Abstract

This master thesis has been done in cooperation with General Motors and covers the design process of constructing a cost efficient hybrid car. The test car for the assignment is an Opel Astra.

Simulations models in Simulink have been constructed to evaluate the different hybrid solutions for the Opel Astra. The simulation models supplied performance measurements as well as fuel consumption for the different hybrid solutions.

To give an overall look at the cars performance; acceleration times, top speed and the distance the car can drive with only electric power has been recorded.

Because the task was to construct a cost efficient hybrid, economics has played a crucial part when choosing the final solution. The solution that gave the best performance was often the one with the most expensive components which lead to large investment costs. A compromise between economics and performance lead to the final solution of how to hybridize the Opel Astra.

Sammanfattning

Detta examensarbete har gjorts i samarbete med General Motors och behandlar hur en kostnadseffektiv hybridbil skall konstrueras. Bilen som har stått som modell för utvecklingsarbetet är en Opel Astra.

För att kunna utvärdera de olika hybridlösningarna och dess komponenter har simuleringsmodeller, konstruerade i Simulink, använts. Genom att använda dessa modeller kunde bilens prestanda, bränsleförbrukning och färdsträcka med endast eldrift bestämmas.

Eftersom uppgiften var att skapa en kostandseffektiv hybridbil så har ekonomiska faktorer spelat en stor roll i utvecklingsarbetet. Den lösning som t.ex. gav bäst prestanda medförde oftast höga investeringskostnader. En kompromiss mellan prestanda, bränsleförbrukning och ekonomiska faktorer fällde avgörandet till den slutgiltiga hybridlösningen.

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Industrial Electrical Engineering and Automation

Cost Efficient Hybrid Car

-SAAB Automobile

Fredrik Boberg

Axel Gustafson

Dept. of Industrial Electrical Engineering and Automation

Lund University

Contact information

Fredrik Boberg
Master of Science in electrical engineering, LTH Sweden

Trullsibrunnvägen 12D
23638 Höllviken

Phone: 070-6457377
e-mail: fredrik_b_82@yahoo.se

Axel Gustafson
Master of Science in electrical engineering, LTH Sweden

Magistratsvägen 57 D:21
22644 Lund

alt.

Hjorttorp Hedeberg
51197 Hajom

Phone: 073-3821676
e-mail: axel_g_24@yahoo.se

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1 Introduction

1.1 Background

The climate changes in the world today are noticeable for every person living on planet earth. Our way of life has to change in some way so that the climate changes don't get worse. If the use of fossil fuels would be lowered, the climate situation may be stabilized and hopefully get better. When fossil fuel is burned, greenhouse gases are produced and released in to the atmosphere and causes global warming. The transportation sector is responsible for 14% **[10]** of the total emissions of greenhouse gases. The car industry is trying to lower the dependence on fossil fuel by introducing so called hybrid cars. The most common type of hybrid car combines a regular combustion engine with an electric machine. This type of car has lower fuel consumption then a regular car and is therefore more environmentally friendly.

To make a difference to the climate situation the hybrid cars must be more common than they are today. If the range of hybrid cars availably to the customers would increase, more people would be able to find a model that they like. The price of the hybrid car is probably the most important factor if the amount of hybrid cars should increase. Hybrid cars today are relatively expensive and far from everyone can afford one. Cheap hybrid cars are therefore crucial to assure an environmentally friendly transportation fleet.

1.2 Objektive

Our objective is to choose a suitable hybrid solution and dimensioned the components in a cost efficient way for an Opel Astra. To do this, a simulation model of the Opel Astra has been constructed. Two cars with different degrees of hybridization shall be constructed, one with emission free drive and one without. **[5]**

1.3 Delimitations

In this master thesis paper emissions are not taken in to consideration. Fuel consumption is the only environmental parameter that is accounted for.

1.4 Opel Astras position

Opel Astra is considered to be a working class car or the household's second car. Generally Opel is not considered to be a status brand and the car is often bought for its functionality. To attract customers that also want performance Opel has launched a performance line called OPC; which includes larger engines and styling kits. With this new line, Opel is slowly trying to change there image so they can be considered as a sporty car.

The main markets for the Opel are Germany and Western Europe. **[5]**

1.5 Who is the costumer?

The Opel Astra customer is often a person or family with medium income that uses the car in city environments. The demand for innovation is very limited and therefore the price of the car should be as low as possible. Fuel economy is an important factor for the Opel Astra owner because of the increasing fuel costs. **[5]**

1.6 Demands on the Opel Astra Hybrid car

1.6.1 Cost

Because the Opel Astra is a relatively cheap car the costumers don't want to pay a lot of extra money for a hybrid version. If the costumer chooses to get the hybrid version, the extra money in initial cost should be covered by lower fuel consumption, and the benefits of not having to pay the environment taxes in the cities. **[5]**

1.6.2 Space

The space in the Opel Astra today is very limited in terms of adding new components for a hybrid solution. This limits which type of hybrid solution that is possible without rebuilding the car completely. The main components that consumes the most space is the electrical machine/machines and the battery. To be able to make room for the new components it might be necessary to sacrifice inner space. A part of the trunk area for example can house the batteries. When adding new components to the Opel Astras existing structure it's important that the deformations zones also stay intact. **[5]**

1.6.3 Weight

The increase in weight is direct proportional to the size of the battery and the electric machine/machines. Some components can be removed from the original structure depending which hybrid solution that is applied. All types of hybrid solutions increases the weight of the conventional Opel Astra. Low weight is very important because it affects the cars performance in terms of fuel consumption, acceleration times, speed and handling. **[5]**

1.6.4 Performance

The performance of the hybrid version must be as good as the normal car in terms of acceleration times, speed and handling. The fuel consumption of the hybrid car should off course be much lower than the normal car. Depending on what hybrid concept that is applied and how the components are dimensioned the performance of the car will vary. **[5]**

1.6.5 Reliability

The reliability of the hybrid Opel Astra should be as good as the normal petrol version. The new components need to have the right quality to meet this demand.

With the batteries available today they would probably not last the life time of the car, and would have to be changed one or two times during the cars lifespan. **[5]**

1.7 Existing drive lines

The hybridization of car can be done in many different ways but all the concepts share the major components. These components are the electric motor, the internal combustion engine and power electronics. Batteries or capacitors are also needed to complete the hybrid solution.

1.7.1 Hybridization levels

Depending on the installed electrical power, hybrid drives are broadly classified as micro hybrids (~ 1-9 kW), mild hybrids (10-39 kW) or full hybrids (~≤40 kW). The micro hybrid has the lowest power rating and can only operate at startup. This concept is the cheapest but doesn't give as low average fuel consumption as the mild hybrid and full hybrid. The mild hybrids have more electrical power and can support the combustion engine at low to medium speeds. This makes them a good compromise between micro and full hybrids. Full hybrids have the power to drive purely electric with the combustion engine turned off at low speeds. Pure electrical drive requires that the power rating of the electrical machine is high to achieve reasonable performance. The electrical machine can also work as support to the combustion engine during high speeds. Because the Full hybrid requires a larger electrical machine as well a larger batteries the price is much higher then the mild and micro hybrid. If there is no requirements for pure electrical driving mode the mild hybrid would be preferred because of its lower price. **[1], [2], [3]**

All three hybridizations levels can store braking energy; this principle is explained in chapter 2.2.2. The micro hybrids are only capable to convert a very small amount of the brake energy. The power rating of the electrical machine must at least be 10…15 kW to be able to convert a noticeable amount of brake energy. A further increase in power rating will only be useful during heavy deceleration which occurs relatively rarely.

The fuel consumption savings will vary depending on the hybridization level. Figure 1-1 shows how much different driving options can affect the consumption.

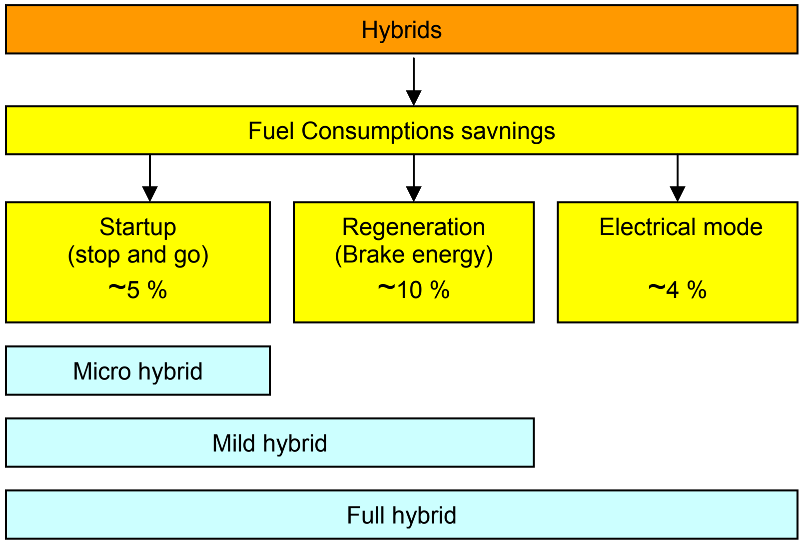

Figure 1-1 fuel consumptions savings

1.7.2 Hybridization solutions

The existing hybrid drivelines can be divided in to three different technical solutions. Parallel hybrid is the simplest of the three and is easier to apply to an existing car then the other solutions. The car can be driven forward by either the combustion engine or the electrical motor by it self, or both working together. The second of the three is the complex hybrid; it uses two electrical machines connected to a planetary gear. **[1]**

The third technical solution is very different from the other two, and it is always considered a "full" hybrid. A simple way to describe the technical solution is to say that it is an electrical car with a combustion engine. The combustion engines only purpose is to power a generator that gives the power needed to the electrical propulsion motor. This concept is very common in large applications like locomotives or boats

2 The Hybrid Car

2.1 The hybrid cars main components

The main components in a hybrid car are the combustion engine, the electric motor, some kind of energy storage and power electronics. These components are shared in the existing hybrid concept. **[2]**

2.1.1 Energy storage

The main function of the energy storage is to store and handle variations in the energy consumption. This variation can occur during heavy acceleration and deceleration when energy is either consumed or absorbed. When the car accelerates extra power is needed, this power is taken from some kind of energy storage. During breaking it's preferable to absorb the cars kinetic energy in contrast to transforming it to friction energy.

There are two major energy storages that are used today, batteries and super capacitors. The super capacitors are primarily used as power storage, which means that it gives a lot of power during a short time interval. This is especially good during heavy acceleration when extra power is needed. A battery deliver less peak power than the capacitors but will last much longer before recharging. **[2]**

2.1.2 Electric motors

Depending on hybrid concept the number of electric motors can vary between one to five motors. The motors should be design so that the maximum torque is high at low speeds; this is done to achieve good stating properties.

There are, in a simplifying description, two different kinds of electric motors, direct current machines and alternate current machines. The alternate current machines can be divided in to two types, asynchronous and synchronous. The asynchronous motor is based on induction. The synchronous motor is magnetized by letting current flow in the windings or by using permanent magnets. **[2]**

2.1.3 Power electronics

The power electronics are used to control the input power to the electrical machines and the batteries. The power rating of the electrical machine affects how the power electronics should be dimensioned. A large electrical machine needs plenty of power; this power has to be delivered by the power electronics. **[2]**

2.1.4 The internal combustion engine

The combustion engines that are used for hybrid cars are the same as in regular cars. When adding an electrical propulsion motor the power of the internal combustion engine can be lowered. The power loss of the combustion engine should be compensated by the electrical motor/motors power. **[2]**

2.2 Advantages of hybridization

2.2.1 Stop and go

Stop and Go means that the hybrid car has the possibility to shut of the petrol engine during standstill, for example when the car has stopped at a red light. This is especially useful when driving in the city where short stops occur frequently. During standstill the combustion engine has very low efficiency and it's therefore very beneficial to turn the combustion engine of. Turning of the combustion engine is unnoticeable for the driver and lowers the consumption significantly. **[2], [6]**

2.2.2 Regenerative breaking

In a conventional car the power flow between the car and the road is unidirectional; this means that engine produces power that's turned into a force. If this force is larger then the cars friction and wind resistance the car accelerates. The acceleration is accumulated into kinetic energy. When a regular car needs to decelerate it uses its friction brakes, and all the kinetic energy stored in the car is transformed into heat. This is a waste of energy.

The optimal would be to somehow absorb all the kinetic energy when the car decelerates. This would make the power flow between the car and the road bidirectional. In a hybrid car this is called regenerative braking, this means that the car uses its electric engine to brake the car during normal deceleration situations. The energy from the electrical machine is then stored in the battery to be used later for propulsion. During a panic braking situation where the electrical machine is unable to brake the car, the friction brakes are used. **[2]**

2.2.3 Purely electric drive

The best way to lower the fuel consumption is to use the combustion engine as little as possible. The optimum would be not to use the combustion engine at all if the battery is charged from the power outlet; this is possible by using purely electric drive. This means that the car uses only its electric engine to provide the drive torque needed to propel to car forward. This is especially useful in city driving where the top speed requirements are low, below 80 km/h. **[2]**

The emission guidelines in the future will probably favor no emission vehicles by reducing congestion taxes and lowering parking fees. The key to make purely electric drive a success is to increase the energy density of the batteries and make it possible to charge the battery directly from the electrical grid, a so called plug in hybrid.

2.2.4 Efficiency improvement to the ICE

To lower the fuel consumption the cars combustion engine needs to work as efficiently as possible. Because the hybrid cars control system chooses the gear in the gearbox the driver is no longer in control of the gear changes. This allows the gearbox to select the gear that gives the lowest fuel consumption. By shifting up to a higher gear the efficiency of the ICE in, Figure 2-1, is increased from 15% to 28%. **[7]**

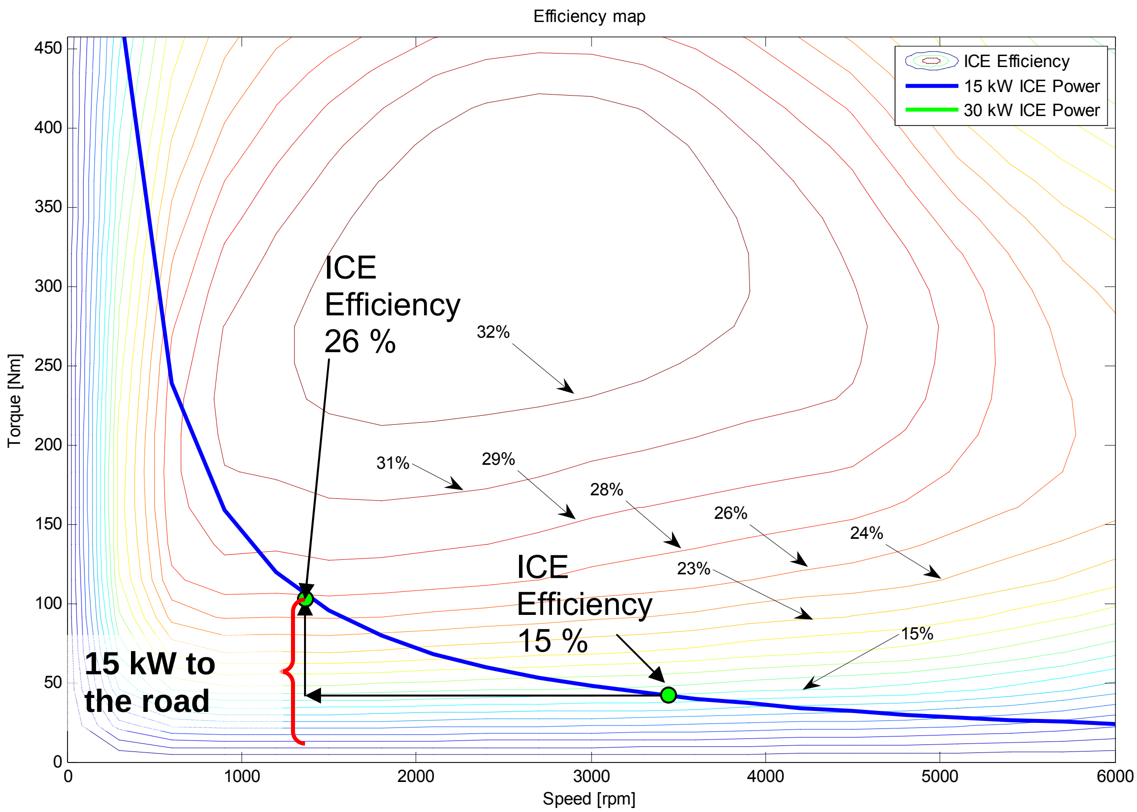

Figure 2-1 Efficiency map of a petrol engine

Because the car is a hybrid it is possible to increase the efficiency even further. This is done by letting the combustion engine work harder and thereby increasing the power output. This means that the combustion engine delivers more power then is need to maintain the cars speed. The excess power is used to charge the battery; this is illustrated in Figure 2-2.

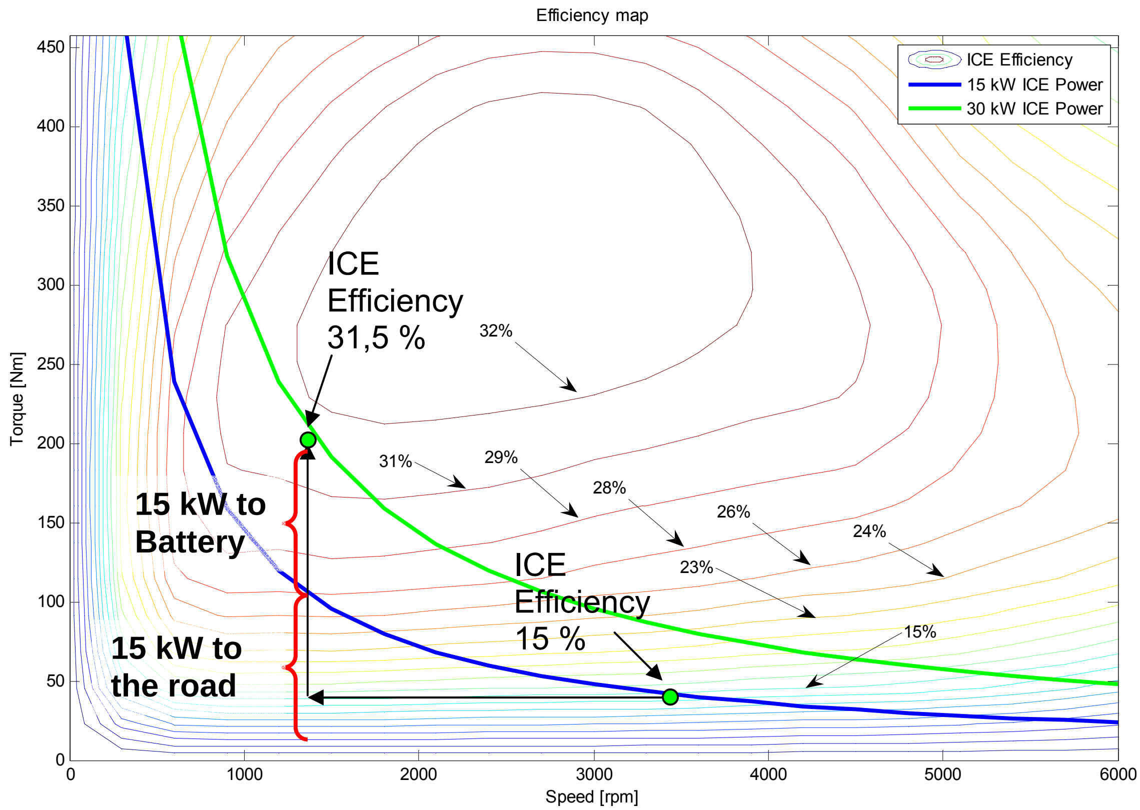

Figure 2-2 Efficiency map of the petrol engine in hybrid mode

2.3 *Technical specifications of the different hybrid solutions*

2.3.1 Parallel hybrid

The parallel hybrid is the simplest and probably the cheapest solution for a hybrid car. This solution to the hybridizing problem basically means that the generator and starter motor are replaced with a larger electric machine that can work in parallel with the combustion engine. This means that the combustion engine and electric motor work together to deliver the drive torque needed to propel the car forward.

In the parallel hybrid there are four different ways the power can flow in the driveline. During normal operation both the combustion engine and the electrical machine deliver drive torque to the wheels, see Figure 2-3. The ideal way to propel the car is to only use the electric machine; this eliminates all emissions from the car, see Figure 2-4. There is only two ways to charge the battery during a driving cycle, one is to use the electric machine to brake the combustion engine and the other is to use regenerative braking, see Figure 2-5 and Figure 2-6. **[2]**

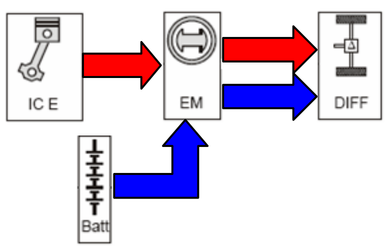

Figure 2-3 Both the ICE (Red) and EM (Blue) delivers drive torque

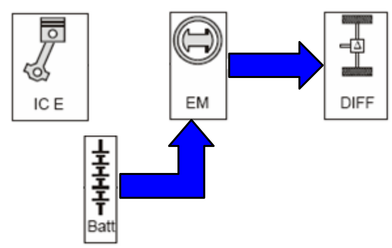

Figure 2-4 The car is in purely electric mode, only the EM (Blue) deliver drive torque

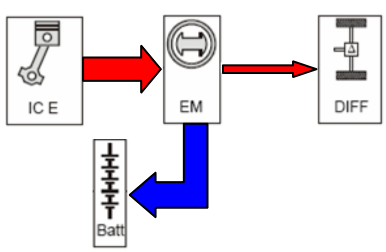

Figure 2-5 The ICE (Red) delivers drive torque and EM (Blue) is in generator mode

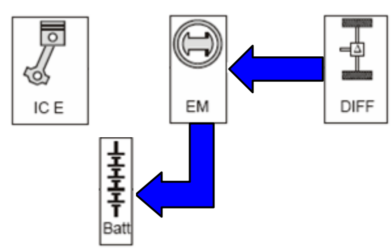

Figure 2-6 The EM (Blue) is braking the car, charging the battery, so called Regenerative braking

Principles of the different designs

Figure 2-7 show the basic setup of a FAS (**F**lywheel, **A**lternator and **S**tarter), the principle for a FAS is to replace the flywheel with a high inertia electrical machine. The reason for having a high inertia machine is to keep the function of the flywheel intact. The advantage of the FAS is the ability to drive in purely electric mode. The reason this is possible is the clutch between the electrical machine and the combustion engine. When driving purely electric the clutch is opened and the combustion engine is turned off.

Figure 2-8 show a version of a BAS (**B**elt driven, **A**lternator and **S**tarter), the principle for a BAS is to have an electrical machine outside of the gearbox connected via a belt or chain. In this setup purely electric drive is possible because the electrical machine is connected to the right side of the clutch.

Figure 2-9 show how the basic FAS and BAS concept can be merged together by adding a low inertia electrical machine to the FAS concept. The reason for adding a low inertia machine is its ability to electrically synchronize the transmission. Having low inertia makes the synchronization faster and thereby smoother gear changes are possible. Without mechanical synchronization it's possible to add more gears to the transmission without increasing it´s dimensions and thereby increase comfort. **[2]**, **[9]**

Figure 2-10 show the classic BAS concept used by most micro hybrid solutions. In this concept an electrical machine is connected to the crankshaft via a belt or chain. The connection is on the left side of the clutch and therefore purely electric drive is non possible. **[6]**

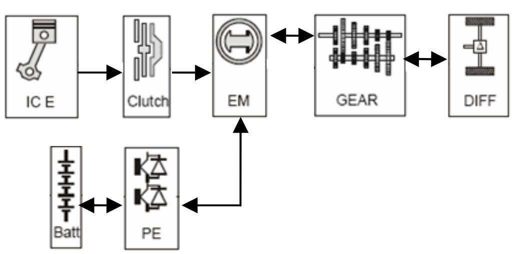

Figure 2-7 an FAS, "Flywheel alternator and starter" setup in a parallel Hybrid.

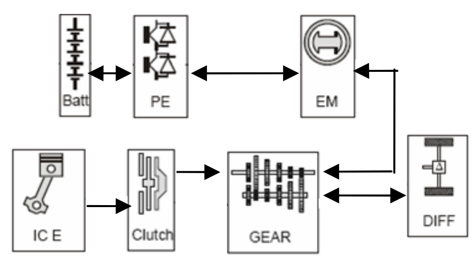

Figure 2-8 an BAS, "belt driven alternator and starter" with EM on input shaft of the transmission

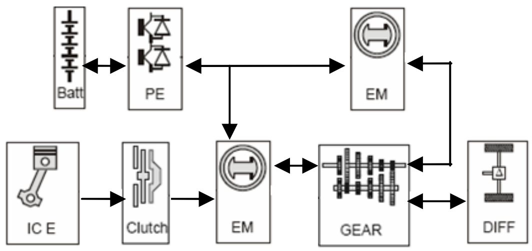

Figure 2-9 an FAS and BAS concept, with EM on both sides of input shaft of the transmission in a parallel Hybrid.

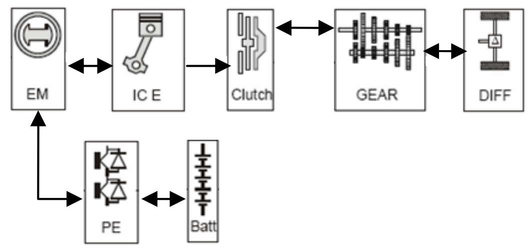

Figure 2-10 an BAS, "Belt alternator and starter" EM connected via belt to the Combustion engine

Space requirements/flexibility

Because the parallel hybrid is a very simple solution to the hybridization problem it's fairly easy to adapt it to an existing car. The starter motor and generator is removed while the regular driveline is kept intact, an electrical machine is then connected using a belt, chain or gears. The electrical machine is placed beside the transmission, where the generator used to be. It is also possible to replace the flywheel with a high inertia electrical machine. All these setups cause minimum changes to the existing driveline. This makes the Parallel hybrid a very flexible and space efficient solution to the hybridization problem. **[5]**

2.3.2 Series Hybrid

This concept is very different from a regular car that uses the combustion engine for its propulsion. A series hybrid uses its regular petrol or diesel engine to power a generator that generates electrical power. The generated power can be temporarily stored in either a battery or super capacitors.

The propulsion is taken care of by one or several electrical motors that takes power from the battery/super capacitors or directly from the generator. To control the electric machine/machines power electronics are used.

When designing this hybrid concept all the components have to be matched to each other. For example the ICE has to be able to drive the generator efficiently and the generator by it self has to deliver enough power to sustain battery state of charge limits. The electric traction motor has to be designed for peak power because of heavy accelerations. **[2]**

The power flow in the hybrid system varies depending on the situation; see Figure 2-11, Figure 2-12 and Figure 2-13

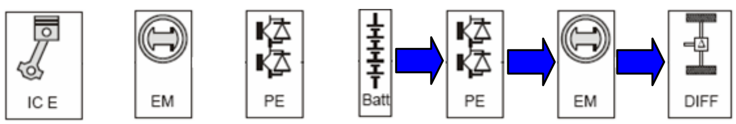

Figure 2-11 (Purely electric drive)
The battery delivers the power by the power electronics to EM

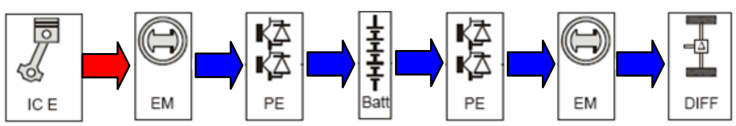

Figure 2-12 (Regular drive)
The ICE drives the generator that gives power to battery and the EM

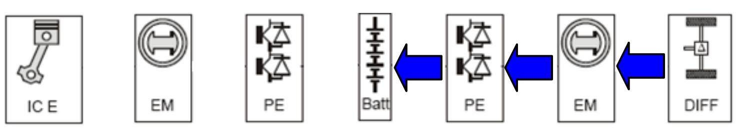

Figure 2-13 (Breaking)
The EM used for propulsion now works as a generator absorbing the moving energy, and charges the batteries.

Principles of the different designs

There are two main principles when designing a series hybrid, with our without batteries/(super capacitors). The solution without batteries needs to have the ICE constantly running to provide the power needed to drive the car forward. The main advantages with batteries are that pure electric drive and regenerative breaking are possible. See Figure 2-14 and Figure 2-15.

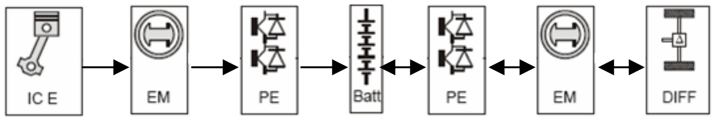

Figure 2-14 this layout includes batteries/super capacitors.

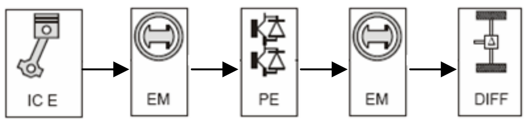

Figure 2-15 without batteries/super capacitors.

Space requirements/flexibility

If this hybrid concept is applied to an Opel Astra with the existing combustion engine the modifications has to be extensive. The standard gearbox, the generator and starter motor can be removed from the car and be replaced by a minimum of two electrical motors and power electronics. The electrical propulsion motor need to have a large amount of power because of the performance requirements. A motor with this amount of power will consume a lot of space in the car.

The electrical propulsion motor needs to be placed in the engine compartment if the Opel Astra should sustain its front wheel drive. To place the electrical motor here will lead to extensive reorganization to the existing configuration. Another solution is to make the car rear wheal drive and placed the electrical propulsion motor near the rear axel. The best solution in terms of space savings would be to integrate electrical propulsion motors in to the cars wheels. This solution requires minimum two motors, one in each wheel, and two setups of power electronics.

The generator needs to be mechanical connected to the outgoing shaft of the combustion engine, and therefore needs to be placed nearby. A possible solution is to place it were the old gearbox was mounted.

If the solution with batteries is preferred the amount of batteries depends on how long the car should be able to drive purely electric. The trunk or maybe under the backseat can house the batteries depending on size.

Any solution previously menaced would lead to extensive modifications of the existing structure.

2.3.3 Complex hybrid

The complex hybrid is a combination of a parallel and series hybrid, this hybrid concept is also called a parallel/series hybrid. This solution is implemented by Toyota in all there hybrid cars. It was designed to merge the advantages of both a parallel hybrid and a series hybrid. The complex hybrid uses one generator and one electrical propulsion motor like in the series hybrid. The different is that it can also use the combustion engine for direct propulsion like in the parallel hybrid. Two sets of power electronics is also used to get the right power needed and a battery.

The hart of the Complex hybrid is the planetary gear. The combustion engine and the electric motors is attached to the planetary gear, see Figure 2-16

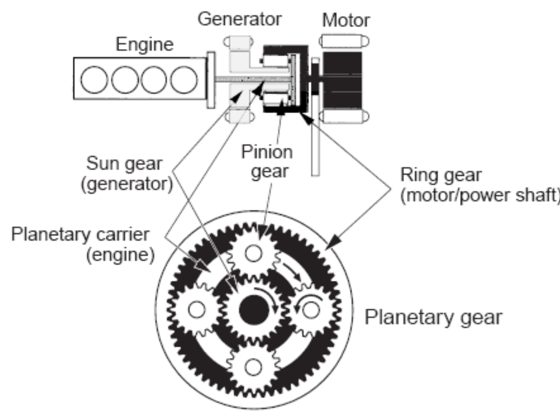

Figure 2-16 (Planetary gear)

The electrical propulsion motor is attached to the ring wheel, and the generator is connected to the solar wheel. The internal combustion engines outgoing shaft is also connected to the planetary gear by the planetary carrier. Because the planetary carrier is in direct connection with the solar wheel it is possible to have the internal combustion engine turned off while the car is still moving. This is accomplished by letting the ring wheel rotate in the opposite direction. The propulsion is therefore taken care of by the electrical motor, and the car will drive in purely electric mode. The planetary gearbox does not need a clutch to achieve this type off control that otherwise would have been necessary. **[6], [7]**

A complex hybrid doesn’t need a gearbox with fixed gear ratios like a regular car. The planetary gear works as the cars gearbox, and its behavior is similar to to a CVT, (**C**ontinues **V**ariable **T**ransmission). A CVT is a type of transmission with no fixed gear ratios. The gearbox can change speed while continuously varying the rpm of the combustion engine, the generator and the electric motor in relation to vehicle speed. **[3]**

Depending on the situation the complex hybrid can work as pure parallel or series hybrid. The main factor that determines this is speed. At low speeds for example the car can work as a series hybrid or purely electric. At higher speeds the car also need help from the combustion engine for the propulsion and it becomes a parallel hybrid. A combination of these two principles is also possible. The combustion engine will therefore drive the generator and deliver power to the wheels at the same time. The power from the generator can then be distributed to the electrical propulsion motor or to the battery. When the generator takes power from the internal combustion engine it can affect the engines working point. A better chosen working point increases the efficiency of the combustion engine.

There are many different combinations depending on the situation how the power flows in the system. Some examples of different power flows can be seen in Figure 2-17, Figure 2-18, Figure 2-19, Figure 2-20 and Figure 2-21.

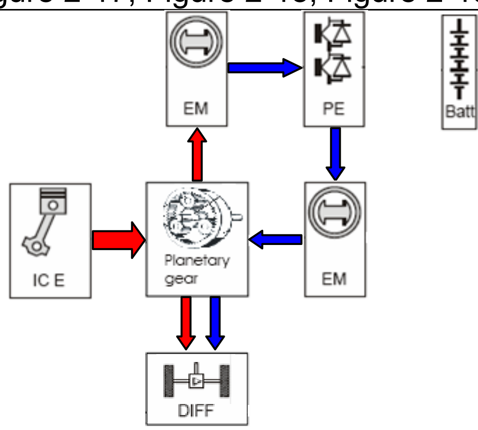

Figure 2-17 (Normal driving) The ICE gives power to the generator and the diff. The power from the generator feed the EM that gives power to the diff.

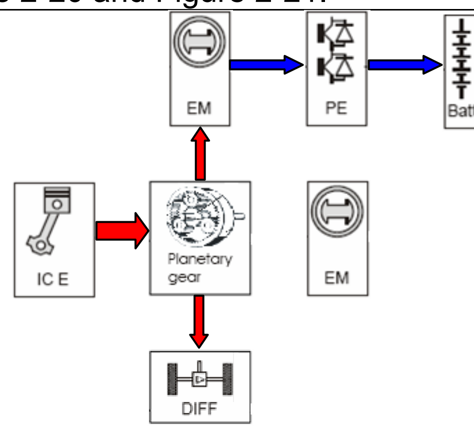

Figure 2-18 (Battery recharge) The ICE gives power to the generator and the diff. The generator charges the battery.

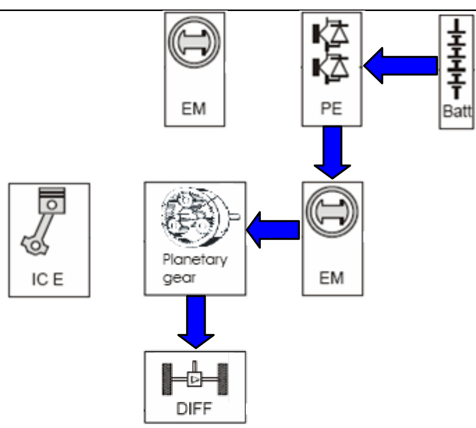

Figure 2-19 (Pure electric drive) The battery gives power to the EM that is connected to diff

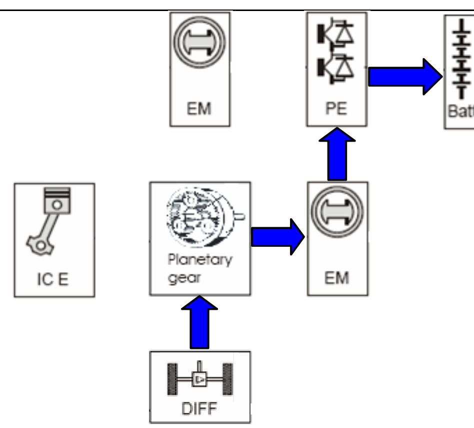

Figure 2-20 (Regenerative braking) The wheels are connected to the EM that transforms the cars kinetic energy to electrical power. This power is used to charge the battery.

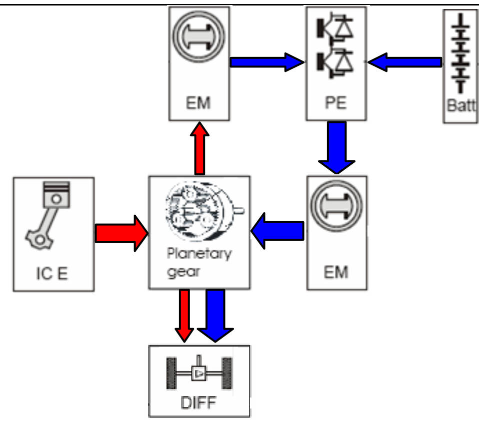

Figure 2-21 (Heavy acceleration) The power flow is exactly the same as in Figure 2-17 (Normal driving) except that the battery supply the extra power needed.

Principles of the different designs

There is basically only one way to construct a complex hybrid today. The main problem to solve in this type of hybrid is how to split and distribute the power from the internal combustion engine, the electrical propulsion motor and the generator. To solve this problem a planetary gear is used like menaced before. See Figure 2-22

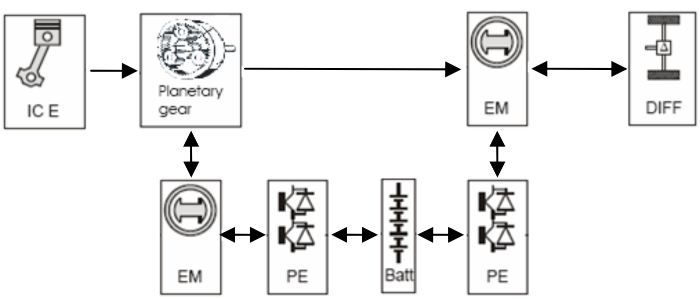

Figure 2-22 Complex hybrid

Space requirements/flexibility

When Toyota decided to produce their complex hybrid car the “Prius” they designed the car from scratch so that all components should fit perfectly. The Opel Astra is a car that already is constructed with no consideration to future hybridization. This makes it very difficult to add new components to the existing platform.

To implement the complex hybrid solution to the existing Astra would lead to extensive modifications. The regular gearbox, the clutch, the starter motor and the generator would be removed from the existing platform. The main components that have to be added are two electrical motors, two sets of power electronics and a planetary gearbox. The new components except the battery have to fit with in the engine compartment.

The amount of batteries is depending on how long the car should be able to drive purely electric. The batteries can be housed in the trunk or under the backseat depending on its size.

This complex solution is probably not possible if the existing platform is not allowed to be altered in any way. If some changes to the platform are possible the complex hybrid would be a viable solution

3 Simulations

In car industry today computer simulations are frequently used to predict and optimize the cars performance. A god simulation model is constructed to be as close to reality as possible. This type of computer models saves a lot of money for the industry because their ability to predict the cars behavior before physically building it.

In our case simulations are critical to be able to choose a suitable hybrid solution for the Opel Astra. The hybrid types we have decided to simulate are the parallel hybrid, the series hybrid and the complex hybrid. The simulation models for these hybrid solutions are constructed in Simulink. The original Simulink programs were made by professor Mats Alakϋla LTH, but they have been modified to fit our needs.

The simulation programs main goal is to test different sizes of electrical motors and batteries, and see how they affect the cars fuel consumption and performance.

3.1 Physical data and limitations

Dispute the different hybrid solutions and their simulation models there are some physical facts and limitations that is applied to all of them.

Bellow there are a list of the physical facts and the limitation that has been taken in consideration in the computer simulations.

Weight of the car

The original car with the 100 kW petrol engine weighs 1300kg (curb weight). In the simulations models the weight increases if new components are added and decreases if something is taken away from the original car. When an electric motor is added the increase in weight is 1kg/kW. Batteries also affect the weight of the car by 1kg/100Wh.

Air and rolling resistance

The breaking force acting on the car is the sum of an air resistance and a rolling resistance. Equation 3-1 shows how the breaking force is calculated in the simulations models. Table 3-1 specifies what the different terms mean.

$$F_f = \left(C_r M_v g + 0.5 \rho_a C_d A_v v^2\right)$$

Equation 3-1

Wheel radius	Air resistance	Roll resistance	Front area
R = 0.30 m	C_d = 0.26	C_r = 0.008	A_v = 2.55
Air density	**Vehicle speed**	**Gravitation**	**Vehicle mass**
ρ_a = 1.2	v	g = 9,81 m/s^2	M_v

Table 3-1 show the different terms that acts as the cars breaking force

The combustion engine
The parallel hybrid and the complex hybrid have a 66kW petrol engine in their simulation models. This motor is the smallest available to the Opel Astra today and will be complemented by an electrical motor. The series hybrid model uses a range of petrol engines from 10 kW to 70 kW. The reason for testing different sizes of the combustion engine in this simulation model is because the power needed is limited by the generator it self. The generator only needs a certain amount of power to deliver the power needed to the electrical traction motor, it's therefore desirable to find a combustion engine that meets this demand and have the lowest fuel consumption.

The battery
The battery used in the simulations models are based on litium-jon technology and can store 0.1 kWh/kg. The SOC, (**S**tate **O**f **C**harge) is limited to a minimum discharge level of 55 %, this is done to assure a long lifetime of the battery. The default SOC level is set to 85 % to assure that some brake energy can be stored.

3.2 Batch file

The Batch file is designed to be a test case for the simulations models. The file scenes different sizes of electrical motors and batteries to find the optimal combination that meets the demands. The performance of a combination can be measured in fuel consumption during any given driving cycle.

The table below lists the parameters that the batch file sweeps depending on hybrid concept.

		Parallel Hybrid	Series Hybrid	Complex Hybrid
EM 1 Generator	Max continues power (W)	-	Auto set V	Auto set III
	Max torque (Nm)	-	Auto set I	Auto set II
EM 2 Traction	Max continues power (W)	Yes	Yes	Yes
	Max torque (Nm)	Yes	Yes	Yes
ICE	Max continues power (W)	No	Yes	No
	Max torque (Nm)	Auto set IV	Auto set IV	Auto set IV
Batteries	Max capacity (Wh)	Yes	Yes	Yes

Table 3-2 the different components swept by the batch file

The equations below show how the different auto set functions are calculated in the simulation model.

I The maximum torque of the EM 1 that acts as a generator in the series hybrid is calculated from the maximum torque of the ICE, see Equation 3-2.

$$TEM1\_\max = 1{,}2 \times TICE\_\max$$

Equation 3-2

II The maximum torque of the EM1 (The Generator) is calculated from ICE maximum torque and the planet gears gear ratio between the ICE and generator; Equation 3-3.

$$TEM1\_\max = \left(\frac{1{,}2 \times TICE\_\max}{1 + ratio} \right)$$

Equation 3-3

III The maximum power of the EM1 (The Generator) is calculated from the maximum speed and the torque of EM1. The maximum speed of the EM1 is calculated from ICE maximum torque and the planet gears gear ratio between the ICE and generator; Equation 3-4.

$$WEM1\_\max = (WICE\_\max) \times (1 + ratio)$$
$$PEM1\_\max = (TEM1\_\max) \times \left(\frac{WEM1\_\max}{1{,}1} \right)$$

Equation 3-4

IV The maximum torque of the combustion engine is calculated from the engines maximum power divide by the speed of the engine at the maximum efficiency. The combustion engines efficiency related to the engines speed and torque are based on data from a Toyota Prius engine.

$$Tice\_\max = \frac{Pice\_\max}{Wice\_optimal}$$

Equation 3-5

[V] The maximum Power of the EM 1 that acts as a generator in the series hybrid is calculated from the maximum Power of the ICE, see

$$PEM1\_\max = 1{,}1 \times PICE\_\max$$

Equation 3-6

3.2.1 Driving cycles

To evaluate the performance of the different combinations listed in Table 3-2 special test cases are used. There are five different driving cycles that each combination is tested on. The cycle contains a speed reference over time that the car has to follow. When using this cycles the cars performance in different areas are registered for later evaluation. The driving cycle's layout and function are explained below; see Figure 3-1 to Figure 3-5. **[2]**

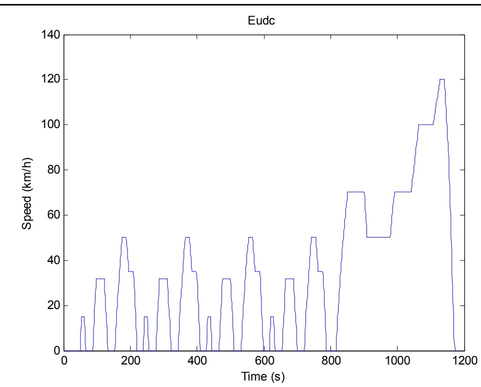

Figure 3-1 Eudc; This driving cycle combines city and freeway driving.

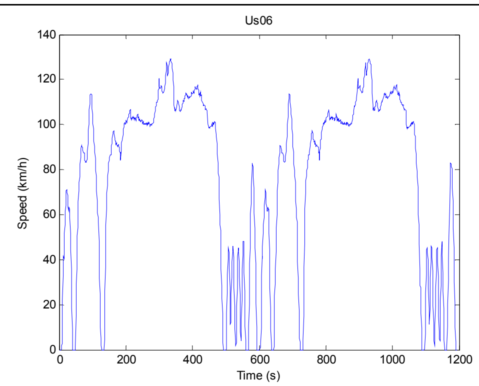

Figure 3-2 Us06; This driving cycle simulates freeway driving.

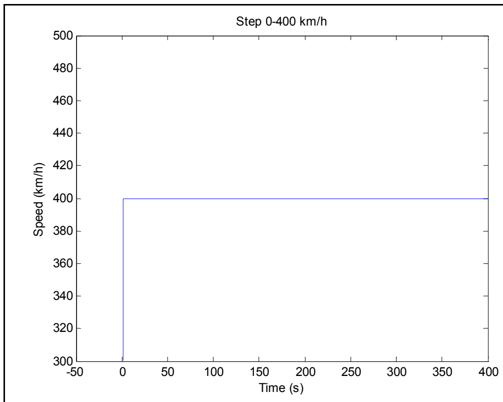

Figure 3-3 Step 0-400 km/h; This cycles function is to test the cars top speed and 0-100 km/h time

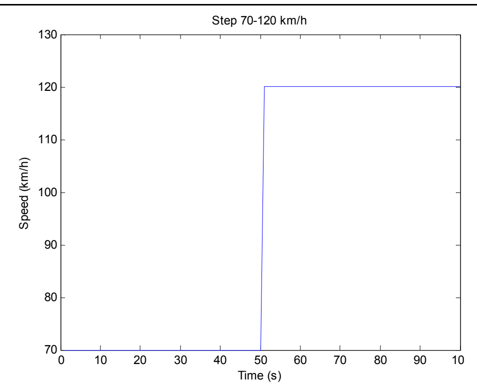

Figure 3-4 Step 70-120 km/h; This cycles function is to test the cars acceleration time between 70-120 km/h

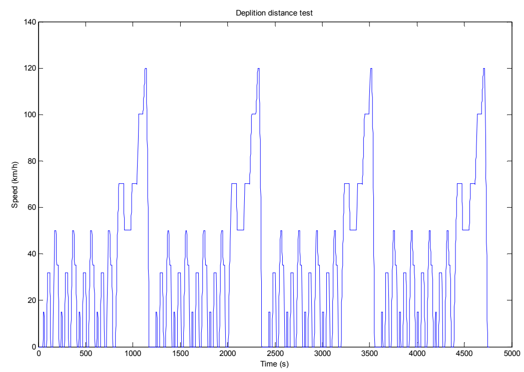

Figure 3-5 This driving cycle are used to see how long a car can drive in pure electric (Depletion mode). Four eudc cycles are used, total distance 45km

3.3 Reference vehicle

The reference vehicle is a regular Opel Astra (100kW petrol engine) with no hybrid components installed. This car has also been simulated in Simulink and the technical result can be observed in Table 3-3. The hybrid cars performance, fuel consumption and economics are all compared with the reference vehicle. Our goal is that the final hybrid car that is chosen should be better in all this areas.

Fuel consumption eudc	Fuel consumption us06	Performance 0-100 km/h
0,65 l/10km	0,83 l/10km	8,5 s

Table 3-3 Simulation results for the regular Opel Astra

3.4 Parallel Hybrid

The functionality of the parallel hybrid has been discussed earlier; this chapter will cover the transition from principle design to Simulink model.

3.4.1 How the Simulink model works

The model is designed using different sub blocks to simulate the different physical components found in a Parallel Hybrid. The most important blocks are the Driver model (gray), the Controller model (green), the ICE-model (yellow), the electrical machine model (blue), the battery (red), Brake controller (magenta), transmission model (turquoise) and the road model (orange). **[2]**

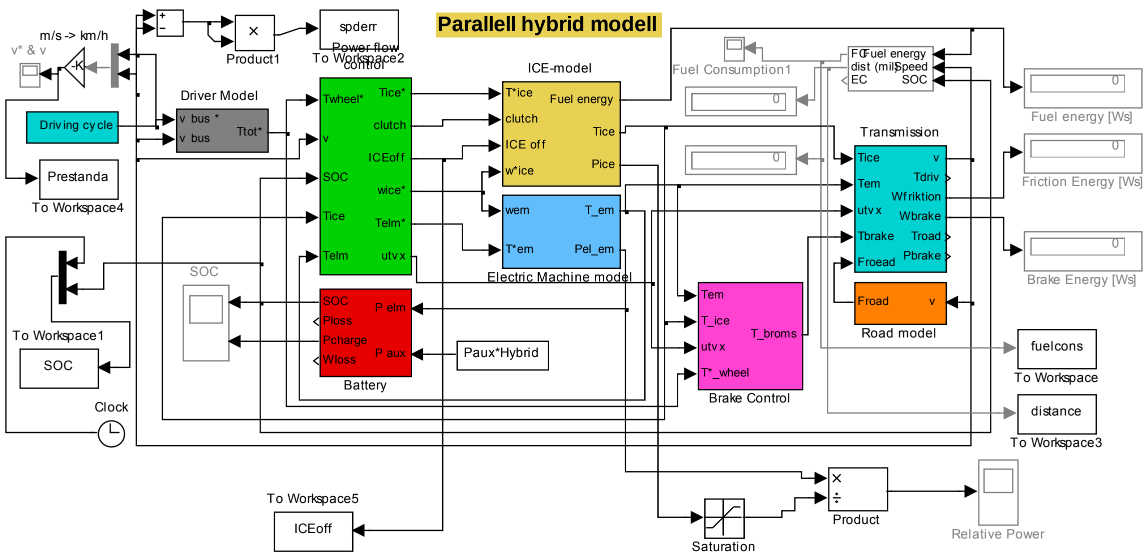

Figure 3-6 the Simulink model of the parallel hybrid solution

Driver model

In the driver model the difference between the speed reference and the actual speed of the vehicle is transformed into a torque reference. The speed reference is taken from a specific drive cycle, for example the eudc drive cycle. The torque reference is calculated by a PID regulator, see Figure 3-7. The torque reference corresponds to the amount of torque that needs to be applied to the wheels in order for the vehicle to match the speed reference.

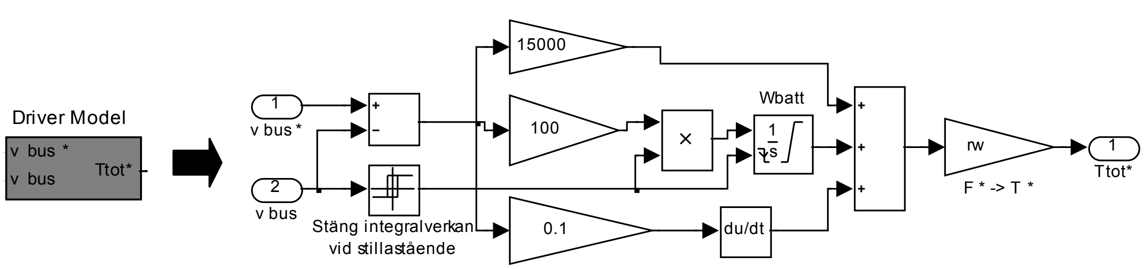

Figure 3-7 the Driver Model used in the parallel hybrid model

The Controller

The controller has two main tasks; the first is to select the gear that makes the combustion engine work as efficiently as possible, this is done in the red and the turquoise blocks. The red block calculates the optimal operating point and then the optimal gear is selected in the “växelval ny” block (turquoise). The second task is to transform the wheel speed -and wheel torque reference into separate references to the ICE model and the electrical machine model.

To calculate the reference torque to the electrical machine the actual wheel torque is transformed to the relative wheel torque at the electrical machine, this is done by dividing the wheel torque reference with the gear ratio. The ICE torque is then subtracted from the relative wheel torque to give the reference torque to the electrical machine.

To calculate the reference torque to the combustion engine the difference between the electrical machine torque reference and the actual torque produced by the electrical machine, is added to the ICE torque reference given by the optimum operating point block.

The controller also controls the state of charge of the battery, making sure it’s kept with in limitations. See Figure 3-8.

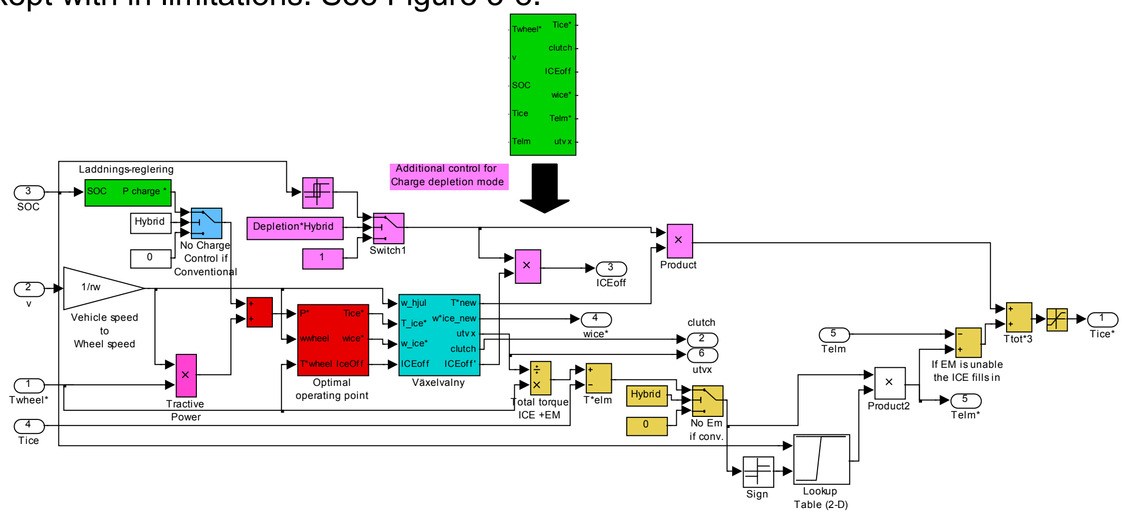

Figure 3-8 Simulink model of the parallel hybrid

The ICE-model

The ICE model is a simulation of the combustion engine. Inputs to this block are speed and torque reference, these parameters are then limited due to physical limitations of the combustion engine. Then fuel power or ICE efficiency is calculated and converted to fuel energy. This fuel energy is the total fuel energy used so far in the drive cycle.

The ICE off and clutch input are only used to control the combustion engine, for example the combustion engine is turned off during standstill when stop and go is activated or when the car is in depletion mode. See Figure 3-9.

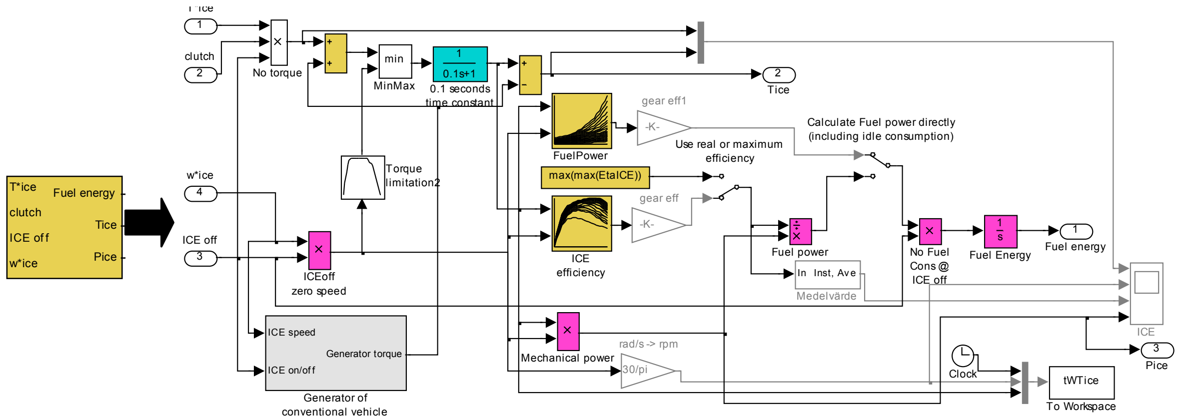

Figure 3-9 The ICE model in the parallel hybrid

The Electrical machine model

In the electrical machine model the torque reference is limited by the electrical machines physical and electrical limitations, this limited torque is the actual torque that the machine delivers at this moment. Then the efficiency of the machine, at the given torque and speed, is calculated in a Look-Up table. The torque, speed and efficiency are then used to calculate the electrical power of the machine. See Figure 3-10.

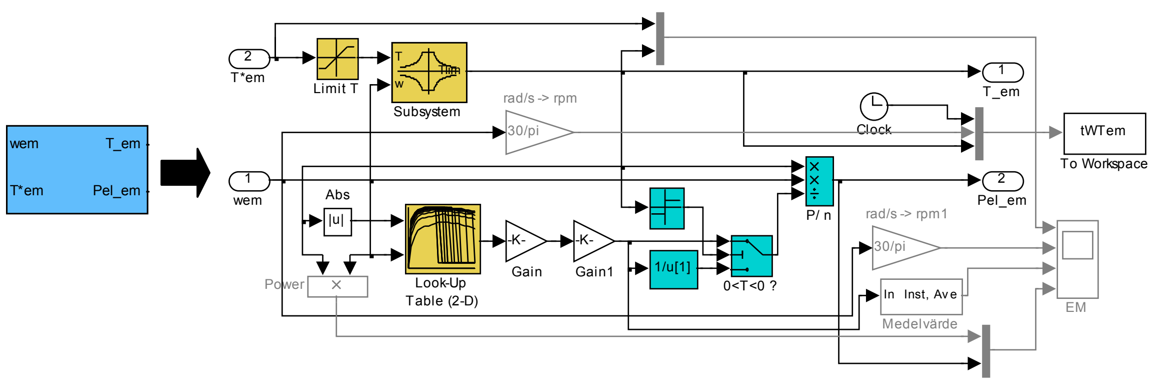

Figure 3-10 the Electrical Machine Model in the Parallel hybrid solution

The battery

In the battery model the power taken or given by the electrical machine and the power needed to operate the electrical equipment in the car is added together. This combined power is then multiplied with the efficiency of the battery at the given charge condition. This charge power is then integrated to energy; this energy is the energy that's left in the battery. State of charge is then calculated by dividing the energy that is left in the battery with the maximum energy that the battery can store. See Figure 3-11.

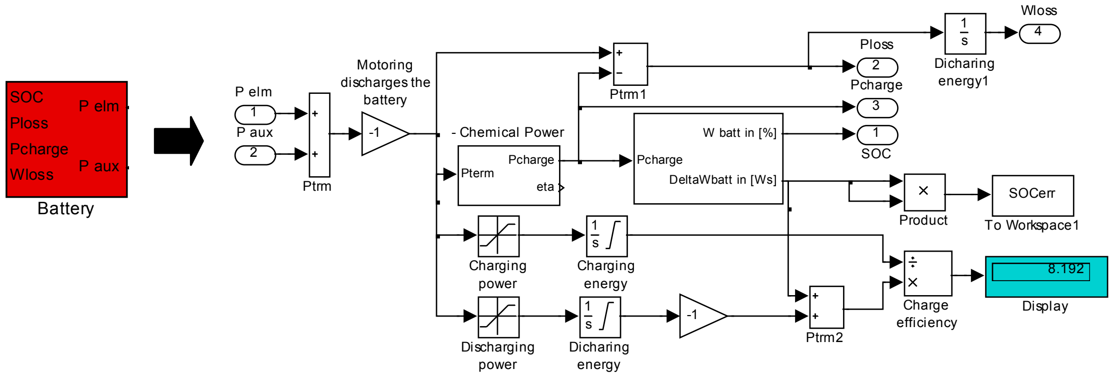

Figure 3-11 the battery model used in the parallel hybrid solution

The Brake controller

The brake models only task is to compare what torque needs to be applied to the wheels in order to brake the car according to the drive cycle. If the braking torque from the electrical machine is inadequate, the friction brakes of the car need to be used. See Figure 3-12.

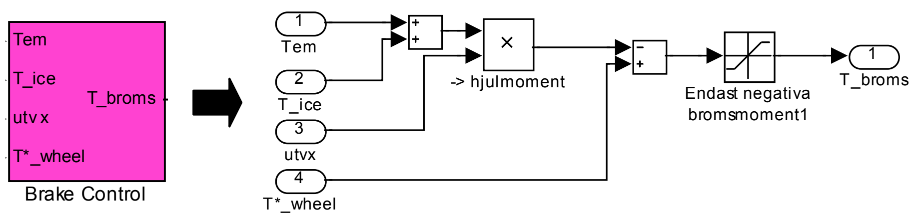

Figure 3-12 the brake controller used in the parallel hybrid solution

The Road model

In the road model the force that acts against the car is calculated, this force is a combination of friction and air resistance. See Figure 3-13.

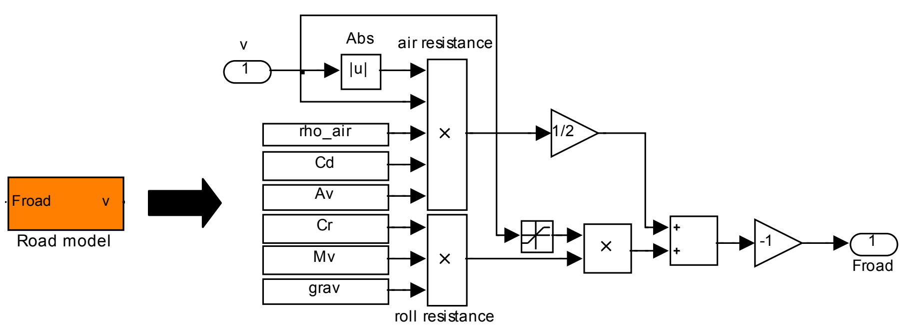

Figure 3-13 the road model used in the parallel hybrid solution

The Transmission model

In this model the torque from the electrical machine and the combustion engine are combined with the torque from the friction brakes and then transformed to a force. This force is then added together with the road force, the friction force and air resistance force. This combined force is the force that either accelerates or decelerates the car. The force is then transformed to acceleration and integrated into speed. See Figure 3-14

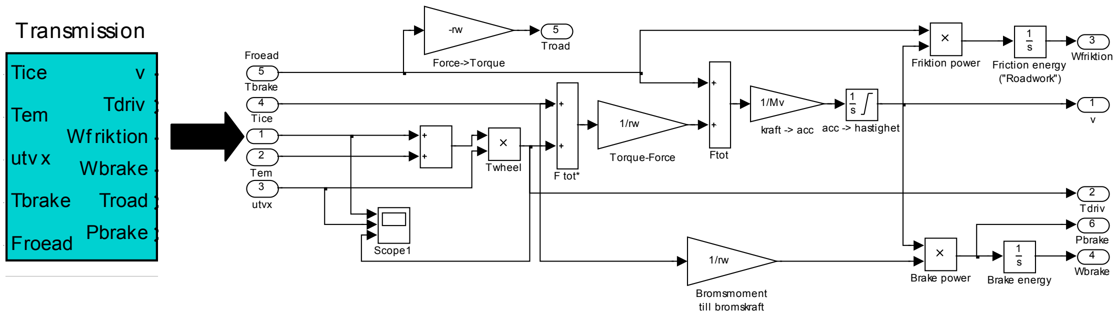

Figure 3-14 the transmission model used in the parallel hybrid solution

3.4.2 Results

In the simulation of the Parallel Hybrid a large number of different combinations of components have been tested. The selected maximum and minimum values represents reasonable limits to the cars hybrid system. These limits have been chosen in regards to performance as well as cost.

	Min Value	Step	Max Value
Electrical Machine Power	5 kW	5 kW	55 kW
Electrical Machine Torque	50 Nm	50 Nm	350 Nm
Battery Weight	15 kg	5 kg	125 kg

Table 3-4 show the limitations to the main components sizes

For all these combinations fuel consumption and performance has been simulated and the results can be viewed in Figure 3-15 to Figure 3-22.

Fuel consumption

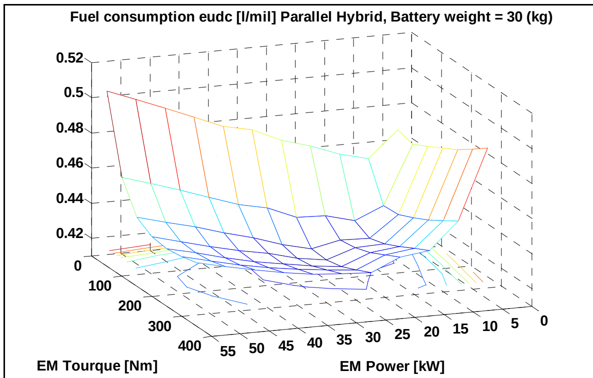

Figure 3-15 Fuel consumption using the eudc drive cycle based on EM torque and EM power. A battery weight of 30 kg has been chosen.

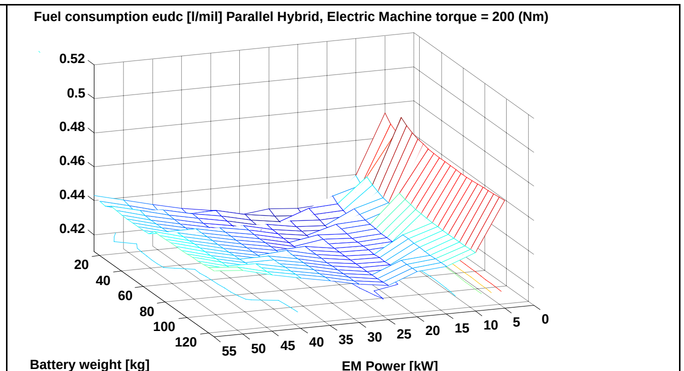

Figure 3-16 Fuel consumption using the eudc drive cycle based on battery weight and EM power. An EM torque of 200 Nm has been chosen.

In Figure 3-15 and Figure 3-16 the fuel consumption trend using the eudc drive cycle is shown. The graphs show minimum fuel consumption when an electrical machine with 25 kW of power and 200 Nm of torque are used. Figure 3-16 also shows that the battery weight has little impact on fuel consumption. It's interesting to observe that using a larger electrical machine than 25 kW impacts the fuel consumption in a negative way. The graph also makes it clear that the electrical machines maximum torque needs to be high to assure low fuel consumption. Having a electrical machines with a maximum torque below 150 makes a large negative impact on the fuel consumption.

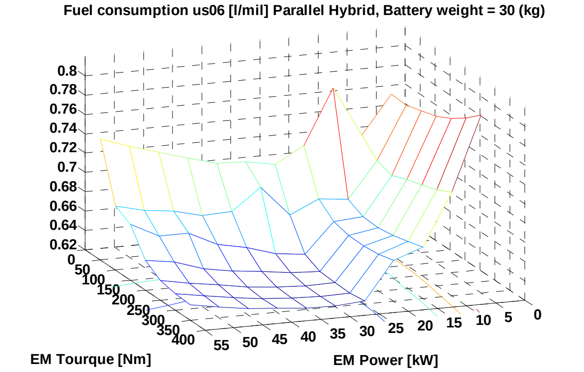

Figure 3-17 Fuel consumption using the us06 drive cycle based on EM torque and EM power. A battery weight of 30 kg has been chosen.

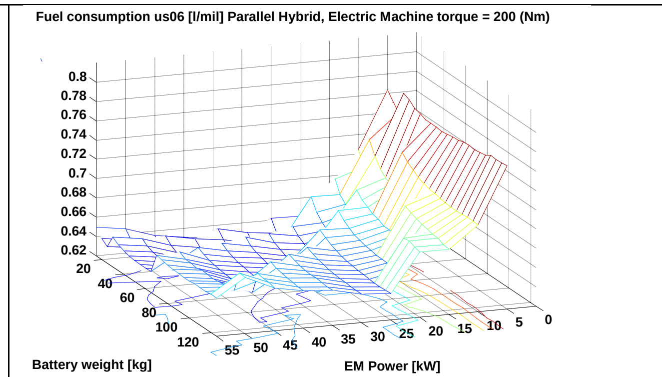

Figure 3-18 Fuel consumption using the us06 drive cycle based on battery weight and EM power. An EM torque of 200 Nm has been chosen.

The fuel consumption trend of the us06 cycle is very similar to the fuel consumption trend for the eudc drive cycle. The largest difference is that the car requires a higher maximum torque, 300 Nm instead of 200 Nm, to achieve minimum fuel consumption. Figure 3-17 also shows that an electrical machine with 25 kW of power gives the lowest fuel consumption. Figure 3-18 shows that the size of the battery has little impact on the fuel consumption.

Performance

In order to assure acceptable performance some acceleration test has been carried out. The results can be seen in Figure 3-19 to Figure 3-22

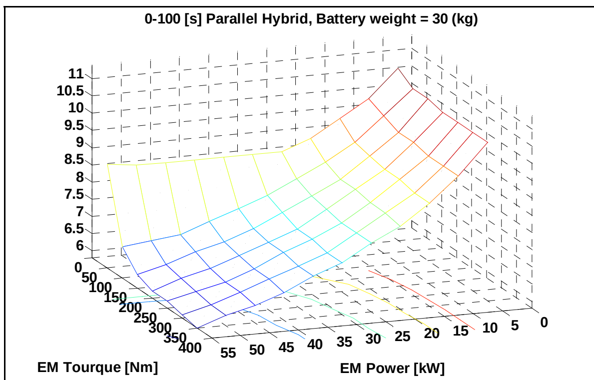

Figure 3-19 Acceleration 0-100 km/h based on EM torque and EM power. A battery weight of 30 kg has been chosen.

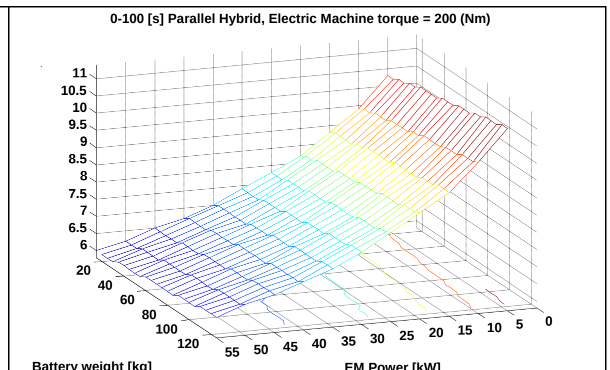

Figure 3-20 Acceleration 0-100 km/h based on battery weight and EM power. An EM torque of 200 Nm has been chosen.

The results in the acceleration graphs, Figure 3-19 and Figure 3-20, are obvious. Acceleration times decrease when electrical machine power increases. This result is expected because adding more tractive power should decreases acceleration times. It's also clear that adding more battery weight increases the acceleration time slightly. Increasing the maximum torque of the electrical machine affects the performance in a positive way. This is also easy to understand, when the maximum torque is increased the maximum amount of drive torque also increases and the car can accelerate faster.

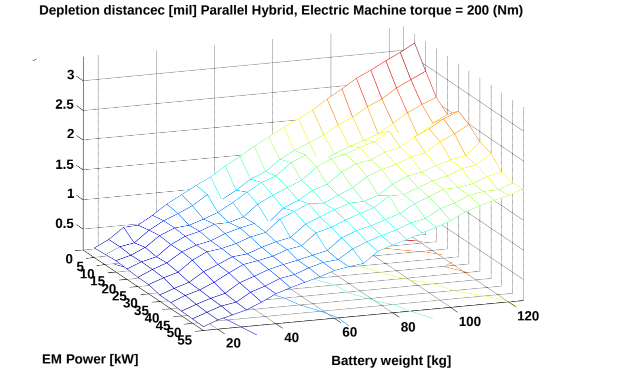

Figure 3-21 Maximum distance in emission free mode based on battery weight and EM power. An EM torque of 200 Nm has been chosen.

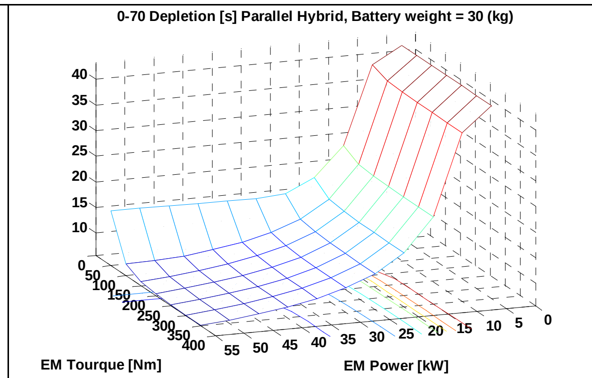

Figure 3-22 Acceleration 0-70 km/h in emission free mode based on EM torque and EM power. A battery weight of 30 kg has been chosen.

Figure 3-21 show that the relationship between the maximum distance in emission free mode and the size of the battery is almost linear, larger battery increases the maximum distance. This result is expected, adding more batteries increases the amount of energy available to the electrical machine. On the other hand increasing the power of the electrical machine decreases the maximum distance the car can travel in emission free mode. The reason for this is that an electrical machine with more power can drain the energy storage more quickly.

The acceleration 0-70 km/h in emission free mode is shown in Figure 3-22, the result is expected. Having more tractive power delivered from electrical machine decreases the acceleration time.

Maximum distance in emission free mode with acceptable performance, acceleration 0-70 km/h below 10 seconds, is achieved with 125 kg of battery and an electrical machine with 40 kW of power and 200 Nm of torque. The distance the car can travel with this configuration is 22.5 km.

Cost efficiency

The most expensive components in the parallel hybrid are the electric motor, power electronics and the battery. The prices for these components are shown in Table 3-5 and are based on the manufactures costs. The cost for the customer maybe larger depending on the manufactures profit margins.

Using the Parallel hybrid concept the generator and starter motor can be removed. The original 5-speed fully mechanically synchronized gearbox is replaced with a 7-speed gearbox without synchronization rings. The synchronization is carried out by the electrical machine. **[9]**

Settings	
Petrol fuel	12 SEK/liter
Pure electric mode (depletion)	OFF
Stop and go	ON
Subtracted Cost	
Old transmission 5-speed	-5500 SEK
Old generator/starter motor	-400 SEK
Added Cost	
Battery	+200 SEK/kg
Electric machine and power electronics	+500 SEK/kW
New transmission 7-speed electrically synchronized	+4500 SEK

Table 3-5 shows the cost for petrol fuel and the cost of the different components affected by the hybridization. “Pure electric mode” and “stop and go” are driving options for the hybrid car.

There are two ways to calculate economical benefits for owning a hybrid car, Payback distance and Total savings. Figure 3-23 illustrates the two different economic principles and how they apply to the hybridization of the Opel Astra. Payback distance illustrates how fast the increased cost for buying a hybrid car is paid back. Total savings shows how much money the costumer is going to save or loose, in comparisons to the regular car. **[4]**

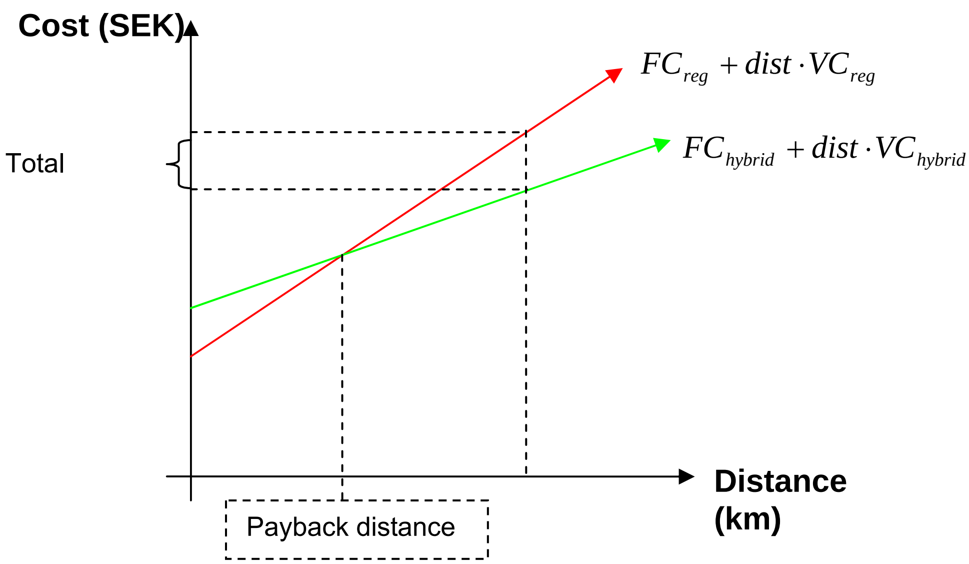

Figure 3-23 A illustration of Payback distance and Total savings

$$TS = TC_{reg} - TC_{hybrid}$$
$$TC_{reg} = FC_{reg} + VC_{reg} \cdot dist$$
$$TC_{hybrid} = FC_{hybrid} + VC_{hybrid} \cdot dist \qquad \textbf{Equation 3-7}$$

$$TS = TC_{reg} - TC_{hybrid} = FC_{reg} - FC_{hybrid} + (VC_{reg} - VC_{hybrid}) \cdot dist$$

FC_{reg} : The fixed cost for the regular car, retail price. (SEK)
VC_{reg} : Variable cost for the regular car, the fuel consumption. (SEK/10 km)
FC_{hybrid} : The fixed cost for the hybrid car, retail price. (SEK)
VC_{hybrid} : Variable cost for the hybrid car, the fuel consumption. (SEK/10 km)
TS : Total savings, the difference in total cost between the regular car and the hybrid car (SEK)

Payback distance

The initial costs for a hybrid car should be covered by lower fuel consumption and therefore lead to better fuel economy. Figure 3-24 to Figure 3-27 shows how many Swedish miles (10 km) costumer has to drive to cover the increased investment cost for the hybrid car. These graphs are meant to give an indication/trend to what components sizes that gives the shortest payback time in the different drive cycles. **[8]**

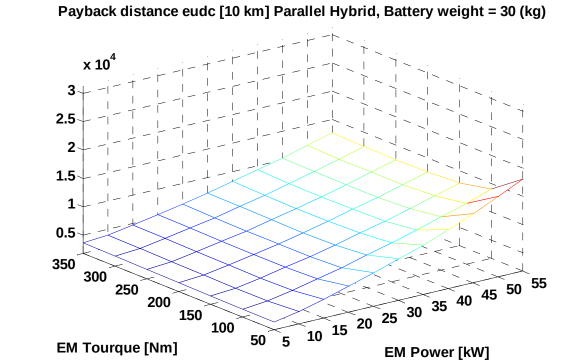

Figure 3-24 This graph shows the payback distance when driving the eudc driving cycle, as a function of EM power and EM torque. The battery weight is set to 30 kg.

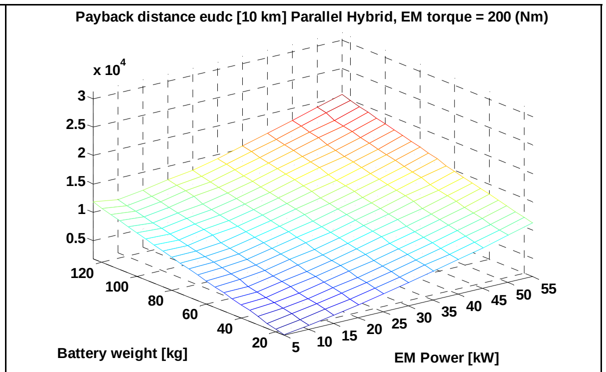

Figure 3-25 This graph shows the payback distance when driving the eudc driving cycle, as a function of EM power and battery weight. The EM torque is set to 200 Nm.

The payback distance, when driving the eudc driving cycle, is almost direct proportional to the EM power and battery weight. A large EM and battery will therefore give a longer payback time. The EM torque affects the payback time very little as long as it's greater than 100 Nm. To get the shortest payback time the EM power should be 5 kW, the battery weight 15 kg and the EM torque 100 Nm. Using these components the payback time would be approximately 18000 km.

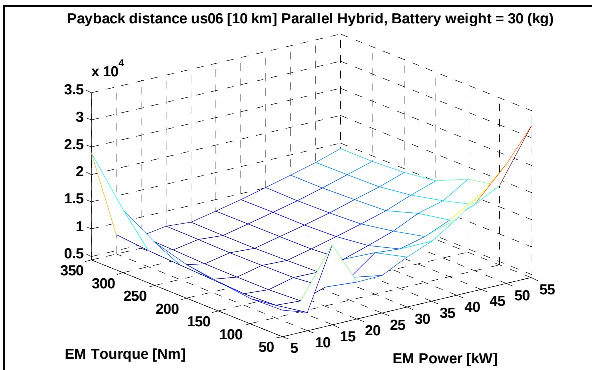

Figure 3-26 This graph shows the payback time (10 km) when driving the us06 driving cycle, as a function of EM power and EM torque. The battery weight is set to 30 kg.

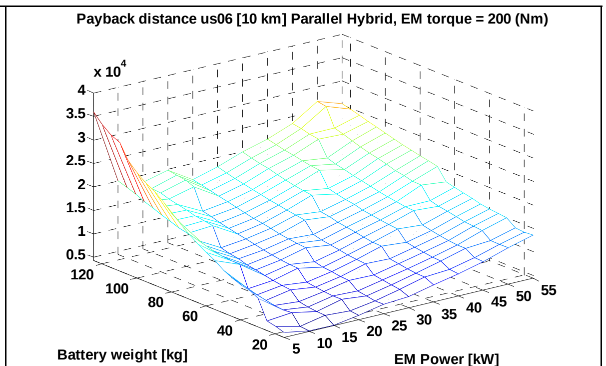

Figure 3-27 This graph shows the payback time (10 km) when driving the us06 driving cycle, as a function of EM power and battery weight. The EM torque is set to 200 Nm.

The payback distance trend, when driving the us06 driving cycle, is similar to the eudc driving cycle. The difference is that the us06 cycle demands more power and torque from the EM. To get the shortest payback time the EM power should be 15 kW, the battery weight 15 kg and the EM torque 200 Nm. Using these components the payback time would be approximately 43000 km.

Total savings

The total savings indicates how much the customer would gain or loose by buying and driving a hybrid version of the Opel Astra. Three different driver types have been simulated, the specifications for these drivers can be observed in Table 3-6. Driver 1 is supposed to represent an ordinary driver that uses the car for short commuting to and from work. Driver 2 represents a driver that uses the car for longer commuting, approximately 30000 km per year. Driver 3 has a company car, probably a sales person that travels long distances in the line of duty. These simulations only takes saved fuel cost into consideration when calculating Total savings. **[8]**

	Driver 1	Driver 2	Driver 3
Driving distance before selling the car	50000 km	100000 km	150000 km

Table 3-6 Driver specifications

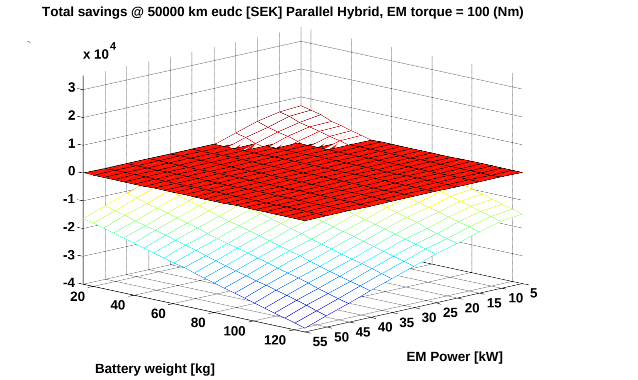

Figure 3-28 eudc driver, 50000 km. 15kg battery, 5 kW Power and 100 Nm torque; saves 7500 SEK

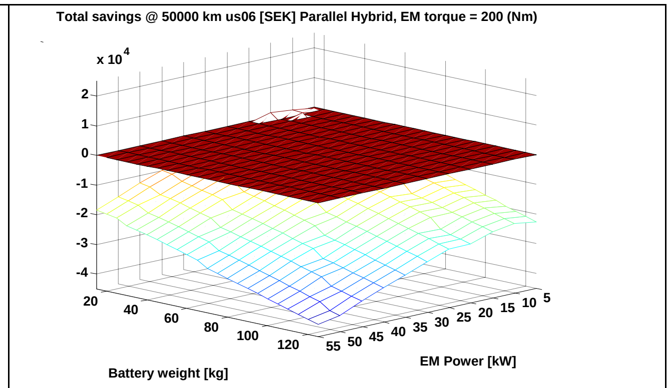

Figure 3-29 us06 driver, 50000 km. 15kg battery, 15 kW Power and 200 Nm torque; saves 1500 SEK

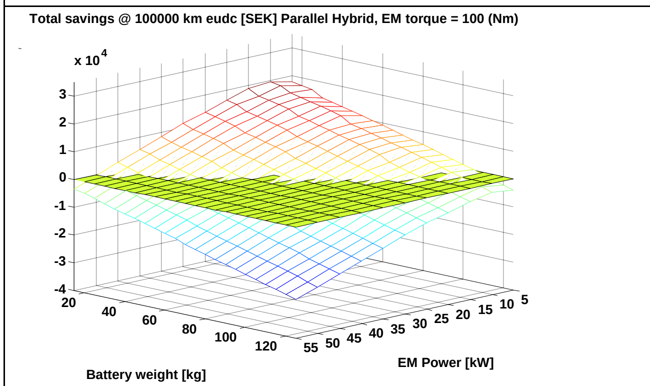

Figure 3-30 eudc driver, 100000 km. 15kg battery, 10 kW Power and 100 Nm torque; saves 20000 SEK

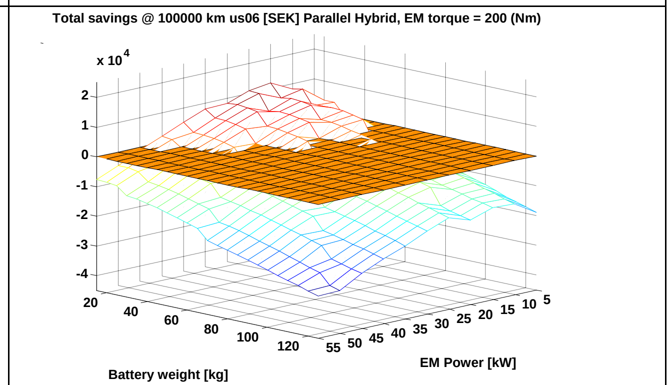

Figure 3-31 us06 driver, 100000 km. 15kg battery, 15 kW Power and 200 Nm torque; saves 12000 SEK

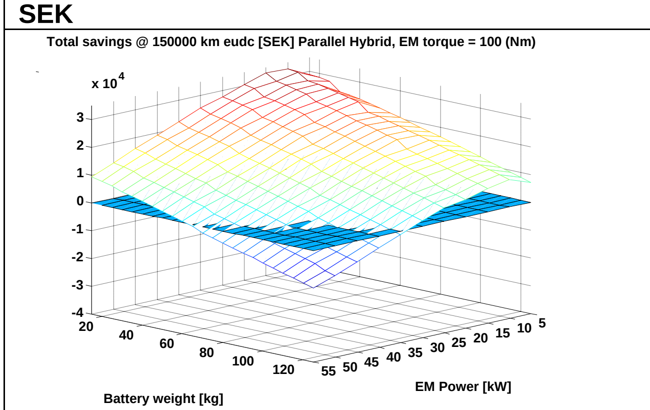

Figure 3-32 eudc driver, 150000 km. 15kg battery, 10 kW Power and 100 Nm torque; saves 34000 SEK

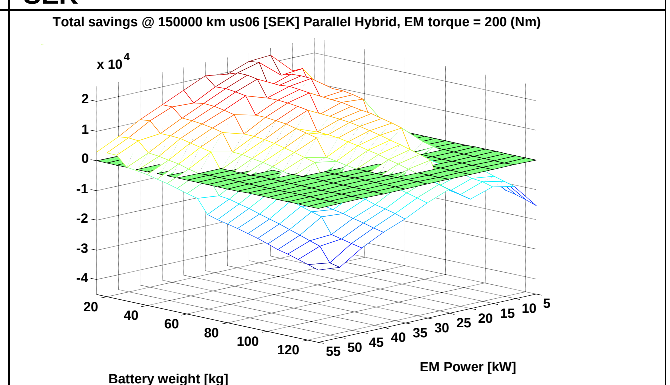

Figure 3-33 us06 driver, 150000 km. 15kg battery, 15 kW Power and 200 Nm torque; saves 23000 SEK

In the graphs above the total savings for three different drivers can be observed, the left column shows them driving the eudc cycle and the right column show the us06 cycle. Positive numbers on the Z-axis indicate that the costumer has saved money and negative numbers means that he/she has lost money. The most interesting thing to observe is that when driving longer distances there is a lot of money to be saved by investing in a hybrid car. The farther you drive the more money you can save. In Table 3-7 and Table 3-8 the optimal combinations of components are listed that will be most economical.

Eudc				
Distance	EM power (kW)	EM torque (Nm)	Battery weight (kg)	Total savings (SEK)
50000 km	5	100	15	7500
10000 km	10	100	15	20000
15000 km	10	100	15	34000

Table 3-7 show which combination of components that give the largest saving to the customer using the eudc drive cycle

Us06				
Distance	EM power (kW)	EM torque (Nm)	Battery weight (kg)	Total savings (SEK)
50000 km	15	200	15	1500
10000 km	15	200	15	12000
15000 km	15	200	15	23000

Table 3-8 show which combination of components that give the largest saving to the customer using the us06 drive cycle

3.4.3 Conclusion Parallel hybrid

The result from the simulations shows how to dimension the different components in the parallel hybrid car. There are three main groups of variables, environmental, performance and economics, to consider when dimensioning the main components for the two different hybridization levels.

	EM Power [kW]	EM Torque [Nm]	Battery Weight [kg]
	Environmental		
Fuel consumption eudc	25	200	15
Fuel consumption us06	25	300	15
	Performance		
Acceleration 0-100 km/h [I]	15	200	15
Maximum distance in emission free mode [II]	40	200	125
	Economics		
Payback distance eudc	5	100	15
Total savings eudc	10	100	15
Payback distance us06	15	200	15
Total savings us06	15	200	15

Table 3-9 A summery of the results from the Parallel hybrid simulations.

[I] The component sizes are selected to assure that the hybrid version has the same performance as the regular car, 0-100 km/h in 8.5 seconds.

[II] The component sizes are selected to assure acceptable performance in emission free mode, 0-70 km/h below 10 seconds

Mild Hybrid

Because the Opel Astra is sold mainly for its functionality and low price the most important basis for choosing the components are economics.

The most economical components sizes in terms of total savings and payback distance differ between the eudc and us06 drive cycles. Because the us06 drive cycle is more demanding the component choices generated are more all-round. The larger electrical machine that’s more economical in the us06 cycle also assures low fuel consumption during both the eudc and us06 drive cycle.
With these components the performance will meet the specified acceleration time, 0-100 km/h in 8.5 seconds.

The best compromise between environmental, performance and economics for the mild hybrid is an electrical machine with 15 kW of power and 200 Nm torque, together with 15 kg of battery. The manufactures cost for this hybrid solution would be 9100 SEK.

Full Hybrid

The main focus for the full hybrid is the ability to drive in emission free mode, therefore the most important variable is performance. In order to meet the acceleration specifications for the emission free mode, 0-70 under 10 seconds, an electrical machine with 40 kW of power and 200 Nm torque should be used.

The distance that the car is able to travel in emission free mode is proportional to battery size and the depth of discharge limit. In the simulations the state of charge limits were set to 85% to 55% which is rather small span, if the limits instead were set to 90% to 30% the emission free distance would be doubled. A battery size of 125 kg would then give an emission free distance of approximately 45 km. The manufactures cost for this hybrid solution would be 43600 SEK.

3.5 Series

The functionality of the series hybrid has been discussed earlier, this chapter will cover the transition from principle design to Simulink model.

3.5.1 How the simulink model works

The Simulink model of the series hybrid is designed in the same manner as the parallel hybrid, discussed earlier. The Series model has some fundamental blocks in common with the parallel model. These blocks are the driver model, ICE model, electrical machine model, brake model, battery model and road model. The only models that do change are the controller model, transmission model and how the different blocks are connected together. **[2]**

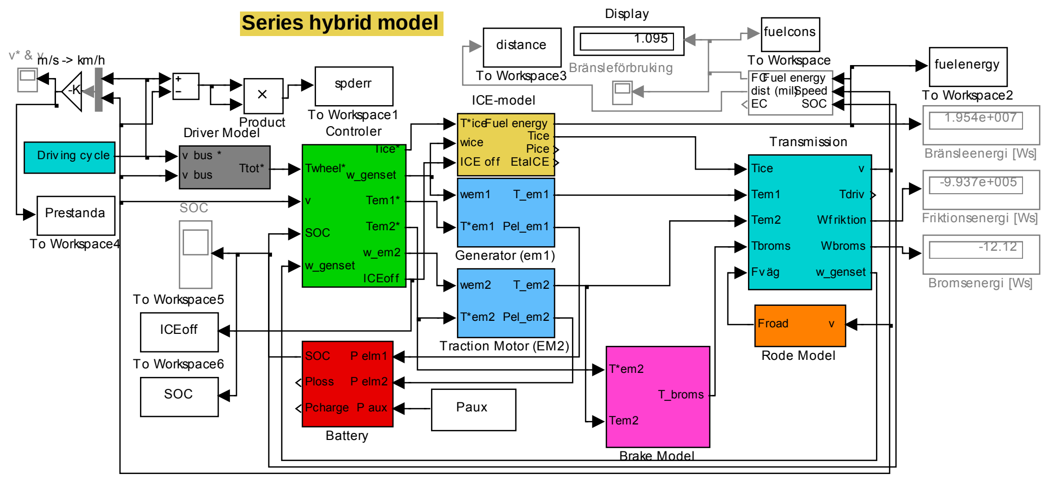

Figure 3-34 simulink model of the series hybrid solution

The Controller

The controller model in the series hybrid is rather different from model used in the parallel hybrid. Because the series hybrid has two electrical machines two separate torque and speed references need to be given from the controller. The torque reference to the traction motor is given directly by the wheel torque reference, via a final gear ratio. The speed reference to the traction motor is given by the speed of the car via the same final gear ratio that was used to calculate the torque reference. The torque and speed reference to both the combustion engine and the generator is given by the optimal operating point block, the red block in Figure 3-35.

The controller also keeps the battery state of charge at its reference value. Control over the state of charge is carried out bye the green and purple blocks in Figure 3-35.

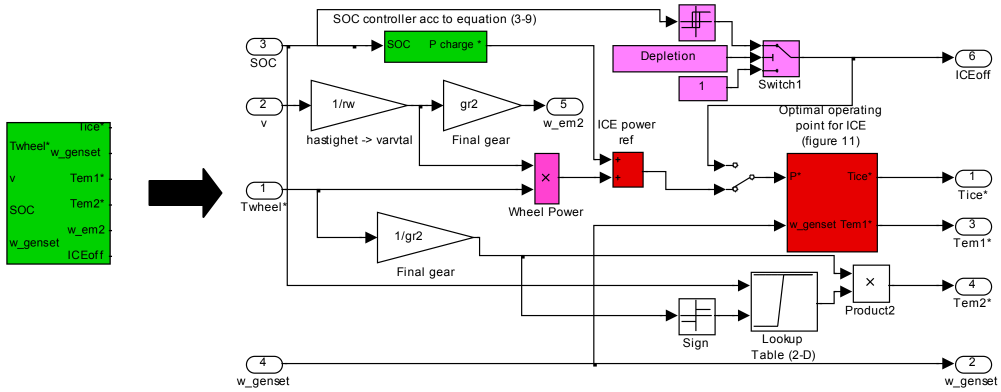

Figure 3-35 Controller model in the series hybrid

The Transmission model

The transmission model looks somewhat different from the one used in the parallel hybrid model. The top part of the model adds the drive torque with the brake torque and then transforms the sum to a force. This force is then turned into acceleration and then integrated to vehicle speed.

The bottom part of the model is used to calculate the speed of the generator; this is done by adding the Combustion engines torque with the Electrical machines torque, this sum is divided with the inertia of the generator and then integrated to the generator speed.

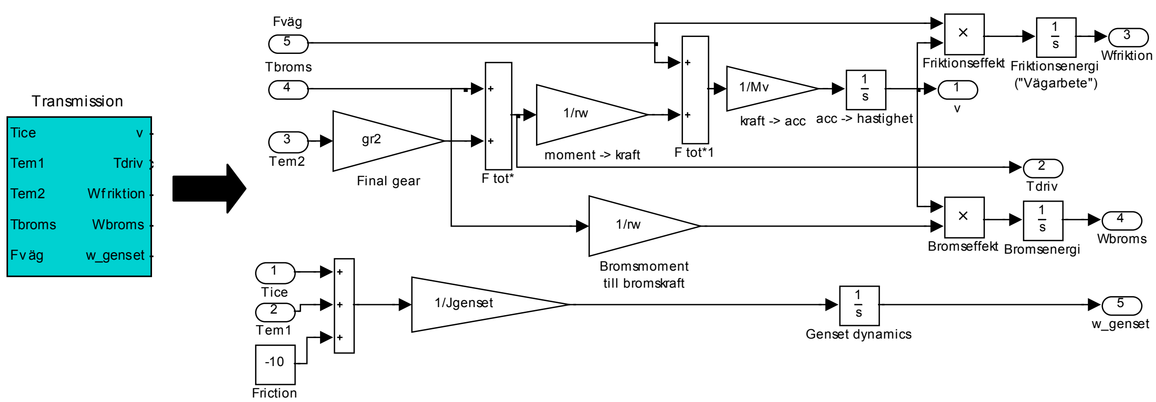

Figure 3-36 Transmission model in the series hybrid

3.5.2 Results Series Hybrid

In the simulation of the Series Hybrid a large number of different combinations of components have been tested. The selected maximum and minimum values represents reasonable limits to the cars hybrid system. These limits have been chosen in regards to performance as well as cost.

	Min Value	Step	Max Value
ICE Power	10 kW	5 kW	70 kW
Electrical Machine Power	50 kW	10 kW	140 kW
Electrical Machine Torque	150 Nm	50 Nm	500 Nm
Battery Weight	20 kg	25 kg	125 kg

Table 3-10 show the limitations to the main components sizes

For all these combinations fuel consumption and performance has been simulated and the results can be viewed in

Fuel consumption

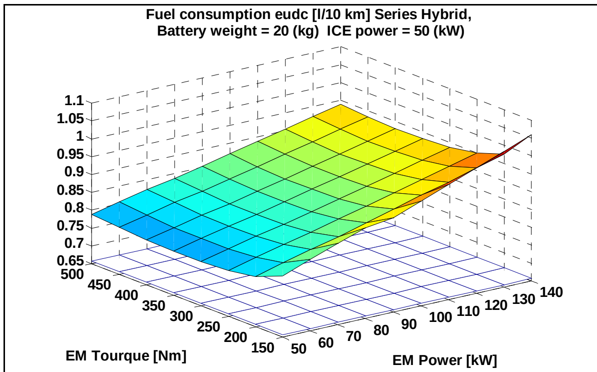

Figure 3-37 Fuel consumption using the eudc drive cycle based on EM torque and EM power. A battery weight of 20 kg and ICE Power of 50 kW has been chosen.

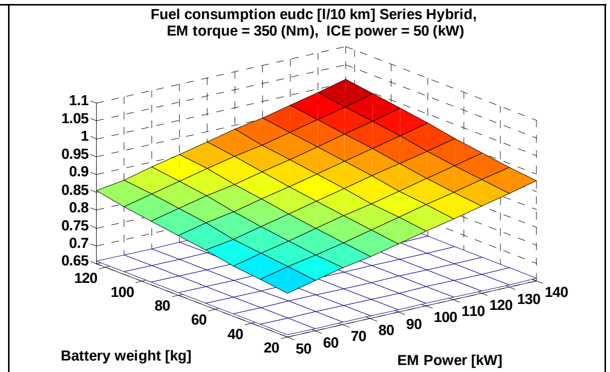

Figure 3-38 Fuel consumption using the eudc drive cycle based on battery weight and EM power. An EM torque of 350 Nm and ICE Power of 50 kW has been chosen.

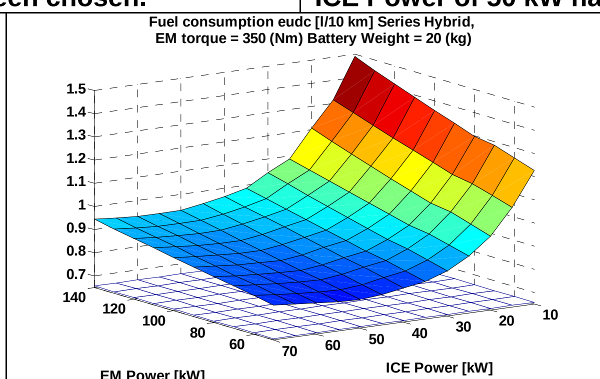

Figure 3-39 Fuel consumption using the eudc drive cycle based on ICE power and EM power. A battery weight of 20 kg and EM torque of 350 Nm has been chosen.

In Figure 3-37, Figure 3-38 and Figure 3-39 the fuel consumption trend using the eudc drive cycle is shown. The blue grid represents the regular cars fuel consumption of 0.65 liter/10 km. It's clear that all combinations of main components generate higher fuel consumption then the regular car.

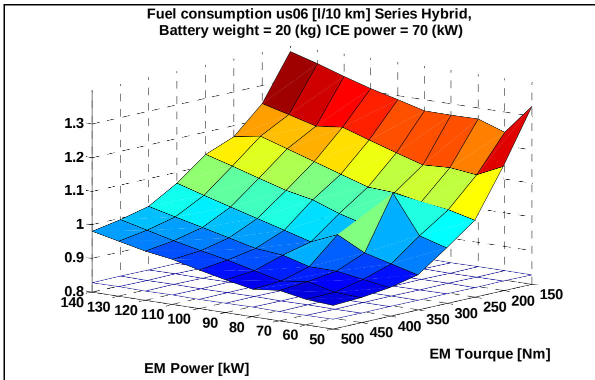

Figure 3-40 Fuel consumption using the us06 drive cycle based on EM torque and EM power. A battery weight of 20 kg and ICE Power of 70 kW has been chosen.

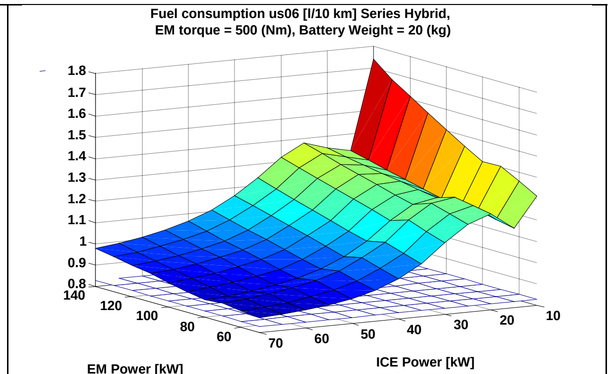

Figure 3-41 Fuel consumption using the us06 drive cycle based on battery weight and EM power. An EM torque of 500 Nm and ICE Power of 70 kW has been chosen.

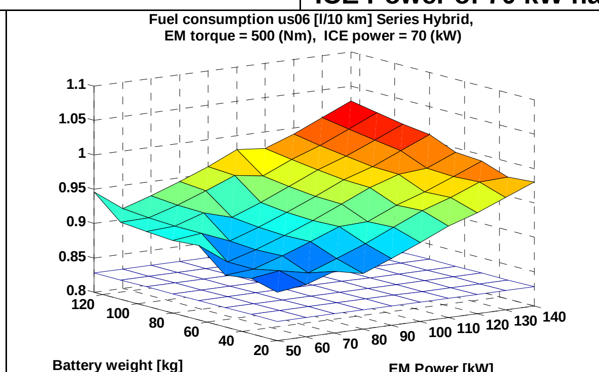

Figure 3-42 Fuel consumption using the us06 drive cycle based on ICE power and EM power. A battery weight of 20 kg and EM torque of 500Nm has been chosen.

In Figure 3-40, Figure 3-41 and Figure 3-42 the fuel consumption trend using the us06 drive cycle is shown. The blue grid represents the regular cars fuel consumption of 0,83 liter/10 km. It's clear that all combinations of main components generate higher fuel consumption then the regular car.

3.5.3 Conclusions Series Hybrid

Because none of the component combinations generated lower fuel consumption then the regular car, no further simulations regarding performance and cost are necessary.

The reason why the series hybrid performs so poorly is the number of energy conversions needed to drive the car. Figure 3-43 shows the different energy conversion and there efficiency as well as the total efficiency. The total efficiency is rater low, 18%. This is the reason for the bad fuel consumption.

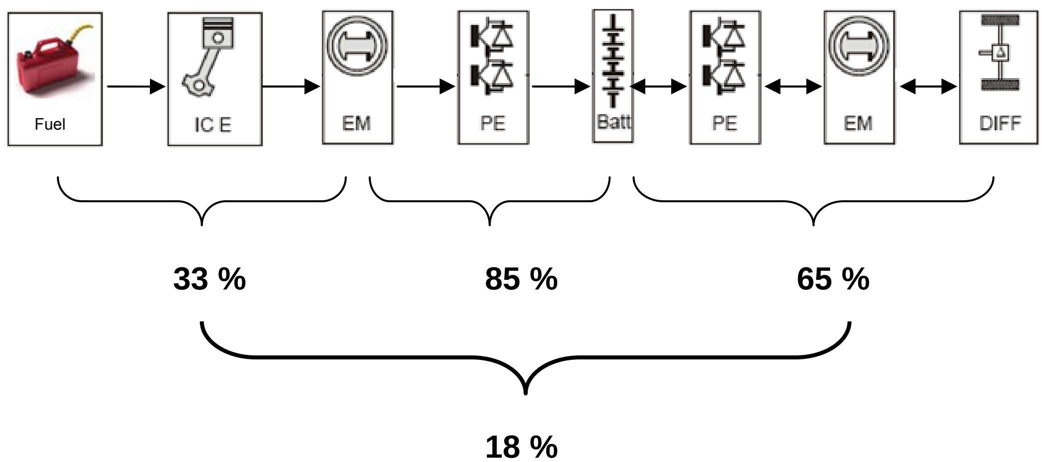

Figure 3-43 the energy conversion of the series hybrid

3.6 Complex Hybrid

The functionality of the complex hybrid has been discussed earlier and in this chapter will cover the transition from principle design to Simulink model. The two electrical machines are named in the same manner described in chapter 3.2 and table 3.2.

3.6.1 How the Simulink model works

The Simulink model of the complex hybrid is designed in the same way as the parallel and the series hybrid model. The blocks that are shared with the other models are the electric machine model, ICE model, driver model, brake model, battery model and road model. The only blocks that changes are the controller model and the transmission model. **[2]**

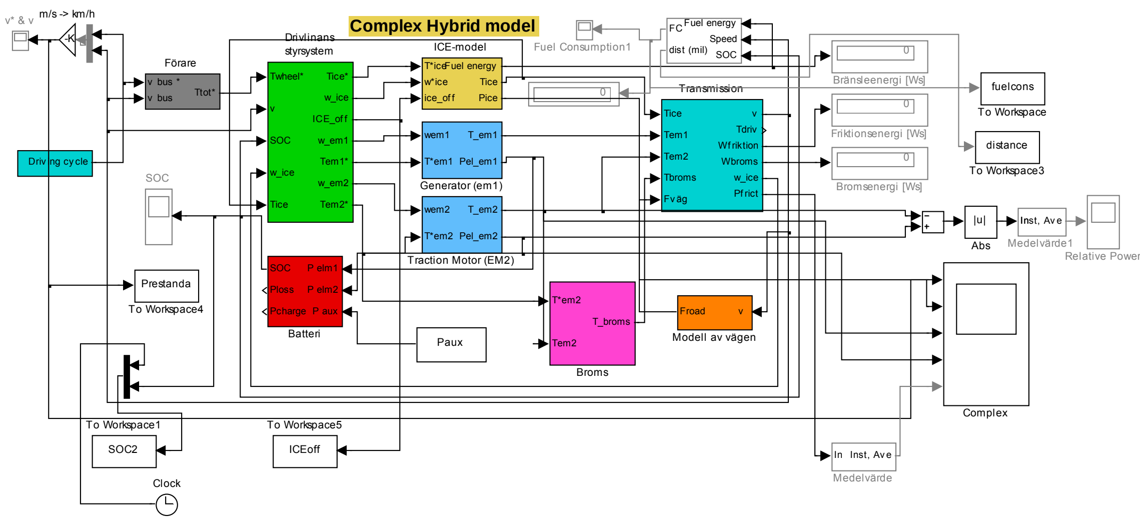

Figure 3-44 Simulink model of the Complex Hybrid

The controller model

Because the complex hybrid has two electrical machines the controller need to calculate two speed and torque references. The torque reference for the electric traction motor is calculated from the actual torque of the ICE, via a final gear ratio, and the wheel torque reference, via the gear ration between the ring wheel and the planetary carrier in the planetary gear. The relative torque of the ICE is then subtracted from the relative wheel torque; this gives the torque reference.

The speed reference for the electrical traction motor is given directly by the speed of the car via the same final gear ratio that was used to calculate the torque reference.

To calculate the reference torque for the generator the difference between the actual and reference speed of the ICE is transformed into a torque, this torque corresponds to the torque that is needed to increase the generator speed. The torque is then subtracted from the ICE torque and transformed into a relative torque at the generator, via the gear ratio between the sun gear and the planetary carrier in the planetary gear.

The speed reference for the generator is calculated from the difference between the relative reference speed of the electrical traction motor and the relative ICE speed. The relative reference speed of the electrical traction motor is calculated by using the gear ratio between the solar wheel and the ring wheel. To calculate the relative speed of the ICE the gear ration between the solar wheel and the planetary carrier in the planetary gear are used.

The speed and torque reference for the ICE is given by the optimal operating point block, the red block in Figure 3-45.

Another function for the controller is to regulate the SOC level in the battery; the green block in Figure 3-45 controls this function.

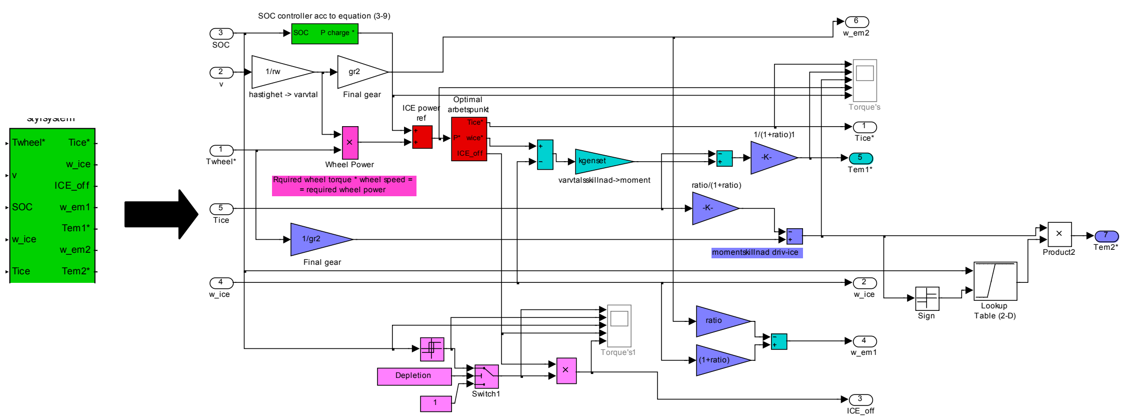

Figure 3-45 the controller subsystem in the complex hybrid

The Transmission model

The vehicle is modeled as a mass that is driven by the force of the electric traction motor and the ICE. These forces are calculated via the gearbox gear ratio and the breaking torque from the mechanical breaks. The forces are then summarized and recalculated to drag force via the cars wheel radius.

The vehicle is simultaneously held back by a friction force. This friction force consists of air resistance and roll friction. See Figure 3-46.

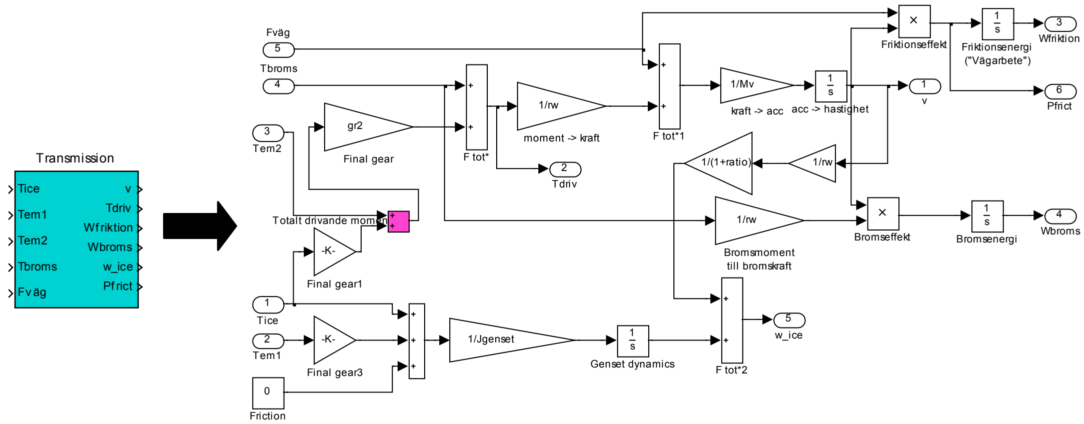

Figure 3-46 the transmission subsystem in the complex hybrid

3.6.2 Results Complex Hybrid

In the simulation of the Complex hybrid a large number of different combinations have been tested. The selected maximum and minimum value represents reasonable limits to the cars hybrid system. These limits have been chosen in regards to performance as well as cost, see Table 3-11.

	Min value	Step	Max value
EM 2 Power kW	5	5	55
EM 2 Torque Nm	50	50	350
Battery weight kg	15	5	125

Table 3-11 Simulation setup data

For all these combinations fuel consumption and performance has been simulated and the results can be viewed in Figure 3-47 to Figure 3-54.

Fuel consumption

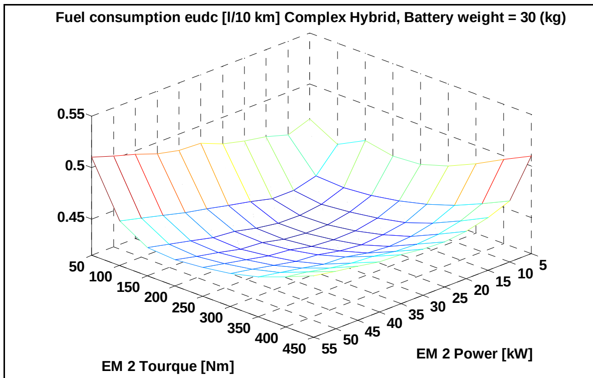

Figure 3-47 Fuel consumption using the eudc drive cycle based on EM 2(traction motor) torque and EM 2 power. A battery weight of 30 kg has been chosen.

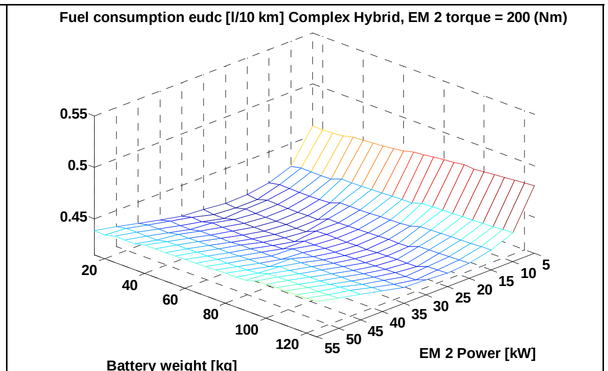

Figure 3-48 Fuel consumption using the eudc drive cycle based on the battery weight and EM 2 power. An EM 2 torque of 200 Nm has been chosen.

In Figure 3-47 and Figure 3-48 the fuel consumption trend using the eudc drive cycle is shown. The graphs show minimum fuel consumption when an electrical machine with 20 kW of power, 200 Nm of torque and 15 kg of batteries are used. It also shows that the battery weight has little impact on fuel consumption. It's also interesting to observe that using a larger electrical machine then 20 kW impacts the fuel consumption in a negative way. Having an electrical machine with maximum torque below 100 Nm has a huge negative impact on the fuel consumption.

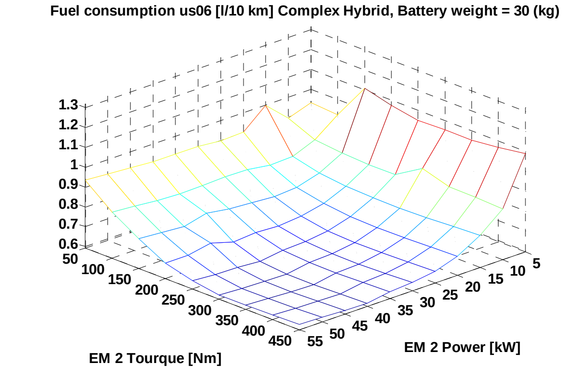

Figure 3-49 Fuel consumption using the us06 drive cycle based on EM 2 torque and EM 2 power. A battery weight of 30 kg has been chosen.

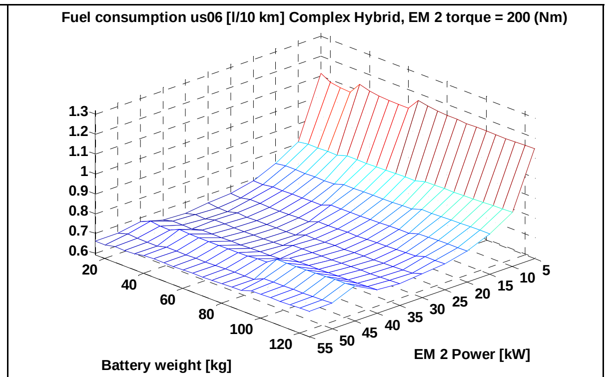

Figure 3-50 Fuel consumption using the us06 drive cycle based on the battery weight and EM 2 power. An EM 2 torque of 200 Nm has been chosen.

In Figure 3-49 and Figure 3-50 the fuel consumption trend using the us06 drive cycle is shown. The graphs show minimum fuel consumption when an electrical machine with 40 kW of power, 350 Nm of torque and 15 kg of batteries are used. It also shows that the battery weight has little impact on fuel consumption. Having an electrical machine with maximum torque below 300 Nm has a negative impact on the fuel consumption. The regular cars fuel consumption in the us06 cycle was 0.85 liters/10km and form Figure 3-49 its clear that some combinations of components in the complex hybrid gives higher fuel consumption then the regular car.

Performance

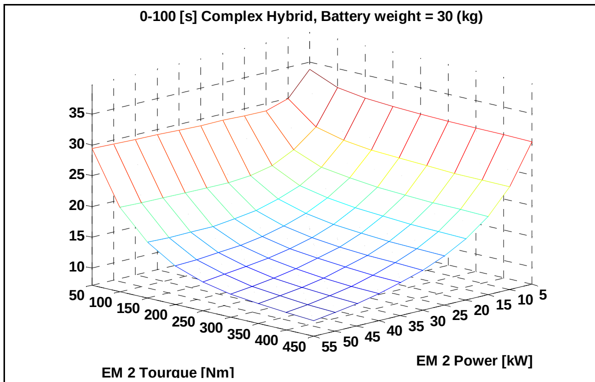

Figure 3-51 Acceleration 0-100 km/h based on EM 2 torque and EM 2 power. A battery weight of 30 kg has been chosen.

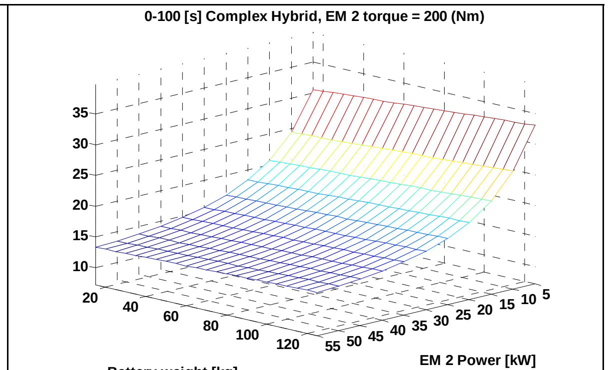

Figure 3-52 Acceleration 0-100 km/h based on battery weight and EM 2 power. An EM 2 torque of 200 Nm has been chosen.

The results in the acceleration graphs, Figure 3-51 and Figure 3-52, are obvious. Acceleration times decrease when electrical machine power increases. This result is expected because adding more tractive power should decrees acceleration times. It's also clear that adding more battery weight increases the acceleration time in a small way. Increasing the maximum torque of the electrical machine affects the performance in a positive way. This is also easy to understand, when the maximum torque is increased the maximum amount of drive torque is also increased and the car can accelerate faster.

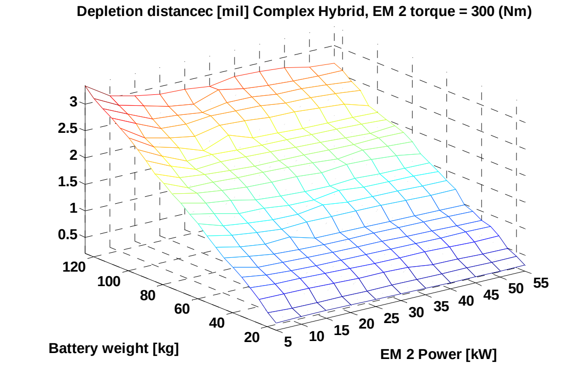

Figure 3-53 maximum distance in emission free mode based on battery weight and EM 2 power. An EM 2 torque of 300 Nm has been chosen.

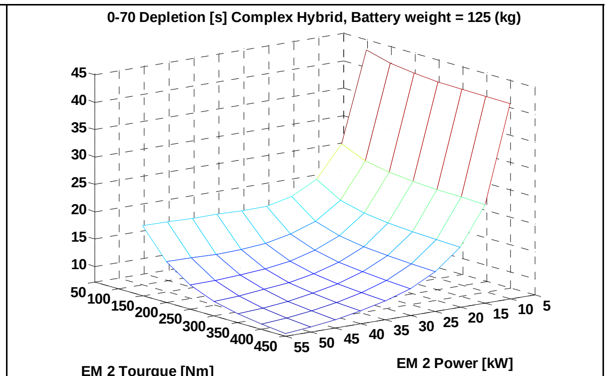

Figure 3-54 Acceleration 0-70 km/h based on EM 2 torque and EM 2 power. A battery weight of 125 kg has been chosen.

Figure 3-53 shows that the relationship between the maximum distance in emission free mode and the size of the battery is almost linear, larger battery increases the maximum distance. This result is expected, adding more batteries increases the amount of energy available to the electrical machine. It's also interesting to see that larger electrical machine has little impact on the maximum distance.

The acceleration 0-70 km/h in emission free mode is shown in Figure 3-54 the result is expected. Having more tractive power delivered from electrical machine decreases the acceleration time

To achieve maximum distance with acceptable performance in emission free mode, acceleration 0-70 km/h below 10 seconds, an electrical machine with 50 kW of power and 300 Nm of torque should be used.

Cost efficiency

The most expensive components in the complex hybrid are the same as in the parallel hybrid, the electric machines, power electronics and the battery. Table 3-12 show the cost of the main components needed to realize the complex hybrid solution.

Settings	
Petrol fuel	12 SEK/liter
Pure electric mode (depletion)	OFF
Stop and go	ON
Subtracted cost	
Old transmission 5-speed	-5500 SEK
Old generator/starter motor	-400 SEK
Added cost	
Battery	+200 SEK/kg
Electric traction machine and power electronics	+500 SEK/kW
Generator 22 kW	+11000 SEK
New transmission planetary gear	+800 SEK

Table 3-12 shows the cost for petrol fuel and the cost of the different components affected by the hybridization. "Pure electric mode" and "stop and go" are driving options for the hybrid car.

Payback distance

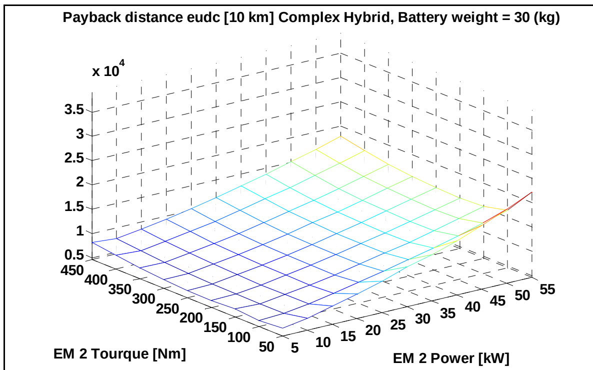

Figure 3-55 This graph shows the payback time (10 km) when driving the eudc driving cycle, as a function of EM power and EM torque. The battery weight is set to 30 kg.

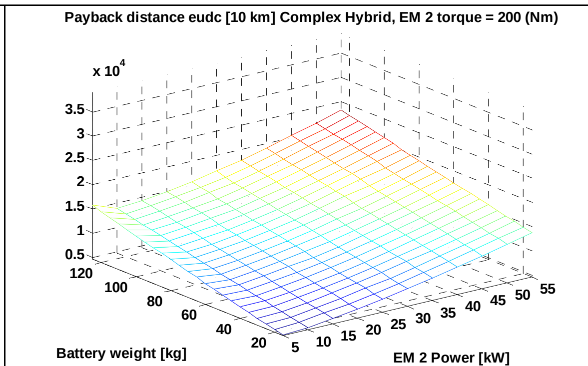

Figure 3-56 This graph shows the payback time (10 km) when driving the eudc driving cycle, as a function of EM power and battery weight. The EM torque is set to 200 Nm.

The payback distance, when driving the eudc driving cycle, is almost direct proportional to the EM power and battery weight. A large EM and battery will therefore give a longer payback distance. The EM torque affects the payback time very little as long as it is greater than 100 Nm. To get the shortest payback time the EM power should be 5 kW, the battery weight 15 kg and the EM torque 100 Nm. Using these components the payback time would be 46000 km.

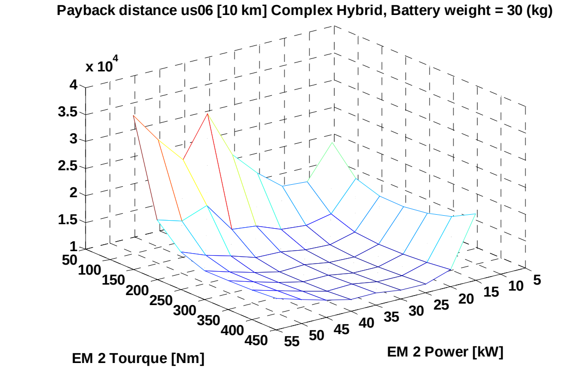

Figure 3-57 This graph shows the payback time (10 km) when driving the us06 driving cycle, as a function of EM power and EM torque. The battery weight is set to 30 kg.

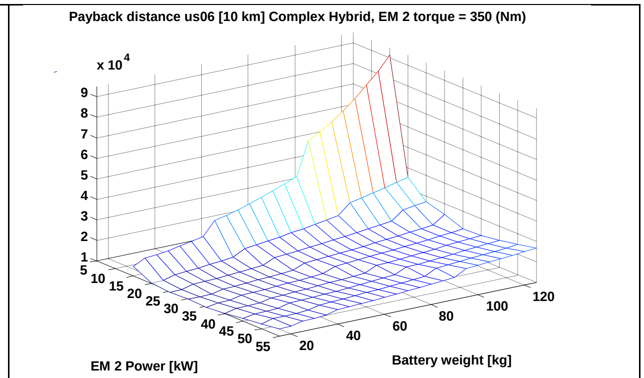

Figure 3-58 This graph shows the payback time (10 km) when driving the us06 driving cycle, as a function of EM power and battery weight. The EM torque is set to 350 Nm.

The payback distance using the us06 drive cycle depends on all three components. The largest impact is having low torque, below 200 Nm. The battery weights impact on the payback distance is proportional, having more batteries increase the payback distance. To get the shortest payback time the EM power should be 35 kW, the battery weight 15 kg and the EM torque 350 Nm. Using these components the payback time would be 94000 km.

Total savings

The total savings for the complex hybrid is calculated in the same way as for the parallel hybrid.

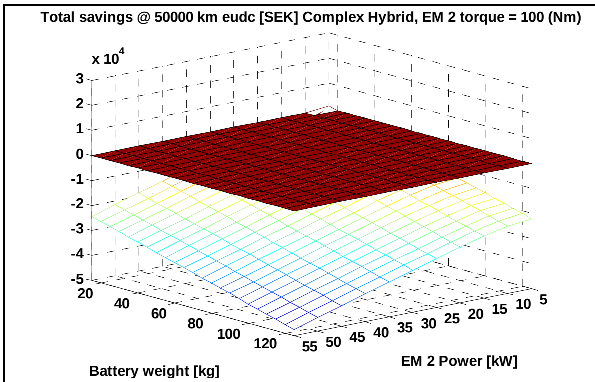

Figure 3-59 eudc driver, 50000 km. 15 kg battery, 5 kW Power and 100 Nm torque; saves 1000 SEK

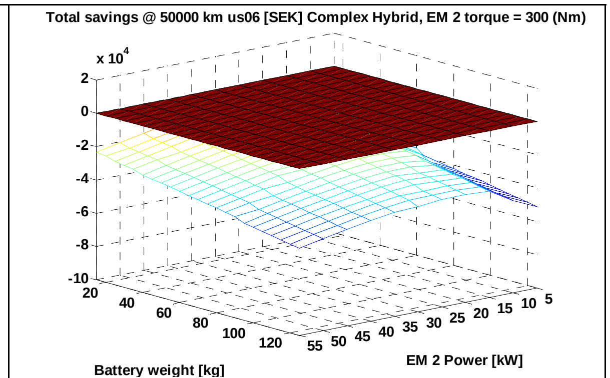

Figure 3-60 us06 driver, 50000 km. 15kg battery, 20 kW Power and 300 Nm torque; saves -9000 SEK

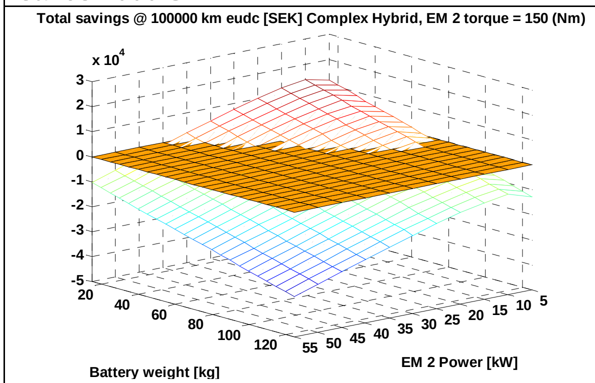

Figure 3-61 eudc driver, 100000 km. 15kg battery, 10 kW Power and 150 Nm torque; saves 13000 SEK

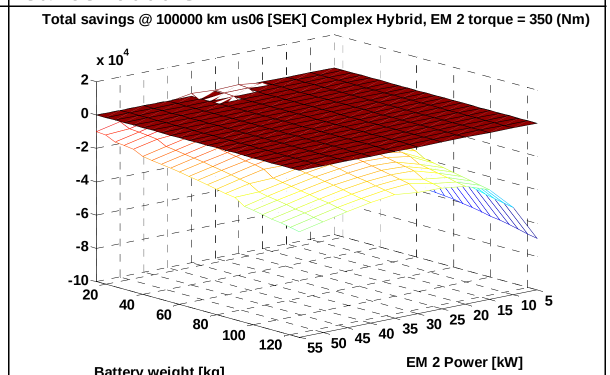

Figure 3-62 us06 driver, 100000 km. 15kg battery, 35 kW Power and 350 Nm torque; saves 1600 SEK

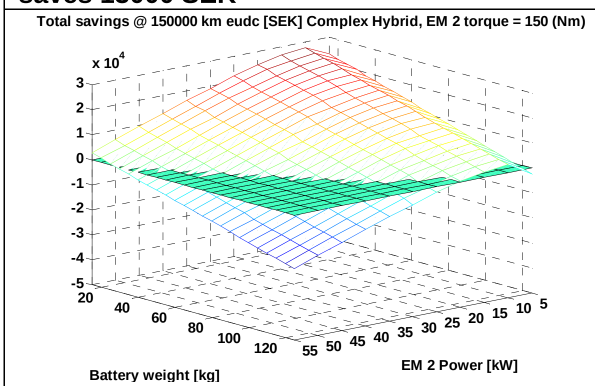

Figure 3-63 eudc driver, 150000 km. 15kg battery, 10 kW Power and 150 Nm torque; saves 27000 SEK

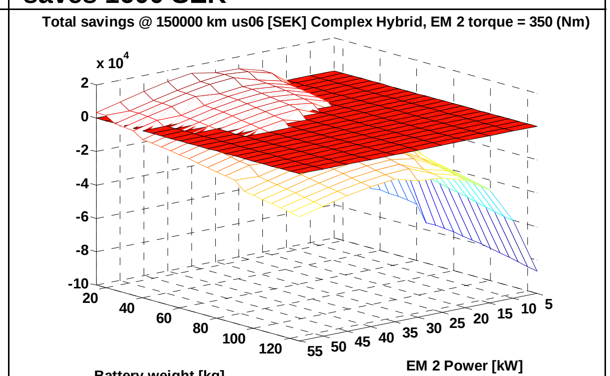

Figure 3-64 us06 driver, 150000 km. 15kg battery, 35 kW Power and 350 Nm torque; saves 16000 SEK

The graphs above show how different components sizes impact the total savings. The most obvious result is that driving longer distances assures higher economically gain. A compiled list of the total saving can be observed in Table 3-13 and Table 3-14

eudc				
Distance	EM power (kW)	EM torque (Nm)	Battery weight (kg)	Total savings (SEK)
50000 km	5	100	15	1000
10000 km	10	150	15	13000
15000 km	10	150	15	27000

Table 3-13 show which combination of components that give the largest saving to the customer using the eudc drive cycle

us06				
Distance	EM power (kW)	EM torque (Nm)	Battery weight (kg)	Total savings (SEK)
50000 km	20	300	15	-9000
10000 km	35	350	15	1600
15000 km	35	350	15	16000

Table 3-14 show which combination of components that give the largest saving to the customer using the us06 drive cycle

Conclusion Complex hybrid

The result from the simulations shows how to dimension the different components in the complex hybrid car. There are three main groups of variables, environmental, performance and economics, to consider when dimensioning the main components for the two different hybridization levels.

	EM Power [kW]	EM Torque [Nm]	Battery Weight [kg]
	Environmental		
Fuel consumption eudc	25	200	15
Fuel consumption us06	40	350	15
	Performance		
Acceleration 0-100 km/h [I]	35	300	15
Maximum distance in emission free mode [II]	50	300	125
	Economics		
Payback distance eudc	5	100	15
Total savings eudc	10	150	15
Payback distance us06	35	350	15
Total savings us06	35	350	15

Table 3-15 A summery of the results from the Complex hybrid simulations.

[I] **The component sizes are selected to assure that the hybrid version has the same performance as the regular car, 0-100 km/h in around 8.5 seconds.**
[II] **The component sizes are selected to assure acceptable performance in emission free mode, 0-70 km/h below 10 seconds**

Mild Hybrid

The most important factor when constructing a mild hybrid of the Opel Astra is cost. The best choice based on economics is an electrical machine with 35 kW of power and 350 Nm of torque together with 15 kg of batteries. This correlates well with lowest fuel consumption as well as acceleration 0-100 km/h. The manufactures cost for this hybrid solution would be 26400 SEK.

Full Hybrid

The main focus for the full hybrid is the ability to drive in emission free mode, therefore the most important variable is performance. In order to meet the acceleration specifications for the emission free mode, 0-70 under 10 seconds, an electrical machine with 50kW of power and 300 Nm torque should be used. The distance that the car is able to travel in emission free mode is proportional to battery size and state of charge limits. In the simulations the state of charge limits were set to 85% to 55% which is rather small span, if the limits instead were set to 90% to 30% the emission free distance would be doubled. A battery size of 125 kg would then give an emission free distance of approximately 54 km. The manufactures cost for this hybrid solution would be 55900 SEK.

3.7 Choosing the final solution

3.7.1 Mild Hybrid

The specifications for the two mild hybrid solutions are shown in Table 3-16. These are the best solutions from the parallel and complex hybrid. The evaluation is shown in Table 3-17.

		Parallel	Complex
ICE Power	(kW)	66	66
EM 1 Power (Generator)	(kW)	-	22
EM 2 Power (traction motor)	(kW)	15	35
EM 2 torque (traction motor)	(Nm)	200	350
Battery weight	(kg)	15	15

Table 3-16 the specification for the two mild hybrids

		Parallel	Complex
Fuel Consumption			
Fuel consumption eudc	(liter/10km)	0.43	0.44
Fuel consumption us06	(liter/10km)	0.62	0.59
Performance			
Acceleration 0-100 km/h (s)		8.5	12.9
Economics			
Payback distance eudc	(10km)	3200	9900
Payback distance us06	(10km)	4300	9400
Total savings eudc 50000 km	(SEK)	4900	-13100
Total savings eudc 100000 km	(SEK)	18900	209
Total savings eudc 150000 km	(SEK)	33000	13600
Total savings us06 50000 km	(SEK)	1500	-12400
Total savings us06 100000 km	(SEK)	12100	1700
Total savings us06 150000 km	(SEK)	22700	15800
Flexibility			
Adaptability to existing platform		Very Good	Good

Table 3-17 the evaluation of the two mild hybrid solutions

In the evaluation table it is obvious that the Parallel hybrid is the best solution. The financial benefit of the parallel hybrid is obvious, the payback distance is much shorter and the total savings is a great deal larger then the complex hybrid. The acceleration time of the parallel hybrid is also much faster than the complex hybrid.

The fuel consumption of the two solutions is almost the same, the parallel hybrid has lower consumption in the eudc drive cycle and the complex hybrid has the lowest consumption in the us06 cycle.

3.7.2 Full hybrid

Now the two Full hybrid solutions will be evaluated and a final solution will be selected. The main focus is financial but performance and fuel consumption are also considered when choosing the final full hybrid solution. Table 3-18 show the two full hybrid solutions

Technical specifications			
		Parallel	**Complex**
ICE Power	(kW)	66	66
EM 1 Power (Generator)	(kW)	-	22
EM 2 Power (traction motor)	(kW)	40	50
EM 2 torque (traction motor)	(Nm)	200	300
Battery weight	(kg)	125	125

Table 3-18 the technical specification for the two full hybrid concepts

Economics in full hybrid

To calculate the economical factors in the full hybrid
Equation 3-8 is used. The calculations are based on driving 50% in emission free mode. When the battery state of charge reaches its lower limit, during the 50% in emission free mode, the battery is recharged from the power grid. This type of hybrid car that can be recharged from the grid is called a plug-in hybrid.

The total savings graph can be viewed in Figure 3-65. The graph shows the total savings for the two different hybrid concepts both in the eudc and us06 drive cycle.

$$T_{Savings} = (V_{cost\_regular} - 0.5 \cdot V_{cost\_hybrid} - 0.5 \cdot V_{\mathrm{cost\_hybrid\_el}}) \cdot dist - F_{cost\_hybhrid})$$

Equation 3-8 Total savings in the Full hybrid when driving 50% emission free mode

$T_{Savings}$	Total savings using the Full hybrid
$V_{cost\_regular}$	The fuel cost if the car was a regular Opel Astra (12 SEK/liter)
V_{cost_hybrid}	The fuel cost when driving the car in hybrid mode (12 SEK/liter)
$V_{\mathrm{cost\_hybrid\_el}}$	The energy cost when driving in Emission free mode, purely electric mode (1 SEK/ kWh)
$F_{cost\_hybhrid}$	The cost for the hybridization
$dist$	The distance where the total cost was calculated

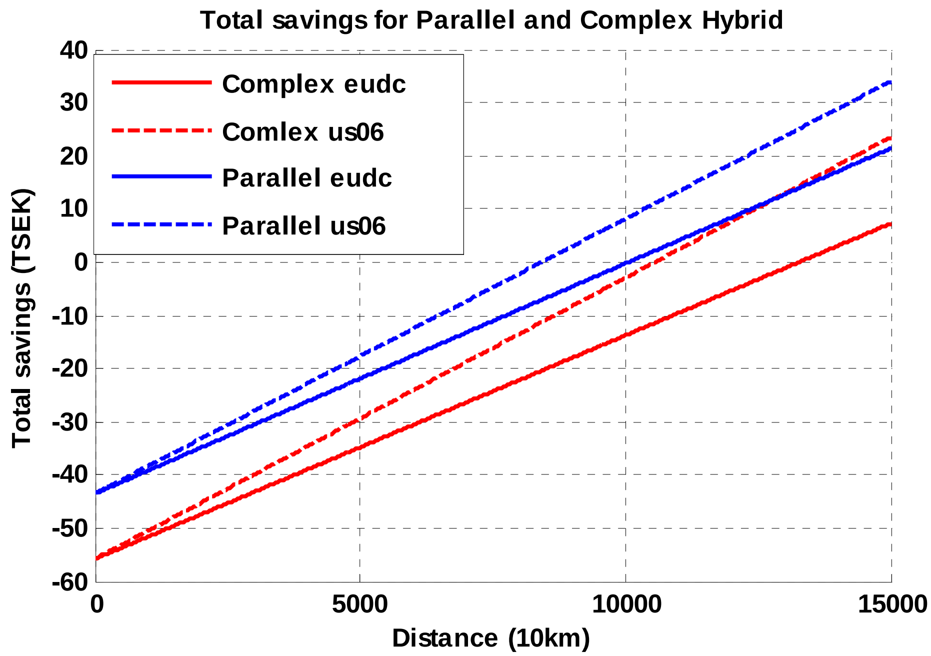

Figure 3-65 Total savings using the parallel and complex Full hybrid solution

Evaluating the two solutions

Table 3-19 show all the different basis for evaluating the full hybrid.

		Parallel	Complex
Fuel Consumption			
Fuel consumption eudc	(liter/10km)	0.44	0.46
Fuel consumption us06	(liter/10km)	0.66	0.64
Performance			
Acceleration 0-100 km/h	(s)	7.2	11.6
Maximum distance, emission free mode	(10km)	4.5	5.4
Acceleration 0-70, emission free mode	(s)	8.5	10
Top speed, emission free mode	(km/h)	159	172
Economics			
Payback distance eudc	(10km)	10000	13000
Payback distance us06	(10km)	8500	10100
Total savings eudc 50000 km	(SEK)	-22000	-34100
Total savings eudc 100000 km	(SEK)	-350	-12400
Total savings eudc 150000 km	(SEK)	21000	9300
Total savings us06 50000 km	(SEK)	-17700	-28700
Total savings us06 100000 km	(SEK)	8000	-16400
Total savings us06 150000 km	(SEK)	33900	25500
Flexibility			
Adaptability to existing platform		Very Good	Good

Table 3-19 the evaluation table for the two Full hybrid solution, Green show the winning, red the losing solution.

From Table 3-19 it's clear that the parallel hybrid solution is superior in most areas, especially in economics. The difference in total savings is huge both for the eudc and us06 drive cycle.

The fuel consumption is almost the same but the parallel hybrid has ha slight edge in the eudc drive cycles whereas the complex hybrid has an advantage in the us06 cycle.

The parallel hybrid has better acceleration in both hybrid drive and emission free mode but the complex hybrid has the ability to drive longer distances in emission free mode.

Overall the best solution is the parallel hybrid because its superiority in total savings. The difference in fuel consumption is so small that it has little effect on the choosing of the final solution. The Parallel Hybrid is also the easiest to adapt to an existing platform. The main objection against the parallel hybrid would be the shorter distance in emission free mode.

4 Final simulations

During the final simulations some minor adjustments was made to the simulation program to achieve a more realistic result. The changes did not change any vital information that was used to choose the final solutions. The main difference is slower acceleration times from 0-100 km/h. This meant that the final simulation came closer to the real Opel Astras performance figures. One change was incorporating a better battery model from saftbatteries.com, this lead to a increase in maximum distance in emission free mode. The second change was to implement a rev limiter to the combustion engine that abruptly stops the engine at 6300 rpm. Table 4-1 shows the final two hybrid solutions specifications. The final simulations can be observed in Appendix A and Appendix B.

	Mild hybrid	**Full hybrid**
Weight		
Weight (unladen)	1350 kg	1470 kg
Combustion engine		
Max ICE Power/rpm	66 kW / 4770 rpm	66 kW / 4770 rpm
Max ICE torque/rpm	135Nm /1430-4770 rpm	135Nm /1430-4770 rpm
Transmission		
Gear ratio gear 1	13.53	13.53
Gear ratio gear 2	10.35	10.35
Gear ratio gear 3	7.83	7.83
Gear ratio gear 4	5.93	5.93
Gear ratio gear 5	4.57	4.57
Gear ratio gear 6	3.5	3.5
Gear ratio gear 7	2.62	2.62
Electrical machine		
Max EM Power	15 kW	40 KW
Max EM torque	200 Nm	200 Nm
Performance		
Acceleration 0-100 km/h	10.7 s	9.4 s
Acceleration 70-120 km/h	9.8 s	8.1 s
Acceleration 0-70 km/h in emission free mode	-	8,8 s
Distance in emission free mode 10 km	-	5,1
Top Speed	200 km/h	220 km/h
Drag Coefficient	0.26	0.26
Fuel consumption eudc	0.44 liter/10km	0.45 liter/10km
Fuel consumption us06	0.63 liter/10km	0.68 liter/10km
Battery		
Battery Weight	15 kg	125 kg
Battery Energy	1.6kWh	13.3 kWh
Max Battery Power	59 kW	450 kW

Table 4-1 The final cars specifications

4.1 Cost comparisons for the Mild and Full hybrid.

The mild and full hybrids have very different setups and therefore different initial investment cost. Because the Full hybrid can drive purely electric it has some financial and environmental benefits compared to the mild hybrid. It is therefore interesting to investigate which solution that would give the largest financial gain to the end costumer.

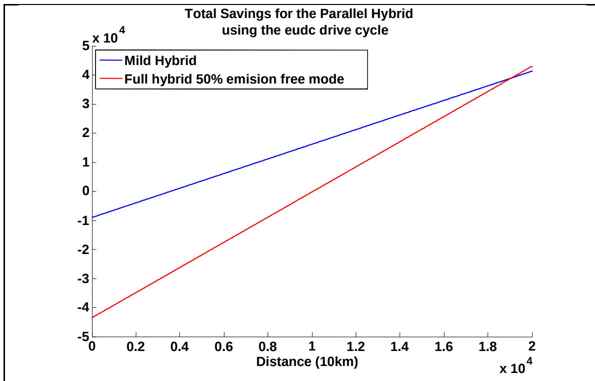

Figure 4-1 Total savings using the eudc drive cycle

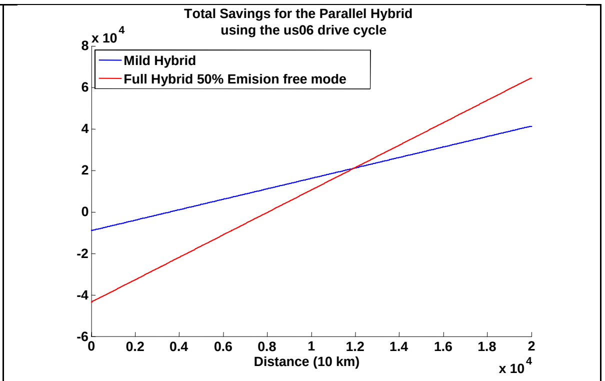

Figure 4-2 Total savings using the us06 drive cycle

From Figure 4-1and Figure 4-2 it is clear that it takes a lot of mileage before the Full hybrid is more economical then the mild hybrid.

5 Conclusion and Future work

The final conclusion is that the best solution is the simplest one. Using small to medium size components that can work efficiently together is the best way to build a hybrid car if low cost is the main focus.

Future work for this thesis would be accounting for emissions and implementing the final solutions into a real car. This is two possible and interesting future thesis projects. Emissions are especially important because they effect the environment in a huge way.

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Appendix A, Simulations for Mild hybrid

Graphs for full hybrid using eudc drive cycle

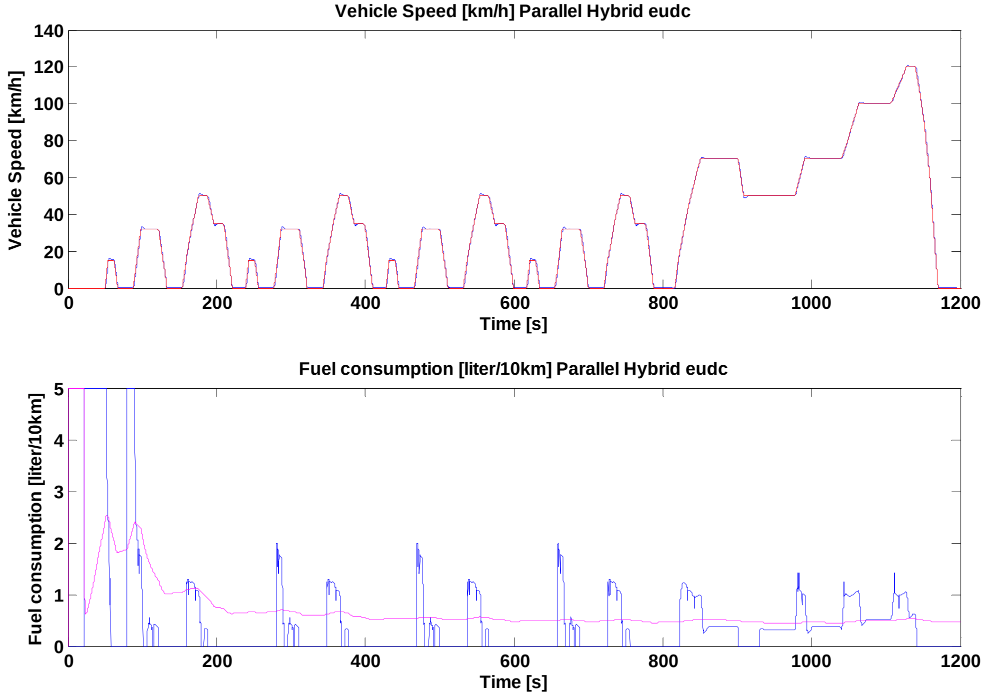

Figure 0-1 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

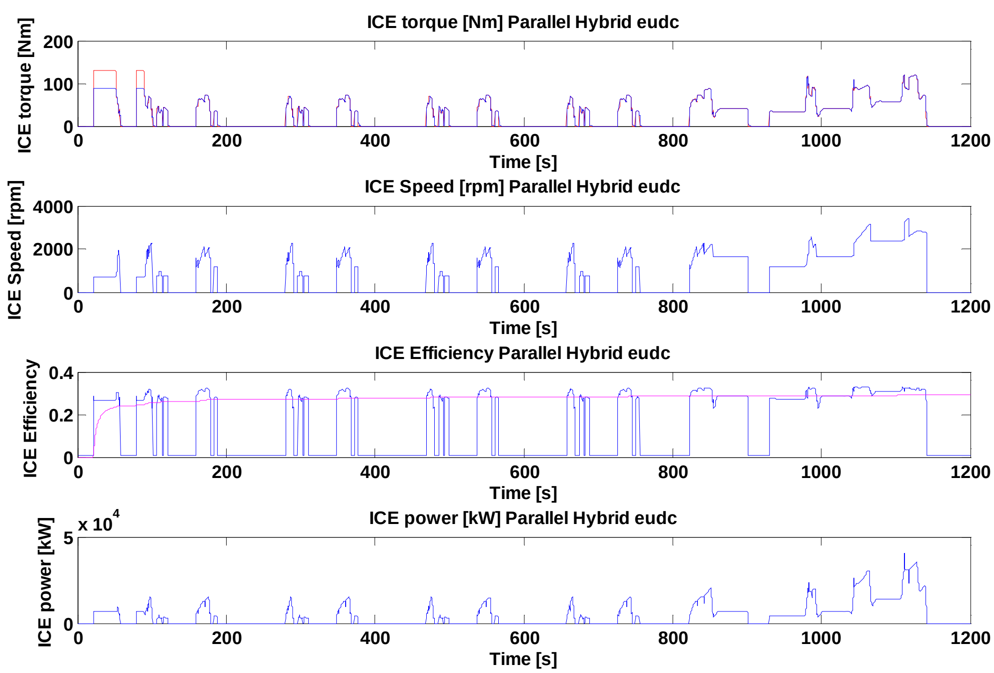

Figure 0-2 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

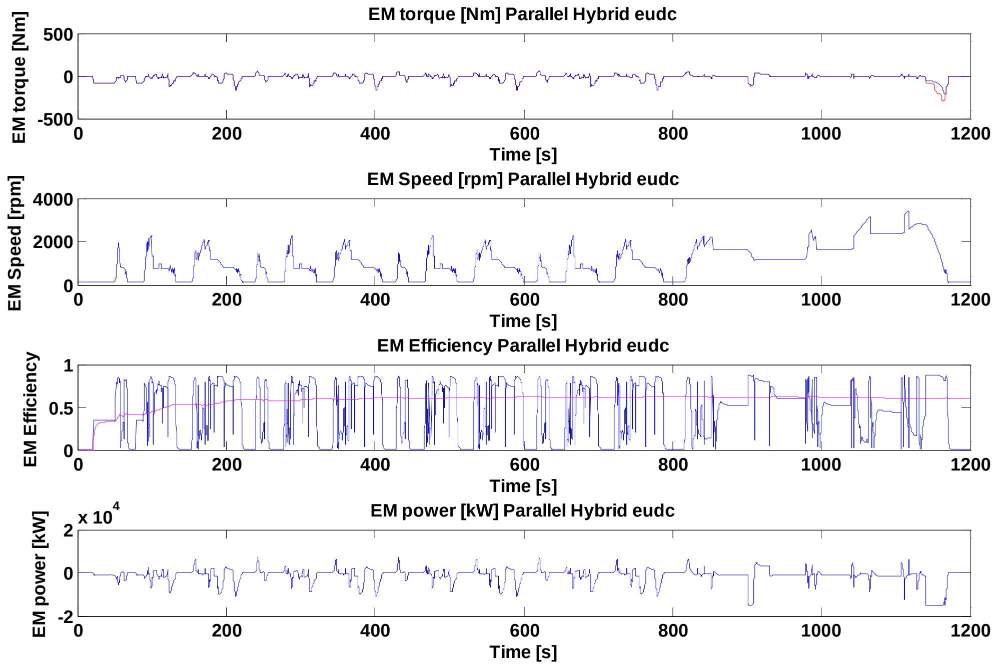

Figure 0-3 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

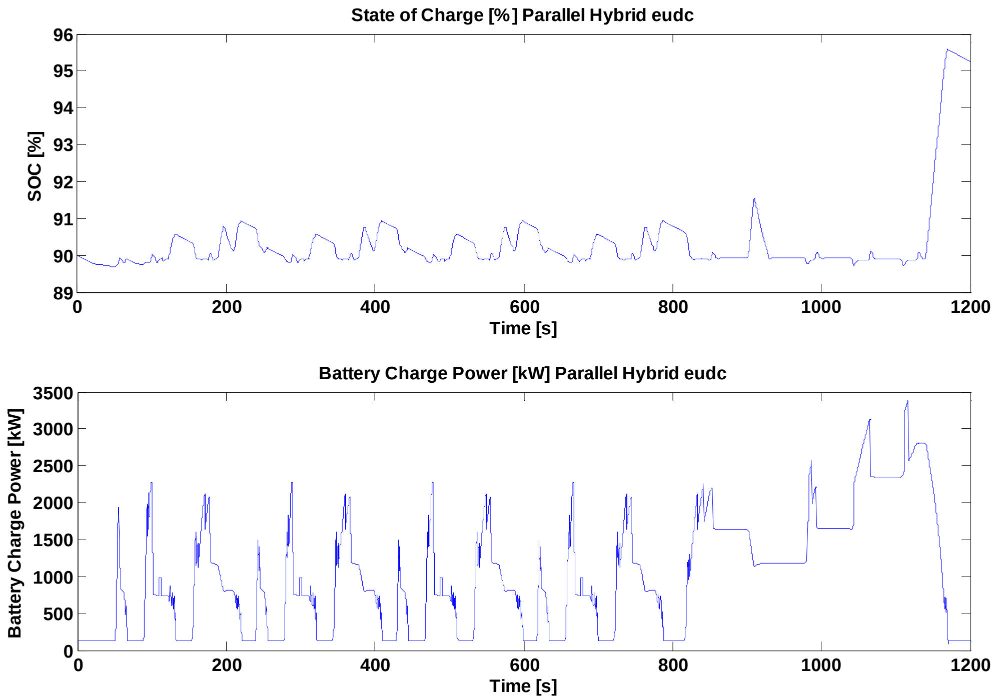

Figure 0-4 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

Graphs for mild hybrid using Us06 drive cycle

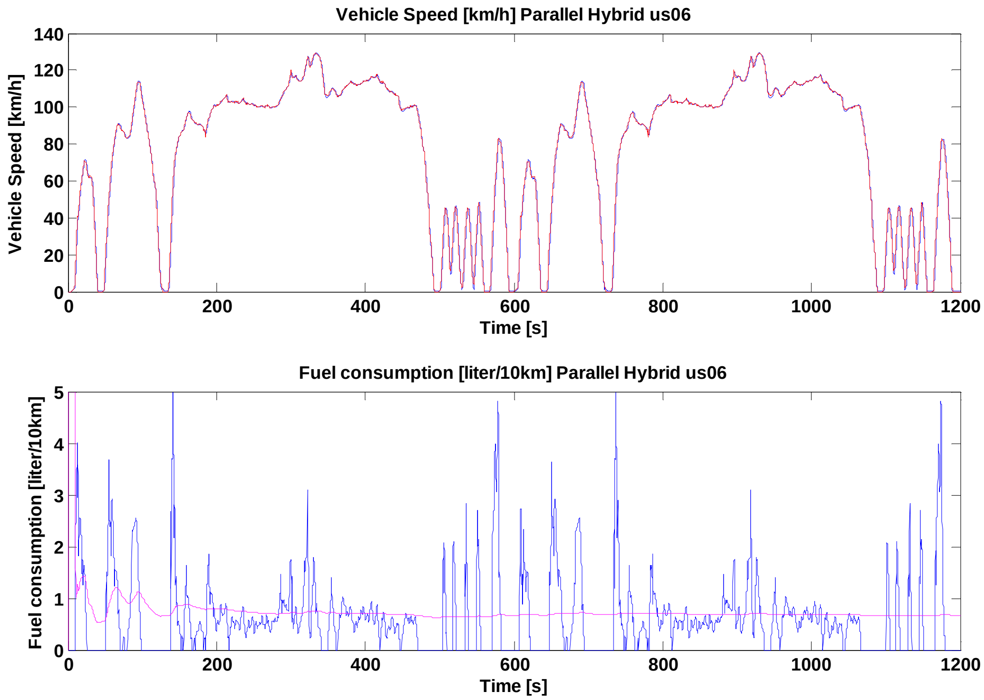

Figure 0-5 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

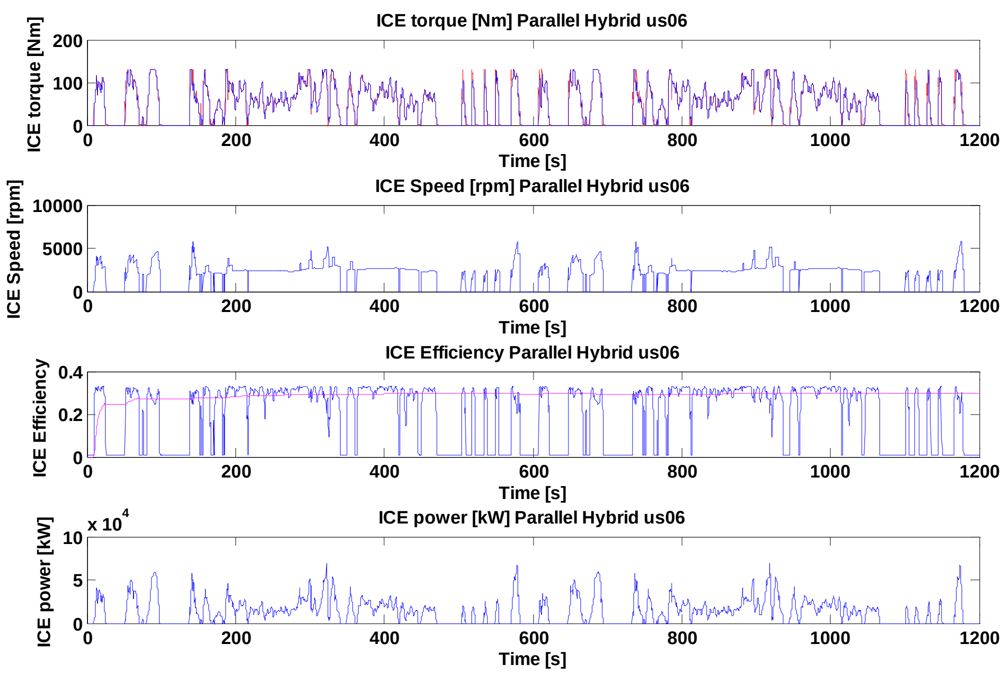

Figure 0-6 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

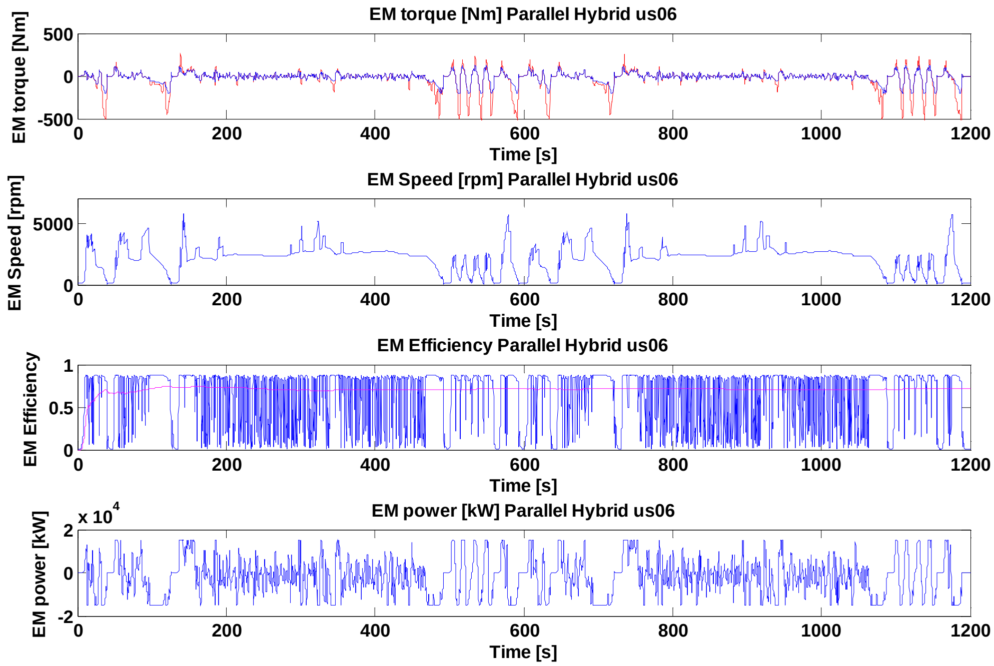

Figure 0-7 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

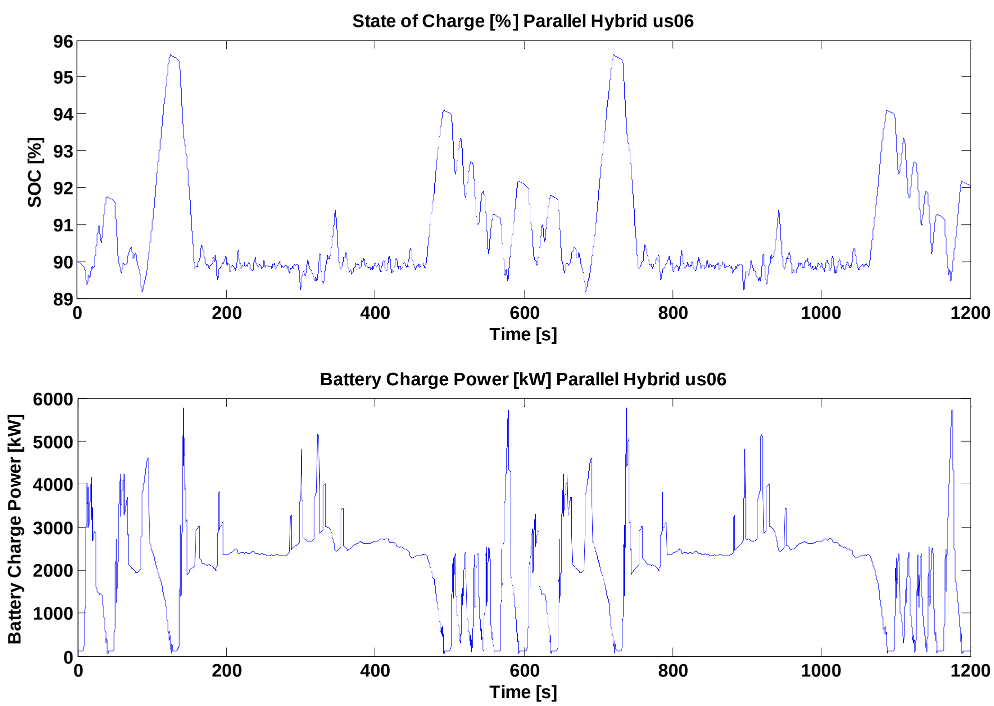

Figure 0-8 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

Graphs for acceleration 0-400 for mild hybrid

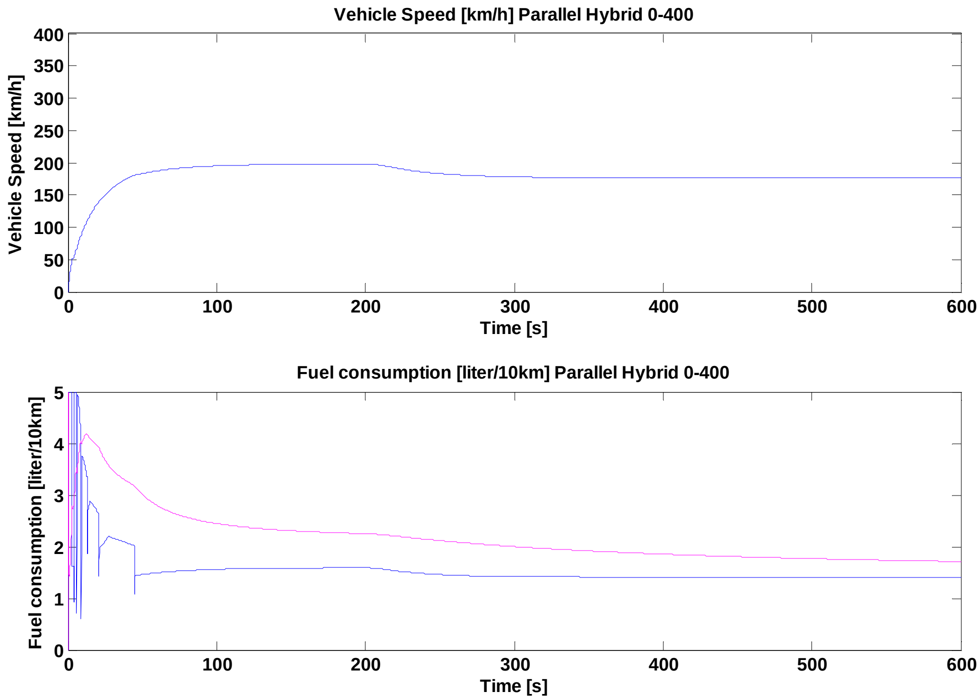

Figure 0-9 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

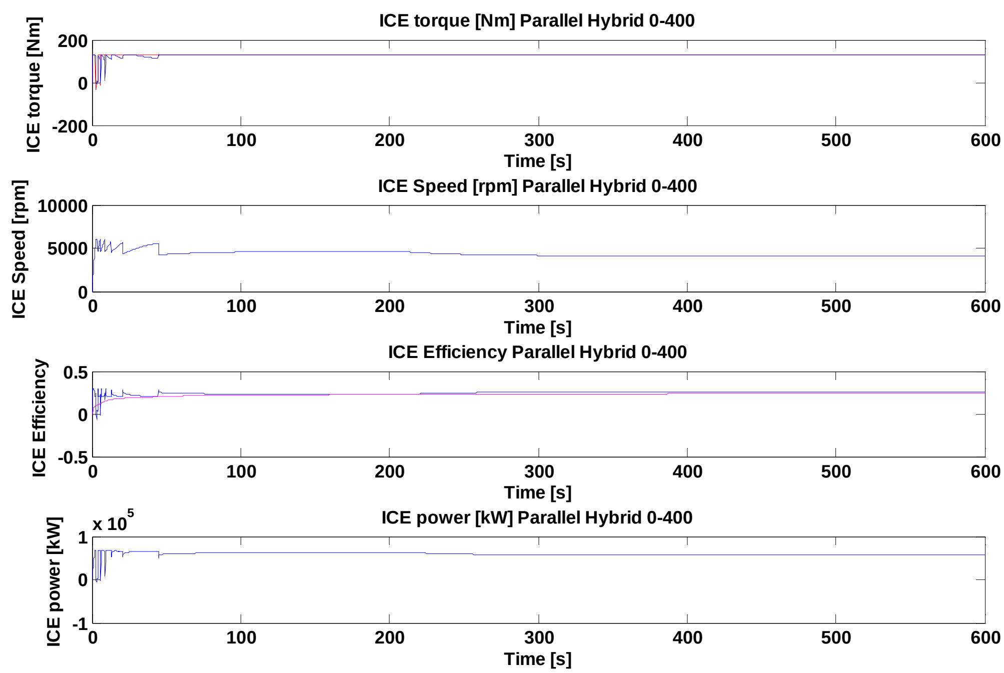

Figure 0-10 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

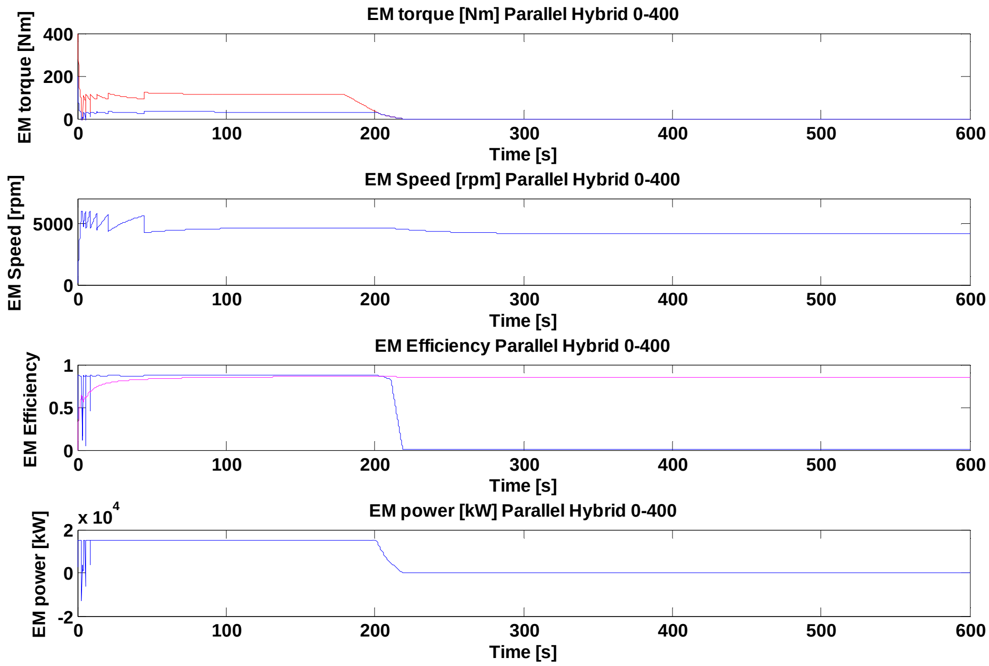

Figure 0-11 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

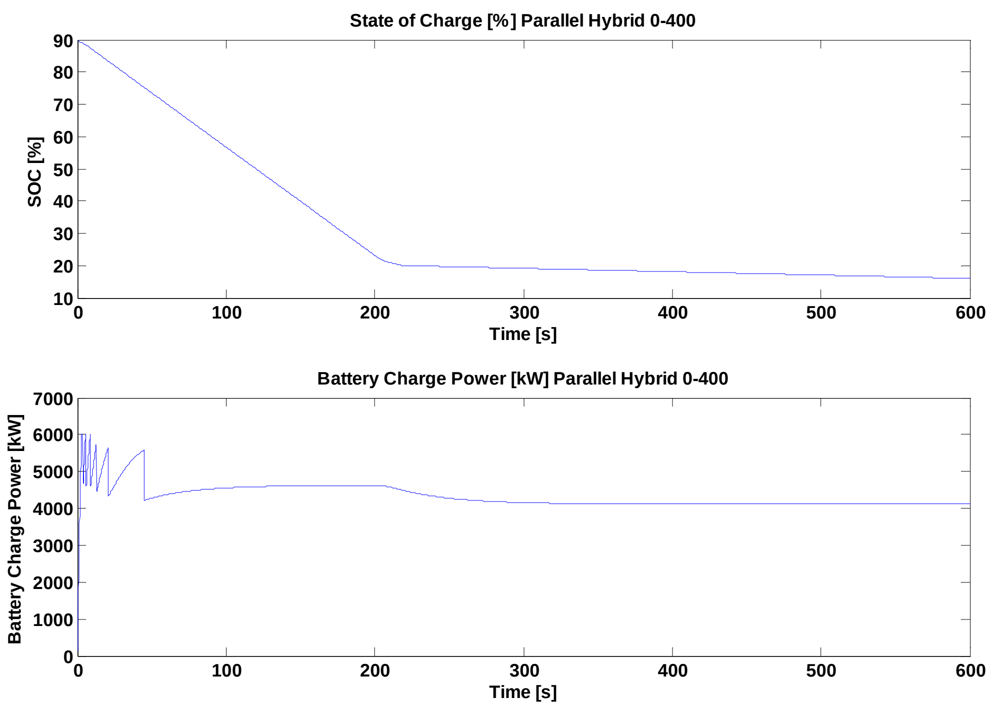

Figure 0-12 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

A. Appendix B, Simulations of Full hybrid

Graphs for full hybrid using eudc drive cycle

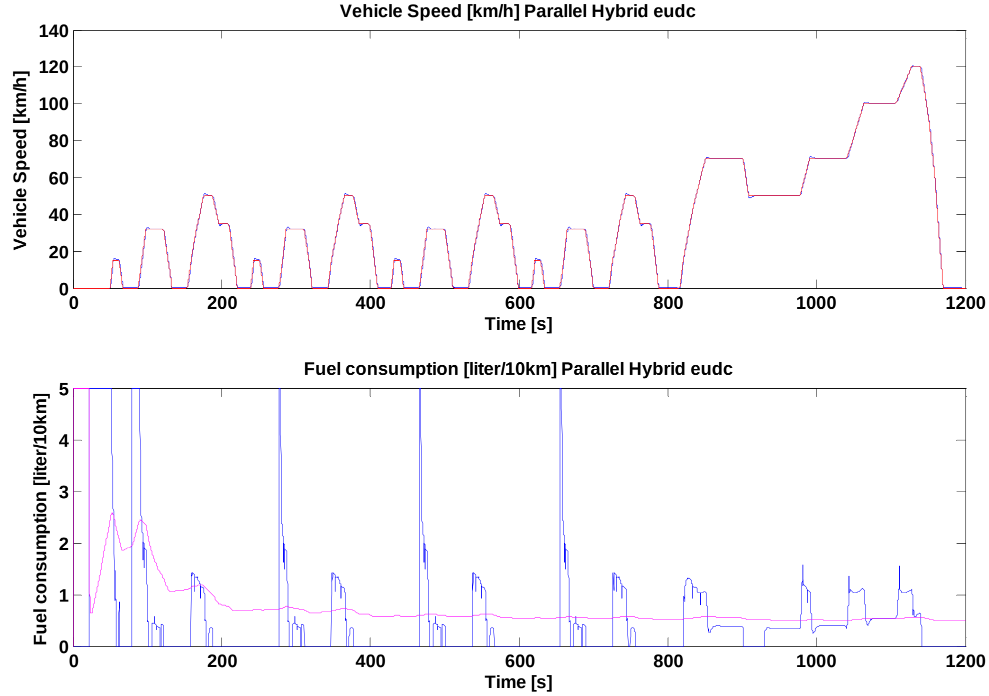

Figure A-1 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

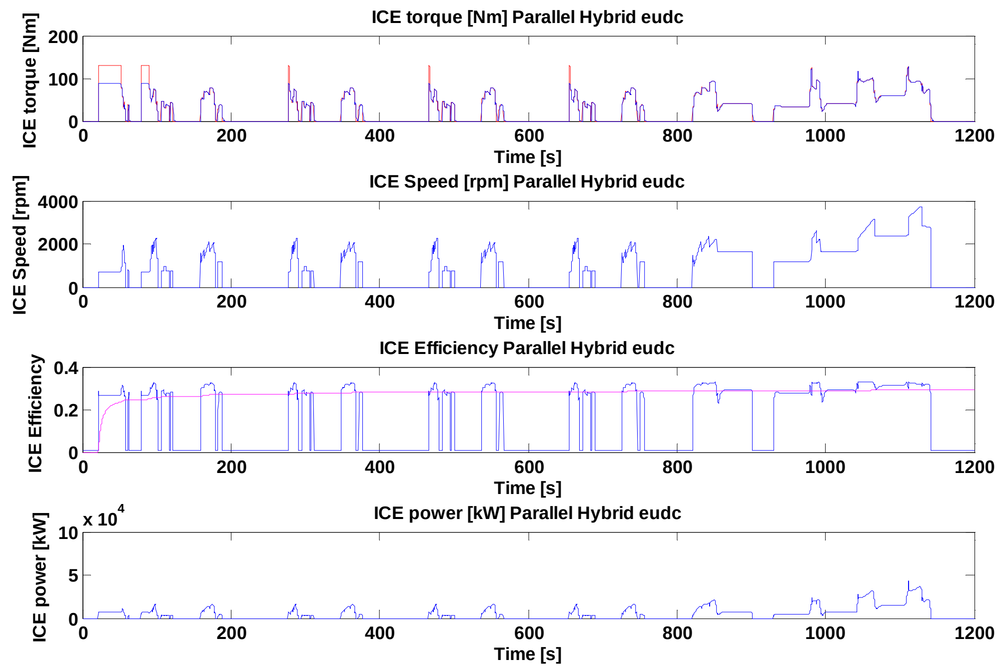

Figure A-2 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

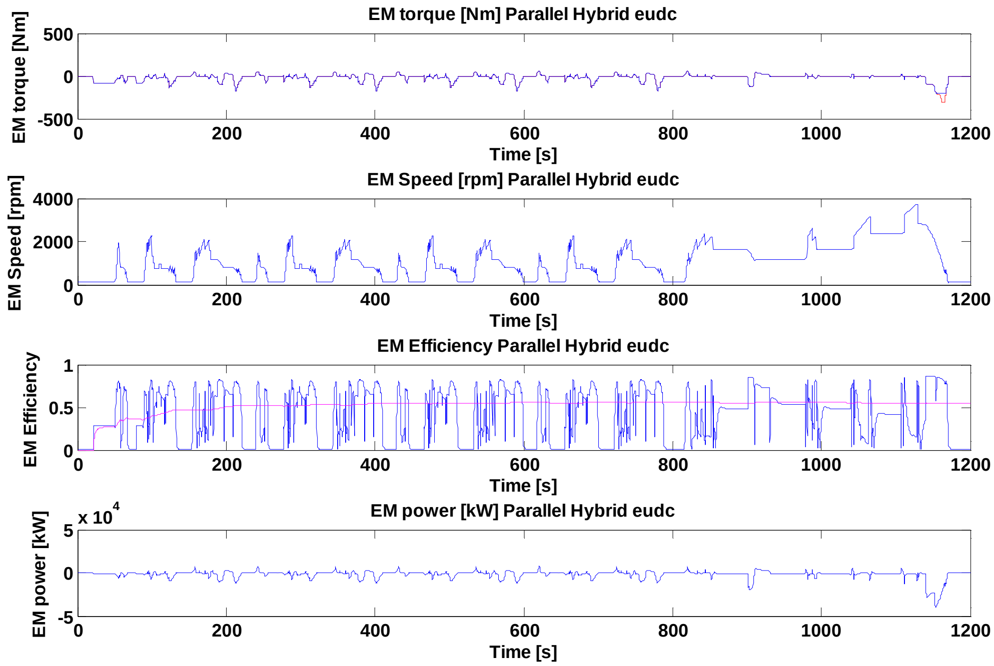

Figure A-3 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

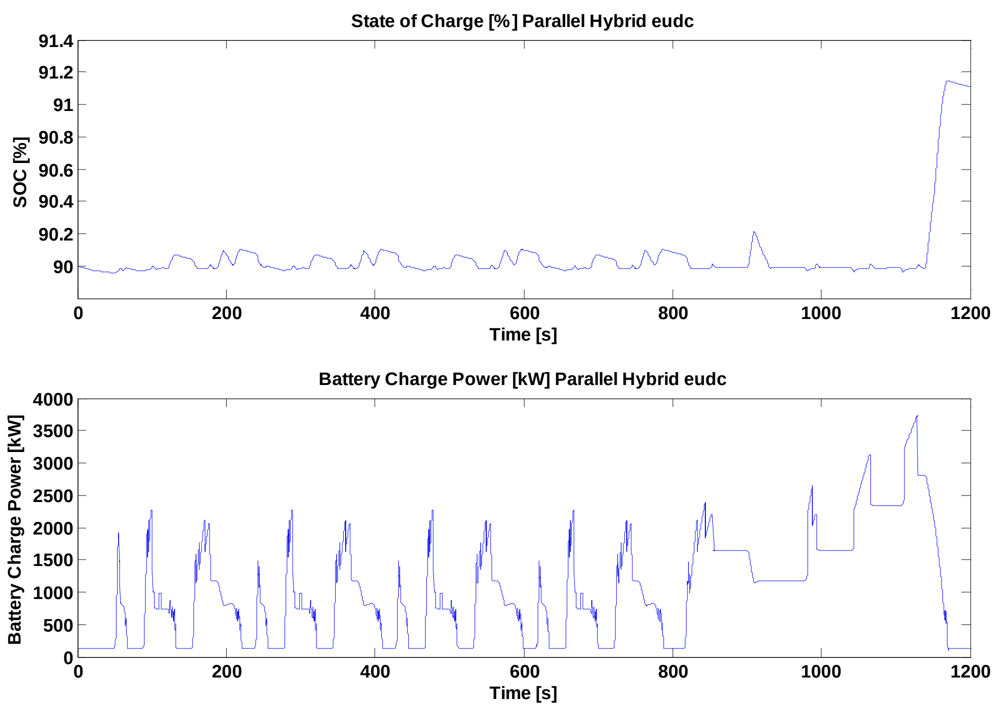

Figure A-4 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

Graphs for full hybrid using Us06 drive cycle

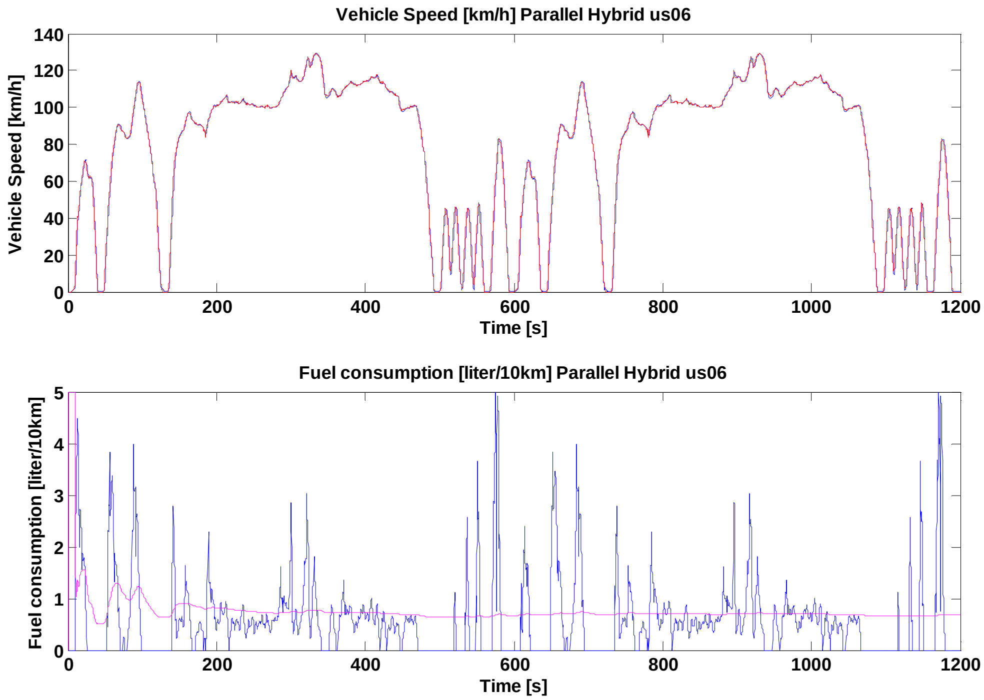

Figure A-5 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

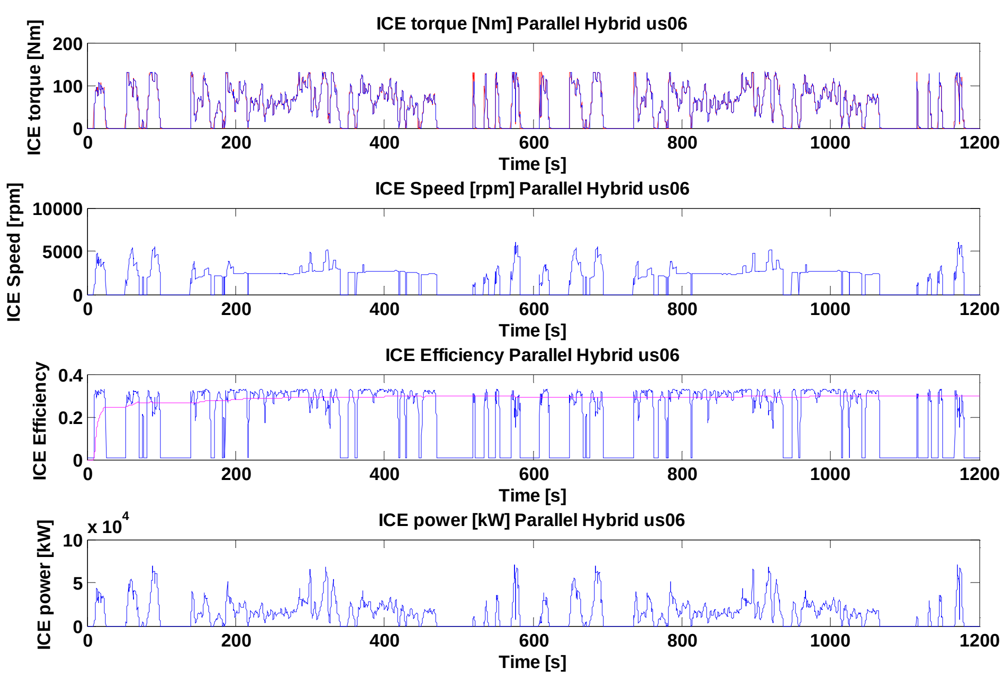

Figure A-6 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

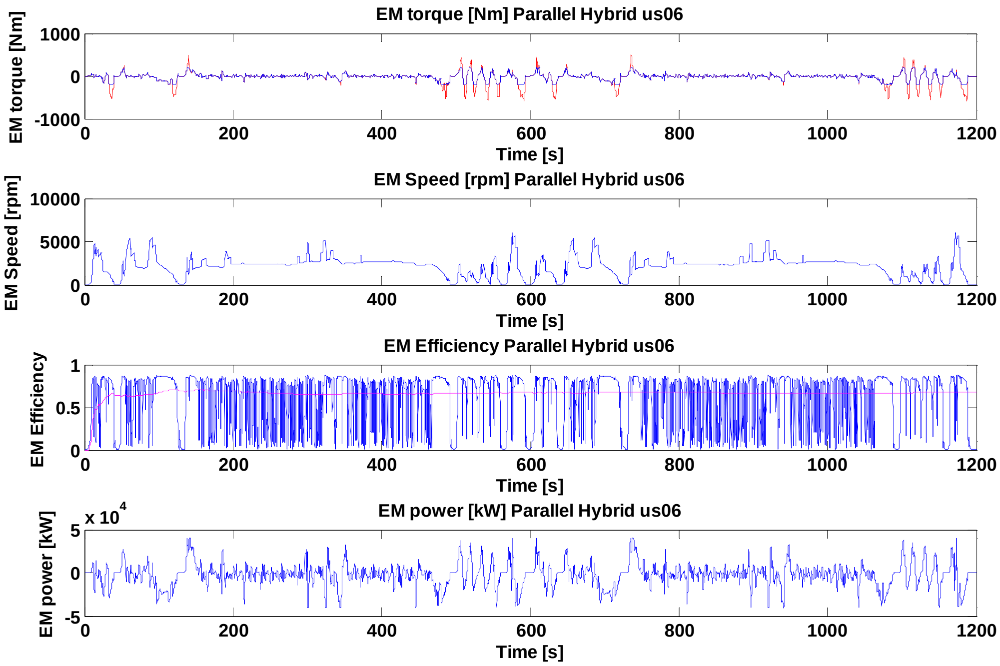

Figure A-7 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

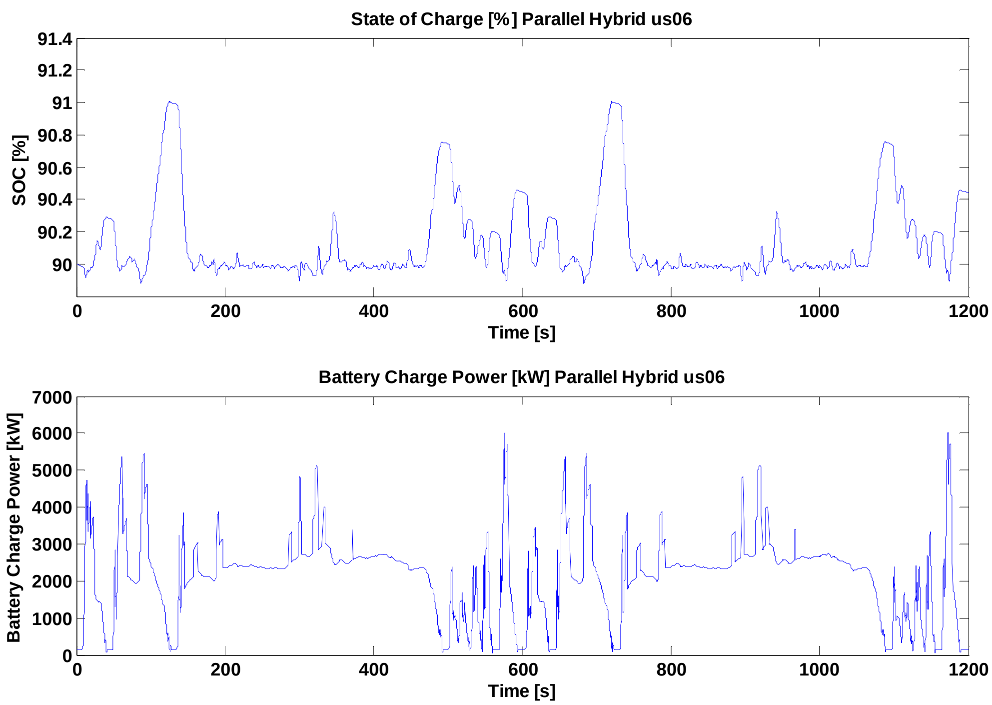

Figure A-8 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

Graphs for acceleration 0-400 using full hybrid

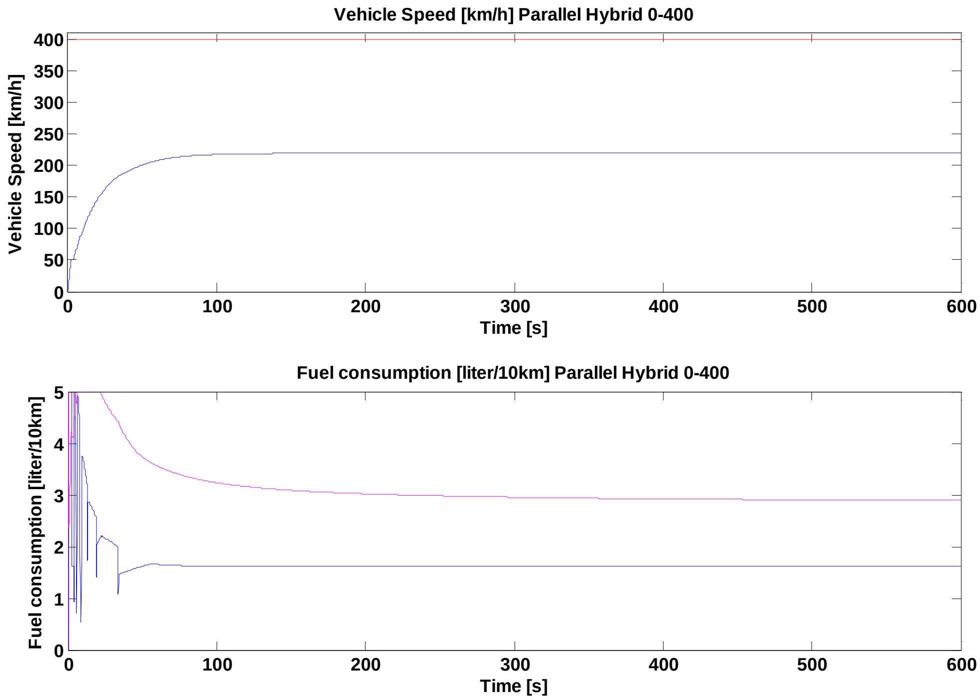

Figure A-9 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

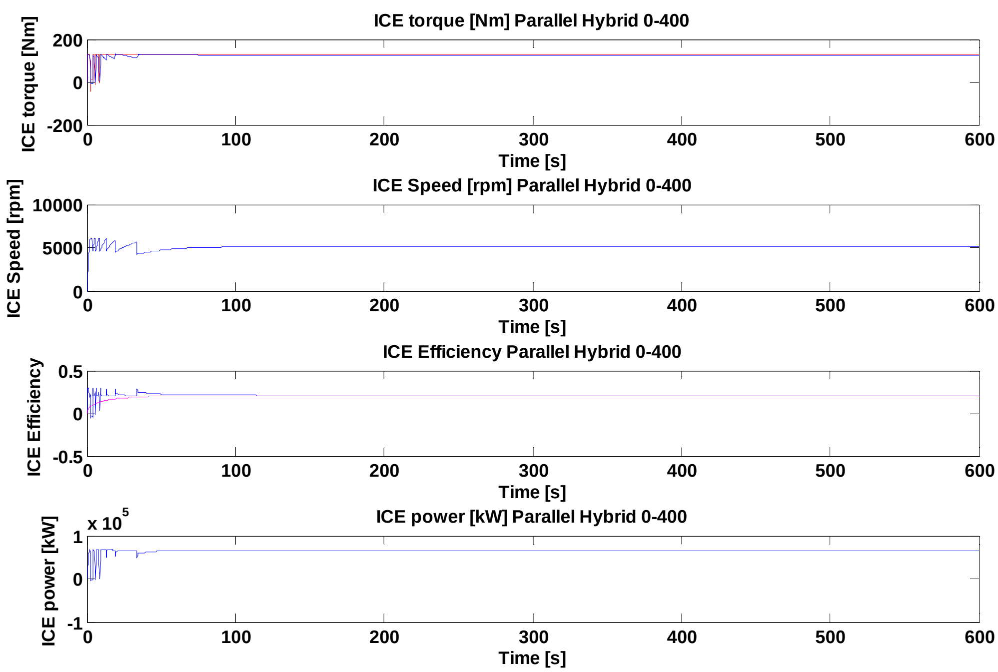

Figure A-10 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

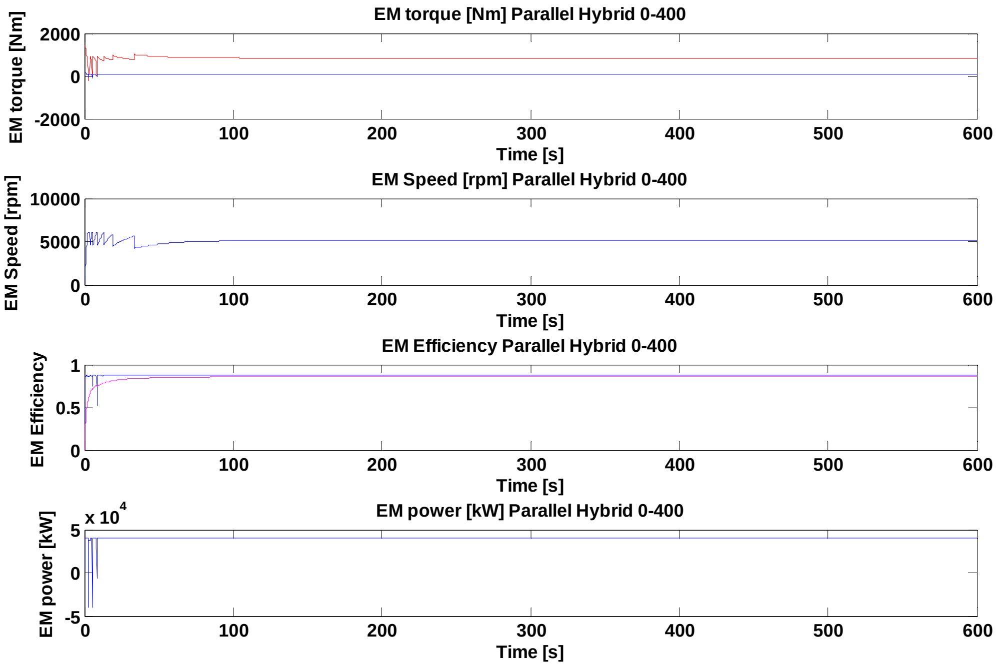

Figure A-11 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

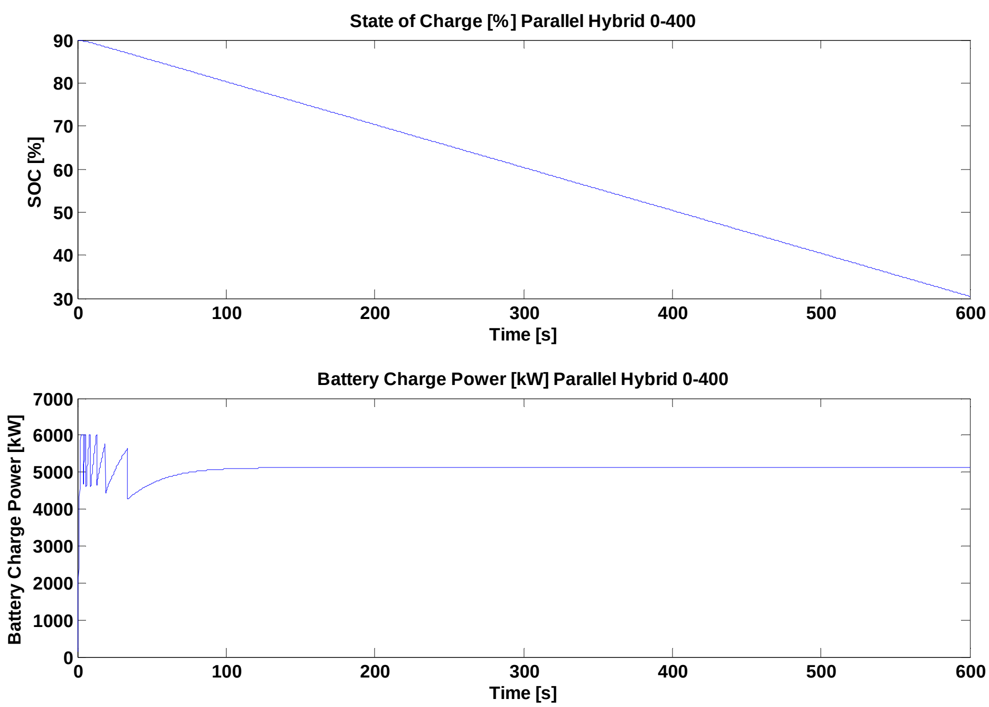

Figure A-12 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

Graphs for full hybrid in Emission free mode

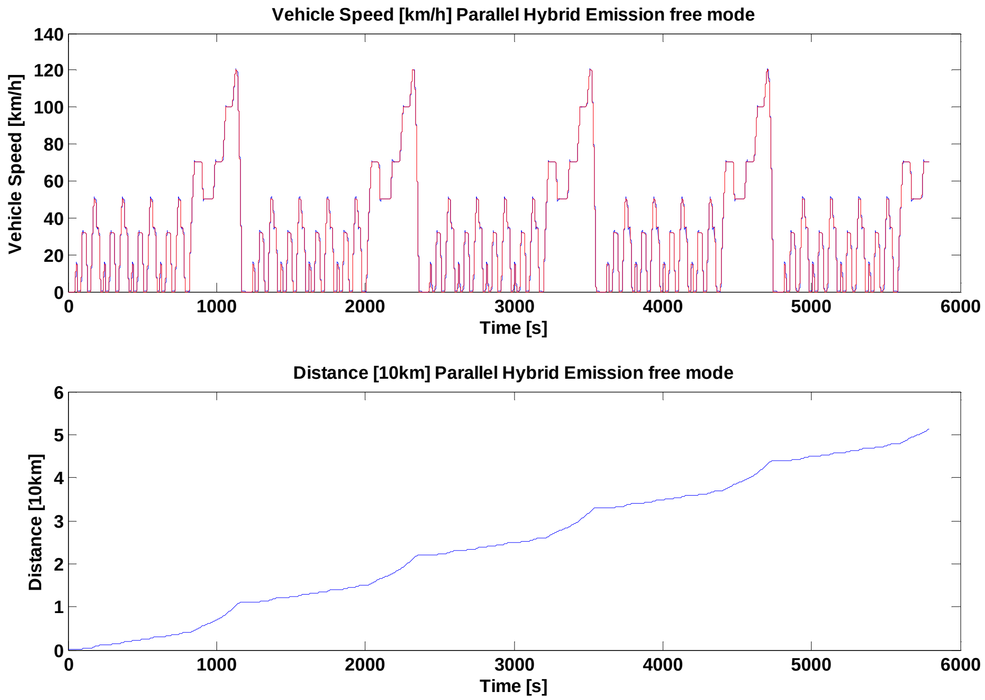

Figure A-13 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

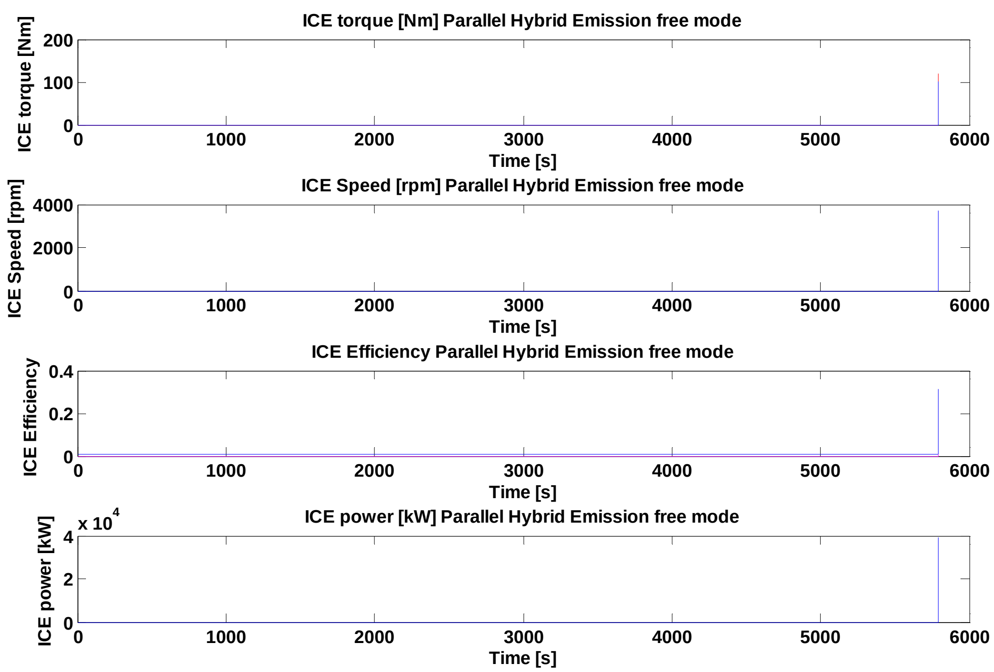

Figure A-14 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

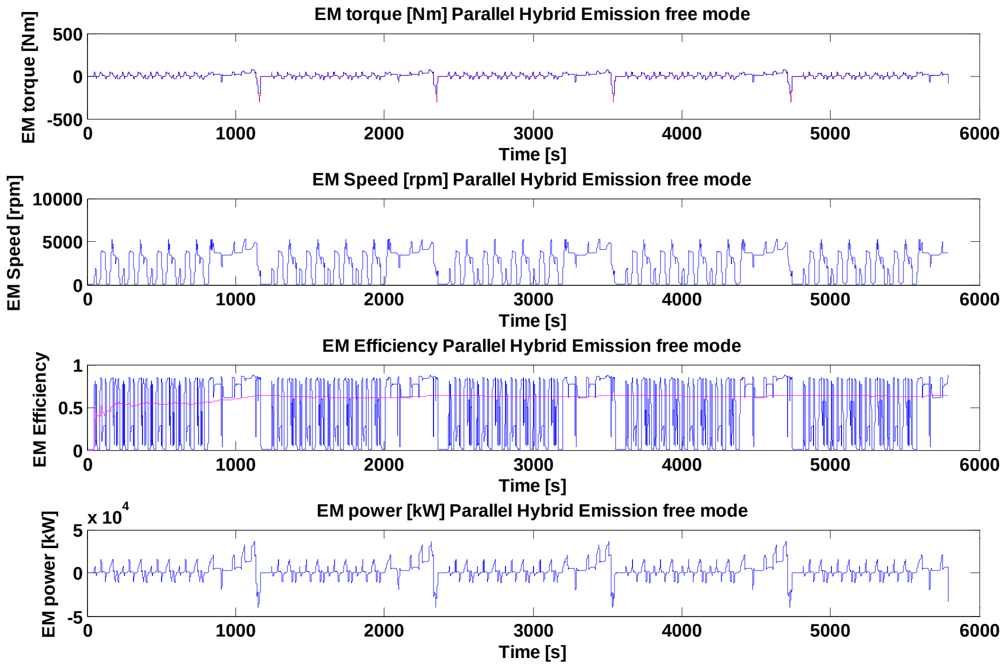

Figure A-15 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

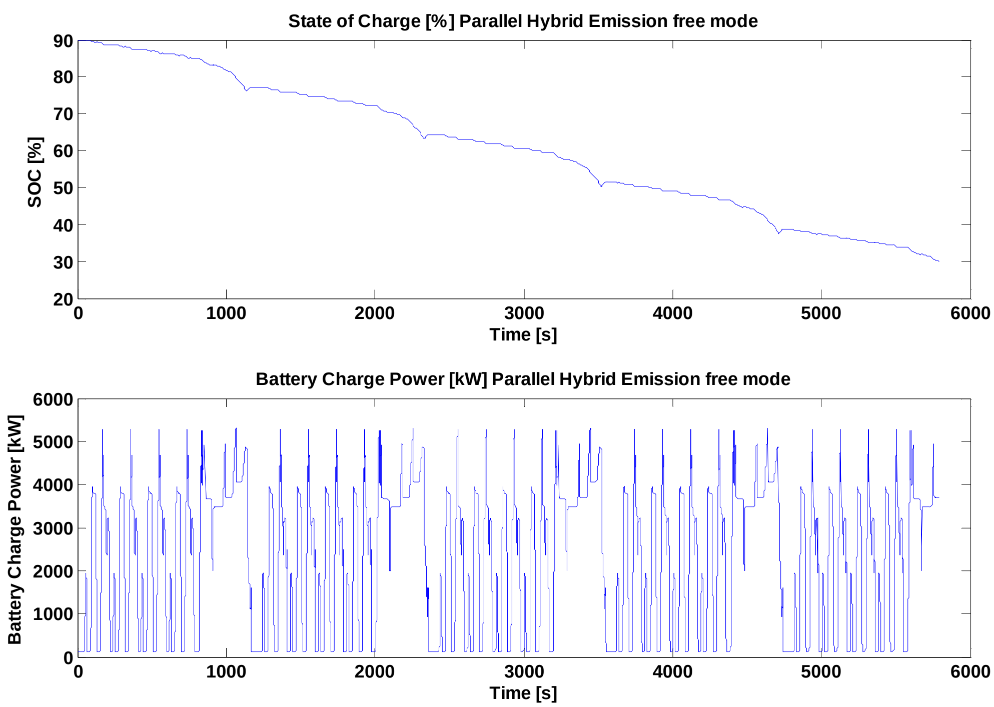

Figure A-16 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

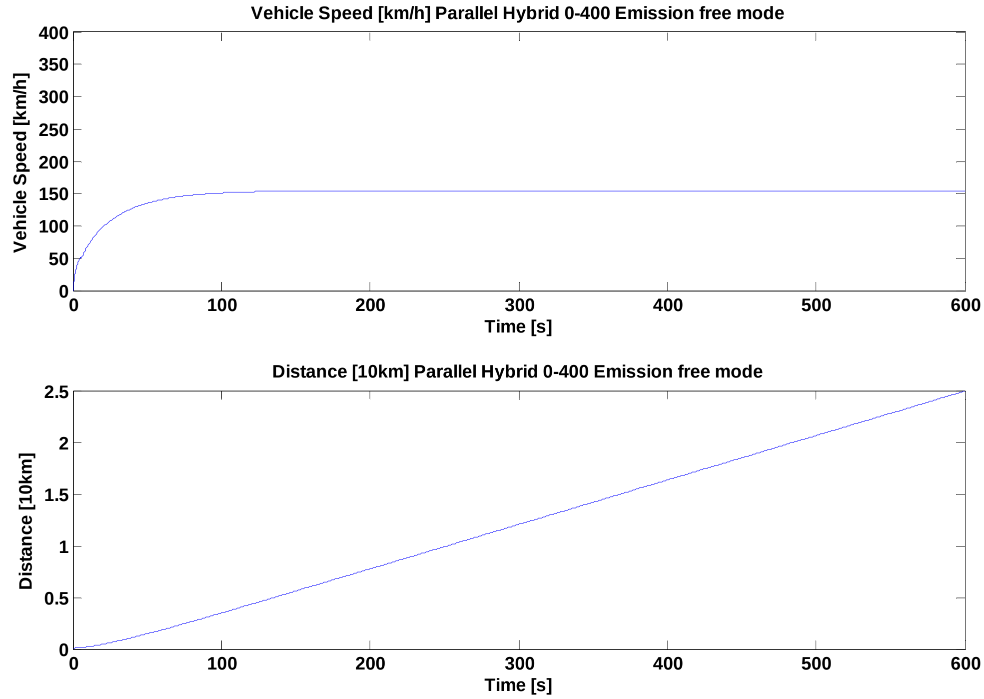

Figure A-17 vehicle speed and Fuel consumption, red is reference values, blue is the actual value and magenta is average value

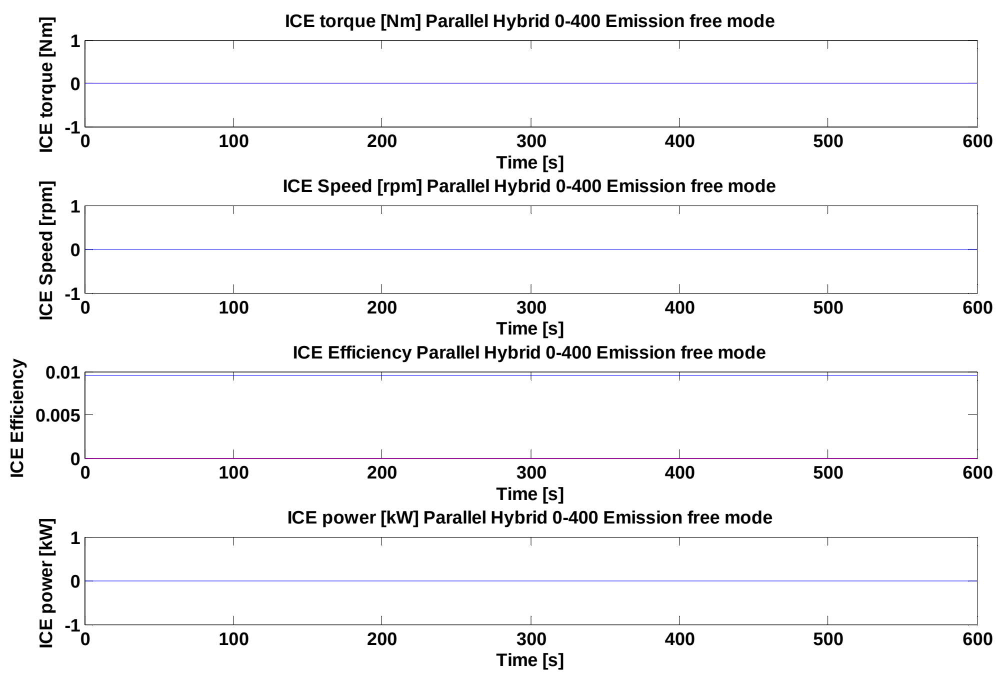

Figure A-18 The Combustion engines simulation data, red is reference values, blue is the actual value and magenta is average value

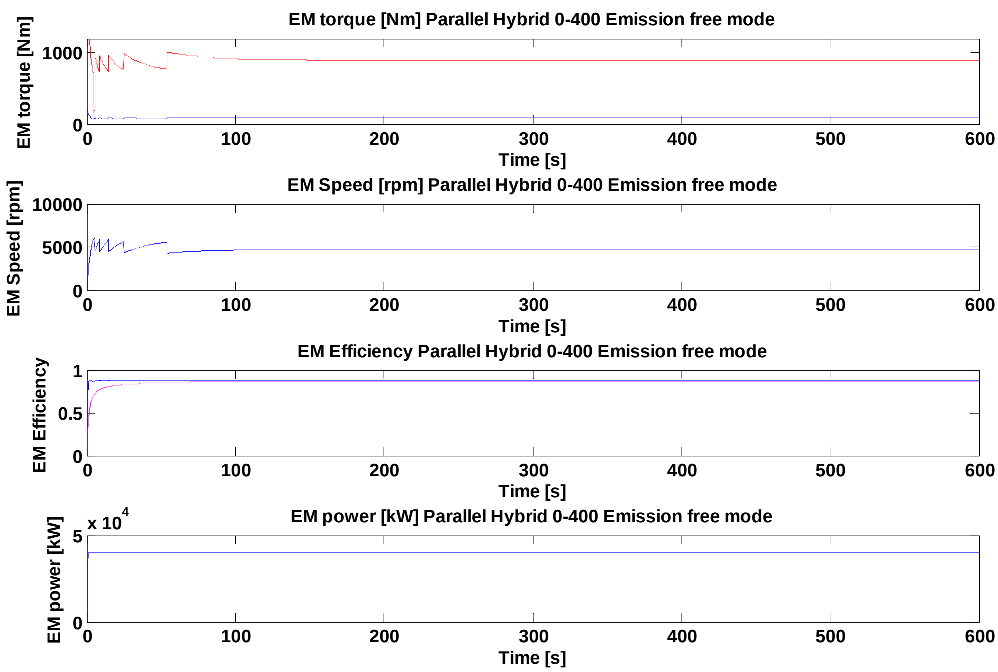

Figure A-19 The electrical machines simulation data, red is reference values, blue is the actual value and magenta is average value

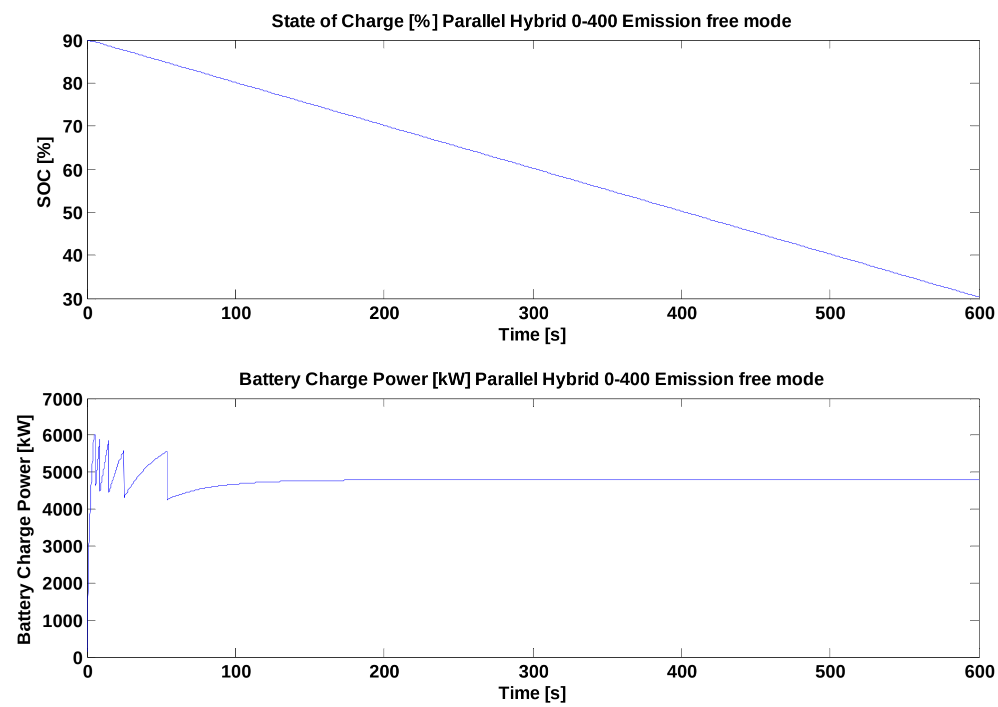

Figure A-20 The state of charge and charge power of the battery, red is reference values, blue is the actual value and magenta is average value

B. Appendix C the final cars specifications

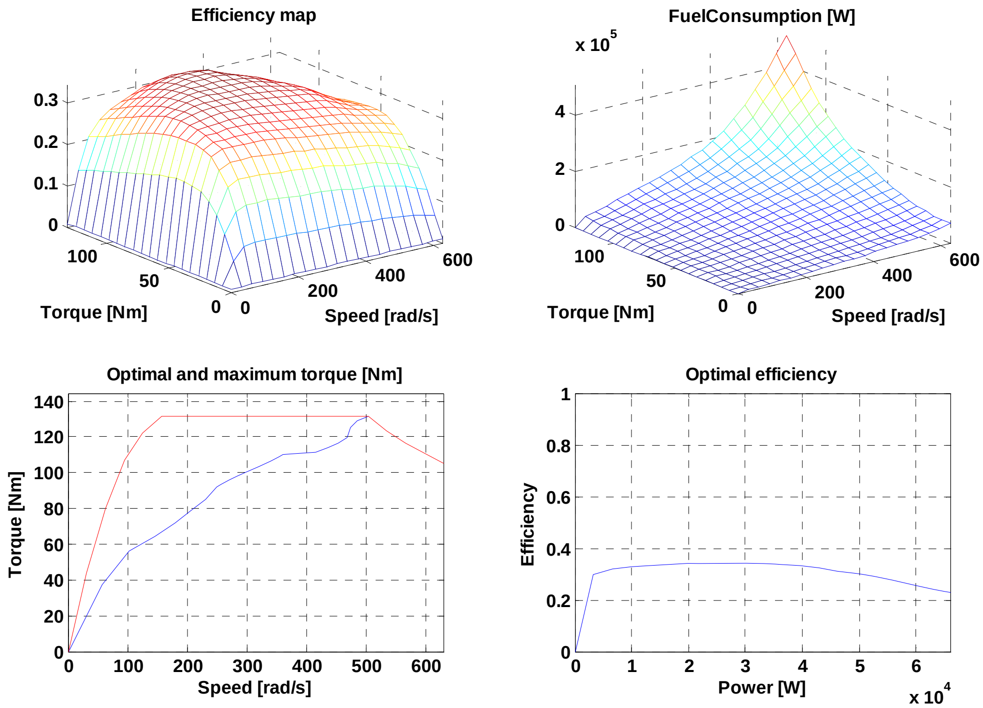

Figure B-1 The Combustion engines specifications

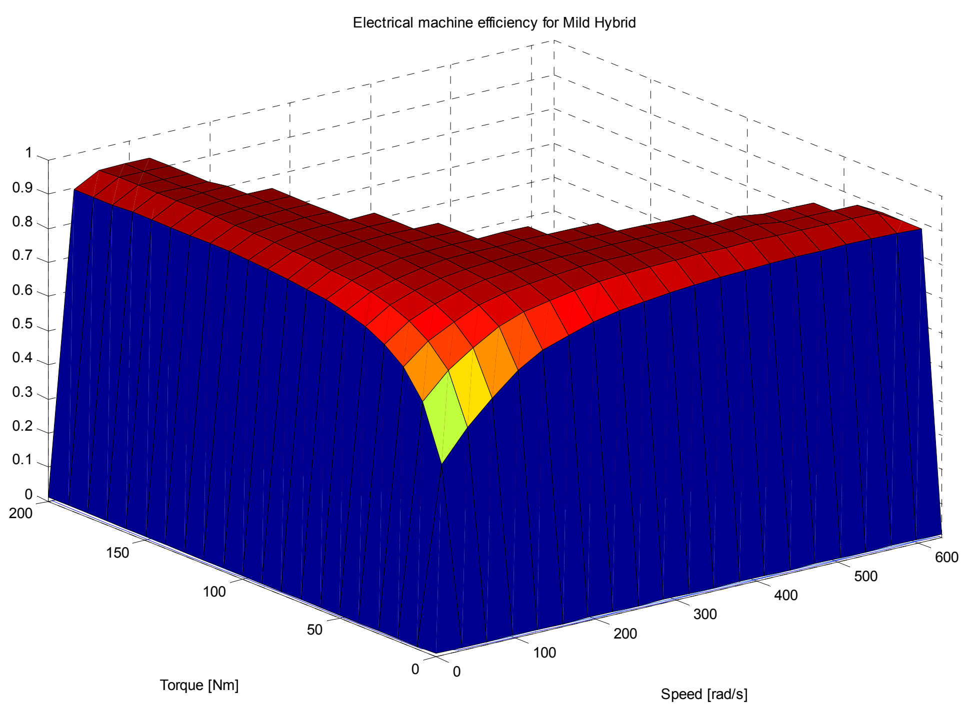

Figure B-2 The electrical machines specifications for the mild hybrid

Figure B-3 the batter charge efficiency for the mild hybrid

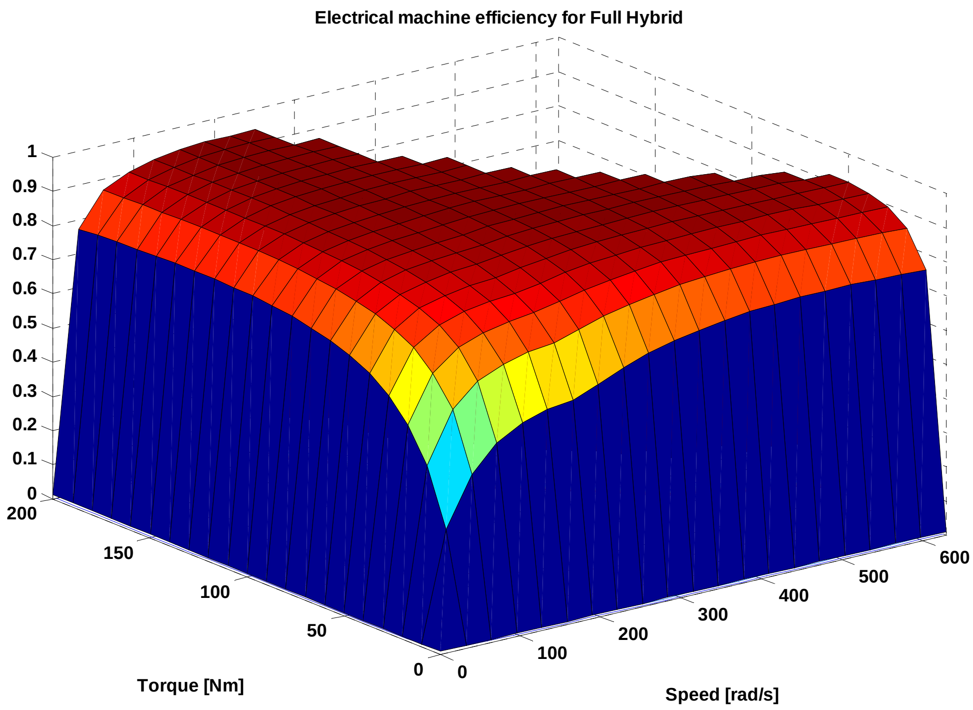

Figure B-4 The electrical machines specifications for the full hybrid

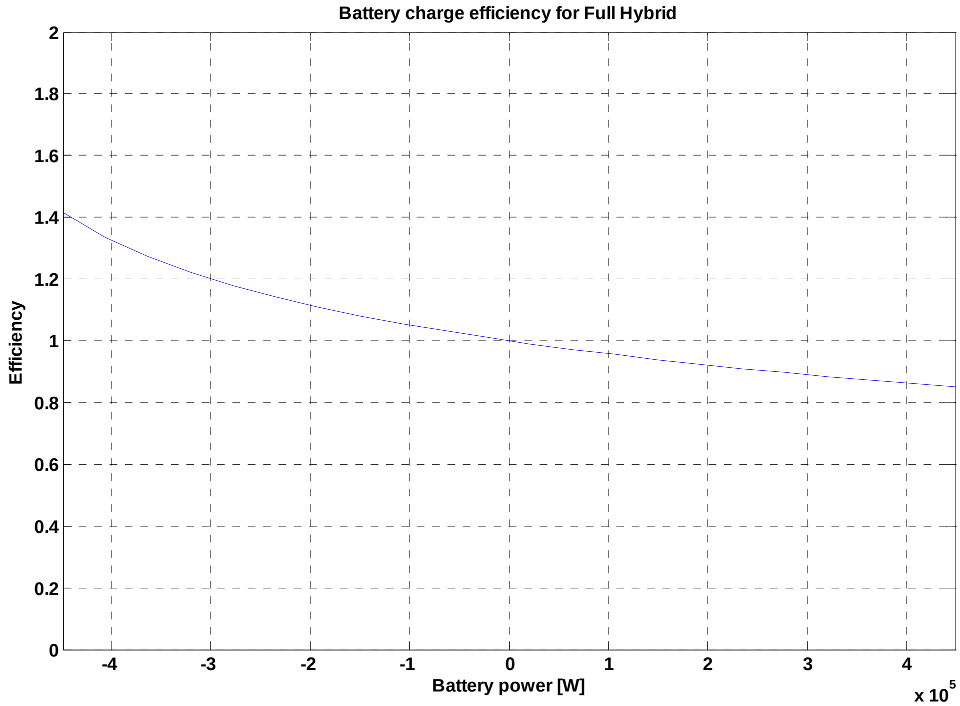

Figure B-5 the batter charge efficiency for the full hybrid