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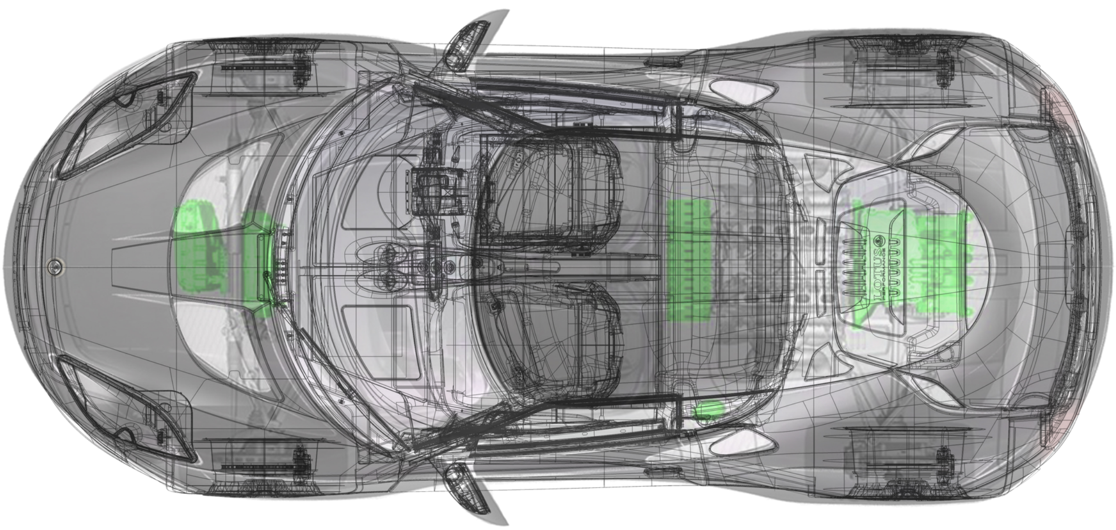

# Future Vehicle Technology and its Implementation

A Study and Evaluation of Road Vehicle Propulsion Technology

*Master's Thesis in Automotive Engineering*

KRISTIAN NÄSHOLM & JOSEFINE WALKER

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: An schematic illustration of a Lotus Evora with a hybrid powertrain

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# Abstract

The automotive industry is facing several challenges right now, such as economical crisis and tough competition. At the same time the demand of alternative transportation technologies is increasing and the legislations on emissions for light duty vehicles are tightening.

To be able to survive in this harsh business climate, new and creative solutions are needed and the changes have to be fast. Today's vehicle fleet is almost entirely dependent on fossil fuels and scientists are indicating that the increasing amount of $CO_2$ in the atmosphere is contributing to the global warming. The challenge for the industry is to increase the vehicles fuel economy and make them run further on the same amount of fuel, or even better, by not using any fossil fuels at all.

This master thesis's main objective is to help Lotus Engineering making up general guidelines and information for the selection of new automotive technology through analysis of several new powertrain technologies and fuels. The following technologies are being considered:

- Internal combustion engine vehicles
- Mechanical hybrid vehicles
- Electric vehicles
- Hybrid electric vehicles and plug-in hybrid electric vehicles
- Fuel cell vehicles
- Alternative fuels: Bio-diesel, natural gas, ethanol, methanol, hydrogen and synthetic fuels

The vehicle structure and design is another important factor when it comes to fuel economy, since aerodynamic drag, weight and rolling resistance are major factors that affects the fuel economy. This thesis gives information about how to design and reduce weight of the car.

This thesis also contains a simulation chapter, where a series and a parallel hybrid are compared in terms of fuel economy to help knowing when to use which type of system. All of this is summarized in the future vision chapter.

The analysis is made to show the potential of each technology to make it in the future society and consider cost, the potential to implement it into our current society and infrastructure and how much support the technology has amongst leading governments and commissions. No full cost analysis is done since this thesis is focusing more on the technical aspects of the technology than the economic aspect. The driving behavior of the car users has also been taken in to consideration, even though in a very basic manner. The research only reaches into a feasible future, until about 2050.

# Acknowledgments

First of all we would like to thank our examiner at Chalmers, associate professor Sven Andersson.

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We would also like to give thanks to our families and friends at home, but also all our new friends at Lotus engineering and in Norwich who supported us and helped us throughout the thesis.

## Nomenclature

| | |
|---|---|
| APU | Auxiliary Power Unit |
| BEV | Battery Electric Vehicle |
| bmep | break mean effective pressure |
| bsfc | break specific fuel consumption |
| CVT | Continuously Variable Transmission |
| DCT | Dual Clutch Transmission |
| DI | Direct Injection |
| DfT | Department for Transport |
| DoH | Degree of Hybridisation |
| EM | Electric Machine |
| EPA | Environmental Protection Agency |
| EV | Electric Vehicle |
| FCHEV | Fuel Cell Hybrid Electric Vehicle |
| FCV | Fuel Cell Vehicle |
| GHG | Greenhouse Gas |
| HEV | Hybrid Electric Vehicle |
| ICE | Internal Combustion Engine |
| ICEV | Internal Combustion Engine Vehicle |
| KERS | Kinetic Energy Recovery System |
| MHV | Mechanical Hybrid Vehicle |
| mpg | miles per gallon |
| mph | miles per hour |
| NEDC | New European Driving Cycle |
| NGV | Natural Gas Vehicle |
| PEM | Polymer Electrolyte Membrane or Proton Exchange Membrane |
| PHEV | Plug-in Hybrid Electric Vehicle |
| rpm | revolutions per minute |
| rps | rounds per second |
| SMR | Steam Methane Reforming |
| SoC | State of Charge |
| ZEV | Zero Emission Vehicle |

## Translation of units

| | |
|---|---|
| 1 mph | 1.6 km/h |
| 1 mile | 1.6 km |
| 1 mpg | 282.481 l/100km |
| 1 lbft | 0.738 Nm |
| 1 km/h | 0.625 mph |
| 1 km | 0.625 miles |
| 1 l/100km | 282.481 mpg |
| 1 Nm | 1.356 lbft |

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# 1 Introduction

The transportation system today uses 26 % of the annual global energy produced and is almost entirely dependent on fossil fuels [1-2]. The large bulk of transports consist of road transports where personal transports alone are responsible for 11 % of the worlds $CO_2$ emissions [2-3]. The current average $CO_2$ concentration in the atmosphere is 286ppm and is increasing at a rate of 2ppm per year and will, during a business-as-usual scenario, increase to somewhere in the regions of 700ppm until 2100. A radical change in the use of fossil fuel is therefore needed to stabilize the atmospheric $CO_2$ at a lower level [3-6]. To be able to meet the increasing emission and $CO_2$ legislation's, vehicle manufacturers are forced to increase fuel efficiency by both implementing new solutions and increasing efficiency of existing parts [8-10].

Future transports are seen as zero emission vehicles and have zero or very low well-to-wheel $CO_2$ emissions. These can be fuel cell vehicles (FCVs) with $CO_2$ neutral $H_2$ or pure electric vehicles (EVs) charged with $CO_2$ neutral electricity. Depending on a number of factors this future still has many years in the making, maybe as much as 40 years [3, 5]. The technology behind hybrid electric vehicles (HEVs) has been around for more than 100 years and modern equivalents have been in production for a bit more than a decade [11-12]. The focus of the automotive industry the last 20 years have been vehicle performance with more powerful engines as a consequence. There has however been a shift in this focus the last few years, starting with the Toyota Prius in Japan 1997, towards making more fuel efficient cars. HEVs are one of the most prominent solutions in the wait for more sustainable transports. HEVs themselves may not be the perfect solution to combat climate change, but they are a step in the right direction and will probably work as a temporary solution during the transition to the sustainable alternatives for personal transport.

HEVs consist of complex system interactions that need to be optimised to achieve as high a fuel economy as possible while fulfilling requirements on performance and drive-ability [13]. How the future will turn out is still unclear, however this report aims to predict how the nearest future in HEV technology will look like. It will also attempt to make a template for the selection of which hybrid powertrain to utilize for a specific car with specific characteristics to further help streamline the development process of HEVs.

## 1.1 Problem description and objectives

The demand for alternative transportation technologies is increasing and the emission legislations for light duty vehicles are getting narrower. It will be the vehicle manufactures that have to solve the problem of providing new technology that can meet these demands. But there are several things for a car manufacturer to take into account when introducing a new model and even more if changing the majority of the vehicles powertrain which can be both costly and time consuming. However, to be able to stay in the front line of car manufacturing, hybrids and other alternative technologies will be important to consider. It is therefore important to have as much information about new vehicle technologies as possible.

This master thesis's main objective is to help Lotus Engineering set up guide lines and gather information for the selection of new automotive technology through analysis of several new powertrain technologies. The research in this report will be based on two things. First a benchmarking and literature research of different road vehicle propulsion technologies, both existing and future, and secondly a systems evaluation through simulations. The literature research includes investigations of components in the different powertrains and the simulation includes a study of how parameters such as weight and the extent of hybridisation can influence the choice of propulsion system. The main goal is to present the status of current and future automotive propulsion technologies and thereby suggest which of the technologies that has the greatest potential to make it in the industry in the nearest future.

The first part, the investigation and benchmarking of future propulsion systems and components, will only reach into a feasible future and only consider the following technologies:

- Alternative fuels: Bio-diesel, natural gas, ethanol, methanol, hydrogen and synthetic fuels produced from air
- Internal combustion engine vehicles

- Electric vehicles
- Mechanical hybrid vehicles
- Hybrid electric vehicles and plug-in hybrid electric vehicles
- Fuel cell vehicles

The analysis of each technology is based on trends and findings from the benchmarking of present and coming car models and concept cars. The literature research helps to support these findings with facts. The analysis is made to show the potential of each technology to make it in the future automotive society and will consider cost of the technology, the potential to implement it into the current infrastructure and how much support the technology has from leading governments and commissions. But no full cost analysis is shown since the paper is focusing more on the technical aspects of the technology than the economic aspect. Even the driving behavior of the car users have been taken in to consideration, even though this analysis are very basic, see chapter 2.

Both the simulations of hybrid drivetrains and the research will focus on passenger cars and not consider heavy vehicles such as buses and lorries. The simulations will only consider hybrid electric and fully electric systems, not mechanical hybrids nor fuel cell vehicles. The simulations are done using the NEDC and a modified European city cycle.

The simulations are mainly focused on technical aspects as fuel economy and vehicle weight and do not focus on factors such as development costs or costs of production. But since cost of the vehicle is a very important factor, both to the vehicle manufacturers and to the customers, the cost factor is briefly discussed in the analysis from the benchmarking as described earlier.

## 1.2 Report outline

This report is divided into 9 chapters. The first chapter after this introduction is the background. In the background, the need for alternative technology and car usage is presented and it also includes a presentation of Group Lotus is given, since the thesis has been carried out at Lotus Engineering.

In Chapter 3 the different powertrains and their components are presented. The chapter aims to give the reader more information about the vehicle technologies that has been taken into consideration in this report. But a reader that is very familiar with the subject can thereby leave this chapter out. The next chapter, chapter 4 Principles for selection and implementation of new technology, presents some guidelines for strategic implementation of vehicles with new and different powertrain technology in current production.

In the chapter 5 Future technology, a presentation of the analysis from both the benchmarking and the literature research is given. The potential of each technology is described individually and in the end of the chapter a summary can be found, where three hypothetical future scenarios for the technology distribution are presented.

After this the results from the second part of the project are present, in chapter 6 which is the simulation section. In this chapter some of the powertrain systems that are presented in chapter 3 are validated to show where and how to use which system. Chapter 4, 5 and 6 all starts with a presentation of facts and a analysis and ends with a summary which summarises the most important findings from the chapter.

The whole report is being summed up in the end through the discussion and conclusions in chapters 7 and 8. The last chapter, chapter 9, gives some recommendations of future work in this area.

# 2 Background

Chapter 2 gives a background of this thesis and will explain the need for alternative propulsion and why alternative solutions are important and how they are linked to this work. It also gives a presentation on average car usage in the UK, since this is an important factor when investigating the possibilities for new propulsion technology. A short introduction of Group Lotus and their background is given as well since this master thesis is carried out at Lotus engineering.

## 2.1 Need for alternative technologies

The atmospheric $CO_2$concentration has been getting higher and higher during the last century and it is still rising at an exceptional rate, see figure 1. If nothing is done about the global $CO_2$emissions from fossil fuels, i.e. during a business-as-usual scenario, the $CO_2$concentration will almost be doubled by the end of this century, see figure 1 [2-3, 5-7].In later years the increased knowledge about the connection between atmospheric $CO_2$, global warming and sea level rise have put environmental issues on top of everyone's agenda. The industry, energy and transport sectors are the three largest contributors of $CO_2$and have accordingly given the main responsibility for lowering their use of fossil fuels [2]. With this in mind, the transport sector, which is responsible for 25 % of the worlds $CO_2$emissions, has to make a drastic change in the amount of fossil fuels consumed [2]. In the personal road transport sector hybrid powertrains, alternative fuels and small fuel efficient diesels are three of today's most used ways of attempting to reduce the environmental impact whilst at the same time trying to meet the 2020 goal of 95g-$CO_2$/km [14]. The different hybrid systems and the vehicles they are implemented in will play a significant role towards lowering fuel consumption and reducing the carbon footprint until more sustainable alternatives are available on a larger market.

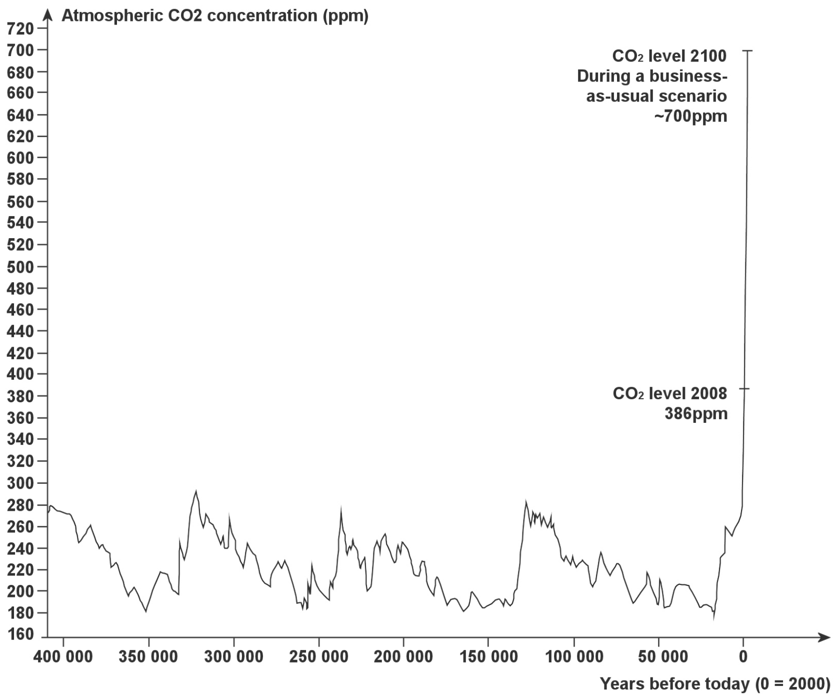


Figure 1: Average atmospheric $CO_2$ concentration [6, 15]

The worldwide growth of the vehicle fleet is another problem to be considered, especially in the developing countries where the increase is most substantial, see figure 2. In order to keep the increase in energy needed at an absolute minimum, cheap, fuel efficient or zero emission vehicles (ZEV) are needed. Car manufacturers that want to be on the environmental bandwagon need to consider hybrid systems, fully electrical systems and alternative fuels as a part of their model range.

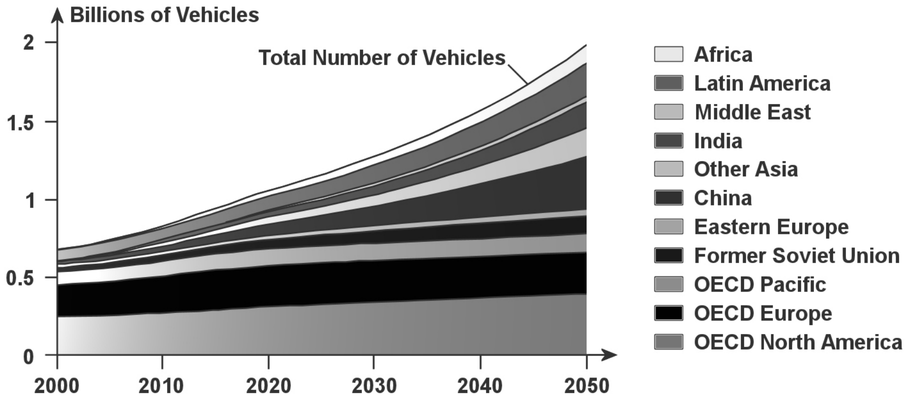


Figure 2: Predicted worldwide growth of the vehicle fleet [16]

All attempts to develop and implement more environmentally friendly technology will be of interest to the automotive industry. The potential of using hybrid technology to lower the fuel consumption can be seen in figure 3, where conventional petrol driven internal combustion engine vehicles are compared to petrol-electric hybrids with similar engine displacement.

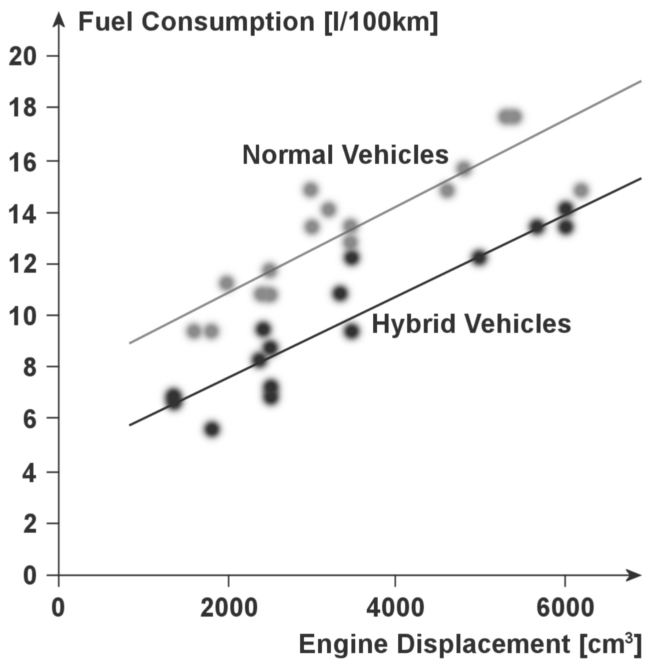


Figure 3: Potential of lowering fuel consumption with hybrid technology [17-54]

Investigating the different hybrid systems and their components thereby supplies useful information to the automotive manufacturers when developing a new hybrid model. This master thesis therefore attempts to investigate the latest developments and the predicted future of hybrid propulsion and other upcoming automotive propulsion technology. To make the introduction phase of new powertrains faster and more efficient a strategy is needed and together with simulations for validation. The results of this work aims to be a help for Lotus engineering when dealing with these kinds of problems. The results from the future automotive propulsion technology benchmarking are presented in chapter 5 Future automotive propulsion technology and simulation results in chapter 6 Simulations. The results from the simulations aims to act as a guide to the selection of the right technology for the right car model depending on factors such as vehicle weight and degree of hybridisation, DoH, which will be further explained in section 6.2.

## 2.2 Four-wheel vehicle usage in the UK

One important factor in the investigation of possibilities for current and coming vehicle propulsion systems is the average car usage amongst drivers. According to the UK department for transport (DfT), the average car mileage was 8,870 miles per year in 2007. This means that the average mileage per day is about 24.3 miles for a four-wheeled car [55].

By analysing how much time the average car user spends in their vehicles each year, an important fact is given. This information can be crucial when studying recharge times for electric based vehicles. According to the latest statistics from DfT the average time spent on travel ling by car was 232 hours per year in 2006 [55]. This means that the cars only are driven for about 40 minutes each day and is then parked for the rest of the time.

A summary of the average four-wheeled vehicle usage amongst UK driver can be seen in table 1.

Table 1: Average four-wheeled vehicle usage amongst UK drivers

| Average car usage | Per year | Per day |
|---|---|---|
| **Milage** *[miles]* | 8870 | 24.3 |
| **Time** *[h]* | 232 | 0.67 |

## 2.3 Group Lotus

As mentioned above this master thesis was made on the behalf of Lotus Engineering. Lotus is a British car manufacturer that designs and builds race and production automobiles with light weight and great handling characteristics. Anthony Colin Bruce Chapman built his first racing car in 1948 and founded the Lotus Engineering Company in order to build racing cars in 1952. In the year of 1966 the company moved into a purpose built factory at a former American second world war airfield in Hethel, Norfolk, where it still remains today. The facilities include a factory, engineering offices and have a 2 mile test track where ride and handling can be tested.

Group Lotus consists of two parts, Lotus Cars and Lotus Engineering, which 1996 was sold to the Malaysian car manufacturer Proton. Lotus Engineering is a consultancy company and the client base includes many of the world's major car manufacturers. New engineering centers have been established in the majors markets such as USA, China and south east Asia. Lotus Engineering also develops their own brand of cars produced by Lotus Cars [56]. The Lotus brand has a far going racing pedigree and a history of prestigious car models as the Lotus Esprit, the Elan and the Elite. Five different car models are produced today, the Lotus Elise, Exige, Evora, Europa and 2-Eleven, where the Evora is the latest addition to the family as it was released in the spring of 2009. Figure 4 shows 2008's sales of the different models [57].

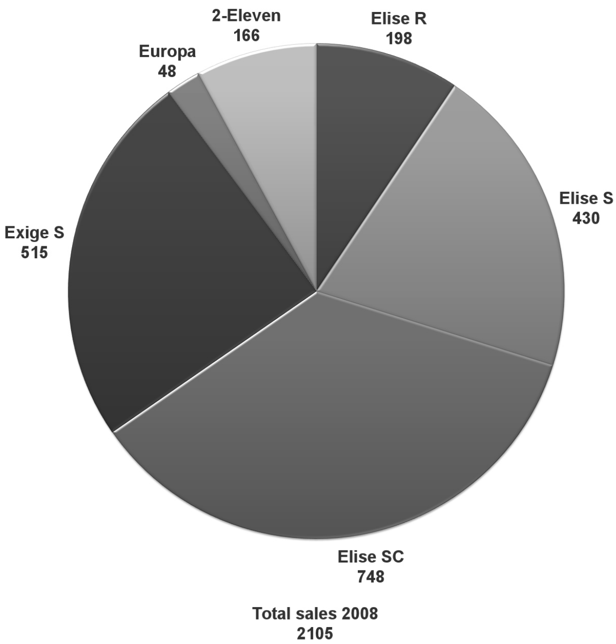


Figure 4: Cars sold by Lotus per model in 2008

Even though Lotus engineering are involved in several different development projects, do they not yet produce any hybrids among their own brand models. Fuel consumption for the current models are presented in table 2 which summarises some important specifications for the current car models. The table can be used as a comparison to the vehicles analysed in the benchmarking.

Table 2: Vehicle specifications of Lotus's current models

| Model | Fuel Consumption Urban [l/100km] | Fuel Consumption Extra urban [l/100km] | Fuel Consumption Combined [l/100km] | CO2 Emissions [g/km] | Maximum Power [kW] | Max Torque [Nm] | Acceleration 0-100km/h [s] | Top Speed [km/h] | Weight [kg] |
|---|---|---|---|---|---|---|---|---|---|
| Elise S | 10.6 | 5.8 | 7.6 | 179 | 100 | 172 | 6.1 | 207 | 860 |
| Elise R | 11.6 | 6.2 | 8.2 | 196 | 141 | 181 | 5.4 | 222 | 860 |
| Elise SC | 11.8 | 6.4 | 8.5 | 199 | 163 | 212 | 4.6 | 233 | 870 |
| Exige S | 11.9 | 6.5 | 8.5 | 199 | 164 | 215 | 4.7 | 238 | 935 |
| Europa | 12.7 | 7.3 | 9.3 | 220 | 147 | 272 | 5.8 | 230 | 995 |
| Europa SE | 13.4 | 7.7 | 9.8 | 229 | 165 | 300 | 5.3 | 235 | 995 |
| 2-Eleven | n/a | n/a | n/a | n/a | 142 | 181 | 4.5 | 225 | 720 |
| Evora | 12.4 | 6.5 | 8.7 | 205 | 206 | 350 | 5.1 | 261 | 1382 |

# 3 Vehicle powertrains and components

In this section current production and R&D powertrains are presented and explained, followed by some more detailed information about the components.

## 3.1 Internal combustion engine vehicles

The most common vehicles on the road today are petrol powered internal combustion engine vehicles (ICEVs). The powertrain is rather simple, consisting of an internal combustion engine (ICE) and some kind of transmission. The ICE produces torque which is transferred by the transmission to the wheels. The power produced in the engine corresponds to the power necessary at the wheels, including transmission losses, to propel the vehicle. A net surplus of power will accelerate the vehicle and subsequently a shortage of power will decelerate the vehicle [58]. Figure 5 schematically shows the powertrain for an ICEV with front and rear wheel drive.

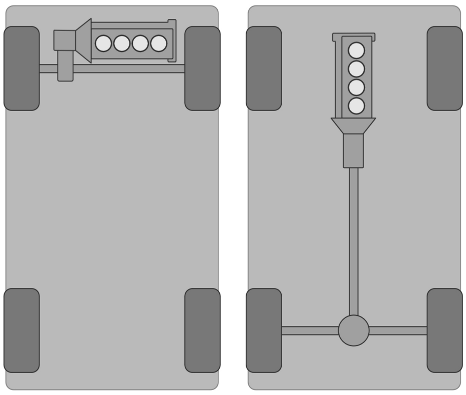

Figure 5: Conventional vehicle with a) *left:* Front wheel drive b) *right:* Rear wheel drive

The most common transmission is the fixed-step gearbox, either as an automatic gearbox or as a manual. More about how the transmission works can be found in chapter 3.6 section 3.6.5. The downside with conventional vehicles is that it is hard to combine high performance with low fuel consumption, since the power supplied for propulsion is dependent of the engine power and size [58].

## 3.2 Mechanical hybrid vehicles

A mechanical hybrid vehicle (MHV) can, among other things, have a flywheel, pneumatic or hydraulic system [59]. The main advantages with the mechanical hybrids is that they don't require a heavy and expensive battery pack as the hybrid-electric system, see section 3.4. The systems are usually quite simple and do not need that many separate devices which makes the mechanical system less expensive than an electrical system. Since the MHVs get their power from regenerative braking, the technology is very useful for vehicles traveling in urban areas such as delivery vehicles and city buses. But this is a technology that very well can be applicable to passenger cars as well and a short description will be given for each system in the following sections.

### 3.2.1 Flywheel system

The flywheel system usually combines an ICE with a flywheel. The flywheel recovers and stores the kinetic energy from deceleration and braking that would otherwise be wasted in a conventional powertrain. The physics for energy storage for a rotating flywheel can be described by the mathematical equation for a rotating solid disc or ring, see equation 1 and 2. Simply put, more mass, bigger radius and higher speed will allow more kinetic energy to be stored in the flywheel [60-61].

$$T_{solid} = \frac{1}{4}mr^2\omega^2 \tag{1}$$

$$T_{ring} = \frac{1}{2} m r^2 \omega^2 \quad (2)$$

The flywheel system is fully mechanical and do not need an extra battery/supercapacitor and can thereby avoid some of the problems with energy-buffers associated with hybrid electric powertrains, see section 3.4. The flywheel can be coupled as a series or parallel system. In the series two continuous variable transmissions (CVTs) are needed (see section 3.6.5), one between the engine and the flywheel and one between the flywheel and the differential connecting to the wheels, see figure 6a. In the parallel only one CVT is needed and the configuration is basically just a conventional powertrain with a flywheel connected to it through a CVT, figure 6b.

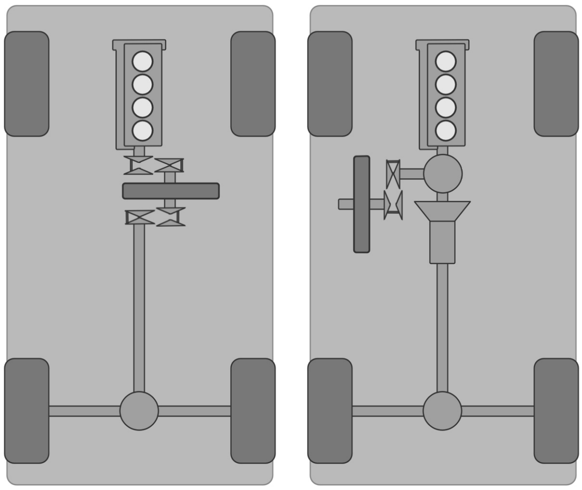

Figure 6: Flywheel configurations a) *left:* Series flywheel hybrid b) *right:*Parallel flywheel hybrid [59]

The energy in the flywheel will be stored as mechanical energy which means that there is no extra energy conversion between the wheels and the ICE. This makes the whole system more efficient compared to a hybrid electric vehicle, since less energy conversions equals less energy lost. Most flywheel systems are still under development and no vehicles have been produced beyond prototype stage [60]. But the kinetic energy recovery system (KERS) which is a mild hybrid system known from formula one racing, can be constructed with a flywheel, more about KERS in section 3.4.2.

### 3.2.2 Pneumatic system

In the pneumatic hybrid system a pressure tank is connected to the engine. Every cylinder is connected to the tank, which contains pressured air, through a fully variable charge valve, figure 7 shows the schematic setup of the pneumatic engine cylinder [62].

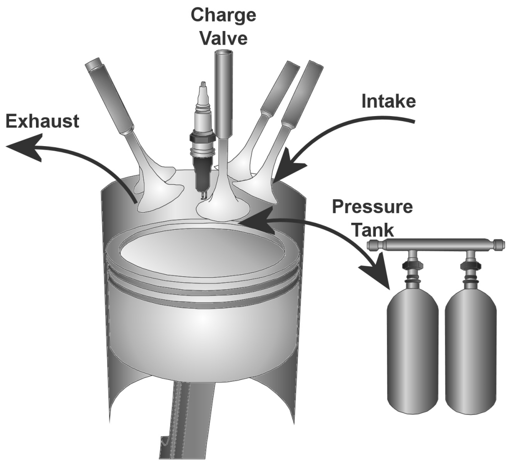


Figure 7: Pneumatic engine cylinder [59]

With the compressed air as an extra boost the engine can be downsized, but still be able to produce the same amount of power due to the boost. If decreasing the number of cylinders it is possible to decrease the friction losses and thereby increase the average efficiency of the engine. In the pneumatic hybrid the air is compressed during braking and is released trough electronic valves to start or drive the engine. The pressurised air can be used as an extra boost when starting from stop or just as extra boost during acceleration [62]. In figure 8 a schematic drawing can be seen of the pneumatic powertrain.

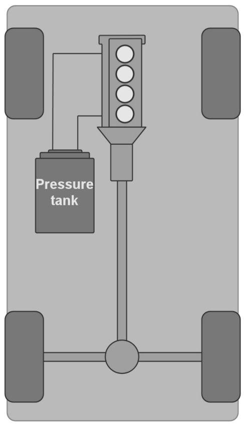


Figure 8: Schematic pneumatic powertrain layout [59]

#### 3.2.3 Hydraulic system

The hydraulic hybrid system consists of three main components; fluid stored in a low-pressure reservoir, a high-pressure accumulator and a pump connected to the low-pressure reservoir that moves the fluid from the reservoir to the high-pressure accumulator. The system can be coupled either as a series or a parallel system. In the series hydraulic hybrid the engine is connected to the hydraulic pump, which is then connected via an high-pressure accumulator to the a hydraulic pump/motor unit at the wheels, see figure 9a. The parallel system is more like a conventional powertrain with a hydraulic pump/motor coupled to the system between the engine and the gearbox, seen figure 9b [59]. As the other mechanical hybrids the hydraulic system receives its energy from regenerative braking. The energy is stored in the high-pressure accumulator and is then converted through the pump/motor to the drive shaft which drives or accelerates the vehicle. This makes the system suitable for vehicles in urban areas with a lot of starts and stops. An example of implementation is an American delivery company that has some hydraulic hybrids in their vehicle fleet [63].

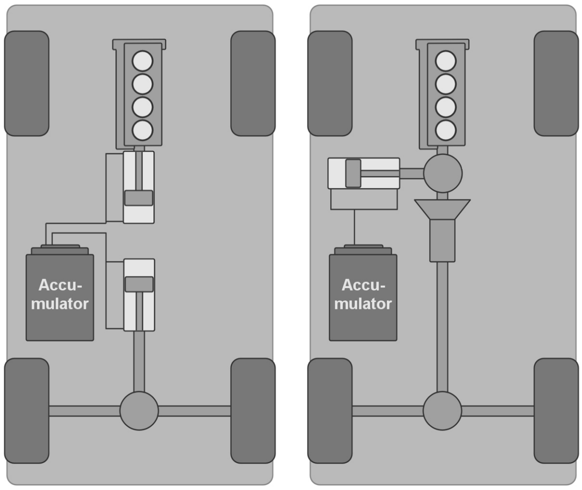


Figure 9: Hydraulic hybrid configurations a) *left:* Hydraulic series hybrid b) *right*: Hydraulic parallel hybrid [59]

### 3.3 Electric vehicles

Battery electric vehicles (BEVs), or as they are more commonly called, electric vehicles (EVs), are characterised by having pure electric propulsion. They mainly consist of an electric energy buffer, in the form of a battery or supercapacitor and an electric motor with its controller. The EV only has one energy conversion throughout the drivetrain which allows for a high overall efficiency [64]. The EVs have a number of attractive attributes such as operating on a high efficiency with zero exhaust-pipe emissions. It also has the possibility to regenerate most of its braking energy to recharge the battery during deceleration [16]. The EVs have a number of attractive attributes such as operating on a high efficiency with zero exhaust-pipe emissions. It also has the possibility to regenerate most of its braking energy to recharge the battery during deceleration [65]. The range of the EV is also very short compared to the range of an ICEV. The EVs which provides the best range only reaches about 250 miles on one charge whilst an ICEV can reach up to 1000 miles on one tank [17-54, 65]. Even if a battery with high specific energy is used it is difficult to reach a moderate range without adding too much weight or use too much space in the vehicle. Specific energy for batteries is further explained in section 3.6.3. The high cost of batteries and the maintenance needed are other reasons why EVs have not become more popular on a wider scale [16].

### 3.4 Hybrid-electric vehicles

Currently all the mass produced hybrid electric cars are petrol-electric system based vehicles [17-54, 59]. Hybrid-electric vehicles are characterised by having two or more types of energy sources, in contrast to ICEVs and EVs. The hybrid electric vehicle (HEV) generally includes an ICE as fuel converter or irreversible prime mover combined with an electric machine (EM) and a rechargeable energy buffer. These components together can achieve a better fuel economy compared to an ICEV, without necessarily sacrificing performance. The potential benefits of hybridisation are presented in chapter 2 figure 3. Different types of electric prime movers are used, such as standard DC or AC motors. More information regarding EMs can be found in section 3.6. One of the main advantages the HEV has is that it combines some of the advantages of previously discussed propulsion systems (ICEV and EV). The hybrid system enables the possibility of an efficient energy management and also allows the use of some of the energy usually lost during deceleration and braking to run the vehicle [64, 66].

Another type of HEV is the plug-in hybrid electric vehicle (PHEV) which according to the IEEE have at least following characteristics [67]:

- A battery system of at least 4 kWh

- The ability to recharge from an external electrical source
- Achieve at least a fully electric range of 10 miles

The PHEV essentially works in the same way as a HEV but has the ability to recharge its electric energy buffer from the power grid. The PHEV has a moderate pure electric driving range and it usually has a small ICE that acts as a range extender when the electric energy runs out. It can thereby combine the advantages of an EV together with the less range limited behavior of a conventional HEV. The operation scheme of the PHEV, see figure 10, can be said to have two modes. First the "charge depleting" mode, where the PHEV is run of the battery until it reaches its minimum state of charge (SoC). It then switches over to "charge sustaining" mode which has the vehicle operation functionality equivalent to a conventional HEV. In the second mode the vehicle will maintain the SoC within a limited operating range, using the stored energy to support the ICE and recharging via regenerative braking or direct charging from the ICE. The driving modes are illustrated in figure 10.

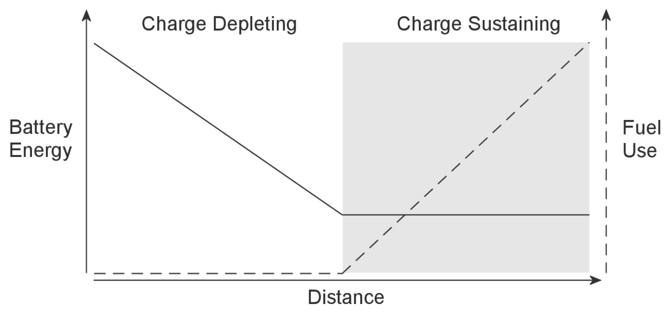


Figure 10: Driving modes for the PHEV [16]

PHEVs have recently been discussed as an alternative to conventional vehicles and conventional HEVs [16].

The HEVs have several different system configurations which can be divided into three main types, series hybrid, parallel hybrid and split hybrid. The different types of system configurations are presented in sections 3.4.1, 3.4.2 and 3.4.3 subsequently.

### 3.4.1 Series hybrid

One or more EMs act as the only prime movers of the vehicle in a series HEV. The electric energy is supplied from an energy buffer which can be a battery, a supercapacitor or an ICE driven generator. In the series hybrid the ICE is utilized as a range extender to increase the range further than in an EV. A generator is connected to the ICE to convert the mechanical energy output to electrical energy that can either charge the battery or directly feed the EM driving the vehicle [64]. A schematic layout of the series hybrid can be seen in figure 11.

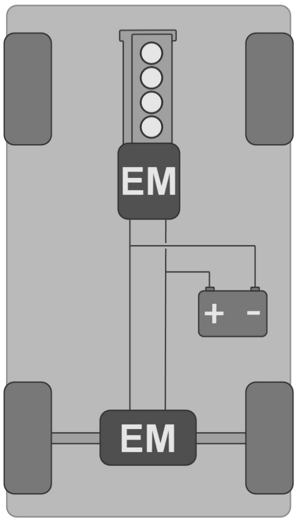


*Figure 11: Layout of the series hybrid powertrain*

One of the advantages of the series hybrid powertrain is the mechanical flexibility of the system, the ICE can be mounted almost anywhere since it works independently to the wheels. Subsequently the working point of the ICE is independent of the traction power, which means that it is possible to run the engine at its optimal operating point. More information with regards to the optimal efficiency point can be found in section 3.6.1. On the other hand the efficiency of the system is fairly low, as a consequence of all the energy conversions throughout the system. The EM by the wheels need to be relatively large, since it must handle all traction power on its own, but this on the other hand allows for more power to be recuperated during braking [58].

### 3.4.2 Parallel hybrid

A parallel HEV normally only have one EM that operates on the same drive shaft as the ICE, in that way the EM and the ICE can add traction power individually or simultaneously. Figure 12 shows a principal layout of the parallel hybrid drivetrain. The parallel hybrid can be seen as an ICE-based vehicle with an additional electrical path as opposed to the series hybrid where the ICE acts only as a support to generate power to the electric drivetrain [64].

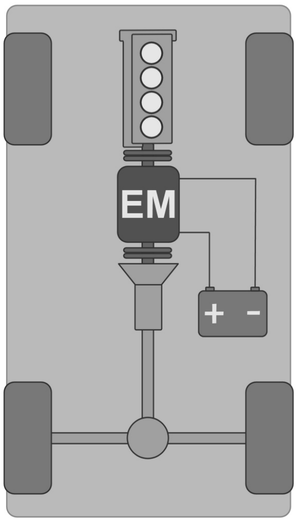


Figure 12: Principal layout of a parallel hybrid powertrain

The parallel hybrid powertrain is much more efficient than the series hybrid powertrain, since the ICE is mechanically connected to the wheels which results in fewer energy conversions in the system, the EM can also assist the ICE to run at a more optimal operating point. The system is less mechanically flexible compared to the series hybrid powertrain where the mechanical connection between wheels and ICE is not necessary.

The ICE is not able to work completely independently from the traction power, since it is dependent on the gear ratio of the transmission. The ICE is therefore not able to work at its optimal operating point at all times, but it is however able to work closer to the optimal point than in a conventional ICEV. Since the EM either can assist or brake the ICE towards a higher efficiency and thus a lower fuel consumption [58, 64].

#### 3.4.2.1 Mild hybrid

The most simple parallel hybrid is the so called mild hybrid configuration. The mild hybrid is characterized by having an over sized starter motor that assists the ICE and allows the ICE to be turned off during idling, coasting or braking. The auxiliaries, such as electrical power steering, air condition etc. can run on electrical power while the engine is off and the EM turns the engine up to operating speed before injecting fuel. In a mild hybrid about 15 % or less of total powertrain power are supplied by the EM. In a full, also called strong, hybrid the EM and ICE are of equal power and thereby have the ability to recuperate more braking energy and therefore achieve a better fuel economy than the mild hybrid [68].

Figure 13 shows a schematic layout of a mild hybrid drivetrain. The kinetic energy recovery system (KERS) is a form of mild hybrid and has been a hot topic in Formula 1 racing in the season of 2009. There are two types of KERS, one electric, with battery or supercapacitor and EM, and one that is flywheel based. In the electric system the power from braking is stored in a supercapacitor or a battery and is then released as extra power to the wheels when needed. In the flywheel based system the braking power is stored in a flywheel which is then coupled through a clutch to the wheels when the extra boost is needed. In the case of Formula 1 the KERS technology is not used to improve fuel economy but is instead used to give the cars better acceleration performance to help overtaking [69-70].

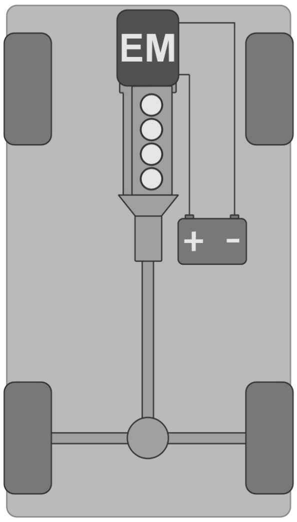


Figure 13: Layout of a mild parallel hybrid

### 3.4.3 Split/combined hybrid

The split hybrid powertrain is a Toyota solution and is due to the success of Toyota/Lexus's hybrids, the worlds most common type of hybrid powertrain [71].

The split, also known as combined hybrid powertrain is a combination of the series and the parallel hybrids. The powertrain design is close to that of a parallel hybrid, but it contains some features from the series hybrid as well, such as using the engine as range extender [64]. To be able to split the power between the EM and ICE a planetary gear is used, this can be seen in figure 14 which shows the layout of a split hybrid drivetrain. Further information about the planetary gear can be found in section 3.6.5.

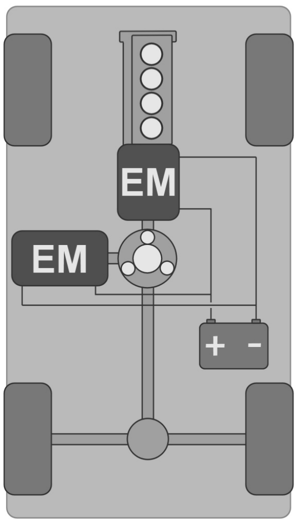


Figure 14: Layout of a split hybrid drivetain

Since the planetary gear seamlessly can split the power independently from one source to the other, it is possible for the split hybrid to run in several different operating modes such as engine only mode, zero emission mode and engine power assist. The disadvantage is that the powertrain contains a large amount of components which makes it more complex and expensive compared to a series or a parallel hybrid powertrain [58, 64].

## 3.5 Fuel cell vehicles

A vehicle with an electric drive can utilize a fuel cell to generate electricity on demand, instead of using a battery or a supercapacitor which is normally used in the PHEV and the HEV. In a fuel cell vehicle (FCV) the fuel cell will generate an electric current which is supplied to an EM that provides mechanical power to drive the vehicle, figure 15a. The fuel cell can also be used instead of an ICE in a HEV or PHEV application, which then becomes a fuel cell hybrid electric vehicle (FCHEV). In this case the fuel cell can both charge the energy buffer and supply power directly to the EM, as can be seen in figure 15b. In everyday life, it is normally this type of configuration that is referred to when talking about fuel cell vehicles. The third fuel cell powertrain configuration a type that uses a reformer connected to the fuel cell. The reformer allows for on-board hydrogen production from, for example methanol, figure 15c.

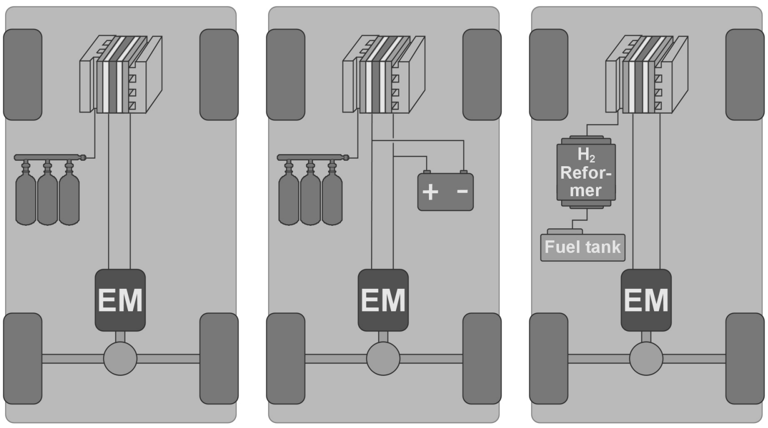


Figure 15: FCV configurations a) *left:* FCV b) *middle:* FCHEV c) *right:* FCV with reformer [58]

In the automotive industry the proton exchange membrane (PEM) fuel cell, also known as polymer electrolyte membrane, is the most common. The fuel cell characteristics are explained further in section 3.6, subsection 3.6.2. The fuel cell uses $H_2$ that normally is produced through electrolysis, using a primary energy source. The $H_2$ is then compressed, and in some cases also as much as into liquid, before it is stored, distributed and finally used in the vehicles. The entire well-to-wheel energy conversion of $H_2$ can be seen in figure 16.

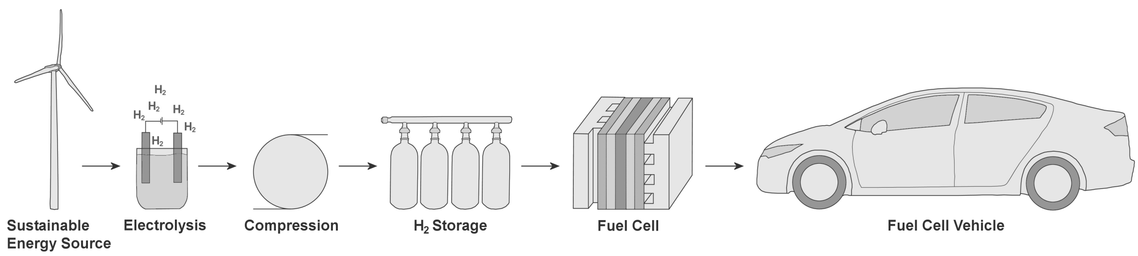


Figure 16: Energy conversion from primary energy source to fuel cell vehicle [72]

The main advantage with the FCV is that the only tailpipe emissions it creates is water ($H_2O$) and the $CO_2$ emissions are equal to zero from the vehicle itself if running on hydrogen. If the hydrogen is produced from either nuclear power or a renewable energy source, such as wind or hydro power, the entire energy conversion chain from well-to-wheel, can be $CO_2$ neutral. The problem is if the $H_2$ is produced from for example coal power or any other fossil fuelled energy source. In this case the well-to-wheel emissions can be equally bad or even worse than for an ICEV.

Another advantage of the FCV compared to an ICEV, is that the fuel cell has an energy conversion efficiency of about 50 % which is much higher than any ICE. The main disadvantage of the FCV is the storage of hydrogen on-board the vehicle. The problem is that hydrogen has to be highly compressed to allow enough hydrogen to be stored to get a reasonable driving range. To be able to do that, a high pressure, 350-700 bar, gas storage tank is needed, which takes up a considerable amount of space and adds a fair bit of weight compared to the usual sheet metal or plastic fuel tank used in an ICEV. This also leads to a new safety aspect, since the high pressure tank can become a considerable risk in a collision.

Other factors that influence the FCVs from penetrating the market are the high production costs of fuel cells, which make FCVs less economically competitive, and the issue with hydrogen infrastructure. The higher costs of a FCV can in some extent be counteracted by government incentives, but the infrastructure requires a much larger investment. What needs to be done is to create a new infrastructure for both producing and distributing $H_2$. This problem can in some extent be avoided if using a hydrogen reformer in the vehicles. However, this will mean an extra energy conversion in the powertrain, which results in a lower efficiency, and also adds more weight and cost since extra components are needed [58, 65, 72].

## 3.6 Main technology characteristics of the powertrain components

There are several important components included in the powertrains presented in the sections above. In this section the theory behind each of them will be presented.

### 3.6.1 Internal combustion engine

The internal combustion engine converts chemical energy stored in the fuel to mechanical energy through combustion. The combustion of the fuel occurs in the combustion chamber usually using air as an oxidizer [73]. The expansion of the high pressure and high temperature gasses produced by the combustion, force the moving parts of the engine (piston or turbine blades) to move and thus creating mechanical energy. The most common fuels that are used for conventional vehicles are petrol and diesel, but alternative fuels such as ethanol and bio-gas are becoming more common. The ICE has a very low thermal efficiency, which together with the mechanical losses, gives an overall efficiency of around 0.25-0.3 for a petrol engine and 0.4 for a diesel engine [58].

The ICE produces different torque at different angular velocities and at these different speed/torque points the engine runs with varying efficiency. The engine has a certain speed and load, represented by a torque, where it is operating close to its optimal efficiency point. This can be illustrated by plotting the brake specific fuel consumption (bsfc) contours in a graph with brake mean effective pressure (bmep) as a function of engine speed in revolutions per minute (rpm). The bsfc is in this case a measure of fuel efficiency while bmep is directly proportional to torque. Equation 3 below explains the equations behind bmep (figure 17).

$$bmep = \frac{P_b n_r}{V_d N} \tag{3}$$

Where $P_b$ is the brake power [kW], $n_r$ the number of crank revolutions for each power stroke per cylinder, which means that $n_r=2$ in a four-stroke engine, $V_d$ the displaced volume, [l] and N the engine speed in revolutions per second (rps). The bsfc can be used as a measure of how efficiently the engine is converting the fuel to work. Equation 4 shows that bsfc is the fuel mass flow per unit power output.

$$bsfc = \frac{\dot{m}_f}{p_b} \tag{4}$$

where $\dot{m}_f$ is the fuel mass flow and $P_b$ is the brake power output [73]. As can be seen in figure 17 the maximum bmep, and thus the maximum torque, will occur at one engine speed and the most fuel efficient point will in almost all cases occur at another speed and at part load.

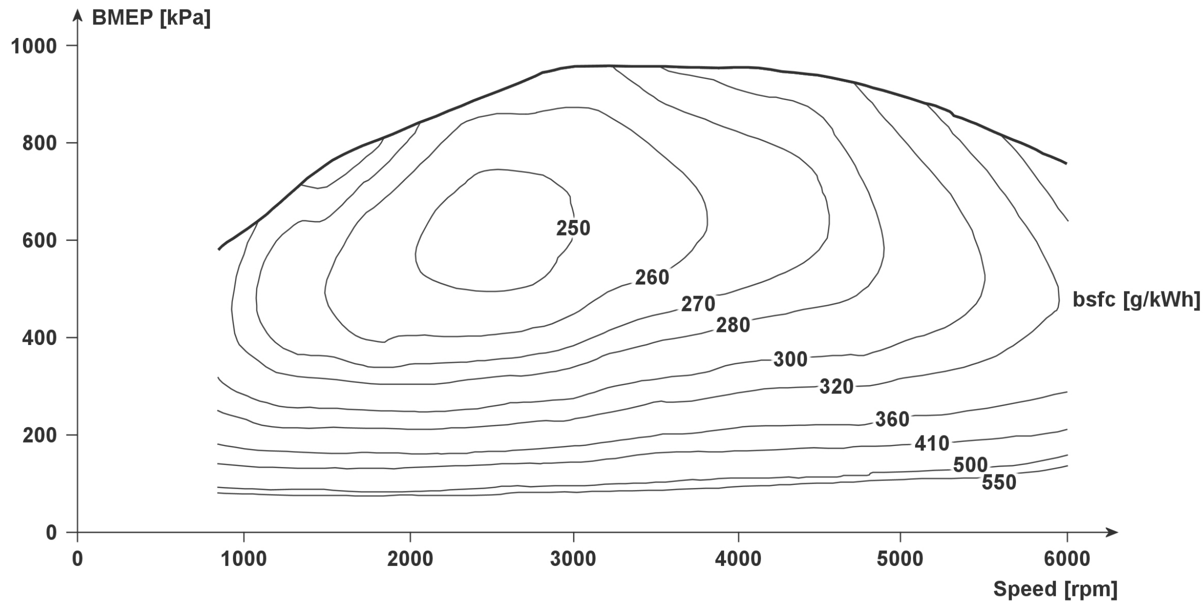


Figure 17: Engine fuel consumption map [73]

### 3.6.2 Fuel cell

The fuel cell is an energy conversion device that converts the chemical energy stored in a fuel such as hydrogen gas, $H_2$, into electrical energy. But other fuels such as methanol, ethanol and petrol can be used as well. Even if there are several different types of fuel cells, the basic principle of all of them is the same. They are supplied with hydrogen which is split into positively charged protons and negatively charged electrons through a catalyst next to the anode, see figure 18. Since the electrons cannot pass through the negative anode they will have to take a longer way through an external circuit to re-unite with the protons and the added oxygen at the cathode on the other side of the membrane, where the protons and electrons react with oxygen to form water. If hydrogen is continuously added a stream of electrodes will flow through the circuit and thus creating an electric current. The only exhausts from a fuel cell are water and a small amount of hydrogen that did not react at the anode [65, 72].

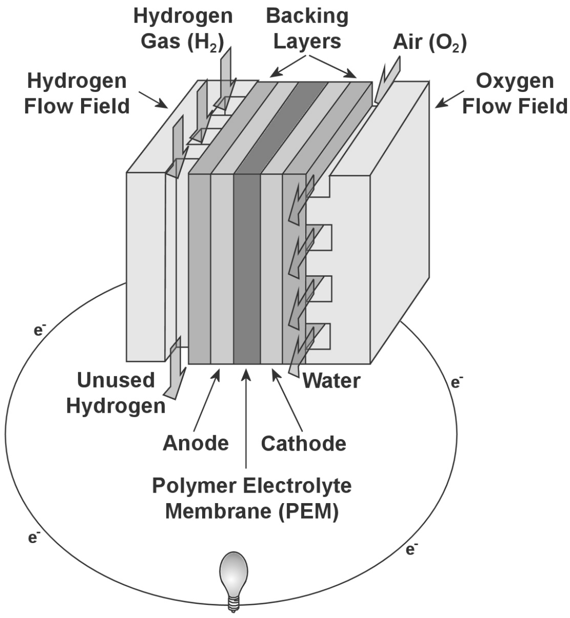


Figure 18: Layout and machinery description of a fuel cell [65]

### 3.6.3 Rechargeable energy storage systems

There are two main types of rechargeable, electrical energy storage systems, batteries and supercapacitors, that both will be described in the following sections.

#### 3.6.3.1 Battery

A battery, in a vehicle with some kind of electric drive, is used to store energy used by the electric motor or motors. Batteries transform chemical energy to electrical energy during discharging and vice versa during charging [64].

The battery is usually the component responsible for 25-70 % of the increased weight, volume, and cost associated with various hybrid configurations compared to a standard ICEV [74]. A critical factor for batteries is their long term reliability where wear and abuse can decrease the length of the batteries life. A problem with batteries is that the practically usable energy is much less than the total energy stored, this to not shorten the battery life. To avoid shortening battery life the state of charge (SoC) of the battery should keep within a approximately 20 % span of the total capacity of the battery, see figure 19. The SoC describes the amount of energy, or charge, remaining in the battery, expressed as percentage of its nominal capacity [64].

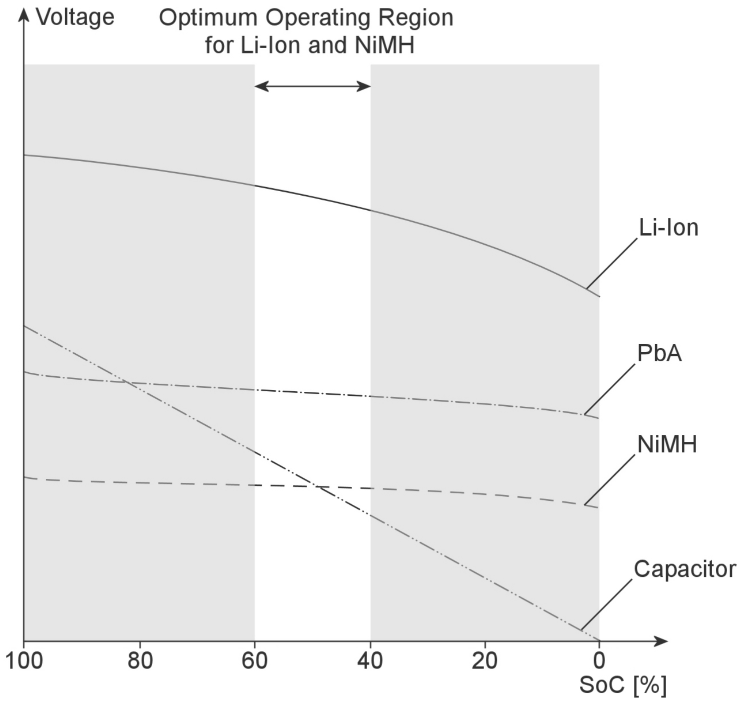


Figure 19: Usable energy span for Li-ion and NiMH batteries

Having batteries with a low weight is very important factor in keeping the overall weight of the car at a minimum and thereby using less energy during driving. The production HEVs available on the market today, utilize batteries with rated capacities of 0.6 to 2 kWh (see Appendix A), depending on which kind of hybrid configuration used. Mild hybrids generally require smaller batteries than full hybrids. Figure 20 shows the specific energy (Wh/kg) and specific power (W/kg) for some of the most common battery types.

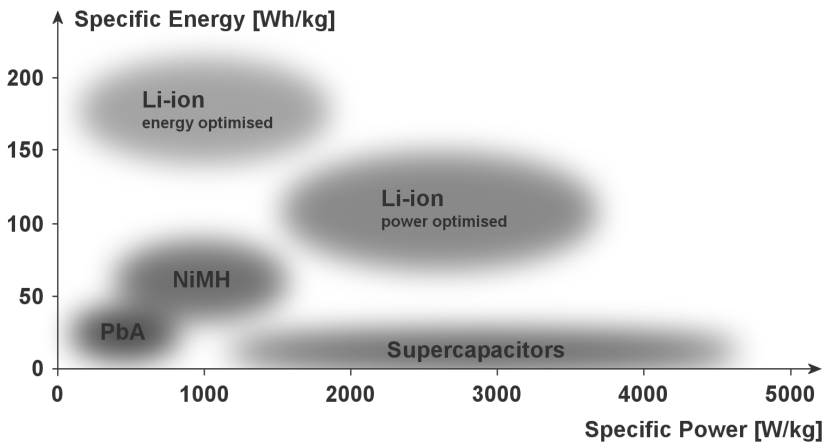


Figure 20: Specific energy for common battery types [75]

The early HEVs used lead acid (PbA) batteries since there was no other alternative [75]. Today the nickel-metal-hydride (NiMH) is the most commonly used battery, used in both Toyota and Honda hybrids. This is a more environmentally friendly and lighter battery with higher capacity than the PbA batteries. Lithium-ion (Li-Ion) batteries are just being introduced in production hybrids and is the most common battery type amongst PHEV concepts (see Appendix A).

#### 3.6.3.2 Supercapacitor

A supercapacitor is a kind of electric storage device that can be used instead, or together with, a battery in a vehicle with electric drive. The capacitor stores energy as electric charge and not as chemical energy as the battery does. This means that there are almost no losses when charging or discharging the supercapacitor [58]. The energy efficiency of a battery is normally, depending on battery type, 50-95 % and the losses are dissipated as heat. The efficiency losses of a typical supercapacitor are only in the range between 0.5 and 5 %, which means almost up to a hundred percent efficiency. Another advantage with supercapacitors is their high charge and discharge times. The reason for this is that supercapacitors can allow a higher charge and discharge current than batteries. As can be seen in figure 20 the supercapacitors has a higher specific power than the batteries, but due to problems with having a too high potential it is limited to having a low specific energy [76].

Figure 21a illustrates how efficiently the energy buffers can deliver power in different temperatures. The supercapacitor is only affected by very little by the shifts in temperature while the Li-ion battery hardly works at all until the temperature reaches 20 degrees. Another advantage with supercapacitors is illustrated in figure 21b. As can be seen, it is possible to discharge the supercapacitor completely without decreasing the cycle life by very much, while the batteries on the contrary suffers a huge decrease in cycle life if cycled more than 20 % of SoC.

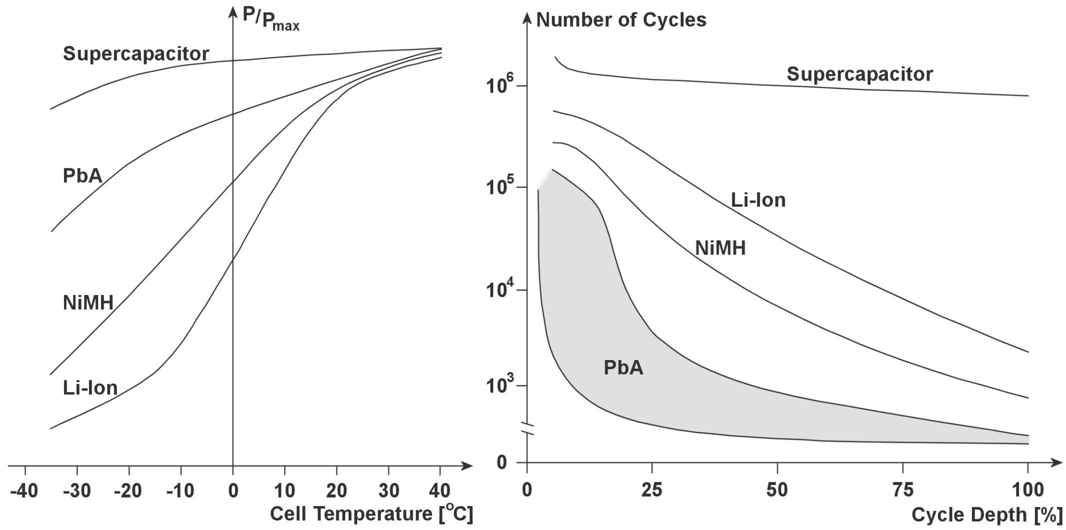


Figure 21: Comparison of different energy buffer types a) left: Power output for the energy buffers over different temperatures b) right: Cycle life depending on cycle depth

### 3.6.4 Electric machines

The electric machine (EM) is a key component in the hybrid-electric powertrain. The electrical machine converts electrical energy into mechanical work. The transformation is usually produced by the interaction of conductors carrying current perpendicular to a magnetic field. There are several different types of electrical motors and they all differ in the way the field and the conductors are arranged and also in the amount of mechanical output as torque, speed and power that can be achieved [77]. The torque provided at different speeds by an EM is very different compared to an ICE, see figure 22. The EM provides a very high torque at low speeds which makes it very good for starting and accelerating a vehicle, but less effective at high speed.

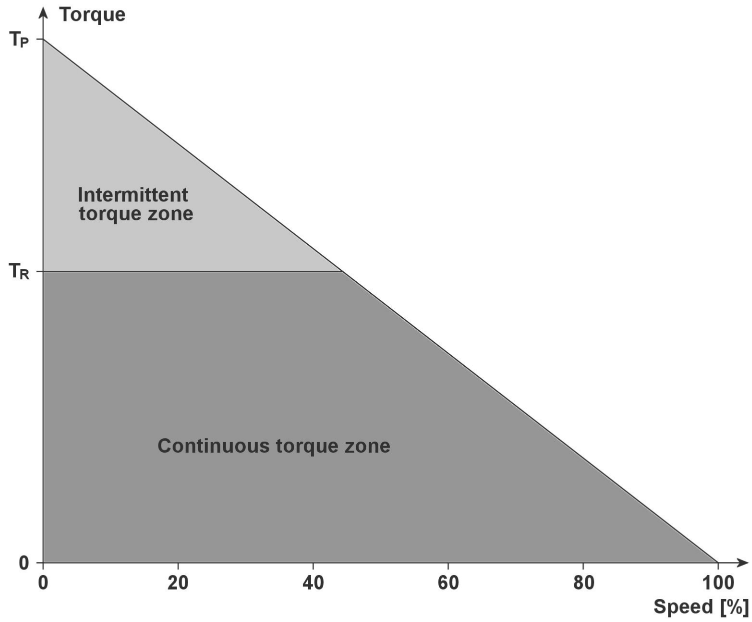


Figure 22: Torque at different speeds for an electric motor

The reversed process, mechanical to electrical energy, can be also be achieved by an EM when used as a generator [78]. In hybrid vehicles the EM is in almost all cases reversible and can work both as an electric motor and a generator. It is possible for the EM to work in several different ways: convert electrical energy from the battery to mechanical traction power to drive the vehicle, recharge the battery by either converting the mechanical power from the ICE or through regenerative braking. As can be seen in figure 12 the parallel hybrid powertrain will only need one EM to provide all features such as battery charging and traction power. Whereas a series and split hybrid, figure 11 and 14, need two separate EMs, one traction motor that can both supply traction power and recuperate braking energy and one generator that also can act as a starter motor for the ICE [64].

#### 3.6.5 Transmissions

The transmission adjusts, transmits and distributes power between power sources, electric machines and wheels in the powertrain. A transmission is required since the different components in the powertrain either need a higher or lower speed or torque compared to one another. The wheels will for example rotate slower than the ICE and are therefore in need of a step down in rotational speed. The meaning of the word transmission, in an automotive context, often refers to the gearbox. Even though simple gears, planetary gears, drive shaft, final gear and half shafts may be included. There are three main types of gearboxes; the manual transmission, the automatic transmission and the continuously variable transmission (CVT) [58].

The manual gearbox dominates the automotive market outside North America where the automatic transmission is the most common. The manual transmission has a fixed number of gears and is almost exclusively used together with a clutch. In comparison to the automatic transmission, that also has a fixed number of gears, but instead of an ordinary clutch uses a hydrodynamic torque converter or an automated clutch. It will also, as the name suggests, shift gears automatically without any signal or action from the driver. Both the manual and the automatic transmission gearbox have a finite number of gears with fixed gear ratios.

Another kind or gearbox is the continuously variable transmission which is becoming more common amongst both conventional vehicles and, perhaps, mainly hybrid vehicles. The CVT can be seen as having an infinite number of gears which offers continuous gear ratios within a limited range. The CVT is mainly used because of its ability to get the engine to run more efficiently, closer to its optimal efficiency point. The CVT is able to vary the gear ratios continuously, which means that it works as an automatic transmission but with an infinite number of gears. This makes the CVT very suitable for hybrid powertrains, since the optimal gear ratio can be selected in order to keep energy efficiency and performance as close to its maximum as possible [79].

Figure 23 shows the maximum power curve of an engine in a schematic graph with the traction force as a function of vehicle speed. With a CVT it is possible to always stay on the line representing the maximum power curve. The five box-shaped areas illustrate the possible regions with a conventional fixed five step gearbox [64].

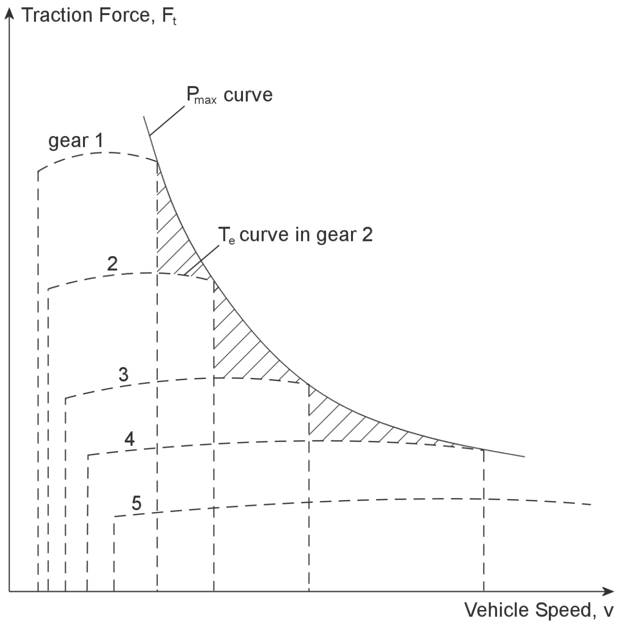


Figure 23: The traction force, Ft as a function of the vehicle speed, v

To be able to split power between different components in the split hybrid powertrain, a planetary gear can be used, as done in for example the Toyota Prius. The planetary gear can be defined as an assembly of meshed gears consisting of one sun gear, three or more planet gears held together by the planet carrier and one ring gear. In the Prius the ICE is connected to the carrier, the traction motor to the ring gear and the generator to the sun gear, a schematic drawing of the planetary gear can be seen in figure 24 [58]. The full layout of the split hybrid can be seen in figure 14, section 3.4.3 .

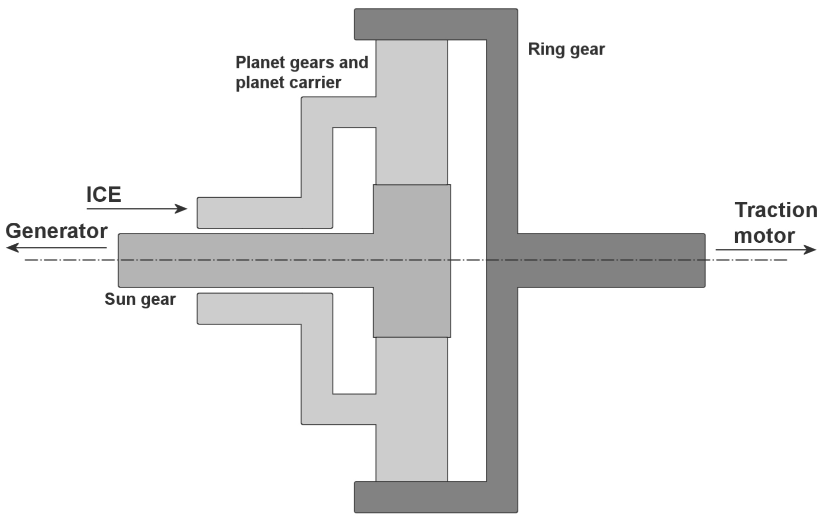


Figure 24: Layout of a planetary gear in a Toyota Prius

# 4 Principles for selection and implementation of new technology

Several things need to be taken into consideration when putting a new car model into production. Furthermore, if the new model has an entirely different powertrain, like a hybrid system, there are several additional aspects that need to be taken into account. This section will include a discussion regarding these significant factors involved in selecting and implementing a new system, and relevant factors will be assigned observing the process from a manufacturer's point of view.

## 4.1 Vehicle introduction strategy and system selection

From a car manufacturer's view, there are more issues to be considered when introducing a HEV than solely the environmental aspect. The manufacturer needs to have a well planned roll-out strategy, and there is also a need for building up supplier partnerships and having a clear path throughout the entire development phase. Also, it is important to have a long-term goal, so that the first introduction becomes a stepping stone in the implementation of future forms of propulsion systems, such as PHEVs, EVs or FCVs. The first factors that need to be regarded are saleability and cost, and the introduction step involving these factors could be summarised as follows:

- The competitiveness possessed by the new system, and the ICEV competition already present in the same market segment
- The customer needs and knowledge regarding the new technology
- Compatibility and differentiation, i.e. to what extent the base vehicle can be used and which changes are required if a base vehicle is available
- Benchmarking of available technology
- Supplier availability and pricing
- The legislative driven needs

To summarise, it is important to have a good knowledge about the market and the customers, but also to highlight the base vehicles if the new system is meant to be based on an existing model. Benchmarking of the available market and spotting trends are important initial steps before selecting a new technology. Although, even if there are plenty of new solutions on the market, these will only be available if a supplier can deliver the technology to the manufacturer at the right price. Further information regarding technology trends and benchmarking can be found in section 5.1.2.

Taking a closer look at the legislative needs, the European commission have decided on emissions standards for all newly produced light-duty vehicles regardless of the powertrain technology being used. The currently used emission standard is the Euro 4, but already in September 2009 the Euro 5 will come into force. The difference between Euro 4 and Euro 5 is denoted in table 3 where an overview of the European standards for emissions from Euro 1-6 is given.

Table 3: The European emission standards

| Tier | Fuel | THC | NMHC | NOx | HC + NOx | CO | PM | PN |
|---|---|---|---|---|---|---|---|---|
| | | mg/km | | | | | | #/km |
| Euro 1[1)] | Petrol | - | - | - | 970 (1130) | 2720 (3160) | - | - |
| | Diesel | - | - | - | 970 (1130) | 2720 (3160) | 140 (180) | - |
| Euro 2 | Petrol | - | - | - | 500 | 2200 | - | - |
| | Diesel | - | - | - | 700 | 1000 | 80 | - |
| Euro 3 | Petrol | 200 | - | 150 | - | 2300 | - | - |
| | Diesel | - | - | 500 | 560 | 640 | 50 | - |
| Euro 4 | Petrol | 100 | - | 80 | - | 1000 | - | - |
| | Diesel | - | - | 250 | 300 | 500 | 25 | - |
| Euro 5 | Petrol | 100 | 68 | 60 | - | 1000 | 3 | - |
| | Diesel | - | - | 180 | 230 | 500 | 3 | $5x10^{11}$ |
| Euro 6 | Petrol | 100 | 68 | 60 | - | 1000 | 3 | - |
| | Diesel | - | - | 80 | 170 | 500 | 3 | $5x10^{11}$ |

[1)] Values in brackets are Conformity of Production (COP) limits

The saleability of the vehicle also needs to be balanced with the vehicle attributes and features. This can be approached in different ways, focusing on one hand on performance such as speed and power and on the other hand on fuel economy. When considering the selection of a new system technology and choosing market segment, the offset between performance and fuel economy is very central. Regarding this aspect, there are three main approaches that can be applied:

- Performance only approach
- Performance/fuel economy approach
- Fuel economy only approach

In a premium customer approach the performance is the most essential part and the production cost can be considered less. The performance orientated systems usually have a minimal effect on the lowering of $CO_2$ emissions since the new technology is used to add power to the vehicle rather than making it more environmentally friendly. The customer segment is rather small, since the strategy is usually applied only to luxury car models which already lie within the high priced segment. To get a broader customer appeal, the focus on the aspects of performance gain versus economy needs to be equal. The vehicle production cost has to be considered to a greater extent to approach a bigger market segment than that approached by the performance oriented vehicle. In the third approach listed, economy is the most important and the vehicle is to approach a big market with cheap affordable cars. Still, even if the segment has a big customer base there will also be more competition, meaning that the system needs to be rather cheap to be competitive. Subsequently, the cost of production is a very important factor. In conclusion, the first step in the development process is knowing the market situation and deciding which segment to aim for [80].

After choosing in which implementation segment one is to place the vehicle, it is rather easy to decide upon which propulsion technology to use, since choice of segment basically determines the budget for the new introduction.

If a HEV propulsion system is chosen, this system needs to be complemented with the right degree of hybridisation (DoH). The degree of hybridisation basically defines the relationship between ICE and EM power in a HEV, see section 6, equation 6. To be able to know which DoH that will result in the desired performance and fuel economy some kind of validation, such as simulations, is needed.

Using simulations is always a good way of validating the selection of system and to establish the improvements actually contributed to the vehicle by usage of the selected hybrid system. Rather simple simulations can give a good indication of performance and fuel economy of the new system and this data can easily be compared to the original model. Through the simulations one is able to see to what extent previous decisions in performance and fuel economy will be affected by various properties such as weight and DoH. The simulations performed to validate the test vehicles used as a basis for this report are presented in chapter 6 Simulations.

## 4.2 Summary hybrid system selection

The system selection can be summarised in six main steps, all of equal importance.

- Gather information about your market, customer and legislations
- Investigate validity of the current vehicle base model
- Choose implementation segment: Performance oriented, performance-economy oriented or economy oriented
- Select propulsion technology
- Choose desired vehicle properties that match up with the implementation segment and technology
- Validate selections through usage of simulations

# 5 Future automotive propulsion technology

This chapter contains a review of the prospects and prognosis' of old and upcoming technologies, technologies which was described in previous chapters. Most of the technologies can easily be implemented into the current vehicle fleet without any major efforts from politicians or manufacturers. However some technologies, which have been presented in previous chapter and which will now be further highlighted, might stand or fall with designs and efforts from the governments.

The future of transports can be described in the three possible scenarios: an "electrical based" society, a "hydrogen based" society or a third society with a mix of technologies. In the third society, no radical government decisions are made and the manufacturers have to find their own approach to implement new technologies into the current infrastructure. Regardless of which future scenario that will occur, all of the mentioned technologies have a potential to make a change in the fight against $CO_2$ emissions from transports. Thereby all future prospects will be discussed as possibilities due to the potentials of technologies, even though they may rely on governmental support to a larger extent, and less on knowledge and availability.

## 5.1 Benchmarking and research

In this section the results from the benchmarking and technology research will be presented. An overview of the information about the vehicles studied for the benchmarking can be found in Appendix Aand the references for the research can be found at the end of the report.

### 5.1.1 Methodology benchmarking and research

To be able to investigate and get an indication of the hybrid technology and components suitable in future production, benchmarking is of great importance. The aim of this research is to identify trends in the development of technologies, to describe currently available powertrains, but also to try identifying which coming technologies that will be available for future vehicles. The benchmarking performed is based on a total of 54 vehicles, mainly consisting of HEVs, EVs and PHEVs, although ICEVs and FCVs are also included. [17-54, 81-84], see Appendix A.

The literature study is based on information from several articles, papers and books. Databases mainly used in the study are the IEEE (institute of electrical and electronic engineers) and SAE (Society of automotive engineers). For the benchmarking, several internet sources have been used to gather information about the vehicles concerned in the study. Bibliography and other references used as basis for this thesis can be found in the reference list at the end of the report.

### 5.1.2 Technology trends overview

This section will present the trends found when performing the benchmarking of a number of different production, upcoming and concept vehicles. The benchmarking is made to identify trends in concepts and existing vehicle powertrains on the market, and thereby giving an indication of how the future in automotive engineering will turn out.

Figure 25 shows how vehicle weight influences fuel consumption. This fact might seem obvious, however it is still important to highlight since weight savings can be done in almost every application of the vehicle. Thus, to keep the weight of the vehicle body down, it is important to keep the weight in mind during production of its separate components. In section 5.5 more information can be found on how to construct the vehicle, with the aim towards a lower weight.

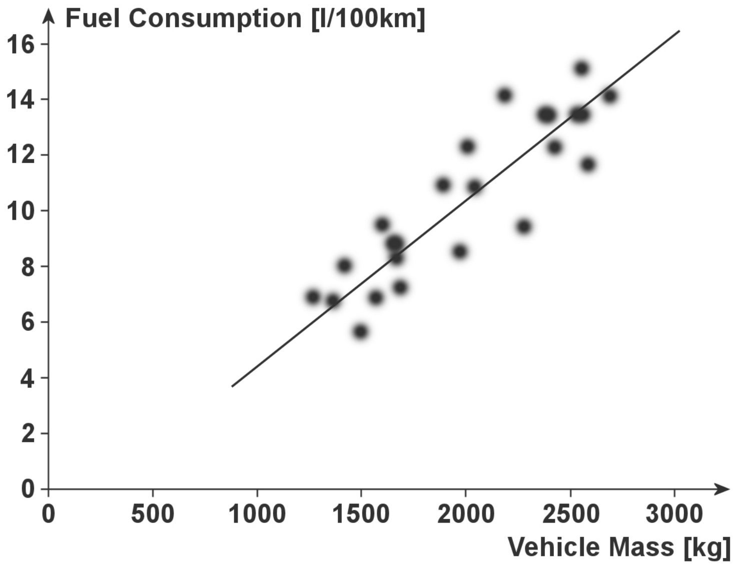


Figure 25: Fuel consumption compared to vehicle weight

Table 4 present a comparison between three fuel efficient diesel sedans and three petrol-electric HEVs. They are all five seat passenger vehicles with similar size and weight.

Table 4: Comparison between diesel and HEV passenger cars

| Model | $P_{ICE}$ [kW] | $P_{EM}$ [kW] | DoH [-] | $V_{dICE}$ [cm3] | F.C. Urban | F.C. Extra-Urban | F.C. Combined | $CO_2$ [g/km] | $V_{max}$ [km/h] | 0-100 km/h [s] | Weight [kg] | Length [m] | Width [m] | Height [m] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Volvo S40 DRIVe | 80,0 | - | 0 | 1560 | 4.9 | 3,6 | 3,9 | 104 | 190 | 11.4 | 1386 | 4,476 | 1,770 | 1,454 |
| VW Polo Bluemotion | 59,7 | - | 0 | 1422 | 4,9 | 3,2 | 3,8 | 99 | 174 | 12.8 | 1284 | 3,916 | 1,650 | 1,467 |
| VW Golf Bluemotion | 78,3 | - | 0 | 1598 | 5,2 | 3,5 | 4,1 | 107 | 189 | 11,3 | 1443 | 4,199 | 1,786 | 1,479 |
| Toyota Prius | 73,0 | 60,0 | 0,45 | 1795 | 3,9 | 3,7 | 3,9 | 89 | 180 | 10,4 | 1495 | 4,460 | 1,740 | 1,490 |
| Honda Insight | 65,0 | 10,3 | 0,14 | 1339 | 4,6 | 4,2 | 4,4 | 101 | 186 | 12,6 | 1275 | 4,400 | 1,700 | 1,430 |
| Honda Civic Hybrid | 70,0 | 15,0 | 0,18 | 1339 | 5,2 | 4,3 | 4,6 | 109 | 185 | 12,1 | 1368 | 4,545 | 1,750 | 1,430 |

In previous chapters, a similar comparison between petrol-electric HEVs and petrol ICEVs have been presented in figure 3, section 2. It can be concluded that the petrol-electric HEVs have a huge advantage in fuel consumption in comparison to petrol ICEVs, although, when it comes to efficient diesel ICEVs and petrol-electric HEVs the scenario is very different. In the case presented, all the ICEVs are using a supercharged, direct injected four cylinder diesel engines. Moreover, it can be seen in the comparison study that the ICEVs have an equally good or slightly better fuel economy than the HEVs.

These results from the benchmarking indicates that diesel ICEs may become more common amongst ICEV “green car” models. Also, this is a possibility for HEVs and PHEVs, since a diesel ICE can be used in these powertrains as well.

Furthermore, the benchmarking shows that the HEVs and EVs available on the market mostly use NiMH batteries whilst almost every concept are using Li-ion battery packs. This is a strong indication that NiMH batteries belong to the past and that future models of EVs, HEVs and PHEVs with all certainty will depend on the usage of Li-ion batteries. This development is due to the fact that most concept cars are EVs and PHEVs which depend on an all-electric driving mode and thereby demands more energy stored onboard. Li-ion batteries have a much higher specific energy than other battery types (see figure 20) and are therefore a better choice for this application.

Table 5: Battery chemistry used in current and coming concept EVs, PHEVs and HEVs

| Type | Existing | Concepts |
|---|---|---|
| NiMH | 91% | 25% |
| Li-Ion | 4.5% | 75% |
| Zebra | 4.5% | 0% |

The analysis of the HEVs and the PHEVs in the benchmarking indicates that split and parallel systems are mostly used in HEVs, but in PHEVs, where the ICE works more as a range extender, the series powertrain is the most common. Regarding the trends concerning fuels, all HEVs on the market are petrol-electric, although one can identify an increasing amount of diesel-electric amongst the concepts.

Amongst the new "green car" concepts analysed, the majority of vehicles are using battery based system while the alternate hydrogen based systems are used only in a few vehicles. Thus when analysing the findings from the benchmarking, it seems like the electric based vehicles are more attractive on the automotive market compared to the hydrogen cars.

## 5.2 Future fuels

As highlighted in previous chapters, the amount of produced cars will increase in an exponential rate in the upcoming years, with a resulting energy need that has to be satisfied and fuel needs that somehow will have to be provided. The uncertainty regarding the lasting of oil reserves of the earth as well as the increasing environmental awareness has established a demand for a fuel and energy source that is cleaner and more environmental friendly.

As discussed in previous chapter, the European commission implemented emission standards and the Euro 4 standard is currently in force, but already in September 2009 the Euro 5 will come to pass as the new standard and in January 2014 even tougher standards will be implemented as Euro 6 enters as the new emissions standard. To preserve the air quality, new cars will have to stand more extensive testing before being approved for sale in the European Union. In table 3 in chapter 4, section 4.1 one can see the new light-duty vehicle emission standards of Euro 5 and 6 which new petrol and diesel cars have to live up to [85].

The future fuels needs to be cleaner and more efficient to satisfy the demand of new vehicles and tougher legislation's. In sections below, some future alternative fuels will be presented which can create a higher variety of fuels and make the world less oil dependent.

### 5.2.1 Biodiesel fuel

Biodiesel is a form of diesel produced from vegetable oil, animal fat or recycled restaurant grease waste. The biodiesel is cleaner and produces less air pollutions than the conventional petrol based diesel, since it is produced by renewable sources such as new and used vegetable oils.

Biodiesel is currently used as a mix with petrol diesel, with 2, 5 and 20 % biodiesel in the blend (B2, B5 and B20). One problem with the biodiesel is that the efficiency of the blends is not as good as for pure petrol-based diesel. Another drawback is that the biodiesel currently on the market is more expensive than conventional fuels, which becomes a problem when trying to get it accepted by the consumers. Also, another major issue is that even if most of the emissions (PM, CO, HC) decrease when more biodiesel goes into the blend, the $NO_x$ will increase. This problem can be diminished by usage of a catalyst which absorbs the $NO_x$. For now, present engine manufacturers do not recommend usage of blends greater than B5, since a higher blend can damage the engine. This means that the use of biodiesel will be very much dependent on conventional fossil fuel based diesel. Conclusively, biodiesel is not a substitute for conventional fossil-based diesel at the moment and thus it will not solve the dependence of fossil-fuels. However, if engines are developed to manage a higher blend of biodiesel this can be a good complement to fossil-based diesel and thereby decrease the overall oil dependence [86-88].

### 5.2.2 Ethanol and methanol fuels

The two alcohols ethanol (ethyl alcohol) and methanol (methyl alcohol) can be used as alternative fuels in internal combustion engines. Ethanol is available as E85, which means 15 % fossil petrol and 85 % ethanol, which can be used to power flex-fuel vehicles. The ethanol fuel can be made from starch and sugar based feedstock or from cellulose feedstock such as crops, grass and wood [89].

Brazil is a very good example of a society using alternative fuels, where all the petrol sold the last 15 years has contained about 22 % ethanol. The fleet has about 4 million fully dedicated ethanol vehicles and about 13.5 million vehicles which are using an ethanol-petrol blend [90].

The main reason for Brazil to be a less oil-dependent society was a consequence of the oil shocks that occurred almost 40 years ago. This event launched the usage of ethanol as a replacement for oil based petrol, and it is a good example not just when it comes to the use of ethanol fuels but also when it comes to proving that it is possible to actualise the decisions that are made regarding such a large societal change.

When looking at the capacity of reducing $CO_2$ emissions with the usage of ethanol it is necessary to examine the whole production chain for ethanol. This chain includes the following steps: growing the crops, transporting the crops to the production plant, producing the ethanol, distributing and transporting the ethanol and finally burning it in the vehicle. In a place like Brazil where they use sugar canes to produce the ethanol they have obtained a very good performance for the ethanol vehicles due to several reasons. Because of the local sugar cane agriculture, the transportation distance is minimal and the usage of these canes for ethanol production gives a high reduction in $CO_2$ emissions. Because of the local mass production in Brazil they have also been able to keep down the cost of the fuel and have made it competitive to the conventional fuel. In contrast, if a country do not have the possibility to produce the corps locally, the cost of producing ethanol fuel can be much higher and the gain in $CO_2$ emissions reduction will not be as high as desirable due to the increased need of transportation. In figure 26 is it possible to see the difference between some of the energy sources used to process ethanol fuel [91].

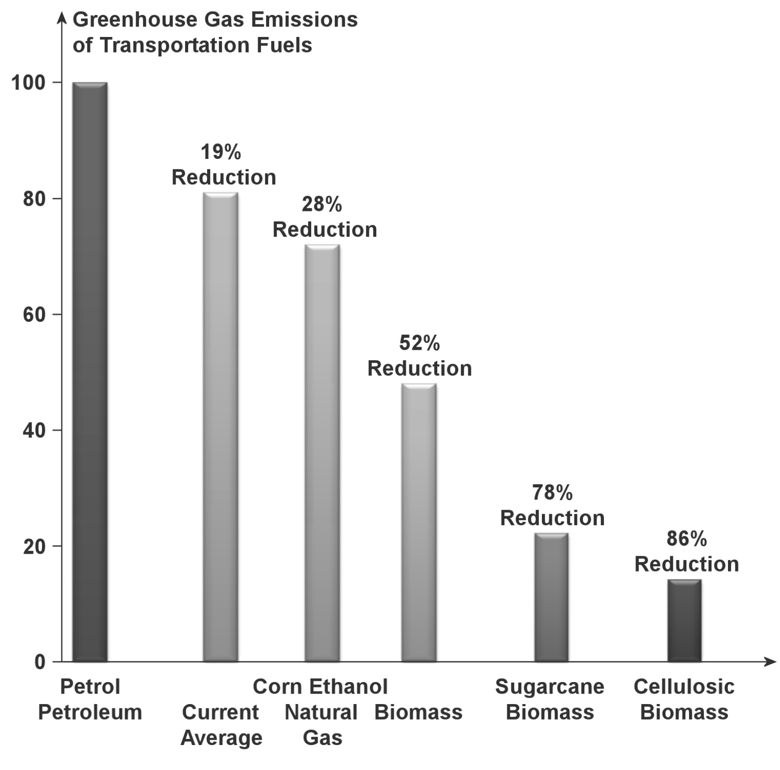


Figure 26: GHG emissions from transport fuels by type of energy source

Methanol can also be used in a blend with petrol. It is produced by the fermentation of biomass and has therefore got the name “wood alcohol”. Methanol as a substitute to conventional petrol has not received the same attention as ethanol, even though it has similar potential. However, the production of methanol is being discussed more when it comes to on-board reformers in fuel cell vehicles. On a methanol fuel cell the reformer will transform methanol into hydrogen which in turn will run the fuel cell. In this case it will be possible to refuel the vehicle with methanol while still having a hydrogen-based fuel cell vehicle. This will be further discussed in a coming section.

#### 5.2.3 Natural gas

Running vehicles on natural gas can also be used as a substitute to conventional fuels such as petrol and diesel. Today, there are about 8.7 million natural gas powered vehicles worldwide. Natural gas is a fossil fuel, though the Natural Gas Vehicles (NGVs) $CO_2$ emissions are much lower than those from a petrol-powered vehicle. The natural gas contains less carbon and produce less $CO_2$ per mile travelled, however when comparing NGVs to diesel-powered vehicles the $CO_2$ emissions are only 3 % less and might even be lesser if looking at a well-to-wheel scenario. However, NGVs do perform very well in fighting local pollutants and can thereby contribute to cleaner air in urban areas [90, 92].

Honda have produced a NGV in its Honda Civic GX which was awarded ”Americas greenest car” 2008 by the American council for energy-efficient economy. The Civic GX is a commercially available NGV sold mostly in Southern California, where an adequate natural gas infrastructure is already developed [93]. Otherwise it is fleets, usually operating a number of vehicles in city areas such as taxis and buses, which represents the highest potential for NGVs.

A concern when it comes to natural gas is the methane emissions, where the loads of methane released through the exhaust have a much greater impact in terms of greenhouse gases. To sum up the potential for natural gas, it can first of all be seen as an insurance of future energy supply, making the world less dependent of the availability of oil. Also, it is a good substitute for oil based fuel in urban areas where air pollutions is a major problem, but it does not necessarily produce less greenhouse gas (GHG) emissions than an fuel efficient diesel engine. Finally, the introduction of a natural gas infrastructure can be the gateway towards the introduction of a hydrogen based society, since they need a similar infrastructure. Also, natural gas can be used in FCVs that converts it to hydrogen through an onboard converter. The potential of hydrogen as fuel well be further discussed in the next section.

#### 5.2.4 Hydrogen fuel

Hydrogen, $H_2$, is one of the two elements in water and it is not an energy source itself, but functions more as an energy carrier. This is due to the amount of energy that can be realized when extracting $H_2$ from water. Currently $H_2$ is mostly used as an industrial gas, but during the past years the discussion of using hydrogen as a fuel for road vehicles has increased. $H_2$ is usually thought of as a fuel linked to the use of FCVs, but $H_2$ can be used as fuel in ICEs as well.

The idea of using hydrogen in ICEs is not a new invention, experiments with $H_2$ have been made for more than a hundred years and have been used as fuel for rocket engines for decades. The idea of using hydrogen in road vehicles has lately been brought up to the surface again when trying to find alternatives to fossil fuel. The exhausts created in an ICE running on hydrogen are water vapour and $NO_x$ and can achieve an about 20 % increased energy efficiency compared to an ICE running on petrol. The downside with running an ICE on hydrogen is that it typically cost more than a conventional ICE and it requires a turbo or supercharger to get the air needed to achieve full power. The fact that the $NO_x$ emissions tends to get rather high is also a challenge for the hydrogen ICE. Nevertheless, if developing the technology and overcoming these challenges, the hydrogen ICE have great potential to make a change in the future vehicle fleet [94].

$H_2$ can also be used to run a vehicle through the powering of a fuel cell. In the same way as EVs, FCVs are able to run as a zero emission vehicles (ZEV), since the only emission created is water. The fuel cell technology have been highlighted as an alternative to the conventional ICEV and Honda for example have introduced a commercial fuel cell vehicle with its FCX clarity, see Appendix A. On the downside, the cost of fuel cell technology is rather high and the $H_2$ fuel availability is quite limited [83,90, 95].

There are only a few currently used methods for producing hydrogen, although new methods are under development. Of the existing production methods the two main ones are steam methane reforming (SMR) and electrolysis. SMR consists of two steps; reformation of natural gas and shift reaction. The first step involves methane reacting with steam at high temperatures (750-800°C) to make a synthesis gas which is a mixture of carbon monoxide, CO, and hydrogen. The second step is a water gas shift reaction, which includes a reaction of carbon monoxide (from the first step) and water steam over a catalyst forming hydrogen and carbon dioxide, $CO_2$. If using natural gas in the production of hydrogen, an energy efficiency of 78 % can be reached. Although, in performing this process in a non-$CO_2$ adding fashion, the capturing of carbon dioxide results in an 20 % efficiency decrease down to 58 %. To make the SMR into a sustainable process, biomass can be used to produce methane. Still, this is not a very likely scenario since six times more biomass is needed for one unit of hydrogen, meaning that the biomass would have to cover large areas and make the whole process very costly [90, 95].

In electrolysis, electricity is used to split water into hydrogen and oxygen. The reaction takes place in a so called electrolyser, which consists of an anode and a cathode separated by a membrane in the same way as in a fuel cell. This form of hydrogen production can result in zero GHG emissions depending on how the electricity is produced. If the electricity is produced by wind or nuclear power for example, the GHG emissions get close to zero. The problems with the electrolysis are the rather low overall efficiency (about 30 %) and the high cost of the electrolyser. However, researchers are now working on improving the efficiency and lowering the investment costs. They are also trying to imply the compressing of hydrogen into the process, since the hydrogen needs to be stored under high pressure in the vehicle [90, 94].

The production step is not the only obstacle for $H_2$ to enter the market as a commercial fuel. An entirely new infrastructure would be needed for storing and distributing of the fuel. This is a major problem since the hydrogen based infrastructure would compete with the electrically based infrastructure and also the current one for petrol and diesel. One option is to combine production with the filling stations to minimise the transports, but this still means building numerous new refuelling stations which thereby does not avoid the problem with infrastructure. Perhaps a better solution will be the on-board reforming, with the transformation of for example methanol into hydrogen. Even though solving some problems with this approach, the problem of reducing the GHG emissions still remains. Thus this is not a solution to the problem, although it can be a first step in the introduction of hydrogen and fuel cell vehicles.

Conclusively, even if the technology exists for production of $H_2$, this is a very new approach which is still in the development phase, and it will probably be several years until the $H_2$ becomes an accepted and widespread alternative to fossil fuels.

### 5.2.5 Synthetic fuels

Synthetic fuels are usually defined as liquid fuels obtained from the processing of for example coal or natural gas. Using these kind of materials for processing always result in fossil $CO_2$ emissions, but there is a way of reducing the net $CO_2$ emitted. For example by processing biomass that almost, depending on a number of factors, can achieve zero net $CO_2$ emissions. The main advantage of these fuels is that it allows for a greater variety in fuel sources which will make the transports less oil dependent. One problem with ethanol, methanol and biodiesel when it comes to producing enough, is the competition over land areas that normally could be used for food production instead of producing biomass.

However, all the building blocks for making methanol, ethanol and even petrol can be taken directly from the atmosphere as well. Recently other approaches have been made to obtain synthetic fuels. One of the research projects are "Sun to petrol" which is the name of a ongoing project run by the American research corporation Sandia [96]. The goal is to produce petrol with help from sun energy and synthesis. This project is still only in the research phase, but might act as an alternative in the future fuel mixture.

## 5.3 Future for powertrain technologies

Even though cleaner fuels is one step towards less emissions and air pollution, future powertrain technology may be an even more important step. The basics of the powertrain technology was presented in chapter 3 section 3.1 to 3.5. This chapter will present the predicted future and introduction of a number of different powertrain technologies

### 5.3.1 Future internal combustion engine vehicles

Internal combustion engine vehicles utilize the most common and known technology presently on the market, the combustion engine. Although the technology has not, after more than a hundred years, reached the end of its development and there are still things that can be done to improve the efficiency and emissions of the ICEVs. An example are the new DRIVe vehicles from Volvo, which still use ICE technology but presents impressive mileage and $CO_2$ emission numbers. The new Volvo s40 DRIVe use a small diesel engine, and a comparison to the Toyota Prius can be found in table 4 [97]. The Volvo is a little less powerful but the cars have similar dimensions and are definitely in the same market segment. In section 5.1.2 Technology trends overview table 4 are more examples showing that small and light vehicles using efficient diesel engines can be almost as fuel efficient as HEVs in the same segment. A big advantage that speaks for the ICEVs is the cost. If looking at fuel efficient sedans in the same segment as the HEVs, the price can differ with up to $10 000 (see Appendix A)

The future market of ICEVs will stand or fall with the development if the internal combustion engine, as will be further discussed in section 5.4. Nevertheless, the ICEV will as mentioned still play a large role in the next decades. Also, the development of efficient ICE systems will be important for the introduction of alternative fuels, HEVs and PHEVs. Diesel engines combined with effective after-treatment will, according to the trends increase its market shares together with HEVs, since they both have proved to deliver very good fuel economy. Also, the vehicle structure has played a part in the promising fuel consumption numbers presented by the fuel efficient diesel ICEVs. The importance of shape, weight and tires are discussed in more detail in chapter 5.5 Vehicle structure.

### 5.3.2 Future mechanical hybrid vehicles

The mechanical hybrid systems are good alternatives to boost the fuel efficiency of ICEVs. The mechanical hybrid vehicles (MHV) might be an effective solution to the problems with high costs of batteries, which have been one of the largest obstacles for the EVs and HEVs to make it in a wider scale. The different mechanical systems can play different roles in different vehicle segments depending on their size and weight.

Considering the flywheel mechanical hybrid, this type of hybrid is not a new invention. A flywheel assisted bus was developed and used as early as in the 1940s, and the early applications had a lot of advantages. The flywheel hybrid added a bit of fuel efficiency, but the disadvantage however was that a very big and heavy flywheel was required to be able to recover a reasonable amount of kinetic energy during braking. This fact made it hard for the flywheel hybrids to compete with pure ICEVs. Nevertheless, during recent years, the flywheel hybrids have returned as an alternative which can support the ICE instead of an electric hybrid with a battery pack.

The flywheel system is more efficient than the electric system since it has less energy conversions. The possibilities of this system are that it is very applicable under conditions when short periods of boost are required, and may thereby be very effective for city traffic with many starts and stops. On the contrary, a highway situation requiring long distance cruises, a long and even boost is needed and the flywheel support will not be satisfactory due to the limited amount of energy stored in it. In this case a battery electric system will be better suited.

One suggestion is to use a flywheel hybrid where both flywheel and battery electric drive are combined. This would protect the battery from shock loads, since the flywheel can provide energy at fast and sudden accelerations and the battery can take over the boosting when the vehicle demands an even and constant load. This hybrid system in an ICE vehicle might have the ability to increase the range with hundreds of miles [98].

The pneumatic hybrid is not a new technology either. The option to run a car with a compressed air motor has existed in many different applications and forms during the last two centuries [99]. This system is quite similar to the flywheel system in the sense of having an extremely low energy density, making it rather inefficient during highway driving. In urban driving on the other hand, the system can make a huge improvement in fuel efficiency. In a city with start and stop environment, the system will be able to build up a storage of compressed air, and then releasing it again when needed. According to research made by Lino Guzella, a professor at ETH in Zürich, a pneumatic air hybrid can obtain a fuel economy that is 32 % better compared to a convectional ICEV and it can also offer about 80% of the fuel saving currently offered by the HEVs.". Despite the fact that the pneumatic system cannot reach the same fuel economy levels as the HEV, the cost is much less. The biggest potential for the pneumatic hybrid might then be as a more affordable alternative to the current HEVs. Providing almost as good fuel economy as the HEVs to a lesser cost it is possible for the pneumatic system to enter the "green car" market [99].

The first hydraulic hybrid ever was constructed by the US Environmental Protection Agency (EPA) and its partners in June 2006. The vehicle was a delivery-van with a full series hydraulic hybrid drivetrain. As described in previous examples this technology is also very well suited for urban driving. Therefore the implementation and choice of a delivery truck as testing vehicle for the hydraulic hybrid was very successful. According to the EPA, the vehicle have achieved a 60-70 % better fuel economy in laboratory tests, with a 40 % reduction in carbon-dioxide emissions and an ability to recover the additional cost for the new technology in less than 3 years. Furthermore, EPA states that design breakthroughs have been made to make the accumulator and pump/motor more efficient, allowing the system to be used in light-duty vehicles as well.

All the mechanical hybrids are quite simple solutions and can also be implemented easily to the current ICEV powertrains. Another advantage that the systems have compared to HEV is that the critical factor of battery cost can be ignored. On the other hand the electric hybrids have a greater potential when it comes to fuel savings, so if the mechanical hybrid is to have a fair chance in the green vehicle market, this chance is probably at the time being while they can still act as a more affordable alternative to the HEVs. The price of battery packs (lithium-ion) will with all certainty decrease as the technology becomes more of common use, thereby diminishing this impact of the cost difference in the future [74]. The mechanical systems are probably best suited for heavy vehicle applications, since the components in some of the powertrains tends to be rather heavy in order to deliver and store a reasonable amount of energy.

### 5.3.3 Future electrical vehicles

Two of the greatest obstacles to overcome for the EVs are range limitations and recharging times for the batteries. Another issue for the EVs is the mentioned high cost of battery packs. This issue combined together with the insufficient availability of recharging stations have prevented the EVs from penetrating the market on a larger scale. The question is whether it always will be a necessity for vehicle to provide a range greater than 250 miles. According to the UK department for transport (DfT), the average car mileage was 8,870 miles per year in 2007. This corresponds to the average mileage of 24.3 miles per day for a 4-wheeled car [55]. Hence, the average UK driver travels 225.7 miles shorter than the possible range of presently available EVs.

Analysing the second problem with recharging times being too long, it can be compared to how much time people actually spend in their cars on average each year. According to the latest statistics from DfT the average time spent travelling by car per year was 232 hours during 2006 [55]. Thus, the cars are only driven for about 40 minutes each day and stay parked for the rest of the time. Since the cars are parked most of the time during a day there will be plenty of time for charging the car whilst it is parked, and the time of recharging should therefore not be such a big problem. Nonetheless, there will be travels exceeding 250 miles where the driver spends several hours in the vehicle. However for the everyday driver, who goes back and forth to work, the EV and will be a very good substitute for the ICEV with the benefit of zero tailpipe emissions.

Moreover, another aspect that has been discussed is the problem that might occur if a majority of the traffic switch to electric power sources and the question is then how this will affect the electrical power grid. A study made by Jaguar and Land Rover, together with, and part-founded by the UK Government's technology strategy board, have shown that an increase in PHEVs and EVs will have much less of an impact in the UK grid than was previously estimated. The worst case scenario with uncontrolled domestic charging and an assumed 10 % market penetration of PHEVs and EVs in the UK fleet, corresponding to about 3 million passenger and light goods vehicles, would result in a daily peak increase of less than 2 %, or about 1 GW [100]. Further, since most of the charging would occur over night, and not during the grid peak hours, an EVs implementation will probably be possible without any major changes in the current power grid infrastructure. When discussing the electricity to power the EVs, it is the source of the electricity that is of major importance. The entire point of having zero tailpipe emissions will be undone if the electricity production itself leads to increased $CO_2$ emissions.

The EVs can however be a very good alternative when it comes lowering the emissions from traffic and improving the air in urban areas. Nevertheless, the future of EVs is very much dependent on governmental decisions; the infrastructure is there although needs to be adjusted to the EVs. As previously discussed, charging stations are needed throughout the cities and preferably linked to parking areas to ensure convenient recharging. This is also an important factor for attracting customers; it will be hard to motivate anyone to buy an EV if the charging possibilities are limited. To be able to produce EVs and PHEVs on a large scale and to sell them in Europe, it is important that the recharging possibilities are the same throughout the European countries. In April 2009 in Hanover, the German electricity company RWE presented a wallplug that might be used all over Europe. This plug demands up to 400 volt from the grid and is designed with 3 pegs. The introduction of this design standard was supported by several car manufacturers such as BMW, Fiat, Mitsubishi, Toyota, VW, Ford and GM. It also found support from several major electricity companies such as Eon, Vattenfall, EDF, Endessa and Enel [101]. This might be a huge step forward in the development of the EV fleet, since it is a guideline for the countries on how to build up of the infrastructure and also for the manufactures on how to produce the vehicles.

In summary, the final factors that will determine the future of the EVs are the future cost of battery packs and their durability. The recharging time and range will be of less importance if using the EVs as city vehicles. Since, according to presented facts, these factors are not limiting and the average users are travelling well beneath the maximum range that is reached by current EVs.

For those users who wish to use the vehicle for longer transport distances, there is at the moment no EV that can deliver a range of 1000 miles. In these cases when it comes to high mileage driving, PHEVs can be a good compliment for EVs. More information about PHEVs in section 5.3.5. A list of future EVs can be seen in Appendix A Benchmarking overview.

### 5.3.4 Future hybrid electric vehicles

The HEVs have penetrated the automotive market and can already be seen in the European vehicle fleet. The Toyota Prius started the trend of HEVs more than 10 years ago and the technology is well established and known by consumers. The main advantage of HEVs compared to EVs, PHEVs and FCVs is that the use of this vehicle does not demand any alteration of the infrastructure. The HEVs is also a better "all-round" driving option, since the combination of energy buffer and ICE is better adapted to a combination between city and highway driving. Despite these advantages, the additional costs of the HEV powertrain have been the main obstacle, and the battery pack is the main reason for this cost increase. However, if studying the benchmarking overview in Appendix A one can see that amongst the newly presented hybrids several of the HEVs have a price of around $20000. This is not an unrealistically high price for a brand new car, but the fact that the consumer can buy a small fuel efficient ICEVs as a Ford Focus or a Nissan Versa for $6000 less makes it difficult for the HEVs to compete on the market. Even if the technology has matured in a rapid pace during the last year, the HEVs are still more expensive than ICEVs in the same segment, which continues to be an obstacle. Although the petrol-electric HEVs have a better mileage than comparable petrol ICEVs (see figure 3 in section 2). It can take many years before the extra cost of a HEV pays off in the form of increased fuel efficiency.

Nevertheless, the technology is still young and has several improvement areas and development opportunities. In the benchmarking, Appendix A, it can be seen that manufacturers are still trying hard to improve the technologies with new, smart hybrid solutions in their concept vehicles. One of the new ideas that have been thought of is the combining of a diesel engine and an electric system, to be used instead of petrol-electric systems which are the combination used in the current HEVs. Small and efficient diesel engines have become more popular amongst fuel efficient ICEVs, which have been shown to be a good solution when it comes to lowering fuel consumption, see table 4 section 5.1.2. Bio-diesel can also be used in this application, which can take the HEVs even closer to the goal of zero well-to-wheel emissions.

Moreover, the cheaper the battery packs and energy buffers become, the more electrical energy will be used in the HEVs, since the electric system is much more efficient. This means that HEVs will probably be pushed towards becoming more similar to PHEVs, which use the ICE only as a range extender, and subsequently EVs. Most of the HEVs on today's market are combined or parallel systems, and this is a fact that also might change along with the battery pricing, since series HEVs are more suitable for PHEV systems where the engine only is used as a range extender. The future of PHEVs will be described in more detail in the next section.

### 5.3.5 Future plug-in hybrid electric vehicles

Since HEVs currently have been produced in several hundreds of thousands units per year, the energy buffers and EMs have rapidly achieved major improvements in cost and performance. This development have created a platform from where manufacturers can obtain knowledge and components to create what several authors and researchers claim will be the next generation of "grid-connected" hybrids, referred to as plug-in hybrid electric vehicles [72, 102]. If studying the benchmarking in Appendix A, it is even more obvious that the plug-in technology is available and ready to be implemented into the vehicle fleet. Chevrolet Volt is one of the new plug-in concepts that shows promising results, and Toyota believe that they will be able to have a Prius plug-in model on the market by 2012. Furthermore, Fisker have used plug-in technology successfully in their new model Karma [82]. The questions when it comes to the future for PHEVs are the same as for the EVs: What will the governments decide on, and what will the future charging possibilities look like?

The PHEV is similar to an EV in the sense that it can be recharged from the power grid when not being used, but it has at the same time a small ICE that supports the system when needed, making it less sensitive to range limitations. As discussed in the previous section, the ICE will probably become more of a support to the electric powertrain, which is more efficient than being dependent on a conventional ICE powertrain.

The PHEV technology can be a very suitable complement to the EVs in a future where electricity is the dominating energy source over liquid fuels. In a future scenario where politicians decide to aim for an electric powered vehicle fleet, PHEVs would be a good alternative for longer trips without any stops for recharging. In this case the ICE can be used to obtain energy to recharge the battery or even run the vehicle when the battery is running out. The total $CO_2$ emissions from the PHEVs are very much dependent on how the electricity is produced. This since the overall well-to-wheel emissions are the most important when it comes to eliminating the GHG contribution from the transport sector. However, in similarity to the EVs, the GHG emissions can be very low if the energy is produced from a renewable or nuclear energy source.

The problem of limiting emission levels in a PHEV is that this system is still dependent of an ICE to get the extra driving range. However, the amount of emissions due to the ICE can be minimised if using a highly efficient engine using bio-diesel or other alternative fuels such as methanol or ethanol. In this way, the fossil fuel dependence of the PHEVs will be decreased to a great extent.

In similarity to both EVs and HEVs, the future of the PHEVs will be very much dependent on the cost and availability of battery packs. Further, the PHEVs have other specifications compared to HEVs, since it needs to deliver an all-electric drive as well as hybrid-electric drive. The considerable more severe duty cycle of the electric powertrain of PHEV, compared to the HEV, demands a significantly higher electric energy stored in the batteries in order to live up to the specifications. A PHEV with an electric range of 32 km will need a battery with an energy capacity that is six times higher than that of today's HEVs [74]. This will be discussed further in section 5.4.4 Future energy buffers.

### 5.3.6 Future fuel cell vehicles

If comparing the FCVs to ICEVs several advantages can be listed for the fuel cell vehicles. For example, the FCVs have the same advantage as the EVs in that they can run with zero tailpipe emissions, a very valuable feature in the attempts of lowering GHGs and air pollutions. A vehicle run by an electrical motor and using a fuel cell as power source also provides much better energy efficiency. The fuel cell has 40-60 % fuel conversion efficiency, whilst a petrol driven ICEV converts less than 20 % of the energy in petrol. Also, a fuel cell system offers a great design flexibility since the fuel cell stacks can be placed almost anywhere in the vehicle [65]. If moving on to technological aspects and availability, it can it be seen from the benchmarking overview that fuel cell vehicles are already available, however in quite limited numbers. As an example, Honda has introduced a fuel cell model, the Honda FCX Clarity [83], showing that it is possible to power a full sized passenger vehicle with a fuel cell run on compressed $H_2$.

This is probably the largest obstacle for the FCVs to overcome in order to be able to enter the market in a greater scale. The consumers will not be ready to accept the new technology unless there are a sufficient number of refuelling stations available. This problem might however be possible to solve by having FCVs using a reformer as a part of the powertrain. The reformer can then reform petrol, methanol or natural gas into $H_2$on board the vehicle. Although, in this case some of the advantages with the FCV will be less significant; the energy efficiency will decrease and the system will emit GHG [65].

If the leading governments instead decides to aim for a hydrogen-based society, converting $H_2$ through electrolysis and introducing $H_2$ refuelling stations, it will be possible to use FCVs without reformers. In this case all the advantages discussed earlier will apply, and the only emissions on a well-to-wheel basis will be dependent on the primary energy source; how the $H_2$ is produced. If the energy provided for $H_2$ production comes from a sustainable energy source, such as nuclear or renewable energy, there would be no production of GHG during any stage of the, well-to-wheel, energy conversion chain.

The fuel cells are still in the testing phase, but if the hydrogen society comes into force in the coming years, a niche market could be created for the FCVs in a very near future. By creating a market where the FC technology is more available for consumers, the FCVs can become more accepted amongst the public. A market entry on a greater scale can be expected earliest around the year of 2020, given that the manufacturers are able to offer a wide range of FCVs. If a hydrogen based society becomes a reality, the FCVs will probably not reach a major market penetration until the year of 2025 at the earliest. The forecast is illustrated in figure 27 [90].

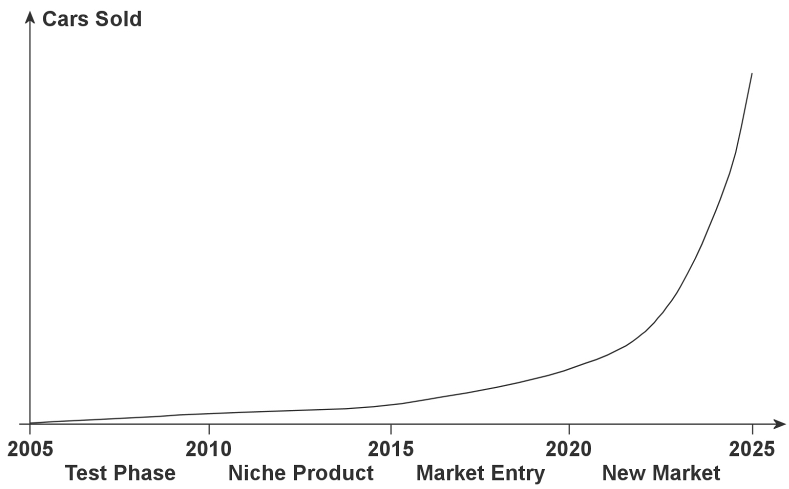


Figure 27: Predicted market penetration of FCVs in a hydrogen based society

Additionally, this hydrogen-based society scenario seems rather unlikely, since the transformation into an electricity-based society seem both easier and more inexpensive. In a electricity base society scenario, the electricity will be used to power the vehicle directly from the grid, which his nearly three times more efficient than using the electricity to create hydrogen for storage in the vehicle which is then converted back to electricity using a fuel cell [72]. The complete energy conversion chain for a FCV can be seen in figure 16 section 3.5.

Moreover, FCVs also faces the problem of component costs. The fuel cell system is much more expensive than the ICEVs, especially since it is dependent on both the price of the fuel cell and the battery.

## 5.4 Future for powertrain components

In this section the estimated future of the main components in the previously discussed powertrains will be presented. Also, the powertrain development areas and possibilities for the technology to reach the market will be discussed.

### 5.4.1 Future ICE

Even though the ICE technology is quite old, there are several areas of it that can be improved to create a better overall efficiency. As discussed in previous sections, there are several alternatives to the fossil fuels that are usually associated with the ICE. Also, the possibilities of supercharging also have enabled the possibility to downsize, use smaller engines, which still produce the same amount of power as a larger engine. Supercharging combined with downsizing can be an effective way to reduce fuel consumption and emissions, and at the same time increase torque and power output. Even though the power output increases from the engine, the use of supercharger will not necessarily guarantee an emission decrease of the engine system.

Another possibility would be to use variable displacement engines, where it is possible to deactivate some of the cylinders at low loads in order to improve fuel efficiency. For example, in an 8 cylinder engine, 4 cylinders can be deactivated during lower loads, and if higher torque is demanded during acceleration the full displacement volume can be available. This technology requires a variable valve train with switchable tappets, finger followers or a cam less, fully variable valve train. The technology is not yet wide spread, but for example GM has a system called "active fuel management" which uses a 5.3-liter V8. Also both Daimler-Chrysler and Honda have presented variable displacement systems [90, 103].

A variable valve train can also lower fuel consumption itself. A conventional ICE has constant valve timing and lift, regardless of conditions such as full load, part load or start and stop. If the valve timing is controlled and changed according to the situation, it is possible to reduce the pump losses in the engine and thereby the fuel consumption.

As a compliment to the supercharger it is also possible to use a variable turbine or compressor. By using variable turbine nozzle geometry it is possible to get a high charge pressure both at low engine speeds as well as at high. In the variable design the turbine diameter will be reduced during low engine speeds so that the pressure increases in front of the turbine, and at high speeds the diameter will increase to lower the back pressure. By using a supercharger combined with a variable tribune or compressor some of the disadvantages with the supercharger can be prevented and the fuel consumption can be further reduced [90].

Another hot topic when it comes to improving the efficiency of ICEs is direct injection (DI), where the mixing of air and fuel occurs inside the combustion chamber. Figure 28 shows the difference between a direct injection and port injection, which is usually used in petrol ICEs.

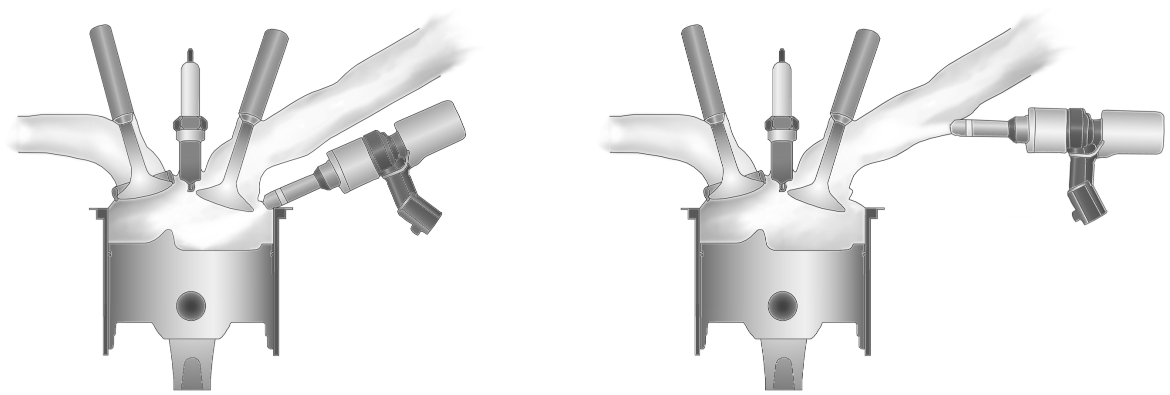

Figure 28: Illustration of different injection types a) left: Direct injection b) right: Port injection

Direct injection has been used in diesel engines for a long time to make the combustion more clean and efficient; meanwhile the technology is rather new for petrol engines, at least on a wider scale. As an example, Lexus are using a DI petrol engines in the GS450h and LS600h models (see Appendix *A* Benchmarking overview). Direct injection gives a greater control over the combustion process, allowing a greater amount of combustion operating modes, adaptable to the load demand. This enables a more lean combustion which reduces pump losses and thereby decreases the fuel consumption, giving the DI engine possibility to reach a higher efficiency. With its advantages, the DI technology is and continues to take over more of the market share, but the technology also has some disadvantages. The technology will have higher $NO_x$ emissions than conventional injection systems due to the lean burning. The system thereby needs better after treatment and this together with the more advanced injection technology makes the system more expensive than conventional systems. Consequentially, a challenge of introducing DI systems will be the new emission standards, that are getting tougher on $NO_x$ emissions in the next stage, Euro 5[90, 104-105].

All the discussed technologies can be used as combinations as well as on their own to improve fuel economy. Some of the technologies have the ability to work more efficient but do not necessary lower all emissions, meaning that the engine technologies are very dependent on after treatment systems and efficient catalytic converters.

The technologies mentioned are all obviously a step forward for the ICEVs, but they can also be an important part in the development of HEVs and PHEVs, since the ICE is the component contributing with emissions in these systems.

### 5.4.2 Future fuel cell

Using a fuel cell in a powertrain instead of a conventional ICE has many advantages. It will result in a decrease of tailpipe air pollutions and GHGs, which can lead to an improvement of public health. Moreover, the fuel cell can be powered by a diversity of fuels which can increase the energy security. Additionally, the fuel cell have the ability to lower vehicle noise, since it runs much quieter than a conventional ICE [90].

However, if analyzing the fuel cell as a component it is possible to see that there still are several challenges to overcome before a large scale implementation in the automotive industry is possible. First of all, the technology is still young and the maturing process of the fuel cell has just begun. Secondly, fuel cells are still very expensive compared to ICEs which has been known and used for a much longer period. If looking at the PEM fuel cell which is the most commonly used in the vehicle industry, it have had rather poor results running at low temperatures. As a solution for this, precious metals are used to make the electrolysis work properly. The use of rare metals in the fuel cell makes more difficult to lowering the cost, and research is needed to find other solutions [106].

Also, the fuel cell works best at part load since the efficiency will be significantly lowered at high loads. The effect of this can in a great extent be eliminated when using an energy buffer to smoothen the load curves. If for example looking at the Honda FCX clarity, a lithium-ion battery is used as an energy buffer [83]. By using a battery pack as an electric buffer the battery can be used to supply the vehicle with energy during high loads, whilst the fuel cell charges the battery. This means that the fuel cell will not eliminate the need of energy buffers such as batteries and supercapacitors, which will lead to additional costs associated with the vehicle. On the other hand, the FCVs will not have the problem with recharge times and range limitations as EVs [90].

The cost of the technology and the availability of $H_2$ fuel, which have been discussed in both section 5.2.4 and 5.3.6, will probably prevent the fuel cell from properly entering the market within the nearest future. A big scale implementation of fuel cell powered cars have been predicted to happen 2020 at the earliest [75], see figure 27 in section 5.3.6. Another factor slowing down the progress of FC technology is the competition with electrically based systems. The trend from leading governments such as the US and UK governments has been to put more money into the development of electric based systems than into FC technology. In the US, most of the projects involving funds for FCVs have been put on hold and more money has been put into battery research instead.

### 5.4.3 Future electrical machines

The development of electrical machines as electric motor and generators will have a great impact not only on EVs, but also for HEVs, PHEVs and FCVs. This means that the development of EMs will be important in both an electric based and a hydrogen based society. The electric machines are the major components in several of the new powertrains, and new applications for how and where to put them in the vehicle has been launched in the last years. Volvo for example has presented a PHEV with four separate in-wheel motors, and the concept car has a series hybrid powertrain where the generator, connected to an ICE, supplies the electric motor with electric energy.

Lately, electric machines have been more utilized in the automotive industry, due to the HEVs and their increased importance. The machines have thereby been more and more adapted to the needs of road vehicles, but there are still room for improvement in many areas; the machines can be even smaller and lighter, more efficient, and achieve a longer life cycle. The electric machines are one of the major parts in all electric based powertrains, which means that EM development will improve the overall efficiency of the entire system.

Since the EMs run most efficiently near their designed power rating, the best efficiency will be achieved if operating close to full load [107]. To improve the overall efficiency of the electric system in the vehicle, it could be better to use more than one EM for propulsion. If doing this, it is possible to use all the EMs at high loads and then decouple EMs during partial load. In this way one would be able to operate the EMs close to their full load rating at all times.

### 5.4.4 Future energy buffers

In discussing the future for batteries as energy buffer, there are two main categories of battery chemistries that need to be highlighted: nickel-metal hydride (NiMH) and lithium-ion (Li-ion).

NiMH batteries are used in most of the HEVs currently in production (see table 5 in section 5.1.2), and a technology trend overview has shown it to be very well suited for this application. The NiMH chemistry has proved to be safe enough for vehicle application and also have longevity in both calendar and cycle life. However, the NiMH batteries are not the ideal energy-storage device for HEVs since it have several drawbacks. They have rather moderate energy conversion efficiency, reduced life with high depth-of-discharge cycling and an unsatisfactory performance at high and low temperatures.

As discussed in previous chapter, the cost of batteries is one of the main drawbacks for hybrids and EVs. Even if NiMH batteries have been on the market for quite a while, the potential for cost reduction is limited, even as production volume further increases. This is due to the high price of nickel, which is the main component in the battery [74, 108]. Another problem with the NiMH chemistry is that it is reaching productive maturity, meaning that there will not be many further modifications that can be done to improve the technique. This fact can be crucial for the NiMH battery when it comes to the introduction of PHEVs, which demands higher peak power and energy capacity from its batteries, features that are rather limited for NiMH batteries, see figure 20 in section 3.6.3 [74].

If turning the focus towards the lithium-ion batteries, one can see when looking at figure 20 that it is possible for this technique to offer more power and energy per unit weight. Thereby, the Li-ion batteries can come to be the future replacement of the NiMH batteries. Several automakers have noted this fact, and have during the latest years started to evaluate the option of using Li-ion batteries for HEV and PHEV applications. Even EVs could benefit a lot from the features of the Li-ion battery. Since the higher specific energy and power makes it possible improve the range without adding weight to the vehicle.

The safety of Li-ion batteries is another aspect to consider. If a high rate voltage is applied to the battery this may lead to thermal runaway, cell venting, and even burning of the electrolyte solvent and graphite. This risk requires a great degree of voltage and temperate control in the battery pack over the cells. Furthermore, the Li-ion batteries also have a tendency to become unstable and there is a risk of them exploding at temperatures around 150-200 ºC, a temperature which can be reached during for example a collision.

Even though the Li-ion batteries have not reached the market on a larger scale, the development of vehicles using Li-ion batteries have now reached both the concept and production state, see table 5 section 5.1.2 Technology trend overview and AppendixA.Also, even if the Li-ion batteries currently are more expensive than the NiMH batteries, the Li-ion price is expected to drop if reaching the same volumes as NiMHs today.

The Li-ion seems to be the only type of battery chemistry that can meet the demand from PHEVs and EVs, see section 3.4, which requires an entirely electric drive. Therefore the Li-ion technology has been used in most of the new PHEV concepts found in the benchmarking, see Appendix A [109].

There are several materials that can be used in the making of Li-ion batteries. The more common Li-ion batteries uses a graphite anode and a cathode consisting of $LiCoO_2$, $LiMn_2O_4$ or $LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$ at the cathode. Lithium itself is not a very rare material. Cobalt however has limited availability in nature, and the fact that it is toxic makes the potential of cost reduction through mass production fairly low. Therefore cobalt is usually used together with nickel and manganese which lower the costs while keeping the properties similar but with the drawback that it has a limited cycling behaviour. The combination minimizes the drawbacks and lower the cost, but does not eliminate the cobalt problem. As a result, several new materials have been introduced as prototypes, but they are still far from being ready for mass production. One of the alternatives is the $LiFePO_4$, which have been proven to be much more stable, but have the problem of not reaching up to the high specific energy that is required in an EV or PHEV [110 and 111].

If looking at the supercapacitor as an energy buffer instead of the battery, it has been shown in previous sections (figure 20) that the specific energy is much lower for the supercapacitor than for example the Li-ion battery. It can on the other hand handle a lot of power per unit weight, and it could thereby find a niche in vehicles which have a high power demand but not as high demand on energy [110]. Thus, for vehicles that demands high power during a short period of time, the capacitor could be a good alternative. The KERS used in formula one (see section 3.4.2) is one example of this application, where the energy stored in the system needs to be released fast, delivering a high amount of power during a very short time period. As long as no supercapacitor can reach higher levels of specific energy, it will probably only be used in these mild hybrids where it is only used for limited time intervals.

#### 5.4.5 Future transmission

The transmission traditionally transfers the torque and speed output from an ICE to the wheels of a vehicle. So far the most common transmissions has been the manual and automatic transmissions, both described in section 3.6. Having an efficient transmission that allows the engine to work close to its optimal can almost be equally important as running the car with an efficient engine. In Europe the manual transmission have been the most common for many years, whereas the automatic have been the most dominating in North America. During the recent years this has changed however, and the trend have been that also European manufactures goes towards using automatic transmissions. Or in many cases a manual, dual clutch transmission (DCT), which has the ability to change gears automatically.

However, the most recent transmission technology to come in to the spotlight is the continuously variable transmission (CVT). The CVT have an almost infinite number of gear ratios within a limited span which lets the ICE to run close to its optimal point at all times. Thereby contributing to a reduction in fuel consumption with up to 5 % compared to a 5 speed automatic transmission. The CVT can lower fuel consumption and emissions, and at the same time offer a good driving comfort. In contrast to conventional transmissions that uses several sprockets in the gearbox; most of the CVTs use a belt or a link, which makes the CVTs lighter than these systems.

Since the automatic transmission is getting more popular amongst European customers and vehicle manufacturers, the dual clutch transmission is also getting more popular. The DCT has as good efficiency as a manual transmission but has the ability to be automated to change gears automatically, just as in an automatic gearbox. This means that the DCT can offer the comfortable driving of an automatic transmission, while still delivering efficiency of a manual transmission.

The DCT consists of two automated manual gearboxes that are operating in parallel, each with its own clutch. One gearbox holds the first, third and fifth gear while the other holds the second, forth, sixth and reverse. This means that whilst driving in second gear, the third gear can be preselected in the other gearbox, making the gearshift very fast and smooth [90, 112]. This makes it a good and more efficient alternative to the conventional automatic transmission.

The planetary gear has been very important to enable the combined/split hybrid. This solution is used by Toyota in for example the Prius. There it acts as the power split device, and it will keep being an important component in this kind of system.

## 5.5 Vehicle structure and design

Disregarding which technology or components used in the powertrain, the vehicle structure and design plays a significant role in the fight against high emissions and fuel consumption. If only looking at the basic mathematical expression F=ma, force equals mass times acceleration, it is possible to see that the heavier a body is, the more force will be needed to accelerate it. It can also be seen from the technology trend overview, section 5.1.2, that the light vehicles have a generally lower fuel consumption. During normal operating conditions, a weight reduction of 100 kg can save between 0.3 and 0.4 litres and even up to 0.8 litres per 100 km. Fuel consumption is however also dependent on external conditions, tires and vehicle design [90]. Figure 29 shows the decrease of the demanded power due to weight reductions over different speeds for a passenger car that weighs 1500kg. The values are derived from equation 5 in section 6.

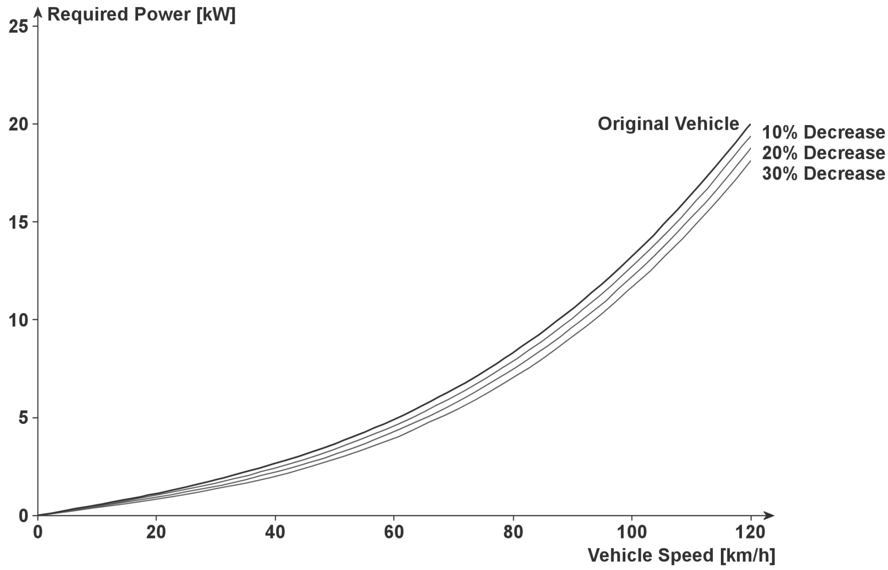


Figure 29: Power demand decrease due to weight reductions over speed

Replacing components that traditionally are made of steel or cast iron with aluminium or other light weight materials is as important as anything else when it comes to reducing fuel consumption. In table 6 some changes, that leads to weight reductions and improved fuel economy, are presented [90].

Table 6: Fuel economy improvements due to weight reductions

| Improvement | Weight Reduction | Fuel Economy Improvement at Constant Performance |
|---|---|---|
| Packaging Improvements | 2.1% | +1.5% |
| High-Strength Steel Bodies | 4.4% | +3.1% |
| Lightweight Interior | 1.8% | +1.2% |
| Lightweight Chassis | 5.6% | +4.0% |
| Aluminium Body Closures | 3.8% | +2.7% |
| All-Aluminium Body | 11.3% | +8.6% |
| Aluminium Cylinder Heads | 1.0% | +0.7% |
| Aluminium Engine Block | 1.8% | +1.2% |

The problem with using new or rare materials is usually the cost, but also problems with recycling and manufacturing. Conclusively, the materials can be more expensive than the original and there can be problems with joining and connecting the new materials into the original vehicle, but with an overall reduction in fuel economy, it might be worth it [90]. Worth to mention is also the improved vehicle performance that is a welcome side effect of lowering a vehicles mass.

The German company EDAG is the world's largest independent development partner, which develops concepts for mobility needs of the future. They presented their light weight concept, EDAG light car, at the Geneva motor show in 2009. This light car addresses the problem with using new materials which are light and recyclable by using a 100 % recyclable basalt fibre material. According to EDAG the material is showing almost the same strength properties as conventional materials, while being less expensive and lighter than both aluminium and carbon. Furthermore, the raw material used has almost infinite availability. This is one example of fields of research that might lead to a breakthrough material which can compete with the conventional vehicle materials, and thereby bring down the overall weight of the road vehicles.

Another important factor when it comes to fuel saving is to try to keep down the amount of aerodynamic drag and rolling resistance. In figure 30 a to c, the impact of drag and rolling resistance can be see seen for a small passenger vehicle that weighs 1500 kg. The graph is derived from the road load power equation, see equation5 section 6.

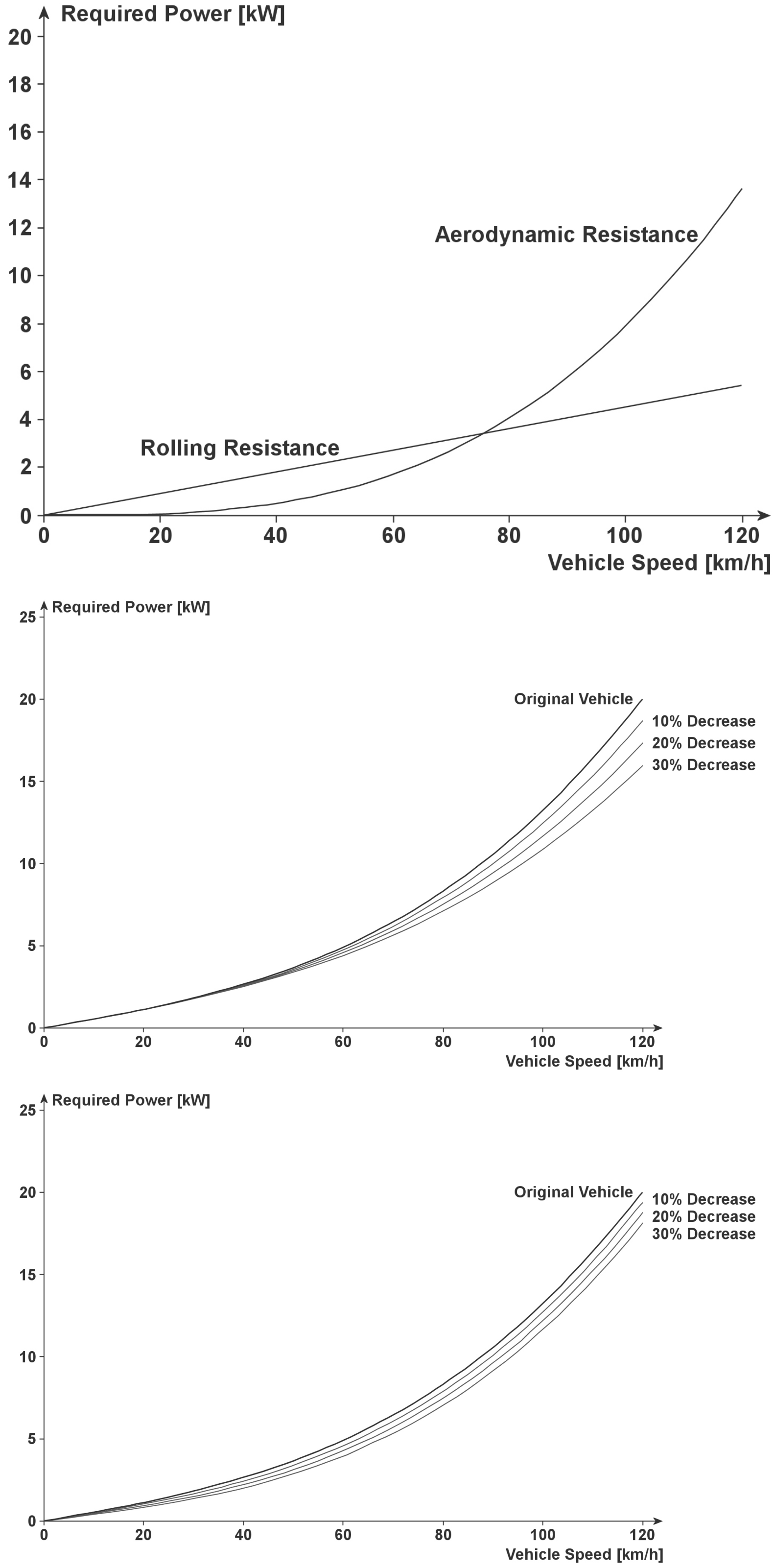


Figure 30: Required road load power and the effects of different improvements a) top: Power needed to overcome rolling resistance and aerodynamic drag at certain speeds b) middle: Power demand reductions due to decrease in aerodynamic drag c) bottom: Power demand reductions due to decrease in rolling resistance

At lower speeds, rolling resistance will have the biggest influence on the power need, while at around 75 km/h the aerodynamic drag resistance will have a larger influence and will continue to increase exponentially. Thereby the shape of the car and type of tires can play a significant role in lowering fuel consumption. Aerodynamics can usually be improved without necessarily adding extra weight or cost associated with the vehicle or its production.

A good example of the progress that can be by modifying the shape, the tires and optimising the ICE and transmission, is the WV polo BlueMotion. The engineers behind this model have worked with keeping the weight down, achieving a low drag coefficient and using low resistance tires [113]. Specifications and fuel consumption for the VW BlueMotion can be seen in table 4 in section 5.1.2.

Figure 31 is showing a summary over the benefits of improving aerodynamic drag, rolling resistance and vehicle weight. The specifications used for the graph are based on an ordinary family, ICE powered, sedan driving the NEDC cycle. However, improving the structure and shape is not an approach that can be used solely to improve the fuel consumption amongst ICEVs. Instead, an approach using light weight materials together with better vehicle structure and design should be used in order to improve the fuel economy and energy consumption for all the previously mentioned powertrain types.

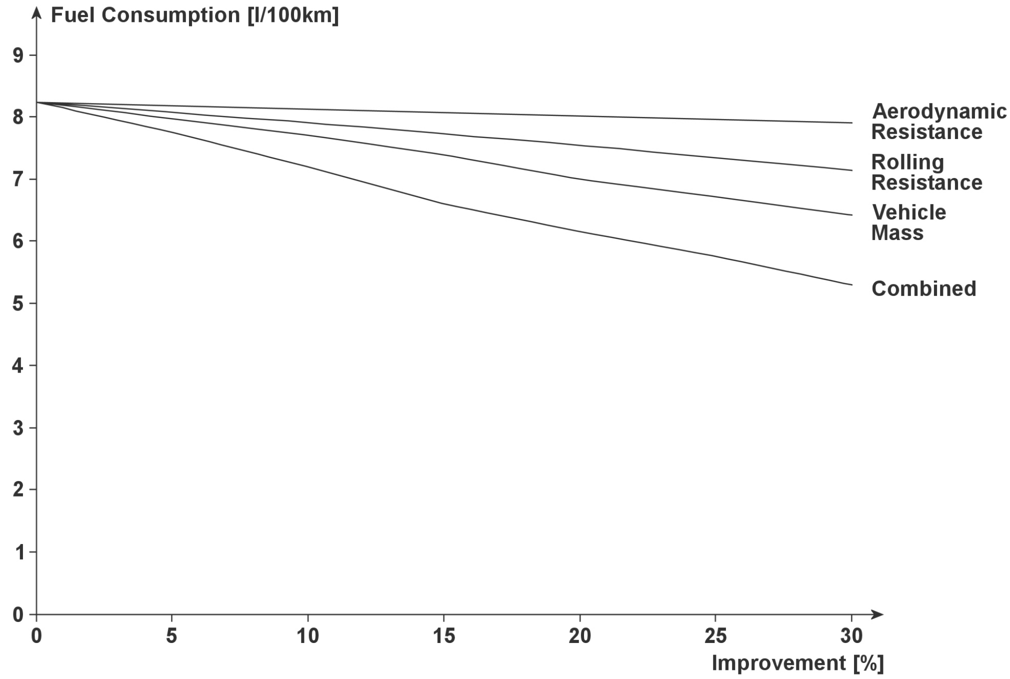


Figure 31: Benefits from improving aerodynamic drag, rolling resistance and vehicle weight

## 5.6 Summary future vision

In this chapter, the future for several technologies and powertrain components has been discussed. This chapter contains three summarising, hypothetical, future visions, namely the:

- Electric based society
- Hydrogen based society
- Mixed fuel/technology society

The electric based and hydrogen based scenario describes two rather extreme scenarios, where either a new infrastructure in form of grid connected recharging stations or hydrogen refuelling stations are implemented. Which scenario that will occur is profoundly dependent on government decisions, but is also dependent on breakthroughs in the electricity generation research. This since both EVs, PHEVs and FCVs are dependent on $CO_2$-neutral energy sources and a low electricity prices to give the largest positive impact on the environment.

All scenarios are predictions based on the facts and trends presented in previous sections. The outline of the vehicle fleets will probably vary depending on region and differences in current infrastructures, although the scenarios are for simplicity reasons based on the global passenger car fleet with the same car-growth as presented in figure 2. Figure 32-34 are presenting each scenario, where ICEV G2 represents a second generation of fuel efficient ICEVs using a more advanced ICE technology. Such as ICEs with supercharger, direct injection, variable valve systems and variable displacement. Whereas ICEV G1 represents the first generation of ICEVs using conventional ICE technology.

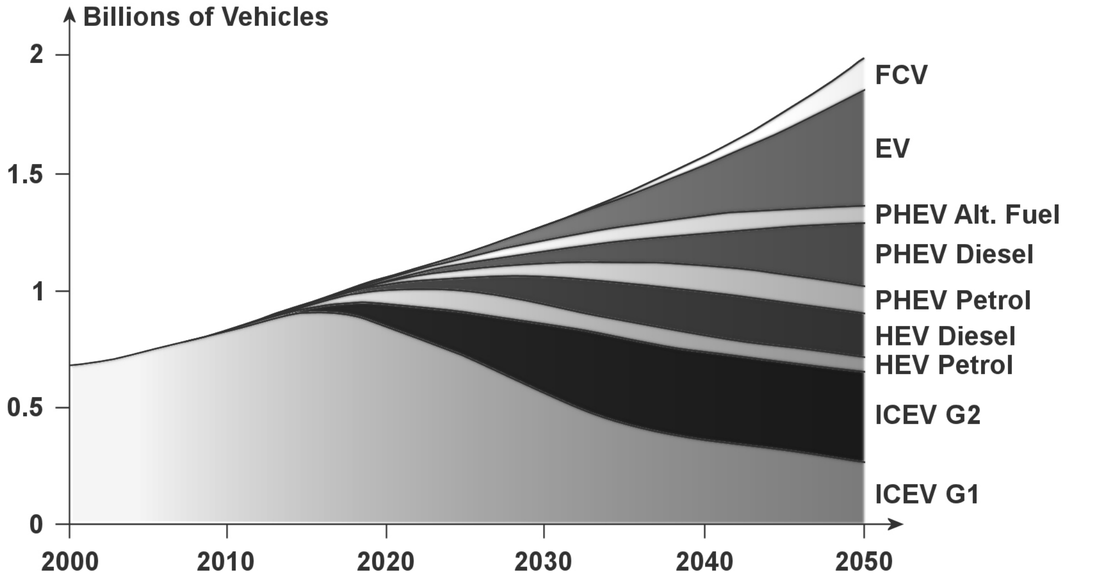


Figure 32: Hypothetical future distribution in the vehicle fleet in a electricity based scenario

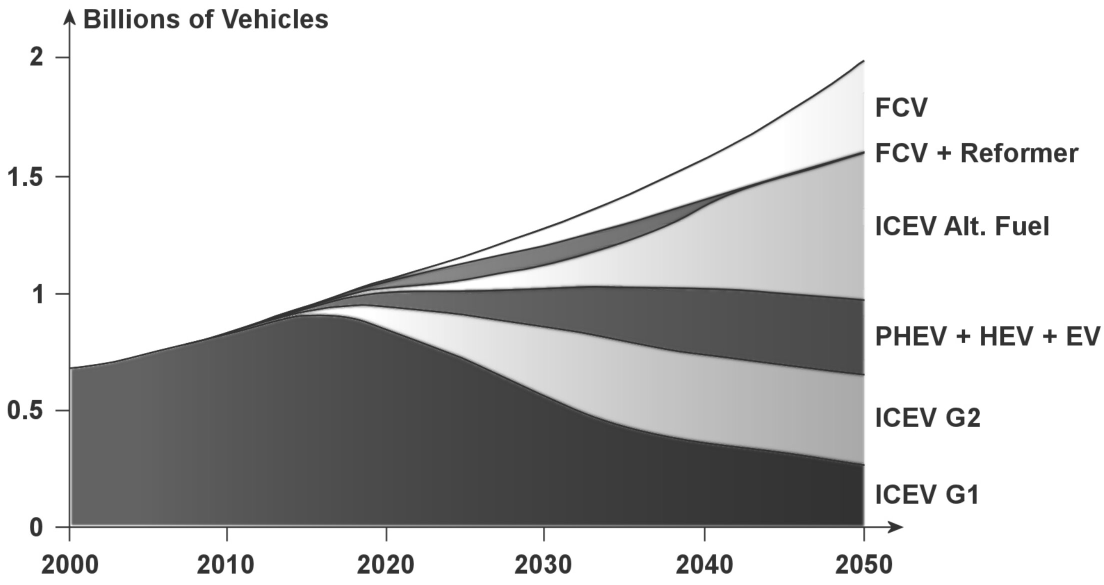


Figure 33: Hypothetical future distribution in the vehicle fleet in a hydrogen based scenario

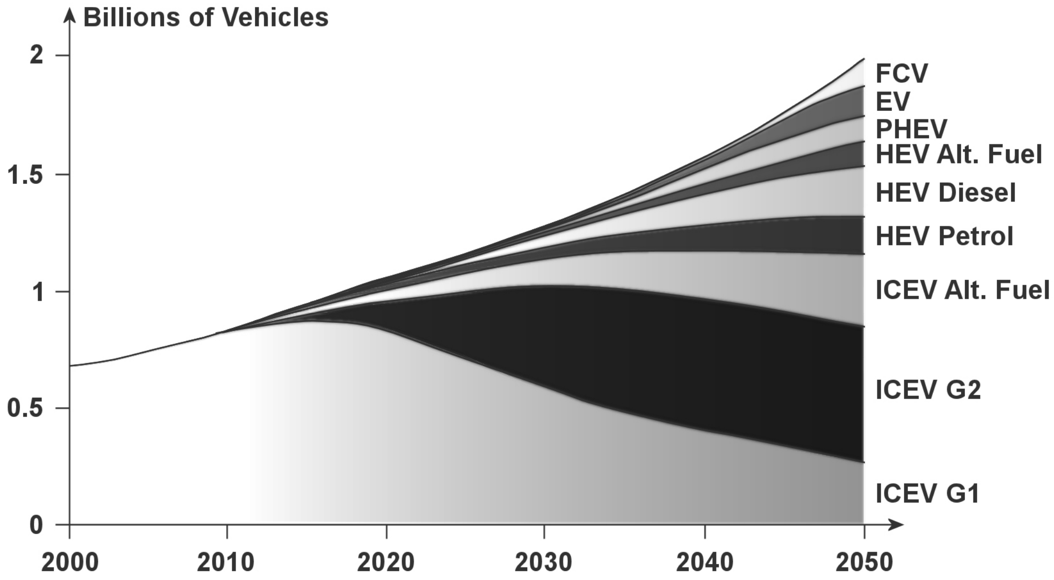


Figure 34: Hypothetical future distribution in the vehicle fleet in a mixed fuel/technology scenario

As can be seen in all three graphs, the first years will consist of a mix of several technologies. This is the development that is already starting to show, where different HEVs and even test fleets of FCVs and EVs can be seen in certain cities in the world. While at the same time alternative fuel ICEVs running on natural gas and ethanol are getting more common. The ICEVs are obviously the dominating technology at the moment, although HEVs have entered the market in a steady pace and EVs and PHEVs are starting to get more common amongst concepts and test vehicles (see Appendix A Benchmarking overview). When it comes to the ICEVs alternative, ICEs running on ethanol and even hydrogen have been developed. Also, smaller and more efficient diesel engines are becoming more common amongst the ICEV "green car" models, which also have proven to be a very efficient approach. Even HEVs and PHEVs can be expected to be equipped with diesel engines, instead of petrol-electric systems which so far have been the most common combination among them.

The battery electric based systems will still have a head start over the hydrogen powered vehicles, since HEVs have been mass-produced for several years. Building up an electric infrastructure in the form of grid-connected recharging units is rather simple, and the electrical concepts thereby seem to be the most promising alternative to ICEVs in the near future. The technology is more known to the costumers due to the current HEVs, and also has a leading edge over FCVs in terms of a more accessible infrastructure. In the case of an electric-based society the EVs, but also the PHEVs will be more common. This will probably result in a shift from split hybrid systems that are the most common in today's HEVs, to series which are better suited for PHEV applications.

The EVs and PHEVs needs to be charged from the power grid, and the charging stations needs to be of the same design all over Europe to make the grid charged vehicles more appealing to the customers. Joint efforts have been made lately between energy producers and car manufacturers in order to agree on a common plug and recharge voltage. Those efforts could be a huge step in the progress towards an electric-based society; however official decisions are still required on a governmental level, stating which infrastructure standard to be used. Perhaps a breakthrough in electricity generation, such as development of fusion power, might be necessary as well to supply $CO_2$-neutral and affordable electricity in order to power the future vehicle fleets.

Fuel cell vehicles seems to have an even further way to go, and even if the future scenario proves to be a hydrogen based society, a FCV fleet is still decades away (see figure 27 section 5.3.6). This is due to both the lack of a working infrastructure as well as the price of the fuel cell technology. Although as highlighted in section 5.2.4 hydrogen can be used as fuel in conventional ICEs as well. Thus, in a hydrogen based society the ICE can act as a first step, burning hydrogen instead of fossil fuels. Also, a hydrogen ICE can be used in HEVs if the $NO_x$ problem is minimized through controlled combustion and after-treatment.

FCVs, EVs and PHEVs are dependent of a $CO_2$ neutral energy source to not just transfer the emissions problem over to the energy sector. So to get a $CO_2$ neutral society the efforts from the energy sector are as important as the efforts made from the car industry.

The mixed fuel/technology scenario represents a more passive scenario from the leading governments, where no breakthrough occurs that make neither electricity nor hydrogen the obvious choice. In this case there will be a greater blend between new technologies and fuels, and a time where only one technology becomes the leading one will be further away.

Regardless of what future scenario may occur, the structures and design of the vehicles will be very important. Designing the vehicles to get a low weight combined with a low aerodynamic drag and rolling resistance will make a huge difference in fuel economy. These areas of improvement combined can be applied for ICEVs, HEVs and PHEVs as well as for FCVs, and improve the potential fuel savings even more. Furthermore, light weight materials are being introduced in the industry and research in this area will with all certainty continue in the future. If considering the development and prospect from a more economic point of view, it can be seen from the benchmarking that the price of HEVs, EVs and PHEVs is rather high compared to ICEVs car in the same segments. The battery price per kilowatt hour is still rather high for both batteries used today and coming battery types. Hence EVs and PHEVs, that demands more energy stored in their batteries to deliver a decent electric range, are very sensitive to the price of the batteries. Ordinary HEVs, which do not normally need to deliver an all-electric drive, are less dependent on batteries with high specific energy content, and thus giving them a greater potential of being able to keep prices low in the neat future.

# 6 Simulations

In this chapter some of the previously described powertrains are tested and evaluated. The testing is done with simulations, to see the potential of using new technology in different vehicles with different parameters such as vehicle weight and degree of hybridisation. The simulations also aim to investigate in which driving conditions the technologies have the biggest potential for improvement in fuel economy.In this chapter some of the previously described powertrains are tested and evaluated. The testing is done with simulations, to see the potential of using new technology in different vehicles with different parameters such as vehicle weight and degree of hybridisation. The simulations also aim to investigate in which driving conditions the technologies have the biggest potential for improvement in fuel economy.

## 6.1 Methodology simulations

To be able to look at the potential improvement from hybridisation of an ICEV the simulation tool QSS is used. QSS toolbox is a MatLab/Simulink based tool that uses a quasistatic approach to simulate an entire vehicle. The first step in making the model is to create a very basic model of an ICEV. This is done to be able to add hybrid components such as a hybrid controller, EM, generator and battery one by one.

The first thing to be added to the model is a hybrid controller module that is created to only control the ICEV. When that is done an EM and battery is added to lay the foundation for a parallel hybrid. The controller is then modified to be able to control the parallel HEV and also an EV. The next step is then to add the remaining components for the series hybrid, where the generator is the main module. When the controller is working well enough to be able to simulate the different powertrain setups, the different components are optimised. First out are the gearboxes followed by the EM, generator and ICE. To be able to simulate the charge sustainability of the model several driving cycles have been placed after each other. When the components are optimised the only thing left to optimise is the controller and thereby the entire vehicle. Finally the simulation is run in a number of different setups from where the results are collected and analysed. A table with all vehicle parameters can be found in Appendix B.

## 6.2 Theory simulations

The key idea behind QSS is to reverse the normal cause and effect relationship of a dynamic system. Instead of the driver pushing the accelerator pedal down and subsequently producing a traction force that causes acceleration and finally a speed. The quasistatic approach is reversed and rather than calculating speeds from given traction forces, the QSS toolbox calculates acceleration and the necessary forces from required speeds in the driving cycle. The basic theory behind QSS is the road-load power equation found below in equation 5. The equation is a representation of the forces acting on a vehicle multiplied with vehicle velocity giving the required power to overcome. The first part of the equation represents the rolling resistance, the second the aerodynamic resistance, the third the force from road inclination and finally the force to accelerate the vehicle. In the simulations done the road inclination is set to zero and acceleration is given from the driving cycle and is therefore also set to zero. The quasistatic simulations are very computational power efficient, and can give a speedup factor of between 100 to 1000 times compared to a dynamic simulation. This makes it well suited for optimisation of different powertrain models as well as for this thesis work since it quickly can simulate fuel consumption of a complex powertrain [64].

Road-load power:

$$P_{road} = mgC_r v + \frac{1}{2}\rho_{air} C_D A v^3 + mgsin(\alpha)v \tag{5}$$

Where $m$ is the vehicle mass, $g$ the gravitational acceleration, $C_r$ is the coefficient of rolling resistance, $v$ the vehicle speed, $\rho_{air}$ is the air density, $C_D$ the coefficient of aerodynamic drag and $A$ the vehicle frontal area and alpha is the road inclination.

The driving cycles used are the new European driving cycle (NEDC) to represent mixed driving conditions and a modified version of the United Nations economic commission for Europe (ECE-15) as a representation of city driving. The city cycle consists of four consecutive and modified ECE-15 cycles that have three times as long times at stand still as the standard ECE-15, this to better show the potential gains of a HEV. A comparison between the modified ECE-15 and the original one can be seen in figure 35. The NEDC consists of four consecutive ECE-15 cycles followed by an extra urban driving cycle (EUDC) and is in total 1220 seconds long covering a distance of 11007 meters, see figure 36. The drive cycle is the standard test cycle for emissions testing for light duty vehicles in Europe, but it is also used as the standard test cycle for fuel economy. The ECE-15 test is a low load, low speed test trying to represent driving conditions in a large European city such as Paris or Rome. The EUDC part is more aggressive with higher speeds and is as a representation of highway driving. To better be able to simulate charge sustainability several of the used driving cycles are placed in consecutive order. Figure 37 describes how the SoC varies over the modified ECE-15 cycle in the parallel and series hybrid, and thus also the charge sustainability. For simulating the mixed driving conditions, four NEDC are used, and for simulating city driving, seven modified ECE-15 cycles are placed in consecutive order, or in other words, seven times four ECE-15 with three times as long stops. This is done since a regular NEDC only is 1220 seconds long.

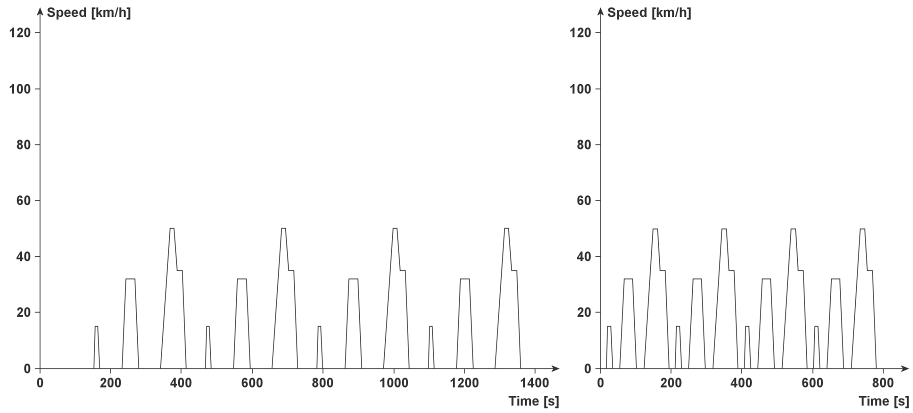


Figure 35: The city cycle part of the NEDC a) left: Modi ed ECE-15 b) right: Original ECE-15

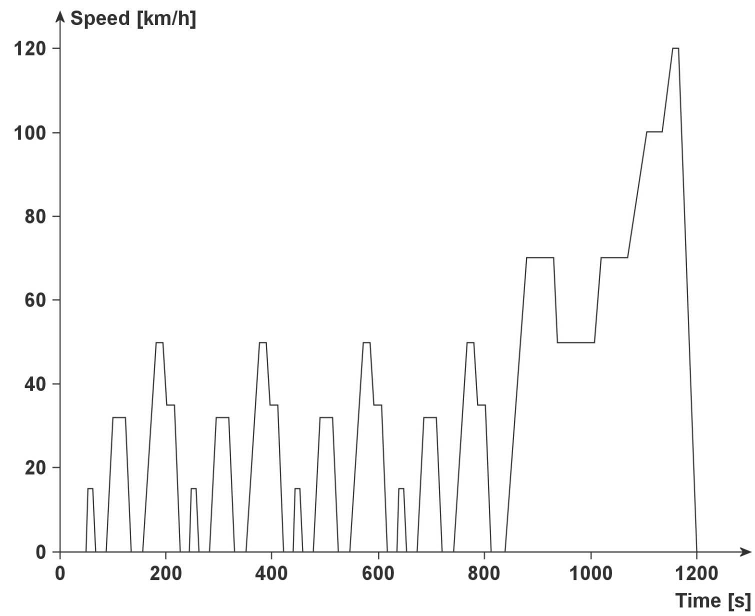


Figure 36: NEDC

To better be able to simulate charge sustainability several of the used driving cycles are placed in consecutive order. Figure 37 describes how the SoC varies over the modified ECE-15 cycle in the parallel and series hybrid, and thus also the charge sustainability. For simulating the mixed driving conditions, four NEDC are used, and for simulating city driving, seven modified ECE-15 cycles are placed in consecutive order, or in other words, seven times four ECE-15 with three times as long stops. This is done since a regular NEDC only is 1220 seconds long.

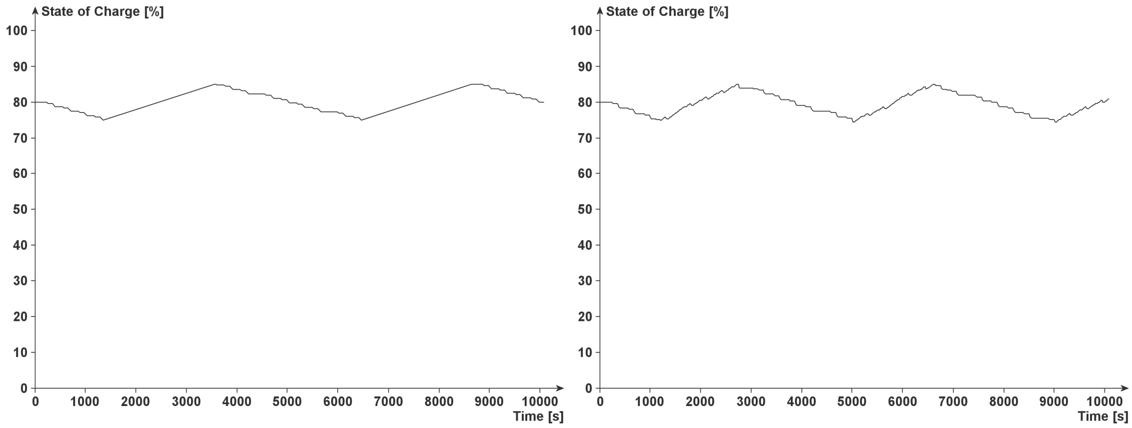


Figure 37: State of charge in the modified ECE-15 cycle *a) left:*Parallel hybrid*b) right:* Series hybrid

The DoH is used to describe the relationship between EM and ICE size, see equation 6. The numerical value of the DoH ranges from zero to one but it is often referred to in percent, then ranging between 0-100 %, where 0 % equals a pure ICEV and 100 % equals a pure EV. Everything between 1-99 % is considered to be a HEV. Where 1-15 % is said to be a mild hybrid and 16-99 % is considered to be a full hybrid.

Degree of hybridisation:

$$\frac{P_{em}}{P_{em} + P_{ice}} \tag{6}$$

To be able to show how cars from different vehicle segments are affected by hybridizing, five different vehicle weights are used. The weights range from 1000 up to 2000kg in 250kg steps. The five weights remain the same throughout the simulations regardless of powertrain type and DoH. This might not be a correct representation of when converting an ICEV to a HEV, but it is closer to the reality when building an HEV from scratch.

## 6.3 Simulation results

As previously mentioned, five different vehicle weights are used in the simulations to represent different vehicle segments. In the case of the parallel hybrid, different DoHs are used to show the potential of increasing the power of the EM. The power of the ICE is at the same time decreased to remain in the same region of total power.

Figure 38 shows the results from using a parallel hybrid powertrain and how different DoHs affect the fuel economy for the five different vehicle weights in both the NEDC and modified ECE-15 cycles. As can be seen the potential for lowering fuel consumption is far greater in the city cycle compared to the mixed cycle. The reason for this is the HEVs start-and-stop ability that turns the combustion engine off at stand still. This however, is not the only advantage the HEV have since it also has the ability to recuperate energy during braking. In the mixed cycle the high DoHs have higher fuel consumption than the low DoHs and the EV. This is because the ICE is too small to be able to recharge the battery at an acceptable efficiency. It is especially noticeable at the higher vehicle weights where even more power is required to follow the driving cycle and therefore more power from the ICE to recharge.

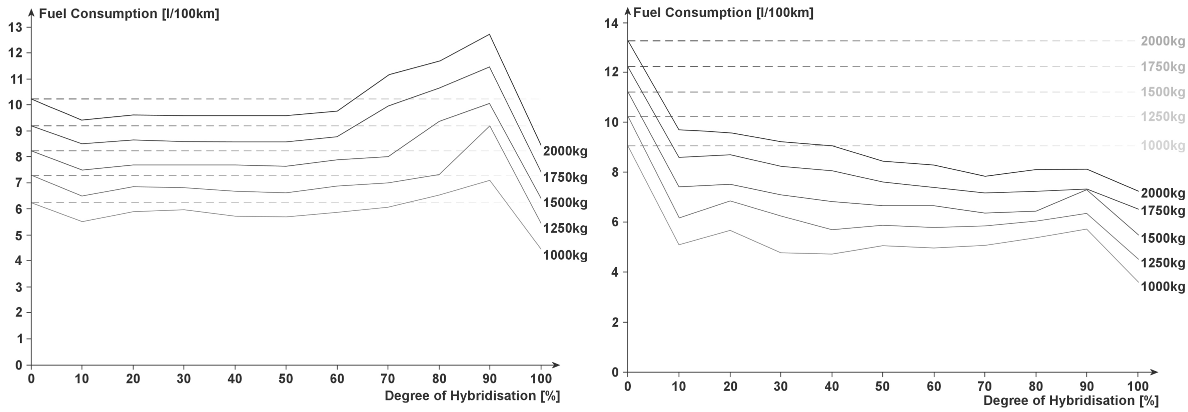


Figure 38: Fuel consumption of a parallel HEV with five different weights over the spectrum of DoH from 0, ICEV to 100, pure EV a) left: In the NEDC cycle b) right: In the modified European city cycle

When looking at the series hybrid powertrain, it can be seen in figure 39 that the benefits from hybridizing an ICEV are much greater in city driving. The main reason for this is the start and stop ability during stand still. This can be compared to NEDC driving where the series actually is worse off than a pure ICEV. The main reason for this is the extra energy conversions occurring in a series hybrid. The first conversion occurs in the ICE which then is followed by one in the generator before storage in the battery and finally one conversion in the traction motor. This can be compared to an ICEV that only has one in the ICE.

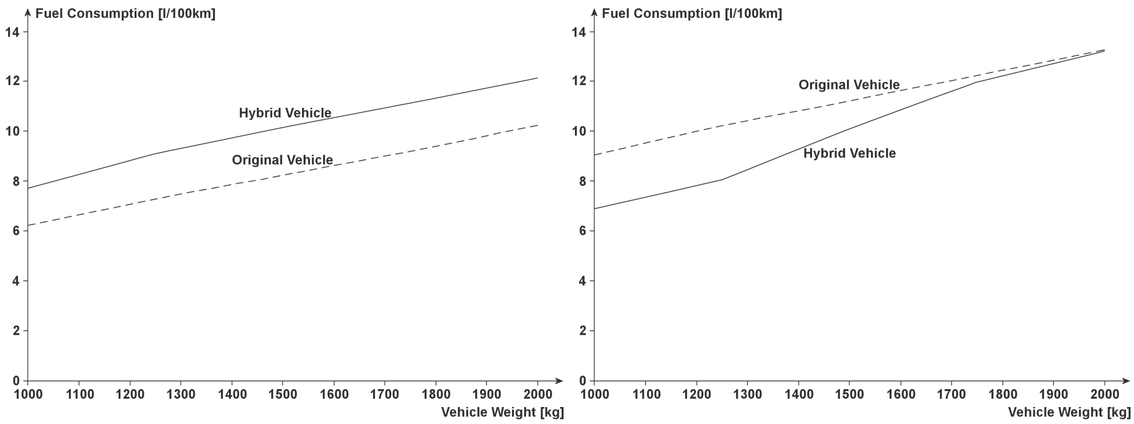


Figure 39: Fuel consumption of a series HEV compared to the original ICEV a) left: In the NEDC cycle b) right: In the modified European city cycle

## 6.4 Summary simulations

The simulations might not give completely accurate numerical values, but they do on the other hand give a good comparison between HEVs, EVs and ordinary ICEVs. It shows that a series HEV demands a special kind of driving environment to be beneficial. It also shows that the parallel HEV improves fuel economy for all vehicle weights and most DoHs. But the parallel powertrain also shows an increased fuel economy in mixed driving conditions as well. The simulations gives a direction of which hybrid powertrain to choose and which degree of hybridisation that might be the best. The simulations indicate that a parallel powertrain suits best for a HEV while the series seem to be better for a plug-in hybrid application. The series hybrid is best suited for dense city traffic and in vehicles such as city buses or refuse collection lorries or in PHEVs where just acting as a range extender.

# 7 Discussion

Many different propulsion technologies are presented in this report, all of them with varying potential to make it as a future alternative to the ICEV. Several countries are using tax reductions, incentives and legislations to accelerate the introduction of alternative technologies into their vehicle fleets. But the main focus is electric based systems such as PHEVs and EVs.

In the UK, the government launched a £25 million scheme to get more environmentally friendly cars into their vehicle fleet. The scheme is the biggest of its kind in the world and its main goal is to boost the sales of EVs. The scheme does not just include car manufacturers but also power companies, regional development agencies and universities that are involved in building infrastructure, charging points and analysing the way cars are used. The £25 million part of the budget that is founded by the UK government is matched by the involved companies, taking the total founding to £50 million. Test fleets will be placed on several locations in the UK to help analyze how the EVs are used. The scheme also includes incentives from £2000 up to £5000 for consumers that buy an electric vehicle [114]. It is clear that the governments are pushing towards an electric based society and this can be an opportunity for the vehicle manufacturers to build up successful projects that involves EVs and PHEVs, since these have potential to get financial support. It is however important to remember that the sustainability of the electric based society is very much dependent on how and from what the electricity is generated. If the electric based scenario is to be successful, the energy needs to be both $CO_2$ neutral and cheap. An example of this is that an investment of a vehicle that mainly runs on electricity will need between five and eight years to pay off if the prices of electricity or vehicle technology does not go down.

The major problem with the current versions of the zero tailpipe emission vehicles such as EVs and FCVs is that they are not ultimate solutions to the $CO_2$ neutral transport sector. The EVs are still very expensive compared to an ICEV, even if governmental incentives are given. Several authors and researchers however predict that the price of batteries will decrease with an increased production. But it is still important to remember that current batteries contain rare metals that might lead to a price increase of the supply of these metals starts to decrease. Fuel cells have similar problems as the batteries, since they also are dependent of rear materials and a high price.

It will be hard to motivate the consumers to buy an EV instead of a small fuel efficient ICEV that do not struggle with range limitations and recharge times. Even if the normal driver seldom will have use for a range of up to 1000 miles or be constricted by the long recharge times during their everyday travels. But this still poses a problem to overcome in the way of how people perceive EVs and how they are used. Instead of seeing the potential of an EV, people sees something that hamper the freedom they are used to with long range and short refueling times. In the long run is it important to come up with solutions with little environmental impact that is affordable for the consumers, since the governments cannot give incentives forever. Thereby are the demand for cheaper and better battery technologies together with the consumer attitude the most crucial obstacles for EVs.

It is important to not reject well known technologies such as ICEs just because they usually are associated with burning fossil fuels. The development of ICE technology can be crucial to make future propulsion systems affordable and still minimize the environmental impact. By combining a fuel efficient and low environmental impact ICE together with an electric system in a HEV, the price can be kept fairly low by not having to use such big, expensive batteries as in an EV or PHEV. The ICE still have a future, and by keeping improving it, using it in combination with alternative fuels and HEVs, the future can reach well into next century. The EVs and PHEVs seems to have a head start over the FCVs, since the trends in research and findings goes more and more towards the electrical solutions.

An important factor to consider is the oil price. Any long term change will affect the development of future vehicle technologies. The development would most likely be slowed and the demand for fuel efficient cars would decrease if a sudden and sustained drop in oil price were to occur. The same would be likely to happen if the price were to hit a plateau and level out. However, if the oil price keeps rising and no major breakthroughs in neither vehicle technology nor oil findings were to happen, the demand and development might look as previously presented in this report.

Another factor to keep in mind the possible cancellation effect that might occur when people are changing from an old car to a new fuel efficient one. The effect of this might be that the lower fuel consumption allows for more driving at the same fuel cost instead of actually lowering the total fuel usage. Therefore it is important to change people's attitudes towards driving less and using the cars in a more efficient manner. It is said that a 5-20 % fuel save can be achieved by only improving the way people drive their cars. It is also important to highlight is how the increase of the total number of cars in the world will affect the possible gain from lowering $CO_2$ emissions.

Alternative fuels are another option for decreasing GHG emissions and oil dependency. A wider use of alternative fuel will be essential for having a sustainable transport sector. Both by using existing fuels and by using more $CO_2$ neutral synthetic fuels. The later will however need some kind of breakthrough to be an affordable and realistic option to fossil fuels.

The vehicle manufacturers have at this time several state of the art technologies at hand that can lower the environmental impact from road vehicle transportation. What to use and when to use it is still a very hard question to answer, even though this work has attempted to sort out some kind of answer. At the time being, a mild hybrid, with start and stop and electric utilities would be the easiest, cheapest and fastest way of improving the existing vehicle program. This can be followed by completely dedicated HEVs such as the Toyota Prius. Later, when batteries become cheaper and better, the PHEV is probably better to aim for than FCV. One reason for the advantage of EVs and PHEVs over FCVs are the amount of energy transformations. In a EV and a PHEV are the electricity used directly from the grid, instead of being used for first conversing electric energy into hydrogen and then back to electricity in the vehicle again.

Also it is important to develop better ICEs and combine them with hybrid technologies to further be able to decrease $CO_2$ emissions. Even further into the future more EVs and FCVs will probably turn up, but that is still very unclear and requires further development of batteries, fuel cells and infrastructure, to have make it on a wider scale. But its been seen that the electric based vehicles probably are the first to make it on a bigger scale, since the leading governments are putting more efforts into supporting battery research, compared to fuel cell research for the automotive industry.

If discussing the different type of systems for HEVs, have parallel and split hybrids been the most common ones and also proven to be more efficient then the series hybrid system. But PHEVs are becoming more common amongst the concept vehicles and thereby also the series system. This is due to that PHEVs basically are EVs with the ICE as a range extender, and a series coupled system works much better for these applications. Future technology advances are also an uncertainty to take into account. If battery technology has a breakthrough, this might push the personal transport sector towards PHEVs and EVs or if fuel cells have a breakthrough FCVs will become more common.

# 8 Conclusions

At the time being, no single particular technology is seen as the right way to go, and will probably not be in the nearest future either. The most likely scenario is that ICEVs continue to dominate until 2050 when other technologies equal the ICEVs in number. At first HEVs will be the most important alternative to ICEVs and has already started to penetrate the market. The HEVs is then followed by PHEVs and EVs as energy storage technologies becomes less expensive and eventually also followed by a small number of FCVs. The possible success of just one dominating technology is very much dependent on governmental decisions, further cost improvements, technology breakthroughs and the research of $CO_2$-neutral energy generation. In a future scenario it is most likely to see the different propulsion technologies in a mix but with ICEVs still making up the major part of the global vehicle fleet.

FCVs will probably not make it on a wider scale in the near future since there are too many obstacles to overcome. The FCVs require a major infrastructure investment to distribute and produce $H_2$. The system also demands an extra unnecessary energy conversation, since electricity usually is used to produce the hydrogen and then transformed back into electricity in the fuel cell again which lowers the overall efficiency.

Conventional ICE technology has been dominating the automotive industry for a century and will with all certainty play a significant role in the future. This is due to that the ICE has a well developed infrastructure and that it is a well known and cheap technology that can be used in combination with electrical systems in HEVs and PHEVs. But it will also help or demand the introduction of alternative fuels and be a stepping stone in an introduction of FCVs, since ICEs have the ability to run on hydrogen.

It is important for vehicle manufactures to validate their choice of system carefully, since different systems has different efficiencies depending on in which environment the vehicle will operate and what kind of properties the vehicle will have. A full hybrid will improve fuel economy in city driving while highway driving might show little if any improvement at all. The fastest and cheapest way of getting the green badge on an existing car model is to make it a mild hybrid, but this will on the other hand only improve fuel economy in city driving. The split and parallel HEVs use the most common types of hybrid electric powertrains today. This since they are more efficient than the series hybrid electric powertrain in this kind of application. The series powertrain will become more common with the introduction of PHEVs where the ICE works as a range extender at its optimal operating point and therefore achieves a higher efficiency than in a normal HEV application.

When comparing petrol and diesel, petrol has been the most commonly used fuel for light duty vehicles, and it has been completely domination in hybrid applications. Diesel has however become more common the last decade and in the nearest future it will also be used in HEV and PHEV applications. The main reason for diesels to not have been used in HEVs this far is their higher price, but their higher efficiency is now starting to compensate this as emissions regulations gets tougher.

There are currently a number of governments around the world giving incentives and tax reductions to get more environmentally friendly cars into the existing vehicle fleets. An example of this is the UK £25 million scheme to boost sales of electric based systems. And it is schemes like this that will, in some extent, allow the diesel engines to penetrate the HEV and PHEV markets. Another opportunity for car manufacturers are the wholly or partially governmental founded projects that aims to further develop environmental technology that in the end can give and edge toward other car manufacturers.

As was said before, it is still uncertain which technology that will be most dominating in the future, so car manufacturers' needs to stay open minded to embrace most new solutions. But when it comes to what kind of hybrid powertrain the car manufacturers are supposed to choose. The benchmarking and simulations show that a parallel hybrid is more suited for HEVs, while a series powertrain is best suited for a PHEV application. Another thing that is for certain is that more fuel efficient cars can be expected in the time to come.

# 9 Future work

To stay in line with the fast changes that occurs in the automotive industry the research and benchmarking of new technology have to be constantly refined to match with the current market situation. Thereby will the benchmarking made to present the results in the report constantly be updated to stay accurate. This goes for research of the legislations and decisions made on government level as well. The current market research needs to be constantly updated, both in a technology perspective and legislation view.

Make a more advanced and accurate model, with better representations of the EMs, ICE and battery. Make a more advanced and smooth controller. Investigate different hybrid setups more thoroughly. Also investigate powertrain components more thoroughly to be able to make simulations with the best possible components to fully see the potential of the different systems. Make a more advanced controller that optimises ICE and EM efficiency at every point instead of just making an average optimisation as done in this work. But to do that a new ICE model with a proper fuel consumption map is needed.To stay in line with the fast changes that occurs in the automotive industry the research and benchmarking of new technology have to be constantly refined and updated to match with the current market situation. This goes for information about new legislations and decisions made on a governmental level as well.

Making a more advanced simulations model can prove valuable in the search for the relationships between parameters such as vehicle weight and optimal degree of hybridisation. The recommended changes to make to the model used in this work are a better representation of the EMs, ICE and battery. Also a more advanced and smooth controller that optimises ICE and EM efficiency at every point instead of just making an average optimisation as done in this work, would also be to prefer. Finally a more thorough investigation of the different hybrid setups could provide some more interesting and refined results.

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# A Benchmarking overview

See attached CD

## B Simulations

See attached CD