# Simulation of NEDC fuel consumption and performance of parallel and series hybrid vehicles using Matlab/Simulink

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## Abstract

With upcoming stricter emission legislations and increasing fuel prices reducing fuel consumption, i.e. CO2 emissions, are one of the driving forces behind development in the automobile industry. One solution to reduce fuel consumption is hybridization, giving the vehicle overall higher engine efficiency. In this thesis it has been investigated if it is possible to reduce fuel consumption via hybridization with maintained performance for different hybrid topologies and degree of hybridization. This is investigated by developing models in Matlab/Simulink which are used in the AVL rapid prototyping's plant model. Results from the simulations shows that there are vehicle layouts that would comply with set demands (fuel consumption and performance) both when using parallel and series topology. The conclusion is that the fuel consumption reductions are large enough to make it interesting with hybridization, however further investigation is needed to determine if the increased costs would make hybridization beneficial.

## Sammanfattning

Stigande bränslepriser och framtida lagkrav har gjort att minskad bränsleförbrukning (CO2-utsläpp) är en av de drivande krafterna i utvecklingen hos dagens bilindustri. Ett sätt att lösa detta är med hjälp av hybridisering, som låter förbränningsmotorn arbeta på bättre effektivitetspunkter. I det här projektet har det undersökts om det är möjligt att reducera bränsleförbrukningen och samtidigt bibehålla fordonets prestanda med hjälp av olika hybridiseringsstrategier och -grader. Undersökningen har utförts genom att modeller har tagits fram i Matlab/simulink och sedan använts med simuleringsverktyget i AVLs rapid prototyping styrsystem. Resultaten från dessa simuleringar visar på att det finns fordon med komponentkombinationer som uppfyller kraven på lägre bränsle förbrukning och prestanda för både parallell- och seriehybrider. Slutsatsen är att bränslebesparingarna är tillräckligt stora för att göra hybridisering intressant, dock behövs vidare undersökningar om huruvida det är ekonomiskt hållbart med hybridisering.

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# 1 Introduction

In recent years the trend within the automotive industry has been to lower the average fleet emissions in order to meet increasing environmental demands. Looking into the near future legislations they will include limited CO2 emissions and fees for incompliance. This has triggered a need for development of hybrid- and electric vehicles with high drivability and costs comparable to existing vehicles. The hybrid electric vehicle (HEV) equipped with electrical machines (EM) and an internal combustion engine (ICE) is a compromise between pure electric vehicles (PEV) and ordinary ICE-vehicles, it includes benefits from both segments but lack most of the drawbacks. However this introduces a new drawback, i.e. the complexity of the control system and how to choose the correct control strategy based on the purpose of the vehicle. Along with different control strategies it is also possible to have different driveline setup; this makes simulation a good tool for an early estimation of drivability and fuel consumption.

This project has been focused on estimating expected fuel consumption from a hybrid vehicle, which size combination of EM, ICE and batteries that is preferable without having to compromise on the performance, i.e. evaluated by acceleration from 0 to 100km/h and 80 to 120km/h, to evaluate take off and overtaking capabilities of the vehicle. Two types of hybrid vehicles have been investigated; Plugin Hybrid Electric Vehicle (PHEV) and HEV in parallel and series configuration. The project is based on a Euro-5 petrol sedan. The Otto engine is chosen because it is more likely to propel future hybrid vehicles since the advantages of a diesel engine are not capable to cover up for the drawbacks and higher costs. The vehicle has been modelled using the software Matlab/Simulink. The goal with the simulations are not to provide absolute values of actual fuel consumption but by modelling the most contributing components to get an understanding for how fuel consumption responds to different combinations and to determine an approximate consumption that could be expected. Modelled components are theoretically based upon literature, theory and measured values.

## 1.1 Objectives

The project seeks to answer the following questions; can an optimal combination of battery weight, ICE displacement volume and electric motor power be estimated to reduce fuel consumption? Can this be done without compromising performance? What CO2 reductions would be possible?

# 2 Background

Until a few years ago the focus has been to increase efficiency of the ICE to lower fuel consumption and thereby CO2 emissions, but this is becoming a more costly way to achieve a reduction due to already high efficiency of modern engines. Instead a hybrid solution incorporating an EM could be used; this minimizes and changes usage of the ICE to reduce the emission per driven kilometre. There are three different types of hybrid system designs on the market today; series-, parallel- and complex hybrid. For the hybrid vehicle to be attractive on the market it has to provide good driveability; this means that the driver has a profile with expectations that includes acceleration, maximum speed, climbing capability, braking, driving range etc.

## 2.1 Hybrid Vehicles

A HEV is a vehicle equipped with a secondary electric power source and/or storage. The HEV can be configured in a number of ways depending on mechanical layout, strategy and range. The measure on the amount of hybridization of a vehicle is referred to as the hybridization ratio. The hybridization ratio is often mentioned in percentage and is calculated as

$$Hybridization\ Ratio = \frac{Pwr_{Motor}}{(Pwr_{Motor}+Pwr_{Engine})} \tag{1}$$

Finding the optimal hybridization ratio is important since a downsized electric powertrain lowers system costs and weight and could therefore result in better performance, on the contrary a larger total electric range can minimizes cold starts and engine running time.[1] Often hybridization ratio is closely connected to the hybridization type of a vehicle as it depends on EM power.

### 2.1.1 Series hybrid

For vehicles with a high hybridization ratio the vehicles are built with a series layout where the electric motor is used for all vehicle propulsion and the engine combined with an electric machine works as an on-board power station to supply and assist the batteries. The series hybrid is defined as a vehicle with an ICE and an electric traction motor that are connected to each other electronically without using the ICE for traction. Instead the ICE is used as a range extender that charges the batteries as the vehicle travels, as a result of independence on vehicle speed and torque demand, a preferred operating point for the ICE is possible. This configurations biggest drawback is the large amount of energy conversion losses that occurs in the vehicle along with having both an EM and an ICE that must be able to deliver power to cover the total power request.

### 2.1.2 Parallel hybrid

The middle range of hybridized vehicles is often using the parallel hybrid setup which means that the same driveline is used for both ICE and EM propulsion. The parallel hybrid has two basic concepts that consist of roughly the same parts, either there is a mechanical coupling between the ICE and the EM operating on the same shaft (integrated starter generator (ISG)) or the ICE is driving the front wheels and the EM is driving the rear wheels (electrified rear axle drive (ERAD)). The latter concept offers the possibility to have a four-wheel drive vehicle that can charge the batteries when the electric motor is in use; this is not possible with the first concept, to be able to charge the batteries in the ISG concept requires an additional generator. A small ISG system is often called mild hybridization and some systems can even be retrofitted. The drawback of this configuration is the complexity in the control system.

### 2.1.3 Complex hybrid

Another hybrid configuration in the middle range is the complex hybrid layout where electric motor, engine and driveline are connected via a planetary gear set. This is until today the most sold hybrid vehicle type with the Toyota Prius as the most common HEV in the world. The complex hybrid vehicle is not covered in this investigation.

### 2.1.4 The hybrid topologies

All of the above mentioned concepts can utilize different control strategies that will have influence on fuel consumption and vehicle performance. The mutual goal is to have the ICE working close to the optimal operating points with an electric motor adding or recovering the difference between the requested traction power and the power output from the ICE. This strategy is in theory fairly basic but in practice the efficiencies in the total energy flow along with the transient behaviour are complicating the choice of operating point. Another approach is to utilize the characteristics of electric motors and let them take care of the transients while the ICE to handles the basic power need. A high hybridization ratio is often profiting from a larger amount of batteries resulting in longer driving range. Larger amount of batteries is often combined with the possibility to externally charge the vehicle, called a Plug in Hybrid Electric Vehicle (PHEV).

### 2.1.5 SOC

State of Charge (SOC) is used as a measure describing the present charge condition compared to when the batteries are at their maximum capacity. It is calculated as

$$\mathrm{SOC(t)} = \mathrm{Q_T} - \int_0^t \mathrm{i}(\tau)\mathrm{d}\tau \qquad (2)$$

Where $Q_T$ is the initial charge at time $0$ and i is the current drawn from the battery. The SOC is the fundamental information that the strategies are based upon. There are two basic strategies; Depletion mode and Charge sustaining.

### 2.1.5.1 Depletion strategy mode

In depletion mode the main objective is to utilize as much of the charge for driving range as possible. If the SOC is above a certain predefined limit the electric motor will be used without any simultaneous charging from the ICE until the lower SOC limit is reached and the ICE starts up and charges the battery until the maximum allowed charged is attained. The disadvantage with this strategy is that the ICE will be used with many cold starts and most batteries suffer from deep discharging. The advantage is that the efficient electric motor will be used as much as possible and charging can be done either at good ICE efficiency or from the electric grid.

### 2.1.5.2 Charge sustaining strategy mode

When charge sustaining is active the ICE will charge the batteries so that an almost constant SOC is obtained. This allows the ICE to be regulated with a large time constant having the electric motor taking care of the transients. The charge sustaining strategy is implemented on the Toyota Prius.

One of the deciding aspects in the selection between these two strategies is which type of battery that is being used. Some battery types works better in deep discharge cycles while other types work better when charged continuously.

## 2.2 Cycles and Certification of Hybrid Vehicles

Certifying hybrid vehicles is different in different regions of the world. North America has historically been early in emission legislations, especially California which still has more stringent rules than the rest of the world.

Certifying ordinary vehicles is a well-known procedure in the vehicle industry; it is done by putting the vehicle through a test cycle on a chassis dynamometer while collecting the exhausts using constant volume sampling technique and expressing the results in g/km. All auxiliary equipment is turned off during the test. For hybrids however, since external power stored in the batteries of a HEV can be used when running the cycle, initial SOC has to be considered when measuring the cycle.

### 2.2.1 Driving cycles

The driving cycles used when certifying light vehicles have been created to represent a normal driving case in considered region. Most driving cycles are combined city and highway driving, but there are also pure cycles for example Environmental Protection Agency's (EPA) NYCC (New York City Cycle) that is a pure city cycle.

In America the FTP75 (Federal Test Procedure) cycle has been used since year 2000 but was 2008 completed with two shorter cycles US06 and SC03, one aggressive highway cycle and one cycle using the air-conditioning. This to make sure estimated fuel consumption more is connected to real world values.[2] The cycle is divided in three sections

1. Cold start phase lasting for 505 seconds, cold FTP (0-505)
2. Transient phase lasting for 864 seconds, HFET (505-1369)
3. Hot start phase 505 seconds, FTP (0-505)

The third phase was added to the cycle to represent a hot start of the engine and has the same velocity pattern as the first 505 seconds. It is performed after the first two phases has been driven and the engine has been shut off for 10 minutes. The total duration is 1874 seconds and the covered distance is 17.77km with an average speed of 34.1km/h. The cycle with the three components marked can be seen in Figure 1. The completing US06 is 12.8km long and has a top speed of 129.2km/h (average 77.9km/h) while the SC03 is only 5.8km and has an average speed of 34.8km/h.

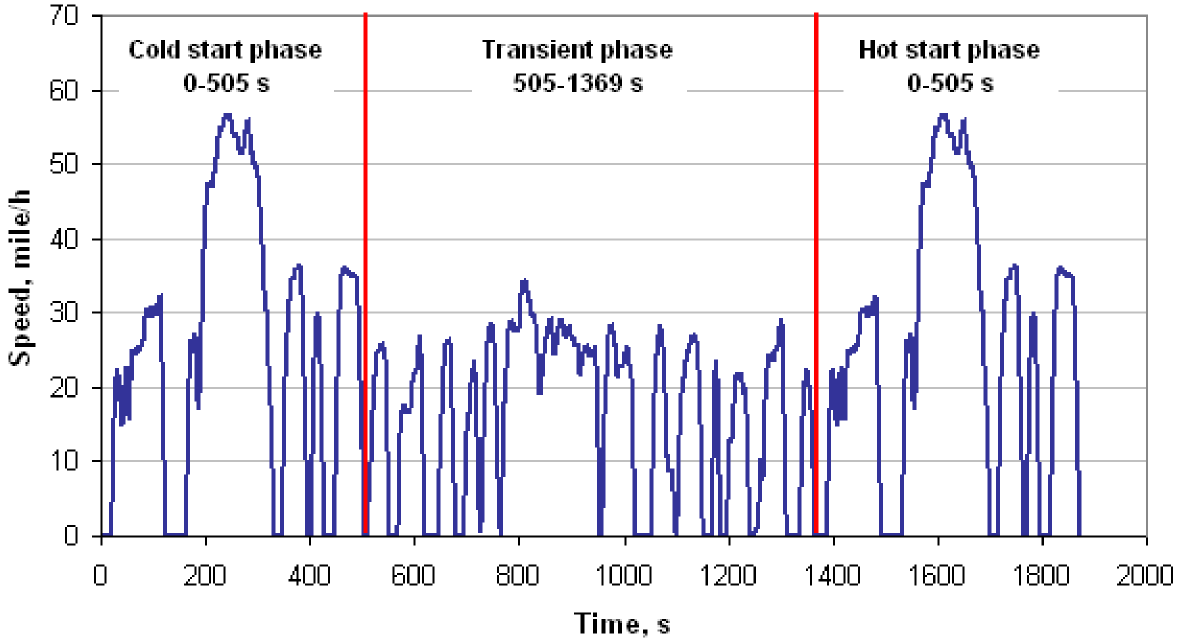

Figure 1 FTP75 cycle, speed profile [4]

In Europe a new certifying cycle was introduced in year 2000 called NEDC (New European Driving Cycle). It is a cold-start cycle containing four repeated ECE Urban Driving Cycles without interruption, representing driving in a large European city. This is followed with one Extra Urban Driving Cycle representing high speed driving. The city part of the cycle is typically represented by low engine load and low exhaust temperature while the highway driving includes high speeds and aggressive driving.

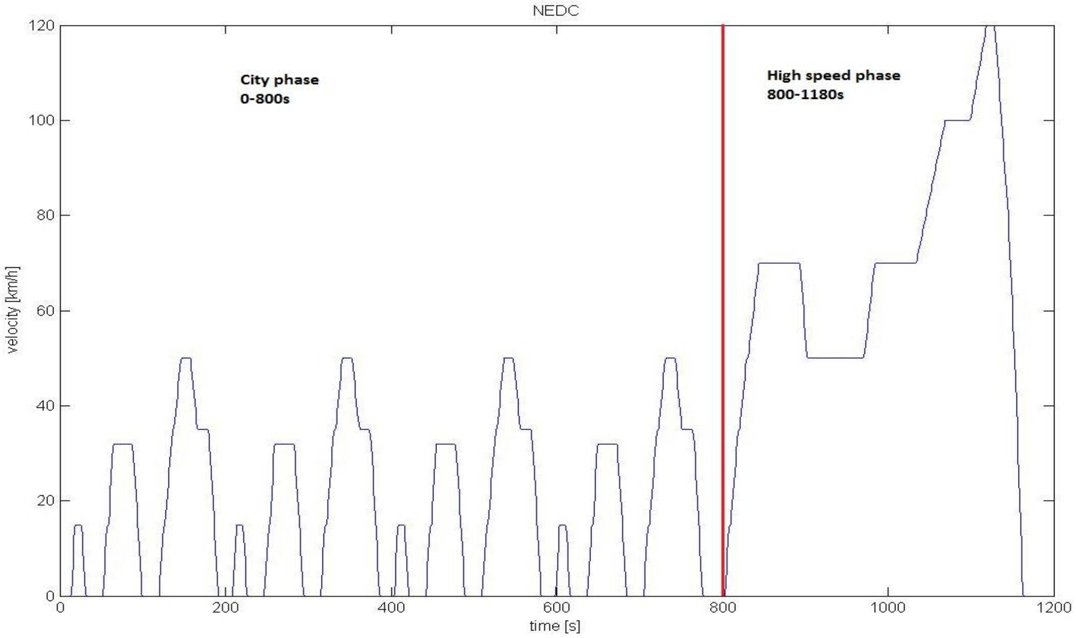

Figure 2 NEDC, speed profile

NEDC (Figure 2) has duration of 1180s and covers a distance of 11km; it reaches from 0-120km/h with an average speed of 33.6km/h. The vehicle performance is measured in the cycle after it has been left in ambient temperature for at least 6 hours. In contrast to the North American cycle there is no measuring with air-conditioning, which can have a great impact on fuel consumption.

## 2.2.2 Measuring Hybrid Vehicles

Since the PHEV both can be run in charge sustaining (CS) and charge depletion mode (CD) researchers have defined the PHEV's consumption (C) characteristics in its designated driving mode, using the utility factor (UF). The UF is based on real-world driving habits investigated in the 2001 National Household Travel Survey (NHTS) [5] in combination with certain assumptions about PHEV usage such as; the vehicle is recharged once/day, the vehicles are driven with the same patterns as the average vehicle and so on. (The Society of Automotive Engineer's (SAE) report J2841 presents the UF in detail [6])

$$C_{weighted} = UF(d) * C_{CD} + (1 - UF(d)) * C_{CS} \qquad (3)$$

where the UF factor is zero when the possible distance in depletion mode of the vehicle is zero (normal HEV).[7] The UF is shown as a function of distance in Figure 3.

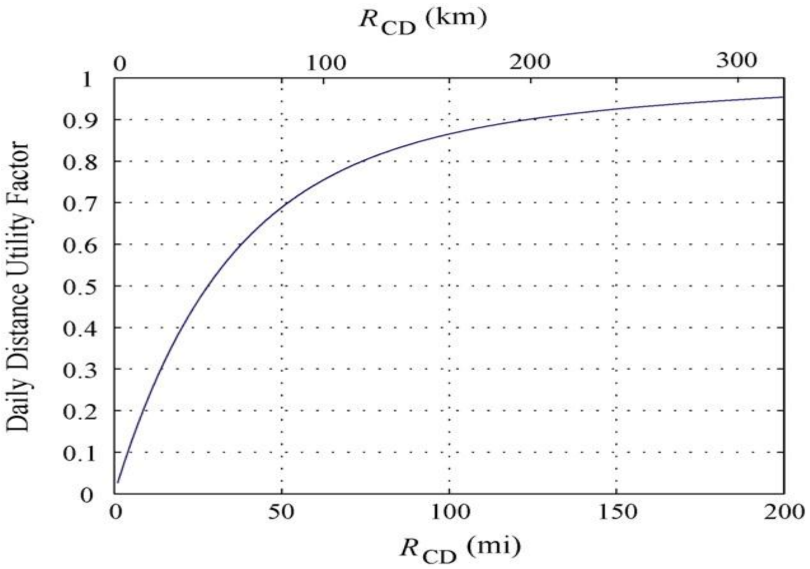

**Figure 3 Utility factor shown against running distance in charge depletion form NHTS[8]**

When EPA calculates fuel economy label of a vehicle for classification the five driving cycles (described above) are used in the following equation

$$Running\ Fuel\ Consumption\ (HEV) = 0.82 * \left[\frac{0.48}{Bag\ 4_{75}FE} + \frac{0.41}{Bag\ 3_{75}} + \frac{0.11}{US06\ City\ FE}\right] + 0.18 * \left[\frac{0.5}{Bag\ 2_{20}FE} + \frac{0.5}{Bag\ 3_{20}FE}\right] + 0.133 * 1.083 * \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3_{75}\ FE} + \frac{0.39}{Bag\ 4_{75}\ FE}\right)\right] \qquad (4)$$

where the emission sample's (Bag) index 75 or 20 is indicating °F i.e. 75 is ambient and 20 is cold temperature (24°C resp. -7°C). It shall however be noticed that deceleration in the FTP75 is never greater than $1.5ms^{-2}$ while real-world measurement shows that the deceleration can be up to 7.5m/s hence diminishing the energy retrieved by regenerative braking.[2] This complies with the average of the American market, in Sweden Statistics Sweden has investigated the driving habits. It can be said that the average swede drives 40km per day at a total of 70minutes, the average trip to work is 16km and 64% of the trips is made by car.[3]

## 2.3 Auxiliary Power Demand

Modern vehicles are equipped with a number of auxiliary systems that normally requires power produced by the engine in a conventional vehicle. Auxiliary appliances are ever increasing on-board modern vehicle due to increased safety, vehicle usability and passenger comfort. The auxiliary equipment is either electrically or mechanically connected to the vehicle. Electric equipment such as fans, window heaters, lights, entertainment systems and so on are connected to the 14V service battery. Mechanically connected systems such as Air Conditioning, brake booster, power steering and more are connected directly to the crankshaft through one or more drive belts, the service battery is charged via a generator connected to a drive belt. In later years many of the direct driven mechanical systems has been changed to more energy efficient electric based systems such as electric power steering, coolant fan and pump.

In the hybrid vehicle where the engine is switched of during driving all on-board systems has to be electric and safety systems has to be fail-safe. Since the hybrid vehicle has an integrated generator the power is converted from the high voltage side to the service battery through an electrically isolated DC-DC converter, showed in Figure 4. Electrifying auxiliary systems is beneficial both in efficiency and ability to place the systems more freely within the vehicle.

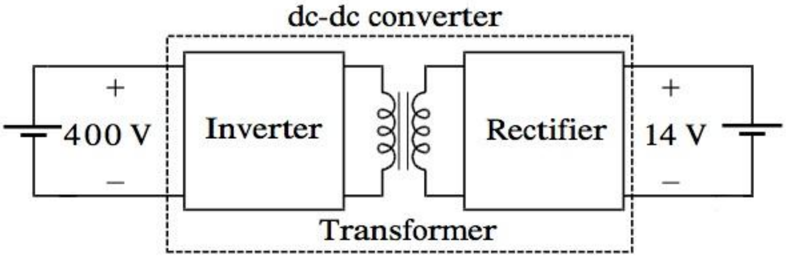

Figure 4 Electrically isolated DC-DC converter

The auxiliary systems of today’s cars add a significant amount to the power demand of the vehicle, as investigated in [9] a luxurious vehicle is measured and estimated power demand is in excessive of 4kW. Under certain circumstances e.g. during a cold start this can rise to three times as much.

As mentioned earlier FTP75 has been extended with two extra cycles from which one of them include measuring the vehicle with the air conditioning on. However measuring vehicles in the NEDC does not take air conditioning into account, it also only includes straight driving therefore no power steering is needed.

## 2.4 Regenerative Braking

The biggest single factor for fuel savings with hybridization is regenerative braking. Instead of wasting the kinetic energy into heat of the breaks it is recuperated, by using the electric motors as generators, into electricity that is stored in the batteries on-board the vehicle. This is called regenerative braking and since the stored energy later can be used to propel the vehicle this will result in saving fuel. Regenerative braking alone can decrease fuel consumption with 20~50% depending on engine size, driving pattern and vehicle.[10]

Braking performance of a vehicle is very important; the brakes must under all circumstance be able to reduce speed quickly while the vehicle still maintains stable. The traction motors of a hybrid vehicle are not able to provide enough braking torque at heavy braking; hence a conventional mechanical brake system is fitted in parallel with the electronically controlled recuperation in the electrical machines.

To be able to use all available friction on the wheels during heavy braking the brake torque has to be distributed among the vehicle wheels depending on driving situation. A fully locked wheel (100% slipping wheel) eliminates the tyre's possibility to take up lateral forces and also lowers the longitudinal adhesion compared to 15-20% slip where the tyre is used to its maximum. This leads to lost steering capability and increased braking distance. To make sure that the vehicle tyres stays within a reasonable slip a slip regulating system is fitted to the vehicle, Antilock Braking System (ABS). The mechanical brake force is controlled by the ABS when the wheels are close to locking, as in a conventional vehicle.[11]

When the translatory speed of the vehicle is low the slip in the tires becomes significantly large and it is difficult to estimate the vehicle speed, which leads to difficulties to control recuperation in these speeds. At low rotational speeds the electromotive forces (voltage) are also very low, making it difficult to generate electric power. This is why the recuperation is not active in hybrid vehicles at too low speeds, however this is not a big loss since in the FTP75 cycle less than 10% of the braking energy is available at speeds below 15km/h.

As mentioned above electric machines in a hybrid vehicle is not able to brake the vehicle at heavy braking and there are not any large benefit with oversizing the electric motors to be capable to provide more torque since simulations shows that only 15% of the braking energy in the FTP75 cycle requires motors larger than 14.4kW.[12]

### 2.4.1 Controlling Regenerative braking

The amount of energy that can be saved by regenerative braking depends on many design parameters e.g. electric motor topology in the vehicle, if the motor powers the rear or the front wheels and so on. By legislation 13 in UNECE [13] it is demanded to have more braking on the front rather than the back wheels.

There are different ways of controlling a braking system. If the system is of the simplest design where a parallel brake system is used with a fixed ratio between the electric and mechanic brake power maximum regenerative braking can be used. If the more advanced fully controllable hybrid brake system is used a control strategy for optimal braking performance can be used, line I in Figure 5.

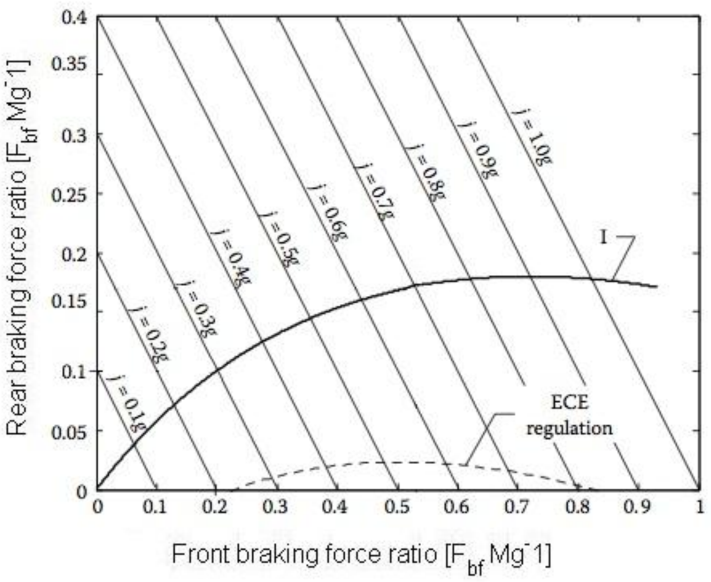

Figure 5 Braking distribution front and rear axle

Depending on strategy different amount of braking power can be utilized, however for simulations using the NEDC or FTP75 cycles this is not important since the deceleration rate never exceed 0.14g for NEDC and 0.15g for FTP75.[12] [13]

# 2.5 Modelled components of the hybrid Vehicle

In the hybrid drive train power is converted from one state to another in different places, these conversions represents the majority of energy loss in the hybrid vehicle. The losses of electric systems are in the vast majority released as heat, to get an understanding and be able to estimate the losses in a HEV it is important to know the characteristics of the HEV's components.

## 2.5.1 Batteries

The biggest obstacle with using electric vehicles is the lack of any high power-density storage that can be put onboard the vehicle. The hybrid vehicle uses the benefits from the fossil fueled cars and combines it with the advantages of the electric vehicle. However this requires an on-board source of electrical energy, energy that can be converted to or from mechanical energy with electrical machines. The contemporary way of storing electric energy in portable devices is using chemical storage, i.e. batteries. The specific energy of batteries is low and the battery packages has to be safe to put in a vehicle, this includes that they have to be crash safe, withstand corrosion, survive harshness of the ride for example. In addition to this the vehicle battery needs a cooling system, service, sensors and surveillance system etc.[14]

#### 2.5.1.1 Lead-Acid batteries

The lead-acid battery is a proven solution that dates back to the 19th century. Today this is the cheapest type of battery to produce, making them a common choice concerning cars and electric vehicles (EV). The cathode consist of lead dioxide and water diluted sulphuric acid is used as electrolyte. During discharge the electron-migration from the cathode to the anode and the following reaction takes place at the anode side of the battery

$$PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e^- \rightarrow PbSO_4 + 2H_2O(l)$$

while at the cathode side

$$Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4 + 2e^-$$

When the concentration of PbSO4 increases the internal resistance will increase along with a transformation of sulphuric acid into water lowering the overall conductivity, giving the lead acid battery its characteristic and nonlinear discharge properties. During recharge the above reactions will take place but in opposite directions, releasing the electrons at the anode and trapping them at the cathode side. All the lead sulphate accumulated at the terminals will disperse as well as the formed water, having a transformation back into lead oxide, lead and sulphuric acid.

The features making the lead acid battery a good battery for use in the light vehicle sector; its low cost due to no noble metals used, its reliability along with it being a proven technology including several different manufacturers and a recycling structure already in place. The main drawbacks are its low specific energy, its poor low temperature characteristics and its short lifetime.

#### 2.5.1.2 Nickel based batteries

Nickel metal hydride (NiMH) and nickel cadmium (NiCd) are two types of alkali batteries where the energy is extracted through a chemical reaction between a metal and oxygen in an electrolyte consisting of an alkali medium. In NiCd the cathode is from metallic cadmium while the anode is made of nickel oxide. The complete reaction in the potassium hydroxide (KOH) electrolyte is

$$Cd + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

The advantages with nickel cadmium batteries are good capabilities in low temperatures, constant discharge voltage, long life time and high reliability. One of the drawbacks of using metals is the increase in cell weight, lowered specific energy. Because of the low specific energy research focus has shifted towards NiMH due to its higher specific energy potential.

NiMH is the successor of the NiCd battery with a few changes, instead of using cadmium in the cathode it consists of a metal hydride, a metal storing hydrogen. The basic principle behind the NiMH battery is that fine particles of certain metallic alloys possess the capability to store and release hydrogen. This process is done many times without any deterioration of the absorbing possibilities for the metal. The reactions at the anode side is

$$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$$

and at the cathode side:

$$MH_x + OH^- \rightarrow MH_{x-1} + H_2O + e^-$$

where M stands for the metallic alloy used. There are two different concept used concerning the metallic alloys, one uses rare earth metals and substituted nickel while the second uses titanium or zirconium and substituted nickel. The latter is the better choice due to lower cost and higher hydrogen storage capabilities. NiMH has the same discharge characteristics as the NiCd, a flat discharge voltage with a specific energy that could be up to four times higher. The NiMH batteries are used in HEVs that currently is in production from vehicle manufacturers such as Chrysler and Toyota. The NiMH has a long service life, can handle inhospitable conditions and certain parts are recyclable. The drawbacks are high cost, a higher self-discharge than NiCd batteries, low cell efficiency and poor charge acceptance at high temperatures.

#### 2.5.1.3 Li-ion

In recent years use of lithium ion technology has increased and has shown an improvement concerning specific energy compared to previously used technologies. Due to the fact that lithium metal is highly reactive when in contact with moisture, this makes a fluid electrolyte impossible. Recent discoveries using intercalated (absorbed) lithium into cobalt or nickel has made it possible to use lithium metal in batteries. The cathode is made up of $Li_xC$ in form of coke or graphite while the anode is made of lithium metallic oxides. The most commonly used oxide for the anode is cobalt oxide that has been proven to work to satisfaction although it is expensive. The reaction that occurs at the cathode side is

$$Li_xC_6 \rightarrow 6C + xLi^+ + xe^-$$

and at the anode side

$$xLi^+ + xe^- + Li_{1-x}CoO_2 \rightarrow LiCoO_2$$

Some of the characteristics that make the Li-ion suitable for use in HEV and EVs are its high specific energy along with high specific power and efficiency, low self-discharge and can operate at high temperatures. The Li-ion battery is also recyclable.

#### 2.5.1.4 Li-Polymer

One of the best performing batteries concerning specific energy is the Lithium-Polymer battery that differs from its predecessor the Li-ion battery by having a solid electrolyte. The most commonly used material for the electrolyte is a polyethylene oxide $V_6O_{13}$ compound. Vanadium oxide could be used for the anode with a potential to hold eight lithium atoms per oxide molecule. Anode reaction is

$$Li_x + V_6O_{13} + xe^- \rightarrow \; Li_xV_6O_{13}$$

Solid electrolytes are capable to conduct ions even at high temperatures on contrary to liquid electrolytes which are more flammable. An advantage of using Li-polymer instead of Li-ion is that the electrodes intercalate the lithium ions making them less reactive during an accident then lithium in its pure metal state. Another benefit is the thin cells making it possible to build a battery in any shape or size that could be optimized for the vehicle along with a long lifetime. The biggest drawback is that the battery stack needs to be kept in temperatures between 80 to 120 degrees to be able to operate.[15]

### 2.5.2 Electric Motors

Even though there are different types of electric machines, the operation principle is the same independent on type of machine. By using the natural magnetic properties of magnets or magnetizing coils a rotor is set in motion as the magnet polarization changes and forces the rotor to rotate. Advantages with the electric motor is its high torque capabilities at low speed along with the possibility to utilize up to three times the rated power during a limited amount of time, making it a good solution for traction application. Electric motors are rated in kW and the rated power is the power that can be delivered continuously without the motor overheating. At low speeds the EM is in the constant torque zone as the power increases. When maximum power is reached at the base speed of the EM, field weakening is used to lower the torque in favor of increasing angular velocity, shown in Figure 6.

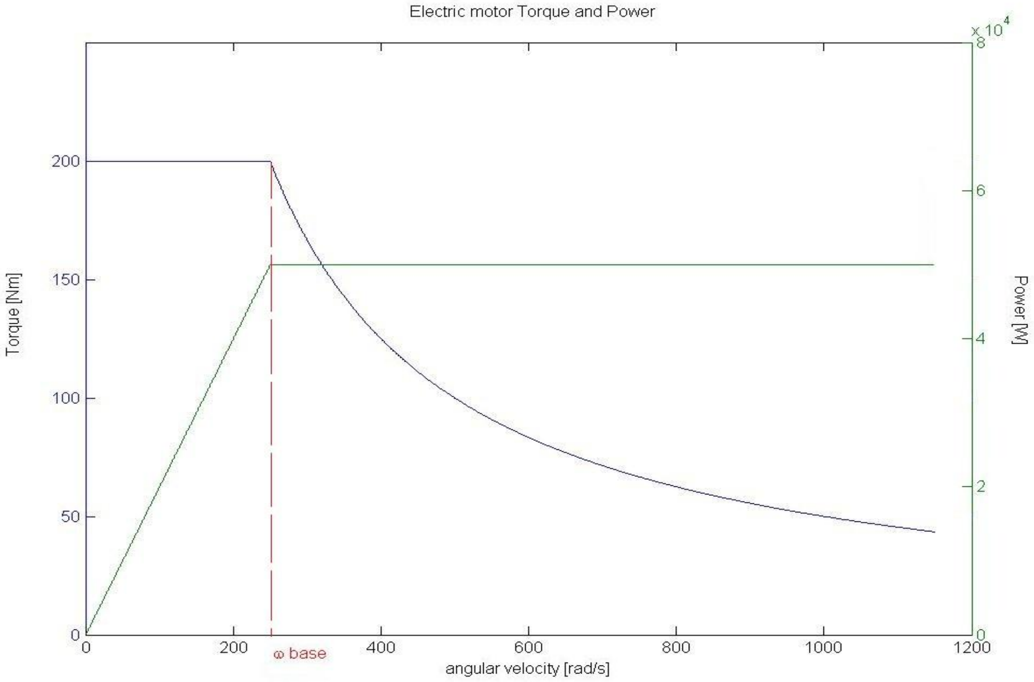

Figure 6 Electric motor torque and power

The torque speed relationship is as follows

$$\omega = \frac{U_{motor}}{K_f I_f} - \frac{R_{motor}}{(K_f I_f)^2} T \qquad (5)$$

where $K_f I_f$ is the magnetic field, $U_{motor}$ the voltage and $R_{motor}$ the resistance. Several of the important characteristics for traction motors used in hybrid vehicles is shown in Table 1 such as controllability, high efficiency, low acoustic noise and ruggedness.

Table 1 Evaluation of electric motor type [16]

| **Motor type** | **DC** | **Induction** | **Synchronous** | **PM** |
|---|---|---|---|---|
| **Torque vs. Speed** | 4 | 3 | 5 | 3 |
| **Efficiency** | 1 | 3 | 3 | 5 |
| **Weight, volume** | 1 | 2 | 3 | 4 |
| **Robustness** | 3 | 5 | 4 | 3 |
| **Maintenance** | 2 | 5 | 3 | 4 |
| **Drive complexity** | 5 | 4 | 3 | 3 |
| **Product maturity** | 5 | 5 | 5 | 2 |
| **Inherent safety** | 3 | 5 | 3 | 2 |
| **Motor cost** | 2 | 5 | 3 | 2 |

#### 2.5.2.1 The DC motor

In the 1980s the DC type of motor was commonly used as traction motors in vehicles but due to its size and maintenance requirements they were later replaced for superior technologies. A DC motor uses windings both on rotor and stator to establish the two magnetic fluxes. To be able to maintain these magnetic fields a commutator and brushes are uxsed. Both the rotor winding (armature winding) and the stator winding (field winding) are fed with DC currents. The magnitude of the torque created depends on the number of turns in the windings and the current.

The advantages of the DC motor are the simple control due to linearity, flux control that is independent of the torque and the fact that it is a mature technology. Drawbacks are its low power to weight ratio and brush wear leading to maintenance along with low efficiency and low maximum speed.

#### 2.5.2.2 The AC motor

In general the AC motors can be divided into two categories; synchronous and asynchronous motors, where asynchronous is an induction type of motor. Both are fed with either single- or multiphase AC, single phase motors are normally used for low power applications.

##### *2.5.2.2.1 Induction Motor*

In an induction motor the magnetic field is generated by current that passes thru the windings that will induce a rotating force in the rotor. There are two types of induction motors, the squirrel cage and the wound rotor motor, where the wound rotor is of less interest for hybrid applications due to high maintenance.

For a squirrel cage motor the windings are located in the stator and as an electromotive force is inducted in the squirrel cage rotor bars, the rotor will start rotating as the force becomes large enough. The rotor is made up of aluminum bars that are short-circuited at both ends using conducting end rings. When a voltage is applied in the stator a rotating magnetic fields is established. As long as the rotor rotates in a speed that is below synchronous speed the field lines will be cut and with a flux change in the rotor circuit a voltage will be induced in the rotor bars.[15]

The speed in an electric machine can never exceed the synchronous speed that is determined by the number of pole pairs and supply frequency; this is due to the lack of relative movement between the rotor and the stator magnetic field, hence no electromotive force or force generated. This difference in speed is called slip and is commonly within 1-3%. A high amount of slip has a negative impact on the torque that can be delivered.

##### *2.5.2.2.2 Synchronous motor*

The synchronous motor has no slip and the rotor magnetic motive force is generated via a permanent magnet or an electro magnet that establishes in the rotor coil when a DC current is fed. The advantage with using a motor without any slip is that the requested movement always will be conducted with high precision. The rotor fed motors have not been considered for use in vehicles as traction motors and will not be discussed while the PM motors are suitable for use in vehicle applications.

##### *2.5.2.2.3 PM motor*

The permanent magnet synchronous motor (PMSM) has a stator with a number of three-phase copper windings. When sinusoidal voltages are applied, currents will move through the windings creating the rotating magnetic motive force. To ensure that the rotor is moving at synchronous speed the stator currents are regulated using a rotor position feedback sensor. Electromagnetic torque is produced when the stator field interacts with the magnetic field from the rotor permanent magnet. The permanent magnets can be mounted either on the rotor surface or buried in the rotor. One advantage that makes the buried option more suitable is its inductance characteristics that enable a more desirable behavior during field weakening operation, resulting in a wider constant power region.[15]

It is possible to use both DC and AC in a PM machine but for modern traction motors the choices are PM synchronous and PM brushless DC motors. These are almost the same type of motor but an accepted definition difference is that the synchronous is fed with a sinusoidal current while the brushless DC motor has a square wave form feed. The shape of the wave form depends on the distribution of windings, to get square wave forms a concentration of the windings are needed instead of using a sinusoidal distribution. Benefits with using a square wave current is that in comparison it has higher integrated current than the sinusoidal wave therefore a larger maximum torque can be produced. The drawbacks are that it has higher losses, higher amount of noise and a potential risk for torque pulsations.  PMSM is a good option to use as a traction motor due to its high efficiency, compact size, and high torque at low speeds along with good control capabilities during generative braking.[19]

#### 2.5.2.3 Switched Reluctance Motor

A fairly new type of motor that shows a lot of promise is the switch reluctance motor. In contrast to the others this motor is salient both in stator and rotor, with windings only in the stator. The stator windings are connected in series with their diametrically opposing counterpart to form one of the phases. During energizing of a stator phase the most adjacent rotor pole pair moves towards the energized stator to minimize the reluctance of the magnetic path. To create rotation the phases are activated in succession and a constant torque is retrieved. Advantages with the switched reluctance machine are; its simple and low cost construction, torque-speed characteristics is easily tailored to the purpose in comparison to inductance and PM motors, most of the losses occurs in the stator which is relatively easy to cool, maximum permissible rotor temperature is higher than for PM motors and high starting torque. The biggest drawbacks of these motors are their torque ripple and high acoustic noise.[15] [16]

#### 2.5.2.4 Hub motor

Instead of having a shaft from the electric motor the motor can be placed in the wheel hub and propel the vehicle directly. This was done already in the beginning of the 20th century by Porsche in their electric car but is still an interesting concept that needs further development. One of the biggest drawbacks is the increase of unsprung mass while the largest benefit is the flexibility concerning the design of the rest of the vehicle. This is due to that all the traction components are located in the wheel hubs. In the future this solution could be relevant but not for the time being.[17]

#### 2.5.2.5 Losses in electrical machines

One of the issues concerning the amount of maximum torque that the machine is able to produce is the developed heat originating from losses in the machine. These losses are mainly; copper, iron (hysteresis, eddy current) and friction/wind losses. All of these exist in both AC and DC motors due to similar components.

##### *2.5.2.5.1 Copper losses*

The largest loss contribution hail from the resistance losses in the copper material used for windings in the machine. These losses is proportional to the square of the current

$$P = R \cdot I^2 \tag{6}$$

where $P$ is the heating effect, $R$ the resistance in the copper and $I$ the current that flows through the material. As the current is proportional to the torque, the produced heat limits the maximum torque that can be taken out from the machine during short periods of time.

#### *2.5.2.5.2 Iron losses*

The iron losses occur in the iron core and can be divided into two separate losses, hysteresis- and eddy current losses.

Hysteresis is the energy required to change the magnetic field in the iron as the rotor turns, enabling the correct magnetic pole alignment. It can be described as the lagging phenomenon between the flux density (B) and the field intensity (H) during changes in magnetization. This energy is converted into heat and lost. One approximation of the hysteresis losses is

$$P_h = V_{material} \cdot K_h \cdot B_{max}^{\beta} \cdot f \qquad [W] \tag{7}$$

Where $V_{material}$ is the volume, f the frequency, $B_{max}$ is the maximum value of the flux density, $\beta$ is the Steinmetz number that varies from 1.5 to 2.5 and $k_h$ is a constant that depends on the ferromagnetic material of choice. For a good magnetically soft iron these losses should be small but not zero.

Eddy currents are currents that flow in the iron which are induced as the magnetic field alternates. These losses are proportional to the rate of change in flux density and described using the Steinmetz model as

$$P_e = V_{material} \cdot k_e \cdot f^2 \cdot B_{max}^2 \qquad [W] \tag{8}$$

where $k_e$ is the eddy current constant

$$k_e = \frac{\sigma \cdot \pi^2 \cdot d^2}{6} \qquad [m/\Omega] \tag{9}$$

where $\sigma$ is the conductivity of the material and $d$ is the thickness of the lamination. To minimize the eddy current losses it is possible to use a rotor that is made out of several thin sheets instead of having one solid piece, where each sheet is separated from another using paint or another insulator.[18]

#### *2.5.2.5.3 Other losses*

During running there will also be both friction losses in the bearings (and brushes if existing) and wind resistance affecting the rotor. The wind resistance will be larger if the machine is equipped with a cooling fan. The wind losses increase with the cubic of speed while the friction losses increase linear with the speed.

$$P_{fwlosses} = T_f \cdot \omega + \frac{1}{2} \cdot \rho \cdot A \cdot v^3 = T_f \cdot \omega + k \cdot v^3 \tag{10}$$

Where $\rho$ is the density for air and $A$ is the area of the cross section facing the air. Ω is rotational speed [rad/s] and v is air velocity.

This means that the total efficiency for the electric machine is

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T \cdot \omega}{T \cdot \omega + R \cdot I^2 + V_{material} \cdot f\left(K_h \cdot B_{max}^{\beta} + k_e \cdot f \cdot B_{max}^2\right) + T_f \cdot \omega + k \cdot v^3} \tag{11}$$

Furthermore an anomalous loss exists that is the difference between measured values and calculated concerning the iron losses. This loss is unexplained and differs in size.[18]

#### 2.5.2.6 Thermal properties

One of the benefits using electric machines is the over rated power capabilities that can be used to improve transient behavior. The limiting factor concerning the magnitude of the power output is the temperature in the electric machine. Another aspect why temperature control is important when using PM machines, is that the magnet is sensitive to high temperatures and will get demagnetized.

### 2.5.3 Power Electronics

Translating throttle request from a driver into torque request in an electric vehicle requires a motor drive and power electronics. The batteries of the vehicle delivers a stiff DC voltage that has to be converted into suitable DC or AC voltage with an adjusted root mean square (RMS) value and frequency. The drive controller (local, not vehicle controller) uses signals from sensors in the batteries and the electrical load (AC or DC motor or aux-loads) along with throttle position to turn on or off the semiconductor power switches inside the switching converter.

#### 2.5.3.1 Drive controllers

Within the vehicle control system the drive controller is a local controller that manages and processes information of the system in order to control the power flow in the drivetrain. It handles torque request from the vehicle controller and sensor readings from battery and motor to ensure right criterions are fulfilled. It reads sensors that are fitted to system providing voltage, current, torque, speed, temperature and flux. Modern controllers are digital and capable of handling complex algorithms, this minimizes errors and process time.[15] [12]

#### 2.5.3.2 Converters, inverters and rectifiers

The electric energy storage of the hybrid vehicle consists of batteries or super capacitors that supply a DC-voltage, to adjust the voltage to the desired level converters are needed. In the case where the propulsion is performed by a DC-motor the voltage is adjusted by a converter, as for the on-board DC 14 volt system (aux-loads and service battery). However is it for personal safety reasons important that the 14 volt system is isolated from the high voltage system. Hence a DC-DC converter with isolation transformer is used for these applications to prevent physical connection.

When an AC machine is used for propulsion the converter has to transform the battery DC to AC waveforms, these are called inverters while transforming AC to DC is called rectifiers. As discussed earlier one of the big advantages of a HEV is the possibility to recuperate deceleration energy that normally would have been wasted, consequently this requires the converter to be able to act as both inverter and rectifier, these devices are called bi-directional or bilateral AC-DC converters. The bilateral AC-DC converter makes sure the electric motor of the HEV can operate in all four quadrants (See Figure 7) i.e. four-quadrant converter. However the switching DC-DC converter is not by its nature able to handle an electric machine in all four quadrants it is in this case depending on the converter's topology. The hybrid vehicle needs the four quadrant converter to be able to reverse without reverse gear and to be able to recuperate brake energy.

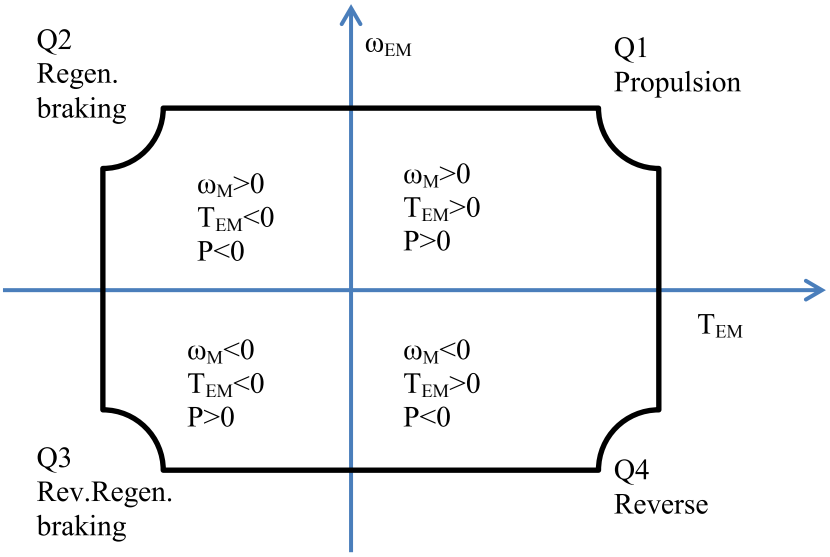

Figure 7 Four working quadrants of converters in hybrid vehicles

### 2.5.3.3 Efficiency of power electronic switches

Power converters consist mostly of switches, diodes and conductors and it is from these losses in the converters appears. In a device that conducts there is a voltage drop and in the diodes there will be a small voltage drop. When the switches inside the converter turn on or off the switching moment is not instantaneous but needs a finite time to open or close; also leading to power loss.

Under low voltages the efficiency is lower but soon after the voltage is increased the efficiency goes up and become more or less stable, because of the relatively narrow voltage span it is reasonable to model the converter as a constant loss i.e. a resistor (a graph on this can be found in [16]). Because of switching converters design and low number of resistors the efficiency is high and suitable in vehicle application, however this does not apply on the older linear converters. While these linear converters have an efficiency of values approximately 50% the switching converter, depending on topology, has efficiencies of 85 to 99%.[16]

### 2.5.4 Internal Combustion Engines

In recent research the effect of hybridization of US light-duty fleet in the near future (2030) was investigated, it was concluded that for the hybrid vehicle due to costs, benefits and technical challenges; the fuel cell, CNG SI-engine and diesel is not as competitive as the petrol engine. However the investigation did not include bio-fuels such as ethanol. Simulations with hybrid diesel vehicles have shown a lower fuel consumption in the order of 5%, this is not considered to cover for the additional price of a diesel engine.[1]

#### 2.5.4.1 Scaling using Mean Effective Pressure

Work performed from a certain engine is commonly measured in torque or power; however are these dependent on the displacement volume. Since this thesis is focused on investigating engines with different displacements that are normally available on the market, there is a problem due to different engine designs and engine technology; the engines have different specific output not fully in line with engine size.

A useful measure to utilize instead of production engine data in this application is the Mean Effective Pressure. Mean Effective Pressure (MEP) is a measurement of engines ability to perform work independent of displacement, it is force per unit area; in metric measurement it is in BAR or kPa. It is work divided by cylinder volume displaced for each cycle, as follows:

$$mep = \frac{W_R}{V_d} \qquad [Bar] \tag{12}$$

using the power it is written

$$mep = \frac{P n_R}{V_d N} \qquad [Bar] \tag{13}$$

where P is the power in Watts and $n_R$ is number of revolutions for one cycle of the engine (2 for 4-stroke), the revolutions N is in revolutions per second. It is also possible to rewrite the formula to use torque instead of power because of the simple relation between torque and power:

$$P = TN2\pi \qquad [W] \tag{14}$$

hence:

$$mep = \frac{T n_R}{V_d} 2\pi \qquad [Bar] \tag{15}$$

The MEP can be broken up into smaller contributing components due to the relation

$$Bmep = Imep_{360} - Fmep - Pmep \qquad [Bar] \qquad (16)$$

where Imep is the indicated mean effective pressure measured in the cylinder, Fmep represents the total friction losses and Pmep the pumping losses (4-stroke engines). Sometimes other MEPs are added e.g. accessory losses from driving pumps, fans, acc and other connected accessories.[20]

#### 2.5.4.2 Engine losses

##### *2.5.4.2.1 Fmep*

Fmep as a general term includes all internal friction losses of an engine e.g. bearings, pumping fluids, cylinder wall to piston ring contact and etc. Friction losses have a constant component but can be modeled as speed dependent, either proportional or quadratic which gives [20]

$$Fmep = C_1 + C_2N + C_3N^2 \qquad [Bar] \qquad (17)$$

##### *2.5.4.2.2 Pmep*

Pumping losses are sometimes included in the Imep, depending on whether the Imep is measured over a cycle or only the compression and power stroke. It can also be included as a component in the Fmep. It is the work done by the engine during the gas exchange revolution (intake and exhaust stroke) which only makes it applicable on four stroke engines, this makes it convenient to define the pumping work as

$$pmep = \int_{360}^{720} p \, dv \qquad (18)$$

##### *2.5.4.2.3 Scaling engine losses*

Investigation on four cylinder engines ranging from 0.85 to 2l has shown that loss increase relative to engine speed with the relation

$$mep = 0.97 + 0.15\left(\frac{N}{1000}\right) + 0.05\left(\frac{N}{1000}\right)^2 \qquad [Bar] \qquad (19)$$

where the equation gives a value in Bar. The losses are linearly dependent on displacement volume. This makes the Bmep a good measure to utilize when designing an engine, displacement given torque or power output at a specified engine speed can be estimated using typical bmep values. Typical values for Bmep in a modern boosted spark ignited engine is in the order of 16-19 bar, where high performing state of the art production engine values are even higher like the 2.0 liter Golf R produces 22.16 bar.[21]

### 2.5.5 Environment analysis

With recent reports concerning on-going and future negative changes in the climate linked to greenhouse gas emissions, a common goal to lower these emissions have been stated. Carbon dioxide is a greenhouse gas with the lowest global warming potential of 1 according to the IPCC standard (see definitions and investigation in Climate Chnge 2007 [22]) and is formed during complete combustion. To lower the CO2 emissions an efficiency increase of the ICE or the source of the fuel/power could be changed.

A solution that utilizes different fuel sources is the PHEV, charging the batteries from the grid instead of only from the ICE. The decrease in emission will then depend on the power generation technology used and will differ both in time and location. During peak hours secondary power sources such as coal power could be used that has a more negative effect on the environment than the primary sources.

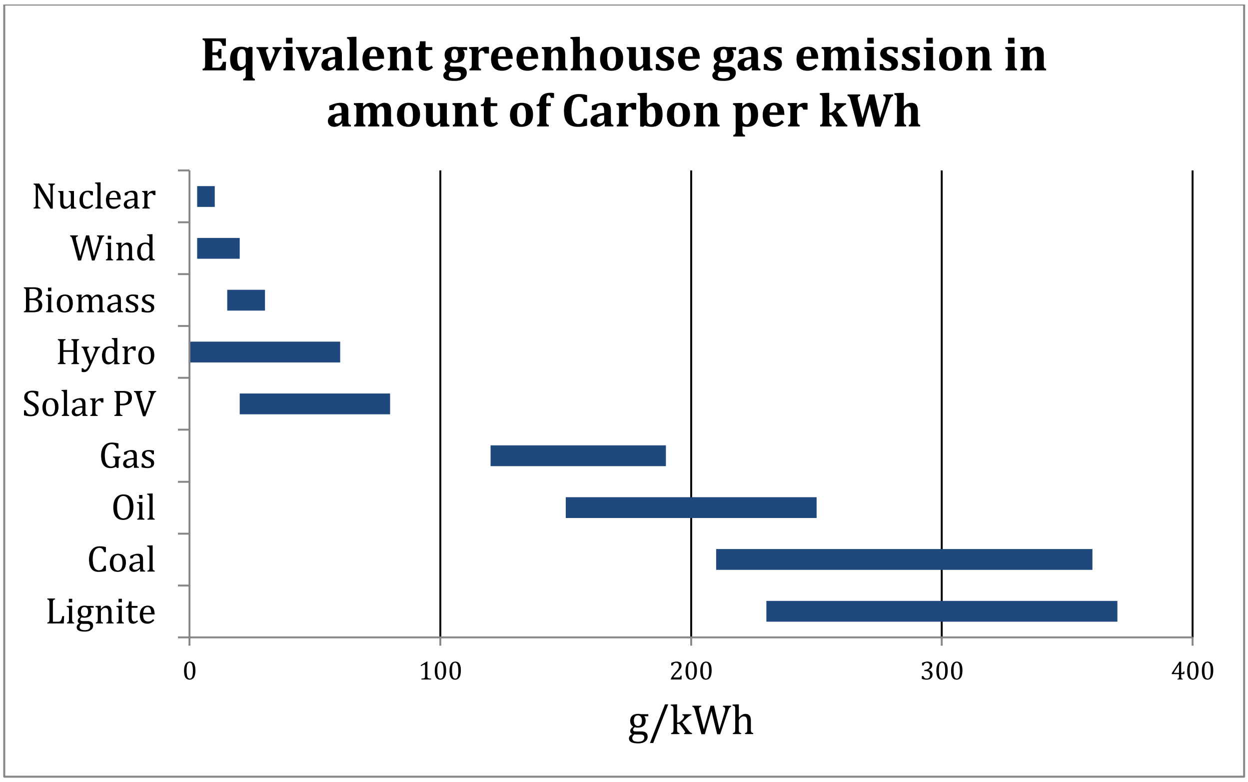

Figure 8 Equivalent CO2 emissions per kWh [23]

The equivalent CO2 emission takes the production, material and environmental aspects into consideration. Figure 8 shows that power generated by renewable energy sources has the lowest amount of CO2 emission although some of these power generation options are not suitable everywhere, depending on geographical location. There are also limitations on to what extent the different power sources can be used, keeping a stable grid frequency and supply the power need independent of transient behaviour. Often each country has a base load capacity using nuclear and/or coal which has a long start up time and high steady state efficiency, while hydro and biomass can be used during transient power need.

Looking at the electricity production in Europe; coal and nuclear power is the predominate sources followed by natural gas and hydropower.

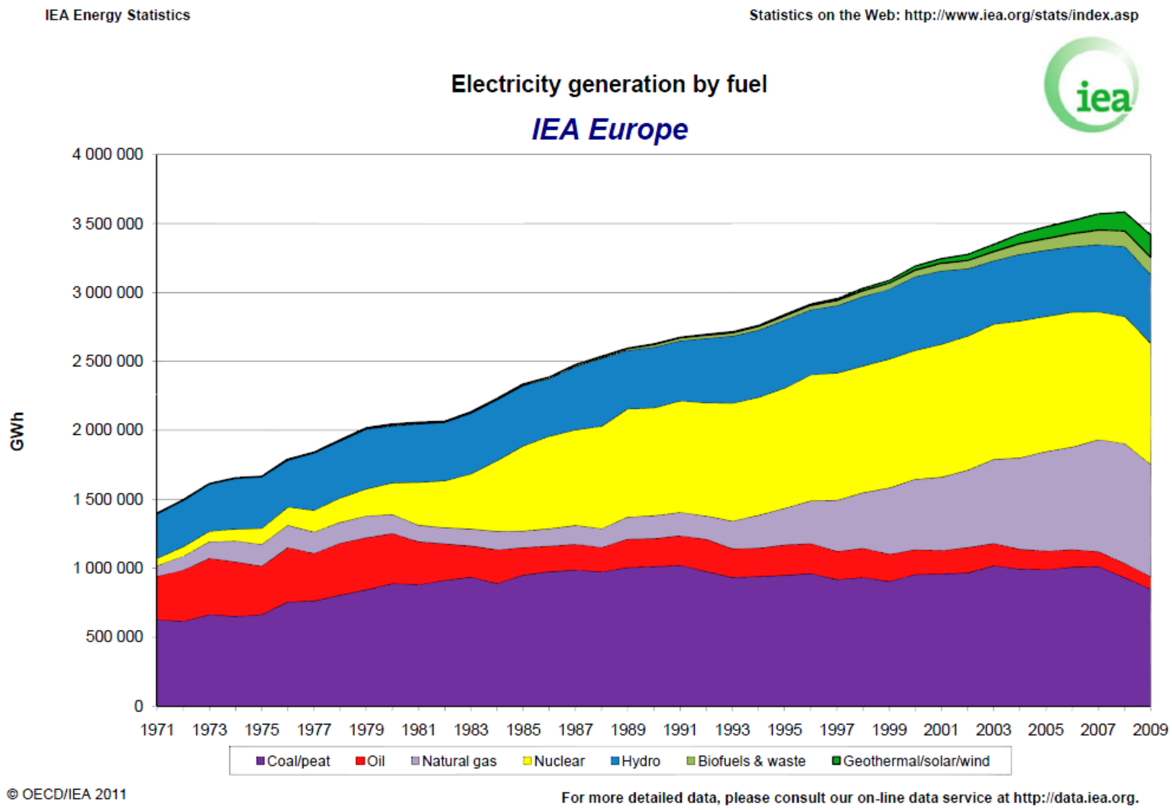

Figure 9 Electricity generation for different fuel sources [24]

Figure 9 shows how the electricity is generated across entire Europe; therefore production will differ for each individual country, so by using this only a rough estimation can be deducted for a country in Europe.

# 3 Results

## 3.1 Modelling

The reference vehicle is a modern mid-size sedan with a 2.0 liter engine and a curb weight of 1700 kg. Measured fuel consumption on dynamometer in the NEDC was 8.1l/100 km, estimated friction- and aerodynamic drag coefficients are 0.0128 respectively 0.2992. A Simulink model was calibrated to match these values having to be used as foundation to build the hybrid models on. Modifications made to the model during hybridization were removing the auxiliary load from the ICE power demand as it is possible to electrify these demands; they were put as loads on the battery instead.

### 3.1.1 Vehicle setup

For the batteries Lithium ion is chosen because of its high specific energy, no need to keep the battery cells at a certain elevated temperature and it is proven technology. The level of specific energy is set to 100Wh/kg. The lower SOC limit is set to 30% to avoid damage of the battery pack.[19]

Electric motors used are 4 pole PM synchronous motors which uses water cooling due to its high efficiency, compact size, high torque at low speeds along with good control capabilities during generative braking. According to [25] the efficiency for the PM synchronous machine is higher than for the IM, 95% compared to 93% in the field weakening area.[26]

A few of the modeled properties in the hybrid simulation models are consistent independent on which type of vehicle modeled. These are; EM maps (efficiency, power curve, torque curve), ICE BSFC, battery and converter efficiency, SOC, ICE maps (concerning losses).

#### 3.1.1.1 EM maps

##### *3.1.1.1.1 Power and torque curve*

Power and torque curves are generated by input of the rated power wanted and base angular velocity. The base velocity is a design parameter and is set to a constant value [12] independent on EM power that is considered to be a normal value for EM used in vehicles. When the base velocity is reached the constant power region is entered resulting in a constant power until cut of speed.

In the torque curve maximum torque is available until the base velocity is reached, afterwards the field weakening process decreases the torque while angular velocity increases, keeping a constant power (seen earlier in Figure 6). The cut-of speed is also set to an appropriate value that is not harmful to the machine and independent of amount of power set, but still allows the vehicle with the chosen gear ratio to reach speeds at 160km/h.

#### *3.1.1.1.2 Efficiency*

Two efficiency maps for the EM were deducted, one that is calculated from a real EM using the delivered power and measured losses and the other one from theoretical loss calculation.

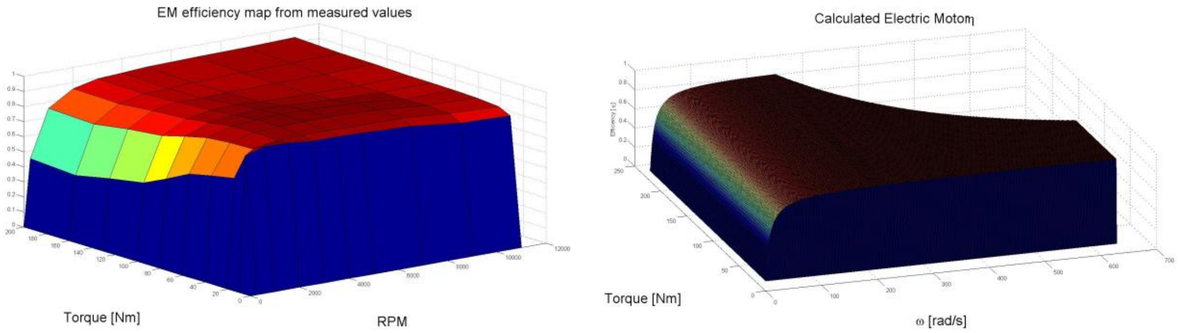

Figure 10 Extrapolated measured and calculated efficiency curve

Comparing the two maps in Figure 10 the same patterns are observed although the theoretical shows a higher efficiency in total along with smaller changes depending on the torque delivered. Another difference is that the theoretical includes the field weakening area while the measured has been extrapolated to be used in simulation software. As stated previously the anomaly losses can be as high as 10%. The measured map for a 50 kW EM was used and scaled depending on the rated power. To avoid areas with low efficiency and to be able to reach a top speed of 160 km/h a gear ratio of 6.5 is chosen for the series and parallel ERAD model and 2 for the parallel ISG.

### 3.1.1.2 EM weight and rotor inertia

Both weight and inertia of the EM has an influence on the performance, especially during acceleration of the vehicle. Values on these parameters was retrieved using data from one manufacturer (Siemens) of electric traction motors was used, regarding 4 pole machines with a rated power between 34 and 94kW to get a rough estimates via inter- and extrapolation. The reason why only 4 pole machines were chosen is due to that their rpm range that is suited for traction motor purposes.[26]

### 3.1.1.3 ICE weight

As all the weights in the vehicle are of interest also the change in weight due to reduced engine displacement is considered. This is however complex because the engine weight depends on the configuration and material used, but according to FEV generalizations can be made within in a certain displacement range that for a cast-iron block the weight increase is nearly linearly connected to displacement volume.

### 3.1.1.4 SOC

The SOC model add or deducts charge from the batteries using the power request from the EM or the power generated from HVG/EM and via the total battery charge delivers a percentage value on the remaining charge. The modeled SOC function is shown in Figure 11.

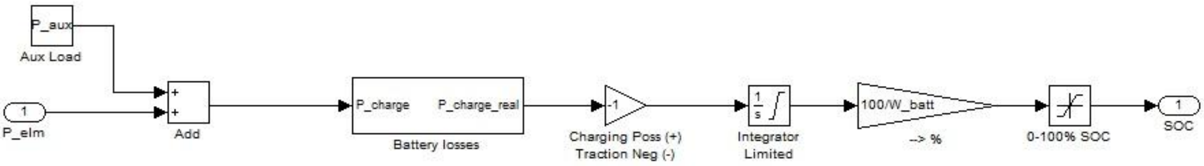

Figure 11 Implemented SOC functionality

### 3.1.1.5 Battery efficiency

The battery losses subsystem in Figure 11 contains the efficiency map for the batteries. This map is generated using Ohms law for a circuit:

$$P_{term} = (e_{batt} + R_{batt} \cdot i_{batt}) \cdot i_{batt} = e_{batt} \cdot i_{batt} + R_{batt} \cdot {i_{batt}}^2 \qquad (20)$$

$$i_{batt} = -\frac{e_{batt}}{2 \cdot R_{batt}} \pm \sqrt{\left(\frac{e_{batt}}{2 \cdot R_{batt}}\right)^2 + \frac{P_{term}}{R_{batt}}} \qquad (21)$$

$$P_{loss} = R_{batt} \cdot i_{batt}^2 \qquad (22)$$

$$P_{charge} = P_{term} - P_{loss} \qquad (23)$$

$$\eta_{batt} = \frac{P_{charge}}{P_{term}} \qquad (24)$$

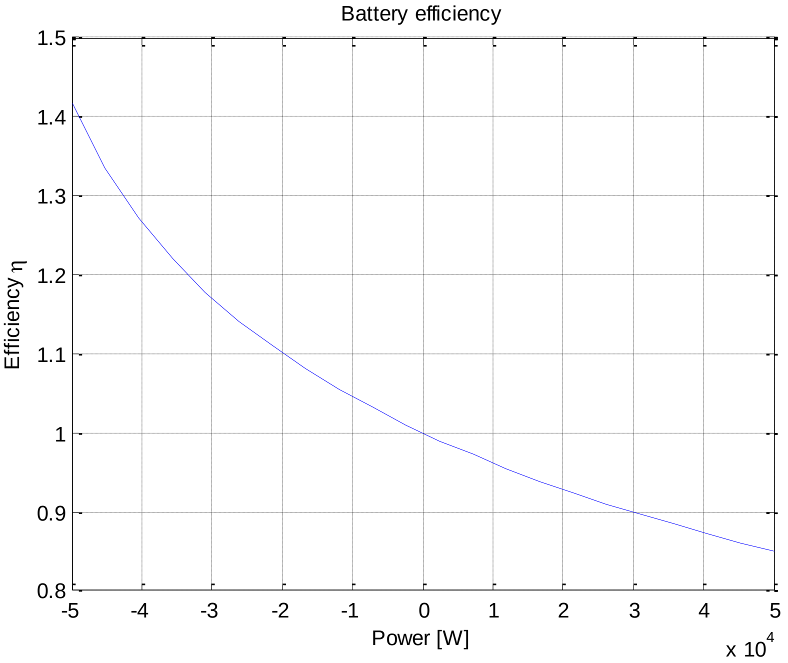

Figure 12 Generated battery efficiency curve

When power is drawn from the battery (negative power) more power than requested has to be drawn to cover for the losses in the battery, similar when power is generated less power than generated power can be captured by the batteries observed in Figure 12. This model does not take into account the temperature of the batteries nor the voltage drop during discharge, as they have a negligible impact when comparing the models.

#### 3.1.1.6 ICE BSFC

The source of the BSFC map is measurements performed on a 2.0 liter turbo charged engine which is scaled using BMEP.

#### 3.1.1.7 ICE losses maps

Engine friction maps from the same vehicle as the BSFC map is used. Additional losses are added to compensate for auxiliary load (i.e. generator).

## 3.2 Method

### 3.2.1 Test sequence

In order to get comparable results some assumptions were made for all of the models, all of the heat losses from parts are assumed to be transferred before overheating occurs, the initial SOC is set to 80%, all of the models are used on the NEDC and the type of batteries are the same.

To be able to produce usable data a test plan has been established that varies three different parameters; ICE power (size), EM power and amount of batteries (kg) onboard. All of the parameters are evaluated using two different levels, high and low. In the tests both high and low values are tested four times giving a good resolution.

Table 2 Example of test setup

| | Variables with value | | | Variables in coded units | | | Response (fuel) y |
|---|---|---|---|---|---|---|---|
| Run | ICE liters (A) | EM kW (B) | Battery kg (C) | A | B | C | |
| 1 | 1.4 | 30 | 150 | -1 | -1 | -1 | |
| 2 | 2.0 | 30 | 150 | +1 | -1 | -1 | |
| 3 | 1.4 | 50 | 150 | -1 | +1 | -1 | |
| 4 | 2.0 | 50 | 150 | +1 | +1 | -1 | |
| 5 | 1.4 | 30 | 250 | -1 | -1 | +1 | |
| 6 | 2.0 | 30 | 250 | +1 | -1 | +1 | |
| 7 | 1.4 | 50 | 250 | -1 | +1 | +1 | |
| 8 | 2.0 | 50 | 250 | +1 | +1 | +1 | |

By using the first four test the effects of A and B can be calculated while C remains constant. It is also possible to calculate how the interaction between A and B affects the outcome. The affect $C_A$ that factor A has on the fuel consumption $\Delta fc$ is the difference between the average values for the two levels

$$C_A = \frac{-y(1)+y(2)-y(3)+y(4)}{2} = \Delta fc \tag{25}$$

And with the same procedure for factor B

$$C_B = \frac{-y(1)-y(2)+y(3)+y(4)}{2} = \Delta fc \tag{26}$$

To be able to determine if factor A and B affect each other graphs are made with the tested values.

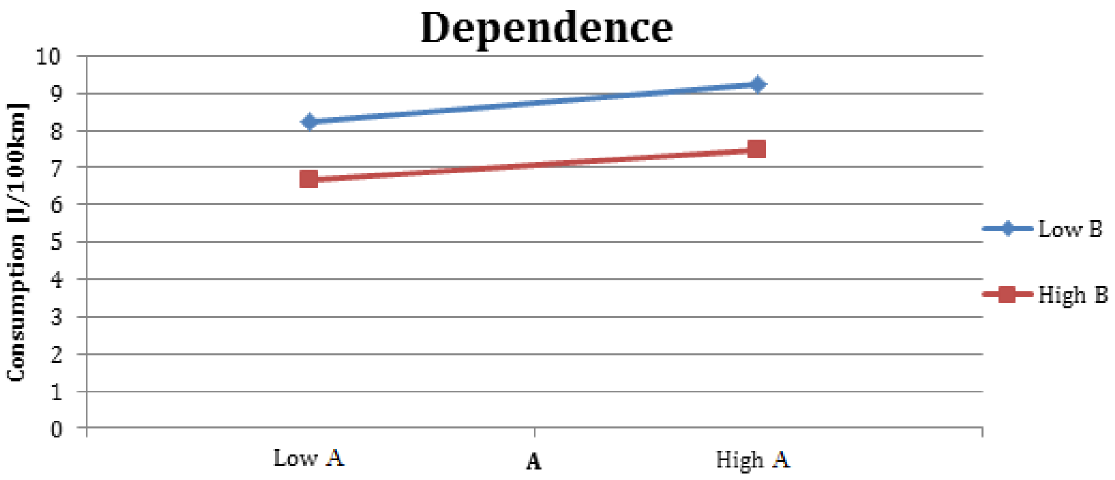

Figure 13 Example of interaction plot of factor dependency

As can be seen in Figure 13 and Table 3there is a very small dependence between the tested factors which implies that their relation should be investigated.

$$C_{AB} = \frac{y(1)-y(2)-y(3)+y(4)}{2} = \Delta fc \tag{27}$$

The same procedure is repeated for the other factors to get a matrix (Table 3) with the interactions as well.

Table 3 Example of L8 table

| Variables in coded units | | | | | | | Response (fuel) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 8,212 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 9,2465 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 6,6632 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 7,4511 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 8,387 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 9,4247 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 6,8415 |
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 7,6342 |
| 0,9132 | -1,67005 | -0,1229 | 0,17865 | 0,002 | 0,00205 | 0,0004 | |

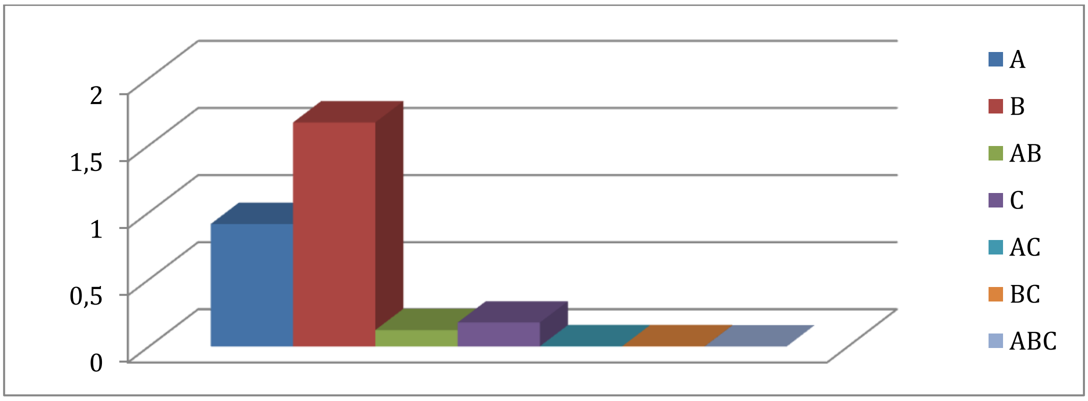

Figure 14 Example of graphical representation of calculated L8 values

As can be seen in Figure 14 it is possible to see that the interaction the EM power and the size of the combustion engine are the most affecting factors, compared to the battery size and interaction factors.

When knowing which two factors are dominating a new test sequence can be performed, varying these two over their whole range with the third factor set to constant. If the third factor shows a slight influence it is possible to vary also this parameter but in much bigger steps to lower time consumption.[27]

## 3.2.2 Acceleration test

In the acceleration test the same procedure as for the NEDC test is used with the exception that the charge mode is neglected (i.e. all are run in depletion mode). The time it takes for the vehicle to reach 100km/h is the response and the interesting measure. This test is also carried out when the vehicle already is motion and overtaking, starting at 80km/h and finishing at 120km/h using full power.

### 3.2.3 Scaling the internal combustion engine

In order to simulate and find an optimal size of the ICE for the HEV the engine must be variable in size. The work has been focused on finding a suitable ICE in the size range of small automotive engines i.e. approximately in the range of one to two litres displacement volume. The choice has been to either use fixed steps with data from production engines or to use a freely scalable engine modelled representation.

By looking at data from different sized turbo charged engines, 1.4 1.6 and 2.0litre of displacement, it was clear that the design difference between different engines affects the output too much to give comparable results. Cylinder head design differences along with different injection technology made the engines incomparable. From this it was decided that better results would be gained if the engine was represented by a scalable model rather than several production engines.

Based on this it was decided that the engine in the reference sedan (see engine specifications in Table 4) should be used and by scaling it using Bmep, calculated in eq.(28), the right displacement could be simulated.

**Table 4 Reference engine data**

| | |
|---|---|
| Displacement: | 2.0liter |
| Max. power: | 210hp (155kW) @ 5 500rpm |
| Max. torque | 300Nm @ 2 500rpm |
| Bore/Stroke: | 86mm x 86mm |
| Compression ratio | 9.5:1 |
| Max. boost pressure | 0.85bar |
| Ignition/Fuel system | MPFI (multipoint port fuel injected) |

$$Bmep(18.85Bar) = \frac{T(300Nm)n_R(2r/c)}{V_d(0.002m^3)}2\pi \qquad (28)$$

While larger engines have high power output they also have high built in losses. However it is worth to notice that the engine's losses increase with speed which will mean that a smaller engine with too low power output will suffer from high engine speed losses at high power request.

### 3.2.4 Calculating equivalent fuel consumption

When simulating a hybrid vehicle in a driving cycle for fuel consumption measure will cause problems since the battery charge level will most likely not end up at the initial level. For the measurements in this project an average efficiency is calculated from the combustion engine during the cycle runtime, this efficiency is then used to compensate for the energy difference in the battery. To calculate the efficiency the total energy during the whole cycle required from the ICE is compared with the total energy in the supplied fuel. A non-compensated curve is shown in comparison with a compensated in Figure 15.

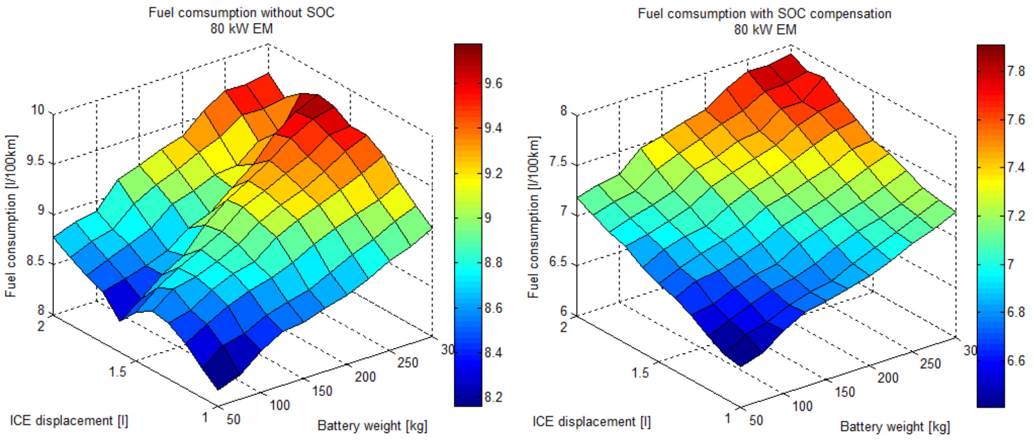

Figure 15 Compensation of SOC difference

### 3.2.5 Calculating equivalent CO2 emissions

Using the average values in Figure 8 a general amount of grams CO2 per kWh can be determined for whole of Europe. This is done via the fraction of power generated by the source and its carbon footprint value per kWh from Figure 9.

$$g/kWh = \sum_{all\ sources} \frac{GWh_{source}}{\sum GWh_{total}} * \left(\frac{g}{kWh}\right)_{source} = 154.5\frac{g}{kWh} \tag{29}$$

This value would decrease greatly if mainly renewable and nuclear sources were used which is the case in Sweden for example.

## 3.3 Models

In this part of the report results from simulations are presented, it is divided in parallel, series and parallel ERAD hybrid. The vehicle setup is described and the results are visualized and analysed.

### 3.3.1 NEDC model

Using the engine model for the predefined vehicle as a base the hybrid logic was then applied. In the model the requested vehicle speed by the NEDC cycle at the specified time is put into the force equation for a vehicle that is multiplied with the speed to get out a requested power. The power request is then used in the hybrid logic which splits the power request between ICE and

EM to achieve the wanted output. The models do not consider start up time for the ICE, this will in real situations increase fuel consumption. No auxiliary load is demanded from the ICE since they will be electrified in a hybrid vehicle application.

### 3.3.2 Acceleration model

The acceleration model is a simplified model that instead of using a speed profile uses a constant power demand which is beyond the maximum power of the vehicle. By having a larger power demand the logic will deliver highest available tractive power at all vehicle speeds. Instead of changing gears as predetermined in the NEDC cycle, the gear change occurs at 5400 rpm for all gears. Unnecessary processes such as light off compensation are removed to simplify the model as much as possible to give a good overview.

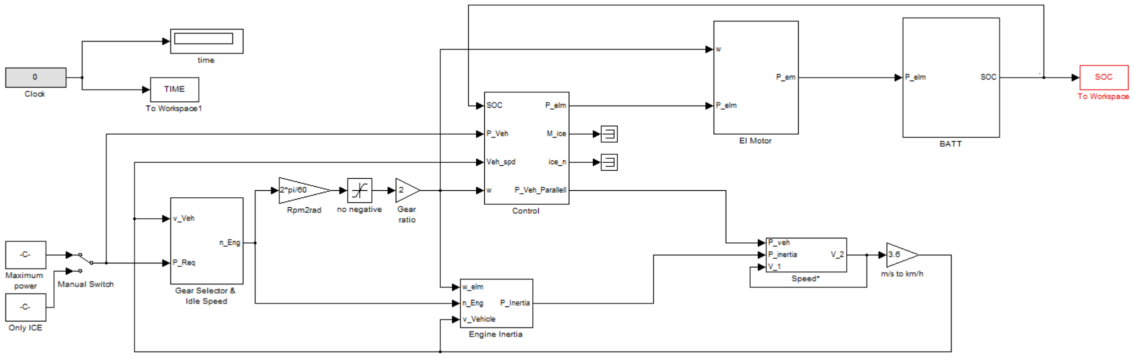

Figure 16 Acceleration model in Matlab/simulink

To calculate the new speed in each sample, same equation used for calculating the power request in the NEDC models is used but backwards. Having the amount of obtainable tractive power the theoretical speed increase can be obtained. This speed increase does not take gear selection time along with clutching into consideration.

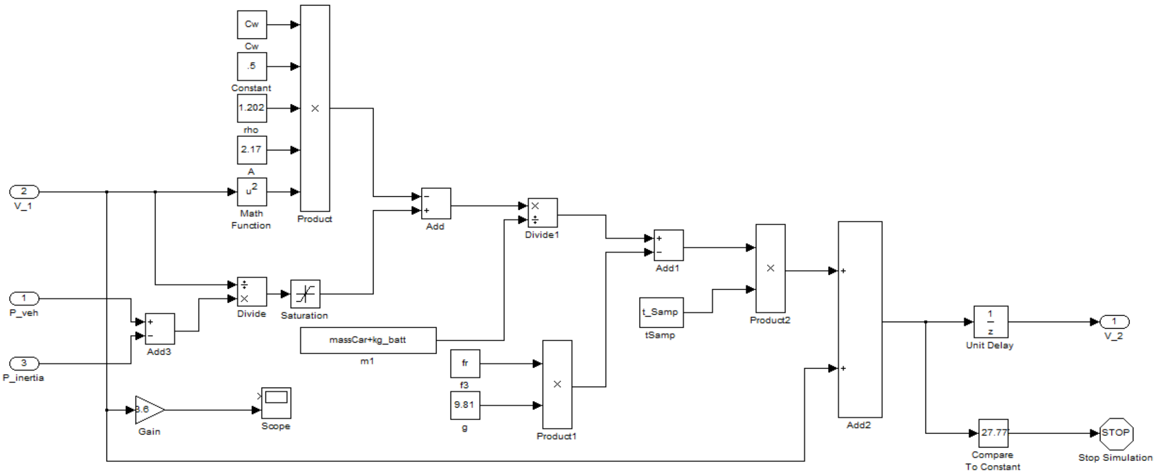

Figure 17 Calculation of velocity in acceleration model

A reasonable time for the acceleration for a middle range sedan with corresponding ICE and weight is 7.9 seconds.

### 3.3.3 Parallel hybrid

The parallel model is modelled as an ISG configured hybrid vehicle where the electric motor is mounted after the clutch and before the gearbox, making it possible to disconnect the ICE and run electric. The parallel is assumed, even though it is possible, not to run in depletion mode. This means the ICE is used to charge the batteries to sustain the chosen SOC and to boost the system with extra power. When the ICE is used to charge the batteries it is controlled via a low pass filter to avoid rapid transient behaviour, this is not the case for the boost function. Regenerative braking is active at speeds exceeding 5 km/h.

#### 3.3.3.1 NEDC Test Setup, Simulations and Results

Results from the test schedule simulations shows that displacement of the ICE (A) along with the electric motor power (B) is the two major influencing factors on fuel consumption.

The test schedule simulations are shown graphically in Figure 18, here it is easier to see that the correlated factor ABC has little influence.

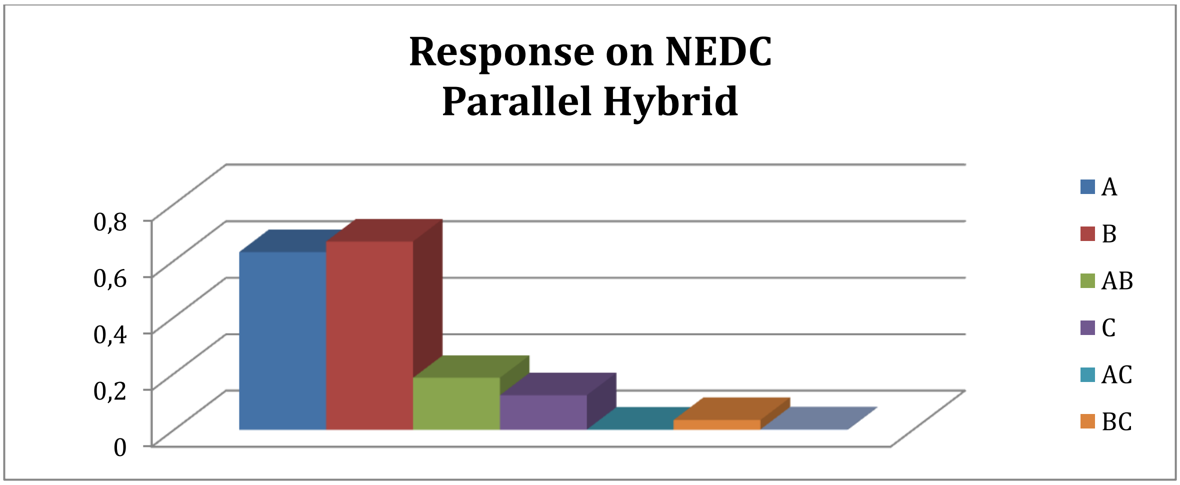

Figure 18 Response on fuel consumption of the parallel hybrid in NEDC

From this the ICE displacement and electric motor power was varied with constant battery weight. As seen in Figure 18 the battery weight influence cannot be neglected, hence to investigate this effect the battery weight was varied in steps of 50kg in an interval of 50-150kg. The simulation runs uses ICE volumes between 1 and 2liters in 0.1liter steps, while the electric motor power output is varied between 10 and 75kW in 5kW steps.

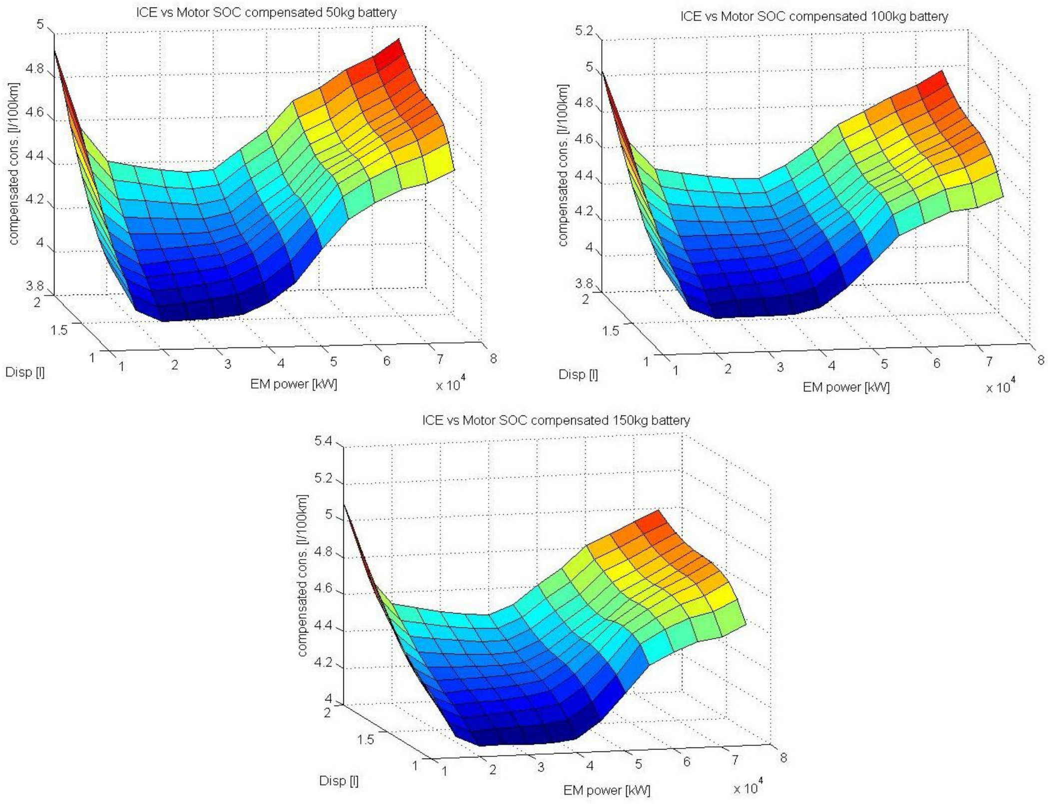

**Figure 19 Simulated fuel consumption parallel hybrid**

It can be seen from simulation, Figure 19, that a too small electric motor will cause higher fuel consumption at all battery weights, due to a movement out of from the efficiency areas for the ICE and is not able to recuperate all available energy. From 20kW and upward an overall fuel increase occurs, this effect is due to operating points for the motor in the NEDC cycle. The quite settle NEDC does not require very intense acceleration or deceleration rates which means that an electric motor of smaller size, until a certain point, will benefit because it has to work harder and ends up at better overall efficiency points. Since in the parallel hybrid it is not possible to choose freely where to operate the ICE due to the physical connection to the drive wheels, the ICE favours the lower displacement volume because here with higher load it can run at better operation point. Even though there is a significant weight reduction of the smaller ICE this has less effect than the load shifting. As indicated in the test setup the battery weight has a small influence on fuel consumption.

In the 20kW and 1.0l ICE case the electric motor can handle almost all driving situations without boost from the ICE this mean that the ice can run at good efficiency when it is ran for charging or boosting. The lowest simulated fuel consumption of slightly above 3.9l over 100km was simulated in a vehicle with the combination 20kW electric motor, 1.0l engine and 50kg of batteries.

#### 3.3.3.2 Acceleration test

Contrary to the series hybrid vehicle the parallel configuration allows both engine and motor, because of the mechanical coupling, to simultaneously propel the vehicle. To achieve the shortest acceleration time possible both the ICE and electric machine send all power to the driven wheels. In order to avoid charge request and power generation to the battery the vehicle is set to depletion mode and the ICE automatically helps through the boost function.

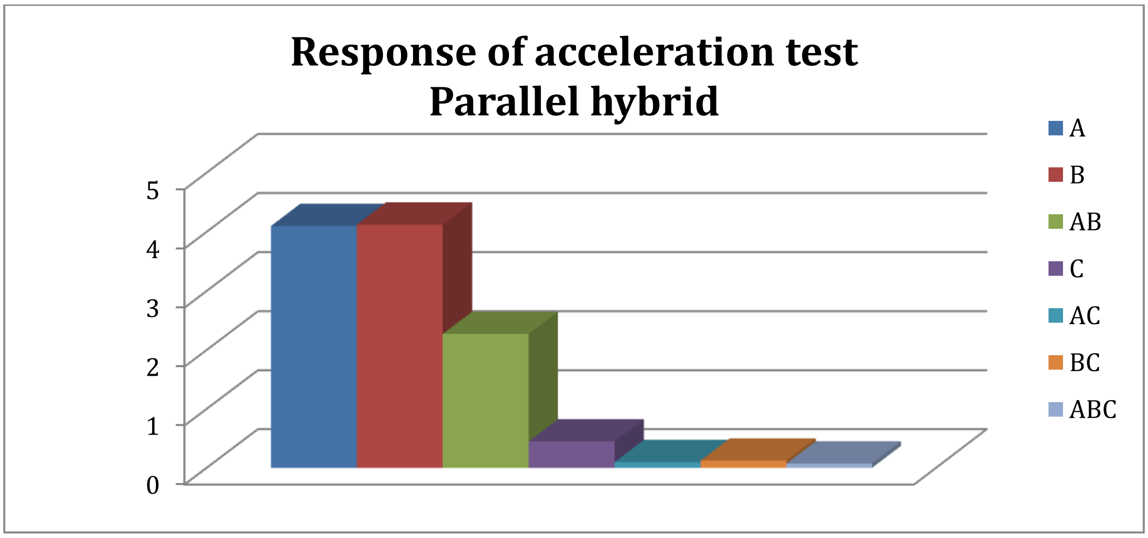

Figure 20 Response on acceleration of parallel hybrid

The test schedule presented in Figure 20 shows that the electric motor (B) and ICE (A) has the foremost impact on the acceleration time while the batteries have a less significant impact.

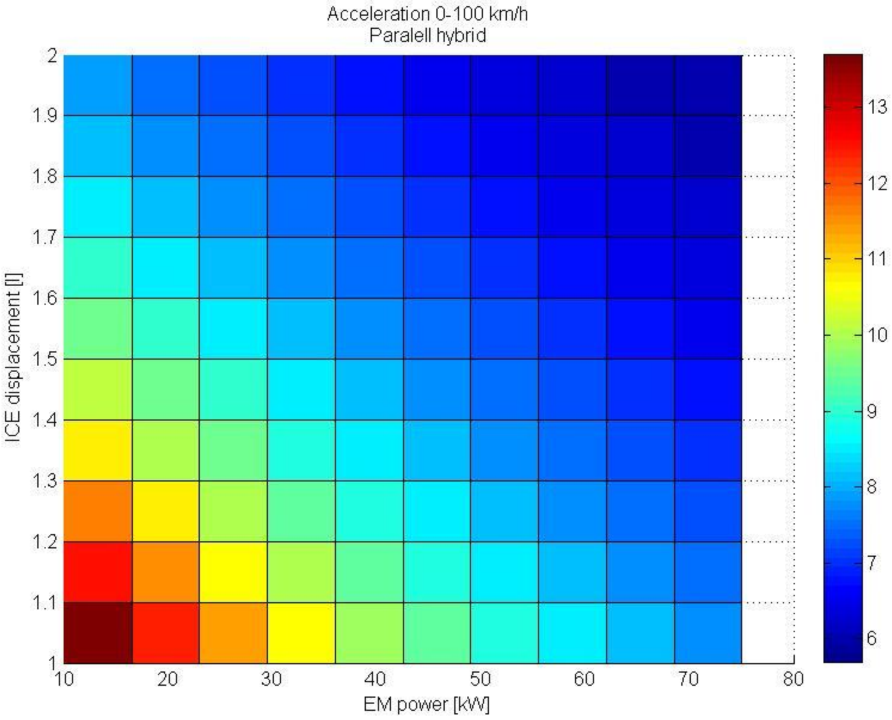

Figure 21 Simulated acceleration time for parallel hybrid

Even though weight and mass moment of inertia increase with the larger ICE and electric motor this gives the best simulated acceleration. The 2l ICE with 75kW reaches 100km/h in just 5.7sec (the distribution of acceleration times is showed in Figure 21). The acceleration from acceleration simulations 80 to 120km/h can be found in the appendix, A1 Figure 1.

### 3.3.4 Series hybrid

In this model the total power requested derived from the wanted speed increase and losses is directly directed to the EM where the minimum value out of the requested power and maximum power that the EM can deliver at the current speed is taken from the power curve. Regenerative braking is carried out in speeds excessing 5 km/h.

#### 3.3.4.1 Charge Sustaining

In this mode the ICE charges the batteries continuously in order to maintain a level of 80% SOC. This will allow the ICE to run without any fast transient behavior and charge the battery at high load and mediate rpms therefore avoid low efficiency load points. The SOC difference in the end of the cycle will be recalculated as fuel consumption by using the mean engine efficiency during engine on time in the cycle.

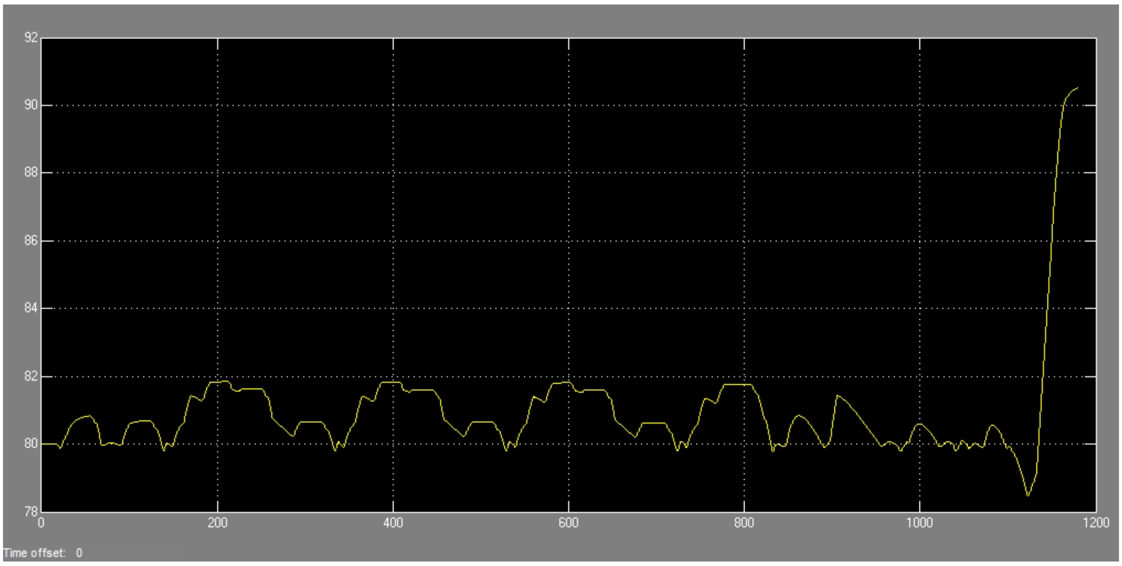

Figure 22 SOC curve for charge sustain

Figure 22 shows the SOC curve from the Simulink model, in the city part of the cycle the SOC is maintained at 80 percent by the ICE but in the end there is a heavy deceleration where regenerative braking is used that charges the battery to a high level of SOC.

Results from the test schedule simulations, Figure 23, shows that the ICE along with the size of the batteries has the biggest influence on the fuel consumption, with the EM power less significant.

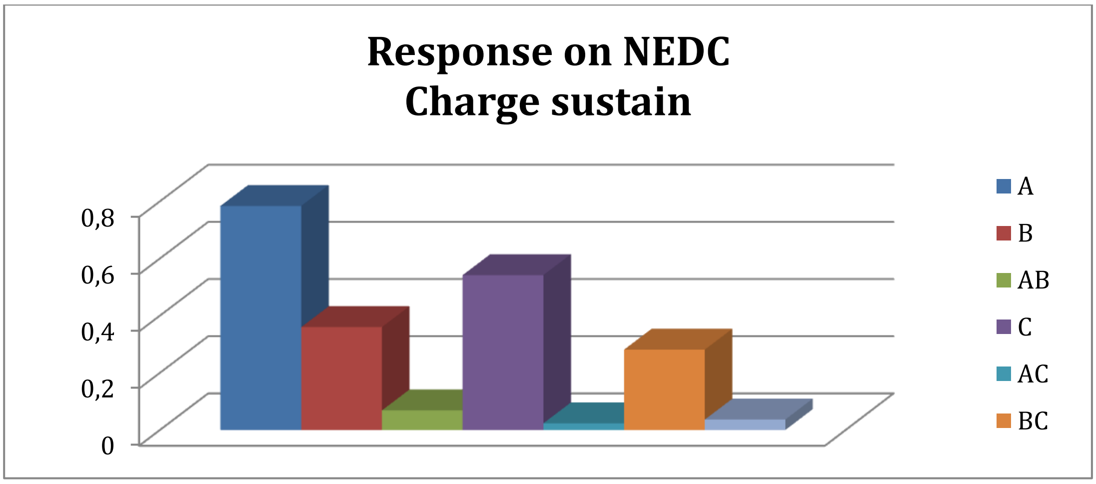

Figure 23 Response on fuel consumption of series hybrid with charge sustain in NEDC

The ICE is enabled during most of the cycle having a low efficiency at lower load, making the ICE displacement influence to the fuel consumption large. When the SOC is below a certain level the ICE starts and the time it takes to reach this level depends on the EM efficiency and the battery pack size. In the NEDC the battery pack size is more important than the EM power; this is due to having a weight increase from the batteries that will affect the power request more than the losses that occurs in a high power EM also the additional amount of possible charge does not outweigh the added weight.

In the two variable simulations the ICE power and battery pack size was varied with constant EM power. The ICE is varied between 1.0 and 2.0liter while the battery pack size is varied between 50 and 300kg with a step size on 0.1 liter respectively 25kg. As seen in Figure 23 the EM power has a non-negligible influence and in order to investigate this effect the EM power was varied in steps of 30kW from 50-140kW.

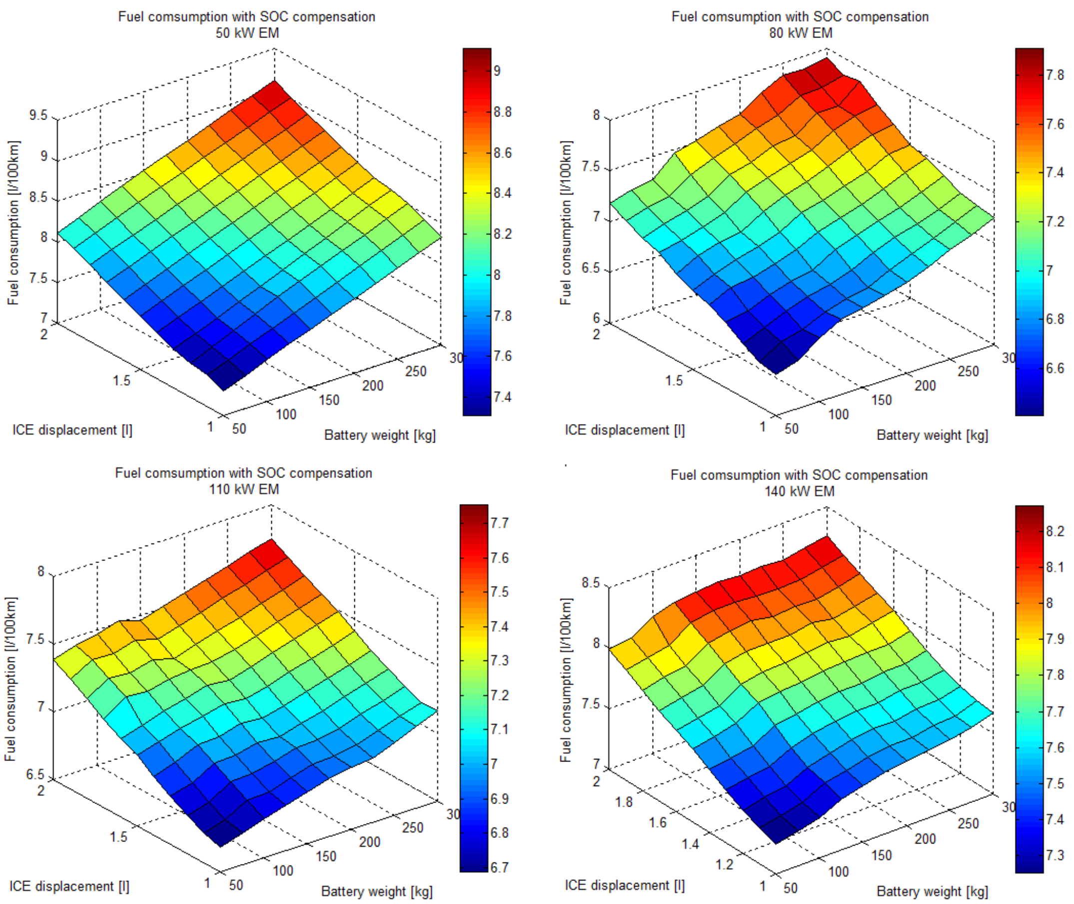

Figure 24 Simulated fuel consumption series hybrid in charge sustain

Each graph shows roughly the same linear behavior and that the lowest values on both ICE and battery pack size will give the least fuel consumption due to lower weight. When looking at the fuel consumptions dependence on EM power it is shown that the lowest consumption is retrieved for a 80kW EM at 6.5l/100 km. Investigating the cause of having an optimal EM at 80kW shows that even though the torque request is higher to compensate for the weight increase the power demand from the batteries is lower suggesting that the higher EM inertia delivering more regenerative power.

### 3.3.4.2 Charge depletion

In charge depletion mode the large amount of batteries will allow the vehicle to purely run on electric power during the entire NEDC cycle generating a zero in fuel consumption. With no on time of the engine no value on the mean engine efficiency enabling calculation of equivalent fuel consumption can be derived. Hence a value of 29% is set for the engine efficiency which has been observed to be thee predominate value during other simulations.

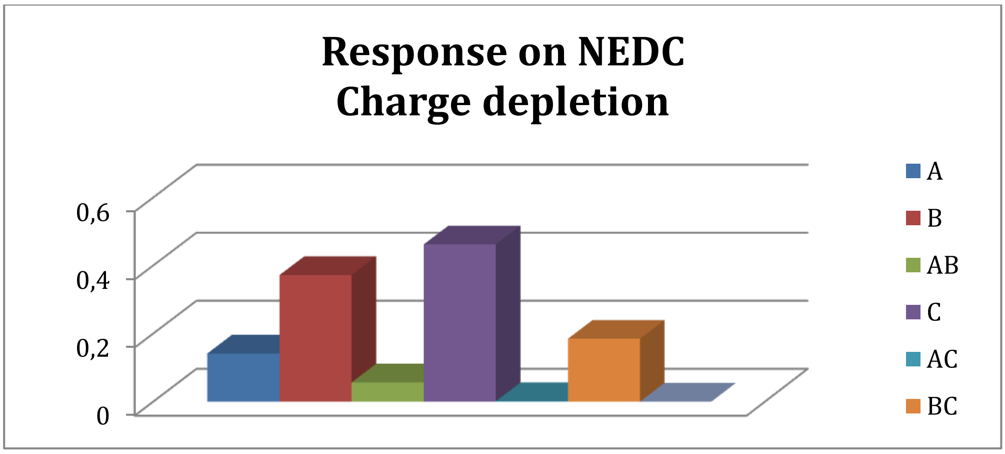

Figure 25 Response on fuel consumption of series hybrid with charge depletion in NEDC

The initial tests shows that in contrast to the sustain mode it is the battery pack size that has the dominating influence followed by EM power while the ICE has a minor influence due to weight variations. Conducting the second test with a variation of the battery pack size from 50 to 300kg and the EM from 50 to 140kW for different ICE displacement following graphs is developed.

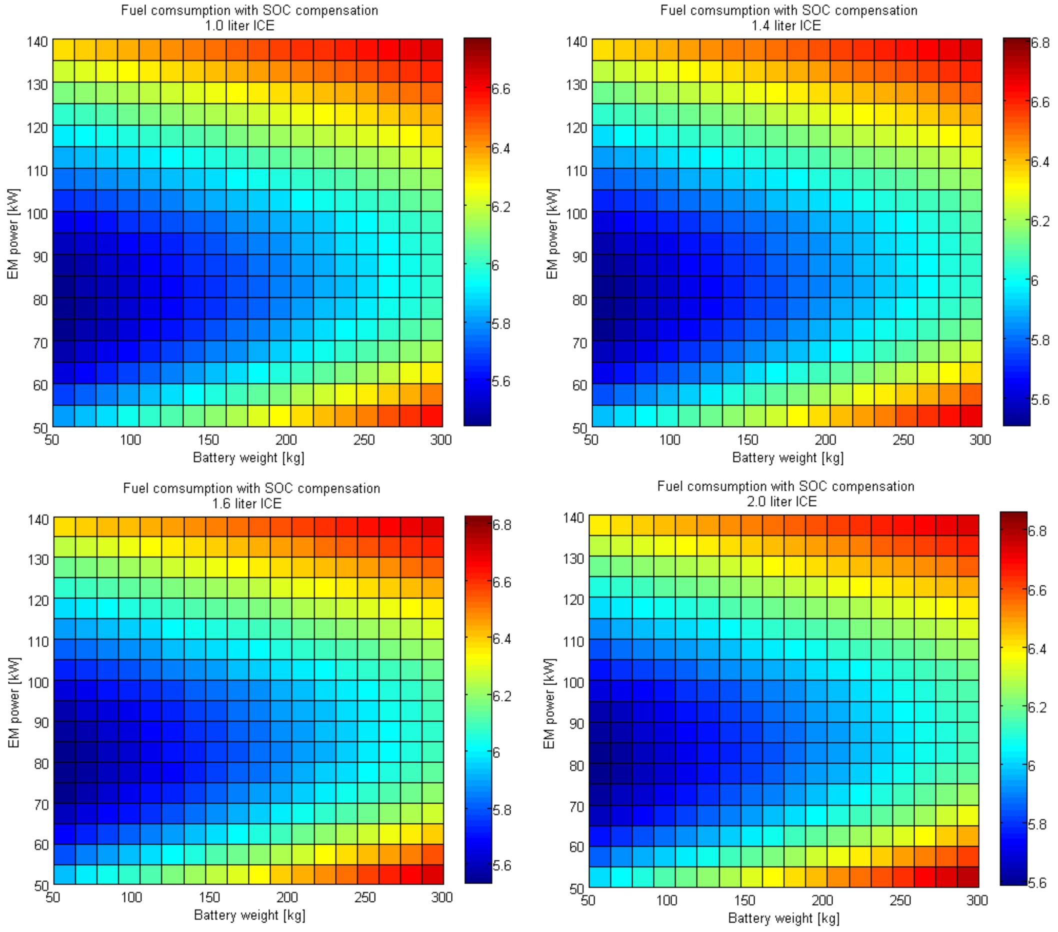

Figure 26 Simulated fuel consumption series hybrid in charge depletion

In all of the simulations the ICE never starts due to SOC values above 30% at the end of the NEDC so the equivalent fuel consumption is calculated for each simulation. As shown the fuel consumption increases with higher amount of batteries, implying that the vehicle weight is more important than the increased storage possibilities. Looking at the EM dependency the impact of EM inertia is even more evident showing that there is an optimal EM size for the NEDC around 80kW. The fuel consumption increases slightly with increasing engine displacement having the lowest consumption for the 1.0liter engine due to lower weight.

### 3.3.4.3 Acceleration test

For the series hybrid depletion or charge sustaining is of no interest when the acceleration time from 0-100 km/h is measured due to the short amount of time it takes to reach target speed.

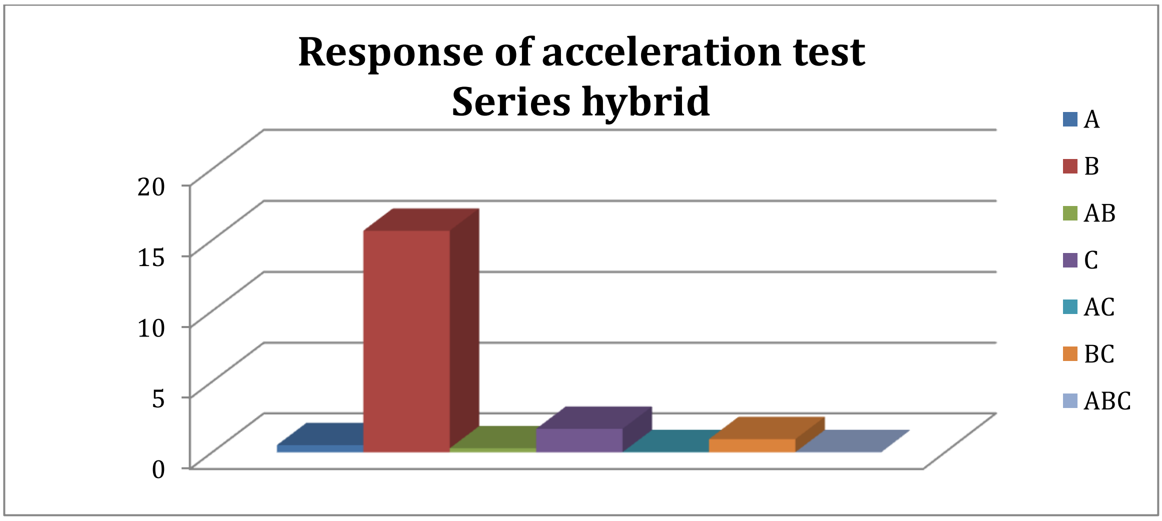

Figure 27 Response on acceleration of series hybrid

Figure 27 shows that the traction motor has the foremost impact on the acceleration time while the batteries have a lesser significant impact. Observing the test schedule along with the SOC curves it is possible to see that the weight has a negative impact i.e. the vehicle has no use for the extra available power during the short acceleration time.

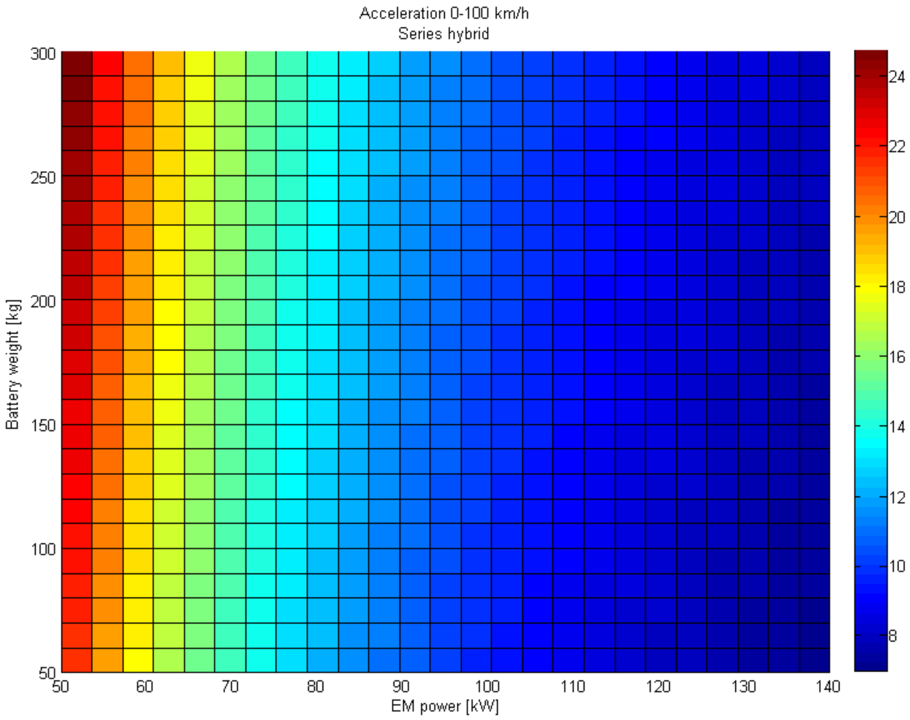

Figure 28 Simulated acceleration time for series hybrid

For the least amount of batteries and the biggest EM the lowest time to reach 100km/h 7.0 seconds is achieved, making the EM power a tradeoff between performance and fuel consumption. Reasons why 140kW gives a lesser time in accelerating than the reference vehicle (which has more power) is due to no gear changes and a more constant power delivery along with a lower inertia. The acceleration from acceleration simulations 80 to 120km/h can be found in the appendix (A1 Figure 2).

### 3.3.5 ERAD parallel hybrid

Instead of having a complex control strategy that depends on SOC level along with the optimal load points for the ICE, a more straightforward strategy can be used. This strategy is incorporated in an ERAD concept having all power requests below rated power of the EM handled by the EM while the ICE is used during higher power needs. The purpose is to have both ICE and EM to work at their highest efficiency with the possibility to do regenerative braking. Because of the low power demands in the NEDC the maximum value of rated power on the EM is set to 25kW and the minimum is set to 10kW. As a result of the low EM power also the battery pack size is set to a low range between 50-100kg. When the EM is at its minimum size the ICE has to assist during most of the power demands leading to more fuel consumption. As the EM is quite small the size of the battery pack does not have to be as big as in previously discussed solutions, lowering the costs and space demand.

In the concept there is no charging using the ICE instead all the charging is done by regenerative braking. To be able to meet the power demand at all times a boost function is incorporated allowing the ICE or EM to assist during power demands exceeding their individual capabilities. When the SOC falls below the set limit at 30% all power request is handle by the ICE until regenerative braking occurs.

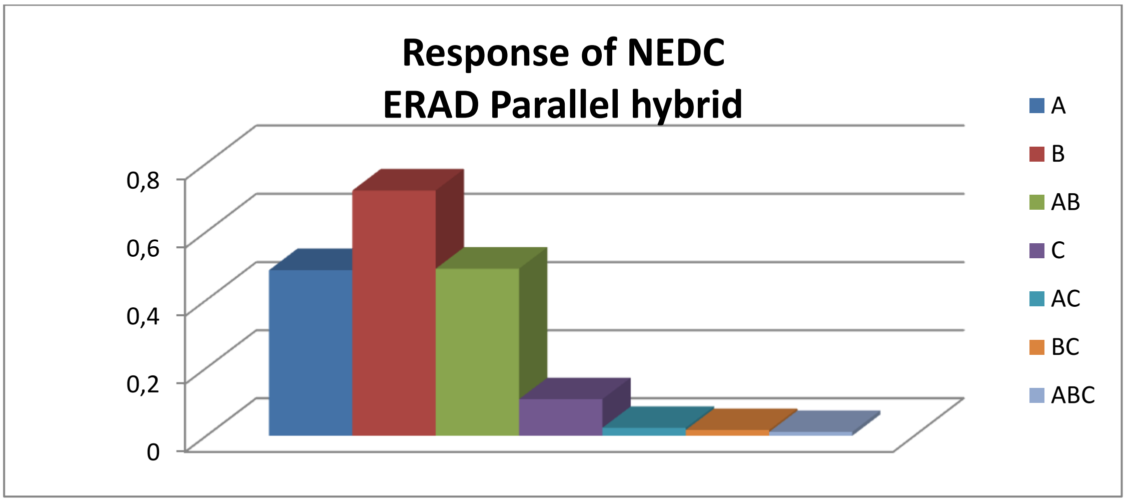

Figure 29 Response on fuel consumption of ERAD parallel hybrid in NEDC

The response is similar as for the ISG in the respect of the significant parameters, EM and ICE compared to battery pack size. The low impact of batteries can be explained by the low battery weight and the fact the SOC never reaches 30% during the cycle. If the high value EM is used then it can cover most of the cycle demands while a low value needs more assistance from the ICE making the interaction essential.

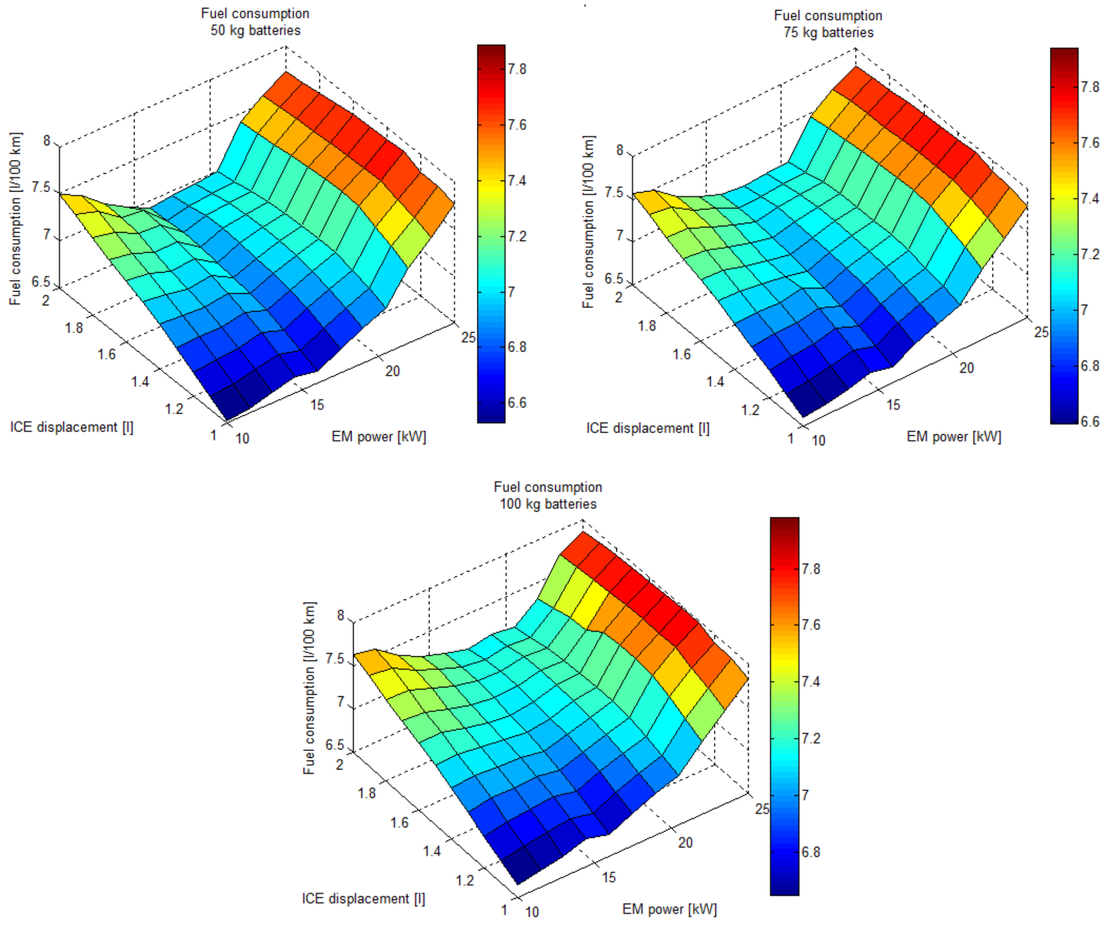

Figure 30 Simulated fuel consumption ERAD parallel hybrid

The ERAD model also shows similarities with the ISG model (Figure 19) concerning the behavior of the fuel consumption. With increasing EM power the losses will increase using more fuel but for some of the EM levels will exceed power demands in the NEDC; for example an EM around 16 kW will be able to cover many power request compared to an EM at 10kW. For the case of a 25kW EM the power demands is not beneficial so the lower overall efficiency during the whole cycle will increase the fuel consumption.

For all battery pack sizes the ERAD model will have a higher fuel consumption than the ISG model because the ERAD model assumes that a high efficiency for the ICE is retrieved by having it taking care of the higher loads but in the ISG model the ICE is run at points known to be good efficiency points for that engine, increasing the engine efficiency.

### 3.3.6 Charging effect on C02

The only hybrid solution that is optimized for being used as a PHEV is the series hybrid run in depletion mode. Due to its large amount of batteries along with the possibility to drive pure electric it is the vehicle most likely to be charged by plugging into the grid. The amount of CO2 that can be reduced per km by changing the charging from ICE to the electric grid is shown in Figure 31 (the graph shown is for the chosen series hybrid).

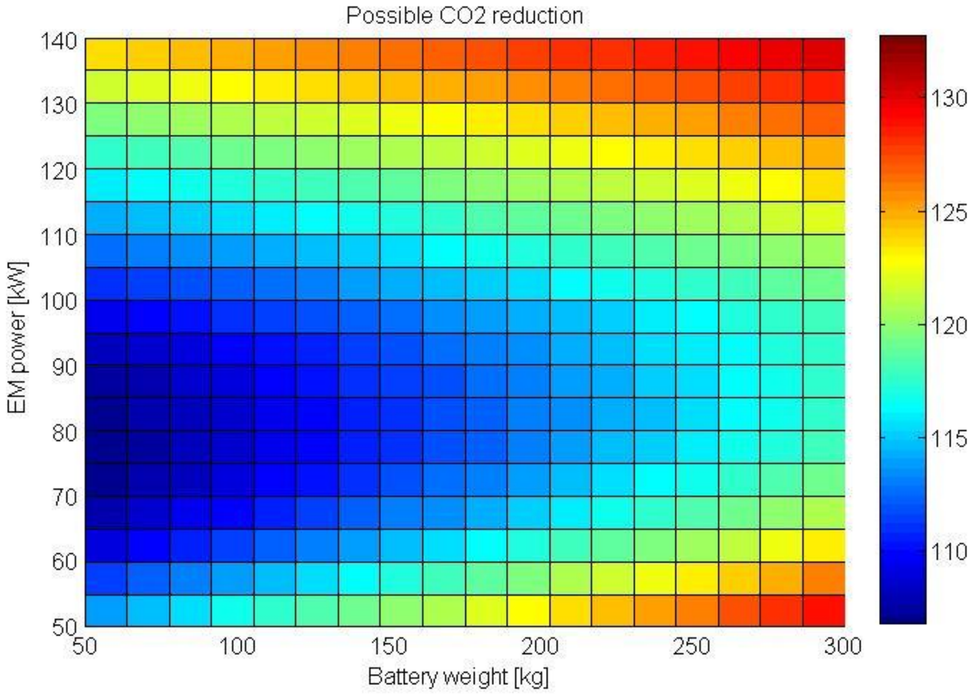

Figure 31 Available CO2 savings between ICE and grid charging [g/km]

For the case with lowest fuel consumption, i.e. 80kW EM and 50kg batteries, 105g/km can be reduced by charging from the power grid. If the PHEV have a battery that can provide enough distance between the charges great savings can be made.

# 4 Conclusion

The intention of this work was to investigate if it is possible to lower the CO2 emissions from a modern sedan by hybridization without compromising performance and to what extent it is depending on the type and configuration of the vehicle. Concerning the performance both the series and the parallel hybrid offers a faster alternatives than the reference vehicle but these configurations does not imply with set out target to reduce CO2. Hence a performance time with a reasonable deviation from the reference time should be chosen. In the case of the parallel ISG a 1.2liter ICE along with a 55kW EM and 50kg batteries will represent about the same performance but the fuel consumption will be lower from the reference to 4.5l/100km, this means a hybridization ratio of 0.37. While for the series hybrid a minimum EM power at 120kW is needed to maintain the reference performance, the lowest fuel consumption is 6.8l/100km for running in charge sustain and 6.2l/100km for depletion mode with a 1.0liter ICE and 150 kg batteries, with a hybridization ratio of 0.53. In charge sustaining the fuel consumption can be lowered with 0.1l if the battery mass is lowered to 50kg and 0.2l for depletion, but this amount of batteries is not considered enough for 120kW and simulations in charge depletion shows that 150kg would be sufficient to cover the average driven distance of 40km/day pure electric. According to the simulations the parallel hybrid is the best solution to minimize the fuel consumption with the possibility to have a better performance and still attain a fuel consumption that is lower than the reference vehicle. The acceleration from 80-120km/h is, as soon as the traction power is enough, not a big issue since here the aerodynamic forces on the vehicle are more important.

Another aspect that can be taken into consideration during the choice of hybridization type is where the primary energy originates from. If a series vehicle in depletion mode is used then the plug in option will allow the user to charge the batteries from the grid reducing the CO2 emissions greatly until the battery pack is depleted and the ICE starts the charging process. Hence it is difficult to state an optimum configuration as the optimum configuration depends on the final usage of the vehicle. But what can be concluded is that hybridization that enables the possibility to reduce CO2 emissions and fulfil power requirements can be done independent of hybridization type studied.

Creating general models for components that depend on make and version from specific data is not optimal but it gives an estimation that can be used to get reasonable accuracy and results. The theoretical battery and EM efficiency maps does not take the thermodynamic behaviour in the components into consideration, this is a simplification made to lower simulation time without compromising the tendencies, but this is an area that need further investigation since the generated heat lowers the battery capacity and disables the ability to run the EM at high power. When taking the heat losses into concern the cooling system is a new parameter that will depend on the EM and battery size and will increase the weight and total power request of the vehicle. In these models only the major components has been modelled which mean that losses from the rest of the system that is needed in and for the hybrid drivetrain will increase fuel consumption.

One dimension simulations in Matlab/Simulink offers an easy to use and follow environment that for this project has provided reasonable simulation times and good tools to analyse desired parts of the model.

The optimal combination of the considered parameters and vehicle cannot be defined specifically for all driving conditions that exist in the real world, however simulations can show trends in what to expect for a certain driveline configuration and driving conditions. The models constructed in this project are to a wide extent simplified representations of real components in a vehicle which means absolute numbers of fuel consumption cannot be expected from a real vehicle. However the simulation results show that for the NEDC in particular it is possible to create a hybrid driveline configuration with such power flow that reductions in CO2 emissions, i.e. fuel consumption, without compromise on vehicle performance are possible, this was observed in the fuel consumption and acceleration simulations in chapter 3.3.3 and 3.3.4. With ICE charging the simulated CO2 reduction differs between 16.2% and 44.5% depending on configuration. As CO2 emissions depend on the energy source charging the batteries, an absolute value on the emissions is difficult to derive but in a European country, charging via the grid would reduce the total CO2 emissions even further based on the NEDC.

This project has not taken cost into account, however the cost (development, production, to customer) of a hybrid vehicle is important for realisation. Furthermore there are many other aspects of a vehicle that make it sellable e.g. crash safety, reliability, comfort and boot space which has to be compromised with the hybrid system.

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# 6 Abbreviations

AC – Auxiliary Current
BMEP – Break Mean Effective Pressure
BSFC – Break Specific Fuel Consumption
CNG – Compressed Natural Gas
CO2 – Carbon Dioxide
DC – Direct Current
EM – Electric Motor
ERAD – Electrified Rear Axle Drive
EV- Electric Vehicle
FMEP – Friction Mean Effective Pressure
FTP – Federal Test Procedure
HEV – Hybrid Electric Vehicle
HVG – High Voltage Generator
ICE – Internal Combustion Engine
IM – Induction Motor
IMEP – Indicated Mean Effective Pressure
ISG – Integrated Starter Generator
MEP – Mean Effective Pressure
NEDC – New European Driving Cycle
PEV – Pure Electric Vehicle
PHEV – Plugin Hybrid Electric Vehicle
PM – Permanent Magnet
PMEP – Pump Mean Effective Pressure
SI – Spark Ignited
SOC – State Of Charge
UF – Utility Factor

# 7 List of figures

# 8 Appendix

## 8.1 Thermal resistance of electric motors

The total thermal resistance depends on the different types of heat transfer that occurs in the electric machine. For modeling the thermal resistance in the air gap between rotor and stator the following equation is used:

$$R_{ag} = \frac{l_g}{N_{nu} K_{air} A_{ag}} \qquad \text{(a1.eq1)}$$

Containing the length of the air gap $l_g$ , the Nusselt number $N_{nu}$, the thermal conductivity of air $K_{air}$ along with the air gap area $A_{ag}$. Equation (a1.eq1)is applicable when the machine utilizes air-cooling, to be able to analyze liquid cooled instead an assumption that the thermal conductivity of the air gap is constant, thus the air gap thermal resistance can be approximated as the value of a equivalent sized cylinder.

$$R_{ag,liquid} = \frac{\ln\left(\frac{r_i}{r_{magnet}}\right)}{2\pi K_{ag} L_{ag}} \qquad \text{(a1.eq2)}$$

Where $r_i$ and $r_{magnet}$ is the inner stator respectively outer magnet radius, $K_{ag}$ is the thermal conductivity and $L_{ag}$is the length. An approximate value for the thermal resistance in the air gap is 10 W/(m*C) that was derived for the Toyota Prius traction motor by Department Of Energy [28].

Due to the lack of heat transfer in the axial compared to the radial direction the thermal resistance in the iron core of the rotor can be evaluated by reusing equation (a1.eq2) with different radiuses.

$$R_{rs} = \frac{\ln\left(\frac{r_{rotor}}{r_{shaft}}\right)}{2\pi k_{rotor} L_s} \qquad \text{(a1.eq3)}$$

Where $r_{rotor}$is the rotor radius, $r_{shaft}$ is the shaft radius, $k_{rotor}$is the thermal conductivity of the rotor core and $L_s$ is the axial length of the core. In a PM the magnets surrounding the core will give a contribution to the total rotor resistance. This contribution is calculated exactly like the iron core losses but instead using the magnet radius and heat transfer constant along with the total coverage of magnets on the core.

The shaft is considered to be a cylinder within the iron core will transfer heat to the casing through the bearings.

$$R_{shaft} = \frac{R_a + R_b}{2} \qquad \text{(a1.eq4)}$$

Where

$$R_a = \frac{1}{2\pi k_{shf} L_s} + \frac{L_{bs}}{2\pi k_{shf}\left(\frac{D_{shf}}{2}\right)^2} \qquad \text{(a1.eq5)}$$

and

$$R_b = \frac{1}{4\pi k_{shf} L_b} + \frac{L_{bs}}{2\pi k_{shf}\left(\frac{D_{shf}}{2}\right)^2} \qquad \text{(a1.eq6)}$$

Where $k_{shf}$ is the thermal conductivity of the shaft, $D_{shf}$is the shaft diameter, $L_b$ is the bearing thickness and $L_{bs}$ is the length between the center of the bearing and the rotor mean.

The stator teeth thermal resistance is derived the same way as the resistance in the magnets, having the radius, the thermal conductivity and coverage of the teeth.

$$R_{stator,teeth} = \frac{\ln\left(\frac{r_{ms}}{r_{is}}\right)}{2\pi K_{iro} L_s \rho} \qquad \text{(a1.eq7)}$$

Where $r_{is}$ is the inner stator radius, $r_{ms}$ is the inner stator yoke radius, $k_{iro}$the stator thermal conductivity and $\rho$ the coverage in percent of teeth compared to the stator surface. Additional thermal resistance originates from conduction of the stator yoke and the conduction between windings and stator seen in equation 11 and 22.

$$R_{stator,yoke} = \frac{\ln\left(\frac{r_{os}}{r_{ms}}\right)}{2\pi K_{iro} L_s} \qquad \text{(a1.eq8)}$$

$r_{os}$ is the outer stator yoke radius

$$R_{winding,stator} = \frac{S_{slot} - S_{cu}}{l_s K_{cu,ir} A_{slot}} \qquad \text{(a1.eq9)}$$

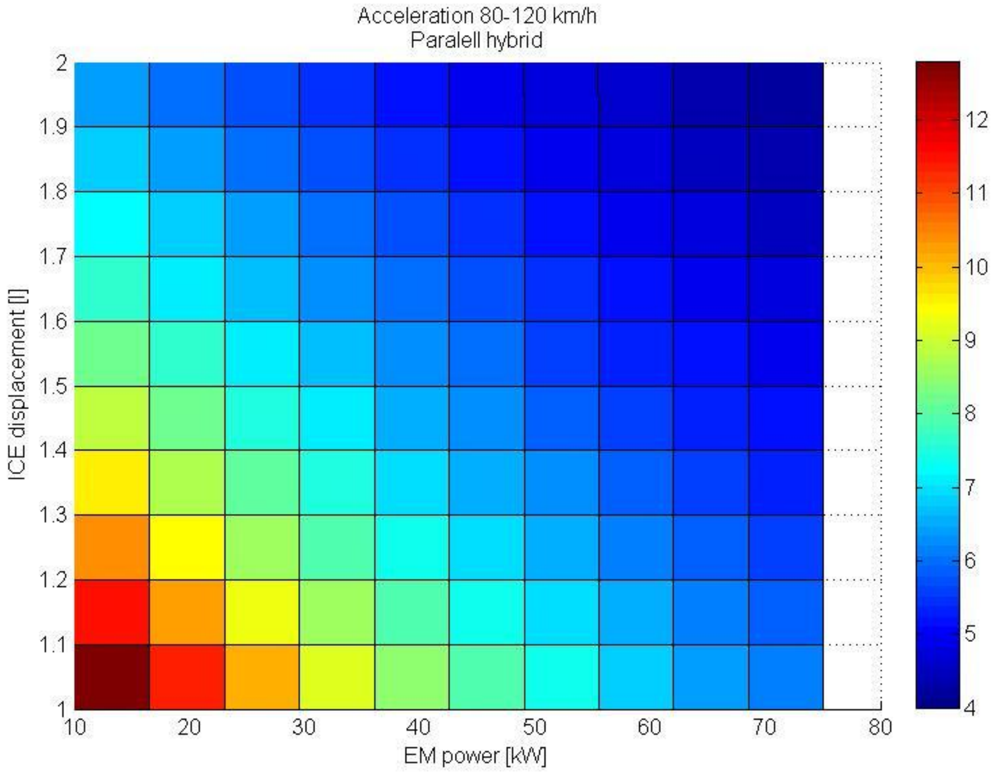
Where $S_{slot}$ is the stator slot surface, $S_{cu}$ the section of copper in the stator slot, $l_s$ is the slot perimeter, $k_{cu,ir}$ is the conductivity coefficient of air along with insulting material in the stator slot and $A_{slot}$ is the interior slot surface.

To get the temperature increase the thermal equivalent to Ohms law is used:

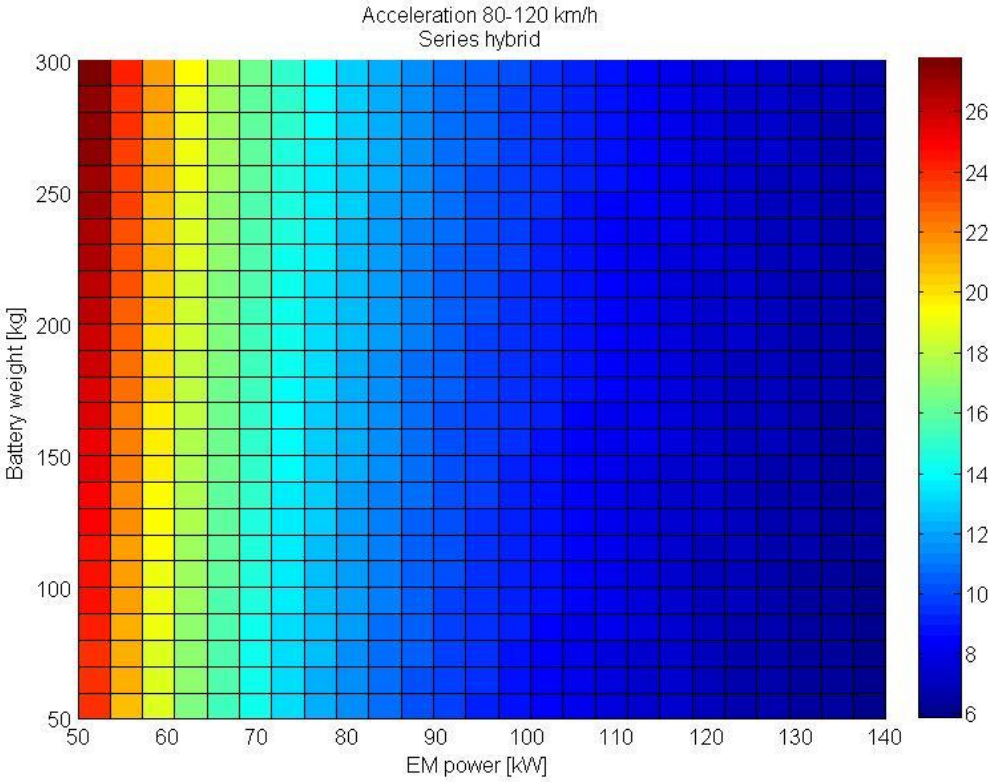
$$\Delta T = R_{th} P_{th} \qquad \text{(a1.eq10)}$$

Where $R_{th}$is the sum of all resistances mention above and $P_{th}$is the power loss in the machine that is the origin for the temperature increase.[19]

# 8.2 Acceleration 80-120km/h



A1 Figure 1 Parallel hybrid acceleration 80-120km/h



A1 Figure 2 Series hybrid acceleration 80-120km/h

## 8.3 L8 Tables

L8 tables from test setups.

**Parallel ISG L8**

| Variables in coded units | | | | | | | Response (fuel) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 4,5407 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 5,357 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 5,4311 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 5,8731 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 4,7002 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 5,5147 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 5,5151 |
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 5,9642 |
| 0,630475 | 0,667725 | -0,18493 | 0,123075 | 0,001325 | -0,03553 | 0,002225 | |

**Parallel ISG acceleration L8**

| Variables in coded units | | | | | | | Response (time) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 13,7 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 7,5 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 7,5 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 5,7 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 14,45 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 7,9 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 7,85 |
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 6 |
| -4,1 | -4,125 | 2,275 | 0,45 | -0,1 | -0,125 | 0,075 | |

**Series sustain L8**

| Variables in coded units | | | | | | | Response (fuel) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 7,3123 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 8,109 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 7,2508 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 7,9893 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 8,3293 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 9,1141 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 7,6651 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 8,2688 |
| 0,730925 | -0,42268 | -0,05982 | 0,678975 | -0,03667 | -0,33208 | -0,03072 | |

**Series depletion L8**

| Variables in coded units | | | | | | | Response (fuel) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 5,8086 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 6,0054 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 6,4213 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 6,5051 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 6,4541 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 6,6531 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 6,6974 |
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 6,7837 |
| 0,141475 | 0,371575 | -0,05642 | 0,461975 | 0,001175 | -0,18463 | 7,5E-05 | |

**Series ACC L8**

| Variables in coded units | | | | | | | Response (time) |
|---|---|---|---|---|---|---|---|
| A | B | AB | C | AC | BC | ABC | y |
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 21,45 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 22,25 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 7 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 7,25 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 24,05 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 24,85 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 7,75 |
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 7,95 |
| 0,5125 | -15,6625 | -0,2875 | 1,6625 | -0,0125 | -0,9375 | -0,0125 | |

**Parallel ERAD L8**

| A | B | AB | C | AC | BC | ABC | Response (fuel) y |
|---|---|---|---|---|---|---|---|
| -1 | -1 | +1 | -1 | +1 | +1 | -1 | 6,5311 |
| +1 | -1 | -1 | -1 | -1 | +1 | +1 | 7,4978 |
| -1 | +1 | -1 | -1 | +1 | -1 | +1 | 7,7719 |
| +1 | +1 | +1 | -1 | -1 | -1 | -1 | 7,7324 |
| -1 | -1 | +1 | +1 | -1 | -1 | +1 | 6,644 |
| +1 | -1 | -1 | +1 | +1 | -1 | -1 | 7,6352 |
| -1 | +1 | -1 | +1 | -1 | +1 | -1 | 7,8276 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| +1 | +1 | +1 | +1 | +1 | +1 | +1 | 7,8583 |
| 0,487275 | 0,72053 | -0,49168 | 0,107975 | 0,023675 | -0,01717 | 0,011425 | |