \times \left(\frac{1}{3600} \text{ h/s}\right)$$

therefore,

$$f = e \frac{\bar{V}}{\bar{P}} \cdot d \times \left(\frac{1}{3600} \text{ h/s}\right) \qquad \text{(Eqn. 5)}$$

Discussion

Equation 5 can serve many purposes in the classroom. For example, one can discuss the way in which fuel economy depends upon power and efficiency. This leads nicely into a discussion of aerodynamic design and its effect on power requirements. As the students tackle the problem of increasing the efficiency, they quickly discover and appreciate the limitations of the heat engine. Often times, an alert student will notice that the fuel economy appears to be directly proportional to the speed. Down with the 55 mph speed limit! Having allowed this blunder to occur, one can slip neatly into a discussion of how the power varies with the speed. As mentioned earlier, this method of averaging power assumes that the power varies linearly with speed over the coasting interval. The power actually varies as V^n ($n > 1$) so that the power output above the average contributes more than the power output below the average. Therefore, power is underestimated and fuel economy is overestimated. An interesting experiment that can be easily conducted is to apply equation 2 at a number of different speeds. A plot of power versus speed on log-log graph paper yields n, the exponent on V. Once n is established, a meaningful discussion of the relationship between fuel consumption and vehicle speed is possible.

Equation 5 may also be used to estimate engine efficiency if the power and fuel economy have been measured. Interesting experiments can be designed to compare various types of automobile engines. Finally, perhaps a word of caution is in order. The power measurement, as described here, cannot be legally performed on a public road in Iowa. Of course it is illegal to drive 97 kilometers per hour and it is also illegal to coast in neutral gear. The prudent experimenter should consider lower speeds and/or private roadways.

Example

Consider the Volkswagen Sedan for which the power output has been measured. This represents a fairly typical four passenger vehicle and requires 10.0 kilowatts (14 hp) at an average speed of 89 kilometers per hour (55 mph).

$$\text{Heat of combustion for gasoline} = 4.77 \times 10^7 \frac{J}{kg} (1)$$

$$d = 4.77 \times 10^7 \frac{J}{kg} \times 677 \frac{kg}{m^3} \times 10^{-3} \frac{m^3}{l}$$

$$d = 3.22 \times 10^7 \frac{J}{l}$$

It is assumed that the efficiency of the engine is equal to the efficiency of a Carnot engine. This represents the efficiency of an engine composed of reversible processes. A real engine contains irreversible processes and its efficiency would approach the Carnot efficiency only to the extent that irreversible processes could be replaced by reversible ones. Moreover, power losses in the transmission and the additional power required to operate the generator, oil pump, fuel pump and cooling system are neglected. Therefore, the

Carnot efficiency is certain to overestimate the automobile's overall efficiency.

$$e = 1 - \frac{T_L}{T_H} \quad \textbf{(Eqn. 6)}$$

Now $T_H = 2750K$ while $T_L = 1150$ K. (2)

therefore,

$$e = 1 - \frac{1150K}{2750K}$$

$$\underline{e = .58}$$

In equation 6, the high temperature, T_H is the peak combustion chamber temperature and T_L represents the exhaust valve temperature. A theoretical efficiency calculation based on the Otto cycle[3] using the compression ratio of the 1600 cubic centimeter VW engine (7.7:1) agrees well with the efficiency used here.
so,

$$f = e\frac{\bar{V}}{\bar{P}}d \times \left(\frac{1}{3600}\ h/s\right)$$

$$f = .58 \times \frac{89\ km/h}{1.0 \times 10^4 w} \times 3.22 \times 10^7\ \frac{J}{l} \times \left(\frac{1}{3600}\ h/s\right)$$

$$\boxed{f = 4\bar{6}\ km/l} \quad (110\ mi/gal)$$

Conclusion

A small automobile requiring 10.0 kilowatts (14 hp) at 89 kilometers per hour (55 mph) under ideal conditions could not be expected to achieve a fuel economy greater than 46 kilometers per liter (110 mi/gal). It should be noted that in at least three ways the calculation overestimates fuel economy. First of all, the Carnot efficiency is much higher than any real heat engine's efficiency. Secondly, the calculation ignores the engine's ancillary power requirements. And thirdly, the method of averaging power used here underestimates the power required to overcome wind and rolling friction. Indeed because of the generous assumptions made in the calculation, we would expect the fuel economy of an ordinary automobile powered by a real, gasoline heat engine to be substantially less than 46 kilometers per liter. Thus, one must view any device or scheme purporting to deliver fuel economy in an ordinary automobile anywhere near 46 kilometers per liter (11$\bar{0}$ mi/gal) with extreme skepticism.

References Cited

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