Dynamics of a car/airplane and fuel economy

Energy in Transportation

- All transportation systems need energy to
  - accelerate up to speed.
  - Make up for losses due to (rolling) friction, air drag, etc.
  - Air planes need additional energy to climb to an altitude of ~10 km.
- Note that for slowing down (almost) no energy is required in most transportation systems (except air planes or ships).
- We see that energy consumption is linked to mass (acceleration, hills, altitude) and size (drag and resistance forces).

Power

- Power is defined as the rate at which work is done. Average power is the amount of work done in a time interval Δt or the amount of energy transferred:

$$\overline{P} = \frac{W}{\Delta t} = \frac{\Delta E}{\Delta t}$$

SI unit: 1 watt = 1W = 1J/s

- Mechanical power:

$$P_{avg} = \frac{\Delta W}{\Delta t} = \frac{F_{\parallel} \cdot \Delta x}{\Delta t} = F_{\parallel} \cdot v_{avg}\,.$$

Transportation

Estimate energy consumption from known forces.

--- the gas mileage of a car;

--- Are trains more efficient than cars?

--- Fuel consumed by jet planes flying at an altitude of ~10 km.

- How does the energy efficiency of a bus compare to a car? What's the minimum number of passengers to make the bus more efficient.
- What is the efficiency of a ship?

Example

- In example 5.8 in Knight, the rolling friction and air drag of a car are estimated to be equal at 23 m/s. (m= 1500 kg and μ_r is given as 0.02).
- Rolling friction: $f_r = \mu_r$ m g = 294 N. The air drag is also ~300 N giving a total of 600 N.

We will find out that the energy consumption of this car.

Cars usually have their lowest energy consumption at~ 80 km/h on an open road and consume 6 – 10 L of gasoline per 100 km depending on size and engine.

Continue….

- In order to maintain speed, the car's engine must do work equal to the work done by friction and air drag: W = F d = 600 N x 100 km = 6×10^7 J.
- Gasoline has an energy of 34.6 MJ per litre. The consumption is thus ~ 1.7 L.
- But car engines have internal energy losses (cooling, exhaust, friction, etc.) resulting in an efficiency of only ~ 20% (Wikipedia).

Taking the efficiency into account leads to a realistic answer of 8.5 L/100km.

Local versus highway

Gasoline consumption is larger in the city than on an open highway although speeds (and air drag) are lower. Why?

Hint: How much work is required to accelerate from 0 – 50 km/h?

Work-energy relation

$W(net)=W(engine) – W(friction, Drag)= \Delta K$

$W(engine) =W(friction, Drag)+ \Delta K$

During cruising at constant speed, $\Delta K=0$.

Acceleration costs extra energy!!

Extra energy for acceleration

How much extra energy is consumed during acceleration?

Assuming that you accelerate from 0 – 50 km/h in 5 s, the acceleration is $a = 2.8\ m/s^2$. The corresponding distance d = 35 m.

The rolling resistance and air drag combine to 400 N (following example 5.8). W = F d = 400 N x 35 m = 14000 J.

$\Delta K = ½\ m\ v^2 = 150\ 000 J$ (m = 1500 kg)

Compare to 1.5 x 105 J needed for the kinetic energy during acceleration phase: Car needs at least 10 times more energy for acceleration.

Hybrid Cars

- Why are hybrid cars more energy efficient?

- Efficiency of combustion engines depends on rpm. Most efficient at relative high speeds ~ 90 km/h.
- Electric motor very efficient at all speeds.

Fuel Economy of Airplanes

A Boing 747 has a maximum range of 13,450 km and a maximum fuel capacity of 216,840 L.

We can calculate the fuel economy from this:
16L/km or 1600 L per 100 km.
The number of passengers is ~500, so each passenger uses 3.2L per 100 km when the plane is full.

This is similar to the fuel economy of a car!

Energy needed to climb up to an altitude of 10.5km

The mass of the plane is 390 000 kg at take-off.
$V = m\,g\,h = 4 \times 10^{10}$ J

Kinetic energy at the cruising speed of 915 km/h (254 m/s). $K = \frac{1}{2} m v^2 = 1.26 \times 10^{10}$ J

- How much fuel is needed for this? The energy efficiency of the jet engines is ~25% (estimated)

Energy in jet fuel: 37.6 MJ/L.

- So we need 1400 L/0.25 = 5600L of jet fuel to accelerate to 915 km/h and go up to 10500 m.

Energy for cruising

- The rest of the fuel (~210,000L) is used to maintain "terminal" speed against air drag.

- Let's estimate the drag force: A 747 has a fuel capacity of 216,840 L and a max. range of 13450km. So 210,000 L are used to counter air drag. W = F d, so F = 147 kN. (Engines have max thrust of 4 x 282 kN). It is less than the air drag on the ground.

Flying at a high altitude reduces the air drag because of a lower air density !! That's why planes fly relatively high although further going high results in a lower upward lifting force.