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Development and Construction of a Serial and Parallel Hybrid driveline

Master of Science Thesis

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Göteborg, Sweden 2011

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Abstract

An increasingly important issue in the transportation sector of today is to reduce the consumption of fossil fuels and also to leave the fossil fuels and make way to renewable fuels. An important possibility to make steps towards this goal is the hybrid systems.

In this project two types of hybrid electrical drivelines has been designed and compared, the first one is a serial hybrid and the second is a parallel. The serial hybrid driveline has also been manufactured and mounted in a vehicle. The vehicle is called Smarter and is build at Chalmers University of Technology; it is designed to compete in Shell Eco-Marathon where it shall travel as far as possible on one liter of petrol. The serial driveline consists of a brushed DC motor for traction, a 48V supercapacitor as the primary energy source and a fuel injected 35cc four stroke engine that powers a dual generator setup that charges the supercapacitor.

The two types of drivelines have been simulated together with the rest of the vehicle using Simulink. The drivelines have been compared while running through different driving situations using a self developed drivingcycle produced with Matlab. They have been compared with aspect to performance and fuel economy.
The results of the simulations shows that the parallel driveline outperforms the serial one in both performance and economy due to that the parallel can run at optimal conditions more time of the drivingcycle. This is especially the case at steady state driving situations, where the petrol engine can be used to both traction the vehicle and charge the electrical energy storage.

The designed serial hybrid driveline was successfully fitted to the Chalmers Eco-marathon vehicle during the Shell Eco marathon competition 2010, where it achieved a distance of 153.8km consuming one liter of petrol resulting in a fuel consumption of 0,0065 l/km, putting the team in an overall 12^{th} place and was the best Swedish team in the Urban Concept class.

Index Terms: Hybrid vehicle, HEV, Plug in hybrid, Electric vehicle, Serial hybrid, Parallel hybrid, Super capacitor, EMS, Fuel injection, Ignition, Internal combustion engine, ICE, Compression ratio, Fuel consumption.

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We would also like to give our thanks to the persons involved in the project in different way such as Oskar Josefsson, Professor Torbjörn Thiringer from the department of Electric Power Engineering who both have helped us in moments when we lost the faith of reaching the endpoint. ”got all stuck”.

We would also like to thank Professor Sven Andersson from the department of Applied Mechanics for giving us the opportunity to apply our designs in Smarter and to be aboard with the ”Eco Smarter Team 2010” on site during the competition in Germany Lausitz.

Christoffer Nylén
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Abbreviations and Nomenclature

- a = Speed of sound in air [$\frac{m}{s}$]
- A = Area of intake pipe [cm^2]
- A_v = Front Area of vehicle [m^2]
- $ABDC$ = After Bottom Dead Center
- AC = Alternate Current
- Acc_{time} = Time to reach specified max velocity [s]
- AFR = Air to Fuel Ratio
- $ATDC$ = After Top Dead Center
- B_r = Cylinder bore radius [cm]
- $BBDC$ = Before Bottom Dead Center
- BLDC = Brushless DC
- $BSFC$ = Brake Specific Fuel Consumption
- $BTDC$ = Before Top Dead Center
- C_d = Drag coefficient
- C_N = Electric machine speed constant [$\frac{rpm}{V}$]
- c_r = Friction of wheel
- C_t = Electric machine torque constant [$\frac{Nm}{A}$]
- C_{wf}/C_{wheel} = Wheel friction coefficient
- CAD = Crank Axle Degrees
- CI = Compression Ignition
- CR = Compression ratio
- CVT = Continues Variable Transmission
- d = Air density [$\frac{kg}{m^3}$]
- DC = Direct Current
- ED = Number of degrees the exhaust valve opens BTDC plus 180deg
- EM = Electric Machine
- EMS = Engine Management System
- η = efficiency
- η_{max} = max efficiency
- F_{el} = Force from electric machine
- FC = Fuel Consumption
- FI = Forced Inducted
- g = Gravitational constant []

- GR = Gear ratio
- HEV = Hybrid Electric Vehicle
- HMS = Hybrid Management Strategy
- I = Current [A]
- I_{max} = Maximum delivered current to the electric machine [A]
- ICE = Internal Combustion Engine
- ID = Inside Diameter exhaust pipe [cm]
- l = intake pipe length [cm]
- L_h = Exhaust header length [in]
- m = Mass of vehicle in [kg]
- m_{cal} = mass of calibration weights [kg]
- m_d = mass of driver
- m_{pb} = mass of dynamometer [kg]
- m_v = mass of vehicle
- MAP = Manifold Air Pressure
- MAT = Manifold Air Temperature
- N = Revolutions per minute [rpm]
- N_{load} = Rotational speed of electric machine during load [rpm]
- $N_{nominal}$/N_{nom} = No load speed of electric machine [rpm]
- N_t = Resonance frequency [Hz]
- NA = Naturally Aspirated
- P = Power [W]
- P_{drag} = Power to overcome aerodynamic resistance
- P_{el} = Electric Power
- P_{in} = Input Power
- P_j = Power of terminal resistance
- P_{mech} = Mechanical power for electric machine
- P_{out} = Output Power
- $P_{rolling}$ = Power needed for rolling vehicle
- P_{vel} = Power to maintain cruising speed
- R = Resistance [Ω]
- R_t = Thermal resistance
- R_{th1} = Thermal resistance winding-housing [KW^{-1}]
- R_{th2} = Thermal resistance housing-ambient [KW^{-1}]
- R_{wheel} = Wheel radius [m]

- S = Engine stroke [cm]
- $S_{vehicle}$/S_v = Vehicle speed in $[\frac{m}{s}]$
- SI = Spark Ignition
- SoC = State of Charge
- T = Torque [Nm]
- T_{max} = Maximum created torque from an ideal electric machine [Nm]
- T_{Nmax} = Max braking torque at max permissable dynamometer speed [mNm]
- T_{nom} = Nominal braking torque for dynamometer [mNm]
- T_{wheel} = Torque at wheel [Nm]
- TD = Torque Distribution
- TDC = Top Dead Center
- U = Volts [V]
- V_d = Cylinder displacement [cm^3]
- V_{eff} = Effective resonance volume [cm^3]
- ω_{wheel} = rotations on wheel
- vel_{mean} = mean velocity of vehicle [m/s]

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Chapter 1

Introduction

It is today widely known that the fuel consumption of a vehicle clearly affect the surroundings where it is used. It is also widely known that the affects of the emissions are not only local but also affecting the climate globally. As a reason to this increasing and today widely spread problem, this report will propose a working solution to lower the emissions and fuel consumption and thereby increasing the overall efficiency. In particular this report will address the hybrid vehicles that have the trend of becoming more and more accepted and popular. The main reason for this is apparently the amount of fuel which is consumed in order to transport the owner from position A to B. In order to make this area even more interesting for universities graduating engineers, several companies arranges competitions where the universities can compete with their own developed solutions to the problem. One of those companies is Shell that arranges the so called Shell ECO marathon each year. (As Chalmers University has decided to enter this competition studies within this field has been done.) As a part of this the following report will address the development of a parallel hybrid driveline to be used in one of Chalmers ECO marathon vehicles called Smarter. Today Smarter uses a series hybrid driveline developed last year, and by switching this to a parallel we hope to be able to lower the fuel consumption even more. The study will begin by comparing the two techniques of hybrid drivelines to point on the reasons to develop a parallel. A simulation to show the possible savings by using a parallel technique instead of series will be done. This will be followed by a discussion of suitable components based on data from Smarter and last year participation. The driveline will then be manufactured and mounted to a test bench that was constructed to bench last year series solution. The goal of the project is to be able to mount the parallel driveline into Smarter and use it during the ECO marathon competition taking place 6-7 May 2010 in Lausitz.

1.1 Problem background

Why is there a need for such a system as hybrid electric vehicles HEV´s?; the main reason is clear as it nowadays are a lot of debates and writings clearly stating that if we do not change our habits using the conventional energy sources, they will run out. The conventional energy sources include coal and in our case specifically the petroleum based fuels. The problem that the petroleum based energy will run out is although not the biggest issue, but its more about the emissions from the vehicles; and especially the emissions in urban areas where a lot of people is in direct contact with the traffic. This means that the emissions can cause serious health problems. The HEV´s are by this reason a way to lower the impact to make the city environment healthier and it will also lower the traffic noise.

Another view speaking for the project is that Smarter last year did not get a result. As the engine assembly and linked parts didn't withstand stresses. The main reason is although as already mentioned the today communities striving for greener transportations. As this is important today both by political as well as environmental means. It is also today important for the company's manufacturing transport vehicles to stick out from the rest having a low fuel consumption aim in the today harsh competition of customers.

By doing this project we will also gain the understanding of the problems connected to a hybrid driveline as well as hopefully being able to find a solution of those.

1.2 Purpose

The purpose of this project is to study and make practical and theoretical models of two of the available electric hybrid system that is available today, namely the parallel and serial hybrid drivelines. The study will include fuel economy, performance and drivability of the systems.

More in detail, an aim is to design the system with all the components carefully chosen in order to achieve the highest possible efficiency. Furthermore, an objective is the vital components such as the electrical motors and the internal combustion engine which will be measured in form of efficiency and power. Moreover, a purpose is to make mathematical models of the measured data in order to achieve highest possible accuracy in the simulation models.

The further objectives are to simulate the complete drivelines with the mathematical models of the measured data. In addition a target link is to join the driveline models together with a model of a real vehicle, the complete model of the vehicle and driveline will then be simulated through different driving cycles to find the pros and cons of the systems.

Last but definitely not least, an important intention is to verify the simulation models to real models of the drivelines which will be placed in the Chalmers Eco-Marathon vehicle Smarter.

1.3 Shell Eco Marathon

The developed drivelines will be fitted in Chalmers hybrid vehicle Smarter. Smarter is a small one person vehicle which is developed for the purpose of attending in competitions to get as far as possible using as little fuel as possible. Smarter was to participate in the Shell ECO marathon competition in Lausitz in Germany 6-7 May 2010.

Shell ECO marathon is a competition where the ultimate goal is to be able to travel with a vehicle as far as possible on one liter of petrol. Or any likely propellant; as nitrogen, gas or diesel where their respective energy density is recalculated so that the consumed volume is to be the same as for one liter of petrol. There are today different classes for the attendants. There are two main classes, the first one called Prototype and the second Urban Concept. The prototype class is not as hard regulated as the Urban class and the designs are allowed to be as they want. The Urban class on the other hand is more restricted and the vehicle needs to fulfill certain rules and conditions. They have to look like a regular vehicle, they need working lights and hydraulic brakes on all four wheels. This is to be able to link them better to real life vehicles. The competition is also divided in different classes when it comes to type of propulsion where one class is hybrid vehicles. The purpose of the competition is to challenge high school and colleges to design, build and test energy efficient vehicles. The winner of the competition is as earlier stated; the team/school that drives the longest distance consuming the least amount of energy [5].

1.4 Objectives

Design and construct a complete working serial hybrid system to be fitted in Chalmers Eco marathon vehicle Smarter. Second objective is to design a complete parallel hybrid system to be used in the same vehicle. The goal includes running the vehicle with the system during the Eco-marathon competition described in *Section* 1.3.

1.5 Limitations

In this report the following limitations should be noted, we decided to limit our research, develop and design criteria's to the actual use of our designed drivelines in the vehicle provided only. The underlying theory that the decisions are based on can although be used in order to redesign the solution to fit to a wider area of use. For example using other figures in the simulation for road load, and hereby the system could be scaled to be used in other applications. The design on the mechanical parts that is manufactured by ourselves are limited to what could be achieved by ourselves according to the maneuvering skills of the available workshop machines achieved during the project only. Those designs are by this reason not flawless and could be enhanced both in aspects of material use as well, as technical by using other manufacturing methods as NC-machining.

Chapter 2

General Theory

In order to conduct this master thesis project, a solid ground to base decisions on is needed, this ground would also be of a great help for the reader to get a better perspective to understand the reason for decision made. The word hybrid is defined as a crossbreed in Nationalencyklopedin [6] a Swedish dictionary. The word originates from the Latin word hy´brida which mean crossing. Combining this word with vehicle most often means the vehicle driveline is equipped with two different power sources. There are today many ways of combining different sources for propulsion of a vehicle. Using the word hybrid car most often means the vehicle driveline consists of a petrol or diesel combustion engine combined with an electrical motor and an electric system for controlling it. There are although other combinations as fuel cell-electric or gas-electric. This report will only deal with the petrol combustion engine combined with electric motor type, in other word, a full hybrid propulsion system.

There are three different combinations or ways of implementing a hybrid system. The two most common are the serial hybrid and parallel hybrid system [7]. The third is a combination of the two. In this report only the series and parallel hybrid system will be discussed and explained. As those those two techniques are of most interest. The parallel-series combination which is also called parallel-split can although be understood by combining the theory of series and parallel. Independent of type; the driveline in a hybrid consists as described above of two types of different sources of energy. Most often an ICE is used in order to charge a battery or equivalent energy storage. The stored energy is then used by an electrical machine EM for propulsion. Common for the two types that will be investigated and discussed here is that they both consist of one ICE, an energy bank/reservoir and one or more EM´s.

2.1 Function Serial Hybrid

A serial hybrid vehicle is in principle an electric vehicle but with the possibility to charge the energy storage when driving, in *Figure 2.1* the function of the serial hybrid system is shown. The source for traction in a serial hybrid vehicle is EM´s, either one or more. They can be connected directly to the traction wheels if the vehicle has more than one EM or through a differential that can split the power between the wheels as for an ordinary driveline. The EM can also give power through a gearbox or a continuously variable transmission further on called CVT. This arrangement gives the vehicle better performance and lets the machine work at an optimal point where the efficiency is high.

To be able to generate electric energy some form of energy source is needed which is an internal combustion engine, further on called ICE. The ICE does not need to be as large as for an ordinary driveline as its only function is to drive a generator which charges the main energy storage. The only requirement is that it should be as powerful as the generator. The ICE is connected to the generator either directly or thru a transmission in order to match their rotational speed for best performance. This means that booth the ICE and the generator will work in a high efficiency region when running.

The operation mode of the ICE and generator are controlled by the State of Charge, the state of charge will be called SoC further on. The SoC is a measure that tells the condition of the energy storage. When the SoC has reached a set lower limit which is dependent on type of energy storage the vehicle is equipped with. The controller starts the ICE in order to generate electric energy; the ICE is then shut off when the SoC has reached the upper set limit, also dependent of type of energy storage used.

In a series hybrid vehicle the ICE is only used in order to charge the secondary energy reservoir, namely the battery. This means that the ICE cannot itself be used to directly drive the vehicle. The ICE is instead directly connected to an EM acting as a generator converting the kinetic energy from the prop shaft into electric energy charging the battery. The ICE will be powered on as long as there is a need to charge the battery, in other word as long as the SoC is lower than set maximum. The energy stored in the battery will then be used by a second EM that is connected either directly to the drive axle of the vehicle or to a gearbox which in turn is connected to the drive axle. There is also need for a separate control system that controls when to start and stop the ICE.

There are of course both pros and cons with the series hybrid, to mention the most important; the pros would be that the ICE together with the generator can be set to only be used in the working area where they are most efficient. Further on the ICE together with the generator can be placed anywhere in the vehicle where there is space, and that will also refer to the traction motors as well. The motors can be placed near the traction wheels which will benefit the overall space in the vehicle.

One of the cons is that in relation to an ordinary driveline there are losses in the electronics, all those losses are dependent on the amount of connections on the way from the generator to the traction motors, however this can be reduced by letting the traction motors be connected directly to the wheels and hereby cancel the need of a transmission. On the contrary the possibility of freely placing the components of a series driveline the total needed space could be larger for the series as there is need of at least two electrical machines.

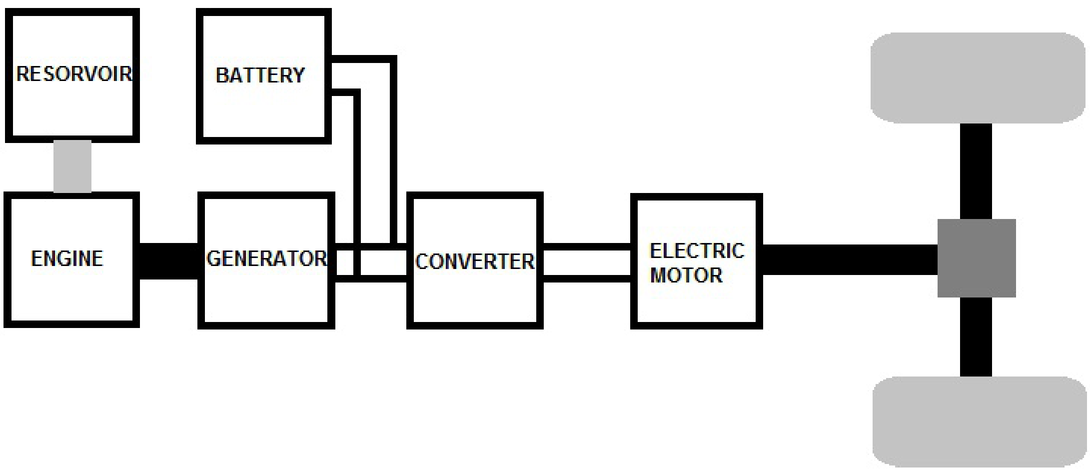


Fig. 2.1 Function chart for typical serial hybrid.

2.2 Function Parallel Hybrid

A parallel hybrid driveline is a combination of a serial hybrid driveline as mentioned before and a conventional driveline which is seen in *Figure 2.2*. It consists of an ICE and a generator that also has the function of an electric motor. The vehicle can be powered by either the ICE or the electric motor or both, depending on how much power that is needed and the actual driving situation. As for low speed and low load, the vehicle will run from the EM and at high speed with low load it will run from the ICE. If the SoC is low at cruising speed the electric motor will work as a generator and charge the battery. As for heavy acceleration, the vehicle will take power from both the EM and the ICE.

Further the EM and the ICE is connected to each other via a clutch and in some cases a transmission to match the speed of each other. The purpose of the clutch is to be able to decouple the EM and ICE, for example if only the electric power is needed. Which were said before, the ICE can run independently from the EM when driving at cruising speed for example, then the ICE also needs a separate transmission to the driving wheel which can be an automatic gearbox or an continues variable transmission, CVT.

If there is no starter motor available in the setup there is need for yet another clutch. The purpose of this clutch is to decouple the drive axle or transmission from the EM. Then in such a setup the EM is used as a starter motor as well. The clutch connecting the drive axle/transmission to the EM is released and this allows then the EM to rotate the crankshaft of the ICE in order to motor it for start. When the ICE is started the clutch can again be engaged in order to transfer the power again to the drive axle making the vehicle moving.
The energy storage consists of the same components as for the series hybrid, why this is not again explained. The control algorithm for the parallel setup also measures the SoC of the energy storage in order to make the decision on when to start and stop the ICE based on a preprogrammed criteria. Also in this case there is a lower and higher set limit.

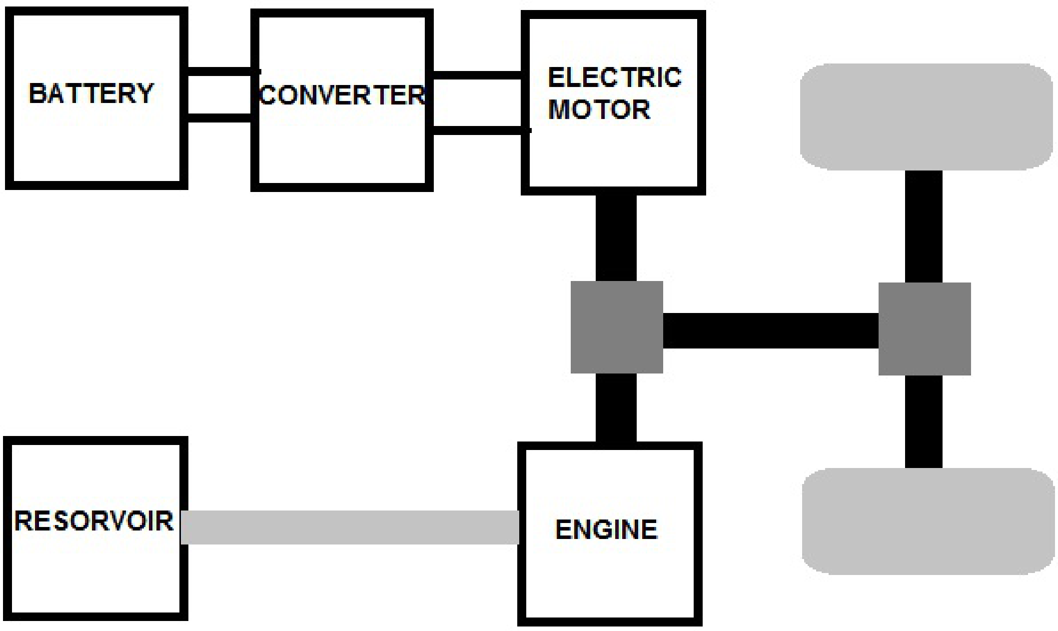


Fig. 2.2 Function chart for typical parallel hybrid.

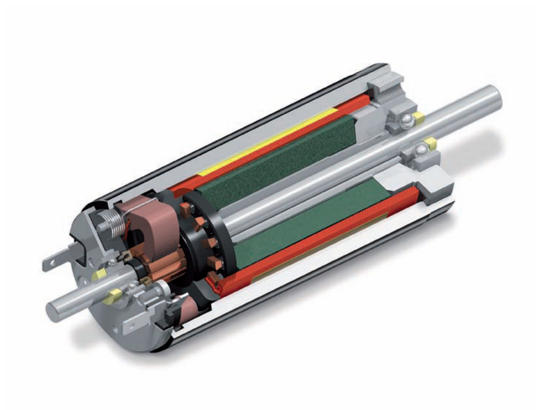
2.3 Components

In this section the components present in a hybrid vehicle system will briefly be described individually. The objective is to give the reader the basic knowledge and functions of each and every component. If more information is needed the reader is kindly asked to find more info concerning the components either by visiting the wanted website of the manufacturer or by using other sources such as internet.

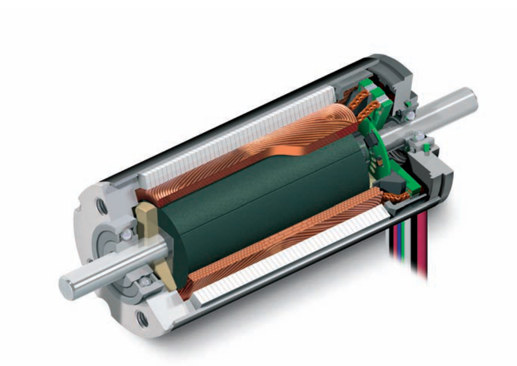
2.3.1 Electric machine

The word electric machine [EM] often refers to electric motors as well as electric generators. This is the reason why the headline is chosen. As the designs presented will contain one or more electric machine acting as either electric motor or electric generator or acting as both in the same design.
What the electric machine does is either using kinetic motion creating a flux and thus transforming a current or from a floating current creating a flux leading to kinetic motion.
The group electric machines can be divided in two subgroups not taking the two different areas of use into account. The two different subgroups are DC-machines and AC-machines. The big difference is the DC-machine works with direct current and the AC-machine with alternate current.

The DC-machine can also be divided into two subgroups which are Brushed DC-machines and brushless DC-machines [8] also called BLDC-machines, the two types is seen in *Figure 2.3(a)* and in *Figure 2.3(b)*. The major differences between those types are that there are not any physical contact between the rotor and commutator for the BLDC-machine. Instead it has permanent magnets moving around its armature and not the armature spinning as in the DC-machine. Having the armature not in motion has its pros as an armature moving will release its windings when reaching to high speeds, this will lead to a fatal breakdown of the EM. On the other hand to make the magnets moving and furthermore make the machine work in the BLDC machine a controller needs to be used as the magnetic field has to switch. The BLDC is fed with a direct current which the controller then applies on the windings of the machine. The windings are most often three and the controller switches between those to make the machine rotating.



(a) Brushed DC-motor [9].



(b) Brushless DC-motor [10].

Fig. 2.3 Different types of DC-motors.

To summarize there are two different kinds of electrical machines, the DC-machine which is a machine working with direct current and the AC-machine which uses alternating current. The DC-machines can be divided into two groups, with or without brushes. A machine with brushes has the drawback of friction losses that the brushless don't have, however a brushed DC-machine are simpler to control than a brushless where it just needs a voltage to control the speed of the machine and a current to control the torque.
The kind of machine that will be used for this design is any type of the DC-machine, which will be used will be presented in a later chapter. The reasons for using the DC-machine are that there will be an energy reservoir aboard the vehicle which will be of any form containing a DC voltage.

2.3.2 Internal combustion engine

A combustion engine converts high density liquid energy such as petroleum and alcohol products to heat and mechanical power in form of rotational motion and torque/thrust. A piston engine which is the common power source used in vehicles provides rotational energy in form of torque and angular velocity. The rotational energy can then be transferred to the wheels of a vehicle and/or to generate electric power through a generator.
There is mainly one type of piston engine used today which is the four-stroke engine, the internal of an four-stroke engine is seen in *Figure 2.4*. The four-stroke engine can be divided into two types; spark ignition (SI) and compression ignition (CI), which means that it can run on petrol/alcohol respective diesel. In SI engines a spark is used to ignite the fuel/air mixture, the spark which comes from a sparkplug is generated by a very high voltage (30 000V) which is then short circuited through the sparkplug. For the CI on the other hand, plain air is compressed very hard, about two times more than for an SI engine. And instead of a spark to ignite, diesel fuel is sprayed directly into the combustion chamber which will create a self ignition.
Then both the spark ignited and compression ignited engines can be divided in two different subgroups, which are natural aspirated [NA] and forced induction [FI] engines. Where the latter means that the air is forced into the cylinder with a pressure higher than the ambient pressure. This gives the possibility of gaining more torque in a small displacement engine.

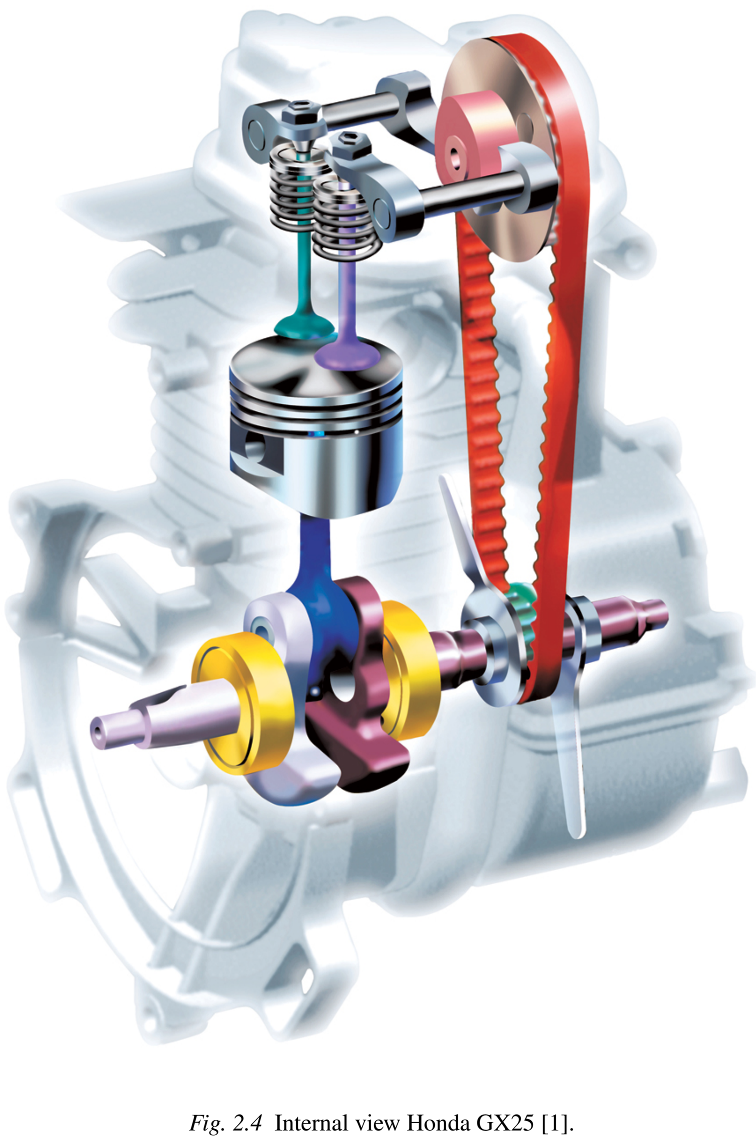
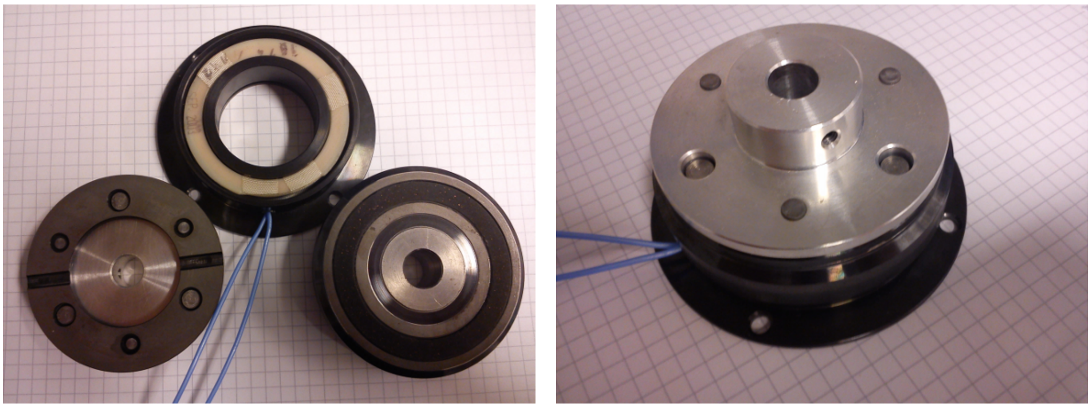


Fig. 2.4 Internal view Honda GX25 [1].

2.3.3 Clutch

Clutches has the function of releasing or engaging one power driven axle from another axle, it is used in any vehicle with an internal combustion engine to separate the gearbox from the engine when changing gears and when starting the vehicle. A clutch is made of at least three parts; a pressure plate, a friction plate and a base plate. The pressure plate will press the friction plate against the base plate to lock the parts together. The pressure plate can either be made of springs that will strive against the base plate, or by electromagnets which will lock against the base plate when current is applied. An electromagnetic clutch is shown in *Figure* 2.5 where the first *Figure 2.5(a)* shows the different pieces of the clutch and the second *Figure 2.5(b)* where it is assembled.



(a) Parts of electromagnetic clutch. (b) Electromagnetic clutch assembled.

Fig. 2.5 Electromagnetic clutch by Warner electric [2].

In a parallel hybrid system where the ICE also will be used for propulsion as well as for generating electric power, a clutch is needed to decouple the ICE from the propulsion wheel. This is needed as the ICE otherwise will turn as long as the vehicle is moving, for example at starting condition when the EM is the main source for traction.

2.3.4 Energy storage

There is also need for some way of storing the energy in a hybrid vehicle. The main idea of the energy storage is to power the electric traction motor and to store regenerated energy when braking which can be used for any hybrid electric vehicle [HEV]. The energy storage will also take care of the surplus energy achieved from the ICE that is not needed for propulsion of the vehicle as for the parallel hybrid system. In *Figure 2.6* different types of energy storages is shown, the first one is a high capacity lead-acid battery used for mild hybrid system such as Start & Stop technology, the second one is a super capacitor based on lithium-ion technology.

Table 2.1: Comparison of battery types, [11, 12]

Type	Power density [W/kg]	Cycles	Energy density [Wh/l]	Energy density [Wh/kg]
Lead-acid	180	600	100	40
Nickel-Cadmium	120	1500	140	50
Nickel-Metal-Hydride	200	1000	300	70
Lithium-ion	430	1200	230	130

The energy storage most often consists of a large amount of battery cells which is spread out in the design of the vehicle. This is done in order to divide the load of the weight to different parts of the vehicle. There are different kinds of batteries that are used. There are some important figures to look at when deciding what energy storage that should be used. What is important when choosing type of energy storage is the energy density, which is a way to measure the energy content stored per volume. For batteries this is measured in Wh/liter. Another important property would be the number of cycles a battery can handle during a life time. The most common types of batteries are presented in *Table 2.1*.

(a) Conventional battery storage from Tudor [13].

(b) Lithium-ion prototype supercapacitor.

Fig. 2.6 Different types of energy storages.

When the need of storing energy isn't as large as needed to be able to run a full scale vehicle, other forms of energy storages can be used. One example would be the super capacitor or ultra capacitor which simply is a large capacitance that holds the energy. The pros of this compared to the regular batteries is the weight as those tends to be lighter. That means the energy density is higher in the capacitor compared to a battery of the same weight. One consequence on the other hand is that the larger the energy density the more unstable the storage tend to be.

A third alternative would be to use fuel cells as containers of energy, this is although the most expensive way of storing the energy. This technique still needs development to be a commercial success due to its current price.

Chapter 3

Case setup/ Methods

In this chapter the particular case where the designed system will be used is explained. This is also the underlying criteria for the simulations and calculations. At all times where applicable the values from and of the vehicle Smarter will be applied. Other assumptions are made but those will then be stated. Where assumptions are to be used they will be explained, in order to be able to refit models for use in other applications.

3.1 Driving cycle

In order to get usable information from the simulations which are described in a later chapter, the inputs to the models which are being used during the simulations needs to be correct. The input data needs to be adjacent to the real values.
The driving cycle need to be as close as possible to the real; this in order to connect the output result from the simulations to the real life application. In order to mimic the real driving cycle the following data have been used in order to produce the driving cycle.
The track map and competition data which is given from the competition organizer Shell [3] can be seen in *Figure 3.1*.

Using those data and simple math gives us the following, formulas for calculating the lowest mean velocity:

$$\frac{53min}{7laps} \approx 7.5\frac{min}{lap} \text{ (rounded downward which gives a slightly higher velocity)} \tag{3.1a}$$

$$\text{Distance to travel every lap } \frac{22096m}{7} \approx 3157m \tag{3.1b}$$

$$\frac{3157m}{7.5min} \approx 417\frac{m}{min} \Rightarrow 6.95\frac{m}{s} \times 3.6 \Rightarrow 25.02km/h \approx 25km/h \tag{3.1c}$$

This means that the average speed should be at least 25km/h in order to complete the race within the time frame. When looking at *Figure 3.1* a Stop sign is shown, this means that the vehicle has to perform a stop every lap. This means that if the race were to be performed without any stops the mean velocity would have to be at least 25km/h. But the way the competition is performed the mean velocity needs to be higher to cover the time taken for braking, the time standing still and the time needed to again accelerate achieving cruising speed.
To be able to calculate the new mean velocity some assumptions for the time needed from starting the brake in process including the stop and acceleration have been made. This is set to be about 30 seconds. This then says one lap around the course has to be performed in roughly 7min, and thus give the lowest velocity to be 27km/h instead of previously achieved. The new calculation will then look like:

$$\frac{3157m}{7min} \approx 447\frac{m}{min} \Rightarrow 7,45\frac{m}{s} \times 3.6 \Rightarrow 26,82km/h \approx 27km/h \tag{3.2}$$

Fig. 3.1 Eurospeedway Racetrack in Lausitz, [3].

A Matlab function has been developed in order to create a suitable drive cycle comparable to the real competition as an input to the Simulation model. Using the Matlab function it is also easy to change the drive cycle, for example if a simulation using a higher or lower maximum speed should be done in order to see how the energy consumption changes. The drive cycle that mimics the real competition can be seen in *Figure 3.2* below.

As the competition is performed with one stop each lap as formerly mentioned, the mean velocity will be higher than stated. But what should also be kept in mind is that cases that we do not reign over could appear. Those changes most likely would yield a need of a higher maximum velocity. This increase in speed also needs the transmission to be designed in a way that there is room for any such upcoming events that might occur during the competition. Such an event could be problems on the track or difficulties of overtaking other vehicles during competition due to lack of space for overtaking. The Matlab function itself gives an opportunity to change this maximum speed but does not take into account any changes in transmission ratio or likely. So by just adjusting the speed to be a maximum of for example 40km/h as an input, will give a drive cycle according to this speed but it does not mean that the vehicle itself is able to operate using this speed. This means that the maximum speed the vehicle is able to travel with, together with the lowest possible should be bear in mind.
The Matlab function for creating the drive cycle to the simulation models can be found in *Section D.1* with comments describing the functions within.

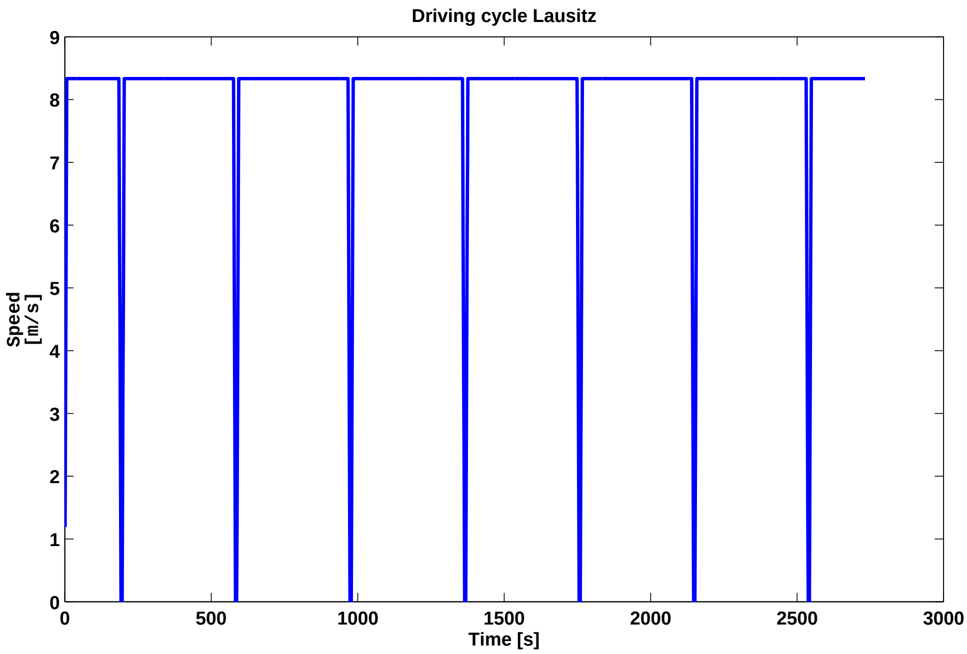


Fig. 3.2 The driving cycle for a simulated Eco-Marathon race.

Chapter 4

Analysis

In this chapter analysis of the components to be used will be done. The different criteria for each component will also be explained/discussed to get a better view of the design aspects.

4.1 Determination of components

In this chapter the choice of components will be discussed. During the project substantial efforts in finding right components have been made. Here different alternatives of every component will be presented and weighted against each others. Pros and cons of each component will be discussed and the choices of them are based upon those. It should also be mentioned that the components chosen might not be the best that could be found, but due to time limit as well as budget (to spend) on finding the best components the following are used.
As the ultimate goal of the project is to design and manufacture a fully functional parallel hybrid driveline all of the consisting components most important point have been their individual efficiency which need to be as high as possible available, compared to its price. As all components individual efficiency adds up to the total efficiency possible of the system. Using the following formula for all components will lead to the overall efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \tag{4.1}$$

Where P_{out} is the outgoing power from the component and P_{in} is the input power.

The size of the components will also have a great impact on the final system why this also have been a key point of interest when the components have been chosen. The size issues of the components are connected to this project in particular since the size of the driveline has to fit the space available in the vehicle. The size of the components is not the only aspect to have in mind, but also the voltage levels where the industrial standard often is 24V DC, where in this case the comparable figure is 12V and 48V DC.
To conclude all components have been investigated and chosen due to their individual properties.

4.1.1 Determine required power for traction

As a master thesis last year was conducted on calculating and simulating the whole vehicle Smarter in different driving situations. This information regarding the shape of the vehicle has been extracted to be used for our simulations, in order to save time. The primary information that is used is the front area A_v of the vehicle and drag coefficient C_d, this parameters which can be seen together with other important numbers of the vehicle in *Table 4.1*. As the parameters have not been verified, the simulation results will just give a hint of the vehicle performance.

Table 4.1: Vehicle data.

	Value
Vehicle mass [m_v]	80kg
Drivers mass [m_d]	70kg
Drag force coefficient [C_d]	0.28
Frontal Area [A_v]	1.4m^2
Wheel friction [C_r]	0.007
Wheel radius [R_{wheel}]	0.273m
Air density at 15°C [d]	1.225 [$\frac{kg}{m^3}$]

$$P_{rolling} = C_r(m_v + m_d)g\frac{S_v}{3.6} \tag{4.2a}$$

$$P_{drag} = \frac{1}{2}dC_dA_v\frac{S_v}{3.6}^3 \tag{4.2b}$$

$$P_{vel} = P_{drag} + P_{rolling} \tag{4.2c}$$

By using the general equations for aerodynamic drag [14] and rolling friction which can be seen in *(4.2)*, the required power to maintain a cruising speed can be calculated. The results which are seen in *Table 4.2* and in *Figure 4.1* are based on a driver weight of 70kg and a fueled and race-ready Smarter at sea level and a temperature of 15 °C.

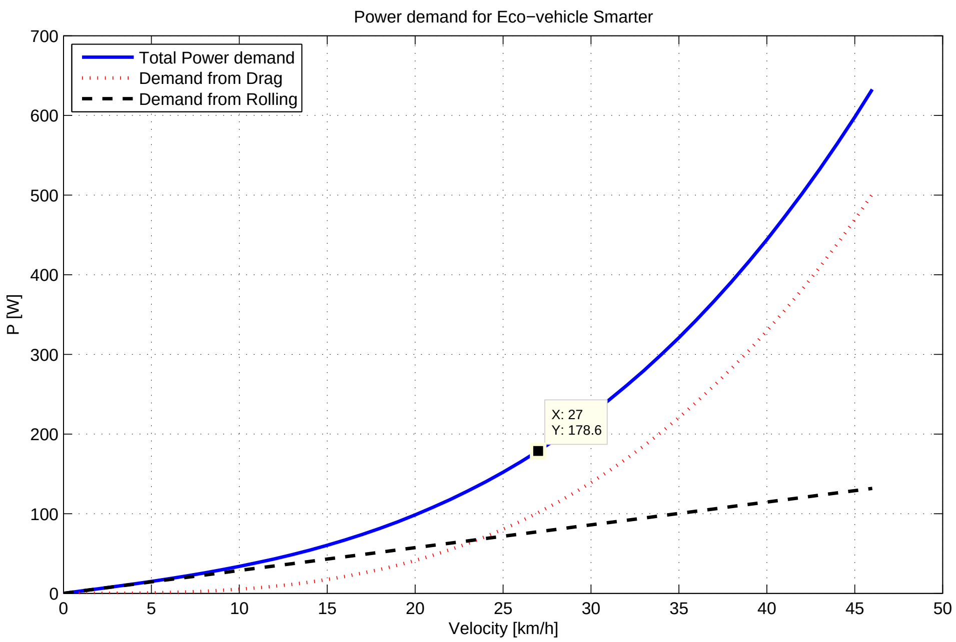


Fig. 4.1 Power demand for Smarter, mass=150kg.

As seen in *Figure 4.1*, the power demand for keeping a certain speed increases by the power of three. So the power required for rolling is just of major interest at lower speed as the air friction takes over at higher speeds. However the rolling friction is very much dependent of the vehicle mass, therefore the power needed for low speed running are much higher for a heavier vehicle as seen in *Figure 4.2*. The increase of 50kg for the heavier vehicle results in a increment of the power demand at 27km/h with:

$$\frac{P_{m200} - P_{m150}}{P_{m150}}100 = \frac{204 - 179}{179}100 \approx 14\% \tag{4.3}$$

Table 4.2: Power requirement for Smarter.

Speed [km/h]	Power [W]
25	152
26	165
27	179
28	193
29	209
30	225
31	242
32	260
33	279
34	300
35	321

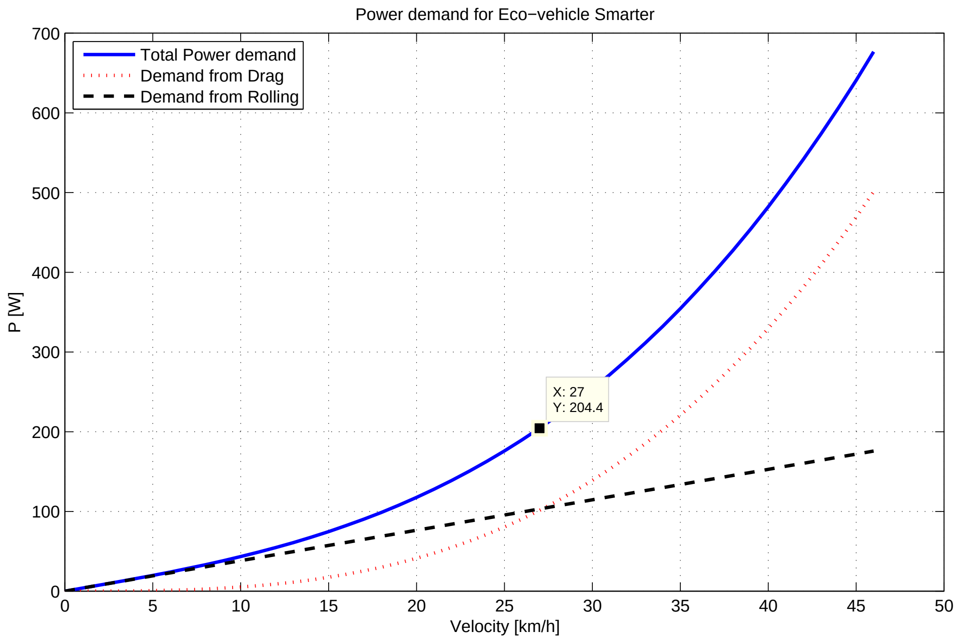


Fig. 4.2 Power demand for Smarter, mass=200kg.

The value 27km/h is taken from *Section 3.1* where the absolute minimum vehicle velocity by the regulations is 25km/h without any pit stops. And by seven pit stops which are required the minimum velocity increases to 27km/h. However, a slightly higher cruising speed is desirable as there is seldom a vehicle like this that is build to be as light as possible that is bulletproof so to speak. Therefore a higher cruising speed can help gaining loss time if something happens during the race. Hereby a new cruising speed of at least 35km/h is desirable which will increase the power demand by looking in *Table 4.2* from 179 Watt to 321 Watt, this leads to an increased need of power by

$$\frac{321-179}{179}100 \approx 79.3\% \tag{4.4}$$

4.1.2 Determine electrical machines

During the investigation to decide what EM to be used both as traction and as a generator, both brushed and brushless motors were compared. The idea was to use a brushless motor for traction mainly by the reason that the friction losses compared to a brushed DC motor would be eliminated, and therefore the overall efficiency would be higher. A list of different DC-machines are provided in *Table 4.3* where three Maxon[1] machines are compared. The two first are brushed machines designed to run at a maximum voltage of 36V delivering 200W respective 250W and the third one is a brushless designed for 48V delivering 400W. Their performance data is also shown in *Figure 4.3*, where the colored area describes continues operation and the white describes the short time operation.

Table 4.3: Performance data Maxon DC-machines.

	RE50	RE65	EC60
$R_t[\Omega]$	0.254	0.365	0.345
$C_t[mNm/A]$	59.4	87	84.9
$C_N[rpm/V]$	161	110	113
$Weight[g]$	1100	2100	2450
$R_{th1[K/W]}$	2.27	1.85	0.5
$R_{th2}[K/W]$	3.8	1.3	1.3
η_{max}	93	87	86

Another important aspect is that the motor needs to be able to work in generative mode as generative braking is performed to reduce the vehicle speed, but also to generate electric power through the ICE. The brushed DC-machines have a major benefit here as it does not need a converter between the generator and the battery as the BLDC-machine does. The BLDC-machine uses three phases compared to the brushed two. This means that it has to be supplied with sensors; usually three hall sensors placed 120° from each other is used to be able to deliver full torque at low speeds. Therefore an advanced controller is needed for running the machine in either directions, namely regenerative or traction.

One reason that makes the brushless machine interesting is that the friction when turning without load is lower than for the conventional brushed DC machine. When it turned out that a working brushless machine could be found, a more thorough research showed that there will be a great loss of efficiency if the brushless EM should be used as a generator. And for the case of the parallel hybrid driveline; where the one and only EM should work for both propulsion and a generator, in some cases simultaneously this might lead to problems. But as stated in *Section 2.2* the EM in a parallel driveline is mostly used as a generator if the possibility of regenerative braking is removed.

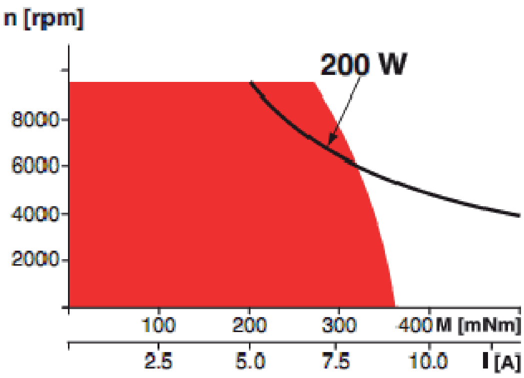
For the brushless motor which is compared in this chapter the only four quadrant controller available by Maxon has a very low efficiency, especially in generative mode. By being four quadrant it means that the controller can be speed or torque controlled in both directions. The machine in particular with the controller had an efficiency of no more than approximately 35$\%$ when used as a generator according to the manufacturer, Maxon . As the found machine had a power output of 400W that would have given us the possibility of regenerating no more than a maximum of:

$$P_{EC60}\eta = 400 \times 0.35 = 140W \tag{4.5}$$

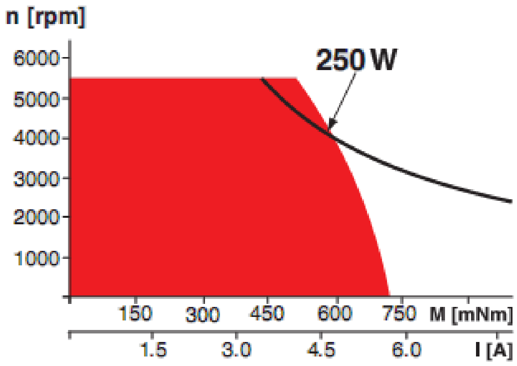
Instead we looked at conventional DC machines and decided to go with the Maxon motors RE65 which has a specified efficiency of 87$\%$ and a rated power output of 250W at 36V which means a higher output will be achieved at 48V. This machine fulfills the earlier stated requirement.

The drawback in using the brushless EM as generator lies in that it have more than one winding and thus

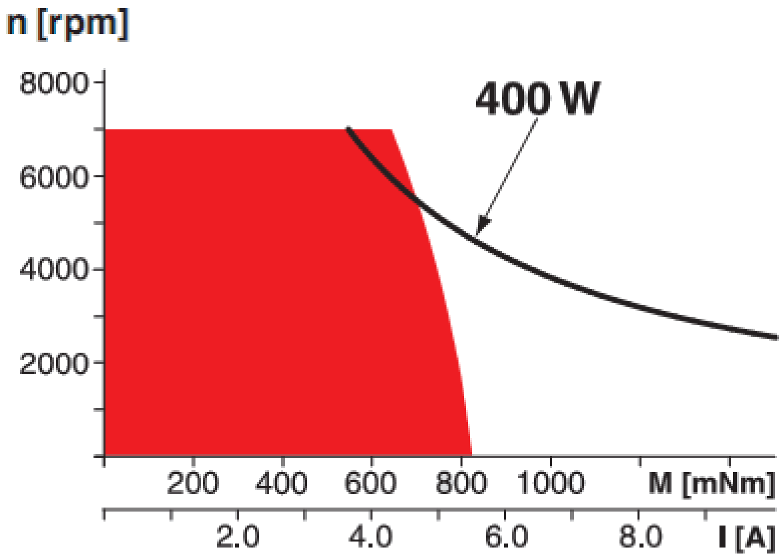
[1] Maxon Motor ag, Sachseln (Switzerland)



(a) Power characteristics for Maxon RE50, [15].



(b) Power characteristics for Maxon RE65, [16].



(c) Power characteristics for Maxon EC60, [17].

Fig. 4.3 Comparison Maxon DC-motors

both run on AC and generates an AC current when used in regenerative mode. To be able to use this generated power having different phases and charge the energy reservoir it has to be rectified. As all steps in the rectifying and ”phase in” process lowers the efficiency the total loss will be too large and thus makes the use of a Brushless EM as a generator not to be an option.

If the conventional brushed EM is investigated this has on the contrary almost the same efficiency both used for propulsion as well as in regenerative mode. The reason to this can be explained by the *(4.6)*, where the power [P] is in Watt and the rotational velocity [N] are in revolutions per minute [rpm].

$$P_{el} = P_{mech} + P_j \tag{4.6a}$$

$$P_{el} = UI \tag{4.6b}$$

$$P_{mech} = \frac{\pi * TN}{30000} \tag{4.6c}$$

$$P_j = RI^2 \tag{4.6d}$$

$$N_{load} = C_N U - \frac{30000}{\pi}\frac{RT}{C_T^2} \tag{4.6e}$$

$$N_{nominal} = C_N U \tag{4.6f}$$

By using the formulas stated above a table of performance is shown in *Table 4.4*, where all the machines formerly presented are compared by produced power at the maximum allowable voltage [U] of 48V and a maximum current [I] of 20A, rotational speed [N] at booth high voltage of 48V and medium voltage of 35V and under full load. The power losses in form of terminal resistance $[P_j]$ is also shown.

Table 4.4: Performance data Maxon DC-machines 2.

	RE50	RE65	EC60
$T_{max}[mNm]$	1188	1740	1698
$N_{48}[rpm]$	7728	5280	5424
$N_{35}[rpm]$	5635	3850	3955
$P_j[W]$	102	146	138

Again having a look at the brushless EM, the problem using it as a generator is connected to the already mentioned phasing in and rectifying process. This could although be addressed by investigating the possibility of designing a converter that has a higher efficiency in regenerative mode. As the market investigation of available systems to use the brushless EM as generator was showing that there are only a few of the converters commercially available that even has the possibility to ”take care” of this energy fed back from the EM. Most of the converters had instead a shunt resistance were the power is converted to heat instead of saved. Although it was found that there is work going on to get better performing converters to be used in generative mode. This might give the possibility to use it in future projects, as a lot is saved due to the decrease of need in maintenance as there are no brushes.

4.1.3 Determine optimal gear-ratio of transmission

As the driveline should be fitted in the eco marathon vehicle Smarter as earlier mentioned there are certain requirements that should be fulfilled except size and weight in order to comply with the rules for the competition. Among those requirements maximum time of completing the seven laps and thus the minimum speed. The minimum speed set by the competition organizer is 25km/h but taking the required pit stops into account this will instead increase to 27km/h as mentioned in *Section 3.1*. What has also been decided is that the transmission should allow the possibility of travelling even faster than the specified minimum velocity of 27km/h due to unknown states of difficulties that might occur. This new maximum speed is decided to be at least 35km/h, and is thus the speed the transmission should be designed to be able to achieve.
For simplicity, a fixed gear ratio is chosen as a geared transmission is heavier and hard to make fully automatic with sustained efficiency. Keeping in mind a geared transmission would also be more complicated to manufacture.

Table 4.5: Vehicle speed with various gear ratios

Gear Ratio	Speed at 35V	Speed at 48V
10:1	39	54
11:1	36	49
12:1	33	45
13:1	30	42
14:1	28	39
15:1	26	36

By looking at *Table 4.5*, where different gear-ratios [GR] is compared and the resulting maximum velocity S_v for both high and low SoC is displayed. One can see that the optimal gear-ratio with respect to the criteria of a minimum velocity of 27km/h is very close to number five in the list by 14:1. This gear-ratio gives the vehicle a top speed of 28km/h at low SoC and 39km/h at high SoC. The list is made from *Equations 4.7* with the Maxon RE65 as source for the speed constant C_N.

$$S_v = C_{wheel}\omega_{wheel}3.6 \tag{4.7a}$$

$$C_{wheel} = R_{wheel}2\pi \tag{4.7b}$$

$$\omega_{wheel} = \frac{(C_{speed}SOC)}{60GR} \tag{4.7c}$$

When the gear ratio is set the acceleration of the vehicle is calculated using the second law of Newton:

$$F_{el} = m_v a \Leftrightarrow a = \frac{F_{el}}{m_v} \tag{4.8a}$$

$$F_{el} = \frac{T_{el}GR}{R_{wheel}} \tag{4.8b}$$

$$\Rightarrow a = \frac{T_{el}GR}{R_{wheel}m_v} \tag{4.8c}$$

Those equations above only calculate the theoretical maximum acceleration with no respect to the aerodynamic drag and rolling friction, which is making the acceleration slower as the velocity increases. Thereby new equations has to be determined by subtracting the force that is required to keep the vehicle at that speed it is accelerating from. The new equations are stated below in *(4.9)* where P_{vel} is taken from *(4.2)*.

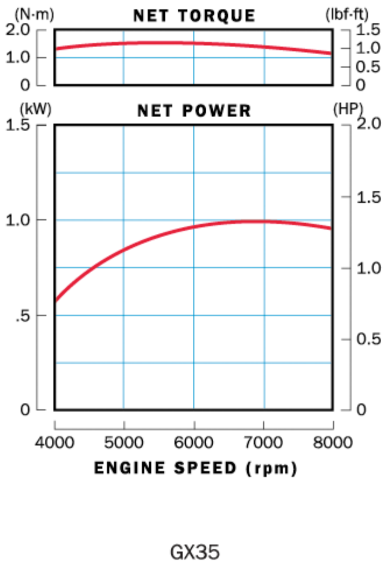
$$a = \frac{F_{el}}{m_v} - \frac{F_{vel}}{m_v} \tag{4.9a}$$

$$F_{vel} = \frac{P_{vel}}{S_v} \tag{4.9b}$$

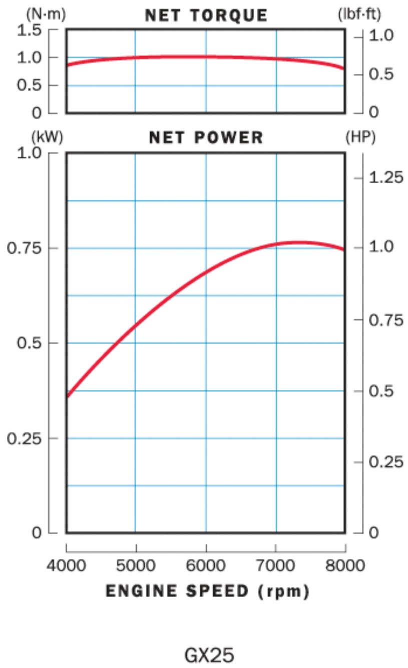
$$\Rightarrow a = \frac{T_{el}GR}{R_{wheel}m_v} - \frac{P_{vel}}{S_v m_v} \tag{4.9c}$$

4.1.4 Determine the internal combustion engine

The combustion engine used was already available as the project started, as the same had been used in a previous project. The ICE is a clearing saw engine from Honda sold under the name GX35. It is a 36cc four stroke natural aspirated spark ignited engine. Originally it comes with carburetor and an ignition system with fixed timing. As the engine was available and had already been successfully modified in another project to get a higher efficiency, there was no reason not to use it. The modification made in this project will be described later on.



(a) Power characteristics for Honda GX35, [18].



(b) Power characteristics for Honda GX25, [19].

Fig. 4.4 Comparison of light Honda engines

The specification for the original engine can be read in *Table 4.6*. The power characteristics of the GX35 engine compared to the smaller and less powerful Honda GX25 which was also available can be seen in *Figures 4.4(a)* and 4.4(b). From those figures one can clearly read out the GX25 is not powerful enough to fulfill the set requirements for the vehicle and thus the GX35 is chosen.

However it should be mentioned that the results could have been different if another engine had been used.

Table 4.6: Engine data GX35.

	Value
Bore [mm]	39
Stroke [mm]	30
Compression ratio [-]	8
Intake port diameter [mm]	10
Exhaust port diameter [mm]	12.5
Intake valve opening [CAD]	10 BTDC
Intake valve closing [CAD]	57 ABDC
Exhaust valve opening [CAD]	48 BBDC
Exhaust valve closing [CAD]	28 ATDC

4.2 Optimization of internal combustion engine

The earlier selected ICE has been modified to match the speed and power characteristics of the chosen generator Maxon RE65. The parts of the engine that has been modified were all external components. Although a research of modifications covering the internal parts have been made, but due to time constraints those have not been performed. The internal modifications would have covered a change of compression ratio as well as an optimization of friction losses. Change of camshaft would also have given the possibility to change the duration of valve opening and lift in order to get a better volumetric efficiency.
On the other hand the largest issue of efficiency originates from the external components such as the originally equipped ignition system and the carburetor. Those were changed to a fuel and ignition management system allowing the user to define the ignition as well as the injection curves to completely control the performance of the engine. A performance plot of the fuel injected Honda GX35 is shown in *Figure* 4.5 together with the brake specific fuel consumption (BSFC) versus the engine speed at full load in *Figure* 4.6. Moreover the intake runner as well as the exhaust pipe has been addressed for modification as those are comparably easy to modify.

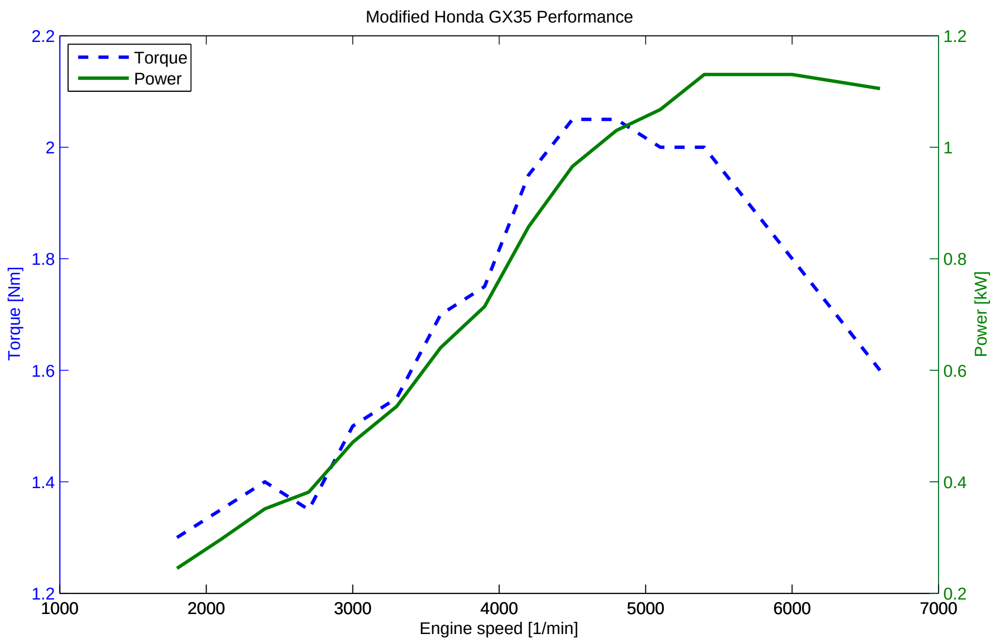


Fig. 4.5 Power characteristics of modified Honda GX35.

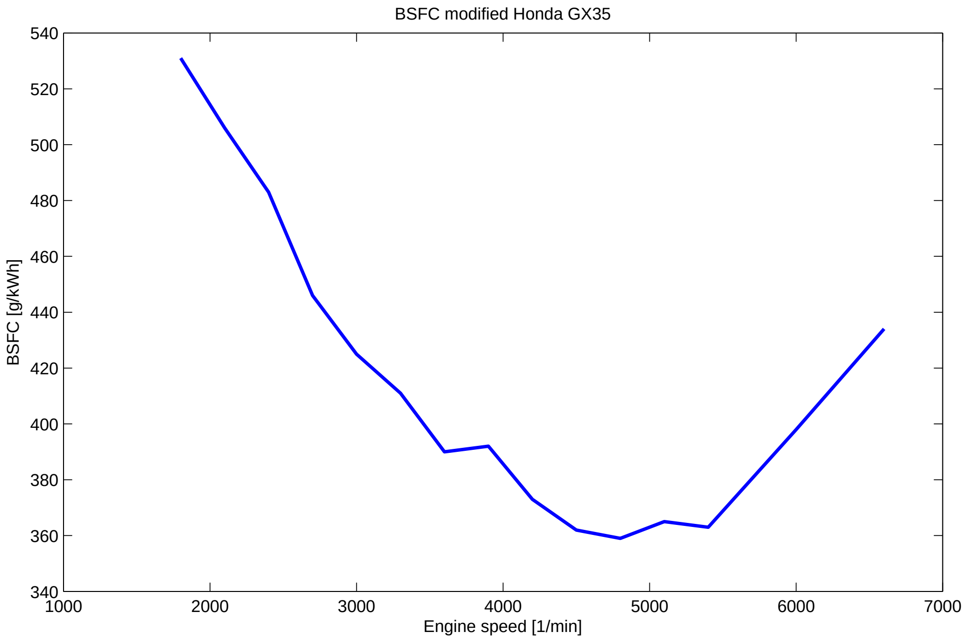


Fig. 4.6 BSFC of modified Honda GX35.

4.2.1 Engine management system

To be able to decide what power and torque that is desired as an output from the ICE a engine management system hereinafter called EMS is used.
The reason that the factory mounted (out of box) ignition system has to be changed is that this is developed with the ability of running the engine easy at merely every occasion, and hereby seldom at the most energy/fuel efficient point. As we want the fuel consumption to be as low as possible at the same time as the power output is as high as possible we have reached a dilemma with the originally equipped ignition- and fuel-system. There are some requisites that the replacement EMS has to fulfill; among those one can find the ability of choosing any point of ignition and allowing the ability of deciding the amount of fuel at every specific point of ignition.

There are some equations that one should strive to always fulfill in order to have a stoichiometric combustion. This means that the mix of fuel and air before ignition is perfect. This is often referred to as air to fuel ratio or AFR. The ideal number of this AFR is 14.7:1, this number can also be presented as the Lambda value λ where 14.7 is represented by λ=1. This value is measured by all EMS in the exhaust pipe with a lambda meter which feed this information back to adjust the fuel up or down.
By using this value and adjusting the fuel amount up or down you can either have a lean or a rich mixture. Most often the goal is to run an engine under stoichiometric relations, but in some cases as for low fuel compensation this is not the case. To get the lowest fuel consumption the AFR most often differs a bit from the stoichiometric relationship. The ideal AFR differs from which kind of fuel is used but it is 14.7:1 for gasoline.

When the EMS for this project was chosen we had some criteria's to fulfill such as size, weight, ability to add and remove sensors, ease of use and support if needed as the time was constrained.
During an earlier project an EMS from VEMS have been used, as there were some problems connected with the use of this system the aim was to find another supplier of the EMS. The common used EMS where compared to each other concerning everything from getting hold of them to ease of setup and the amount of preprogrammed and programmable input and outputs as well as the support available if needed.
The EMS chosen was Nira I3+, this is an EMS developed in Sweden and is known especially among people that builds racing engines for its ease of setup and their easy to use graphical interface, for mapping the engine. But as the Nira is developed for larger vehicles and engines with more than one cylinder it had to

be optimized for the use in the designed system. As a regular vehicle engine and in this case a personal car engine which the EMS is developed for has more sensors than is needed in the design. The EMS needs to be optimized as it comes with a large wire harness for different sensors. As many of the sensors are crucial for the EMS to work not all of them could be removed. During the optimization there was an ongoing conversation with Nira what sensors could be removed and which was needed for the intended way of operating the ICE.
All sensors used by the Nira EMS as well as the controller will be presented in the following section.

Sensors

As mentioned there is a need of sensors in order getting the EMS to work properly, in this section the sensors used and their individual function will be explained.
As the EMS has two main tasks to keep track of, the sensors used can be divided into two different groups. Those groups are the sensors for the ignition and the sensors for the injection. To get the best overview of them they will be presented in list with a short description.
Ignition sensors:

- **Crankshaft position** sensor which is a ferromagnetic sensor that reads the number of teeth on a tooth wheel attached to the crankshaft, on one part of this wheel there is a tooth missing which is the start point of measuring. Such a tooth wheel can be seen in *Figure 4.7*.
- **Camshaft position** this sensor works in the same manner as the crankshaft sensor but reads of the camshaft instead. This is crucial for this application as the engine reach its speed in less than half of a second. As this sensor was not added in the beginning, it caused some problems during the mapping of the engine. As the lack of this signal made the EMS believe the ICE was already in operation due to its high rpm.
- **Ignition Coil** this is not really a sensor but has the function of transforming the voltage to be high enough to create the spark from the sparkplug.

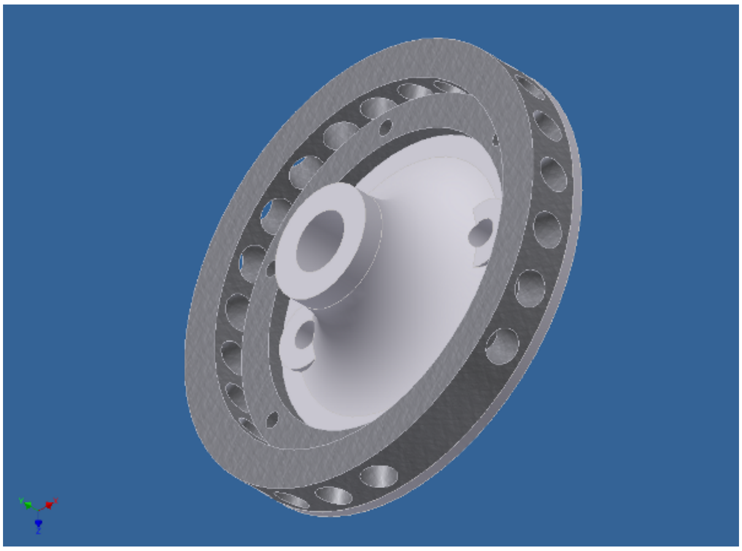


Fig. 4.7 Triggerwheel/flywheel used for EMS.

Fuel injection sensors:

- **Manifold air temperature** or MAT which reads the temperature of the air in the manifold in order for the EMS to get the correct AFR, as different air temperatures contains different amounts of air.
- **Manifold air pressure** or MAP as only the temperature of the air is not telling the whole truth it has to be combined with the pressure of the air to get the correct AFR.

- **Fuel Injector** the fuel injector is also not really a sensor but is needed for the operation. This has to be able to match the amount of fuel that is to be injected. It should not be to large in order to get a correct spray of fuel without droplets for low amounts of fuel, and not too small.

- **Lambda sensor** which has the function to read of the exhaust gas composition in order to give a feedback loop to the EMS telling if the ICE is running rich or lean.

- **Engine temp** this sensor measures the temperature of the engine in order not to overheat it.

Concerning the lambda sensor there are two kinds of different sensors, both measuring the same thing but gives different amount of information. Those are called wide and narrow band-sensors. In the project a wide-band lambda sensor was used as this provides more information but it has the drawback that not all EMS can handle this sensor directly which is the case with Nira I3+. Instead a standalone drive for the lambda sensor is needed. In our case this driver comes from Innovate motorsports and is called LC-1. As this arrived with a separate display and the lambda sensor would not be used during the competition, a nice box was made to it in order to make the connection and use of it simple. This box can be seen in *Figure* 4.8. The stand alone lambda sensor box also makes it possible to easy calibrate other ICE´s used during the project.

A lot of time where also spent on finding a suitable fuel injector, as the engine in the project is relatively small a regular fuel injector produced to fit a car engine would be too large. By to large one talks about the relative amount of fuel the injector is capable to spray in cubic centimeter per minute at a certain pressure. The problem is when a large injector is used for a small engine droplets may appear which means the blend of the fuel air mixture will be bad. The problem to find a suitable injector stems from that there are almost no small engines which is fuel injected due to the cost of the control system.

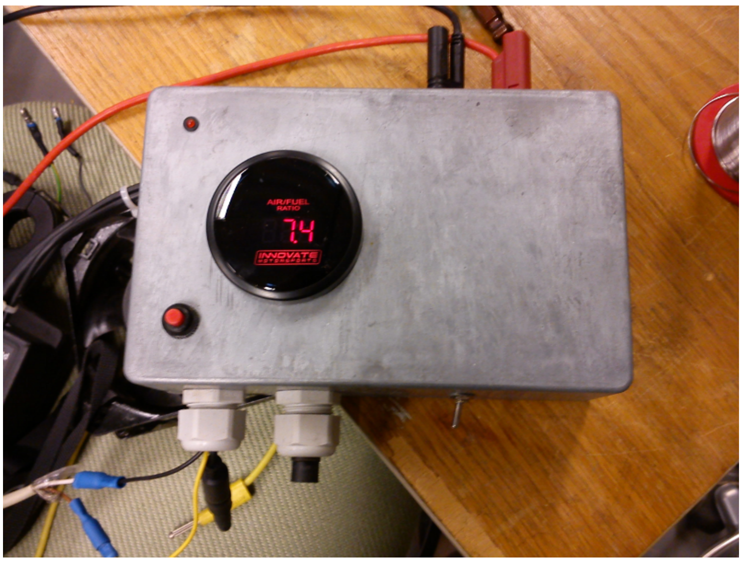


Fig. 4.8 Lambda control box.

4.2.2 Intake runner

As mentioned earlier the intake runner of an engine is simple to modify in order to achieve a better performance. However the problem of the modification is not the manufacturing of the physical part but related to the calculation to get the correct dimensions. The problem often lies in covering the whole engine speed range why often compromises has to be done.

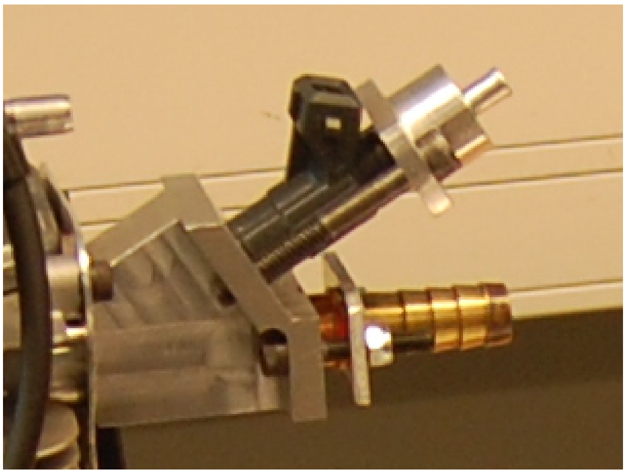


Fig. 4.9 Intake housing for Honda GX35.

The intake of the ICE used had to be redesigned as it was originally equipped with a carburetor and is now operating with a fuel injection without a throttle. The used intake pipe can be seen in *Figure 4.9*. As can be seen in the figure the end pointing away from the engine has a ribbed connection where a hose or a pipe can be mounted. This allows the use of intake runners in different lengths which are optimized for different engine speeds. The function of the intake runner is to help the engine to breath in a good way. As there will be standing waves in the intake during running conditions one can by matching the length of the intake runner to the frequency of those and speed of the engine get a higher volumetric efficiency than 100%. The pressure waves in the intake will then force air into the cylinder as the piston moves towards the TDC.

$$V_d = \pi S B_r^2 \tag{4.10a}$$

$$V_{eff} = (V_d(CR+1))/(2(CR-1)) \tag{4.10b}$$

$$Nt = \frac{955}{2} a(A/(lV_{eff}))^{1/2} \tag{4.10c}$$

By using the *(4.10)* also known as the Helmholtz Resonance model [20] calculations are made where the results are shown in *Figures 4.10* and *4.11*. By adjusting the intake pipe length and diameter and the compression ratio of the engine; the resonance frequency is moved up and down in the working area of the ICE. The results shows that an increment in compression ratio and pipe diameter will raise the frequency but an increment in pipe length will lower the frequency. For a decrement of these parameters the opposite will occur.

The design of the intake pipe is made so that it will be very easy to adjust its tuned length by just adding a rubber hose of the correct length and diameter to the intake pipe housing.

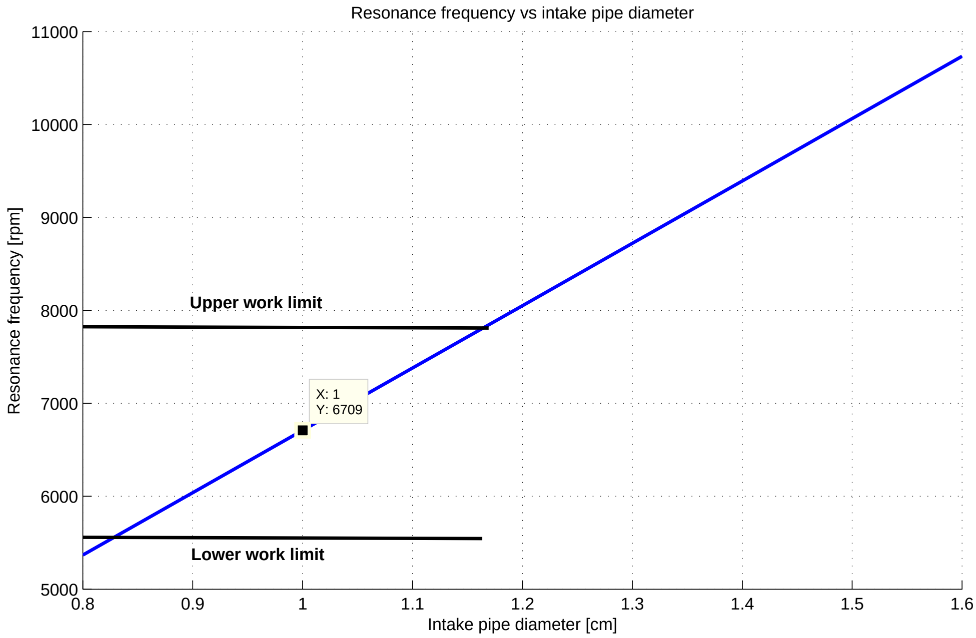


Fig. 4.10 Resonance frequency from different intake pipe diameter.

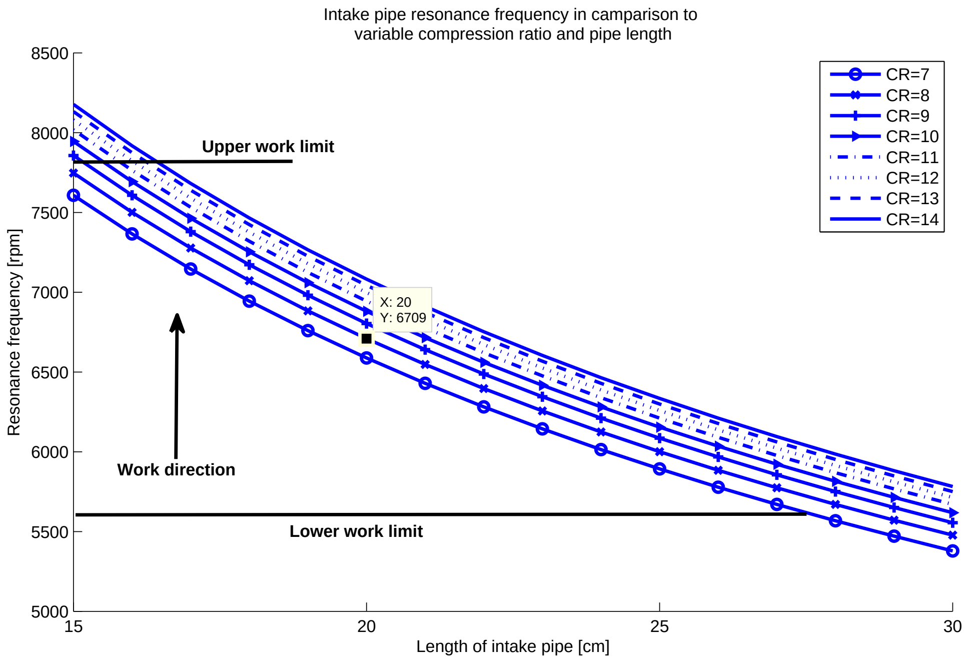


Fig. 4.11 Resonance frequency from different intake pipe length.

4.2.3 Exhaust pipe

An exhaust pipe does more than just transfer the burnt exhaust gases to outside the vehicle. It uses the strong pressure waves created by the opening and closing of the exhaust valve/valves to help the engine breath. By adjusting its length and diameter such as the intake pipe in *Section 4.2.2* the pressure waves have more/less time to transfer in the pipe, so the reflecting pulses can at a certain point perfectly match the engine speed and helps emptying the cylinder from exhaust gases. By improved cylinder emptying, the filling rate of the cylinder will also be improved as there is less exhaust molecules left to be mixed with the fresh air/fuel mixture.
Formulas to calculate the tuned operating point is stated by A. Graham Bell [21] and follows:

$$L_h = \frac{850ED}{rpm} - 3 \tag{4.11a}$$

$$ID = \sqrt{\frac{V_d}{(L_h+3)25}}2.1 \tag{4.11b}$$

The equation for the inside diameter of the pipe *(4.11b)* is based on the pipe length, but as the engine does not want a pipe diameter smaller than the exhaust port of the cylinder head which is 12mm or 1.2cm in diameter as shown in *Table 4.6*. Therefore the equations needs to be rewritten so that the diameter is the input variable, the rewritten equations will look as follows:

$$L_h = \frac{850ED}{rpm} - 3 \Rightarrow \frac{(L_h+3)rpm}{850} = ED \tag{4.12a}$$

$$ID = \sqrt{\frac{V_d}{(L_h+3)25}}2.1 \Rightarrow \frac{V_d 2.1^2}{ID^2 25} - 3 = L_h \tag{4.12b}$$

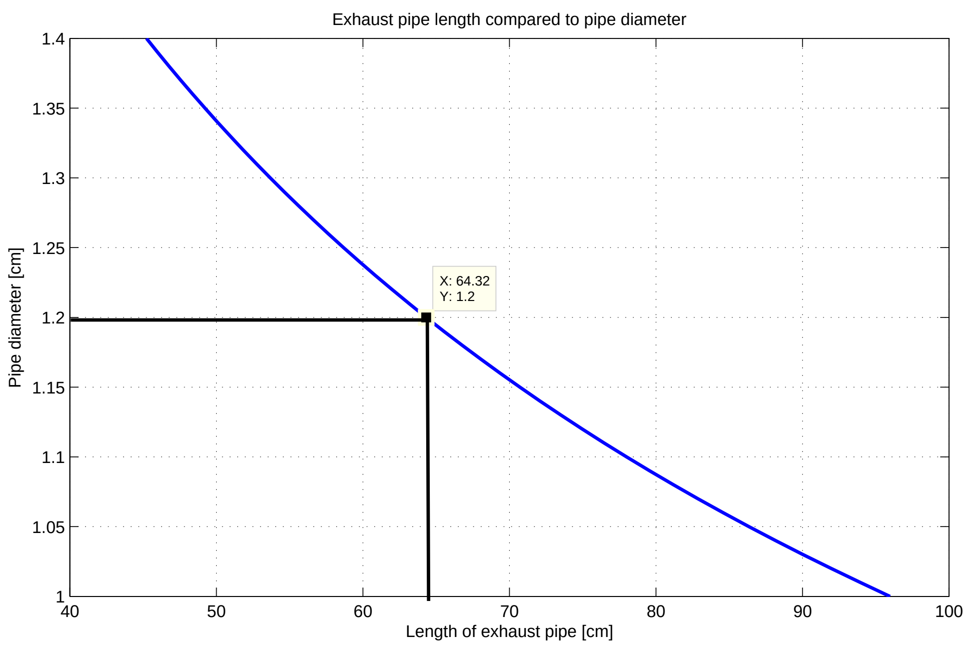


Fig. 4.12 Plot showing how exhaust pipe length varies with the diameter.

From the equations stated above simulations have been made using Matlab to see how the working point changes with different pipe diameters and also by different camshaft angles to suit the different working points for the serial and parallel hybrid system. The original camshaft angles are shown in *Table 4.6* as a reference. The simulation results is shown in the *Figures 4.14* and *4.13*.

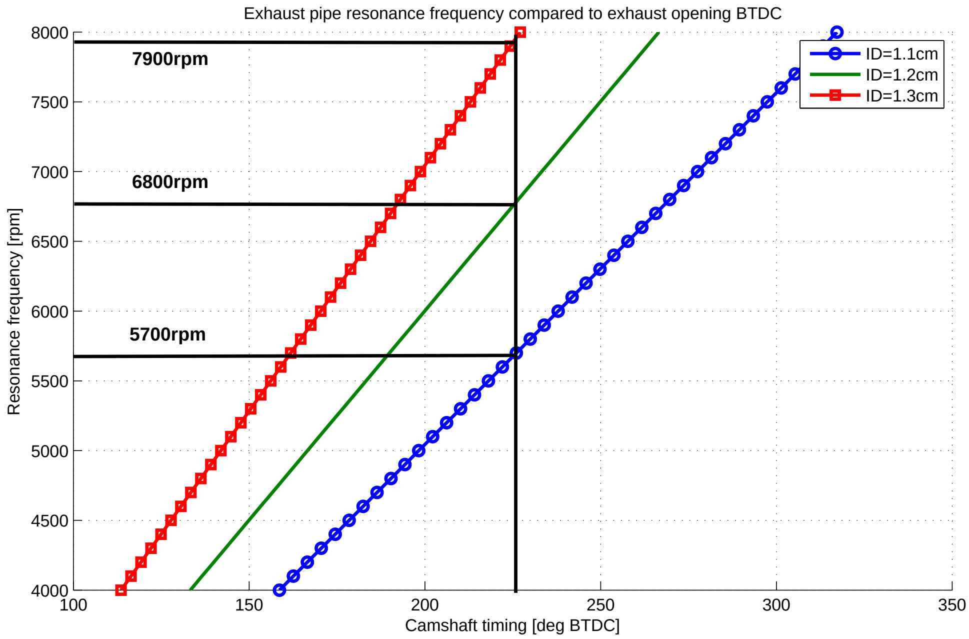


Fig. 4.13 Comparison of resonance frequency with different pipe diameters.

As the exhaust diameter should not be smaller than 1.2cm which is stated above, there is not much that can be done to optimize its resonance frequency without modify the exhaust camshaft or making the exhaust pipe smaller in diameter. From *Figure 4.12* it is shown that the required pipe length is 64.3cm for a diameter of 1.2cm. The resonance frequency will then be 6800rpm which is seen in both *Figure 4.13* and *Figure 4.14*, however the frequency which is quite high suits the generator package used in the serial hybrid well, as this consists of the Maxon RE50. If the diameter decreases as in *Figure 4.13*, a lower frequency will be obtained from the cost of reduced power. An increment in diameter will instead increase the frequency without losing power, instead a small increase in torque can be expected.
To be able to go down in frequency to suit the parallel hybrid with Maxon RE65 as generator, there is two ways to go. Either the pipe diameter is reduced to below 1.1cm which will cost power or, modify the exhaust camshaft to lower the timing. When looking in *Figure 4.14*, it can be seen that a exhaust timing of 180° BTDC would improve the performance in the working area.

4.3 Measurements of the Electrical Machines

To be able to fully understand the performance characteristic of the electric machines chosen in *Section 4.1.2*, namely Maxon RE65 and RE50, measurements had to be done. By using a dynamometer coupled to a measuring device accurate data can be recorded and analyzed which is seen in *Figure 4.15(a)* and in *4.15(b)*.

4.3.1 The testbench

Each machine has been set up for efficiency measurements against a Vibrometer[2] 4PB2.7-8K. It is a small water-cooled magnetic powder dynamometer with a maximum brake torque of 2400mNm up to a speed of 2400rpm which is seen in *Figure 4.16(a)* and *Table 4.16(b)*. Thereafter, at higher speeds the dynamometer brakes to hold a constant power of 600W. This is the power that the dynamometer can manage in form of

[2]Vibrometer is now the same as Magtrol.

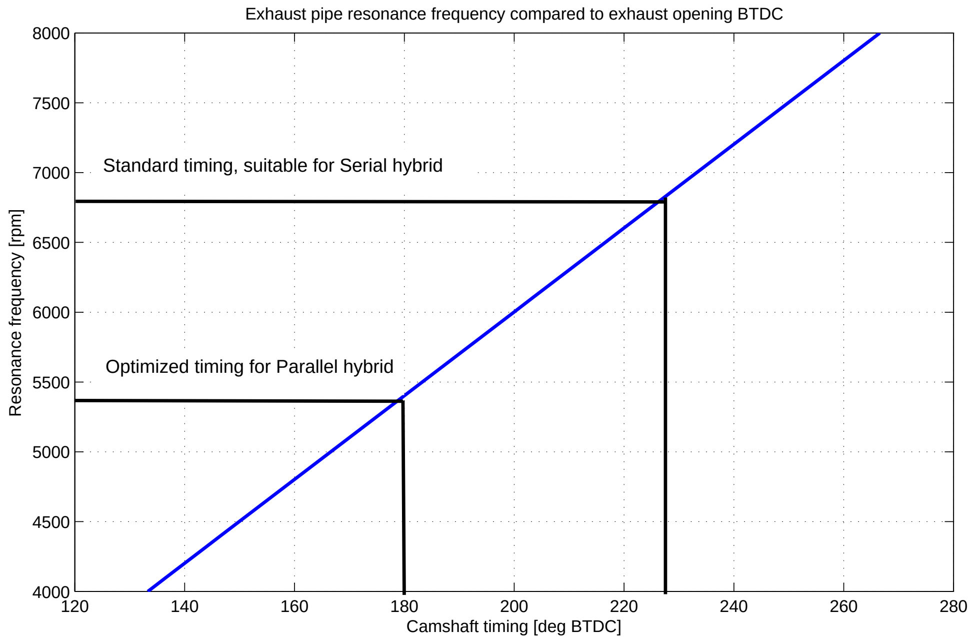
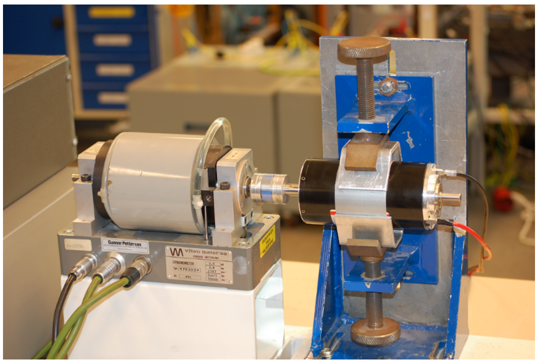
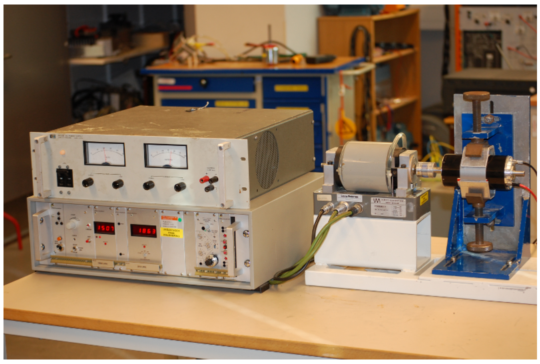


Fig. 4.14 Resonance frequency for Serial and Parallel hybrid with modified camshaft.



(a) Electric machine ready for measuring.



(b) Complete testbench with EM on full power.

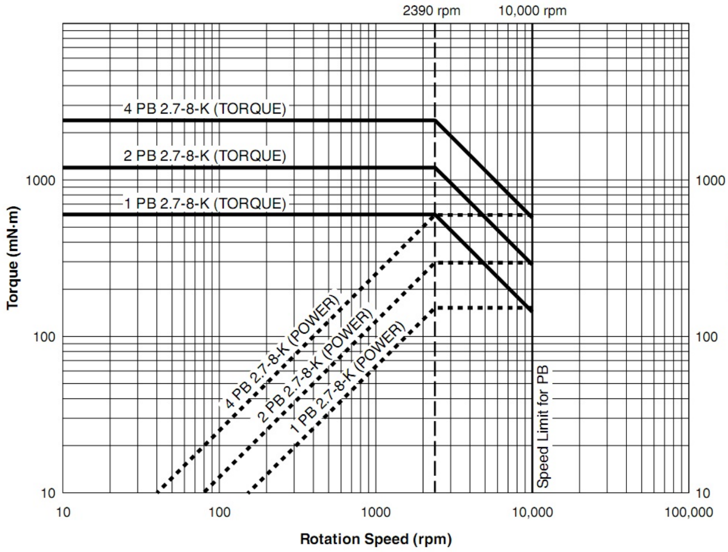
Fig. 4.15 Testbench used to measure small electrical machines.

dissipated heat, short bursts of higher power outtakes is possible but can make it to overheat.

In a magnetic powder brake, a magnetic field is generated by a DC-current passing through the coils of the brake that magnetizes the magnetic powder, which will generate a braking torque. The torque can be varied continuously by varying the current. The magnetic powder dynamometer has the benefit compared to other types of dynamometer such as eddy-current brakes that it provides braking power from standstill.

The dynamometer is mounted on a rigid fixture seen in *Figure 4.15(a)* and in *4.15(b)* which also holds the mounting of the tested machine; this setup makes the whole arrangement less sensitive for vibrations. To connect a machine to the brake, a coupling of some kind is needed. A simple and reliable solution is a coupling made by KTR[3], called Rotex® GS14. It is a three piece device with two end pieces which are connected to the shafts of the brake and the machine, the third piece which is called a "spider" is made by a vibration absorbing material and connects the two end pieces. When ordered, the end pieces come unmachined and look like in *Figure 4.17(a)*. After machining in a lath and mill to match the shaft diameter and making a clamp fixing, it looks like in *Figure 4.17(b)* and the complete rotex coupling can be seen in *Figure 4.17(c)*.

[3]www.KTR.com



(a) Performance data of PB2.7 series, [4].

	Data
T_{nom} [mNm]	2400
T_{Nmax} [mNm]	600
N_{nom} [rpm]	2390
N_{max} [rpm]	10000
m_{cal} [kg]	2.4
m_{pb} [kg]	7.5

(b) Data of 4PB2.7-8K.

Fig. 4.16 Vibrometer 4PB2.7-8K.

(a) Unmachined Rotex GS14. (b) Machined Rotex GS14. (c) Assembled Rotex GS14 with spider.

Fig. 4.17 Rotex vibration absorbing coupling.

Calibrating the dynamometer

The calibration procedure is quite straightforward for this type of dynamometer. First of all two calibration arms are required, the length of the calibration arms are not that important as the measured length from the center of the dynamometer, the calibration length that is 102mm is seen in *Figure 4.18*. The calibration torque for this device is 2400mNm, and to achieve this a calibration weight of 2.4kg is needed. The weight is hanged from one of the arms, depending on which way the torque has to be calibrated, and the measured value is read of the measuring instrument. If the instrument doesn't show zero torque when the weight is off, an offset screw which is located at the front of the instrument can be adjusted to reach zero. And there is also a calibration screw if the torque reading doesn't show 2400mNm; which is also located at the front panel of the instrument.

4.3.2 Measuring the RE65

The RE65 is connected to the dynamometer via a 12mm Rotex coupling which matches the shaft of the machine. Thereafter it is mounted via a clamping device on a fixture which is welded on the support frame of the dynamometer; the fixture which is adjustable in all directions makes it easy to line up the machine to the dynamometer. It is beneficial to line up the machine as good as possible to reduce the friction in the

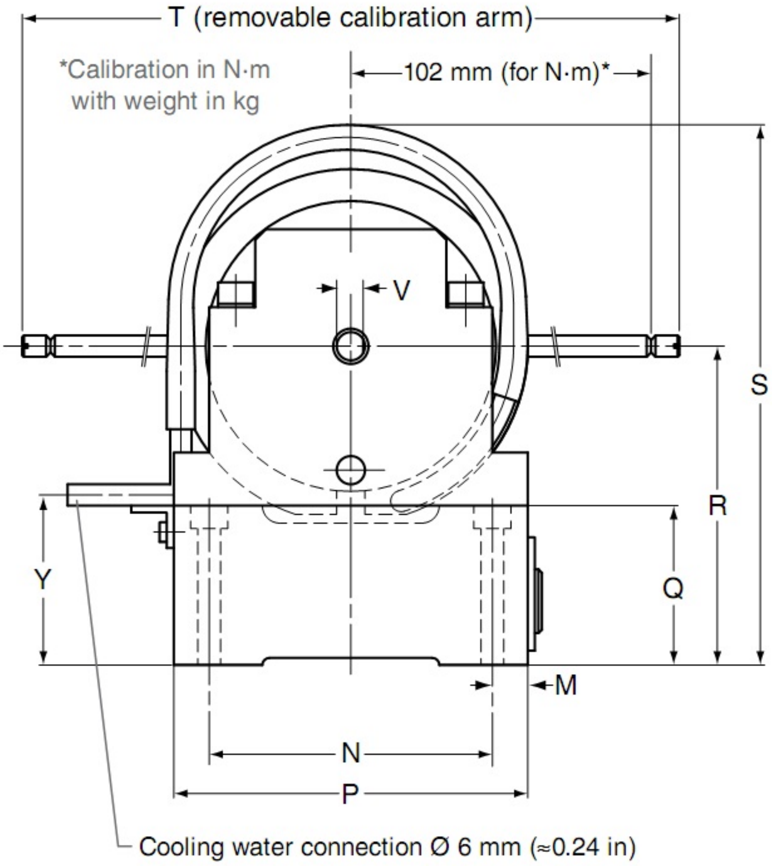


Fig. 4.18 Overview of 4PB2.7-8K showing calibration arms, [4]

coupling and also to reduce vibrations that also leads to power losses.

Table 4.7: No load power RE65

U [V]	I [A]	$P_{measured}$ [W]	P_{calc} [W]	Difference [%]
10	0.48	4.8	0.084	1.74
15	0.53	8.0	0.102	1.28
20	0.59	11.8	0.126	1.07
25	0.62	15.5	0.140	0.90
30	0.79	23.7	0.227	0.96
35	0.76	26.6	0.210	0.79
40	0.76	30.4	0.210	0.69
48	0.90	43.2	0.294	0.68

The measurement of the machine starts at a armature voltage of 10V, which is then increased in steps of 5V until the maximum of 48V is reached. The reason to stop at 48V is that the regulations of the competition prohibit a higher voltage. Before any load is applied, the no load current is measured at each voltage step using a current clamp meter.The results is presented in *Table 4.7*. Thereafter a load is applied with the dynamometer so that the current increases in steps of 1A; the resulting torque is logged together with the speed. The measurement is stopped at 20A which is the maximum current we dare to run the machine at. Running the machine to long at a to high current can overheat and eventually demagnetize its magnets. The rated current for long time operation for this machine in particular is set to 7.8A by the manufacturer.

Table 4.7 also shows the armature losses P_{calc} from the terminal resistance at no load speed with the formula:

$$P_j = RI^2 \tag{4.13}$$

The effect on the total power losses at no load speed is minimal, below 0.3W at a maximum and the difference is less than 2%. This indicates that the majority of the losses are due to mechanical friction.

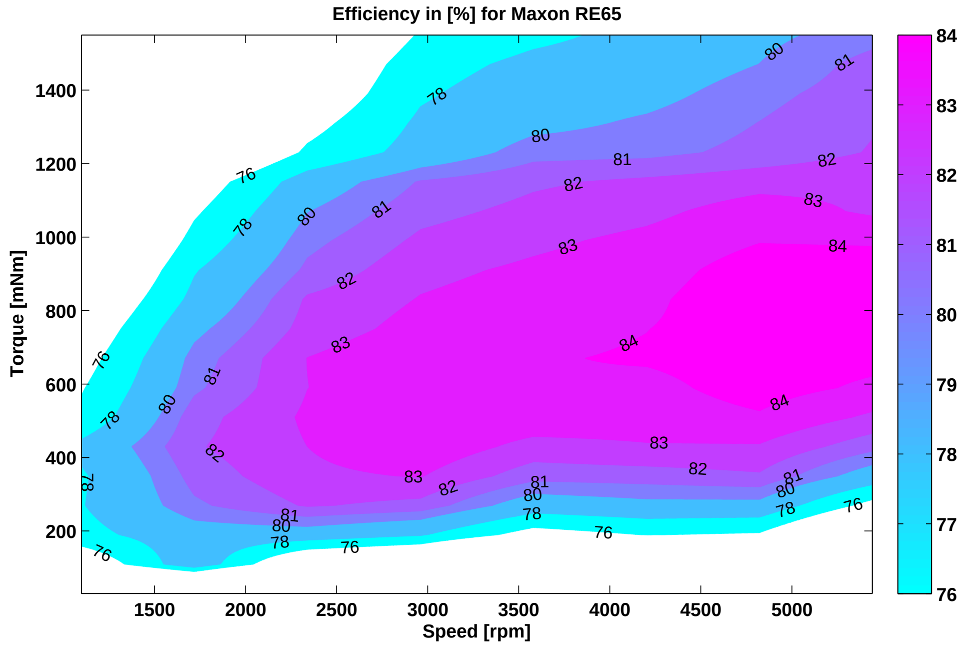


Fig. 4.19 Efficiency of Maxon RE65.

The resulting efficiency at all measured points is seen in *Figure 4.19* where the speed and toque is at the x and y-axis. The figure shows that the machine has its best operating interval between 600mNm - 1000mNm and 4000rpm - 5700rpm. At this area the efficiency is at its maximum of 84% which is 3% lower than what is specified by the manufacturer. The machine performs well up to the extreme points at 20A and 48V, where the efficiency still is above 80%.

4.3.3 Measuring the RE50

The Maxon RE50 is coupled to the dynamometer in the same way as the RE65 described in previous *Section 4.3.2*, however the RE50 which has a smaller shaft of 8mm compared to 12mm for the RE65 require the use of another Rotex coupling. It is of the same type but with a smaller inside diameter. The machine body which itself is also smaller in diameter requires an adapter to be clamped to the fixture.

The measuring procedure for the RE50 is the same as for the RE65, at an armature voltage of 10V and is increased in steps of 5V up to 48V; the measured no load current at each step is presented in *Table 4.8*.The difference compared to the previous measurement is the current. The measurement is done in the same way with an increase of 1A until 15A is reached where the measurement is stopped. This is due to the behavior of the machine which at low speeds and high load stalls and builds up a massive heat. So as a precaution not damaging the machine the max current was set to 15A, which still is almost three times the specified maximum current of 6A stated by the manufacturer.
Which can also be seen in *Table 4.8*, the lower terminal resistance of the RE50 compared to RE65 results in much lower power losses which is less than 0.05W. Hereby the overall power losses of the RE50 is less than 0.6%.

Table 4.8: No load power RE50

U [V]	I [A]	$P_{measured}$ [W]	P_{calc} [W]	Difference [%]
10	0.23	2.3	0.013	0.58
15	0.30	4.5	0.023	0.51
20	0.34	6.8	0.029	0.43
25	0.36	9.0	0.033	0.37
30	0.30	9.0	0.023	0.25
35	0.35	12.3	0.031	0.25
40	0.41	16.4	0.043	0.26
48	0.33	15.8	0.028	0.17

The resulting efficiency-table shown in form of *Figure 4.20* tells that the machine is designed to perform best at lower currents, but also performs well when a higher voltage is applied as there is only a minor efficiency drop at 40V. This gives the machine a wider/larger operating area in the speed region compared to the larger RE65. This region reaches from 3000rpm to its maximum speed of 7700rpm. In this speed range a torque between 150mNm and 450mNm is achieved with an efficiency of at least 86%. In the range between 2000-7700rpm and 0-650mNm the efficiency is at least 84%.

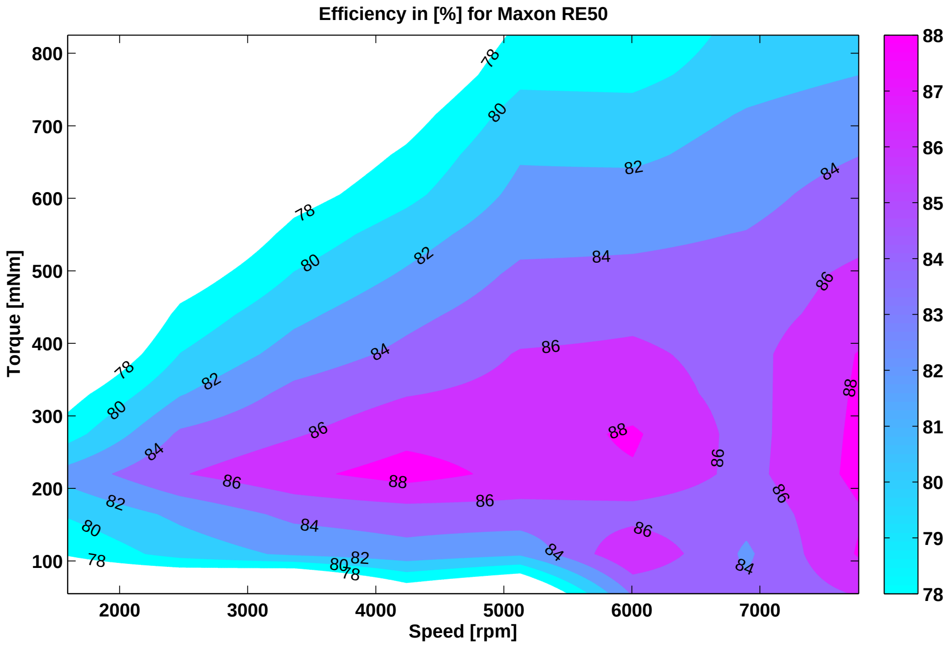


Fig. 4.20 Efficiency of Maxon RE50.

4.3.4 Modeling the Maxon RE65 and RE50

Mathematical models of the machines can easily be derived by using the equations stated in *Section* 4.1.2. The equations of interest is

$$P_{el} = P_{mech} + P_j \tag{4.14a}$$

$$P_{el} = UI \tag{4.14b}$$

$$P_{mech} = \frac{\pi * TN}{30000} \tag{4.14c}$$

$$P_j = RI^2 \tag{4.14d}$$

$$N_{load} = C_N U - \frac{30000}{\pi}\frac{RT}{K_T^2} \tag{4.14e}$$

By making a graph of the no load losses described in previous section, linear models of the losses can be derived as in *Figure 4.21* and *Figure 4.22*. The no load losses thereby includes *Equation 4.14d* which can now be excluded. By rewriting the mechanical power and speed to be torque and ω, the new equations becomes

$$P = T\omega \tag{4.15a}$$

$$N = \frac{30\omega}{\pi} \tag{4.15b}$$

$$P_{mech} = \frac{\pi TN}{30000} = \frac{T\omega}{1000} \tag{4.15c}$$

$$T = C_T I \tag{4.15d}$$

$$N_{load} = C_N U - \frac{30000}{\pi}\frac{R_t T}{C_T^2} \Rightarrow \omega = \frac{C_N U \pi}{30} - 1000\frac{R_t T}{C_T^2} \tag{4.15e}$$

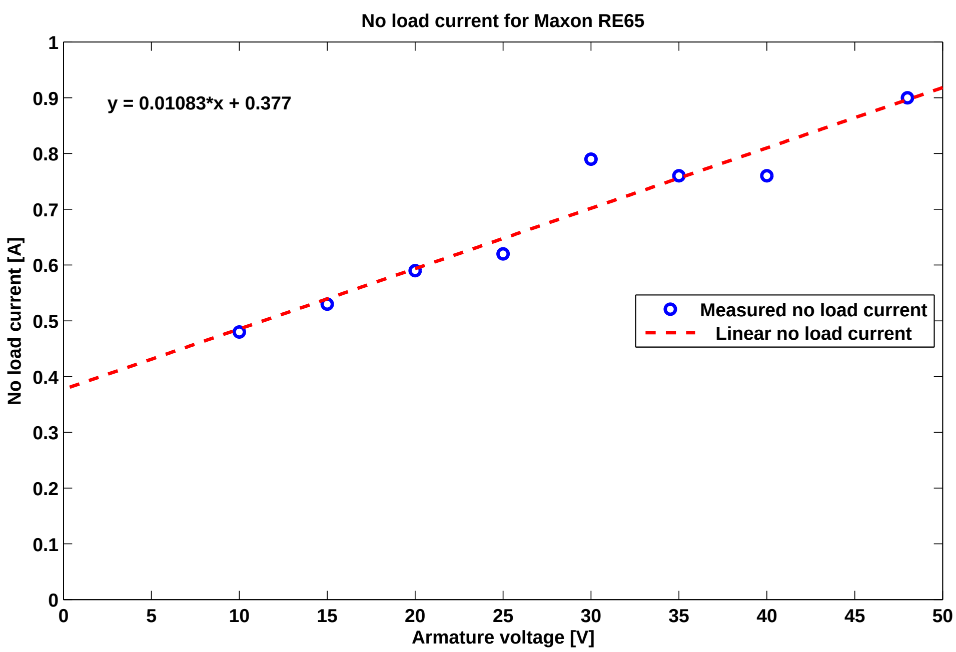


Fig. 4.21 No load current of Maxon RE65.

Inserting the linear models of the no load current losses taken from *Figure 4.21* and *Figure 4.22* into *Equation 4.15d* the new equations becomes

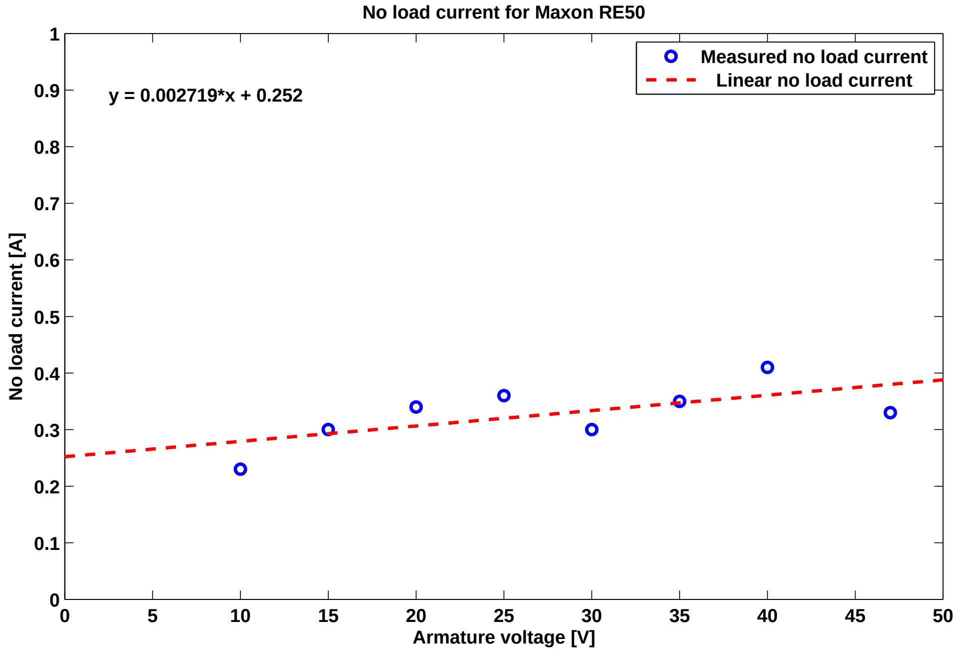


Fig. 4.22 No load current of Maxon RE50.

$$T_{RE65} = C_T(I - 0.01083U - 0.377) \tag{4.16a}$$

$$T_{RE50} = C_T(I - 0.015U - 0.26) \tag{4.16b}$$

Now having a torque-equation which is dependant of the speed, and a speed-equation that is dependant on the torque; realistic simulations can be achieved. Taking the values for the two machines presented in *Table 4.3* and inserting those in *Equations 4.15e, 4.16a* and *4.16b*, and use the measurement inputs stated earlier for the two machines the result becomes as in *Figure 4.23* and *4.24*.

The modeled efficiency of the two machines does not perfectly match the measured efficiency, due to simplicity of the models. However they are still useful as they are partially based on measured values. The maximum efficiency shows however that the models are quite close to the measured. The equations can also be rewritten such as they model a generator by letting the torque and speed be the inputs instead of current and voltage. The equations for generative mode then becomes

$$U = (\omega - 1000\frac{R_t T}{C_t^2})\frac{30}{C_N \pi} \tag{4.17a}$$

$$I_{RE65} = \frac{T}{C_t} - 0.01083((\omega - 1000\frac{R_t T}{C_t^2})\frac{30}{C_N \pi}) - 0.377 \tag{4.17b}$$

$$I_{RE50} = \frac{T}{C_t} - 0.015((\omega - 1000\frac{R_t T}{C_t^2})\frac{30}{C_N \pi}) - 0.26 \tag{4.17c}$$

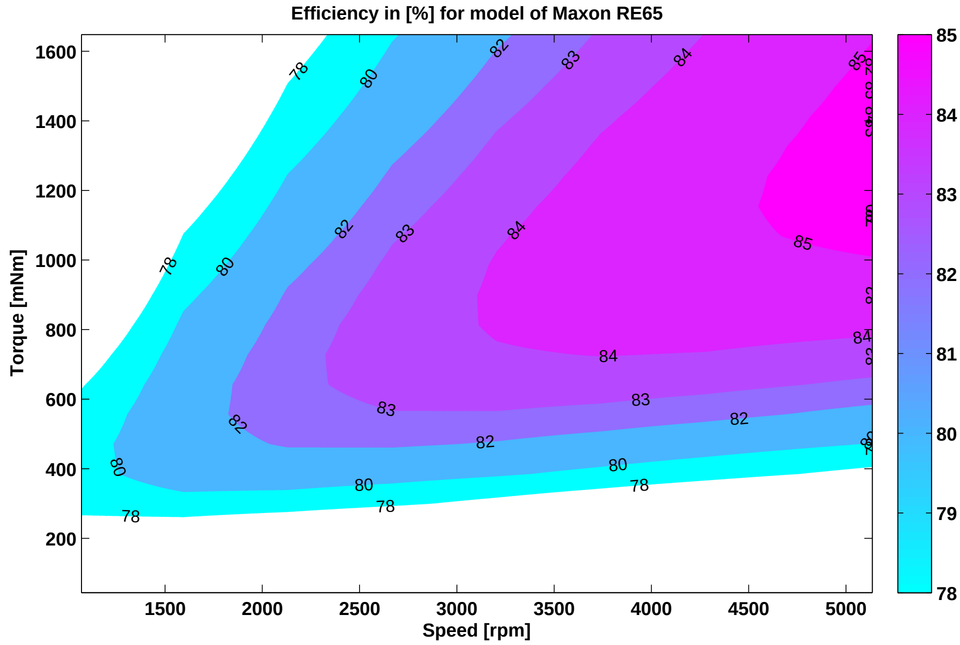


Fig. 4.23 Modelled efficiency of Maxon RE65.

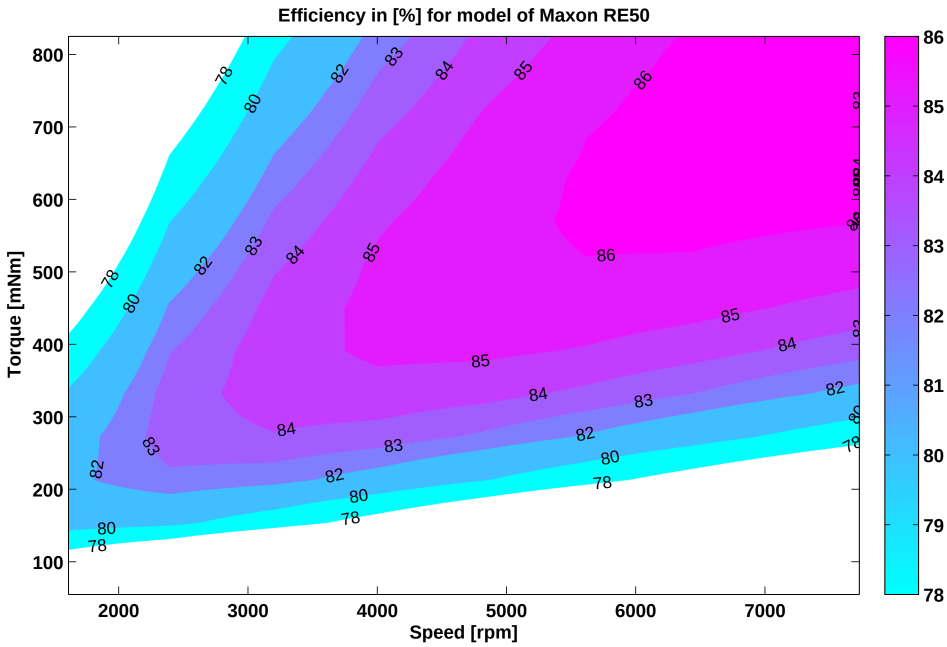


Fig. 4.24 Modelled efficiency of Maxon RE50.

4.4 Transmission

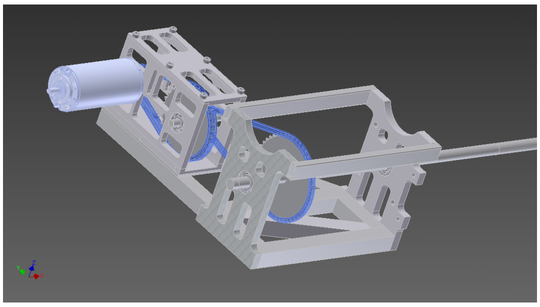
Earlier in *Section 4.1.3* the optimal gear-ratio were discussed and set to 14:1. This is however not always as easy to accomplish as there are many factors that has to be considered; such as space, choice of transmission type and most important what the manufacturer can deliver.
As for transmission type there are mainly three types that can be used namely; belt drive, chain drive and gear drive. The two first are of mainly interest as they are easy to maintain and easier to place within the design compared to the gear drive, which also need constant lubrication. However a gear transmission can be made very compact compared to the others as the gears are directly connected to each other instead through a belt or a chain.

A transmission normally consists of sprockets that transfer the power from one end to another, in the case of the vehicle Smarter the transmission is part of a complete driveline package which also includes the rear wheel suspension and machines for traction. As a reason the transmission ratio, also called gear ratio will be analyzed in this section together with the electric machines which were determined in *Section 4.1.2* and the wheel suspension. The design for each type of hybrid system will be described later on.

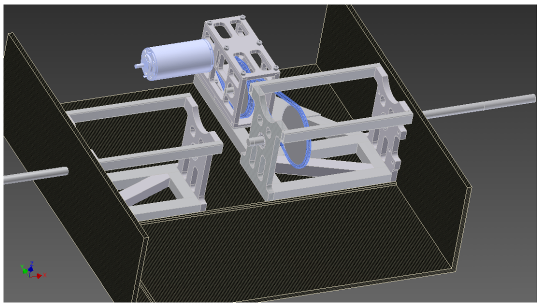
An interesting feature when designing a driveline is how the gear ratio affects the acceleration and speed of the vehicle; for a single gear ratio transmission which is used, the acceleration power at different speeds is of great importance.

4.4.1 Transmission Serial

The transmission made for the serial hybrid is part of the rear wheel suspension for the vehicle Smarter. It is built on rectangular profiled frames of aluminum. The reason to the frame is due to the flexing in the carbon fiber which the entire vehicle is built of.
There is one frame to each rear wheel and they have two uprights mounted on each short side of the rectangular frame. The two uprights on each frame support the rear axis in horizontal and vertical directions. The outer uprights also act as brackets to the brake calipers. The right frame seen from behind the vehicle is extended forward at the long side of the frame with a triangular shape, this triangular extension holds the gearbox as can be seen in *Figure 4.25(a)* where all parts is mounted to the frame together with the gearbox. The complete rear wheel suspension is seen in *Figure 4.25(b)* where it is also placed in a fictive engine bay.



(a) Complete right transmission.



(b) Complete transmission mounted in a fictive engine bay.

Fig. 4.25 Gearbox and wheel suspension.

Due to the compactness of the design, a maximum diameter of the sprocket mounted at the rear axle is limited to 150mm. This reduces the choices of transmission ratios as the transmission type selected is a ISO 05B-1 chain, the specification of the chain can be seen in *Table 4.9*. The largest ISO 05B-1 chain sprocket that fits within the 150mm limit has 57 teeth as can be seen in *Table* 4.10 where the specification of the sprockets used in the transmission are shown. Inside the gearbox the maximum allowable diameter is 110mm which makes a 40 teeth sprocket fit. To achieve a gear ratio of 14:1 the smaller sprockets needs to have a minimum of 12 and 14 teeth respectively. Furthermore the 14 teeth sprockets cannot be fitted to the same axle as the 40 teeth sprocket which needs at least a 15mm axle. Thereby the optimum gear ratio has to be sacrificed in order to fulfill the design. So by choosing the next larger sprocket which has 15 teeth gives a gear ratio of

$$\frac{N1}{N2} \times \frac{N3}{N4} = \frac{12}{40} \times \frac{15}{58} = 12.66 \tag{4.18}$$

Table 4.9: ISO 05B-1 chain specification

Pitch [mm]	8
Roller Dia. [mm]	5
Strength [kN]	4.5
Weight [kg/m]	0.18

Table 4.10: Sprockets used in serial hybrid transmission

N	Diameter [mm]	Bore standard [mm]	Weight [kg]
12	33.7	7	0.09
15	41.7	8	0.1
40	105.3	15	0.77
57	148.6	16	0.97

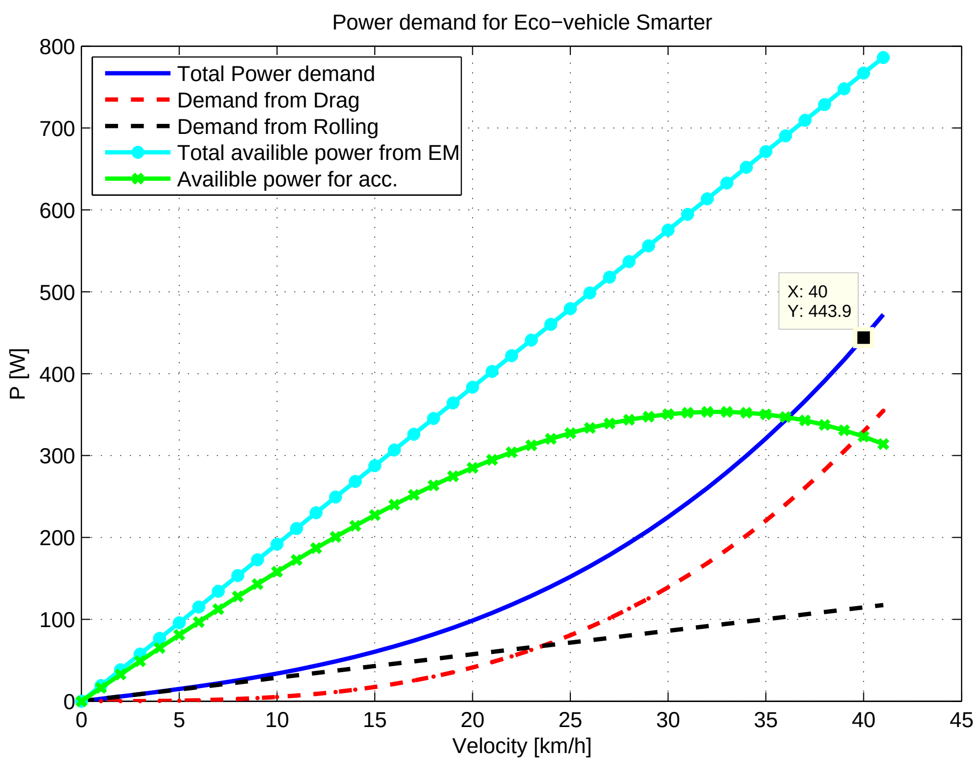


Fig. 4.26 Power demand and available power for serial driveline at HIGH SoC.

Using *(4.7 to 4.14a)* from *Section 4.1.3* the available power for acceleration at different speeds can be calculated. Using the Maxon RE65 for traction which were determined in *Section 4.1.2*, the available power with the gear-ratio of 12.66:1 is seen in *Figure 4.26* when the supercapacitor is in high SoC respectively low in *Figure 4.27*.

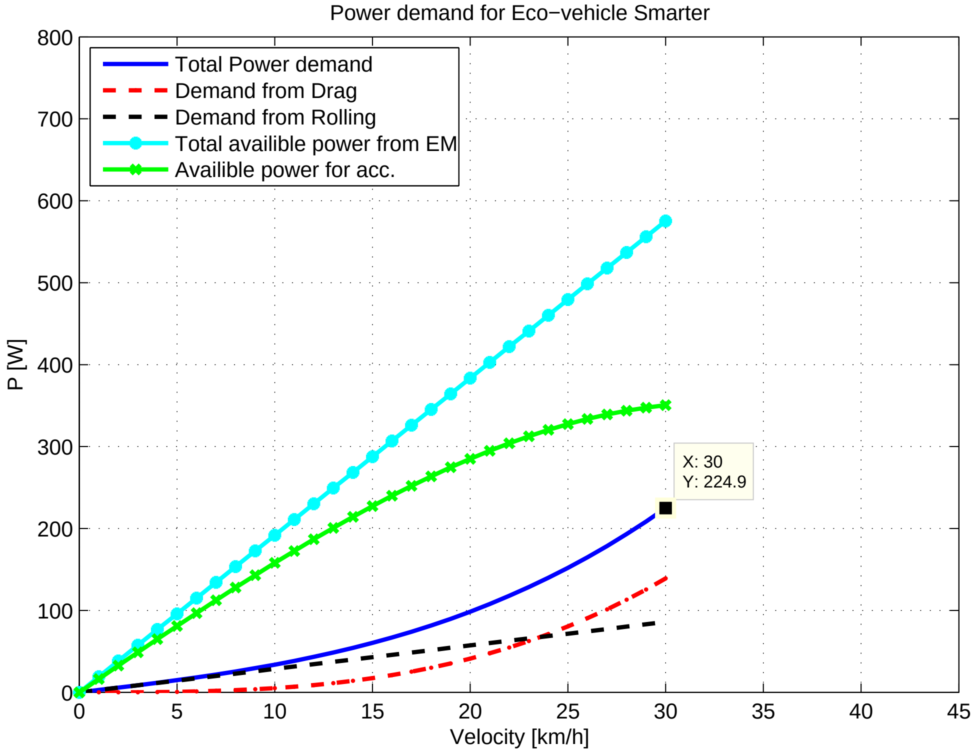


Fig. 4.27 Power demand and available power for serial driveline at LOW SoC.

4.4.2 Transmission Parallel

The transmission for the parallel hybrid system uses the same wheel suspension as for the serial hybrid which is described in *Section 4.4.1*. However the gear box is designed as a separate unit instead being a part of the frame which is the case in the serial design. There are some design aspects that has to be considered when designing the more complex parallel hybrid driveline, as the ICE has to be a part of the system as well as the generator and traction motor. The idea with a parallel powersource driveline is that the system can change path of power as shown in *Section 2.2* where the parallel hybrid system is described. To be able to change source of power two electromagnetic clutches from Warner Electric [2] is used, they are placed between the ICE and the generator, and between the generator and the rear axle as shown in the block diagram in *Figure 4.28*, they can take up to 8Nm of torque up to 10000rpm. This configuration makes it possible to release all powersources when driving, to make the vehicle rolling if that is desirable.

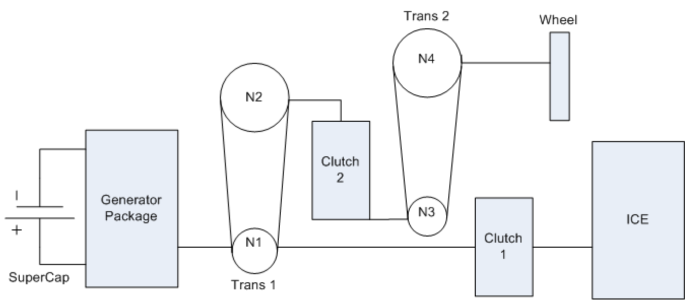
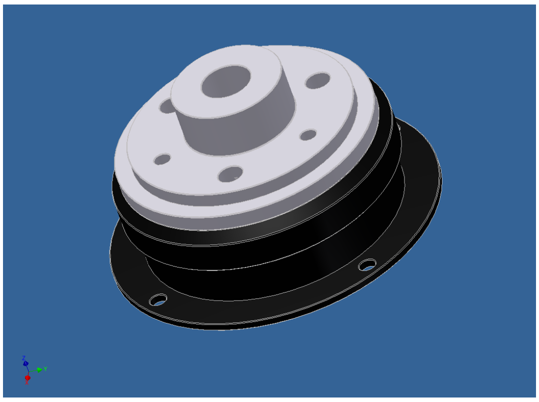


Fig. 4.28 Block overview of transmission parallel.

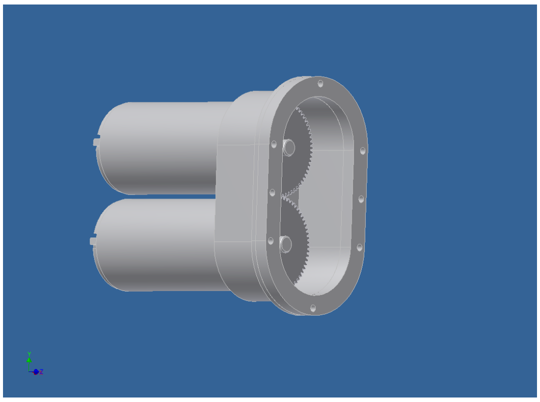
The generator package which is seen in *Figure 4.28* and in *Figure 4.29(b)* has a second function as a traction motor as well. By this design the generator package needs to be more powerful as it should be able to act as a traction motor and generator simultaneously. The generator package consists of two Maxon RE65 fitted to a housing where they are connected in parallel using two cogwheels having low backlash.

The two RE65 will be able to take care of the power from the modified Honda GX35 which were described in *Section 4.2* as well as the power needed to propel the vehicle with the speed of at least 40km/h.

When the ICE is released by the first clutch, the generator package will work solely as a traction motor, for example when starting from a stationary state. Then when more power is needed or when the SoC in the super capacitor is low the first clutch will again be engaged letting the ICE generate power. The ICE has no separate device for starting; as it uses the generator package as a starter motor.



(a) Electromagnetic clutch.



(b) Double Generator/Traction motor coupled together in gearbox housing.

Fig. 4.29 Vital transmission parts.

To transfer the power from the generator package and the ICE to the second axle where the second clutch is located, a timing belt is used. The same type of belt is also used in the second transmission between the second clutch and the rear wheel axle. The belt is of the type T10, which is made of polycarbonate which is reinforced by a steel cord. A polycarbonate belt has very low friction and durability compared to a conventional rubber belt, although it still has very good strength. The specification of the belt is seen in *Table 4.11*. A belt of this type compared to a chain which is used in the serial transmission has the benefit of low weight compared to its strength and merely no maintenance is needed during its lifetime.

Table 4.11: Timing belt profile T10 specification

Pitch [mm]	10
Width [mm]	16
Strength [kN]	5.1
Max transmittable power [kW]	50

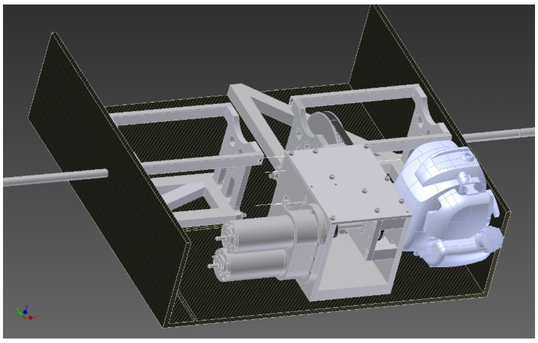
Table 4.12: Timing belt pulleys used in parallel hybrid transmission

N	Diameter [mm]
12	36.35
14	42.70
40	125.45
48	150.95

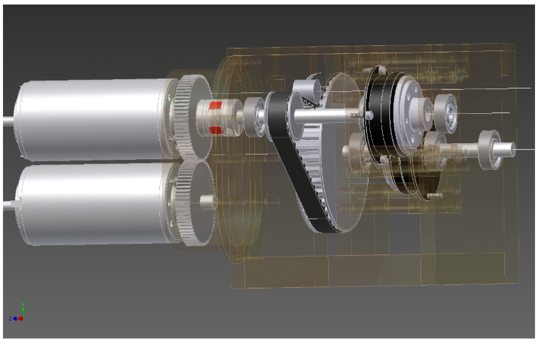
The gear-ratio is set to be 11.43:1 which is a compromise between the optimal gear-ratio of 14:1 and the design. As the space is tight in the engine bay behind the rear axles where the transmission unit has to be placed due to the direction of the rotation on the ICE, the design has to be kept as compact as possible. This is illustrated in *Figure 4.30(a)* where it is placed in a fictive engine bay, in *Figure 4.30(b)* it can be seen in a transparent view. The fact that the T10 profile of the belt causes the belt pulleys to increase in diameter, the gear-ratio has to be lowered. The new gear-ratio is accomplished by the pulleys shown in *Table 4.12* and becomes by the combination of

$$\frac{N1}{N2} \times \frac{N3}{N4} = \frac{12}{40} \times \frac{14}{48} = 11.43 \tag{4.19}$$

Where N1, N2, N3 and N4 refers to the pulleys which is illustrated in *Figure 4.28*.



(a) Complete parallel driveline mounted in a fictive engine bay.



(b) Transmission housing transparent.

Fig. 4.30 Complete transmission parallel.

By this extra power and gear-ratio compared to the serial hybrid it is also interesting to see how much more power the traction motor can deliver at different levels of SoC. So by using *Equation* 4.7 to 4.14a from *Section* 4.1.3, the available electric power when driving is shown in *Figure* 4.31 and in *Figure* 4.32 where the SoC is high in the first figure and low in the second. When the SoC is high it can be seen that the theoretical available power when running at full speed is almost 1000W.

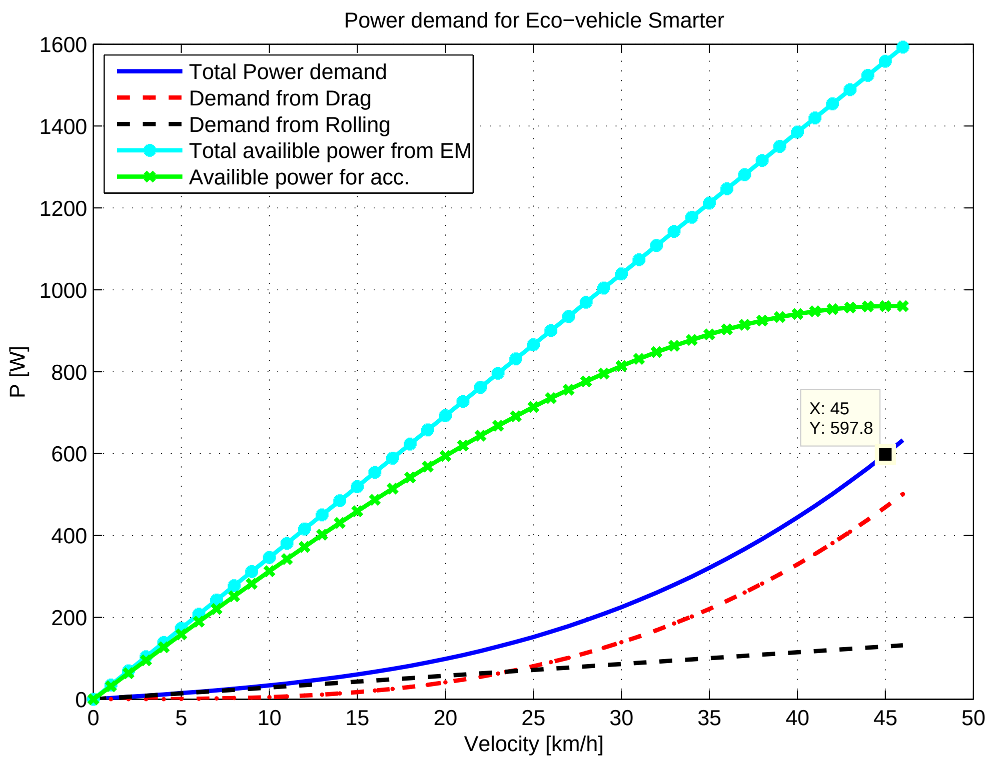


Fig. 4.31 Power demand and available power for parallel driveline at HIGH SoC.

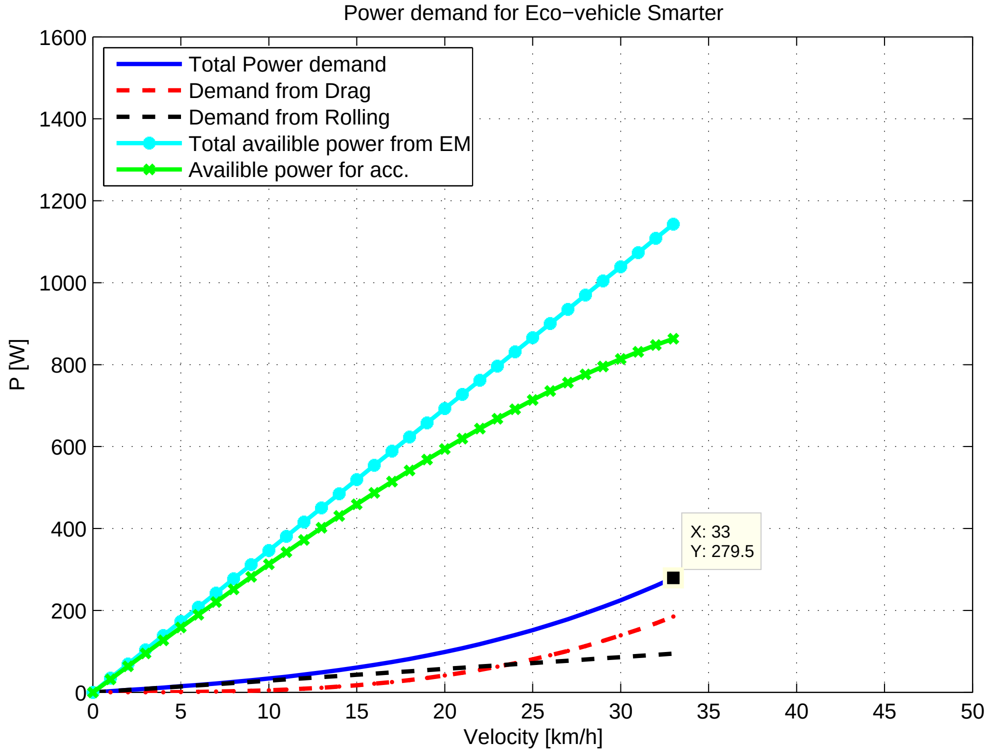


Fig. 4.32 Power demand and available power for parallel driveline at LOW SoC.

4.5 Simulations

In order to get comparable values to either speak for the series or the parallel solution a series of simulations have been carried out using the Matlab software Simulink and the QSS toolbox. Two different models have been developed and used to model the drive train and its included parts during a run.
In order to get values applicable to our system in particular, the drive cycles and vehicle information used as inputs to the models are chosen such as they fit the application. The figures used for the modeling of the ICE and the electrical machines are all taken from data sheets available from the respective manufacturers. Of course as always when using tools for simulating real life scenarios the outcome might be different compared to the real. In our case the total distance that can be run might not be directly translated to the real track distance.

The simulations have been performed using the same ambient data input to both the series and parallel model. The drive cycle is the same, in both test cases. The values that have been changed are the speed, weight and the gear ratio of the vehicle. This is done in order to be able to track the impact of changes made to the vehicle. This information can also be extracted and giving a hint what should be the focus point for upcoming projects connected to the vehicle Smarter.
As the vehicle is the only part of the simulation that we can influence in the real this is where the changes have been made during the simulation. The values used are chosen such as they should possibly be practically implemented. The models have stayed the same throughout the simulations.
As previously mentioned the variables that are chosen to be changed are; the maximum speed the vehicle is able to travel with, the gear ratio and the weight. The chosen speeds are; 20, 25, 27, 30 and 35km/h. Those velocities make the vehicle finish within the set time frame except the two lowest; as those give an average speed lower than minimum, but are kept since the result shows the importance of speed corresponding the impact of drag. The gear ratios chosen are the earlier presented optimal of 14:1, 12.66:1 which is the gear ratio used in the manufactured series driveline and 11.43:1 which is what is chosen for the parallel system. The weight is changed from 150 and 200 in the simulations, where 150kg was the expected maximum weight of a competition ready vehicle. 200kg is chosen in order to tell how the weight impacts the distance

that can be run.

The variables used in the simulations are shown in *Table 4.13* below.

Table 4.13: Simulation variables

Velocity [km/h]	Gear ratio [-]	Weight [kg]
20	11.43:1	150
25	12.66:1	200
27	14.00:1	-
30	-	-
35	-	-

All the variables have been chosen such as they are practically implementable to the driveline or the vehicle as such except the weight which should be kept as low as possible. The simulations have been performed using the same initial values this means the SoC of the energy reservoir have been set to max. The drive cycle used is the earlier described and developed model of the Shell ECO course of the Lausitz speedway more detailed described *Section 3.1*. If the SoC is lower than the initial set when the set distance is finished, the charge process will continue until the SoC reaches its initial value. The fuel consumption of this is added to the total presented, although it should be mentioned that the extra time taken for this charge is not added to the total time. The simulations will be presented separately, first is the series system in next section which will be followed by the parallel.

4.5.1 Serial Hybrid

The simulations have been carried out changing some of the variables describing the vehicle properties. Three variables have been chosen, those are the maximum achievable speed, the weight of the vehicle and the gear ratio of the transmission. The Simulink block diagram showing the model of the series hybrid that has been used for the simulations is shown in *Figure 4.33*.

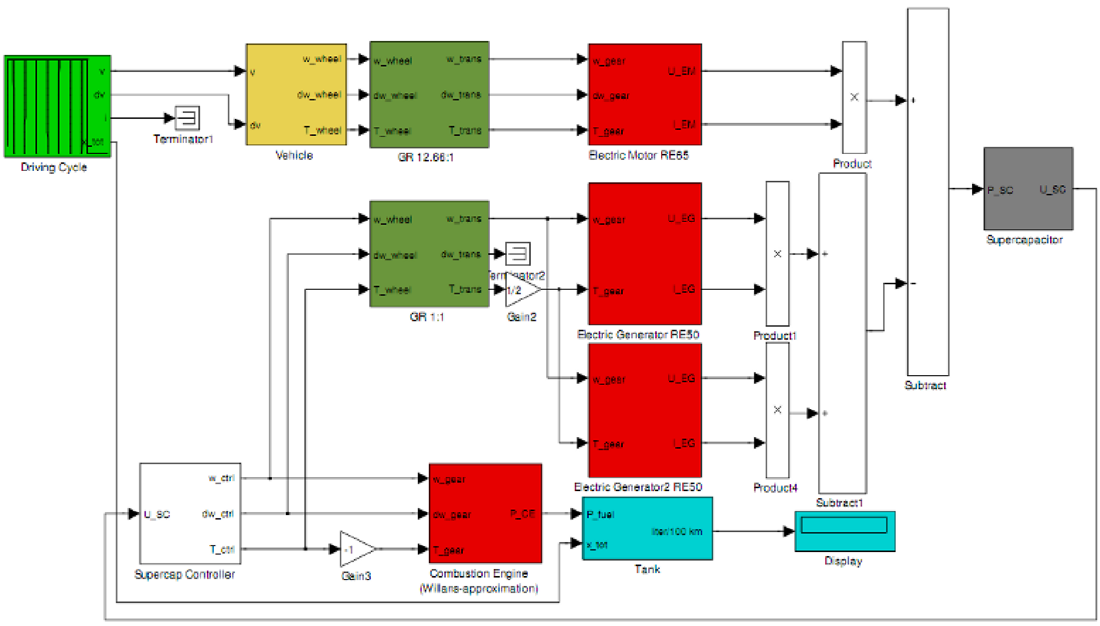


Fig. 4.33 Simulink block diagram for a serial hybrid vehicle.

First series of simulations are performed with a set weight of 150kg and a gear ratio of 11.43:1, the maximum velocity of the vehicle have been changed between 20 and 35km/h. The result of the simulation for the two lowest speeds will as can be seen in *Table 4.14* lead to a longer time to complete the distance than what is allowed by the competition organizer (3180 seconds). Those are decided to be part anyway as the air drag is earlier described as the major friction when the rolling friction have been overcome, and will show the impact of running in higher velocities. By looking at the total distance that can be travelled using the different velocities one can see that by just changing the speed of the vehicle from 20-35km/h gives a change in distance with close to 130km.

Table 4.14: Serial hybrid simulation: gear-ratio 11.43, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.44	4087	11	0.2777	360.2
25	23.96	3317	14	0.3172	315.2
27	25.72	3091	15	0.3374	296.4
30	28.33	2805	16	0.3725	268.5
35	32.38	2454	19	0.4323	231.3

Table 4.15: Serial hybrid simulation: gear-ratio 11.43, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.44	4087	11	0.3272	305.5
25	23.96	3317	14	0.3681	271.1
27	25.72	3091	15	0.3882	257.6
30	28.33	2805	16	0.4246	235.5
35	32.38	2454	19	0.4894	204.3

The second series of simulations use the same inputs as the first except the weight of the vehicle which is changed to 200kg; the results can be seen in *Table 4.15*. Again looking at the result of the distance for the different speeds one can see that the higher the speed the shorter the distance as expected. But the second series of simulations are made in order to track the impact of the change in weight, why the distances are compared to the first series of simulations. Calculating the mean difference of the change in distance, gives roughly a change of 39.5km shorter range by just adding a weight of 50kg.

Table 4.16: Serial hybrid simulation: gear-ratio 12.66, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.48	4079	10	0.2801	357.1
25	24.02	3309	13	0.3208	311.7
27	25.85	3074	13	0.3148	292.5
30	28.41	2797	15	0.3745	267
35	32.61	2437	17	0.4372	228.7

Table 4.17: Serial hybrid simulation: gear-ratio 12.66, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.48	4079	10	0.3279	305
25	24.02	3309	13	0.3696	270.6
27	25.85	3074	13	0.3909	255.8
30	28.41	2797	15	0.4245	235.6
35	32.61	2437	17	0.4926	203

The difference when changing the gear ratio from 11.43:1 to 12.66:1 and 14:1 gives roughly the same numbers within the series of simulations as for using the gear ratio of 11.43:1. The results of those simulations can be found in *Table 4.16* to *Table 4.19*. Looking at all simulations made, one can see that by changing only the gear-ratio does barely not influence the distance travelled. Calculating the mean change in distance for all velocities when changing gear ration from 11.43:1 to 14:1 gives a change of only 4km. This tells that the change of gear ratio only has a minor impact of the distance that can be run. The simulations has also proven that by just changing the weight 50kg the distance can change with up to 54.7km.

But as a conclusion from the simulations of the series hybrid solution one can clearly state that the biggest issue is the air drag. This points out that the aerodynamics of a vehicle is one of the most important aspects when it comes to the fuel consumption.

Table 4.18: Serial hybrid simulation: gear-ratio 14, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.52	4071	9	0.281	355.9
25	24.13	3293	11	0.3227	309.9
27	25.92	3066	12	0.343	291.5
30	28.50	2789	14	0.3755	266.3
35	32.73	2428	16	0.4386	228

Table 4.19: Serial hybrid simulation: gear-ratio 14, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.52	4071	9	0.3294	303.6
25	24.13	3293	11	0.3727	268.3
27	25.92	3066	12	0.3938	254
30	28.50	2789	14	0.4262	234.6
35	32.73	2428	16	0.4947	202.1

4.5.2 Parallel Hybrid

As for the simulations of the series hybrid three variables have been changed throughout the series of simulations. The changes of the variables have been the same. The simulation result clearly shows the weight of the vehicle greatly influences the total distance that can be run. As expected the velocity also has a great impact on the range, as discussed earlier in *Section 4.1.1* the rolling friction is only an issue at very low speeds but then the air drag takes over. This can clearly be seen as the distance becomes shorter when the velocity is increased. *Figure 4.34* shows the block diagram of the model used with Simulink to simulate the parallel hybrid driveline.

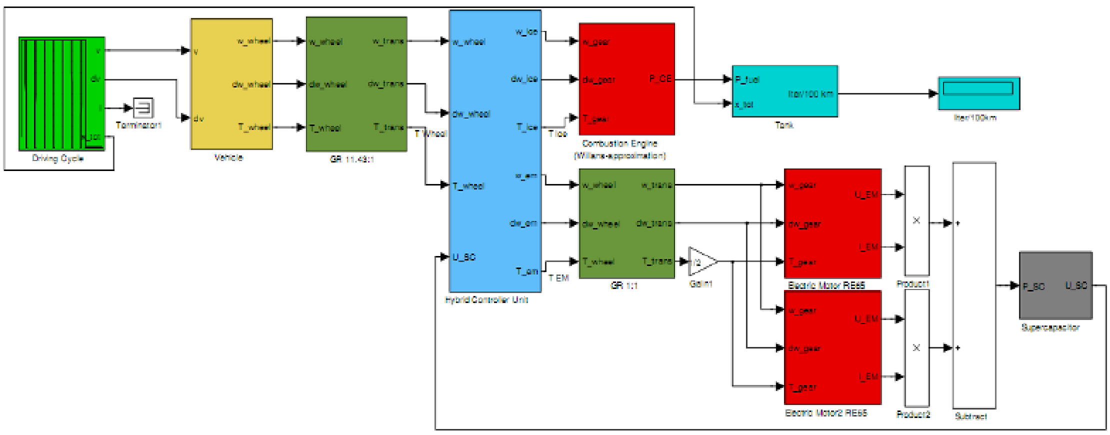


Fig. 4.34 Simulink block diagram for a parallel hybrid vehicle.

As for the serial hybrid simulations the series of simulations starts with a vehicle weight of 150kg and a gear ratio of 11.43:1. The result of those simulations are shown in *Table 4.20* followed by *Table 4.21* which shows the same simulation but with the vehicle weight changed to 200kg. As for the series case the change of weight leads to a decrease of the maximum distance with up to 50km, and an average of 34km. Changing the speed from 20 to 35km/h gives a change of distance of about 100km when the vehicle weight is 150kg, and a bit less around 85km when the vehicle weight is 200kg.

Table 4.20: Parallel hybrid simulation: gear-ratio 11.43, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.63	4048	6	0.2735	365.5
25	24.37	3261	7	0.3111	321.5
27	26.1975	3034	8	0.3268	306
30	29.01	2740	8	0.3553	281.5
35	33.42	2378	10	0.4012	249.2

Table 4.21: Parallel hybrid simulation: gear-ratio 11.43, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.63	4048	6	0.3188	313.7
25	24.37	3261	7	0.3485	287
27	26.1975	3034	8	0.3652	273.8
30	29.01	2740	8	0.3954	252.9
35	33.42	2378	10	0.4419	226.3

The simulation results for the two other gear ratios of 12.63:1 and 14:1 is shown in *Tables 4.22* to *4.25* where both weights of the vehicle are presented. The differences from those simulations compared to the first series made; are small. The changes in distance are almost the same, which means about 100km when the speed is changed from 20-35km/h and around 30km when weight is changed from 150 to 200kg.

Table 4.22: Parallel hybrid simulation: gear-ratio 12.66, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.63	4040	5	0.2881	347.1
25	24.37	3261	7	0.3236	309
27	26.2663	3026	7	0.3291	303.8
30	29.01	2740	8	0.3583	279.1
35	33.5359	2370	9	0.41	243.9

Table 4.23: Parallel hybrid simulation: gear-ratio 12.66, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.63	4040	5	0.325	307.7
25	24.37	3261	7	0.3532	283.1
27	26.2663	3026	7	0.3675	272.1
30	29.01	2740	8	0.3976	251.5
35	33.5359	2370	9	0.4512	221.7

Another interesting outcome from the simulations is that the change in gear ratio does not affect the range much for the higher velocities but has a greater impact at lower speeds. This is probably connected to the higher torque needed for cruising at lower speeds. Analyzing the result more in detail by looking at different cruising speeds for the same weight and gear ratio on can see that the difference becomes smaller and smaller the higher the speed. An explanation to this would then be that for the higher speeds the air drag is the largest issue to influence the distance, and the weight has less impact, at least when the change is in the order of 50kg.

4.5.3 Evaluation of simulation results

By evaluating the overall simulation result for both the series and parallel case one can see that the parallel hybrid solution is as expected in most cases performing better compared to the series hybrid. Although

Table 4.24: Parallel hybrid simulation: gear-ratio 14, vehicle mass 150kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.67	4040	5	0.299	334.4
25	24.43	3253	6	0.3261	306.6
27	26.33	3018	6	0.3449	289.9
30	29.09	2737	7	0.3714	269.3
35	33.65	2362	8	0.4323	231.3

Table 4.25: Parallel hybrid simulation: gear-ratio 14, vehicle mass 200kg

Vel [km/h]	Vel$_{mean}$ [km/h]	Race time [s]	Acc.time [s]	FC [l/100km]	Distance [km/l]
20	19.67	4040	5	0.3289	304
25	24.43	3253	6	0.3642	274.6
27	26.33	3018	6	0.3788	264
30	29.09	2737	7	0.4112	243.2
35	33.65	2362	8	0.4641	215.5

there are some cases where the simulations shows the series solution will reach a greater distance. This is explained by the way the drive lines are designed, where the series driveline in those cases is working in an area where the overall efficiency is better compared to the parallel hybrid. The only time this appears is when the gear ratio of 12.66:1 for speeds below 27km/h and for 14:1 for speeds below 30km/h. Moreover it changes again if the weight of the vehicle is changed from 150kg to 200kg, where the parallel solution again supersedes the series. Another outcome from the simulations is that the results shows there is greater difference for higher speeds compared to lower. This is explained from the torque of the EMs used. As there are two identical electric machines in the parallel design used for propulsion and only one in the series the torque is twice in the parallel. The use of two electric machines in the parallel design is also the explanation to the shorter acceleration time compared to the series. For the other simulated scenarios the parallel solution has a better performance, however what is interesting is that the difference is smaller than what was expected. To get a better overview the most favorable speed to use during the competition only taking the time into consideration disregarding any other events is shown in *Table* 4.26. The overall average difference of the series design compared to the parallel is 8km in favor to the parallel. The overall reason the parallel driveline reaches a better distance can be explained by the overall efficiency which is higher due to the fever steps in moving the energy from ICE prop shaft to the wheels. Where the series first has to store the energy in the energy bank and then using a converter to run the vehicle, the parallel could use the mechanical power directly from the ICE prop shaft to the wheels.

Table 4.26: Simulation results comparing Serial and Parallel at 27km/h

Distance Serial [km]	Distance Parallel [km]	Diff [km]	Weight [kg]	GR
296.4	306	9.6	150	11.43:1
257.6	273.8	16.2	200	11.43:1
292.5	303.8	11.3	150	12.66:1
255.8	272.1	16.3	200	12.66:1
291.5	289.9	-1.6	150	14.00:1
254	264	10	200	14.00:1

4.6 Control system

In this chapter the control system will be described, the function of the control system is to monitor the running process of the vehicle. The control system uses several sensors placed in the vehicle driveline in order to make decisions such as when to start and stop the ICE to charge or to drive the vehicle. The control system uses the information sampled from the sensors and tells the EMS if the ICE should be run or not. The control system is also used for the communication with the driver. Where the driver gets values from the sensors such as speed, SoC, elapsed time and if the ICE is on or off presented on a display in the drivers compartment. The control system also reads of the accelerator in order to control the speed of the electric machines. As the controller itself have not been investigated nor manufactured or designed during this project no detailed description will be made. The only thing discussed will be how the control system should control the ICE during different running conditions and how the power should be transferred to the wheels. Those running conditions will be explained in a later section after the sensors have been introduced.

4.6.1 Sensors

The following sensors are needed in order to control the designed hybrid system; a speed sensor, a sensor measuring the energy reservoir voltage and a current sensor. What also can be added to the system is an acceleration sensor.
The sensors will have different roles as the vehicle is used. The speed sensor will as the name tells read the speed of the vehicle to tell if the vehicle changes speed or is travelling at a maintained speed. If the system has an added acceleration sensor the combined information from the speed and acceleration sensor will be what the control unit should use to decide whether the ICE should be started and used as the primary source of propulsion or not. If the vehicle is accelerating heavily using the combined power from both ICE and EM should be used, or only the EM for lower speeds.
The only function of the voltage sensor will be to constantly serve the control unit with the SoC level of the energy storage. As this is the only information used as the basis for the decision when to start and stop the ICE in order to charge. The function of the current sensor will be to monitor the charge current as well as the current drawn by the EM when cruising to keep this within the set limits, to retain the lifetime of the EM.

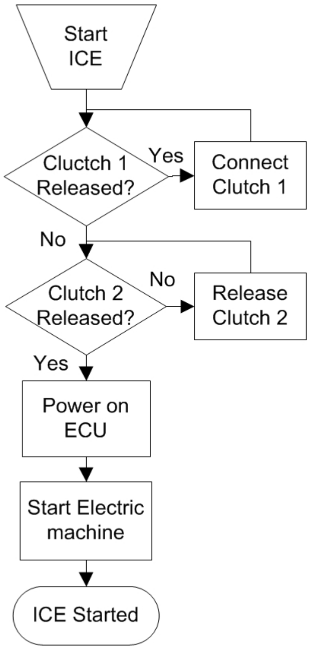
4.6.2 Flowcharts

The following presented flowcharts can be used to design the control unit. The flowcharts will describe different running conditions. The flow charts will try to in an easy way show what should be measured and what decisions should be taken. The running conditions considered will be **Start of ICE**, **Stop of ICE**, **Start of Vehicle** and **Normal running condition** those will be presented for both the parallel and the series design.

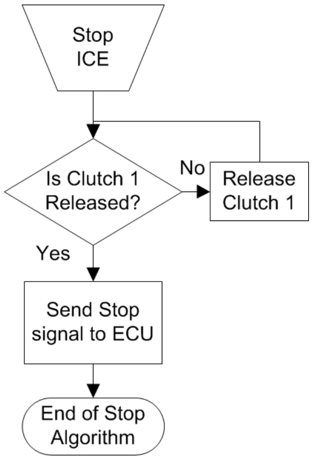
Flowchart Parallel

All names of the blocks in the following flowcharts are referring to the same blocks in the parallel block design overview which can be seen in *Figure 4.28* in *Section 4.4.2*.

The starting process of the ICE can be seen in *Figure 4.35(a)* where the first to consider is if the clutches are released or engaged. This has to be considered as the vehicle should not ”jumpstart” if starting from standstill, and should not roll start the ICE if in movement. Also as the only available electric machines is used as starter motors the clutch connecting them to ICE prop shaft needs to be connected, and of course the power to the ECU.
The stopping of the ICE *Figure 4.35(b)* needs less steps as the only crucial step is to release the connection between the electric machines and the ICE prop shaft, and then send stop signal to ECU.
Starting the vehicle *Figure 4.38(b)* will contain some further steps where the readings of the voltage sensor gets into use. First the voltage of the super capacitor needs to be read in order taking the decision whether using only the electric machines or first starting the ICE using the machines, and then starting the vehicle.
During the normal running condition *Figure 4.38(a)* there is an ongoing loop always reading the signal



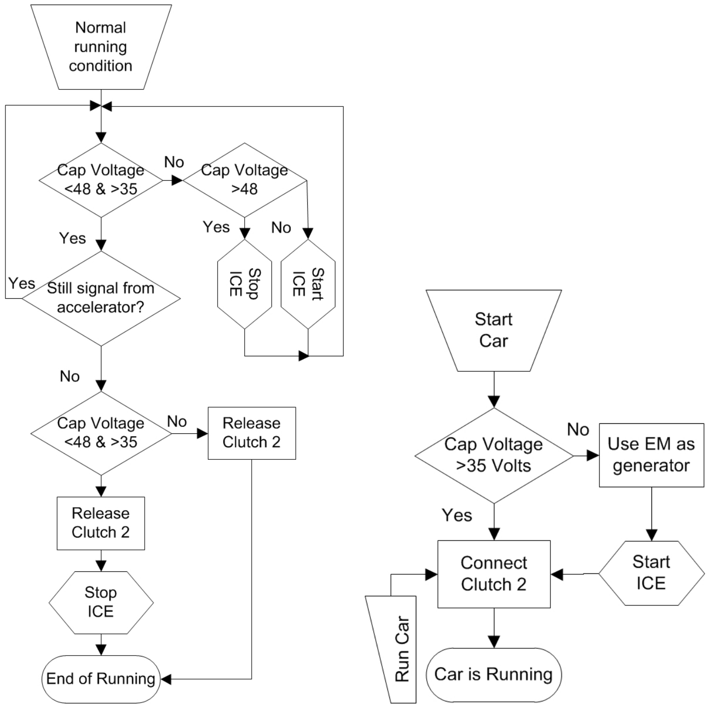
(a) Start ICE.



(b) Stop ICE.

Fig. 4.35 Flow chart for parallel hybrid 1.

from the accelerator this information is used in order to maintain the loop measuring the SoC of the super capacitor. The SoC information is used to control the starting and stopping of the ICE to maintain the SoC within the levels set. When there is no longer any signal from the accelerator this is read as the car is going to stop and thus initiate the stopping process, which contains the SoC check in order to stop the ICE with the SoC within in set limits.



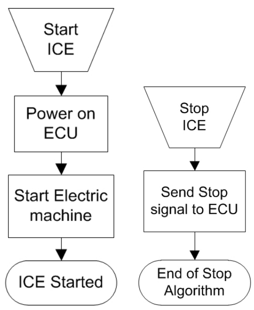
(a) Running condition. (b) Start vehicle.

Fig. 4.36 Flow chart for parallel hybrid 2.

Flowchart Serial

All names of the blocks in the flowcharts are referring to the same blocks in the serial block design. Compared to the parallel design the series drive line is built in a more piece wise independent way. This means the design is easier to control, which means the controller does not need to be as complex as for the parallel design. This can easily be seen in the corresponding flow charts that has the function as the ones earlier presented for the parallel.

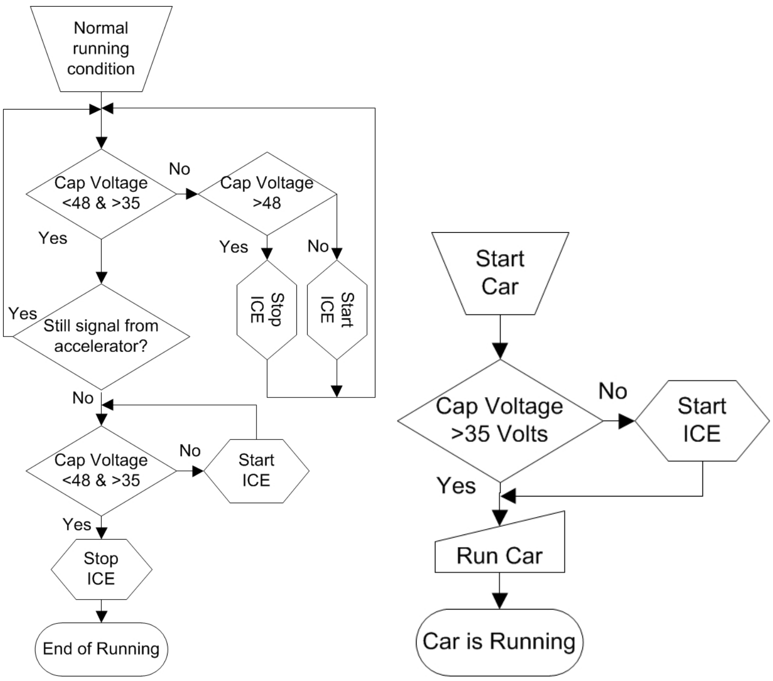
First looking a starting process of the ICE which can be seen in *Figure 4.37(a)*. Here one can see a lot of the steps needed for the parallel are removed as the generator has no physical connection at all to the drive axle of the vehicle. The signal preparing the ECU for starting the ICE and then running the generator as a starter motor is what is needed.



(a) Start ICE. (b) Stop ICE.

Fig. 4.37 Flow chart for serial hybrid 1.

The stopping of the ICE *Figure 4.37(b)* is as easy as the starting and thus only the stop ICE signal is needed from the ECU. The process to start the vehicle *Figure 4.38(b)* only needs to read of the sampled value from the voltage sensor to read the SoC of the super capacitor and then decide if the ICE is needed to charge or not, then just giving the signal of running the traction motor.



(a) Running condition. (b) Start vehicle.

Fig. 4.38 Flow chart for serial hybrid 2.

The normal running condition is the most complex process for the series design *Figure 4.38(a)*. As in the parallel case there has to be a loop always sampling the state of the accelerator as well as SoC and current drawn from the super capacitor. This information is then used to control the start and stop of ICE for keeping the SoC level within the range. When there is no longer any signal from the accelerator this is read as the vehicle should stop.

Chapter 5

Results

The designed serial hybrid driveline was successfully fitted to the Chalmers Eco-marathon vehicle during the Shell Eco marathon competition 2010, where it achieved a distance of 153,8km consuming one liter of petrol resulting in a fuel consumption of 0,0065 l/km, putting the team in an overall 12th place.
By completing this project knowledge and understanding of the problems connected to a hybrid driveline have been gained as well as some ways of overcoming those.

As the purpose of the project was clearly stated in the beginning this has clearly been achieved and the theoretical studies and simulations models made shows that the parallel driveline is the best. Although we only had the opportunity to try out the series design in a real life scenario, the parallel would most likely have turned out to achieve an even better result.

As the driving cycle used for the simulations has been developed by the only data that was available of the track, a more precise model would most likely had been able to extract if the elevation curves would have been available. Although this would have led to a more complex cycle the outcome would have been more closely linked to the actual real result. Adding this together with the quite simple model of the cycle would most likely yield a better result if more time could be spent on the development of the driving cycle.

The available data of the vehicle involved in the project which was extracted from a previous project and used for the simulations have not been verified due to time constraints. Hereby it should be mentioned that the correctness of those data is directly linked to the outcome of this project, and better data would reach a better result.

Moreover if the time would not have been the most critical point an in-house developed controller investigating the possibility of using a BLDC EM could have been made.

Furthermore an investigation of available ICE that could have matched the design targets even better could have been conducted if there was room in budget and time. This could have a great impact on the result as the ICE with its components has a major part of the designs and thus the result.

The measurements of the Electric machines shows they perform close to the specifications from the manufacturer. This in turn means the models used for the simulations which are based on data derived from the measurements gives a result that is close to the specified. As an example the measured efficiency of the RE50 is only 3% less than specified.

Due to the compactness of the designs and the available space the gearboxes have been designed with a 2-stage gear. If the space would have allowed using a 1-stage gear less power losses would have been the result which in turn most likely would lead to a better performance.

The overall result from the simulations made, shows that the intuitive thoughts of the parallel solution being the better choice is true. Although the simulations show that the differences between the two solutions are small it still puts the parallel solution as the winner in almost all of the simulated cases.

To get a better idea of the actual difference of the solutions the most important results from the simulations, which is also most likely to be used on the real vehicle, is shown in *Table* 5.1 below.

Table 5.1: Simulation results comparing Serial and Parallel at 27km/h

Distance Serial [km]	Distance Parallel [km]	Diff [km]	Weight [kg]	GR
296.4	306	9.6	150	11.43:1
257.6	273.8	16.2	200	11.43:1
292.5	303.8	11.3	150	12.66:1
255.8	272.1	16.3	200	12.66:1
291.5	289.9	-1.6	150	14.00:1
254	264	10	200	14.00:1

Referring to the result in the table it is clearly seen that the parallel solution performs better than the serial solution by a difference in driven distance with an average of 8km in favor to the parallel in all cases tested. Moreover is that the parallel solution becomes even more efficient for a heavier vehicle were the difference is even larger.

Eventually one would also expect a lowering of the total weight would lead to the corresponding of simulating for the higher. This means that even though the parallel is more efficient for a heavier vehicle, the result is improved if weight is saved in both designs.

Chapter 6

Future work

To forward or communicate ideas and topics for a prolonging of this thesis, this chapter will deal with questions and problems that showed up during the project that we either decided to not work with or to skip due to their low priority or need of too much time compared to the constraints.

During the project we have of course also reached a point where we found that our particular solution to the problem was not the best, why we came up with ideas what could have been done different and we would here like to share those ideas.
There was a need to optimize an EMS system to fit our small engine; this was done with some discussion with the developer of the system. The problem was that we were told we would not need a sensor that later showed it was needed anyway. We would say it would be a good idea to spend more work in fitting or finding an even better suiting EMS for this small engine.

We were investigating the possibility of designing our own EMS for controlling ignition and fuel injection. We found that there are working modules available to purchase which allows the user to decide what functions to be included in the EMS. The problem for us was the time constraint. But as the EMS is not developed to be fitted to such a small ICE the software could not be used to optimally map it to our engine. By this reason we think a designed EMS for this purpose specifically would have gained a better result.

Now when there is a working series hybrid setup, and a design and parts for the parallel hybrid system is done, there is only the work of manufacturing and put it together.
The control algorithms for the parallel system which is implemented only in the simulations could be built in hardware to be fitted and used together with the complete driveline in the vehicle.

During the market research of available products for our small scale system we found only a few products that could be used in our designs. When the traction-motor/generator was chosen there where two alternatives, either a brushed or a brushless motor. The choice fell on the brushed due to the unavailability of controller that could be used for regeneration.

As it would be beneficial for further studies to compare the brushed machine with the brushless machine future work could be done in developing and constructing a controller solely for the use of this purpose to see whether the total efficiency will be better.

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Appendix A

Results from Shell ECO Marathon 2010

As the series hybrid design was used in Chalmers ECO vehicle Smarter during the Shell ECO marathon competition in Lausitz Germany 7-9 May 2010, it has been tested in a real life application. As the design was finished just before the team competing for Chalmers left, almost none full system test was done. This made the competition days in Germany to be the durability test for the design.

As both of us working with this project went to Germany with the Smarter competition team our responsibility of the vehicle were connected to making the driveline work throughout the race. The first trial running of the vehicle on the race track showed that even if the generators were used outside of their specified range they bear the load better than what was estimated. The only issue from the first trial was the heat from the generator.

The first race went very well besides a communication mistake that unfortunately resulted in that our vehicle traveled eight laps around the track instead of the specified seven. The consequences of this could have been fatal due to the time constraint and the set of rules applied. But as we did not know of the endurance of the vehicle, the driver was told to finish the first race as fast as possible for us to get a result. This meant that there was luckily room for the last lap in accordance to the time constraint. What we did not know was if we were to be disqualified or not.
After the race was finished, the driver and team manager was called to speak with to the competition management who decided that the achieved result should be counted but we had to add the fuel consumption of the eight lap and split it over the first seven which gave us a result even though it became a bit worse. The reasons of the decision was that we had finished within the time frame.
The last day the second race was performed were a lot of time were spent on the structure of the race, where as to try run the race as close to the specified time as possible to keep losses due to air drag as low as possible as those are the largest impacts of friction. The race went very well and only after crossing the finish line the team got the information a brake caliper had came off during the second lap and that the driver had kept it in place with his hand during the rest of the race.

The overall result of the competition showed that the design of our driveline stood up against the durability test. The same generator used throughout the competition was the same, which proved the right components had been chosen. Even though they are used above their rated specifications.

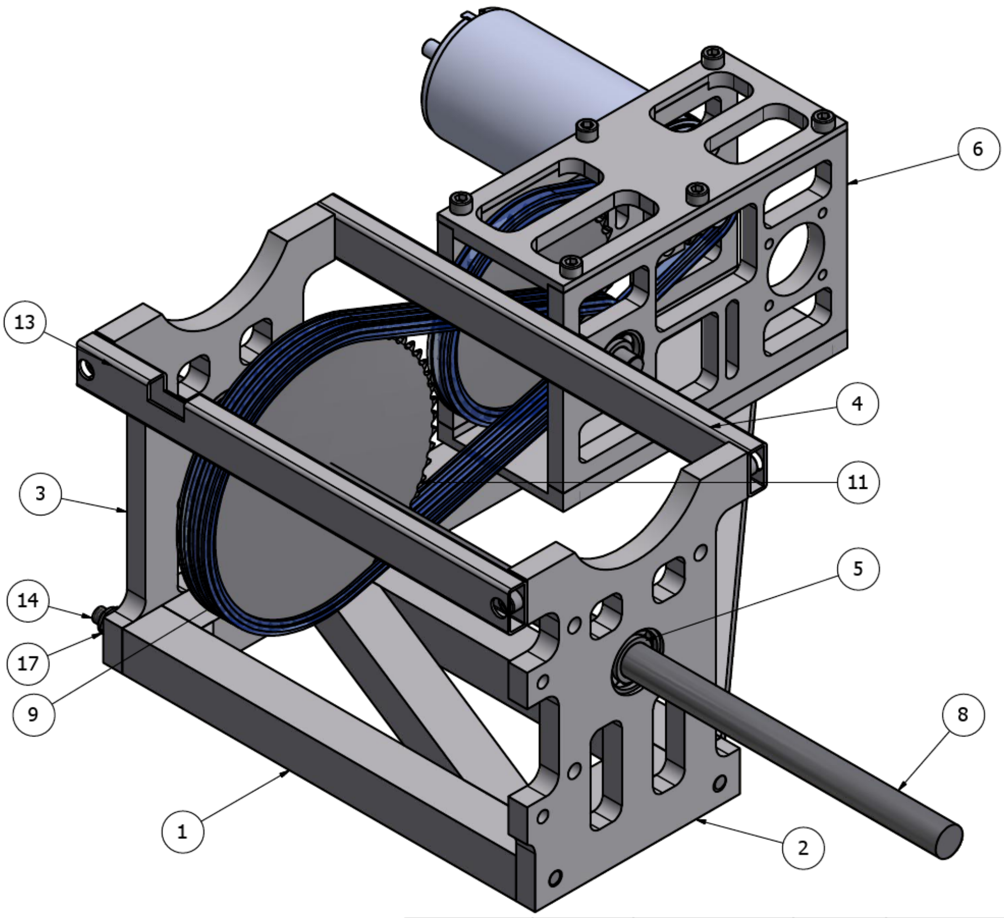
The result for the team in the competition was 12th place in the Urban Concept class using ICE and the best competing team from Sweden. The distance traveled was 115.8km 1st attempt and 153.8km in the 2nd and final attempt both on 1 liter of petrol. The results are the official result made available from Shell [1].

[1] Shell, Shell Eco marathon results from competition in Europe 2010

Appendix B

Drawings Serial hybrid

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Right subframe	Alu 1.5mm
2	1	Outer bearingholder	Alu 7075
3	1	Inner bearingholder	Alu 7075
4	1	Strut bearingholder	Alu 1.5mm
5	2	BS 290 SKF - SKF 6003-2Z	Deep groove ball bearings single row with two Z shields SKF
6	1	Transmission box	
8	1	wheel shaft	
9	1	Roller Chain	
10	1	Roller Chain Sprocket1	15 tooth steel
11	1	Roller Chain Sprocket2	57 tooth steel
13	1	Strut bearingholder2	Alu 1.5mm
14	2	long stud M8	
15	8	AS 1420 - 1973 - M6 x 14	ISO metric hexagon socket head cap screws
16	4	AS 1420 - 1973 - M5 x 14	ISO metric hexagon socket head cap screws
17	2	DIN EN 1664 - M8	Hex Nut



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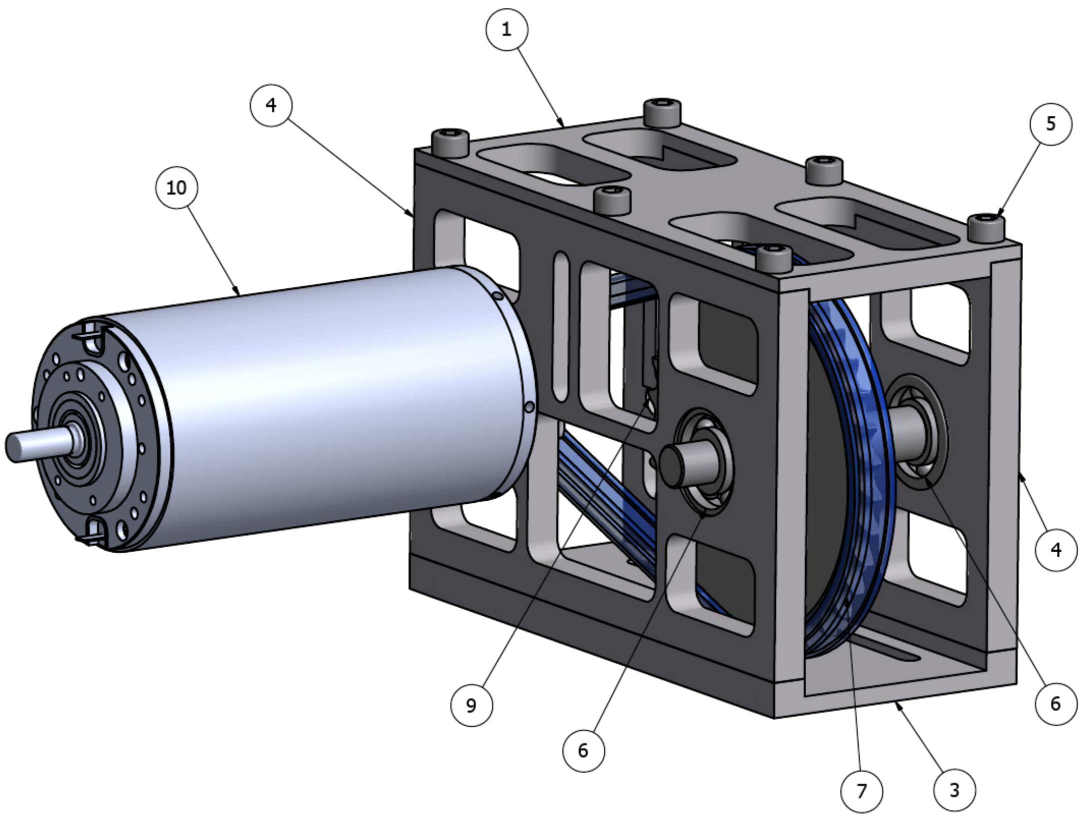
Christoffer Nylén				2011-03-07

	Edition	Sheet
Wheel suspension right		1 / 7

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Top plate	Alu
2	1	Transmission shaft	Mild Steel
3	1	Bottom plate	Alu
4	2	Side plate	Alu 7075
5	12	AS 1420 - 1973 - M6 x 12	ISO metric hexagon socket head cap screws
6	2	Rolling bearing S70000 66201 GB/T 292-94	Rolling bearings - Angular contact ball bearings - Boundary dimensions
7	1	Roller Chain	
8	1	Roller Chain Sprocket1	12 tooth steel
9	1	Roller Chain Sprocket2	40 tooth steel
10	1	Maxon RE65	250W rated



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Wheel suspension right | Edition | Sheet 2 / 7

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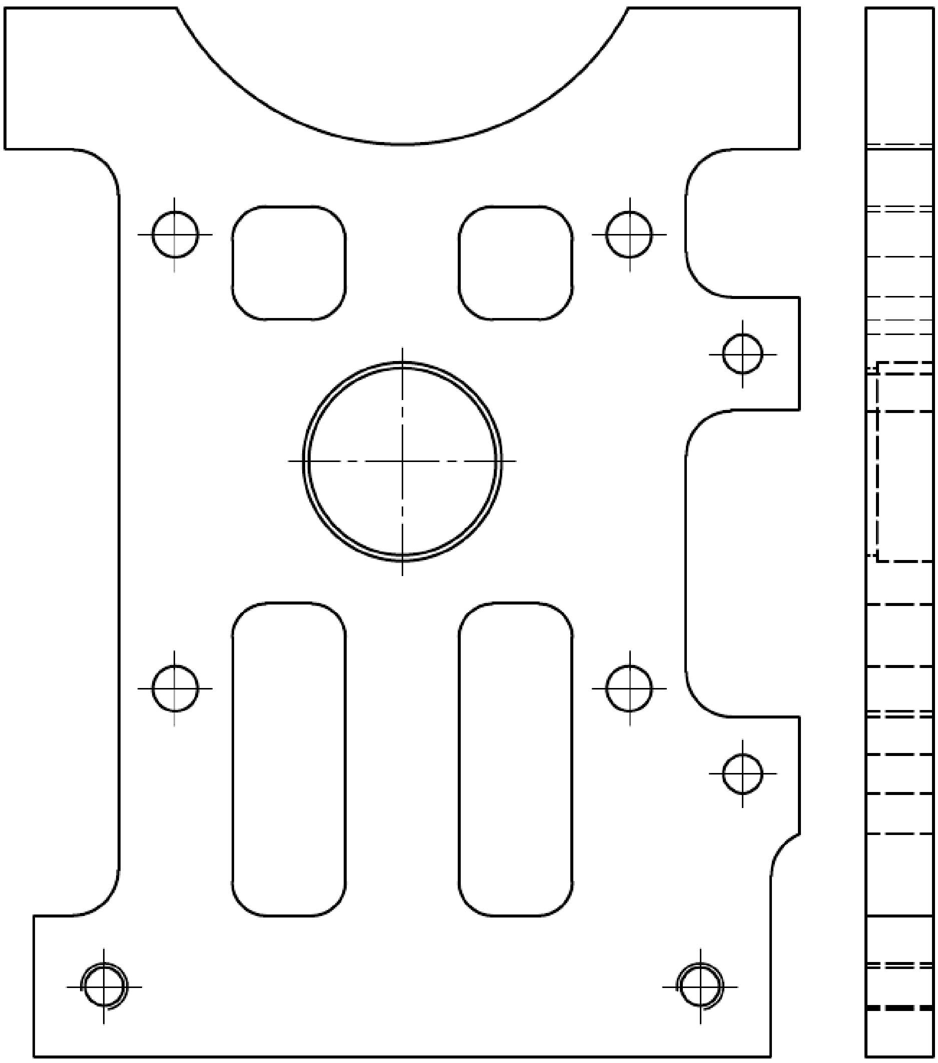

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Wheel suspension right	Edition	Sheet 3 / 7

PARTS LIST			
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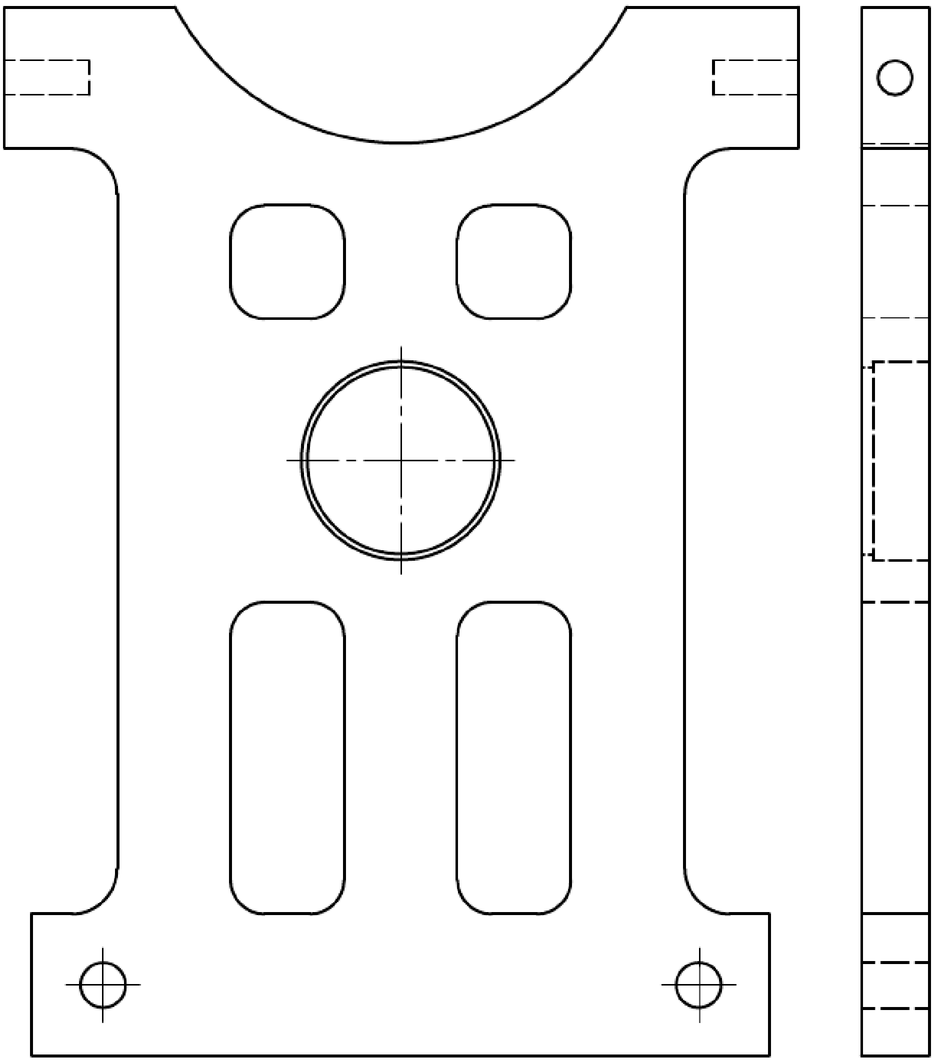
1	1	inner bearingholder	12mm



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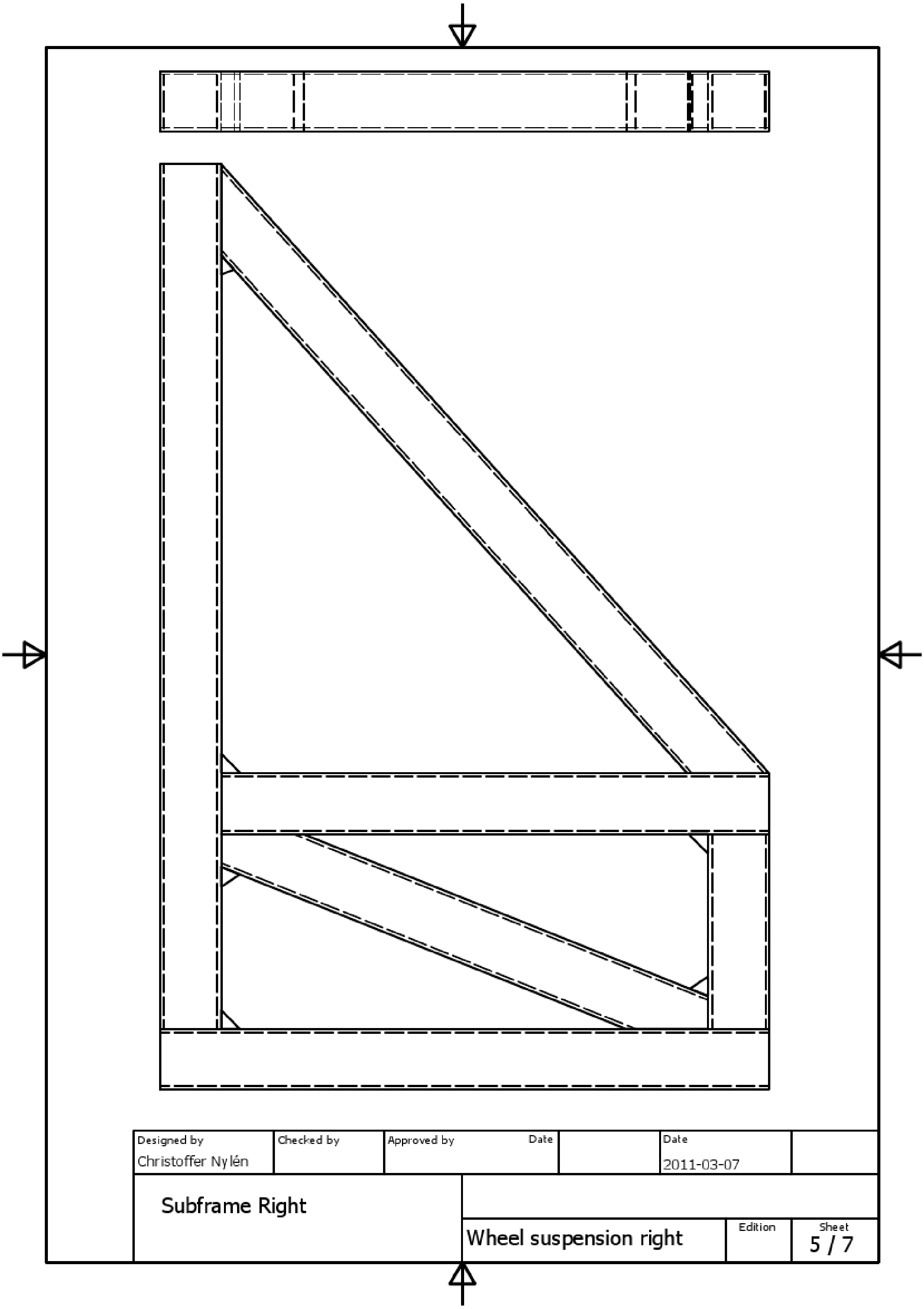

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Subframe Right
Wheel suspension right
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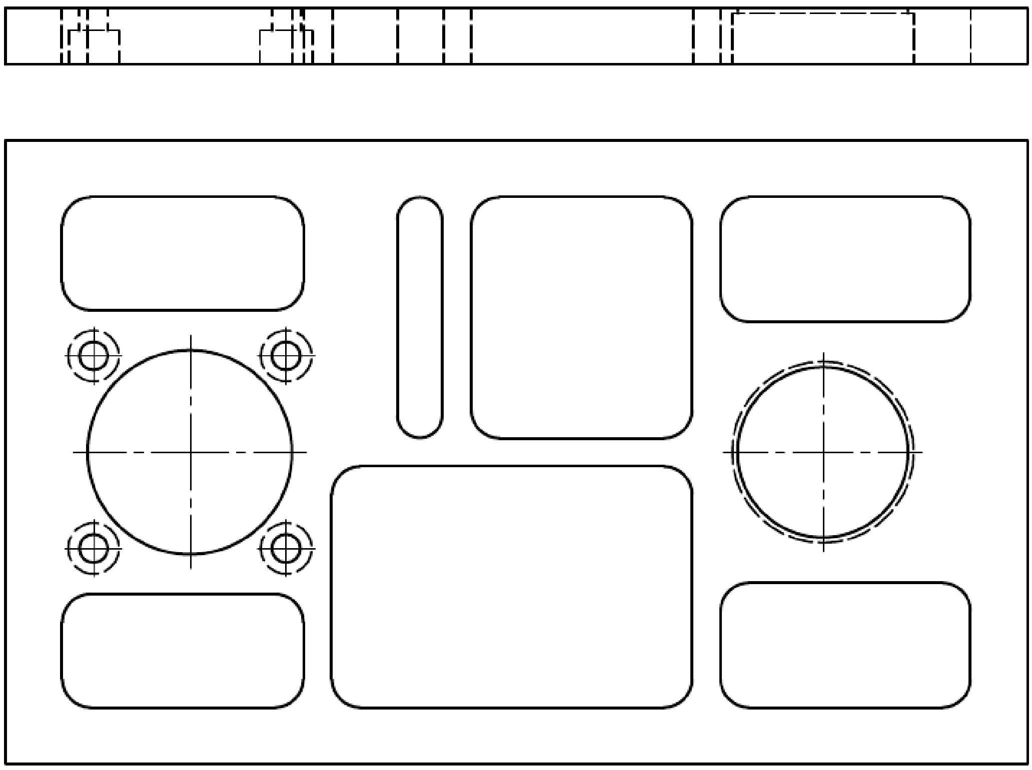
5 / 7

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	Side plate	Alu 7075



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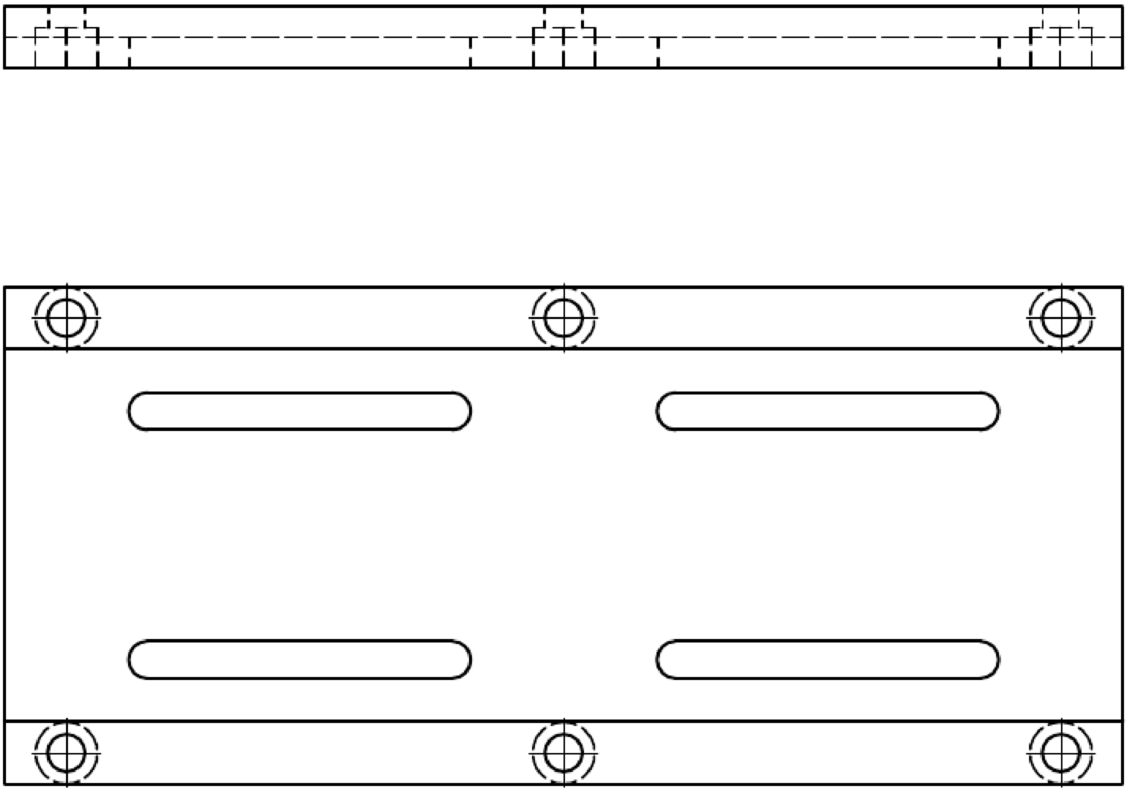
Transmission box		Wheel suspension right		Edition	Sheet 6 / 7

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Bottom plate	Alu



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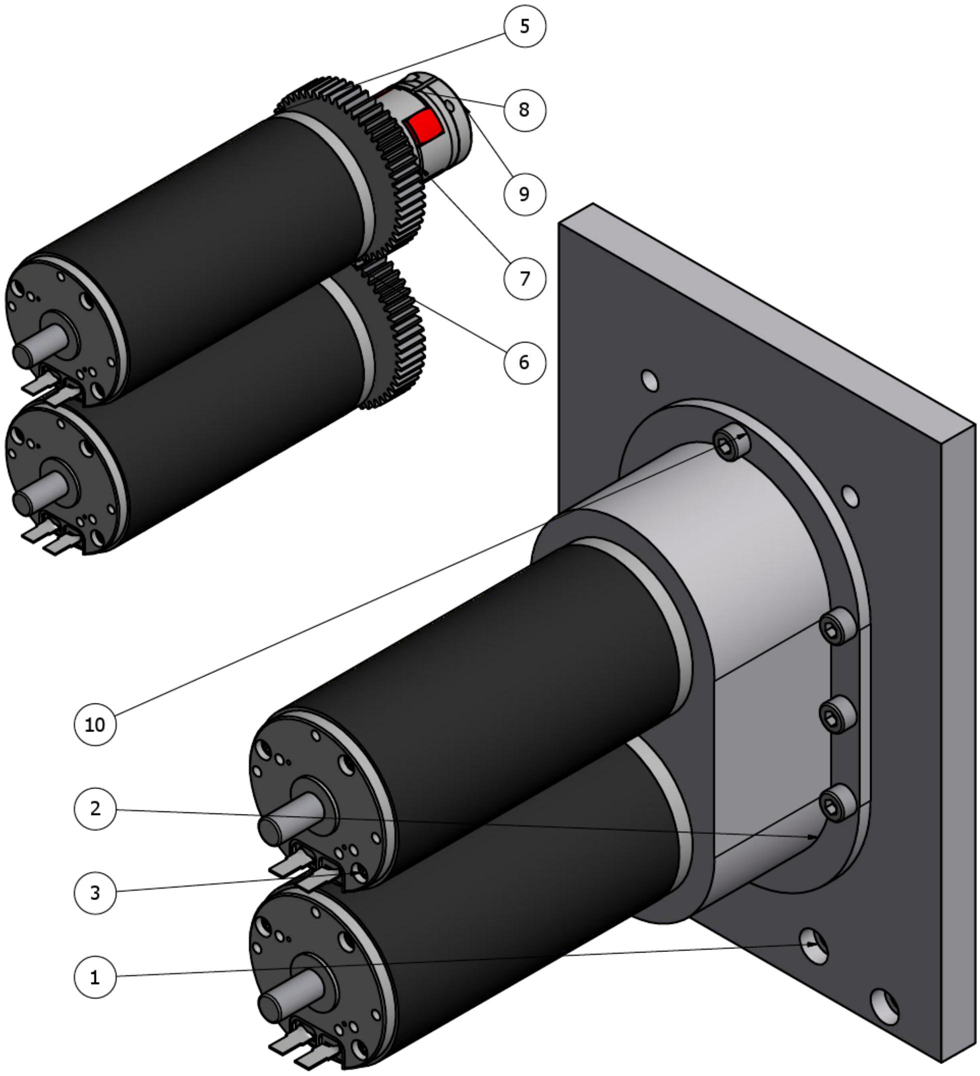
Transmission box	Wheel suspension right	Edition	Sheet 7 / 7

PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Mounting plate	Alu 7075
2	1	Double-generator mount	Alu 7075
3	2	RE50	200W rated
4	8	AS 1420 - 1973 - M4 x 10	ISO metric hexagon socket head cap screws
5	1	Spur Gear1	
6	1	Spur Gear2	
7	1	Rotex GS14-8	
8	1	Spider GS14	
9	1	Rotex GS14-14	
10	8	AS 1420 - 1973 - M5 x 14	ISO metric hexagon socket head cap screws



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Generator serial

Edition

Sheet 1 / 3

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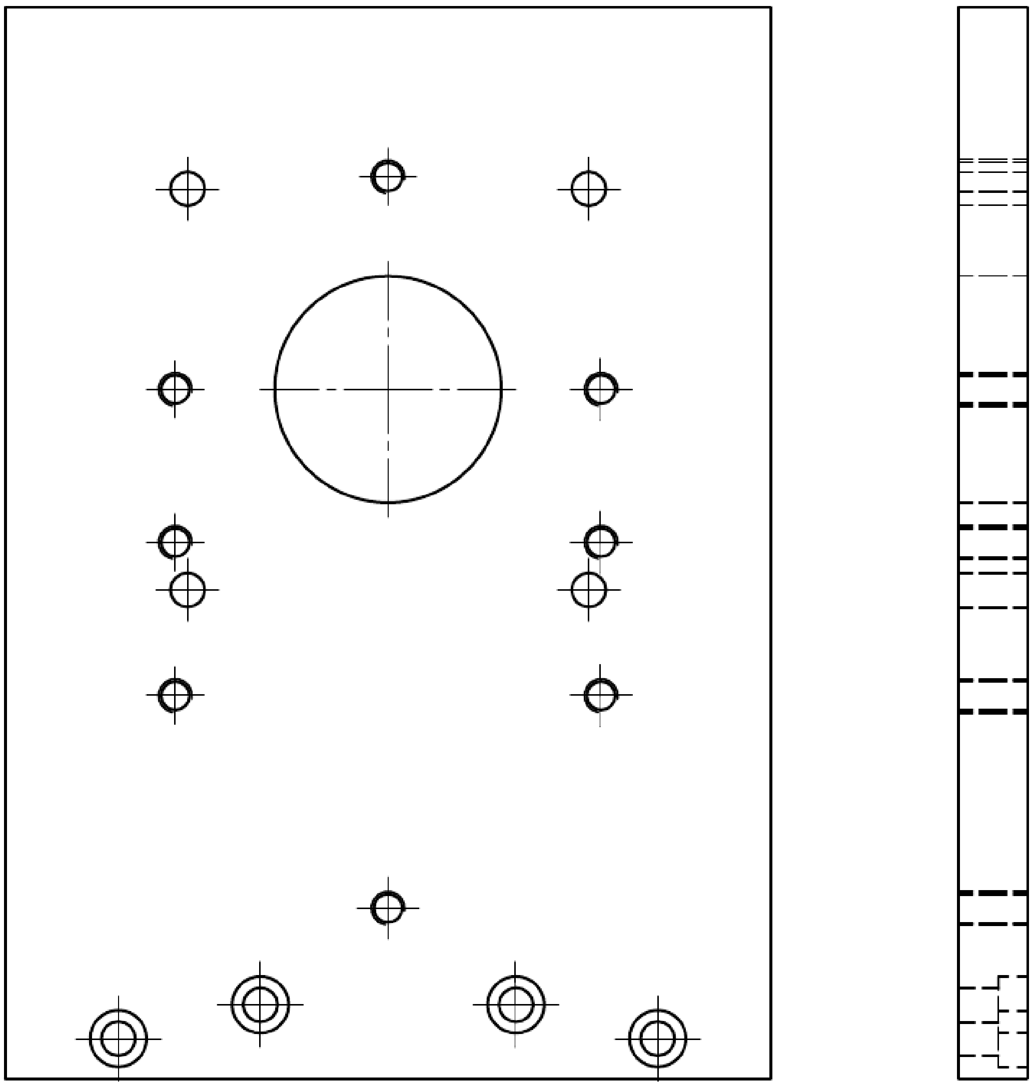
1	1	Mounting plate	



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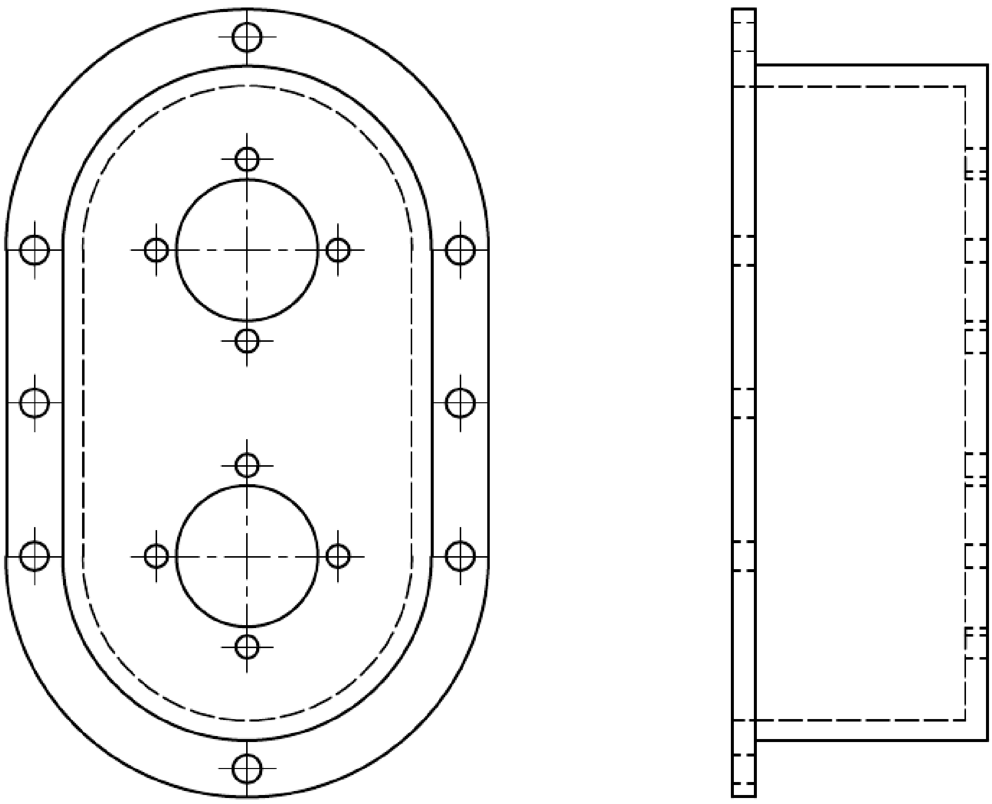
	Generator serial		2 / 3

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Double-generator mount	



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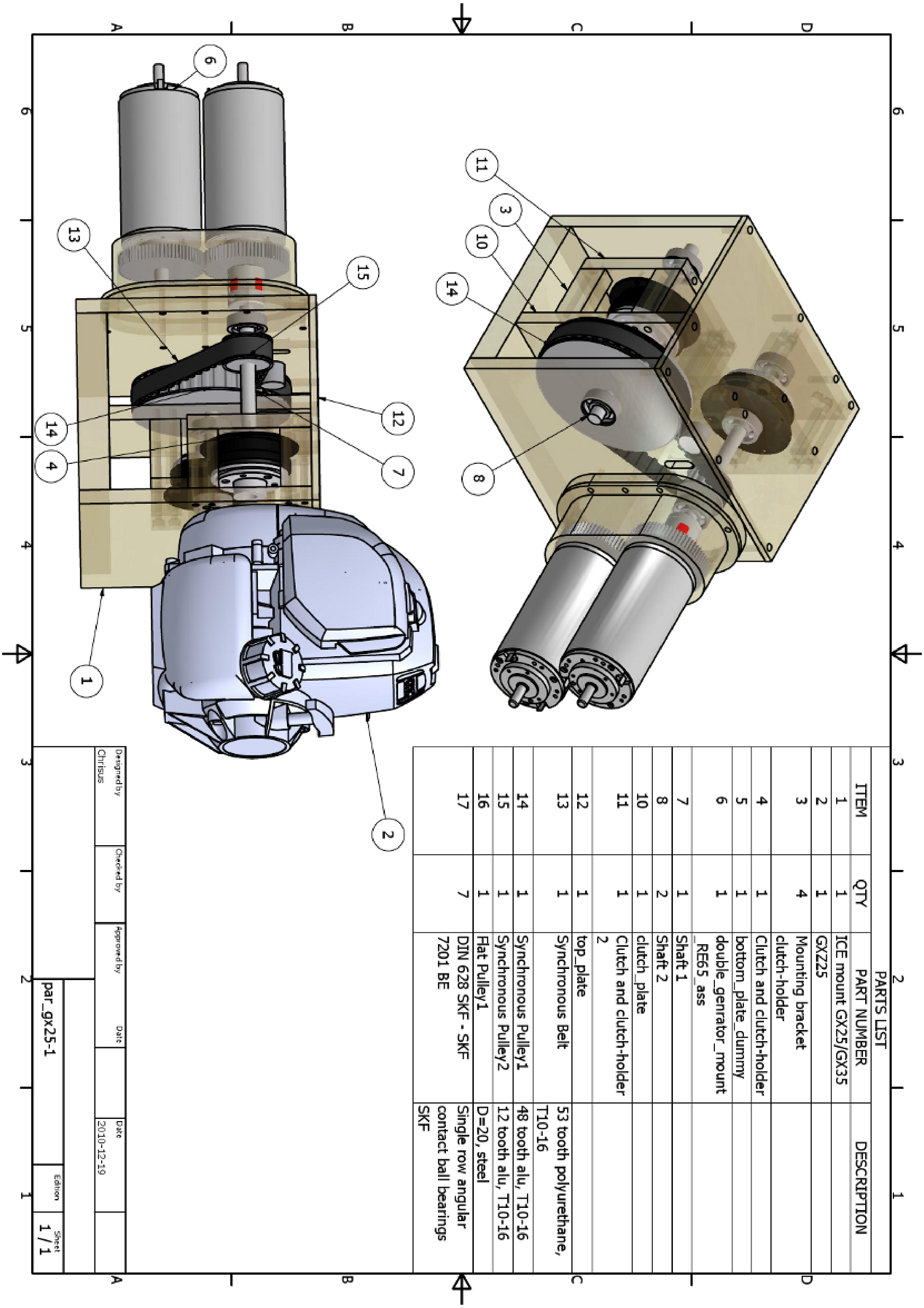
	Generator serial	Edition	Sheet 3 / 3

Appendix C

Drawings Parallel hybrid

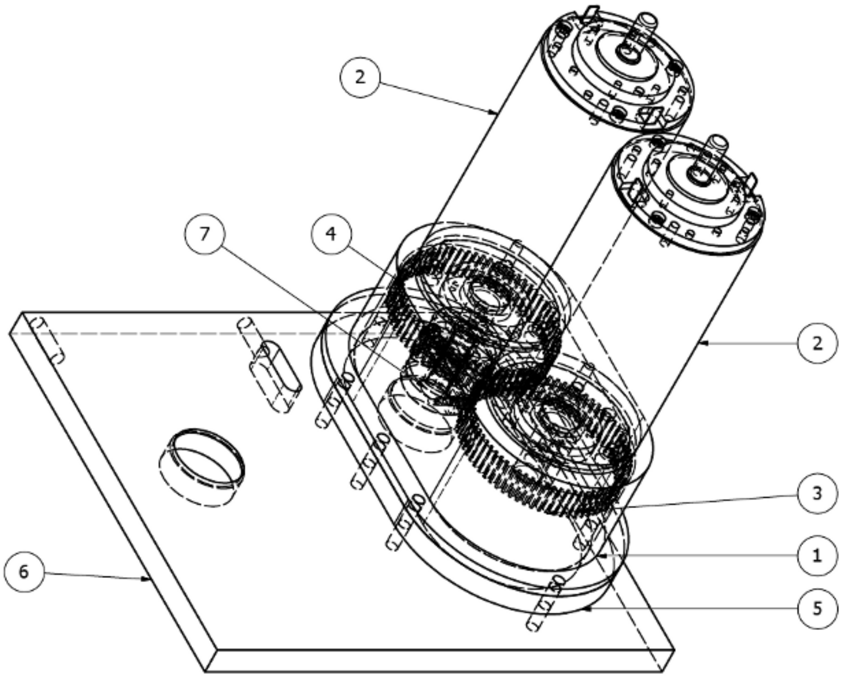


PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	ICE mount GX25/GX35	
2	1	GXZ25	
3	4	Mounting bracket clutch-holder	
4	1	Clutch and clutch-holder	
5	1	bottom_plate_dummy	
6	1	double_genrator_mount _RE65_ass	
7	1	Shaft 1	
8	2	Shaft 2	
10	1	clutch_plate	
11	1	Clutch and clutch-holder 2	
12	1	top_plate	
13	1	Synchronous Belt	53 tooth polyurethane, T10-16
14	1	Synchronous Pulley1	48 tooth alu, T10-16
15	1	Synchronous Pulley2	12 tooth alu, T10-16
16	1	Flat Pulley1	D=20, steel
17	7	DIN 628 SKF - SKF 7201 BE	Single row angular contact ball bearings SKF

PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Double generator mount	
2	2	RE65	
3	1	Spur Gear1	68 teeth
4	1	Spur Gear2	68 teeth
5	1	Double generator mount spacer	
6	1	mounting plate double generator	
7	2	Rotex14_12_1	
8	1	Spider GS14	



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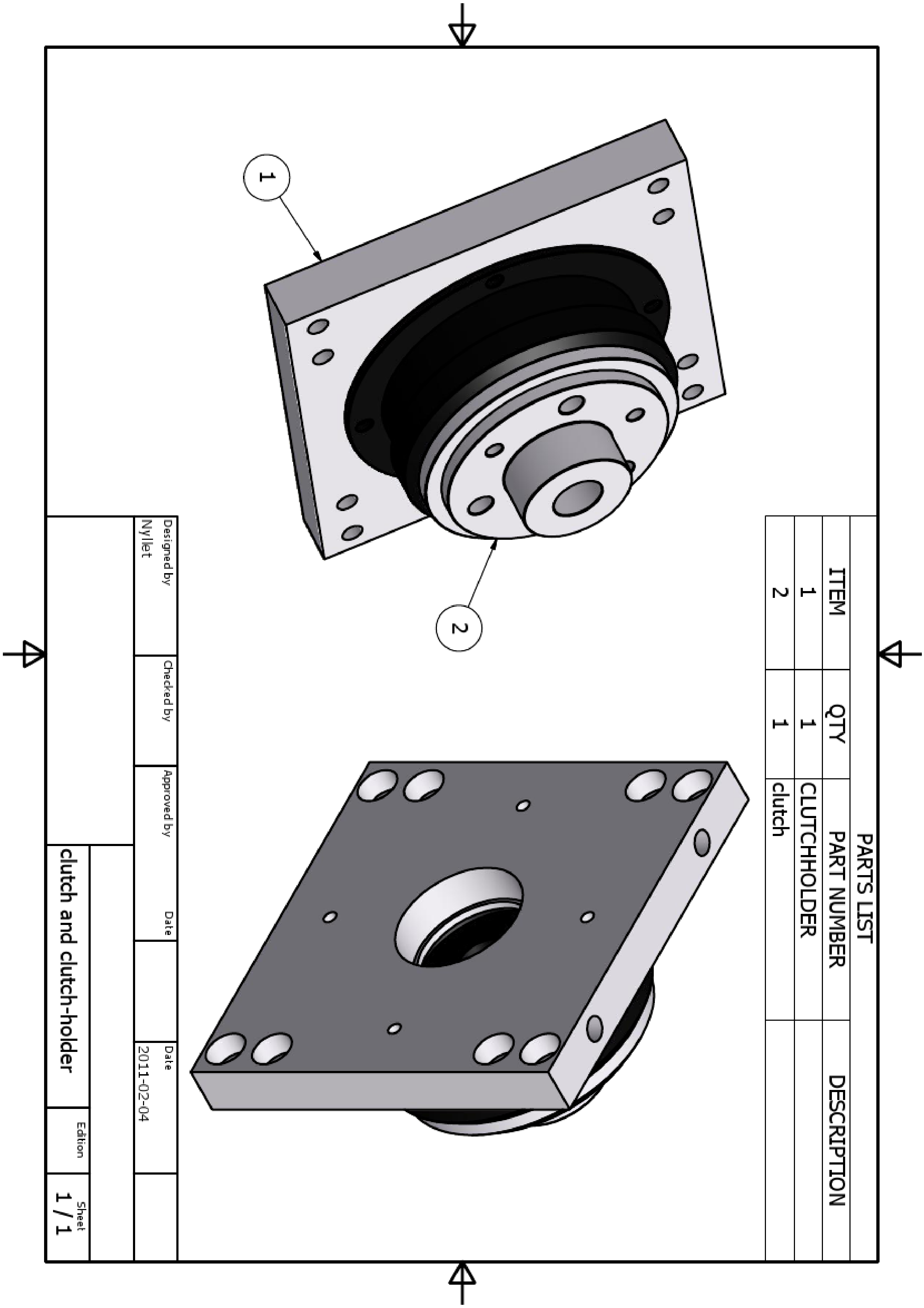
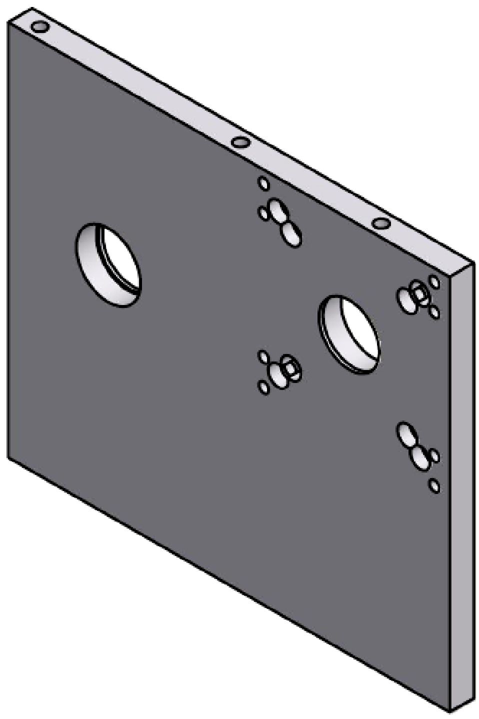
Chrisus				2010-12-19

double_genrator_mount_RE65_ass | Edition | Sheet 1 / 1


1
2
PARTS LIST
ITEM
QTY
PART NUMBER
DESCRIPTION
1
1
CLUTCHHOLDER
2
1
clutch
Designed by
Nyllet
Checked by
Approved by
Date
Date
2011-02-04
clutch and clutch-holder
Edition
Sheet
1 / 1

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	ICE mount GX25/GX35	

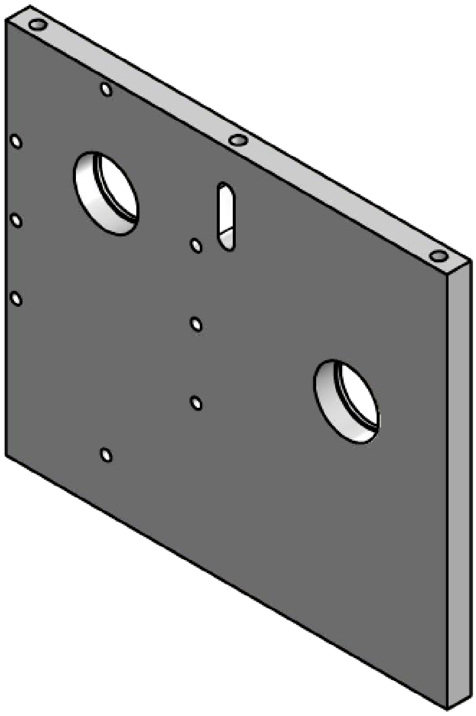
Mounting plate ICE (1 : 2)



Designed by	Checked by	Approved by	Date	Date	
Christoffer				2010-12-19	
	Transmission Parallel				
	transmission_parallel	Edition	Sheet 1 / 2		

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	mounting plate double generator	

Mounting plate EM (1 : 2)



Designed by	Checked by	Approved by	Date	Date	
Christoffer				2010-12-19	

	Transmission Parallel		
	transmission_parallel	Edition	Sheet 2 / 2

Appendix D

Matlab code

D.1 Driving cycle

```
function [T_z, G_z, V_z, D_z, F, A, medelhastkmh, tidforloppmin, ST]
= make_time_acc_supertest3(speed_kmh, ParSer, GR)

%ST, T_z, G_z, V_z, D_z, F, A] = make_time_acc_2ndgen(speed_kmh)

%Call of function
%[T_z, G_z, V_z, D_z, F, A] = make_time_acc_2ndgen(speed_kmh, ParSer)
%speed_kmh=maxspeed, ParSer=1 for Series ParSer=2 for parallel,
%GR=GearRatio
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%% SET Data for the competition  %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

t_min=53; %The maximum time allowed to complete the race [minutes] 53
numb_lap=7; %The number of lap that needs to be completed [minutes] 7
stop_time=5; %The time the vehicle needs to spend not moving every lap


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Vehicle specific data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%GR= 12.66; %[Total Ratio of gears]

M= 150; %[kg] (Weight/Mass)
I= 20; %Amps (Max_current)
CT=(89.1*10^(-3))*ParSer;
%For parallel use times 2 as two ems is used %Newton meters
%(Constant torque of electric machine)

RW=0.26; %meters (Drive wheel radius)
F=(I*CT*GR)/RW; %[N] (The actual force wanting to push vehicle forward
A=F/M; %[m/s^2] (Accelaration of the vehicle)


v_ms=speed_kmh/(3.6); %Convert the input speed from [km/h] to [m/s]
dist=22096; %[m] distance to travel in meters
t_sec=22096/v_ms;
MATRIXTIME=(1:1:t_sec)'; %create matrix corresponding to the amount of
%second for the testcase
lap_time=ceil(t_sec/numb_lap);  %Calculates the time in seconds to complete one lap
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Calculate time to reach max speed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

t_acc=ceil(v_ms/A);     %Calculates time in whole second to reach max speed

%   Assuming no brakes are used to stop the vehicle but the electrical motor gives us
%   the possibillity to use t_acc as stopping as well
%   Else the de acc time needs to be calculated

t_stop=t_acc; %times in seconds to stop;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Create one lap then concatenate it with itself the amount of laps to be
%   driven
%   The D_z (Known as acceleration map)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

acc=v_ms/t_acc;
lap1=(acc:acc:v_ms-acc);
acc_part=lap1;
PB=floor((lap_time-stop_time)/2)-t_acc;
lap1(t_acc:PB)=v_ms;
deacc=fliplr(acc_part);
lap1(PB:(PB+length(deacc)-1))=deacc;
lap1=horzcat(lap1, [0 0 0 0 0]);
lap1=horzcat(lap1, acc_part);
lap1(length(lap1)+1:lap_time)=v_ms;
lap=lap1;
lap(1:t_acc)=v_ms;


for i=2:1:numb_lap
    lap1=horzcat(lap1, lap);
end

%Create G_z information

G(1:15)=0.5;
G(16:20)=1;
G(21:length(MATRIXTIME)-25)=1.5;
G(length(MATRIXTIME)-25:length(MATRIXTIME)-5)=1;
G(length(MATRIXTIME)-5:length(MATRIXTIME)-1)=0.5;
G=horzcat(G,[0]);
length(MATRIXTIME);

%Create D_z information for first lap
D(1:t_acc)=acc;
D(t_acc:PB)=0;
D(PB:PB+t_acc)=-acc;
D(PB+t_acc:PB+t_acc+stop_time)=0;
D(PB+t_acc+stop_time:PB+t_acc+stop_time+t_acc)=acc;
D(PB+t_acc+stop_time+t_acc:lap_time)=0;
D;
%D_z information for lap2 and ongoing
D2(1:PB)=0;
D2(PB:PB+t_acc)=-acc;
D2(PB+t_acc:PB+t_acc+stop_time)=0;
D2(PB+t_acc+stop_time:PB+t_acc+stop_time+t_acc)=acc;
D2(PB+t_acc+stop_time+t_acc:lap_time)=0;
%Create info for whole D_z
for i=2:1:numb_lap
    D=horzcat(D, D2);
end

%output
T_z=MATRIXTIME;
```

```
G_z=G';
V_z=(lap1(1:length(T_z)))';
D_z=(D(1:length(T_z)))';
medelhastms=(sum(V_z)/length(T_z));
ST=t_acc
medelhastkmh=(medelhastms*3.6)
tidforloppmin=(dist/medelhastms)/60
dist=22081; %[m] distance to travel in meters
t_sec=22081/medelhastms;
MATRIXTIME=(1:1:t_sec)'; %create matrix corresponding to the amount of
%second for the testcase
lap_time=ceil(t_sec/numb_lap);  %Calculates the time in seconds to complete one lap

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Calculate time to reach max speed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
t_acc=ceil(v_ms/A);     %Calculates time in whole second to reach max speed
t_stop=t_acc; %times in seconds to stop;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Create one lap then concatenate it with itself the amount of laps to be
%   driven
%   The D_z (Known as acceleration map)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
acc=v_ms/t_acc;
lap1=(acc:acc:v_ms-acc);
acc_part=lap1;
PB=floor((lap_time-stop_time)/2)-t_acc; %tabort semikolon för kontroll
lap1(t_acc:PB)=v_ms; %tabort semikolon för kontroll
deacc=fliplr(acc_part);
lap1(PB:(PB+length(deacc)-1))=deacc;
%lap1(14)=v_ms;
lap1=horzcat(lap1, [0 0 0 0 0]);
lap1=horzcat(lap1, acc_part);
lap1(length(lap1)+1:lap_time)=v_ms;
lap=lap1;
lap(1:t_acc)=v_ms;
%%%%%%%%%
for i=2:1:numb_lap
    lap1=horzcat(lap1, lap);
end


length(lap1);
lap_time;
%lap1;


%Create G_z information
G(1:15)=0.5;
G(16:20)=1;
G(21:length(MATRIXTIME)-25)=1.5;
G(length(MATRIXTIME)-25:length(MATRIXTIME)-5)=1;
G(length(MATRIXTIME)-5:length(MATRIXTIME)-1)=0.5;
G=horzcat(G,[0]);
length(MATRIXTIME);

%Create D_z information for first lap
D(1:t_acc)=acc;
D(t_acc:PB)=0;
D(PB:PB+t_acc)=-acc;
D(PB+t_acc:PB+t_acc+stop_time)=0;
D(PB+t_acc+stop_time:PB+t_acc+stop_time+t_acc)=acc;
D(PB+t_acc+stop_time+t_acc:lap_time)=0;
D;
%D_z information for lap2 and ongoing
D2(1:PB)=0;
D2(PB:PB+t_acc)=-acc;
```

```
D2(PB+t_acc:PB+t_acc+stop_time)=0;
D2(PB+t_acc+stop_time:PB+t_acc+stop_time+t_acc)=acc;
D2(PB+t_acc+stop_time+t_acc:lap_time)=0;
%Create info for whole D_z
for i=2:1:numb_lap
    D=horzcat(D, D2);
end

T_z=MATRIXTIME;
G_z=G';
V_z=(lap1(1:length(T_z)))';
D_z=(D(1:length(T_z)))';
```