COVENTRY
UNIVERSITY

School of Engineering

332MEC Thermodynamics

Assignment 2

Hybrid Vehicles

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Summary

This technical report is about hybrid vehicles. A hybrid vehicle is combining different fuel or propulsion systems, to match one and the same aim. The most common setting is the combination of a combustion engine with an electrical.

The grade of power share divides those cars into *Micro-*, *Mild-* and *Full Hybrid*. Here is only the Full Hybrid considered because its high value of estimated fuel savings. Scientists have found that parallel designs are the most economical. That vehicle has the possibility to run with power by the Internal Combustion Engine and the Electrical Engine at the same time. When stating the engine the car is running under full load. So the car is working under best conditions and with its highest efficiency of about 35 %.

The calculated average power for driving the Urban Driving Cycle is 2.3 kW. Thereby, the mass of the car is 1,400 kg. Burned fuel $\left[C_8H_{18}\right]$, with mixture strength of 0.9, leads to a rate of 11.33 % of carbon monoxide in the wet exhaust gas. The estimated fuel mass flow in a hybrid car is $15.25 \cdot 10^{-5}\, kg/s$ and in a non hybrid car $53.36 \cdot 10^{-5}\, kg/s$. The saving of fuel is 71 % comparing the hybrid with a non hybrid vehicle.

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Abbreviations

NECD - New European Driving Cycle

p - 3.1416

i.c. - Ignition Engine

Physical value	Symbol	Unit		Correlations
Length	l	Metre	m	1 m = 10 dm = 100 cm
Diameter	d	Metre	m	1 m = 10 dm = 100 cm
Area	A	Square metre	m^2	1 m^2 = 10,000 cm^2 = 1,000,000 mm^2
Volume	V	Cubic metre	m^3	1 m^3 = 1,000 dm^3 = 1,000,000 cm^3
Time	t	Second	S	3600 s = 60 min = 1 h
Velocity	v	Metres per second	m/s	1 m/s = 60 m/min = 3.6 km/h = 2.237 mph = 1.944 knots = 1.944 nautical mph
Acceleration	a	Metres per square second	m/s^2	1 m/s^2
Mass	m	Kilogram	kg	1 kg = 1,000 g = 0.001 t
Density	?	Kilogram per cubic metre	kg/m^3	1,000 kg/m^3 = 1 t/m^3 = 1 g/cm^3 = 1 mg/mm^3
Force	F	Newton	N	1 N = 1 kg m/s^2 = 1 J/m
Pressure	p	Pascal	Pa	1 Pa = 10^{5} bar = 1 N/m^2
Energy	E	Joule	J	1 J = 1 Nm = 1 kg m^2/s^2 = 0.2388 cal 1 W s = $3,600,000^{-1}$ kW h
Power	P	Watt	W	1 W = 1 J/s = 1 Nm/s= 1/735.5 Ps
Oil equivalent	oe	Tonnes of oil equivalent	toe	1 Mtoe = 41.868 PJ 1 toe = 7.4 barrels of crude oil in primary energy = 7.8 barrels in total final consumption = 1270 m^3 of natural gas = 2.3 metric tonnes of coal

10^{-12} = p - pico = 1/1000,000,000,000

10^{-9} = n - nano = 1/1000,000,000

10^{-6} = µ - micro = 1/1000,000

10^{-3} = m - milli = 1/1000

10^{3} = k - kilo = 1,000

10^{6} = M - mega = 1,000,000

10^{9} = G - giga = 1,000,000,000

10^{12} = T - tera = 1,000,000,000,000

10^{15} = P - peta = 1,000,000,000,000,000

10^{18} = E - exa = 1,000,000,000,000,000

1 How hybrid vehicles operate

1.1 Introduction

A hybrid vehicle operates either with different propulsion systems or with different fuels. The word hybrid comes from the Greek language and it means *a composite of mixed origins*. The aim of those mixtures is still the same.

Many people think they have never had any contact with a hybrid vehicle. But obviously that is wrong since most of the people in Europe have ever seen a Moped which means nothing else than *motorized pedal bike*. There, an ignition engine is combined with human power to get some movement. Also, most of the trains are pulled by a hybrid system. Typically the movement is produced by an *Electric-Diesel* combining engine. Even a submarine has a hybrid system. Sometimes it is a *Nuclear-Electric* and sometimes it is a *Diesel-Electric* combining system.

Most of the considered vehicles consist of recuperation brakes. That is nothing else than switching the existing electrical engine into its opposite setting, namely a generator. When doing that, the generator produces a load on the main shaft which decreases its turning speed. Thereby the generator converts the motion into electricity by induction. That electricity can now charge a battery. The big advantages of recuperation braking are the use of usually wasted energy, the abrasion of the brakes is reduced and less greenhouse gasses are produced.

Basically hybrid vehicles are divided into two main groups. On one side the vehicles driven by different fuels and on the other side vehicles driven by an internal combustion engine combined with one or more electrical engines.

1.2 Combined fuel combustion

The internal combustion engine is the most commend kind of an engine, to move vehicles. During the process fuel is burned to produce power which is then converted to mechanical movement. Both petrol and gaseous fuels could be used. For example a diesel engine runs also under rape oil. Because petrol and diesel getting more and more expensive this is going to be a divinity alternative. Those alternatives having usually less carbon and thus they can reduce the production of polluting gasses as carbon-monoxide and –dioxide or nitrogen in all its forms. So using more fuel like natural gas will save the environment. But normally the availability of natural gas stations is very less. So it is quite complicated for the people which like to drive with natural gas. That is why the automotive industry often supplies cars with two fuel tanks. So the car could drive with both fuels. It is a so called bivalent car.

1.3 Combined combustion and electrical engine

Those kinds of hybrid vehicles are differentiated usually by how they are connected to each other and the power share of the engines.

1.3.1 Power share

There are basically three types of sharing the power of internal combustion engines to electrical engines.

The smallest share is called *Micro-Hybrid*. Electrical engines in that configuration consist of a power of up to 2-3 kW. It has a voltage of some 12 V. The estimated reduction of fuel is 5-10 %. This Vehicles are supported while starting and stopping and of course the generator mode.

A medium like configuration is called *Mild-Hybrid*. The power supply by the electrical engine is about 3 to 15 kW. A voltage level from 42 V up to 150 V is available. Here the estimated reduction of fuel consumption is about 15-20 %. Next to the support of starting and stopping is this configuration able to boost the vehicle and to recuperate power.

But the most commend configuration is called *Full-Hybrid*. There the power supply by the electrical engine is much bigger than 15 kW. Furthermore the Voltage level is much higher than 100 V and the estimated fuel reduction is up to 40 %. In addition to the support of start, stop, boost and recuperation is this configuration able to move the vehicle only by electricity.

1.3.2 Series or parallel designs

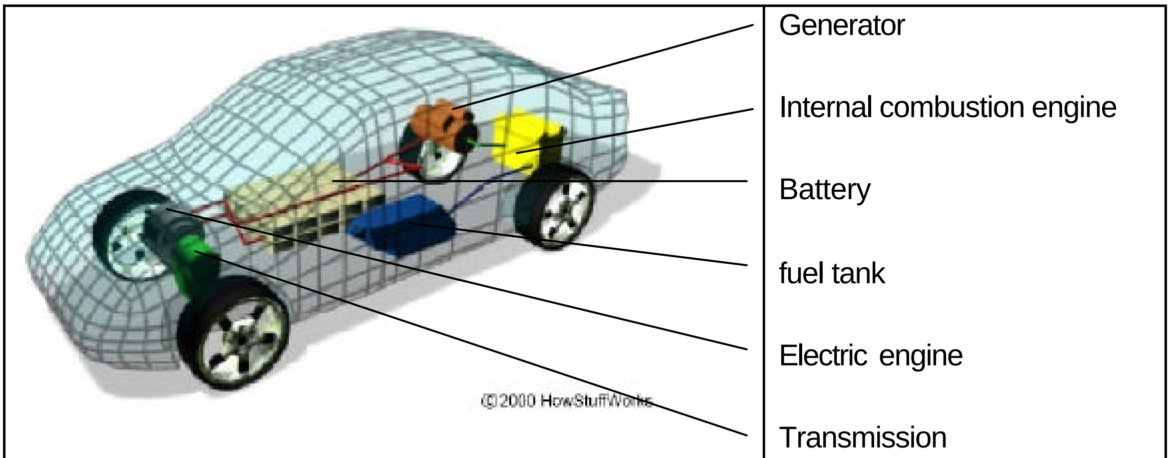

Figure 1: Series hybrid design

If a vehicle is *series* designed, then the internal combustion engine is not directly connected to the transmission at all. Moreover, the internal combustion engine is driving a generator which is producing power. That power could either charge a battery or drive an electrical engine. On the figure below you see a car with parallel hybrid design.

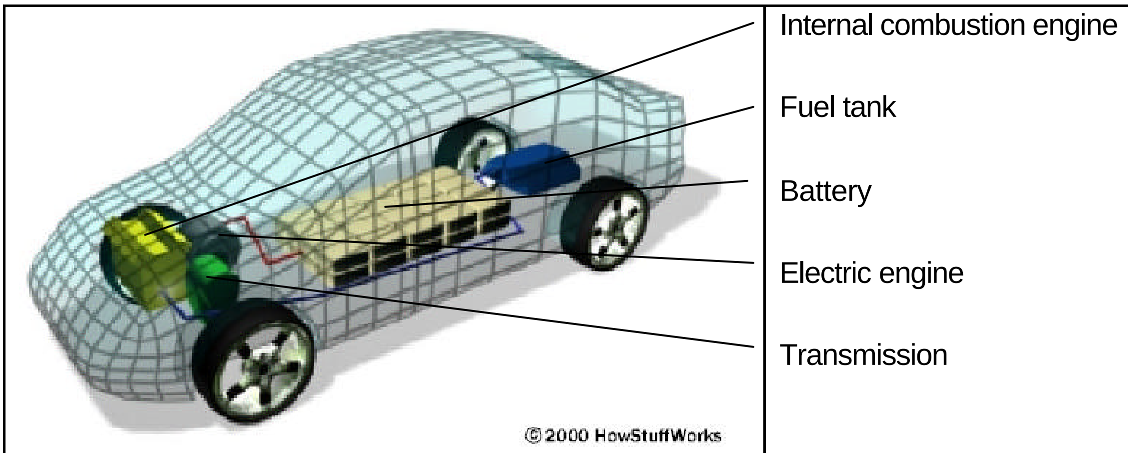

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Figure 2: Parallel hybrid design

A vehicle with a parallel hybrid design gives the possibility to run the vehicle with power by the Internal Combustion engine and the Electrical Engine at the same time. When stating the engine the car is running under full load. So the car is working under best conditions and with its highest efficiency. That is normally for an i.c. engine approximately 35%.

2 Calculation of average power

2.1 The Urban Driving Cycle

To derive the required power of a car it is important to now some basics about driving cycles. The driving behaviour of people is easy to visualize as shown below:

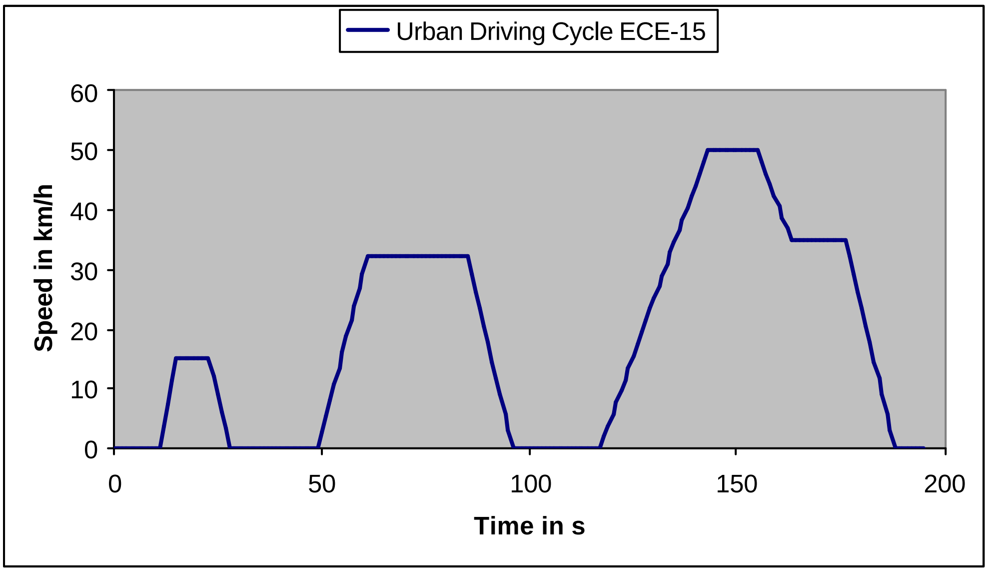

Chart 1: Urban Driving Cycle ECE-15

> A driving cycle is a series of data points representing the speed of a vehicle versus time. Driving cycles are produced by different countries and organizations to assess the performance of vehicles in various ways, as for example fuel consumption and polluting emissions.
>
> Fuel consumption and emission tests are performed on dynamometer. Tailpipe emissions are collected and measured to indicate the performance of the vehicle.Some driving cycles are derived theoretically, as it is preferred in the European Union, whereas others are direct measurements of a driving pattern deemed representative.
>
> There are two types of driving cycle: Transient driving cycles involve many changes, representing the constant speed changes typical of on-road driving. Modal driving cycles involve protracted periods at constant speeds. The American FTP-75, and the unofficial European Hyzem driving cycles are transient, whereas the official European NEDC and the Japanese 10-15 Mode cycles are modal cycles.
>
> The most common driving cycles are probably the European NEDC and the American FTP-75.
>
> [<< http://www.answers.com >>]

It is used for emission certification of light duty vehicles in Europe.

2.2 Average Power

To derive the power need during one period of time we have to know the acting powers. Four different powers occur:

- $P_a = v \cdot m \cdot a$ **Power for acceleration**
- $P_D = \frac{1}{2} c_D \cdot A \cdot r \cdot v^3$ **Power for drag**
- $P_r = c_r \cdot m \cdot g \cdot v$ **Power for rolling resistance**
- $P_{kin} = \frac{1}{2 \cdot t} m \cdot v^2$ **Power for kinetic energy**

They could all occur in the same moment. Putting all together lead to the equation as shown below:

$$P = v\left(m \cdot a + c_D \cdot A \cdot \frac{1}{2} \cdot r \cdot v^2 + c_r \cdot m \cdot g + \frac{1}{2t} \cdot m \cdot v \right)$$

And we know that acceleration is equal to speed divided by time.

$$a = \frac{\Delta v}{\Delta t}$$

In my research I found that an average hybrid driven car has a weight *m* of some 1400 kg. The speed *v* is given by the ECE-15 in chart 1 and the overall time *t* is 195 s. That is the period time of one cycle.

All the parameters of the equation for the steady state power are assumed or given as shown in table 1. They are common values [1].

m	Mass of car:	1400	kg
c_D	Drag coefficient:	0,3	-
?	Air density:	1,225	kg/m³
A	Area faces air:	2	m²
c_r	Rolling resistance:	0,012	-
g	Gravitation constant:	9,81	m/s²

Table 1: Parameters for calculating the power

$$P(v) = v\left(\begin{array}{l} 1400kg \cdot \dfrac{\Delta v}{1s} + 0.3 \cdot 2m^2 \cdot \dfrac{1}{2} \cdot 1.225\dfrac{kg}{m^3} \cdot v^2 \\ +0.012 \cdot 1400kg \cdot 9.81\dfrac{m}{s^2} \\ +\dfrac{1}{2 \cdot 195s} \cdot 1400kg \cdot v \end{array}\right)$$

Steady state power

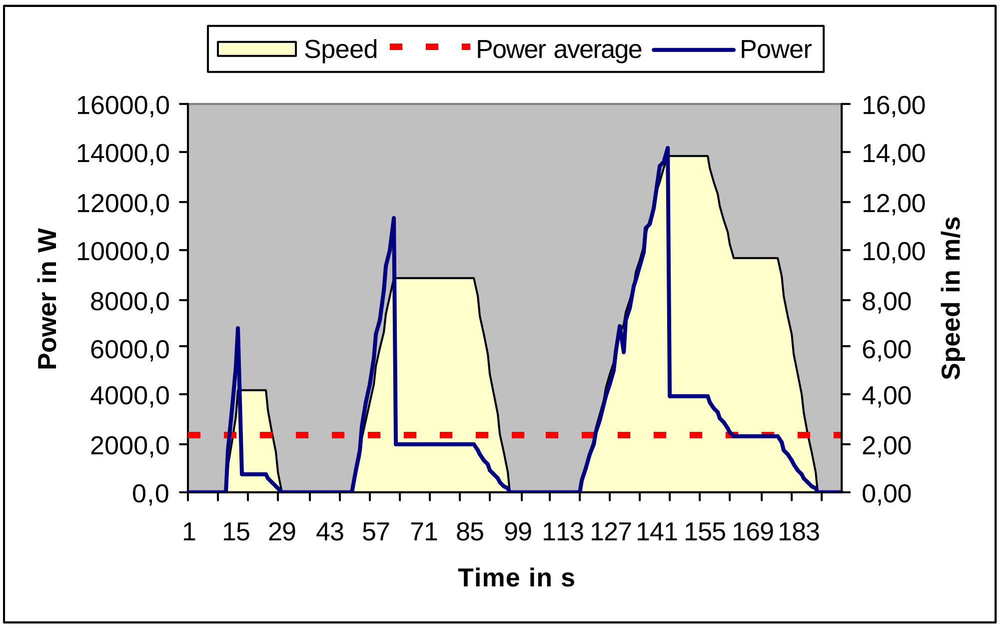

Chart 2: Visualized power need during a cycle

The formula for the steady state power represents the resulting graph of power dependent on the actual velocity in chart 2. Hence, I calculate the average value of power by making the sum of all steady state powers and dividing it by its count:

$$\overline{P} = \frac{\sum_{i=1}^{195} P_i(v)}{195} = 2294W = \underline{\underline{2.3kW}}$$

3 Combustion analysis

Petrol consists predominantly of Octane. The chemical formula is $\left[C_8H_{18}\right]$. The added air has the formula $\left[O_2+\frac{79}{21}N_2\right]$.

- Stoichiometry analysis of source material:

$$C_8H_{18}+12.5\left(O_2+\frac{79}{21}N_2\right)\rightarrow 8CO_2+9H_2O+12.5\frac{79}{21}N_2$$

- The partly constituents are:

1 kmol of fuel $\left[C_8H_{18}\right]$ $=(8\cdot 12)+(18\cdot 1)=\underline{\underline{114kg}}$

12.5 kmol of oxygen $\left[O_2\right]$ $=12.5(2\cdot 16)=\underline{\underline{400kg}}$

12.5 kmol of air $\left[O_2+\frac{79}{21}N_2\right]$ $=12.5\left(2\cdot 16+\frac{79}{21}\cdot 28\right)=\underline{\underline{1716.7kg}}$

- The stoichiometric Air-Fuel Ratio is:

$$\frac{Stoichiometric\_Air}{Stoichiometric\_Fuel}=\frac{1716.7kg}{114kg}=\underline{\underline{15.06}} \qquad \mathbf{AFR_{Stoichiometric}}$$

I assume the mixture strength of 90 %. Therefore, an actual AFR$_{\text{actual}}$ has come to exist. The relation between actual and stoichiometric AFR is given below:

$$mixture\_strength=\frac{AFR_{stoich}}{AFR_{actual}}$$

Hence, it is possible to calculate the AFR_{actual} by changing the formula into:

$$AFR_{actual} = \frac{AFR_{stoich}}{mixture\_strength} = \frac{15.06}{0.9} = \underline{\underline{16.73}} \qquad \mathbf{AFR_{Actual}}$$

The mixture strength of 90 % leads to a more supply of 10 % by air. Thus, the overall air supply is 110 %. Consequently, the stoichiometric equation changes:

$$C_8H_{18} + \frac{1}{0.9}\left(12.5\left(O_2 + \frac{79}{21}N_2\right)\right) \rightarrow 8CO_2 + 9H_2O + \frac{1}{0.9}\left(12.5\frac{79}{21}N_2\right) + \frac{0.1}{0.9}\left(12.5O_2\right)$$

- Thereby, the exhaust gas consist of:

Carbon dioxide	CO_2	$= \underline{8\ kmol}$
Water	H_2O	$= \underline{9\ kmol}$
Nitrogen	N_2	$= \frac{1}{0.9}\left(12.5\frac{79}{21}\right) = \underline{52.25\ kmol}$
Oxygen	O_2	$= \left(\frac{0.1}{0.9}\cdot 12.5\right) = \underline{1.39\ kmol}$

The overall molar mass of the product is about:

$$CO_2 + H_2O + N_2 + O_2 = 8kmol + 9kmol + 52.25kmol + 1.39kmol = \underline{\underline{70.64kmol}}$$

- Wet analysis:

Carbon dioxide CO_2 : $\frac{8kmol}{70.64kmol} \cdot 100\% = \underline{\underline{11.33\%}}$

Water H_2O : $\frac{9\,kmol}{70.64kmol} \cdot 100\% = \underline{\underline{12.74\%}}$

Nitrogen N_2 : $\frac{52.25}{70.64kmol} \cdot 100\% = \underline{\underline{73.97\%}}$

Oxygen O_2 : $\frac{1.39kmol}{70.64kmol} \cdot 100\% = \underline{\underline{1.97\%}}$

- Dry analysis:

$$Exhaustgasses - Water = 70.64kmol - 9kmol = \underline{\underline{61.64kmol}}$$

Thus:

Carbon dioxide CO_2 : $\frac{8kmol}{61.64kmol} \cdot 100\% = \underline{\underline{12.98\%}}$

Nitrogen N_2 : $\frac{52.25kmol}{61.64kmol} \cdot 100\% = \underline{\underline{84.77\%}}$

Oxygen O_2 : $\frac{1.39kmol}{61.64kmolkmol} \cdot 100\% = \underline{\underline{2.66\%}}$

4 Estimation of fuel

A hybrid cars ignition engine is all the time running under full load. Up to 2.3 kW of power the i.c. engine is moving the car and with the rest of the power he is charging the battery. Above 2.3 kW an electrical engine is supplying the additionally power. That makes him high efficient while running under best conditions. Thus, I assume an accurate efficiency of 35 % for the i.c. engine in a hybrid car. Comparing to that, a normal i.c. engine is not running under best circumstances. So, I have chosen an efficiency of 10 % for driving the EDC-15 whit a non hybrid car. An adequate enthalpy for petrol is 43,100 kJ/kg. That is taken from the appendix table 1.

To work out the mass flow of fuel I use the well known equation for efficiency:

$$Efficiency_{Motor} = \frac{Power_{output}}{Power_{input}} = \frac{Power_{Mechanical}}{Fuel_{Massflow} \cdot Enthalpy_{Petrol}}$$

Then, I multiply all by the fuel mass flow and divide it by the efficiency of the engine and hence I get:

$$Fuel_{Massflow} = \frac{Power_{Mechanical}}{Efficiency_{Motor} \cdot Enthalpy_{Petrol}}$$

The parameters of the equation are:

- $Power_{Mechanical} = 2.3kW$
- $Enthalpy_{Petrol} = 43{,}100 \, {}^{kJ}\!/_{kg}$
- $Efficiency_{non-Hybrid} = 10\%$
- $Efficiency_{Hybrid} = 35\%$

Now, I can calculate the fuel mass flow of petrol for a hybrid and a non hybrid car.

$$Fuel_{Massflow\_Hybrid} = \frac{2.3kW}{0.35\cdot 43{,}100\,kJ/kg}\cdot\frac{1kJ}{1kW\cdot s} = \underline{\underline{15.25\cdot 10^{-5}\,kg/s}}$$

$$Fuel_{Massflow\_non-Hybrid} = \frac{2.3kW}{0.10\cdot 43{,}100\,kJ/kg}\cdot\frac{1kJ}{1kW\cdot s} = \underline{\underline{53.36\cdot 10^{-5}\,kg/s}}$$

Those are the mass flows of petrol. It is more familiar to have the solution in litre per second. So I divide the mass flow by the density of petrol or more exactly, octane. The density of octane is 0.703 kg/l.

$$Fuel_{Massflow\_Hybrid} = \frac{15.25\cdot 10^{-5}}{0.703}\frac{kg}{s}\frac{l}{kg} = 21.7\cdot 10^{-5}\frac{l}{s} = \underline{\underline{0.013\frac{l}{\min}}}$$

$$Fuel_{Massflow\_non-Hybrid} = \frac{50.36\cdot 10^{-5}}{0.703}\frac{kg}{s}\frac{l}{kg} = = 71.64\cdot 10^{-5}\frac{l}{s} = \underline{\underline{0.043\frac{l}{\min}}}$$

Using the AFR$_{actual}$ it is easy to show the mass of the produced gasses. First, I have to work out the mass flow of air and then I add air and fuel mass flow together:

$$AFR_{actual} = 16.73 = \frac{Air_{massflow}}{Fuel_{massflow}} = \frac{Air_{massflow}}{15.25\cdot 10^{-5}\,kg/s}$$

$$Air_{massflow-hybrid} = 16.73\cdot 15.25\cdot 10^{-5}\,kg/s = \underline{\underline{255.13\cdot 10^{-5}\,kg/s}}$$

The overall mass flow in a hybrid car:

$$Fuel_{Massflow\_Hybrid} + Air_{massflow-hybrid} = Overall_{massflow-hybrid}$$

$$\left(15.25 + 255.13\right) \cdot 10^{-5}\, kg/s = \underline{\underline{270.38 \cdot 10^{-5}\, kg/s}}$$

The actual emitted polluting gas is shown below:

Carbon dioxide CO_2 : $= 11.33\% = \underline{\underline{30.6 \cdot 10^{-5}\, kg/s}}$

Water H_2O : $= 12.74\% = \underline{\underline{34.45 \cdot 10^{-5}\, kg/s}}$

Nitrogen N_2 : $= 73.97\% = \underline{\underline{200 \cdot 10^{-5}\, kg/s}}$

Oxygen O_2 : $= 1.97\% = \underline{\underline{5.33 \cdot 10^{-5}\, kg/s}}$

5 Conclusions and Recommendations

A hybrid car saves about 71 % of polluting gasses when driving the Urban Driving Cycle. That will decrease rapidly when driving outside the city. The available power of a non hybrid car is much higher than 2.3 kW. That equals 1.72 Ps, which is a more commonly used unit in the automotive and vehicle industry. The approximately compact car has about 50 Ps. That immense difference is based on the much higher demand of power for driving under a real situation.

A more real situation consists of driving much faster. Also, an often changing ground makes a big difference for the rolling resistance to the wheels. Driving a slope needs usually more power as well. All of that will indicate a more real situation with more power demand.

I will emphasize that a hybrid car needs only 29 % of fuel comparing to a non hybrid car. If people, who live in big cities like Birmingham, London or Berlin, would drive more hybrid cars, the world's energy resources would get a longer static lifetime.

But consequently I should say that this is only the beginning of a change. If Politicians or managers saying, our energy system depends on resources which have a static life time of less than 45 years, they are ridicules. We need a kind of energy revolution to cover the demand of tomorrow, and the readiness for marketing of hybrid cars is an indication that people realize this.

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Appendix

I. Energy content of fuels

	GJ per tonne
North Sea Crude Oil	42.7
LPG (Liquefied petroleum gas: Propane, Butane)	46.0
Petrol (Gasoline)	43.8
Petrol (Liquid)	43.1
JP1 (Jet aircraft fuel)	43.5
Diesel / Light Fuel oil	42.7
Heavy Fuel Oil	40.4
Orimulsion	28.0
Natural Gas	39.3 per 1000 Nm³
Steam Coal	24.5
Other Coal	26.5
Straw	14.5
Wood chips	14.7
Household Waste 1995	10.0
Household Waste 1996	9.4
Conversion factors provided by the Danish Energy Agency	

II. CO_2 emissions from fuels

	kg CO_2 per GJ	kg CO_2 per kg fuel
Petrol (Gasoline)	73.0	3.20
Diesel / Light Fuel oil	74.0	3.16
Heavy Fuel Oil	78.0	3.15
Orimulsion	76.0	2.13
Natural Gas (methane)	56.9	2.74
Coal	95.0	2.33 (steam coal) 2.52 (other)
Conversion factors provided by the Danish Energy Agency		