Solutions lecture 1

1.1 Joule's test setup

a) A load of $50kg$ is displaced over a distance of $20m$. All the mechanical energy is converted into thermal energy, which increases the temperature of $5.0L$ water. First, the energy gained by this displacement of the load can be calculated:

$$\begin{aligned} \Delta E_{mech} &= F \cdot \Delta h = m \cdot g \cdot \Delta h \\ &= 50 \cdot 9.81 \cdot 20 \\ &= 9810J \end{aligned} \tag{1.1}$$

All the mechanical energy is converted into thermal energy:

$$\Delta E_{mech} = Q = m_{water} \cdot c_v \cdot \Delta T \tag{1.2}$$

From this, the temperature increase can be calculated, as the mass of the water ($\approx 5.0kg$) and the specific heat capacity ($= 4186J \cdot kg^{-1} \cdot K^{-1}$) are known:

$$\Delta T = \frac{\Delta E_{mech}}{m_{water} \cdot c_p} = \frac{9810}{5.0 \cdot 4186} = 0.47°C \tag{1.3}$$

b) First, some data from diesel has to be found online. The values that should be found online are the density of diesel and the price per liter: $0.85\ \mathrm{kg\,L^{-1}}$ and €1.21 respectively.

With a budget of €1, the amount of liters diesel you can buy is equal to:

$$V_{diesel} = \frac{1}{1.21} = 0.8264L \tag{1.4}$$

The amount of energy in this diesel volume is equal to:

$$E_{diesel} = V_{diesel} \cdot \rho_{diesel} \cdot \hat{E}_{diesel} = 0.8264 \cdot 0.85 \cdot 45.5 = 31.96\mathrm{MJ} \tag{1.5}$$

In the equation, $\hat{E}$ is the given specific calorific value of (or chemical energy in) diesel. Now, we can calculate the number of times the load can be lifted:

$$N_{lifts} = \frac{31.96 \cdot 10^6}{9.810 \cdot 10^3} = 3258\ times \tag{1.6}$$

So, the load can be lifted 3258 times.

c) First, the power is converted to W ($1hp = 746W$):

$$P = 2.5 \cdot 746 = 1865W \tag{1.7}$$

Now, the time it takes to lift this load using the maximum amount of power can be calculated:

$$t = \frac{\Delta E_{mech}}{P} = \frac{9810}{1865} = 5.26s \tag{1.8}$$

It takes longer than 5 seconds to lift the load, which means that the engine is not suitable.

d) The energy in a chocolate bar can be found online, which is equal to approximately 530$kcal$ per 100g. One kcal is equal to 4184J, so the total energy in 900 g chocolate can be calculated:

$$E_{chocolate} = m_{choc} \cdot \hat{E}_{choc} = 0.9 \cdot 5300 \cdot 4184 = 19.96MJ \tag{1.9}$$

The energy required per lift was already calculated: 9810J. The number of days that the engine can run on chocolate then becomes:

$$t = \frac{19.96 \cdot 10^6}{9810 \cdot 120} = 16.96 \ days \tag{1.10}$$

The engine can run for almost 17 days on the chocolate.

e) The electricity costs are given: €0.17 per kWh. One kWh is equal to 3.6MJ. Now, we can calculate how much energy we can get with a budget of €1:

$$E = \frac{1}{0.17} \cdot 3.6 = 21.18MJ \tag{1.11}$$

Comparing this answer to the answer obtained in question 1b, we see that the amount of energy from diesel is higher with the same budget. This means that the diesel engine is the cheaper option.

1.2 Transport by car and bus

a) In both cases the distance to be travelled is $2 \cdot 75 = 150$ km. The car has a consumption of 7.2 liters per 100 kilometers, so the fuel used per car is

$$150\text{km} \cdot \frac{7.2\text{L}}{100\text{km}} = 10.8\text{L}$$

Thus, for six cars a total of $6 \cdot 10.8 = 64.8$L of fuel is needed.

The consumption of the bus is 35 liters per 100 kilometers, so

$$150\text{km} \cdot \frac{35\text{L}}{100\text{km}} = 52.5\text{L}$$

So for the bus, 52.5 L of fuel is needed.

b) The total amount of energy E_{total} is the mass of the fuel m multiplied by the caloric value (chemical energy released when combusted) of the fuel. The mass of the fuel needed is the needed amount of liters V multiplied by the specific mass m_{spec} of the fuel:

$$E_{total} = m \cdot E = m_{spec} \cdot V \cdot E$$

For the car, the above equation becomes:

$$E_{total,car} = 64.8\text{L} \cdot 0.70\text{kg}\,\text{L}^{-1} \cdot 42\text{MJ}\,\text{kg}^{-1} = 1905\text{MJ}$$

Per person this comes down to 79.4 MJ. For the bus:

$$E_{total,bus} = 52.5\text{L} \cdot 0.85\text{kg}\,\text{L}^{-1} \cdot 43\text{MJ}\,\text{kg}^{-1} = 1919\text{MJ}$$

Per person this comes down to 79.9 MJ.

c) For the car, the fuel costs are

$$\text{Price fuel car} = 64.8 \cdot €1.49 = €96.55$$

For the bus, the fuel costs are:

$$\text{Price fuel bus} = 52.5 \cdot €1.14 = €59.85$$

The total costs for the bus is €59.85+€200=€259.85. This means that the going by car is the cheapest option.

d) The minimum amount of kilometers can be calculated by equating the costs of the cars per kilometer to the costs of the bus per kilometer:

$$\text{Costs car} = \text{Costs bus}$$

In order to do so, we need to calculate the costs per kilometer. For the car:

$$\text{Costs per kilometer car} = \frac{96.55}{150} = €0.64$$

And for the bus:

$$\text{Costs per kilometer bus} = \frac{59.85}{150} = €0.40$$

Equating the costs of the car to the costs of the bus:

$$€0.64 \cdot x = €0.40 \cdot x + €200$$

where x is the distance in kilometers. Solving this gives a distance of 833 km.

e) In the lecture sheets, you can find that one hour of cycling at 15 km/h costs a person 1600 kJ of energy. The time needed to travel will be 150 km/15 km/h=10 hours. The amount of energy needed per person is thus $10\text{h} \cdot 1600\text{kJ}\,\text{h}^{-1} = 16\text{MJ}$. Note that this is much less than by car or bus!

The lecture slides also give the definition of the Calvé: 1 Calvé = 200 kcal= $200 \cdot 4.184\text{kJ} = 0.8368\text{MJ}$. For the 150 kilometers of cycling, all students needs

$$\frac{16\text{MJ}}{0.8368\text{MJCalvé}^{-1}} = 19,1\text{Calvé}$$

f) Which travel option is the most efficient, depends on the energy conversions included in the analysis. While cars use less energy than the bus when transporting 24 people, the production of bus fuel might be more efficient than the production of car fuel. The same principle applies to cycling; the energy used while cycling may be five times less than using cars, but to produce, distribute and digest the sandwiches with peanut butter also costs a considerable amount of energy. Cycling is the most efficient, using only the energy conversions in the assignment, followed by cars and then the bus. In reality, factors including the environment, travel time, and costs play an essential role.

1.3 Automobile engine - Hand-in

a) The required amount of energy to travel the distance of 100 kilometers can be calculated from the relationship of power:

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

Where rewriting gives us:

$$\Delta E = P \Delta t$$

The power of the given car is 150 horsepower, equivalent to $P = 111.85$ kW. Furthermore, the 100 km distance should be traveled within a time of $\Delta t = \frac{80}{60} = 1.33$ h. This gives us:

$$\Delta E = P \Delta t = 111.85 \cdot 1.33 = 149.13 \text{ kWh}$$

b) To calculate the required amount of gasoline, we need to know how much energy is required from the gasoline. Only 25% of the energy from gasoline is used for useful purposes. Therefore the total required energy from the gasoline is:

$$E_{\text{combustion}} = \frac{\Delta E}{\eta_{\text{gasoline}}} = \frac{149.13}{0.25} = 596.52 \text{ kWh}$$

So in total 596.52 kWh should be released from the combustion of gasoline. Which is equal to $2.1465 \cdot 10^3$ MJ.

The total amount of energy released from combustion can be expressed in terms of the heating value of gasoline:

$$E_{\text{combustion}} = \text{HHV} \cdot m$$

Where rewriting gives us:

$$m = \frac{E_{\text{combustion}}}{\text{HHV}} = \frac{2.1465 \cdot 10^3}{45.3} = 47.4 \text{ kg}$$

From the relationship with the density $m = V \cdot \rho$ we can derive the number of liters required:

$$V = \frac{m}{\rho} = \frac{47.4}{0.75} = 63.21 \text{ L}$$

We need a bit more than 1 filled tank of 50 liters, so we have to refill only one time.

c) 75% of the energy is not used in a useful way and converted into heat. Which gives us $Q = 447.4$ kWh $= 1.61 \cdot 10^9$ J. Having only 1% being distributed among the engine at steady-state, we find that $Q_{\text{engine}} = 1.61 \cdot 10^7$ J Using the expression for the thermal energy we find:

$$Q_{\text{engine}} = mc_{\text{p}} (T_2 - T_1)$$

$$\rightarrow T_2 = \frac{Q_{\text{engine}}}{mc_{\text{p}}} + T_1 = \frac{1.61 \cdot 10^7}{200 \cdot 500} + 20 = 181 \text{ °C}$$

d) The cost for the gasoline car can be calculated as follows:

$$\text{Cost}_{\text{gasoline}} = €_{\text{gasoline}} \cdot V = 1.87 \cdot 63.21 = €118.2$$

The required energy from the electric car can be calculated as:

$$E_{\text{electric}} = \frac{\Delta E}{\eta_{\text{electric}}} = \frac{149.13}{0.8} = 186.42 kWh$$

With the given price of €0.15 per kWh we can calculate the costs for the electric car:

$$\text{Cost}_{\text{electric}} = €_{\text{electric}} \cdot E_{\text{electric}} = 0.15 \cdot 186.42 = €27.96$$