**CZECH TECHNICAL UNIVERSITY IN PRAGUE**

**Faculty of Electrical Engineering**
**Department of Electric Drives and Traction**

# Optimal Control of Mathematical Model of the Electrovehicle

Master’s Thesis

Study Programme: Electrical Engineering, Power Engineering and Management

Field of study: Electrical Machines, Apparatus and Drives

Supervisor: Ing. Tomáš Haubert

**Bc. Tomáš Hlinovský**

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**Prague 2015**

České vysoké učení technické v Praze
Fakulta elektrotechnická

katedra elektrických pohonů a trakce

# ZADÁNÍ DIPLOMOVÉ PRÁCE

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Studijní program: Elektrotechnika, energetika a management
Obor: Elektrické stroje, přístroje a pohony

Název tématu: **Optimální řízení matematického modelu elektrovozidla**

Pokyny pro vypracování:

1) Proveďte rešerši elektrických pohonů pro elektrická vozidla, která jsou aktuálně nabízena na trhu
2) V prostředí MATLAB/Simulink vytvořte matematický model elektrického vozidla. Matematický model bude obsahovat bloky Baterie, Elektrický pohon, Dynamika vozidla a Řidič, které spolu budou vhodně spojeny
3) Matematický model navrhněte tak, aby byl kompatibilní s platformou dSpace DS1103. Pro tuto platformu navrhněte interface umožňující propojení s dynamometrickým pracovištěm ve VTP Roztoky
4) Navrhněte technické řešení pro měření vlastních jízdních cyklů a rozšiřte model elektrického vozidla o možnost jízdy v těchto cyklech a cyklech NEDC (New European Driving Cycle) a ARTEMIS
5) Pro naměřené jízdní cykly navrhněte optimalizační algoritmus minimalizující spotřebu elektrické energie a vhodně navrhněte příslušná omezení
6) Porovnejte spotřebu elektrické energie vozidla před a po optimalizaci.

Seznam odborné literatury:

[1] Razar, J. N.: Vehicle Dynamics: Theory and Application, 2008, Springer
[2] dSpace: Hardware Installation and Configuration for DS1103
[3] Boyd S., Vandenberghe L, : Convex Optimization, 2009 Cambridge University Press

Vedoucí: Ing. Tomáš Haubert

Platnost zadání: do konce letního semestru 2015/2016

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V Praze dne 1. 10. 2014

# Prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

# Declaration

I hereby declare that I have completed this thesis independently and that I have listed all the literature and publications used in accordance with the Methodological guidelines about adhering to ethical principles in the preparation of the final university theses.

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Signature of the student

In Prague, ………………

# Acknowledgements

I would like to thank Tomáš Haubert, the supervisor of this thesis, and also the team of electric drives measurements of VTP Roztoky for providing information and sharing some valuable experiences. I also must not forget to thank my family, friends and parents who supported me during the studies.

This thesis is a part of the project Predictive control of electric drive in electric vehicle using dSpace system grant no. 14--14, SGS SGS14/068/OHK3/1T/13.

# Abstract

The aim of this master's thesis named Optimal control of Mathematical Model of Electrovehicle was to create a model of electric vehicle in Matlab/Simulink environment compatible with real-time processor dSPACE 1103 which is a part of the dynamometric test-bench for measurements of the electric drives of electric vehicles and hybrid electric vehicles in VTP Roztoky. Further an interface board with selected connectors for communication between the dSPACE 1103 and the test-bench was designed. In the last part he thesis deals with the possibilities of an optimization of driving through a selected driving cycles based on the height profile of the track respectively the slope of the road. Work also includes an overview of the modern electric vehicles produced by major carmaker companies which are currently available on the market.

# Abstrakt

Cílem závěrečné diplomové práce s názvem Optimální řízení matematického modelu elektrovozidla bylo vytvoření modelu elektrovozidla v prostředí Matlab/Simulink kompatibilního s real-time procesorem dSPACE 1103, který je součástí měřicího dynamometrického stanoviště pro měření elektrických pohonů elektrovozidel a hybridních elektrických vozidel ve VTP Roztoky. Dále byla navržena interface deska s vybranými vhodnými konektory pro komunikaci mezi dSPACE 1103 a měřicím stanovištěm. V poslední části se práce zabývá možností optimalizace průjezdu vybraných jízdních cyklů na základě výškového profilu trati resp. sklonu vozovky. Práce také obsahuje přehled elektrických vozidel vyráběných předními automobilovými výrobci, která jsou momentálně dostupná na trhu.

# Keywords

Electric vehicle, optimization, control, energy, consumption, Matlab, Simulink, driving cycle, test-bench, permanent magnet synchronous motor, battery pack, convex optimization, dynamometer, dSPACE

# Klíčová slova

Elektrické vozidlo, optimalizace, řízení, energie, spotřeba, Matlab, Simulink, jízdní cyklus, test-bench, synchronní motor s permanentními magnety, battery-pack, konvexní optimalizace, dynamometr, dSPACE

# Table of content

# List of abbreviations

| | |
|---|---|
| EV(s) | Electric vehicle(s) – (refers to full EV or battery EV as well) |
| HEV(s) | Hybrid electric vehicle(s) |
| EM | Electric motor |
| PE | Power electronics |
| Eff. map | Efficiency map |
| NEDC | New European Driving Cycle |
| EDC | European Driving Cycle |
| SOC | State of charge |
| BMS | Battery management system |
| PCB | Printed circuit board |
| ECU | Electronic control unit |
| ASM(s) | Asynchronous (induction) motor(s) |
| PMSM(s) | Permanent magnet synchronous motors(s) |
| DM | Dynamometer |
| EPA | United States Environmental protection Agency |
| ADC | Analog-to-digital converter |
| DAC | Digital-to-analog converter |
| PWM | Pulse width modulation |

# 1. Introduction

This master's thesis has been part of a larger project dealing with predictive control of electric drive in electric vehicle using dSpace system. Project was funded by the Grant Agency at the Czech Technical University in Prague, grant No. SGS14/068/OHK3/1T/13. The main target of this thesis was to create a mathematical model in Matlab/Simulink environment by MathWorks Inc. which is compatible with the dSpace DS1103 system. DS1103 is a single-board system with a real-time processor which can run a C code generated on the base of the mentioned Simulink model.

Electromobility is becoming a larger phenomenon each day for both general and professional public. History of an electromobility reaches far into 1st half if the 19th century, when a Dutch professor Sibrandus Stratingh managed to create the first electric vehicle in 1835. At the end of the 19th and the beginning of the 20th century the EVs were so popular, that the number of EVs was larger than a number of vehicles with combustion engine in the USA. Nevertheless the development of combustion engines was much quicker than a development of the electrochemical sources cells and accumulators. The idea of a mass production and usage of electric cars was to be rejected for over 100 years, which was quite logical step, because at that time it obviously seemed as a dead end. The development of electric drives made huge steps during this period of time. Electric motors are almost perfect and there is not much space for bigger improvement. In the middle of the 20th century the invention of a transistor made a production of power electronics possible. Power electronics allowed us to use AC motors, along with the already used DC motors, more efficiently. Electric drive consists of a battery, power electronics and a motor or motors. The last two components are ready to be used, but the main problem of electromobility is, and has always been, the battery. With decreasing resources of oil and still larger and larger tendencies to limit the usage of vehicles with combustion engines, the world's greatest automotive companies are investing a huge amount of money in research and development of the hybrid and fully electric vehicles. Latest results of these efforts indicate that the time, when the last obstacle of the vision of electromobility, which is the way of accumulating a sufficient amount of energy, will be overcome, so the electric vehicles (EVs) will be able to compete with the combustion engine based vehicles again. The transition between the combustion vehicles and electric vehicles need to be smooth and natural, because everything takes a lot of time. There are two strategies of the money investments. Some companies try to fund their development departments and speed up the progress in the field of electrochemical sources and some companies, and now I mainly mean the company Tesla Motors, invest in the building of an infrastructure of the customer support and a wide network of charging stations. There is some kind of a natural process during the transition, which caused an expansion of the hybrid vehicles using both combustion and electric motors. Era of these hybrid vehicles started in 1997 when Toyota Prius became the first mass produced vehicle of this type. Today almost all of the major automotive companies have a hybrid vehicle in their offers. The era of the hybrid vehicles is however coming slowly to an end as the major companies are also starting to release new models of EVs and the battery research have some interesting results suggesting that the breakthrough invention is hopefully in the very near future.

## 1.1 Motivation

Why are the major companies willing to invest such a huge amount of money in the development of EVs? Unlike combustion engines, which efficiency is about 25% in case of the petrol type or even nearly 50% of the modern diesel engines, electric motors are very efficient energy converters and their efficiency reaches up to 95%. Electric motor is able to produce the maximal torque even at still-state at zero rpm, which makes the application less demanding on the nominal power. This fact obviously results in the absence of the clutch in the EVs, which is also considered as one of the major advantages of the electric drives among the ability of energy recovery or durability.

However the major problem which is still present nowadays is the range of the electric vehicles. There is even a newly established term in English about this problem and it is the range anxiety. Range anxiety is a fear of the driver that the vehicle will not be able to reach the final destination. The result of the project, which includes also this thesis, should be an intelligent predictive cruise control for electric vehicles. It could be used in both, computer or human driven vehicles. The main aim of the cruise control is to prolong the current range, which could be even far better with the batteries, which are yet to be invented in the future. For now only one attribute which mostly affects the energy consumption will be counted and that is the slope of the road. One of the targets of this thesis is to use an optimization algorithm, which will correct the reference speed values in order to decrease the energy consumption while going up or down the slopes. The part of this thesis also deals with the acquiring of custom driving cycle data including the data about road slope because the driving cycles like NEDC or Artemis do not include this kind of data. Results of this thesis should be used in the future measurements on the test-bench which would be fed with torque and speed data by the dSpace 1103 control unit.

# 2. Electric drives in modern EVs

In this chapter I would like to describe what a modern electric drive in EV generally consists of and which solution is the best in terms of energy saving and range. Electric drive in EV can be basically divided into battery pack, which consists of individual cells (secondary cells - accumulators), power electronics and electric motor. The overall efficiency of the EV drive is given by the efficiency of the individual components (b – battery, pe – power electronics, em – electric motor, tran – transmission).

$$\eta_{ev} = \eta_{b} \cdot \eta_{pe} \cdot \eta_{em} \cdot \eta_{tran} \qquad (1)$$

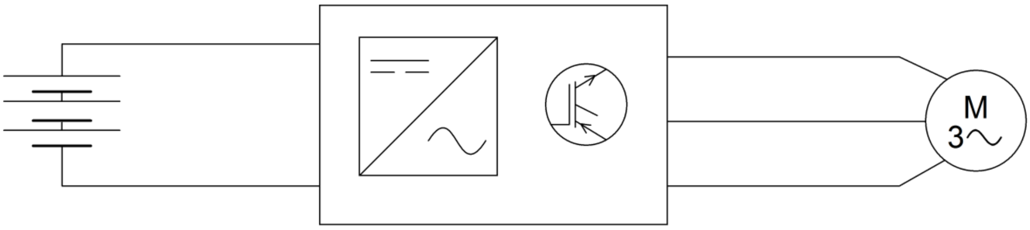


Figure 2-1: Basic EV drive component scheme. (battery – inverter – 3-phase EM)

Following sub-chapters briefly introduces each component and their technological aspects.

## 2.1 Battery pack

Battery pack is defined as a group of connected electrochemical cells which is built in a box providing isolation and space for cooling of the cells. The main technological requirements for the pack are: smallest possible size, good flow of the cooling medium (oil or air), perfect isolation and fire resistance. There are also requirements for the cells as well. Cells need to reach very high energy density in order to prolong the range as much as possible but still keeping the weight of the vehicle relatively low. Batteries should be able to provide high charge and discharge current for long or very short or even pulse periods of time. Also number of charge/discharge cycles and the level of self-discharging in different conditions need to be considered. Important part of the battery pack is so called BMS which stands for battery management system. BMS is a system of PCBs which can provide data about individual or multiple cells in the battery pack like current temperature, voltage, state of charge etc. Sometimes individual cells can be grouped into the modules which are then built in a one battery pack as a whole but that is a matter of specific applications. Battery packs for full electric vehicles usually contain several hundreds of individual cells connected in series or parallel to meet the requirements of total battery pack voltage (generally 300 – 700 V) and current.

Figure 2-2: AMP20 energy modules by A123 Systems (http://www.a123systems.com)

Figure 2-3: Energy core pack by A123 Systems (http://www.a123systems.com)

Batteries used in automotive industry are based on different types of cells. Following sub-chapters describe the most significant ones. There is a plenty of battery chemistries but only some of them are used by the carmakers. In the figure on the next page, we can see the comparison of the energy density between different types of the cells.

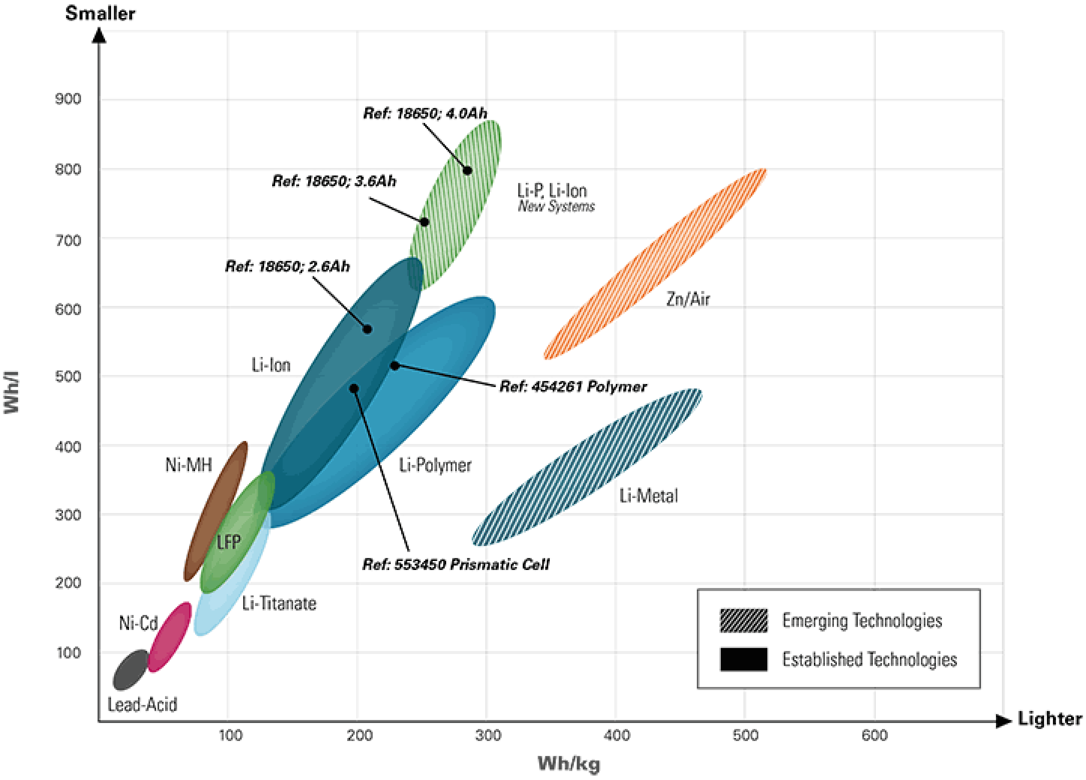


**Figure 2-4: Battery energy density comparison**
**(http://www.iccnexergy.com/battery-systems/battery-energy-density-comparison)**

## 2.1.1 Lead-acid cells

This type of cells is probably well known by its common use as a start battery for vehicles with combustion engines. However it has been used in the first modern electric vehicles such as GM EV1 (first version) or Toyota RAV4EV. Battery consists of positive and negative perforated lead electrodes which are flooded by a concentrate of sulphuric acid and water which works as an electrolyte (medium for conduction of the ions). These batteries are capable of providing high discharge current but should not be discharged below 50% of their capacity in order to avoid shortening of their lifetime. Biggest downsides are that the batteries of this type need frequent controls of the electrolyte level as the water gases out during the normal charging cycle. As well as the rest of the batteries the lead-acid ones are toxic a need to be treated carefully. Fortunately the recycling process is successful and for instance over 99% of the lead from used batteries can be reclaimed in the U.S. Regarding the use of lead-acid batteries in EVs, we are talking about the deep cycle batteries which are able to withstand regular discharging but are not able to provide such a high surge current as the starting batteries. Today these batteries are not really suitable for EV application as the specific energy value is too low compared to the Li-ion or Li-pol batteries. However there are still some EV models, which are still produced today, that use them mainly for their low cost. Lead-acid batteries are also popular among hobby car-makers (figure 2-5).

General technical data:

Nominal cell voltage: 2 V
Specific energy: 30 - 40 Wh/kg
Specific power: 180 W/kg
Energy density: 60 - 110 Wh/l
Average cost per kWh: 120 $ (2011)
Cycle durability: 500 - 800 cycles
Charge/discharge efficiency: 50 - 95%
Self-discharge rate: 3 - 20 %/month

**Figure 2-5: Battery pack of lead - acid deep cycle batteries. (http://www.cbelectriccar.com)**

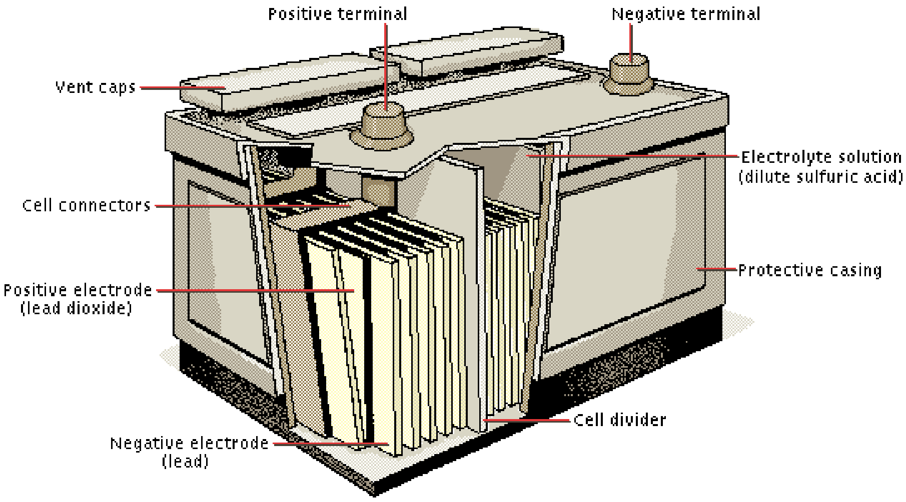


**Figure 2-6: Schematic of the lead - acid battery. ([http://www.reuk.co.uk/Lead-Acid-Batteries.htm](http://www.reuk.co.uk/Lead-Acid-Batteries.htm))**

### 2.1.2 Nickel-metal hydride battery

This type of cells was a transition between the lead-acid and the latest lithium cells. Positive electrode is made of nickel oxy-hydroxide (NiOOH) and the negative electrode is made of metal alloy (Ni, Co, Mn). Potassium hydroxide is usually used as alkaline electrolyte. NiMH cells provide much better energy density up to 120 Wh/kg than the lead-acid cells, which are however more efficient in charging and discharging. Development showed that NiMH cells are performing really well in the field of hybrid electric vehicles. Biggest advantages are very long lifetime, mature technology and lower cost than the modern types of batteries. Main downsides are poor efficiency, high self-discharge, poor performance at cold temperature and an issue with patent encumbrance which lead to limited use of these batteries lately.

| | |
|---|---|
| Nominal cell voltage: | 1.2 V |
| Specific energy: | 60 - 120 Wh/kg |
| Specific power: | 250 - 1000 W/kg |
| Energy density: | 140 - 300 Wh/l |
| Average cost per kWh: | 350 $ (2009) |
| Cycle durability: | 500 - 2000 cycles |
| Charge/discharge efficiency: | 66% |
| Self-discharge rate: | over 30 % / month |

### 2.1.3 Lithium-ion and lithium-polymer batteries

Li-ion batteries are widely used in consumer electronics such as laptops, cell phones etc. Li-ion batteries are still in development nowadays so there are plenty of variants of the chemical composition. Electrolyte in Li-ion cell is a lithium salt in an organic solvent. The negative electrode (anode) is generally made of graphite but some companies and scientists are experimenting by using different materials such as lithium titanate, hard carbon, tin/cobalt alloy or silicon/carbon. The positive electrode (cathode) material, which is generally a metal oxide, is what makes difference in the nominal voltage. For example a cell with lithium-cobalt-oxide ($LiCoO_2$) cathode has nominal voltage of 3.7 V but a cell with cathode made of lithium-iron-phosphate-oxide ($LiFePO_4$) reaches just 3.2 V. In automotive industry the main cathode materials are lithium-nickel-cobalt-aluminium-oxide ($LiNiCoAlO_2$) and lithium-nickel-manganese-cobalt-oxide ($LiNiMnCoO_2$). Short names for these batteries are NCA and NMC. As the development in this field is possibly crucial for the future of the EVs and is still undergoing, the composition of the Li-ion batteries used in the latest EVs is a matter of speculations as many carmakers keep the specifications confidential.

Biggest advantage of Li-ion batteries is their great energy density which reaches over 200 Wh/kg. This makes these type of cells the perfect solution for EVs as their energy capacity is high while keeping the weight of the vehicle lowest as possible to prolong the range of the car. The only downsides include relatively short lifetime and the number of cycles which the battery can withstand without losing to much capacity. Also the toxicity of the cathode material can be a problem but the technology of recycling of the batteries is also in development, so this hurdle can be overcome in the future. Li-ion batteries must be used properly in order to secure safety, but this could also not be taken as an issue as common users should never be able to manipulate with the pack and the charging and other actions are controlled and performed by ECUs or BMS. Basically there are two formats of the cells, prismatic and cylindrical. Cylindrical is the most used format today as it provides greater surface for the cooling medium so the heat can be conducted from the battery more efficiently

| | |
|---|---|
| Nominal cell voltage: | 3.2 - 3.7 V |
| Specific energy: | 100 - 265 Wh/kg |
| Specific power: | 250 - 340 W/kg |
| Energy density: | 250 - 620 Wh/l |
| Average cost per kWh: | 300 $ (2014, will decrease in the future) |
| Cycle durability: | 400 - 1200 cycles |
| Charge/discharge efficiency: | 80 - 90 % |
| Self-discharge rate: | 1 – 1.5 %/month |

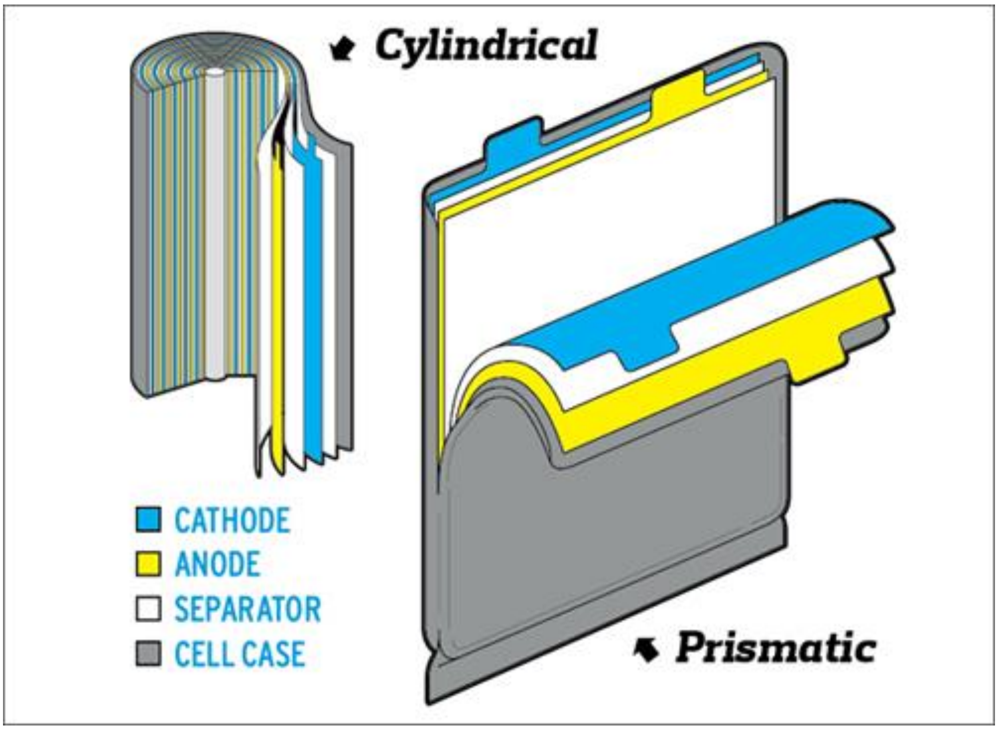


**Figure 2-7: Cylindrical and prismatic structure – applies for NiMH, Li-ion cells. (http://auvac.org/newsitems/view/1082)**

## 2.2 Power electronics

Second part of the modern electric drive for the EVs is a power electronic device. The role of this device, which is commonly known as an inverter, is to convert the DC power of the battery to the AC power for the EM and back (energy recovery), as majority of today’s EVs use AC motors. Usage of DC motors in electric vehicle industry is unthinkable as it suffers from great heat loss and it is generally considered as obsolete. Second role of the inverter is to adjust the parameters of the converted power so the driver can control the propulsion by that way. Inverters use switchable semiconductor components such as IGBT (insulated-gate bipolar transistor) which can be controlled with great frequencies (kHz). Power electronics generally have the best efficiency which usually is around 98 or 99%. This does not mean that there is no cooling as the converted power can be even in hundreds of kilowatts and the heat loss concentrated in such small component could cause serious permanent damage. As a part of the power electronic we can also mention DC/DC converter which usually lower the battery voltage for other DC applications (lights, safety systems, communication etc.). The number of used inverters and converters varies with the specific engineering solutions.

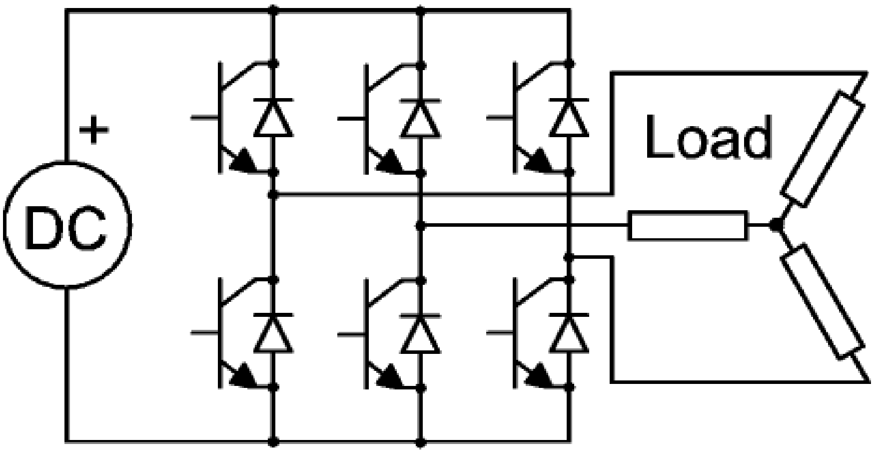


**Figure 2-8: Wiring diagram of the 3 - phase converter.**

Large amount of companies produce complete modules with inverters suitable exactly for EV drive. Inverters are designed usually for a specific use in terms of peak and continuous power, operating temperature, size or weight. Whole inverter system is controlled by ECU which evaluates data from driver and other ECUs. This inverter ECU sets the gate current impulses for the IGBT components according to the desired speed or torque.

**Figure 2-9: AC motor controller Gen 4 by Sevcon. (http://www.sevcon.com/)**

As we can see in the figure 2-9 above the controller is packed in plate housing and all the user can see are the DC and AC wires, input and output for cooling and data connector for the main ECU. Usually the inverter module also contains sensors for voltage and current measurement, protection circuits, thermal protection and inputs for motor feedback (resolver etc.). Technical data of the inverters are dependent on the type of used transistors as their operating voltage, max current and power may vary. Generally the operating voltage can reach up to 800V DC, peak power of hundreds of kilowatts and peak current of hundreds of amps.

## 2.3 Electric motors

Last crucial component of the EV drive is the electric motor which converts electric energy into mechanical energy and therefore drives the vehicle. Basically only two types of AC electric motors are used in the modern EVs, asynchronous induction motor and synchronous motor with permanent magnets.

### 2.3.1 ASM - Asynchronous (induction) motor

Induction motor is an AC electric motor which basic principle is electromagnetic induction of current in the rotor. Current needed for the torque is induced by rotating electromagnetic field excited by 3-phase winding in stator. The main idea of the electromagnetic induction is that the magnetic field must be spatially varying from the rotor point of view so the current in the rotor cage can be induced. The more the motor is loaded the higher current is induced in the rotor cage and the higher current must be delivered to the stator winding. The basic condition for the function of the induction motor is that the rotating speed of the magnetic field excited by stator winding must be higher (in case of the motor regime) or lower (in case of the generator regime) than the rotating speed of the rotor cage. The main advantages of ASM is that it is widely used in industry, the production is usually in big series so it is generally considered as financially available, reliability, lifetime and relatively easy control. Main disadvantage comparing to the PMSMs (permanent magnet synchronous motors) is that the current induced in the cage produces heat loss.

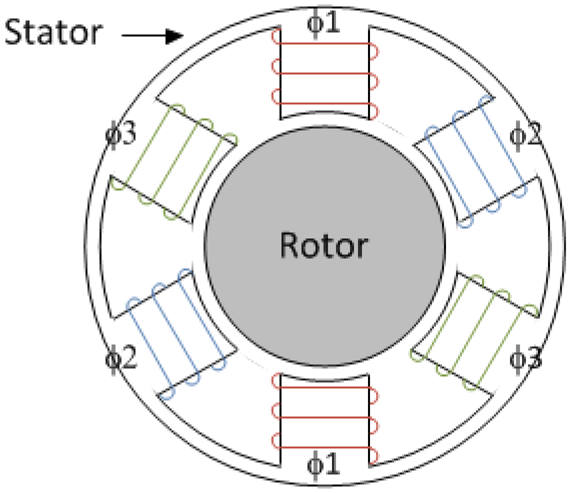


**Figure 2-10: Schema of three-phase two-pole ASM**

Stator consists of laminations made of silicon steel in which the copper windings are wired. Stator windings may contain any number of poles. Rotor is usually made of copper or aluminium bars which are connected with end caps on both ends so the short circuit is secured. Rotor of this construction is called squirrel-cage as it looks like one. The copper or aluminium bars are usually skewed in order to reduce the noise.

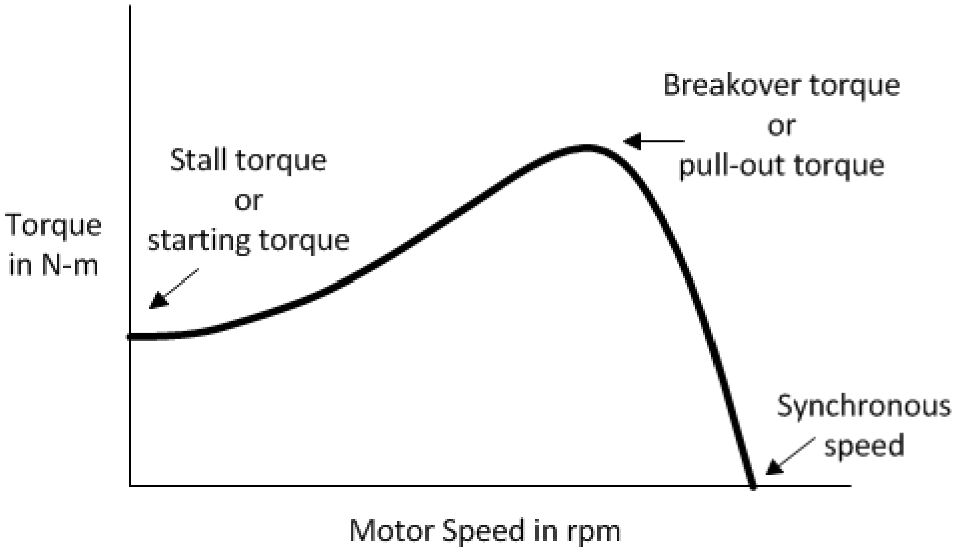


**Figure 2-11: Speed – torque curve of ASM**

General speed-torque curve of ASM (figure 2-11) is not exactly relevant when speaking about EV drive because the point of synchronous speed is being changed by using the inverter. Maximal torque decreases at high speed as the magnetic flux decreases with increasing output frequency of the DC/AC inverter (figure 2-12).

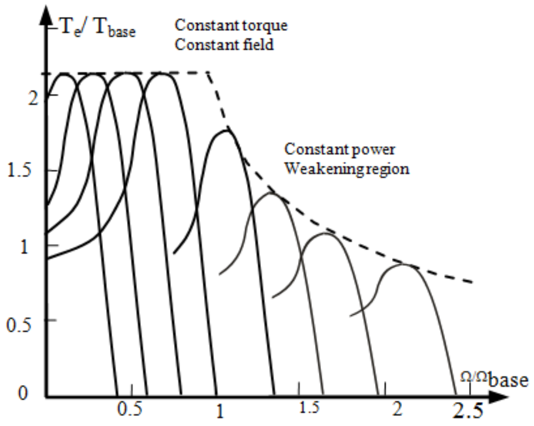


**Figure 2-12: Speed – torque curve of ASM (Voltage/frequency control)**

Crucial data of the electric motor in terms of energy saving is the efficiency map. This map should be provided by EM producer and shows how effectively the EM can work at certain speed and torque. Induction motors are generally known for average efficiency of 92 or 93% in both working regimes. Carmakers must deeply consider and do their own testing and measurement while deciding which electric motor choose for the drivetrain of their EV. Also transmission box and other mechanical elements have to be set according to the efficiency map of the motor.

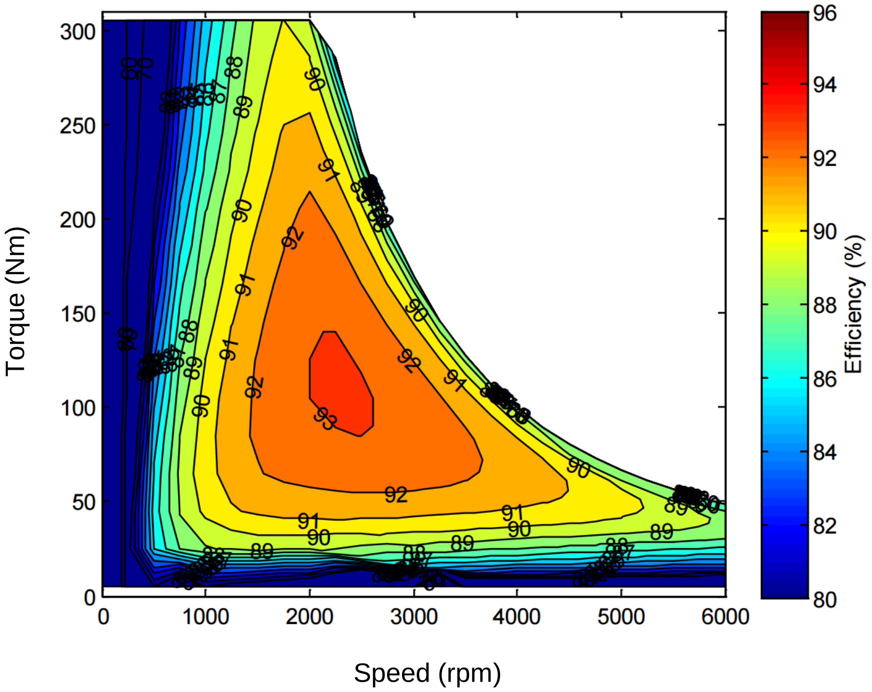


**Figure 2-13: Efficiency map (motor regime) of asynchronous induction motor with copper rotor cage. (Source - Bibliography: 8)**

### 2.3.2 PMSM – Permanent magnet synchronous motor

Second type of electric motor used in modern EVs is permanent magnet synchronous motor or shortly PMSM. Unlike the ASM the PMSM principle is based on the fact that the rotor contains permanent magnets which are dragged by the rotating electromagnetic field. The speed of the rotating field and rotor is same and is called synchronous speed. Main construction difference between ASM and PMSM is the rotor which has surface mounted permanent magnets. Magnets are usually made from an alloy of neodymium, iron and boron or samarium-cobalt. General magnetization of these magnets is about 0.8 – 1.2 T while classic ferrites reach just about 0.4 T. Two types of PMSMs can be distinguished as the rotor can be internal or external. The possibilities of application with external rotor are very limited (so called wheel-hub motors) and they are primarily used in the electric bicycles in form of BLDC motors which can be considered as synchronous motors as well but they are powered by DC supply. Wheel-hub design did not get popular in the automotive industry because the motors increased the unsprung weight of the wheels which directly and negatively affected the handling and driving of the vehicle.

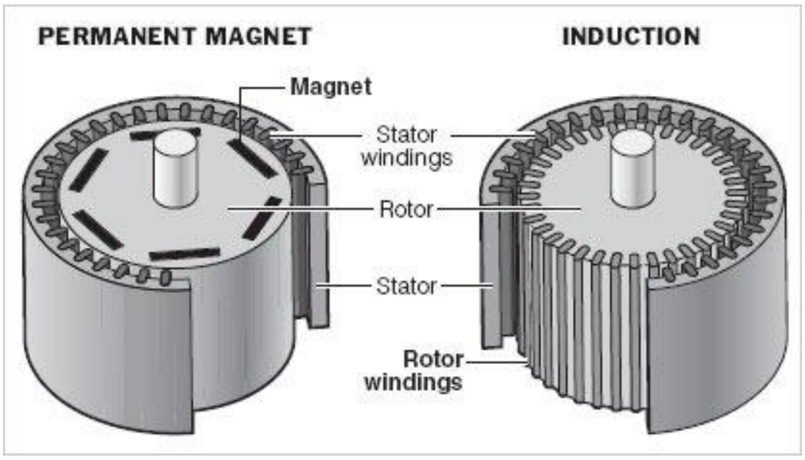


**Figure 2-14: Structure difference between PMSM and ASM.**
**(http://newenergyandfuel.com/)**

PMSMs are generally a bit more expensive because of the rare earth elements and more demanding in terms of maintenance. Main reasons why PMSMs are more used in EVs today is that their efficiency is about 96%, they have small dimensions and weight and there is a possibility of bigger torque overload. One significant restriction regarding the PMSMs is that the temperature of the rotor magnets must be strictly checked because if the temperature reaches over a certain limit (around 150°C for neodymium magnets) the magnets can get slightly demagnetized. Total demagnetization would occur at Curie temperature which is again different for different materials but is usually much higher than the maximum allowable temperature of other parts of the EM such as isolation, silicon steel, wiring etc.

Control strategies are same as for the ASMs so mainly voltage-frequency via PWM or DTC is used. Both types of motor have the same structure of stator so the main torque-speed control is almost the same because of the insufficient excitation by the stator. In high speed the U/f ration cannot be kept on the nominal value because it is not possible to get higher voltage than the source voltage of battery. Resolver is often used as a feedback device for the control.

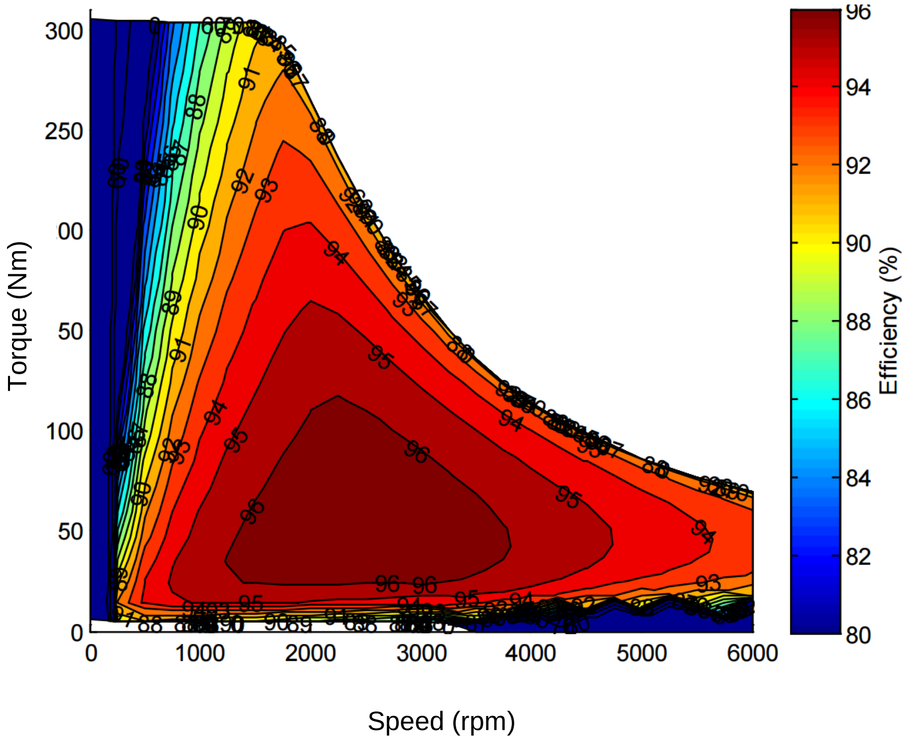


Figure 2-15: Efficiency map (motor regime) of PMSM. (Source - Bibliography: 8)

PMSMs are very popular for their use in the hybrid EVs. Their small dimensions allow the car designers to place the EM right between the internal combustion engine and transmission. I guess that the fact that PMSMs are used in HEVs makes them also very used in the EVs. However we cannot really state which solution is better. In terms of range the PMSM is a better solution because the saved space and weight can be used for bigger battery pack. Bigger battery pack means larger amount of energy and also use of more efficient motor in result gives the longest possible range of EV. The main advantage of induction motors is their low cost and robustness.

# 3. EV market overview

This chapter covers the current situation (April 2015) on market with EVs. List contains cars only currently produced by the major carmaker companies (just a few Chinese EVs are included as the Chinese market is mainly local and the tech. data are also not always available in English). Not all information about each car is publicly available and information about power electronics is usually nowhere to be found so the following list does not contain it. The sources of the information are mainly official but some may also be rumoured by car journalists or professional public.

### 3.1.1 BMW i3 (2013)

***Technical data:***

Top speed (km/h): 150
Acc. 0 – 100 km/h (s): 7.2
Weight (kg): 1195
Official range (km): 160 (EPA)

**Figure 3-1: BMW i3 (Germany)**

***Electric motor:***

Type of EM: BMW manufactured PMSM (AC)
max. power (kW): 125
max. torque (Nm): 250
max. speed (rpm): 11 400

***Battery pack:***

Type of cells: $LiNiMnCoO_2$
Capacity (kWh): 18.8
Voltage (V): 350

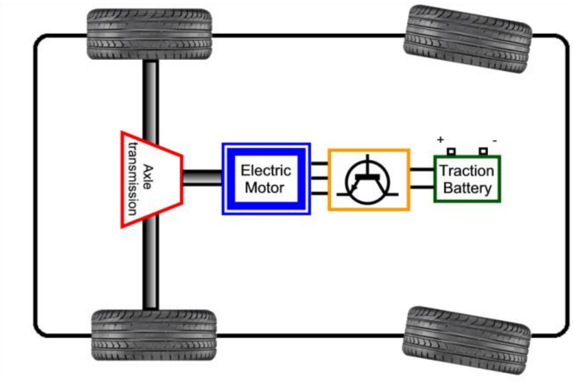


**Figure 3-2: Block scheme of BMW i3 drivetrain**

Electric motor drives the rear axle with fixed transmission. BMW i3 is special EV in a way, because it can be optionally equipped with a range extender which is a small internal combustion engine (25kW, fuel tank for 9 l) which can generate electric power for EM if the batteries are nearly discharged. With this solution the overall car weight reach up to 1270 kg but the range can be extended up to 240 km. However the version with range extender (BMW i3 REx) could be considered as a special kind of hybrid electric vehicle. It is doing quite well on the market but its success may be connected with the huge success of the BMW i8 (PHEV) which belongs to the same model family.

### 3.1.2 Bolloré Bluecar (2011)

***Technical data:***

Top speed (km/h): 110
Acc. 0 – 100 km/h (s): 14.6
Weight (kg): 1120
Official range (km): 150 (highway)
250 (urban)

Figure 3-3: Bolloré Bluecar (France)

***Electric motor:***

Type of EM: presumably PMSM (AC)
max. power (kW): 50
max. torque (Nm): 170
max. speed (rpm): 10 000

***Battery pack:***

Type of cells: lithium polymer metal (LMP) – Bolloré’s own production
Capacity (kWh): 30
Voltage (V): 430 (Operational range: 300 – 435)

This car is produced by French company Bolloré. This vehicle was probably designed as a showcase of the batteries which are one of the main products of the company. Interesting is that the batteries are coupled with supercapacitor which is claimed to enable fast charging and discharging and also to prolong the range of the vehicle. However company does not publish the specific range increase in their documents. Distribution of this vehicle is also interesting as it is based on car-sharing stations. It is a same principle as bike sharing in some cities.

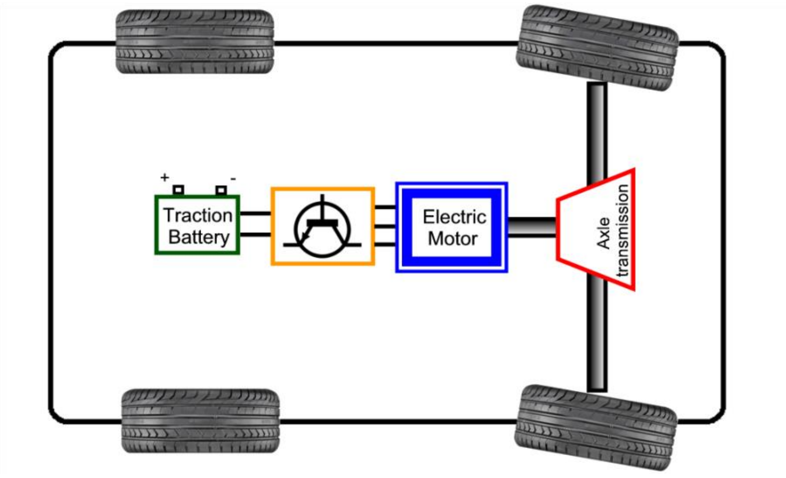


Figure 3-4: Scheme of Bolloré Bluecar drivetrain

### 3.1.3 BYD e6 EU model (2013)

Figure 3-5: BYD e6 (China)

***Technical data:***

Top speed (km/h): 140
Acc. 0 – 100 km/h (s): 14
Weight (kg): 2380
Official range (km): 300 (urban)

***Electric motor:***

Type of EM: BYD manufactured PMSM (AC)
max. power (kW): 90
max. torque (Nm): 450
max. speed (rpm): -

***Battery pack:***

Type of cells: $LiFePO_4$ – Byd’s own production
Capacity (kWh): 60
Voltage (V): -

BYD e6 is an EV produced by Chinese company BYD AUTO. There are a few different model variations suited for the specific markets. For example US model has 160 kW EM. Also all-wheel drive variants exist with one motor on each axle. BYD claims that all the chemical materials used in the battery cells can be recycled. Original release date was in 2009 but it was released in China in 2011. US and EU releases took even longer as the company was concerned about the charging infrastructure. BYD claims that the charging of the e6 can be done in 2 hours with a DC charger. E6 seems to be one of the first Chinese EVs which could be able to compete not only on the Chinese market but also on the worldwide market.

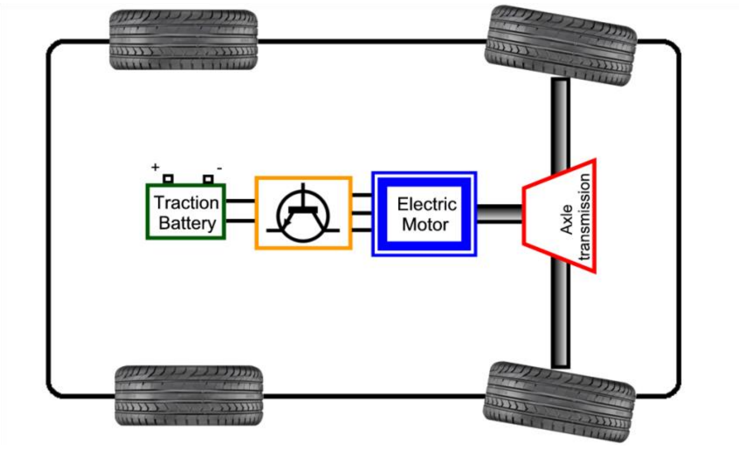


Figure 3-6: Scheme of BYD e6 drivetrain

### 3.1.4 Chevrolet Spark EV (2013)

Figure 3-7: Chevrolet Spark EV (USA)

***Technical data:***

Top speed (km/h): 145
Acc. 0 – 100 km/h (s): 8
Weight (kg): 1356
Official range (km): 132 (EPA)

***Electric motor:***

Type of EM: GM manufactured PMSM (AC)
max. power (kW): 97
max. torque (Nm): 443
max. speed (rpm): -

***Battery pack:***

Type of cells: nanophosphate lithium-ion (A123 systems)
Capacity (kWh): 21.3
Voltage (V): 369

This front axle driven vehicle is interesting because of the new type of batteries. It is currently sold only in the selected states in the U.S. but it far exceeded the GM expectations with its 1684 sold units as of December 2014. From the technical point of view it does not seem as a revolutionary car but also a development test which made it to the market and series production.

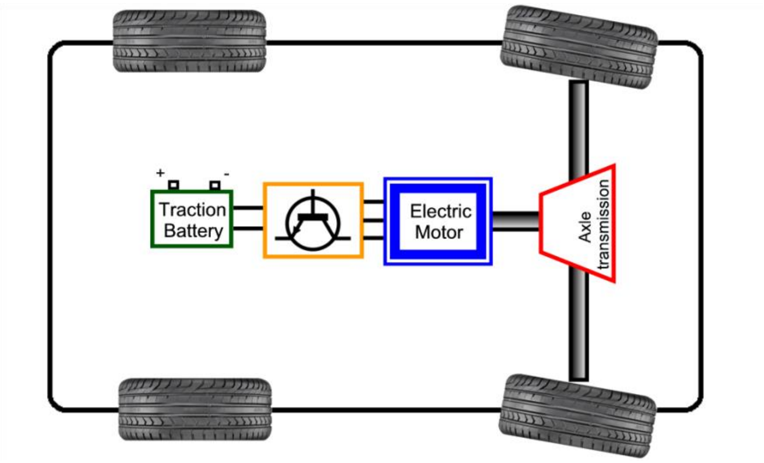


Figure 3-8: Scheme of Chevrolet Spark drivetrain

### 3.1.5 Mitsubishi i-MiEV, Citroën C-Zero, Peugeot iOn (2009)

***Technical data:***

Top speed (km/h): 130
Acc. 0 – 100 km/h (s): 15.9
Weight (kg): 1080
Official range (km): 150 (NEDC)

Figure 3-9: Mitsubishi i-MiEV (Japan)

***Electric motor:***

Type of EM: Mitsubishi manufactured PMSM (AC)
max. power (kW): 49
max. torque (Nm): 180
max. speed (rpm): 8 000

***Battery pack:***

Type of cells: lithium-ion (U.S.), lithium-titanate-oxide SCiB (JAP)
Capacity (kWh): 16
Voltage (V): 330

Electric drive is mounted on the rear axle with single speed drive. This vehicle is also sold in rebadged variants as Citroën C-Zero and Peugeot iOn in Europe. Mitsubishi i-MiEV is considered as the first highway-capable mass production EV. Japanese versions got in 2012 new battery SCiB battery cells which can withstand about 2.5 times more charging/discharging cycles than the original li-ion batteries. Since the start of the production in 2009 over 30 000 units have been sold worldwide in all versions.

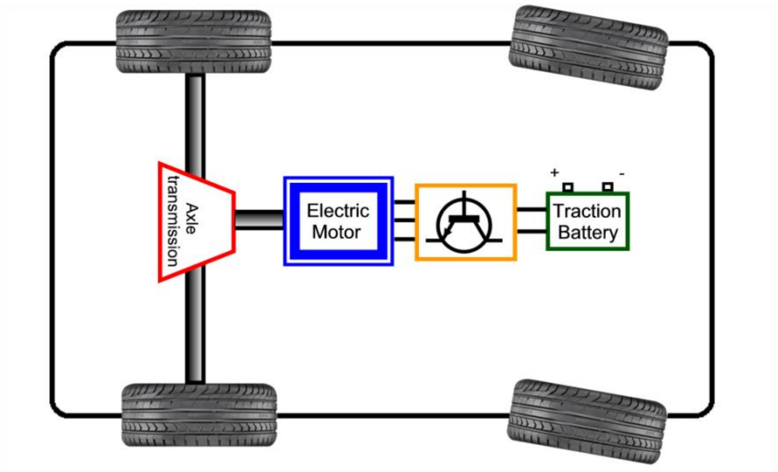


Figure 3-10: Mistubishi i-MiEV

### 3.1.6 Citroën Berlingo Electric (2014)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 110 (limited) |
| Acc. 0 – 100 km/h (s): | 18.7 |
| Weight (kg): | 1420 |
| Official range (km): | 170 |

**Figure 3-11: Citroën Berlingo Electric (France)**

***Electric motor:***

| | |
|---|---|
| Type of EM: | Mitsubishi manufactured PMSM (AC) |
| max. power (kW): | 49 |
| max. torque (Nm): | 200 |
| max. speed (rpm): | 9 200 |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 22.5 |
| Voltage (V): | 330 |

This is an electric version of popular family car which drivetrain is located on the front axle. This car seems to be rather obsolete today as its dynamic qualities are not the best. It is apparently designed for urban usage. It seems that the used electric motor is the same as the one used in Mitsubishi i-MiEV.

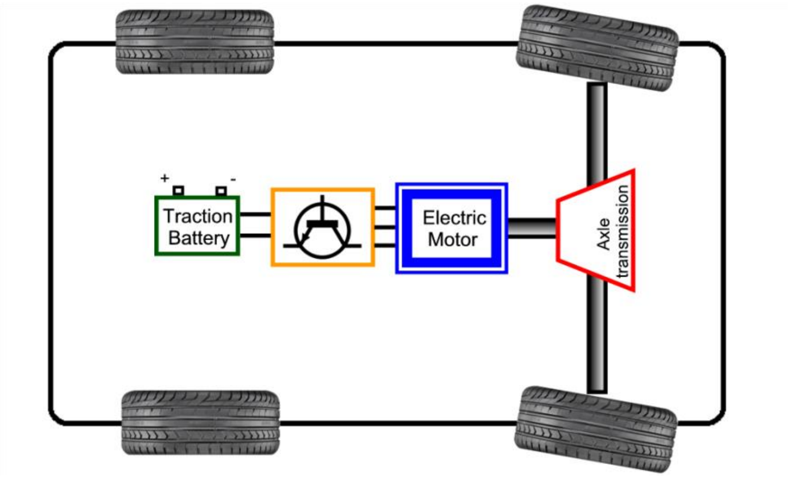


**Figure 3-12: Scheme of Citroën Berlingo Electric drivetrain**

### 3.1.7 Ford Focus Electric (2011)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 137 |
| Acc. 0 – 100 km/h (s): | 8.4 |
| Weight (kg): | 1355 |
| Official range (km): | 122 |

Figure 3-13: Ford Focus Electric (USA)

***Electric motor:***

| | |
|---|---|
| Type of EM: | PMSM (AC) |
| max. power (kW): | 107 |
| max. torque (Nm): | 245 |
| max. speed (rpm): | - |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 23 |
| Voltage (V): | 325 |

Ford Focus electric has a drivetrain located on the front axle. Technologically it does not stand out in any particular way because it is just a result of the early trend when the major carmakers started to equip their already well selling and known models with electric drivetrain and some of them ended up just as prototypes and some ended in production. Ford Focus electric is keeping the great driving qualities but cannot compete because it is overpriced compared to the other EVs. Apparently the car itself is only a result of the California Air Resources Board policy.

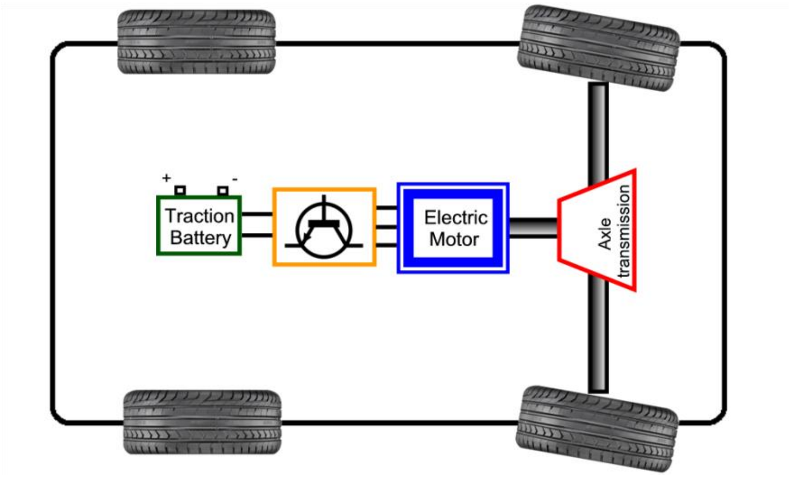


Figure 3-14: Scheme of Ford Focus Electric drivetrain

### 3.1.8 Fiat 500e (2013)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 130 |
| Acc. 0 – 100 km/h (s): | 15.9 |
| Weight (kg): | 1120 |
| Official range (km): | 140 (EPA) |

**Figure 3-15: Fiat 500e (Italy)**

***Electric motor:***

| | |
|---|---|
| Type of EM: | PMSM (AC) |
| max. power (kW): | 83 |
| max. torque (Nm): | 199 |
| max. speed (rpm): | - |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 24 |
| Voltage (V): | 364 |

Fiat 500e has front axle located drivetrain. It is produced only in extremely limited series in the U.S. for keeping the exclusiveness because the main location with biggest sales is California. Main feature of this car is that the engineers succeeded in keeping the overall stylish design but managed to lower the drag coefficient to 0.311 from 0.359 of the original 2013 Fiat 500 model.

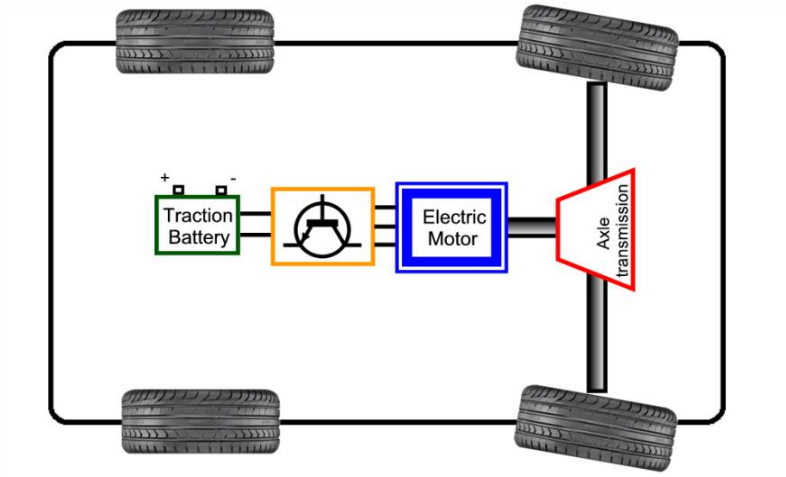


**Figure 3-16: Scheme of Fiat 500e drivetrain**

### 3.1.9 Kia Soul EV (2014)

***Technical data:***

Top speed (km/h): 145
Acc. 0 – 100 km/h (s): 11.2
Weight (kg): 1492
Official range (km): 217

**Figure 3-17: Kia Soul EV (South Korea)**

***Electric motor:***

Type of EM: PMSM (AC)
max. power (kW): 81.3
max. torque (Nm): 285
max. speed (rpm): 8 000

***Battery pack:***

Type of cells: lithium-ion polymer
Capacity (kWh): 27
Voltage (V): 360

Soul EV is the first Kia mass produced EV. First prototypes were tested in 2013. The drive is located on the front axle with single gear transmission. Official specs says that the range is 217 km but the EPA testing resulted in 167 km which is still the largest EPA range in this particular class of EVs. Sales started in Asia and then Europe in 2014. The U.S. sales are scheduled to begin in the 2nd quarter of 2015.

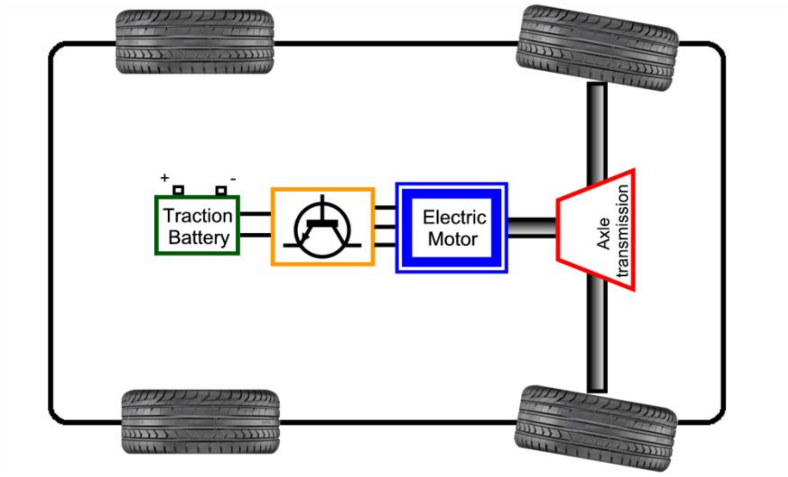


**Figure 3-18: Scheme of Kia Soul EV drivetrain**

### 3.1.10 Mercedes-Benz B-Class Electric Drive (2013-2014)

***Technical data:***

Top speed (km/h): 160 (limited)
Acc. 0 – 100 km/h (s): 7.9
Weight (kg): 1785
Official range (km): 200

**Figure 3-19: Mercedes-Benz B-class Electric Drive (Germany)**

***Electric motor:***

Type of EM: Tesla manufactured 3-phase ASM (induction)
max. power (kW): 130
max. torque (Nm): 340
max. speed (rpm): 16 000

***Battery pack:***

Type of cells: lithium-ion (Tesla-Panasonic)
Capacity (kWh): 36
Voltage (V): -

The production model of B-class ED has been introduced a year after its concept (2012) but the production started in the beginning of the 2014 for U.S. market and in the end of the same year the production for Europe should have started. Its main competitor is the BMW i3 which is a completely newly designed EV instead of the B-class which is just redesigned “gasmobile” (vehicle with internal combustion engine).

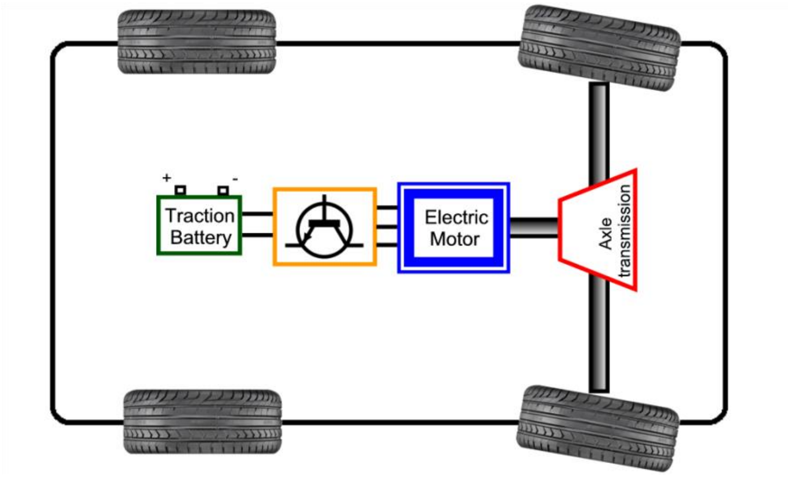


**Figure 3-20: Scheme of Mercedes-Benz B-class Electric Drive drivetrain**

### 3.1.11 Mercedes-Benz Vito E-Cell (2010)

Figure 3-21: Mercedes-Benz Vito E-Cell (Germany)

***Technical data:***

Top speed (km/h): 80 (limited)
Acc. 0 – 50 km/h (s): 6.5
Weight (kg): 3050
Official range (km): 130 (NEDC)

***Electric motor:***

Type of EM: PMSM (AC)
max. power (kW): 60
max. torque (Nm): 280
max. speed (rpm): -

***Battery pack:***

Type of cells: lithium-ion
Capacity (kWh): 36
Voltage (V): 360

Vito E-Cell is the first mass produced electric vehicle by Mercedes-Benz. The E-Cell project is funded by Basque and German government. This car is supposed to gather research data of urban electromobility and it is designed for transportation and courier companies which drivers do not need long range for their tasks.

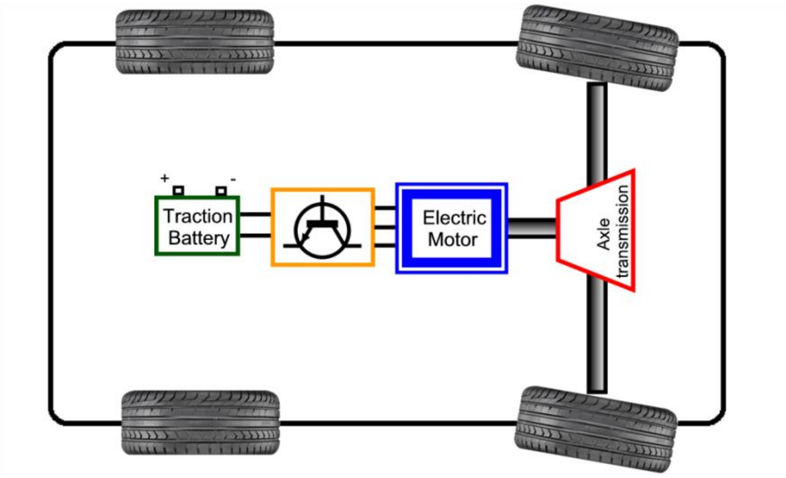


Figure 3-22: Scheme of Mercedes-Benz Vito E-Cell drivetrain

### 3.1.12 Mahindra e2o (2013)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 81 (limited) |
| Acc. 0 – 60 km/h (s): | 12.8 |
| Weight (kg): | 830 |
| Official range (km): | 120 |

**Figure 3-23: Mahindra e2o (India)**

***Electric motor:***

| | |
|---|---|
| Type of EM: | ASM (induction) |
| max. power (kW): | 19 |
| max. torque (Nm): | 54 |
| max. speed (rpm): | - |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 10 |
| Voltage (V): | 48 |

This is rear axle driven urban electric vehicle. Very low overall weight of the car enabled a usage of small battery pack with only 10 kWh of stored energy and the main voltage of only 48 V. Currently it is sold only in India but it is supposed to enter the European market In the first quarter of 2015.

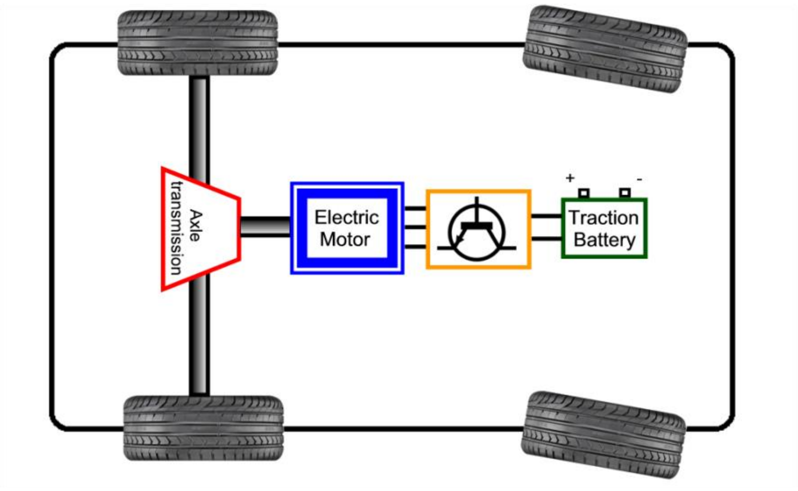


**Figure 3-24: Scheme of Mahindra e2o drivetrain**

### 3.1.13 Nissan Leaf (model 2013)

***Technical data:***

Top speed (km/h): 150
Acc. 0 – 100 km/h (s): 9.9
Weight (kg): 1521
Official range (km): 200 (NEDC)

**Figure 3-25: Nissan Leaf (Japan)**

***Electric motor:***

Type of EM: EM61 PMSM (AC)
max. power (kW): 80
max. torque (Nm): 280
max. speed (rpm): 10 390

***Battery pack:***

Type of cells: lithium-ion
Capacity (kWh): 24
Voltage (V): 360

Nissan Leaf has its front axle driven by PMSM electric motor. It is by far the most competitive and EV with best sales results in the world. Main advantage of this vehicle is that the first model was released in December 2010 so the development has gone a long way since then. Major reason why the sales are going so great is that the vehicle has a relatively small battery pack so the final price is not affected by using a large number of cells but at the same time it has a pretty competitive range of 200 km.

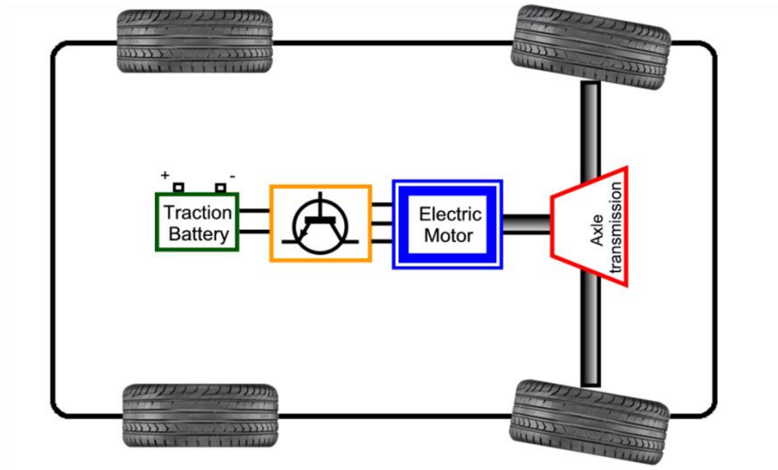


**Figure 3-26: Scheme of Nissan Leaf drivetrain**

### 3.1.14 Renault Twizy (2012)

***Technical data:***

Top speed (km/h): 80
Acc. 0 – 45 km/h (s): 6.1
Weight (kg): 474
Official range (km): 100 (ECE-15)

Figure 3-27: Renault Twizy (France)

***Electric motor:***

Type of EM: 3CG - ASM (induction)
max. power (kW): 13
max. torque (Nm): 57
max. speed (rpm): 7 500

***Battery pack:***

Type of cells: lithium-ion
Capacity (kWh): 6.1
Voltage (V): 58

This rear axle driven EV is not actually defined as a vehicle at all but it is more known as a quadricycle. Renault also offers different versions from the lowest one with 4 kW (33 Nm) ASM, which can be driven by a person without driving license, to the highest Urban 80 or Cargo with an extended boot. Thanks to its low price it is very popular in big cities of Germany, France or Italy with over 14000 units sold by the end of 2014.

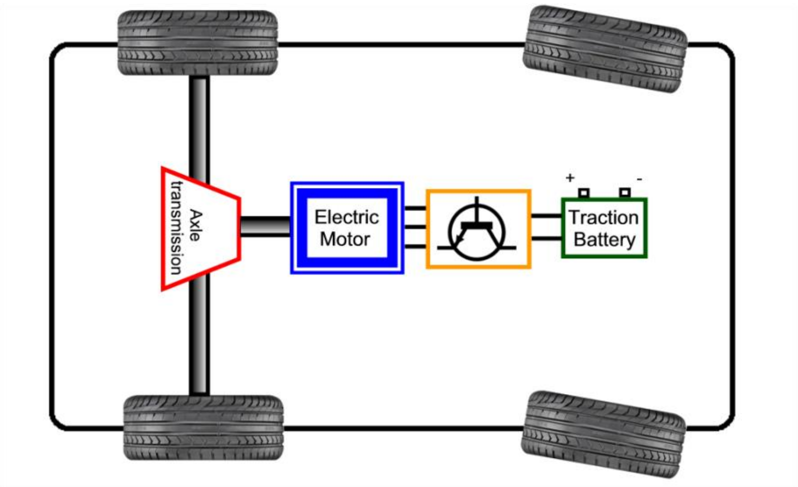


Figure 3-28: Scheme of Renault Twizy drivetrain

### 3.1.15 Renault ZOE (2012)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 135 |
| Acc. 0 – 100 km/h (s): | 13.5 |
| Weight (kg): | 1468 |
| Official range (km): | 210 (NEDC) |

Figure 3-29: Renault ZOE (France)

***Electric motor:***

| | |
|---|---|
| Type of EM: | Synchronous motor with wound rotor (Continental - 5AGen2) |
| max. power (kW): | 65 |
| max. torque (Nm): | 220 |
| max. speed (rpm): | 11 300 |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 22 |
| Voltage (V): | 400 |

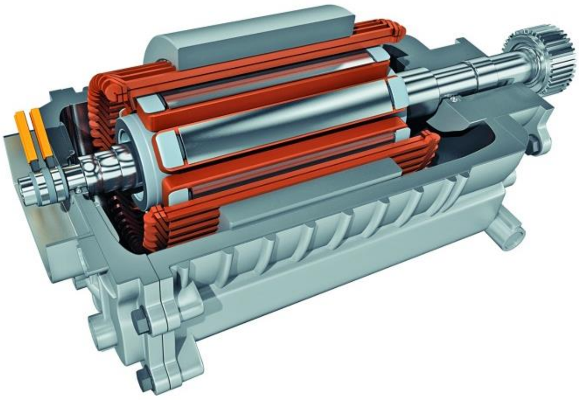


Figure 3-30: Continental synchronous EM with wound rotor

Renault ZOE is a rear axle driven car which is only available in Europe. Nevertheless it reached 6th place in the worldwide most selling EVs in 2013. It is very reasonably priced and even more affordable in countries with government support of EV purchase. Renault surprisingly revealed a type of synchronous motor which is really unusual in the electric vehicle industry. They claim that this motor should have better efficiency then PMSMs for about 10%. The possibility of regulation of the field generated by rotor can improve efficiency and also lowers the voltage induced in the stator windings. However, from the figure above, it seems that the power connection between the rotor winding and its supply is realized by brushes which are generally considered as an obsolete and unwanted mechanical solution which can wear out and break down during the time. Model ZOE 2015 got newly developed unit of electric motor with power electronics and Renault claims that this drivetrain will enable to prolong the current range for aditional 8%.

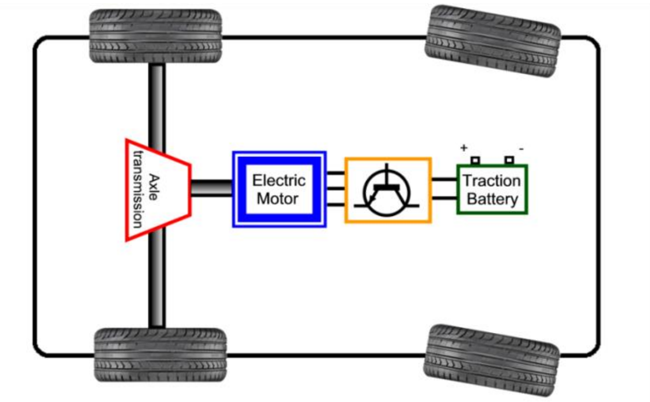


Figure 3-31: Scheme of Renault ZOE drivetrain

### 3.1.16 Roewe E50 (2012)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 130 |
| Acc. 0 – 100 km/h (s): | 14.6 |
| Weight (kg): | 1080 |
| Official range (km): | 180 |

Figure 3-32: Roewe E50 (China)

***Electric motor:***

| | |
|---|---|
| Type of EM: | PMSM (AC) |
| max. power (kW): | 52 |
| max. torque (Nm): | 155 |
| max. speed (rpm): | 8 000 |

***Battery pack:***

| | |
|---|---|
| Type of cells: | $LiFePO_4$ (A123 Systems) |
| Capacity (kWh): | 18 |
| Voltage (V): | - |

Roewe E50 is front axle driven EV from China. It has a similar features and light-weight materials as some EVs from the “western” automotive companies. However E50 is not really competitive as the brand is not well known worldwide and this vehicle is sold only in China. Official range seems to be rather unreal. I think that if the vehicle would have been tested by NEDC or EPA driving cycles the real value would be much lower.

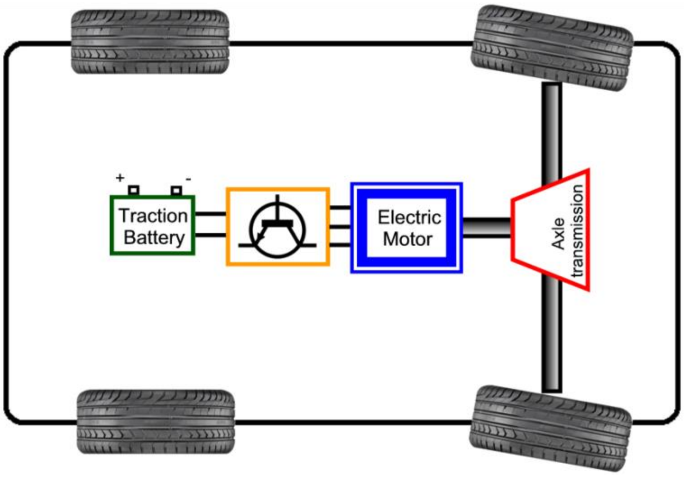


Figure 3-33: Scheme of Roewe E50 drivetrain

### 3.1.17 Smart fortwo ED (2013)

***Technical data:***

Top speed (km/h): 125
Acc. 0 – 100 km/h (s): 11.5
Weight (kg): 900
Official range (km): 109

**Figure 3-34: Smart fortwo ED**

***Electric motor:***

Type of EM: PMSM (AC)
max. power (kW): 55
max. torque (Nm): 130
max. speed (rpm): 12 000

***Battery pack:***

Type of cells: lithium-ion
Capacity (kWh): 17.6
Voltage (V): 400

Smart ED is rear axle driven EV with fast rotating electric motor. It is not a reasonable selection because of the high price and high rental payments for the batteries. Smart fortwo ED 2013 is already the third version of this model.

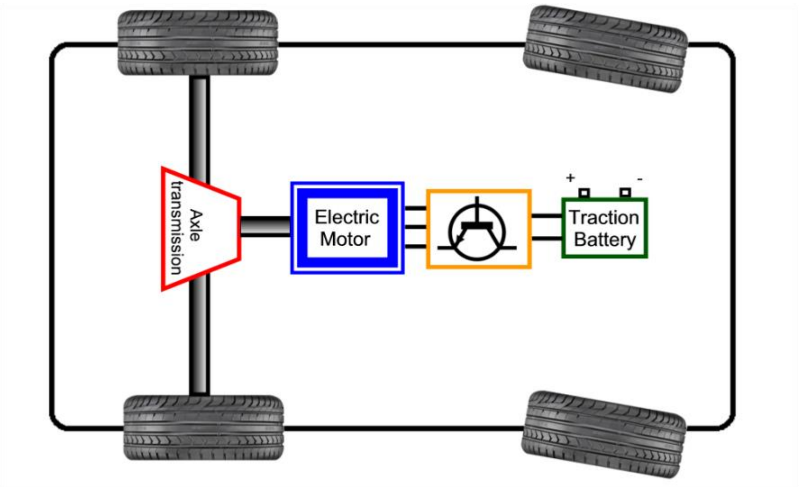


**Figure 3-35: Scheme of Smart fortwo ED drivetrain**

### 3.1.18 Tesla Model S (2012) - 85

***Technical data:***

Top speed (km/h): 210
Acc. 0 – 100 km/h (s): 5.6
Weight (kg): 2108
Official range (km): 426 (EPA)
500 (NEDC)

**Figure 3-36: Tesla Model S (USA)**

***Electric motor:***

Type of EM: Tesla manufactured ASM (induction)
max. power (kW): 270
max. torque (Nm): 441
max. speed (rpm): 16 000 (may vary with different configuration)

***Battery pack:***

Type of cells: lithium-ion (Panasonic)
Capacity (kWh): 85
Voltage (V): 402

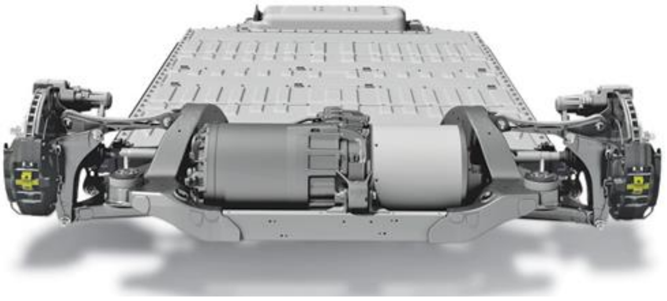


**Figure 3-37: Tesla Model S battery pack with drivetrain**

Famous rear axle driven EV made by company Tesla Motors can be possibly considered as the breakthrough in the field of electromobility. There is currently only one RWD (rear wheel drive) variant of Model S and the capacity of the currently supplied battery packs is 85 kWh. Weaker version (60 kWh) used to be equipped with 225kW/430Nm EM. Not only this vehicle belongs to high class limousines but it beats its competitors by the best range of the currently worldwide sold EVs. Tesla managed to develop a vehicle with great power and energy storage ratio so the vehicle still remains fast and agile while the weight of the vehicle suffers from the large battery pack (around 500 kg). Another cause of the great success of Model S is the wide network of the superchargers currently built in the U.S. and Europe.

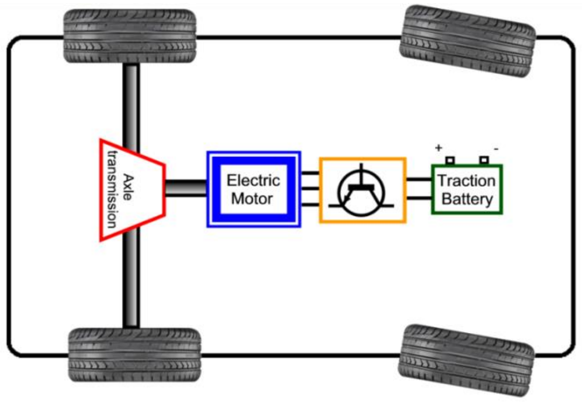


**Figure 3-38: Scheme of Tesla Model S (2012) drivetrain**

### 3.1.19 Tesla Model S (2014) – P85D – AWD (all-wheel drive)

***Technical data:***

Top speed (km/h): 249
Acc. 0 – 100 km/h (s): 3.4
Weight (kg): 2239
Official range (km): 407 (EPA)

**Figure 3-39: Tesla Model S AWD (USA)**

***Electric motor:***

Type of EM: Tesla manufactured ASM (induction)
max. power (kW): 165/350 (front/rear)
max. torque (Nm): 330/600 (front/rear)
max. speed (rpm): 16 000 (may vary with different configuration)

***Battery pack:***

Type of cells: lithium-ion (Panasonic)
Capacity (kWh): 85
Voltage (V): 402

In 2014 Tesla revealed the all-wheel drive version of the Model S. There are two versions both with 85 kWh battery pack but with electric motors of different specs. The weaker model 85D has two identical motors 140kW/245Nm on both axles. In April 2015 also a version with 70 kWh battery pack and total power of 245 kW has been revealed and the 60 kWh RWD version got discontinued. Tesla claimed that this all-wheel drive solution should be the preparation for the following Tesla Model X. It provides excellent all-weather driving abilities and superb acceleration. By the end of the year 2014 nearly 57 000 units have been sold worldwide.

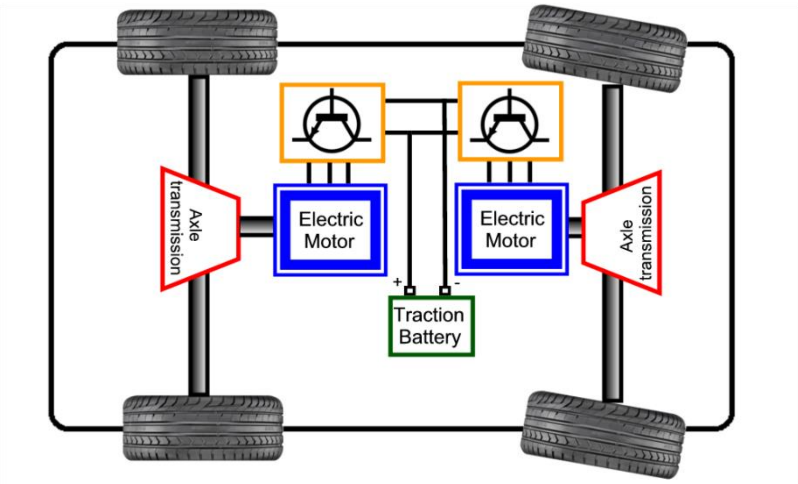


**Figure 3-40: Scheme of Tesla Model S AWD (2014-2015) drivetrain**

### 3.1.20 Tazzari Zero (2009)

Figure 3-41: Tazzari Zero (Italy)

***Technical data:***

Top speed (km/h): 100
Acc. 0 – 50 km/h (s): 5
Weight (kg): 542
Official range (km): 142 (EPA)

***Electric motor:***

Type of EM: ASM (induction)
max. power (kW): 15
max. torque (Nm): 150
max. speed (rpm): -

***Battery pack:***

Type of cells: lithium-ion (Thunder Sky – $LiFePO_4$ ; 3.2 V)
Capacity (kWh): 12.3
Voltage (V): 80

This is an Italian rear axle driven micro EV suitable for urban driving. It also uses ASM as Tesla or Renault Twizy vehicles. It is currently available in European and U.S. market for quite reasonable pricing.

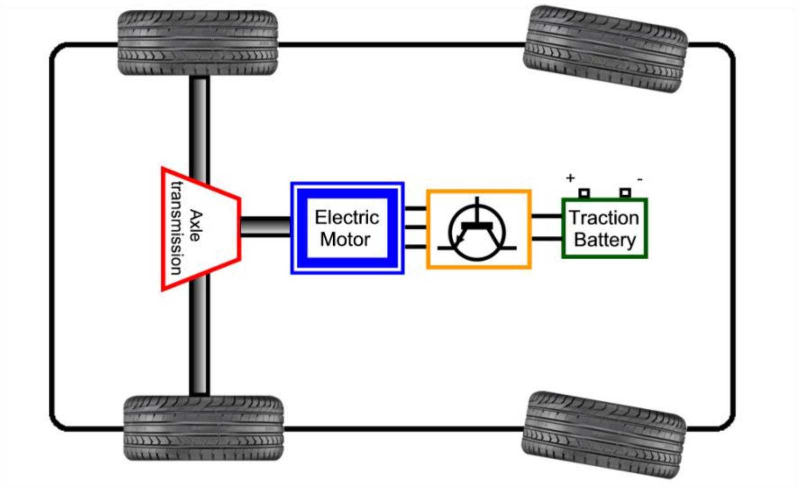


Figure 3-42: Scheme of Tazzari Zero drivetrain

### 3.1.21 Volkswagen e-UP (2013)

***Technical data:***

Figure 3-43: Volkswagen e-UP (Germany)

Top speed (km/h): 130
Acc. 0 – 100 km/h (s): 12.4
Weight (kg): 1085
Official range (km): 150 (NEDC)

***Electric motor:***

Type of EM: VW manufactured EEM 60 - PSM (AC)
max. power (kW): 60
max. torque (Nm): 210
max. speed (rpm): 12 000

***Battery pack:***

Type of cells: lithium-ion
Capacity (kWh): 18.7
Voltage (V): 296-418

The electric version of VW Up is equipped with front-wheel drive. It is the first fully electric car made by the biggest German automotive company. While the main usage of this EV should be focused on urban driving its top speed makes suitable for driving on the highways too even though for a short period of time. It is one of the most successful city EVs on the market right now.

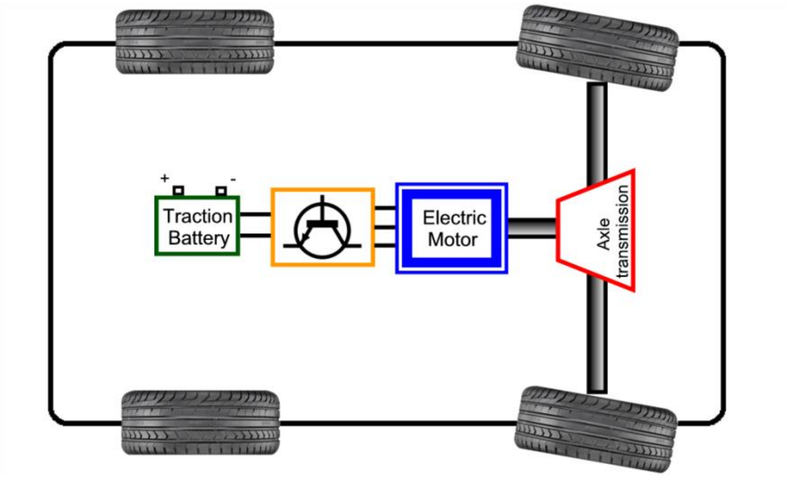


Figure 3-44: Scheme of Volkswagen e-UP drivetrain

### 3.1.22 Volkswagen e-Golf (2014)

Figure 3-45: Volkswagen e-Golf (Germany)

***Technical data:***

| | |
|---|---|
| Top speed (km/h): | 140 |
| Acc. 0 – 100 km/h (s): | 10.4 |
| Weight (kg): | 1585 |
| Official range (km): | 150 (NEDC) |

***Electric motor:***

| | |
|---|---|
| Type of EM: | VW manufactured EEM 85 - PSM (AC) |
| max. power (kW): | 85 |
| max. torque (Nm): | 270 |
| max. speed (rpm): | 12 000 |

***Battery pack:***

| | |
|---|---|
| Type of cells: | lithium-ion |
| Capacity (kWh): | 24.2 |
| Voltage (V): | 250-430 |

VW e-Golf is a result of a development which already started in 2008 with Golf Variant Twin Drive HEV. In 2011 a massive field testing started with 500 units in Europe and then also in the U.S. with a small group of vehicles. Testing in U.S. showed that the high temperatures did not affect the battery performance so there was no need to use a liquid cooling system in the packs. Sales are satisfying as the customers appreciate its similarity to the classic VW Golf.

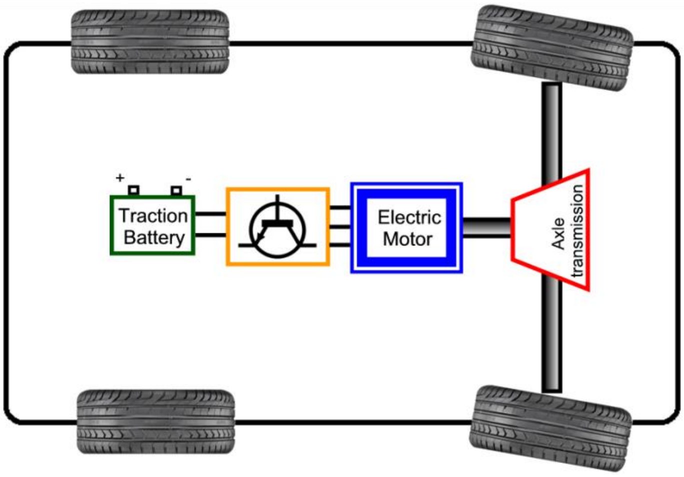


Figure 3-46: Scheme of Volkswagen e-Golf drivetrain

## 3.2 EV models yet to be released

The most anticipated model seems to be the Tesla Model X. It is going to be a CUV (crossover utility vehicle) with the same all-wheel drive used in the Model D (or Model S AWD). We do not know if the electric motors are going to be exactly the same but we can assume that the company will rely on its own manufacturing.

Next awaited models are Rimac Concept One and Audi R8 eTron. Both models will belong to super-sport class so they are most likely to be very expensive. While Rimac Concept One seems more of a company presentation and stil is a concept the R8 eTron is nearly in pre-production phase. It will have a rear-wheel drive equipped with two electric motors of unknown types. The combined maximal torque should be 920 Nm and the maximal power 340 kW. The lithium-ion batteries with capacity around 92 kWh should provide a range up to 450 km. Some car journalists were able to test the prototypes already and claim that these parameters can be reached in the real world.

It is very likely that more new vehicles are going to be announced during the following months.

The vehicle which everyone patiently awaits and which could cause the possible breakthrough in electromobility could be the Tesla Model 3. Model 3 should be a whole series of electric vehicles which should aim for the widest group of customers with a price around 35 000 $ before incentives so the price could be eventually even lower. At the beginning of 2015 Chevrolet revealed his new concept Chevy Bolt which promises range of 320 km at a price around 35 000 $. Both models Bolt and Model 3 are expected to be released in 2017.

## 3.3 Technological future of electromobility

The current year 2015 and the following year 2016 are very likely going to be still the name of plug-in hybrid electric vehicles. Despite this fact I would say that the global automotive industry is on a good path. The plug-in hybrid vehicles are a result of this natural progressing transition from gas vehicles to electric vehicles. This process involves both the customers and the development engineers. It is obvious that the companies are using some of their concepts or even mass produced PHEV for the following development of the all-electric EVs. According to the last rumours and information it seems that the breakthrough will happen in 2017 or 2018 and all car-making companies are surely aware of that.

The so called “Gigafactory” which is right now under construction in Nevada, U.S., will be able to produce a huge amount of top quality lithium-ion cells so the global battery pricing could be even lower in the future.

Moreover the general technological development is continuously underway and its speed is exponentially growing so I think we can expect some results very early. Speaking of the electric drives it is very unlikely that the core of the drive BATinverter-EM will ever change. Now it is the time to come up with new materials, for example highly conductive wires for stator windings and even the rotor windings in wound rotor PSMs. I also registered an idea of adding multi speed transmission in the drive of EVs. Problem is that these transmissions will have to be able to handle high torque and low speed. But if the development departments will eventually come up with durable and stable solution this could increase the range of EVs for 10-20%.

Also the field of nanotechnology looks very promising regarding the electromobility. The whole new field of so called nano-batteries has been created. Lithium-ion battery usually has a graphite anode so the research mainly focuses on reducing the size of materials used in cathode and electrolyte. The electrode is coated by nanoparticles which rapidly increase the electrical conductivity of it. If the scientists will ever master the concept, the theoretical advantages would be excellent. The batteries would be able to provide super high charging and discharging current. The available power of the battery would also increase and even the fire resistance would improve. Also the research of nano-super-capacitors is in progress. Super-capacitors seemed to be really good competitor with lithium-ion batteries but the real applications did not reach the value of stored energy over units of kWh which is clearly insufficient for EVs applications. As mentioned in the previous paragraph the electric motors could also benefit from the new materials and especially nanomaterials. All these points show that electromobility still have a large amount of possibilities as it is still young/reborn technical field.

As I have just summed up the hardware possibilities I cannot forget to also mention that electric vehicles are mainly controlled by computers which are using a theory of control. Today a laic can see the EV also as a computer which gets regular system updates just like his PC or cell phone. Developers are able to improve the general qualities or even the dynamics of the car by even the slightest correction in control or inverter algorithm.

# 4. Dynamic mathematical model of EV

The main task was to create a dynamic model of EV in Matlab/Simulink which would be able to process the driving cycle data. This obviously required a slightly different approach than usual since only the speed of the vehicle is known and the model has to calculate the power, torque, acceleration, energy consumption and all other variables. It was also required that the created model would be compatible with the dSpace 1103 control unit which will be described later in its own chapter. Many automotive companies have their own general vehicle models for prototyping, software development etc. The ideal model would of course respect all possible variables, circumstances and conditions. Every aspect and part of the vehicle model leads to different field of technical studies and sciences so creation of this model is really demanding in terms of time and human resources. Then there are of course models which are respecting only the variables which are related most to the given specific application.

The model created in this project is primarily designed for calculation of energy consumption. Usual approach in field of electric drives is that the known variables are torque and speed of the motor etc. however this model has to calculate them. Model does not contain any calculations with current or voltage as it is a kind of an energy balance calculator. Crucial question is to find out as many variables which could affect the energy consumption and then add the parts individual models. For now the model respects following aspects affecting the energy consumption:

- Driving profile
- Aerodynamic drag - static
- Rolling resistance - static
- EM efficiency (both motor and generator regimes) – dynamic
- maximal EM power characteristic - dynamic

These are only the essential elements of the model. There are of course other elements which could be implemented and therefore refine the accuracy of the calculation of the model but each usually represents an individual physical or technical problem which would need more time to get the right sources, data and of course the creation of the model itself. Other aspects which could be modelled and added are:

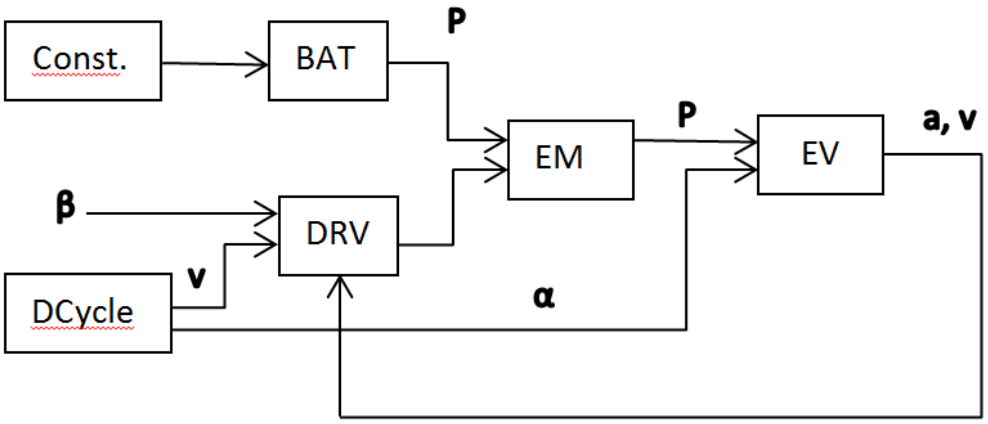
- Battery model – the next most crucial model which would need its own project
- Interior heating – model of the heat transition and energy leakage
- Lights – interior, exterior
- Dynamic aerodynamic drag – calculation with the current weather data (wind, speed, direction etc.)

- Dynamic rolling resistance – calculation with the current state of the road (dry, moist, wet – road surface) or even with tires condition (inflation, wear level)
- Power electronics efficiency – usually around 99% but also can be taken in account
- Analysis of the traffic situation data – prediction, best route

As we can see the mentioned elements are spread in different fields of technical sciences and they would need to be deeply analysed and processed before their implementation to the model.

## 4.1 EV traction model

Original Idea of the model arrangement can be seen in the picture below. Const. stands for a constant source of energy (battery capacity) other block are in my opinion obvious and they should just give the basic idea.



Main variables of the model are power (P), acceleration (a) and speed (v) of the vehicle, β is a position of the accelerator pedal (-1 – 1, 1 full throttle, -1 full braking) and α is the road slope. Model represents an EV with one EM on one axle and generated braking force splits between the EM and brakes. The kinetic energy stored in the movement of the vehicle can be stored in the battery (recuperation) or lost in brakes in form of a friction heat.

Created model of EV includes the main parameters which most affect the energy consumption. The reason why this model is simplified is that the analysis of the affecting parameters and development of the whole dynamic model is not the main task of this work. Mathematical model consists of 4 main equations. The angle of the track (slope) is function of trajectory because it of course matters in which part of the track the vehicle will be at the moment.

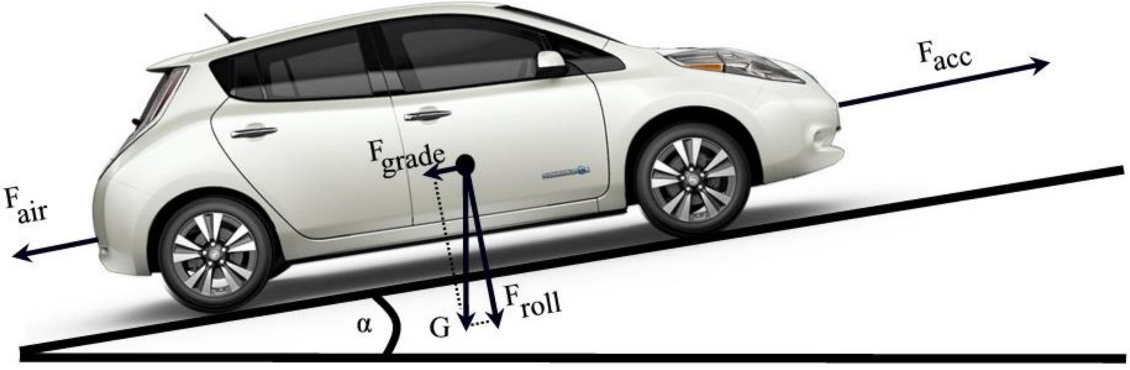


Figure 4-1: Forces affecting motion of a vehicle on a sloped road

Firstly the equation for tractive force and then the overall power balance had to be defined. $F_{acc}$ (2) is the force which is needed to accelerate or decelerate the vehicle. In order to propel the vehicle forwards this force needs to be greater and overcome other forces (vehicle motion resistances) which tend to decelerate the car or even unwillingly move if the car is on a slope. $F_{acc}$ (2) is a linear acceleration force which is applied when the speed of the vehicle is changing according to the Newton's second law of motion which is defined as (2).

$$F_{acc} = m * a(t) \qquad (2)$$

$m$ … weight of EV

$a(t)$ … longitudinal acceleration of the EV

First of the vehicle motion resistances is the rolling resistance. Rolling resistance is mainly caused by the friction of the vehicle moving on the road. Some studies say that it is also dependent on the vehicle's velocity but it has been decided to use just the usual equation with the rolling friction coefficient.

$$F_{roll} = c_r * m * g * \cos(\alpha(s)) \qquad (3)$$

$c_r$ … rolling friction coefficient (depends on the road surface, tires)

$m$ … weight of EV

$g$ … gravity constant

$\alpha(s)$ … slope (function of trajectory)

Next important resistance is the aerodynamic drag. Again commonly known equation (4) has been used because this field as well as the others would need deep down analysis to make it more realistic and real-world representative. This resistance is caused by the friction of the vehicle body (chassis) moving through the air. Main parameter is a so called drag coefficient which is determined by the vehicle producer's testing in the aerodynamic tunnels. Values around 0.3 are generally considered as a good average today. Vans and buses may get even values around 0.7.

$$F_{air} = \frac{1}{2}\rho_a * A * C_d * v^2(t) \qquad (4)$$

| | |
|---|---|
| $\rho_a$ | … air density (varies with altitude, humidity and temperature) |
| $A$ | … frontal surface |
| $C_d$ | … drag coefficient |
| $v(t)$ | … speed of EV |

The most significant motion resistance is the hill climbing force. It is a force caused by the slope of the road (grade) which acts in the direction of the negative gradient of the slope. It is given by the equation (5).

$$F_{grade} = m * g * \sin(\alpha(s)) \qquad (5)$$

| | |
|---|---|
| $c_r$ | … rolling drag force coefficient |
| $g$ | … gravity constant |
| $\alpha(s)$ | … slope (function of trajectory) |

The balance equation (9) can be defined easily as $P(t) = \frac{dW}{dt} = \frac{F \cdot ds}{dt}$ (6) can be simplified to $P(t) = F * v(t)$ (7). This of course applies only in one dimension. The balance equation (9) is then defined as:

$$P(t) = \left(F_{acc} + F_{roll} + F_{air} + F_{grade}\right) * v(t) \qquad (9)$$

## 4.2 Description of the model and its subsystems

Model is created in Matlab/Simulink 2013a (64bit version). Basic subsystem which clearly distinguishes the inputs and outputs is in the picture below. It is possible to set the reference speed or the position of the accelerator pedal. Reference speed is usually by the desired driving cycle data. In case of using the custom measured driving cycle with road inclination the slope data must be included in the block MATLAB function which technically makes the data possible to see as a function of slope (degrees) over travelled distance (km) – α(s). Outputs then should be connected to blocks which enable the dSpace 1103 to send the Speed_EM and Torque_EM data over the interface board to the PLC which then controls the dynamometer. Subsystem named scopes contains just scopes and digital displays for the user usage.

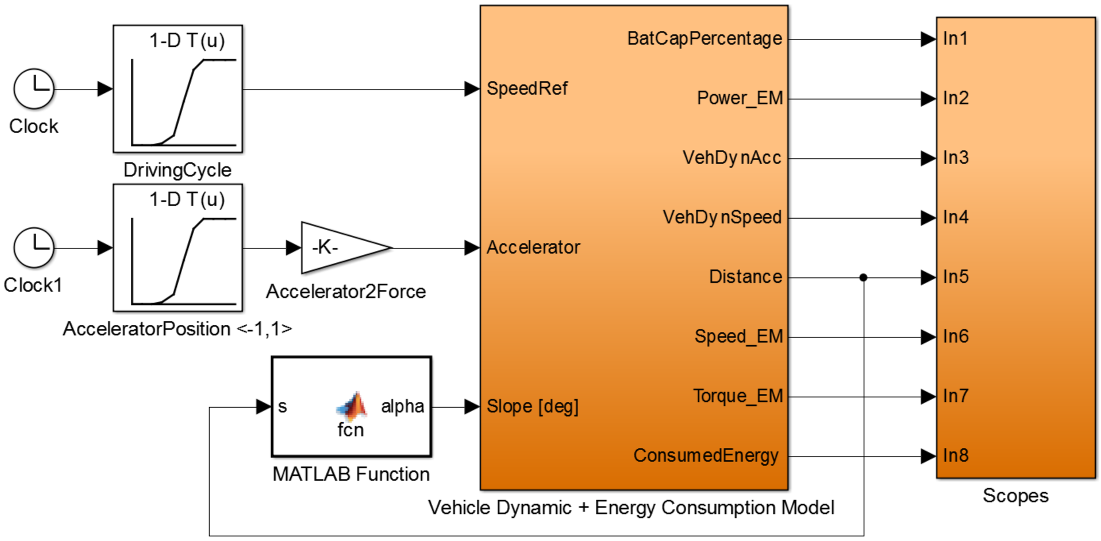


**Figure 4-2: Basic subsystem with I/O**

Gain block named Accelerator2Force converts the signal which value lies in the interval of -1 to 1 (included) to the actual longitudinal accelerating force (N). MaxFacc which is a maximal accelerating force is given by the maximal torque of the electric motor, gear reduction ratio (G) and also a tyre radius (r). The equation for MaxFacc is defined as: $F_{acc_{max}} = \frac{M_{max} \cdot G}{r}$ (10).

Before running the simulation or code generation for dSpace unit an initialization m.file must be checked and other variables must be specified in it such as vehicle parameters, basic electric motor parameters or tyre dimensions.

```
% Init m-file for VehDyn_model (version 6, 23/4/2015)

Stoptime = max(time); % Stop time of the simulation - must correspond with the
driving cycle time


VehDynSpeedInit = 0; % initial velocity of the vehicle in t = 0
%Constants
VehDynGravAcc = 9.81;
VehDynMassDensityOfAir = 1.3; %[kg/m^3]
Cr = 0.01; % Rolling friction coeficient

% Vehicle parameters
VehDynMass = 1200; %[kg]
VehDynFrontalArea = 2; %[m^2]
VehDynAeroDragCoef = 0.3;

% Electric drive parameters
MaxBatCapacity = 24; %[kWh]
MaxTorqueEM = 315; %[Nm]
MaxSpeedEM = 7000; % [1/min]

% Tyre dimensions + calculations
TyreWidth = 185; %[mm]
TyreAspectRatio = 0.6; % [%] Height of the tire itself =
TireWidth*TireAspectRatio*0.01 [mm]
WheelSize = 15; %[Inches] 1 inch = 0.0254 m = 2.54 cm = 25.4 mm

TyrePerimeter = ((TyreWidth*TyreAspectRatio)*2+WheelSize*25.4)*pi*0.001*0.92; %[m],
for EM speed calculation
TyreRadius = (TyreWidth*0.001*TyreAspectRatio*2+WheelSize*0.0254)/2; %[m], for EM
torque calculation

%Drivetrain parameters
GearRedRatio = 4.5; % eg. Tesla Model S has a single speed gear with 9.73/1
reduction ratio.

MaxFacc = ((MaxTorqueEM*GearRedRatio)/TyreRadius); % Maximal longitudinal
acceleration force which the el. drive can deliver

MaxVehDynSpeed = ((MaxSpeedEM*TyrePerimeter)/GearRedRatio*60)); % Maximal speed of
the vehicle in m/s
```

Next step is to load proper data of the driving cycle v = f(t) and α = f(s). This can be realized by blocks like lookup tables or Matlab function with simple for cycle.

Subsystem in the figure 64 contains all the individual subsystems so one can see the relations between them. Orange colour marks subsystems with basal calculations. Blue marked subsystems are mainly filled witch switches and auxiliary blocks. Yellow block is only one and its purpose is mainly for graphical reconstruction of the track profile (altitude over distance).

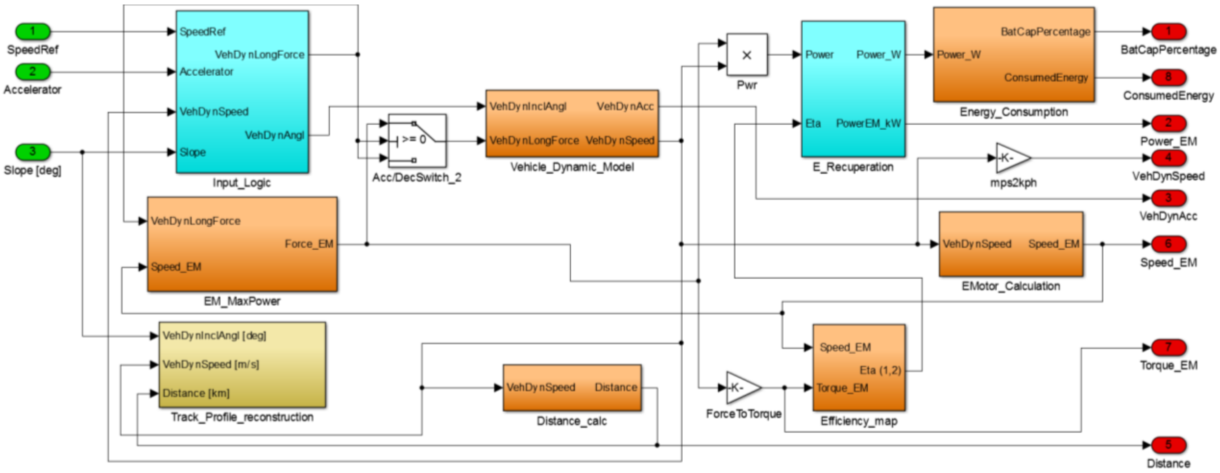


**Figure 4-3: Vehicle Dynamic + Energy Consumption Model - subsystems connections**

First subsystem which contains all three inputs is called Input_Logic. It also contains a PI controller which generates the accelerating force (already in N) and creates a control loop with reference speed and actual speed of the vehicle which represents a negative feedback. Upper limit of the output of the PI controller is given by the MaxFacc (10) variable. Lower limit is set as –MaxFacc but it of course could be more as it represents the maximal braking torque generated by the EM and also the brakes. Switches are there just for the user. If the usual driving cycle (NEDC, Artemis etc.) is run, the switch Road Angle data source should be connected to the 0 slope constant.

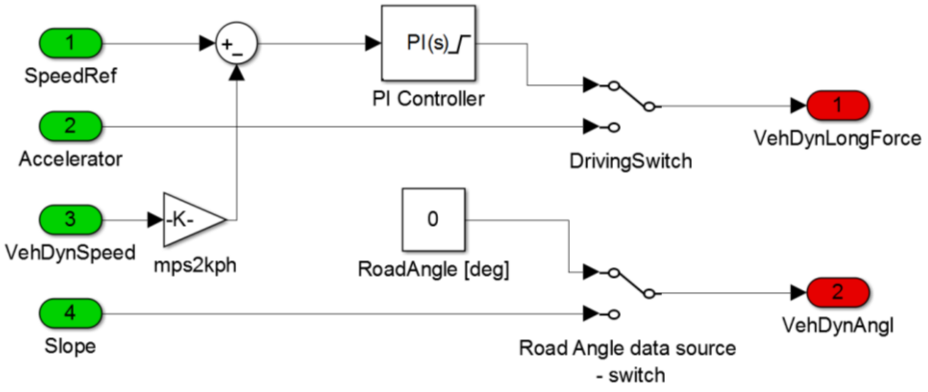


**Figure 4-4: Input_Logic**

Vehicle_Dynamic_Model is the main subsystem which calculates the current longitudinal acceleration and speed of the vehicle. It includes all the equations of the vehicle motion resistances mentioned in chapter 3.1.

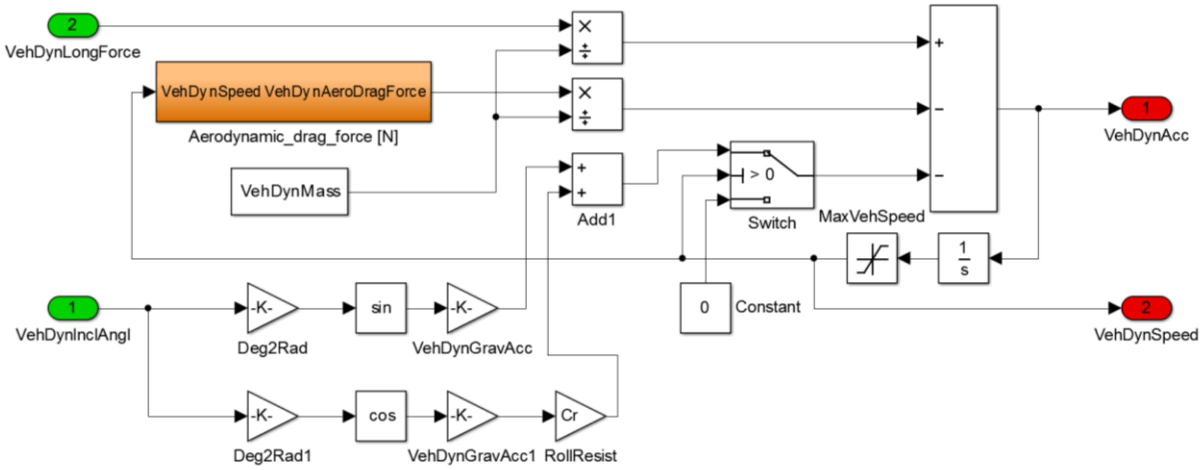


**Figure 4-5: Vehicle_Dynamic_Model subsystem**

Vehicle speed is calculated as: $v(t) = \int a(t)dt$ (11). Initial condition of the integrator can be set in the initialization m.file (will be described later) as variable called VehDynSpeedInit. Saturation block called MaxVehSpeed limits the speed of the vehicle which is calculated as: $v_{max} = \frac{(n_{max} \cdot TyrePerimeter)}{G \cdot 60}$ $(m/s)$ (12). Switch with the zero condition is there because the PI controller is not ideal and creates a delay and steady state error.

**Figure 4-6: Aeordynamic_drag_force subsystem**

Subsystem named E_Recuperation solves the logic when the energy is being consumed from the battery or supplied during the regenerative braking. It also multiplies the power with an efficiency coefficient which is given by the efficiency map. Constant Lights/Cooling/Heating represents constant power consumption by the mentioned elements and just marks the place in the model where the heating model should be connected. Gain block labelled as EnRecoveryEff is a constant efficiency of the energy recovery during regenerative braking. This is the place where the battery model could be.

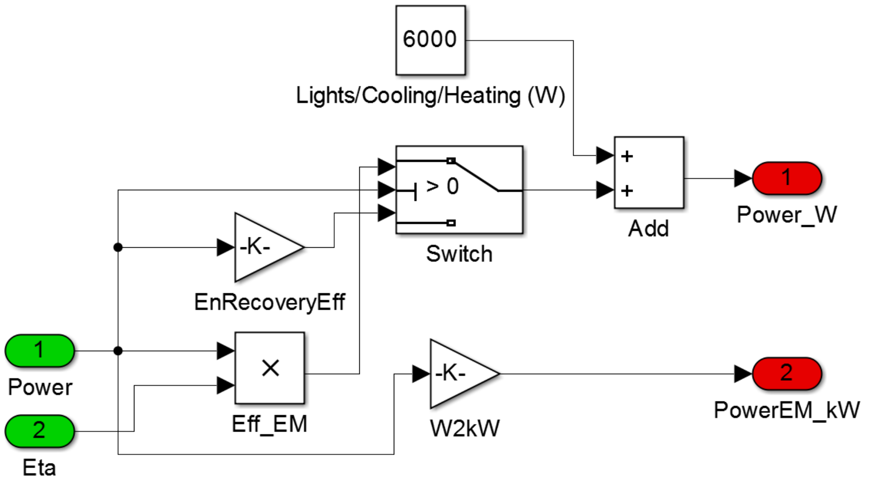


Figure 4-7: E_Recuperation subsystem

Subsystem Energy_Consumption is the one which calculates the consumed energy from the current power. Stored energy is represented in form a constant block with parameter MaxBatCapacity which is also set in the initialization m.file. Consumed energy is calculated from the current power as $E(t) = \int P_{EM}(t)dt$ (13) and then it is subtracted from the battery capacity. Also a condition for stopping the simulation if the SoC drops to zero level is included.

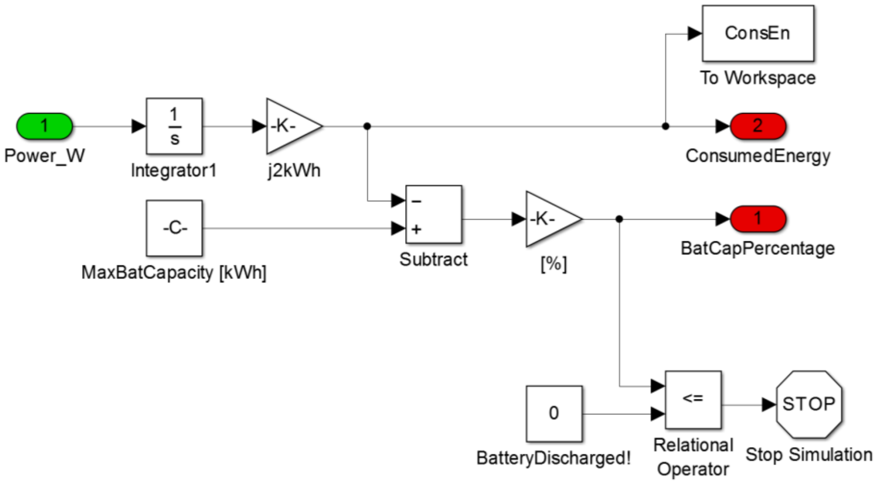


Figure 4-8: Energy_Consumption

Electric motor does not behave in the same way in the whole range of speed and torque. To be able to respect its efficiency and maximal power and torque output it is crucial to know the revolutions of the electric motor. This can be only done with defined dimensions of the tyres and wheels used on the EV. Tyre dimensions are calculated in the initialization m.file (chapter 3.2, page 52) and respect the compression of the tyre by the load of the vehicle mass (compression coefficient 0.92 decreases the tyre perimeter value). Equation for calculation of the speed of the EM is defined as: $n_{mot} = \frac{GearRedRatio*60*\mathrm{v(t)}}{TyrePerimeter}$ (14).

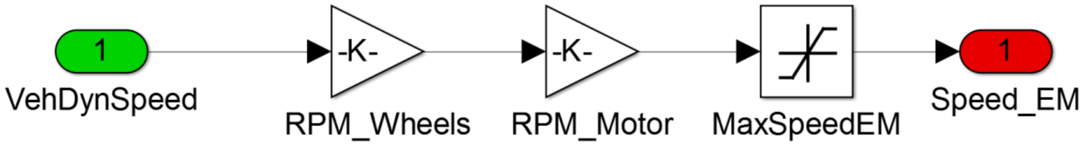
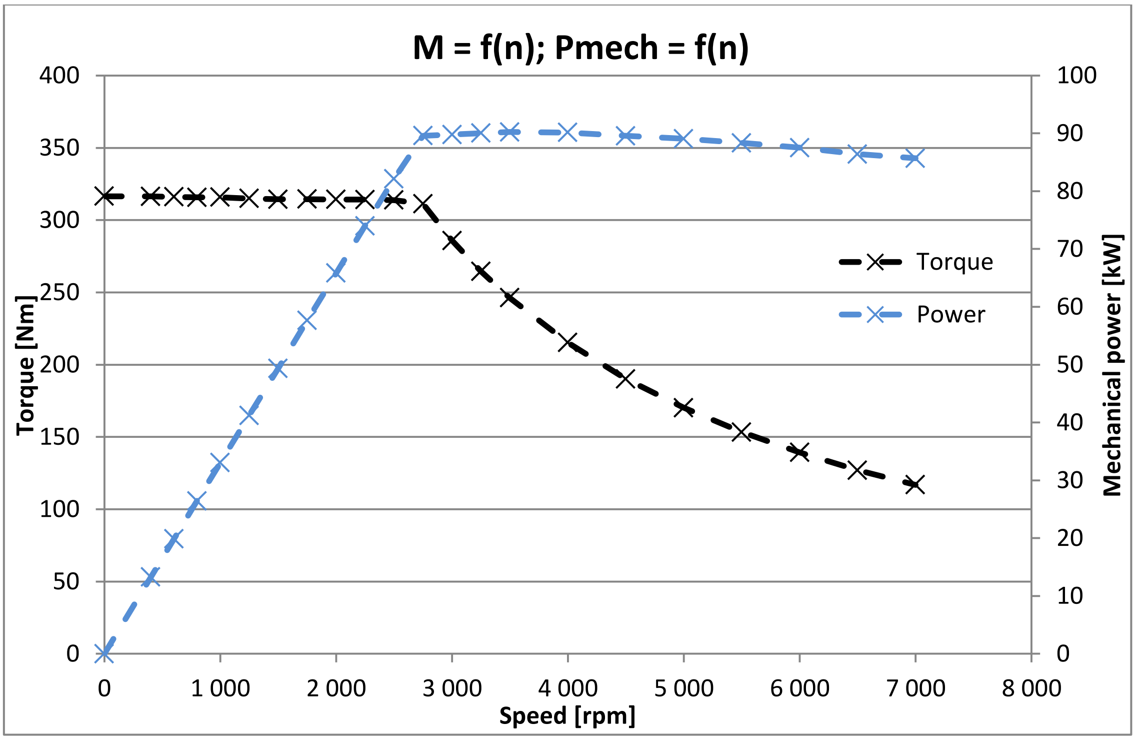


Figure 4-9: EMotor_calculation

Next blocks are dealing with the efficiency and maximal power of the EM. Model assumes that the user has the data of efficiency map of the used motor which is often provided by the producer. Efficiency map is a graphical representation of dependency of efficiency (z axis) on speed (x axis) and torque (y axis). Eff. map actually also provides information about the maximal torque of the motor which is also needed to be represented while calculating the energy consumption. It is assumed that the maximal torque is constant from 0 to 2750 1/min.



Graph 4-1: Torque-speed and power-speed curve of the specific PMSM

Maximal torque from 2750 to 7000 1/min is approximated by a quadratic polynomial $M_{limit} = 8596 \cdot 10^{-9}(n)^{\wedge}2 - 0.128 \cdot (n) + 591.6963$ (15) so the maximal torque is respected by the model in the whole sped range. Maximal torque and efficiency may differ in reality so it is recommended to use measured data from both motor and generator tests. Now it is assumed that the generator characteristic is same as the motor one but with negative torque. EM_MaxPower_Braking is only modified EM_MaxPower_Acc to give the negative torque as the output. EM_MaxPower subsystem connects these two mentioned subsystems with a switch which decides when the energy is being stored or consumed. The decisive parameter is the forward accelerating of the vehicle.

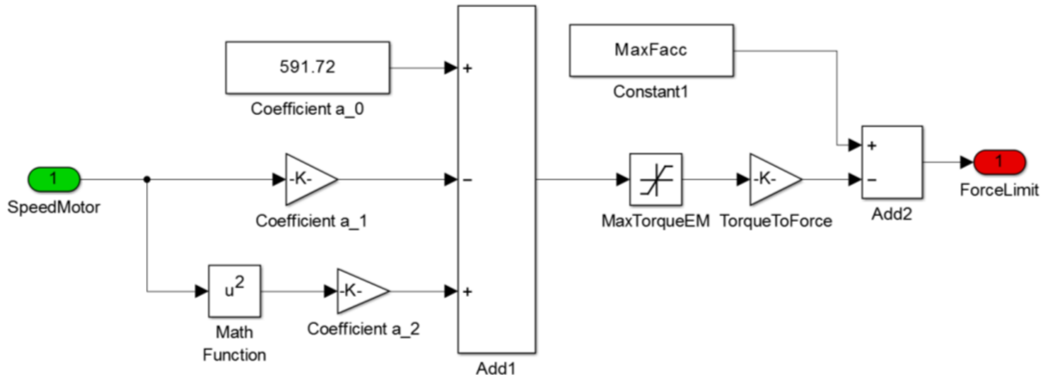


**Figure 4-10: EM_MaxPower_Acc subsystem (EM_MaxPower_Braking)**

With torque and speed of the EM it is possible to find a working point in the efficiency map of the motor. The efficiency map consists of discrete points so a minor deviation is included since the working point does not exactly correspond with the reality in this matter. Result efficiency is saturated to 95% and then must be subtracted from 2 because the energy flow conditions must be kept. So the power supplied by the battery is greater than the power generated by the EM.

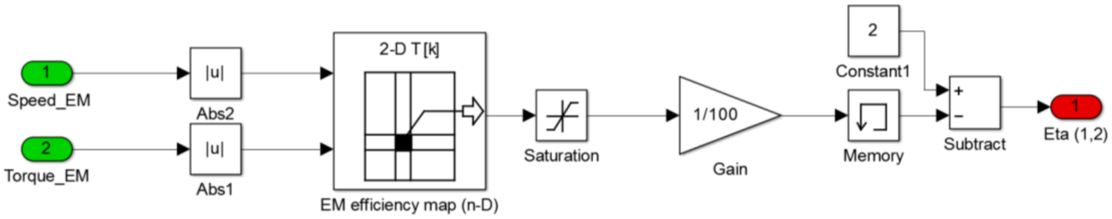
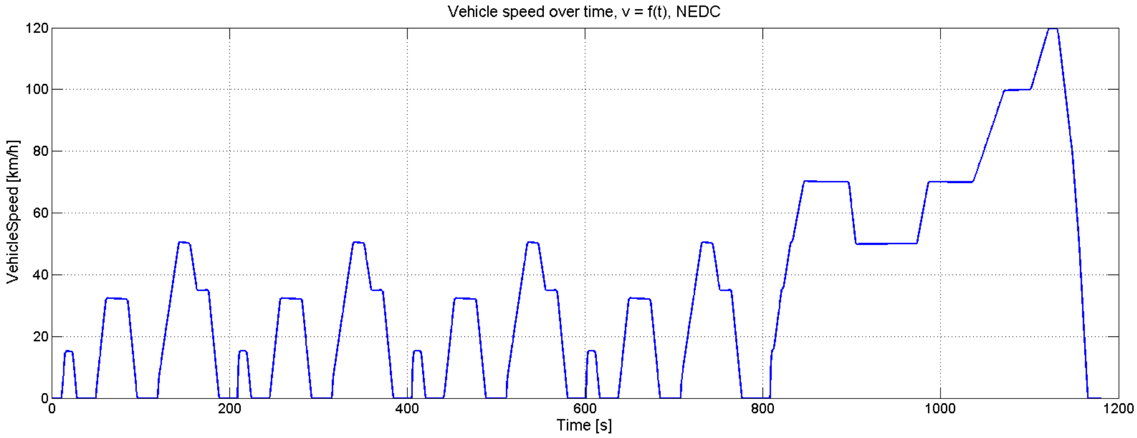


**Figure 4-11: EM_Efficiency subsystem**

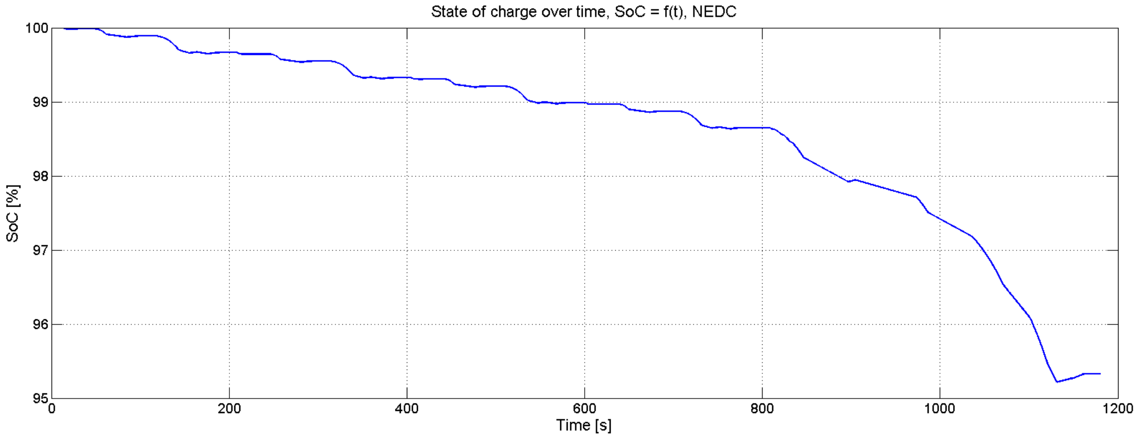
Last subsystem Track_Profile_reconstruction is there just for calculation of the track height profile. Only parameter that is required to enter is the initial altitude of the first sample of the driving cycle.

## 4.3 NEDC Simulation

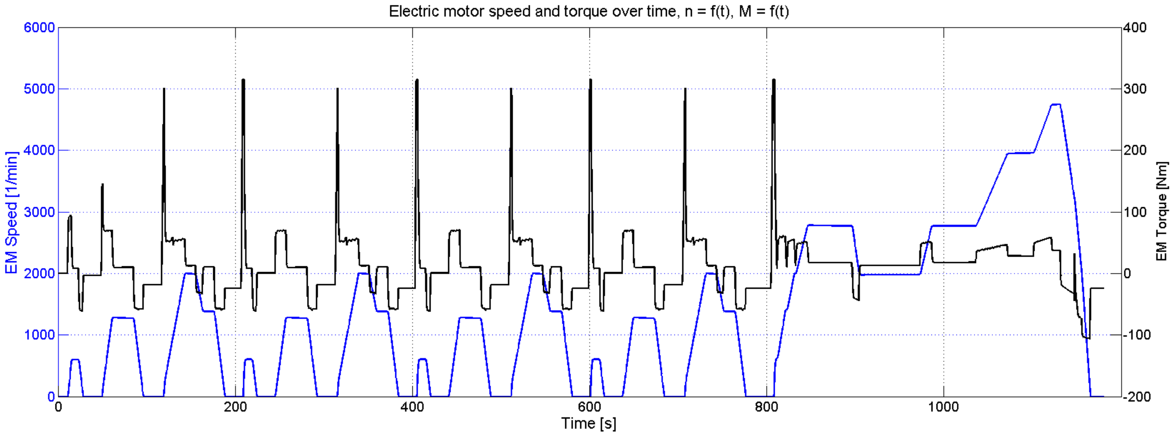
Created model is capable of simulating the commonly used driving cycles for estimation of the energy consumption of defined vehicle. NEDC driving cycle was used as an example and the results are graphically shown below. Consumed energy only used for propulsion was 1.121 kWh. The distance of the NEDC cycle is 11 km.



**Graph 4-2: Vehicle speed, NEDC**



**Graph 4-3: State of charge of the simulated EV battery, NEDC**



**Graph 4-4: Speed and torque of the EM, NEDC**

## 4.4 dSPACE 1103 implementation

After completion of the model it is required to run the code generation which basically compiles the model into a C code which is suitable for the dSPACE 1103 PPC. This can be done by clicking the Code menu in the toolbar of the Simulink. Then the system target file must be set as the rti1103.tlc. The code is then generated by clicking the build button.

Once the build is ready it is possible to download all the necessary files to the dSPACE board. Application files can be downloaded either to the internal 32 MB application memory of the board itself or to the compact flash drive which is then inserted in the pc-card reader which is a part of the auto-boot option. The build of the code generates following files: .ppc, .x86, .map, .trc and .sdf. PPC file is the real-time application for the PowerPC board, x86 file is for DS1103 board, TRC contains variable description which is then used by the ControlDesk user-interface and the last one is SDF which is basically a system description file with references to the all above mentioned files. Driving cycle data is part of the model so they must be loaded in the workspace while the code generation is running.

So far only mode with connection to the host PC has been used so the proper Ethernet connection has to be established by the common LAN cable. After establishing the connection and registering the 1103 platform it is possible to start by creating new project and loading the .sdf file. ControlDesk is a user-interface which enables the user to create a layout to display the selected variables and also with control elements like buttons, switches etc. User can of course download the real-time application to the dSPACE board and start or stop it. Layout with the major variable displays has been created in ControlDesk 5.0 to simulate the dashboard of the real-time simulated electric vehicle.

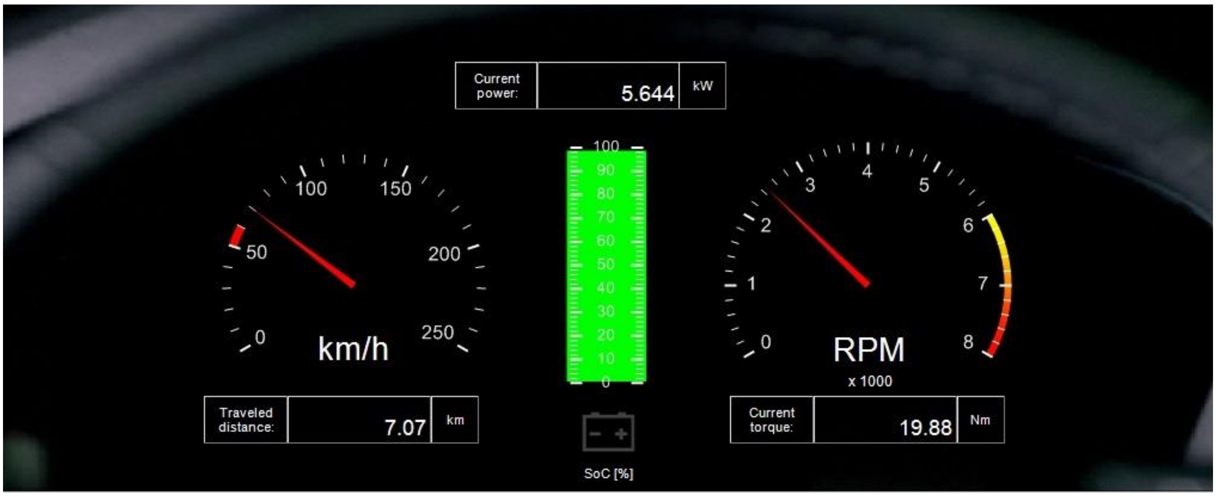


Figure 4-12: Dashboard layout in ControlDesk 5.0

# 5. Driving cycles

Driving cycles are very important in modern automotive industry when the global restrictions are more and more demanding in terms of energy consumption and $CO_2$ emissions. Driving cycle can be defined as a set of data consisting of vehicle speed over time. It basically gives information about the driving style of the driver and also about the traffic flow in certain area like countryside and urban roads or highways. Newly measured cycles are often subjected to deep statistical analysis. Cycles released after this analysis are representing specific traffic situation or driver's behaviour. The main purpose of acquiring and analysing the data of driving cycles is that they are needed for laboratory testing on dynamometer or computer simulation. This obviously can save a large amount of money and both technical and human resources which are necessary for on-road testing.

However the working parties and agencies releasing the driving cycles are not unified. For example the main working party in which most of the European countries and even some non-European ones are participating is called World Forum for Harmonization of Vehicle Regulations (WP.29). It is a working party of the Inland Transport Division of the United Nations Economic Commission for Europe (UNECE). WP.29 was founded already in 1952. The United States have their own agency called the United States Environmental Protection Agency (EPA) which is an agency of the U.S. federal government established in 1970. These two groups are the most important ones regarding the determination of the range of EVs.

There are two basic types of driving cycle modal and transient one. Transient cycle includes many speed changes and it tries to represent real on-road driving. Modal cycle on the other hand represents a driving at constant speed for a long period of time. Cycles can also be distinguished by the area where they were taken or the type of the traffic flow which they represent such as urban, rural or highway. Of course the type of the vehicle (car, bus, van, truck etc.) is important for the category of the driving cycle as well. Main driving cycles group used in the European automotive industry are NEDC and Artemis.

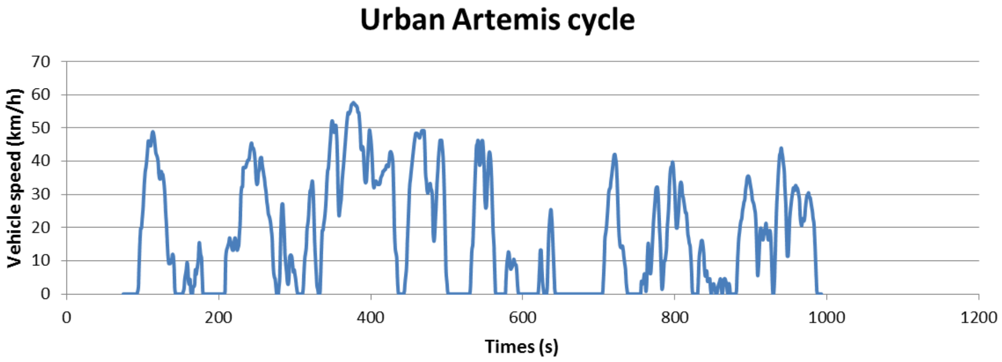


**Figure 5-1: Example of driving cycle: Artemis Urban driving cycle (Artemis.urban_incl_start)**

Driving cycles are today mainly used for emission levels measurements but they can also be used for other purposes such as motor testing, drive-train durability and of course energy consumption. In order to test the energy consumption of the drive-train the data of the driving cycle must also contain the road slope. Road slope data can be acquired easily by the position of the vehicle (GPS) and accurate map data. More expensive but also precise solution would contain some kind of an altimeter which is a device specifically designed for determination of an altitude. Therefore it would be possible to calculate the slope between two points.

## 5.1 Technical solutions of the data acquisition

There are a lot of driving cycles available today which were created by the agencies and groups all over the world. These are all great and useful mainly for the emissions level testing but none of them provides information of the position of the car or about the road slope. It must be said that majority of these cycles was developed for internal combustion vehicles. This project of optimal control of EV mainly deals with the road slope as the energy consumption increases rapidly while going up the hill. Also the important thing is that the driving up the hill can be more easily predicted instead of the regular acceleration or deceleration processes which are often performed at junctions, turns, queues etc.

The cheapest solution for getting own driving cycles is to use an app for smartphones which can export data in for example .csv format for further processing in computer. The data of the smartphone are acquired via its GPS module. Important is if the data contain the altitude from the map data or the GPS. GPS altitude accuracy is known for not being the best. In an early stage of the project like ours this seems to be the best solution. If the smartphone would not be available then a construction of printed circuit board with GPS module and appropriate connectors would also be a cheap and efficient solution.

For more accurate and plausible data obviously more expensive and sophisticated components would be needed. Kinematic data such as speed, acceleration from the accelerometer could be precisely measured and processed by ECU of ESP, ESC, ABS or other traction systems. The data is usually transferred via CAN bus in order to provide it for the other ECUs. The slope could be accurately measured by the use of the digital inclinometer so the calculation of the slope would be avoided. The calculation obviously includes deviations which are caused by the accuracy of the GPS and map data. The inclinometer would of course have to be calibrated to the flat ground level and also the assembly would have to be stable and precisely performed. Beside these components only a suitable data logger with appropriate connections would be needed.

Another technical aspect is the sampling rate of the data logger. There are a few interesting correlations which must be taken into account. The speed of vehicle varies over time and the slope of the road varies with the travelled distance. But distance varies also with speed so it is a full circle of correlations. The solution with GPS module is certainly less demanding in terms of the sampling rate. The bigger the sampling rate the more complicated the following processing of the data would be and also the deviations and errors could be amplified in a way. It also depends on the transition rate of the driving cycle data but for some general urban or highway driving the sampling rate of 0.1 or max 1 Hz would be sufficient. The professional data logger solution with tilt sensor (inclinometer) and telemetry connection would be also equipped with much better memory storage and the quality of the measured data determines it to be sampled in high rates like 1, 10 or 100 Hz. But again the question would be the real application of the driving cycle.

# 6. Hardware part of the project

## 6.1 Test bench and control systems setup

Created model and measured driving cycles are part of the whole measurement system located in a laboratory in VTP Roztoky. Basic arrangement of the system is in the figure below. PMSM stands for the tested traction motor which is usually synchronous with permanent magnets but that does not mean that the ASMs or DC motors cannot be connected to the shaft of the dynamometer (DM) too. DS1103 control unit is connected to the DM interface via RS232 and it controls the value of desired load torque.

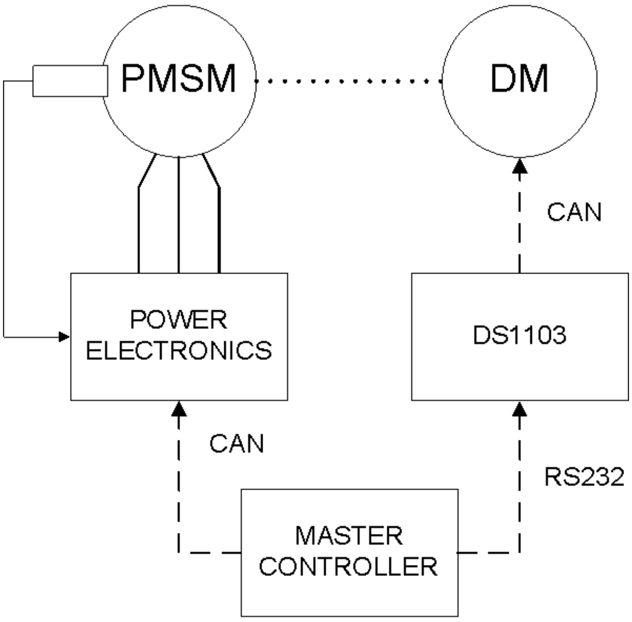
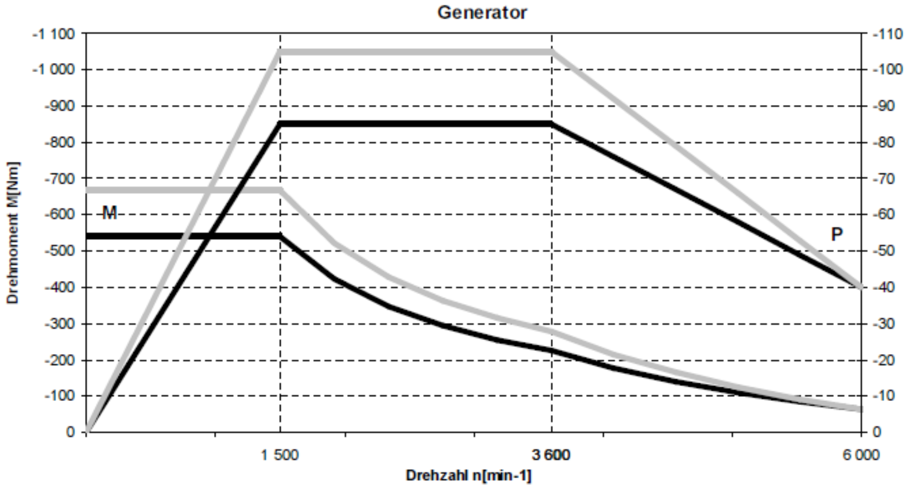


**Figure 6-1: Block-scheme of the system arrangement**

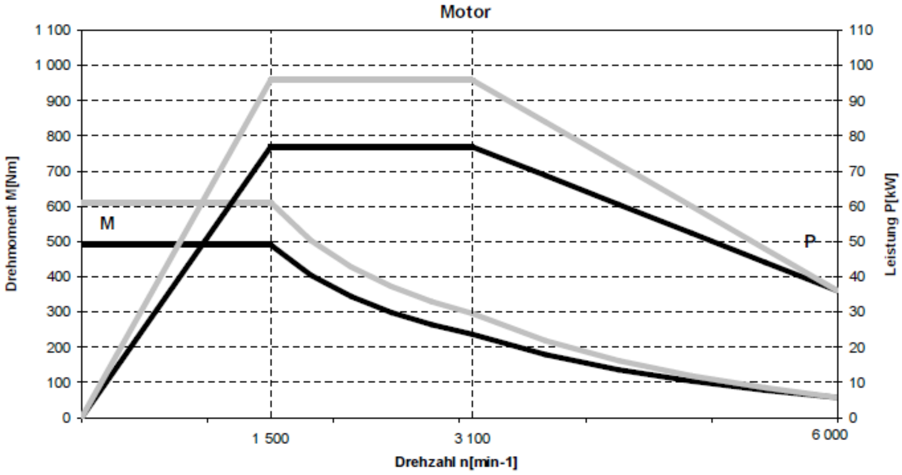
Created model with measured driving cycle (chapter 4) is compiled in Matlab and downloaded to the DS1103. The model runs in real time and starts once the DS1103 is powered up.

Block DM actually includes the interface and PLC computer which controls the inverter for dynamometer (DM is a 3-phase ASM). Automated measurement of electric drives can be run at speed up to 6000 1/min with direct coupling of the DM and tested motor or it can be coupled through reduction gearbox which enables to go up to 12 000 1/min. Test-bench is equipped with universal power supply for testing of ASMs, PMSMs or even a brushless DC motors (can be controlled with the DC/AC inverter as well but rectangular waveforms). Torque is measured by strain-gauge bridge mounted onto the rotary stator of the dynamometer’s induction motor. The maximal torque is 800 Nm.

Figure 6-2: Laboratory of EV's and HEV's electric drives measurement – dynamometric test bench is on the right and power supply rack with control PC is on the left.



Graph 6-1: Torque and power characteristics of the dynamometer in generator operating mode



Graph 6-2: Torque and power characteristics of the dynamometer in motor operating mode

## 6.2 dSPACE 1103 PPC controller board

Dspace 1103 (by dSpace GmbH - Germany) is a single-board controller system with real-time processor PowerPC 750GX (at 1GHz) and wide I/O possibilities. In this project dSpace 1103 is used in “autobox” version which also enables use in a vehicle for on road testing. Main advantage is that the controller is fully programmable by using Matlab/Simulink environment. Once the model is done and compatible with the controller a code generation can be performed and the code then can be downloaded to the PPC. Dspace comes with RTI (Real-Time Interface) which is a kind of an add-on for the Matlab/Simulink so it is possible to define the connections between the model and hardware I/O. This particular DS1103 unit is also, aside the standard application memory of 32 MB, equipped with an auto-boot system with compact flash memory card which enables to run the code right after power-up and boot phase without the need of a PC connection. Autobox version requires 12V power supply and can be connected to PC via Ethernet.

Figure 6-3: dSpace Autobox

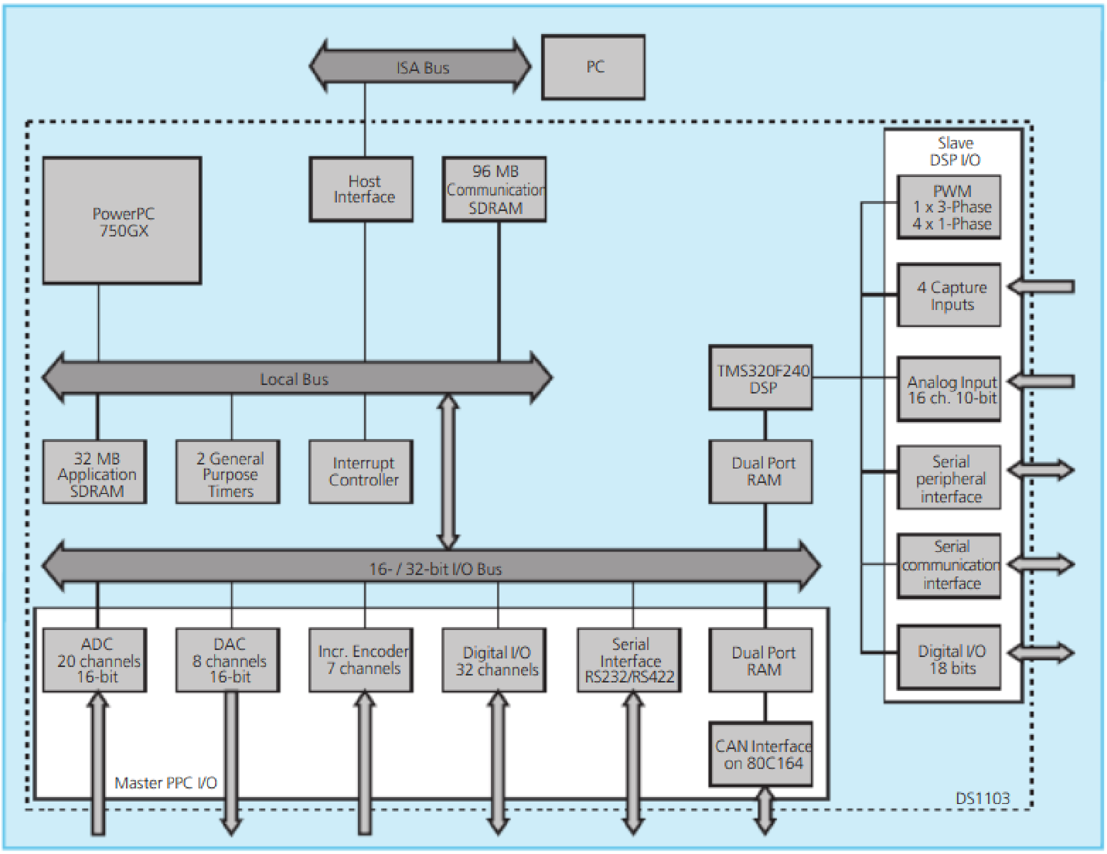


Figure 6-4: Block scheme of the hardware structure of the dSpace 1103 PPC (Source: dSPACE GmbH)

## 6.3 Interface board

Since the Autobox is intended for use in the measurement laboratory an interface board was designed. Dspace provides a so called control panel which contains all the inputs and outputs which 1103 has to offer but its dimensions are unfortunately too large for a laboratory use of this purpose and many I/Os would be necessary. Available HW documentation by dSPACE provided enough information about I/O pin connections so a decision about which signals and communications should had been chosen could be made.

**Figure 6-5: dSPACE 1103 PPC Controller board (Source: dSPACE GmbH)**

DSPACE 1103 PPC has three 100 pin I/O connectors on board marked as P1, P2 and P3. The original cables divided into halves are marked as P1A, P1B, P2A and so on. Therefore the cables are ended with D-sub 50 pin I/O connectors which are connected to the interface board. It has been decided to choose the following signals because they may prove useful in the future stages of the project as well and during the time the interface board was being designed it was not really decided yet how the communication interface with the test bench will be like.

| **P1** | | |
|---|---|---|
| **Signal** | **Analog (CP29)** | **Sub-D PIN** |
| SADCH 1 | 1 | P1B 12 |
| SADCH 2 | 2 | P1A 12 |
| SADCH 3 | 3 | P1B 29 |
| SADCH 4 | 4 | P1A 29 |
| SADCH 5 | 5 | P1B 46 |
| GND | 6 | P1A 17 |
| SADCH6 | 7 | P1A 46 |
| SADCH7 | 8 | P1B 14 |
| SADCH8 | 9 | P1A 14 |
| GND | 10 | P1B 17 |
| DACH2 | 11 | P1B 25 |
| DACH2 | 12 | P1A 25 |
| DACH3 | 13 | P1B 42 |
| DACH4 | 14 | P1A 42 |
| GND | 15 | P1A 44 |

**Table 6-1: List of ADC and DAC signals**

| P1/P2 | | |
|---|---|---|
| **Signal** | **Terminal block 27x (CP30)** | **Sub-D PIN** |
| SADCH1 | 1 | P1B 12 |
| SADCH2 | 2 | P1A 12 |
| SADCH3 | 3 | P1B 29 |
| SADCH4 | 4 | P1A 29 |
| SADCH5 | 5 | P1B 46 |
| GND | 6 | P1B 28 |
| DACH1 | 7 | P1B 25 |
| DACH2 | 8 | P1A 25 |
| DACH3 | 9 | P1B 42 |
| DACH4 | 10 | P1A 42 |
| GND | 11 | P1B 30 |
| SPWM1 | 12 | P2B 28 |
| SPWM2 | 13 | P2A 28 |
| SPWM3 | 14 | P2B 12 |
| SPWM4 | 15 | P2A 12 |
| GND | 16 | P2B 46 |
| SPWM5 | 17 | P2B 45 |
| SPWM6 | 18 | P2A 45 |
| SPWM7 | 19 | P2B 29 |
| SPWM8 | 20 | P2A 29 |
| GND | 21 | P2B 32 |
| IO1 | 22 | P2A 18 |
| IO2 | 23 | P2B 2 |
| IO3 | 24 | P2A 2 |
| IO4 | 25 | P2B 19 |
| IO5 | 26 | P2A 19 |
| GND | 27 | P2B 36 |

**Table 6-2: List of signals routed to the terminal blocks**

Terminal blocks with pitch of 5mm are used mainly for the PWM signals from the slave DSP. PWM and IO1-5 signals goes through LEDs with appropriate resistors for visual control if used.

| P2 | | | | | |
|---|---|---|---|---|---|
| **Signal** | **DIG I/O (CP30)** | **Sub-D PIN** | **Signal** | **DIG I/O (CP30)** | **Sub-D PIN** |
| IO0 | 1 | P2B 18 | IO17 | 26 | P2A 22 |
| IO2 | 2 | P2B 2 | IO19 | 27 | P2A 6 |
| IO4 | 3 | P2B 19 | IO21 | 28 | P2A 23 |
| IO6 | 4 | P2B 3 | IO23 | 29 | P2A 7 |
| IO8 | 5 | P2B 20 | IO25 | 30 | P2A 24 |
| IO10 | 6 | P2B 4 | IO27 | 31 | P2A 8 |
| IO12 | 7 | P2B 21 | IO29 | 32 | P2A 25 |
| IO14 | 8 | P2B 5 | IO31 | 33 | P2A 9 |
| IO16 | 9 | P2B 22 | GND | 34 | P2B 34 |
| IO18 | 10 | P2B 6 | GND | 35 | P2B 35 |
| IO20 | 11 | P2B 23 | GND | 36 | P2B 36 |
| IO22 | 12 | P2B 7 | GND | 37 | P2B 37 |
| IO24 | 13 | P2B 24 | GND | 38 | P2B 38 |
| IO26 | 14 | P2B 8 | GND | 39 | P2B 39 |
| IO28 | 15 | P2B 25 | GND | 40 | P2A 1 |
| IO30 | 16 | P2B 9 | GND | 41 | P2A 34 |
| GND | 17 | P2B 1 | GND | 42 | P2A 35 |
| IO1 | 18 | P2A 18 | GND | 43 | P2A 36 |
| IO3 | 19 | P2A 2 | GND | 44 | P2A 37 |
| IO5 | 20 | P2A 19 | GND | 45 | P2A 38 |
| IO7 | 21 | P2A 3 | INTO(NOT) | 46 | P2B 16 |
| IO9 | 22 | P2A 20 | INT1 (NOT) | 47 | P2A 16 |
| IO11 | 23 | P2A 4 | INT2 (NOT) | 48 | P2B 49 |
| IO13 | 24 | P2A 21 | INT3 (NOT) | 49 | P2A 49 |
| IO15 | 25 | P2A 5 | VCC (+5v) | 50 | P2A 33 |

**Table 6-3: List of used digital I/O signals**

CP30 is a female F50 D-sub connector which mainly contains digital I/O signals.

| P3 | | |
|---|---|---|
| CAN (CP38) Signals | F9 (Pins) | P3 (Pins) |
| - | 1 | - |
| CANL | 2 | P3B 15 |
| GND | 3 | |
| - | 4 | - |
| GND | 5 | |
| GND | 6 | |
| CANH | 7 | P3B 48 |
| - | 8 | - |
| - | 9 | - |

**Table 6-4: List of CAN bus signals and their routing**

CP38 is marking of the CAN bus which is represented by the female F9 D-sub connector (CP40 and CP42). CAN (control are network) bus is a common communications protocol in the automotive industry. It usually connects the ECU to other ECU, simple I/O device or some more sophisticated devices like actuators etc.

| P3 | | |
|---|---|---|
| RS232 (CP40) Signals | CANON 9 (Pins) | P3 (Pins) |
| DCD (**RXD**) | 1 | P3A 18 |
| RXD | 2 | P3B 18 |
| TXD | 3 | P3B 34 |
| DTR (**RTS**) | 4 | P3A 2 |
| GND | 5 | |
| DSR (**CTS**) | 6 | P3A 35 |
| RTS | 7 | P3B 2 |
| CTS | 8 | P3B 35 |
| RI | 9 | P3B 19 |

**Table 6-5: List of RS232 signals and their routing**

| P3 | | |
|---|---|---|
| RS422 (CP42) Signals | CANON 9 (Pins) | P3 (Pins) |
| **TXD** | 1 | P3A 34 |
| TXD | 2 | P3B 34 |
| RXD | 3 | P3B 18 |
| **RXD** | 4 | P3A 18 |
| GND | 5 | |
| **RTS** | 6 | P3A 2 |
| RTS | 7 | P3B 2 |
| CTS | 8 | P3B 35 |
| **CTS** | 9 | P3A 35 |

**Table 6-6: List of RS422 signals and their routing**

Last two mentioned connectors CP40 and CP42 complete the equipment of the interface board as they add the two of the most used serial interfaces today RS232 and RS422. RS232 used to be compatible with almost every Windows based PCs but it stopped being shipped some time ago as a common feature. It is still very used in the industrial applications. RS422 is a modification of the RS232 and thanks to its differential mode of operation it allows to transmit the data with speed up to 10Mbit/s which is about 10 times faster than the RS232.

Board was designed in the Eagle software and the result can be seen in the figure below. Additional pictures of the board design can be found in the attachment section (chapter 10) of the thesis.

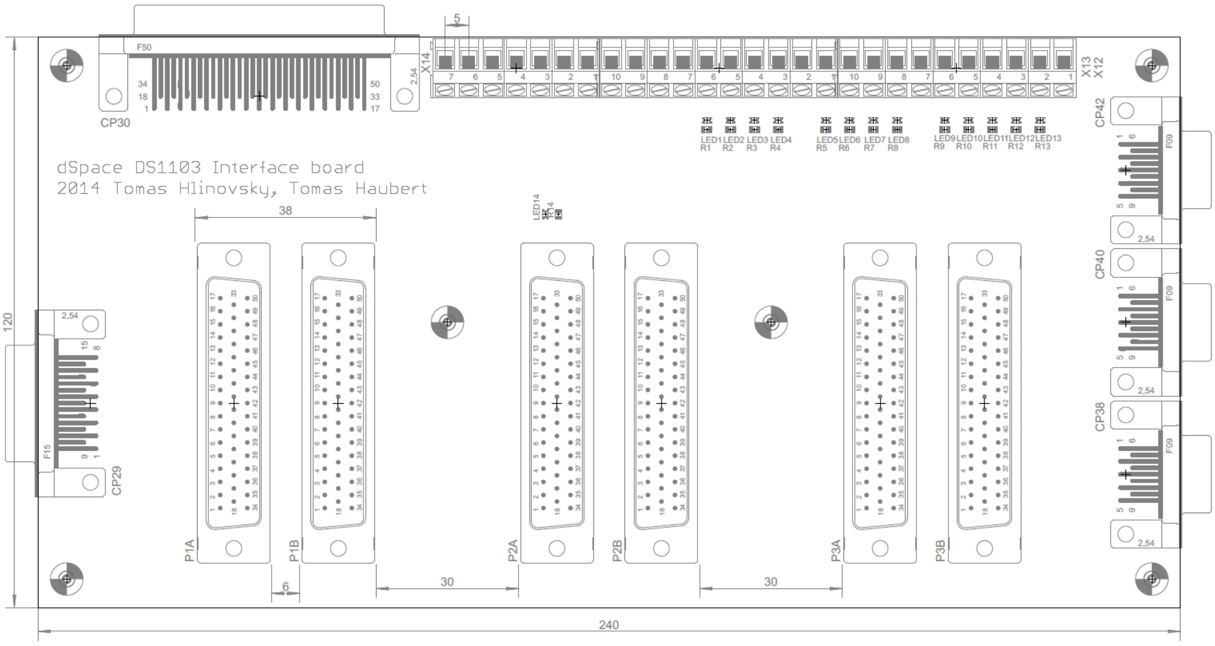


**Figure 6-6: dSPACE 1103 interface board**

# 7. Optimization algorithm and simulations

After completion and validation of the functionality of the model it was possible to try to optimize the reference speed or accelerator position in order to minimize the energy consumption. It has been decided that the best possible way how to reach this goal was to use a Matlab function fmincon which is a part of the Optimization toolbox.

## 7.1 Function fmincon

Fmincon is a MATLAB function which is a part of the Optimization toolbox and usually is connected with field of constrained nonlinear optimization or nonlinear programming. It finds a minimum of a constrained nonlinear one variable or multivariable function with a specified starting estimate. It uses an iteration strategy and 4 different algorithms can be set for finding the minimum. Basically it can be said that the created model is exported to workspace by command *sim* with two main important parameters: vehicle speed and consumed energy. Fmincon function will iteratively try to change the vehicle speed vector values to see which combination (driving cycle) is the best in term of the lowest energy consumption. Constraints of the optimization are very important because they have to define the interval of the speed which the vehicle can go. These constraints would of course have to correspond with the maximal allowed speed on the particular road. Result data should be suggested as a speed of the vehicle which the driver should follow as much as possible to reach the calculated range or the speed data could directly feed the cruise control in some cases.

The general mathematical formula is defined as:

$$\underset{x}{min} f(x) \qquad (16) \qquad \text{subject to:} \quad \begin{aligned} & c(x) \leq 0 \\ & ceq(x) = 0 \\ & A \cdot x \leq b \\ & Aeq \cdot x \leq beq \\ & lb \leq x \leq ub \end{aligned}$$

Where: *x, b, beq, lb,* and *ub* are vectors, *A* and *Aeq* are matrices, *c(x)* and *ceq(x)* are functions that return vectors and *f(x)* is a function that returns a scalar. *f*(x), c(x), and *ceq(x)* can be nonlinear functions.

The general MATLAB syntax of the function:

*[x,fval,exitflag,output] = fmincon (fun, x0, A,b, Aeq, beq, lb, ub, nonlcon, options)*

Where: ***x*** is the calculated minimum of the function, ***fval*** returns a value of the objective function *fun* at the value *x*, ***exitflag*** is an exit description of the function fmincon and ***output*** is a structure with information about the optimization. ***Fun*** is the function which is being optimized, ***x0*** is an initial estimation of the minimum, ***A*** and ***b*** is a definition of linear inequality $A \cdot x \leq b$, ***Aeq*** and ***beq*** is a definition of linear equality $Aeq \cdot x = beq$, ***lb*** and ***ub*** define lower and upper bounds of the solution x $(lb \leq x \leq ub)$, ***nonlcon*** is a function option, which calculates the nonlinear inequality $c(x) \leq 0$ and equality $ceq(x) = 0$, ***options*** – sets the optimization algorithm.

Optimization algorithms (solvers): All algorithms are based on multivariable calculus and use partial differentiation for constructing the Hessian matrixes to get the minimums of the objective function.

- ***Interior-point*** algorithm is the first recommended to use when running the optimization for the first time. It is not that accurate but can solve small and large problems in a short amount of time with quite reasonable usage of memory. Bounds are satisfied in all iterations.

- ***Sqp*** (sequence quadratic programming) algorithm is suitable for small and medium sized problems. It also satisfies bounds in all iterations.

- ***Active-set*** algorithm can be used for solving small and large problems and the main advantage is that it can make huge steps which accelerate the solving process significantly.

- ***Trust-region-reflective*** algorithm can be used for any problem but needs a gradient of the object function to be defined. It also needs only one type of constraints like minimum or maximum bounds or the linear equality constraints.

It is also possible to use a command *optimtool* which opens an application of the optimization with simple graphical user interface which helps with defining the parameters of the fmincon function.

## 7.2 Simulations and speed optimization

Measurement of custom driving cycles have been performed on a smartphone iPhone 5S by using myTracks app (freeware) which is a GPS data logger. The .gpx files are then processed by Matlab script EVOpti01 which is a function developed at the VTP Roztoky. This function parses the .gpx data and also reduces the amount of samples significantly. The default sampling rate of the application is 1 Hz and if stationary the logger is frozen till the phone starts to move again. EVOpt01 function also reduces the number of samples significantly but tries to keep the result data of the cycle as much as accurate to the original data. This reduction is very important otherwise the fmnicon function would have to process too many iterations, which would be very time consuming.

Following m-file EVOpt01_data_preparation selects the time, speed, distance and road angle data.

```
%   Custom driving cycle data - initial preparation script
%   Gathers parsed data from the EvOpt01 function.
%
%   Only parsed data to be optimized!
%------------------------------------------------------------

distance = s(:,5);        % distance data [km]
slope = s(:,9);           % road slope data in [degrees]
time = s(:,7);            % time [s]
speed = s(:,6);           % Speed [km/h]
Stoptime = max(time);     % Stop time of the simulation [s]
InitAltitude = s(1,3);    % Initial altitude (m)
%------------------------------------------------------------
```

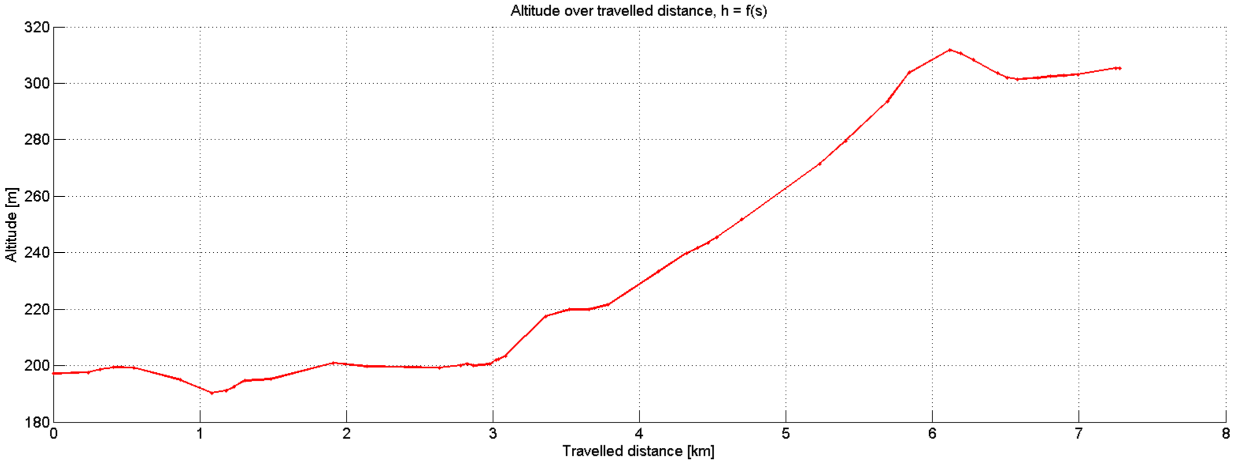
Selected variables are then used in the look-up tables which serve as data sources to feed the model. Now it is possible to run the simulation with a referenced speed measured in real traffic and respecting junctions, corners etc. and see how much energy was consumed.

As an example custom driving cycle has been measured in urban traffic with only 7.3 km travelled distance. EVOpt01 function managed to reduce the number of samples from 865 to 46 which are still sufficiently representing the real data and allow the following optimization to run much faster.

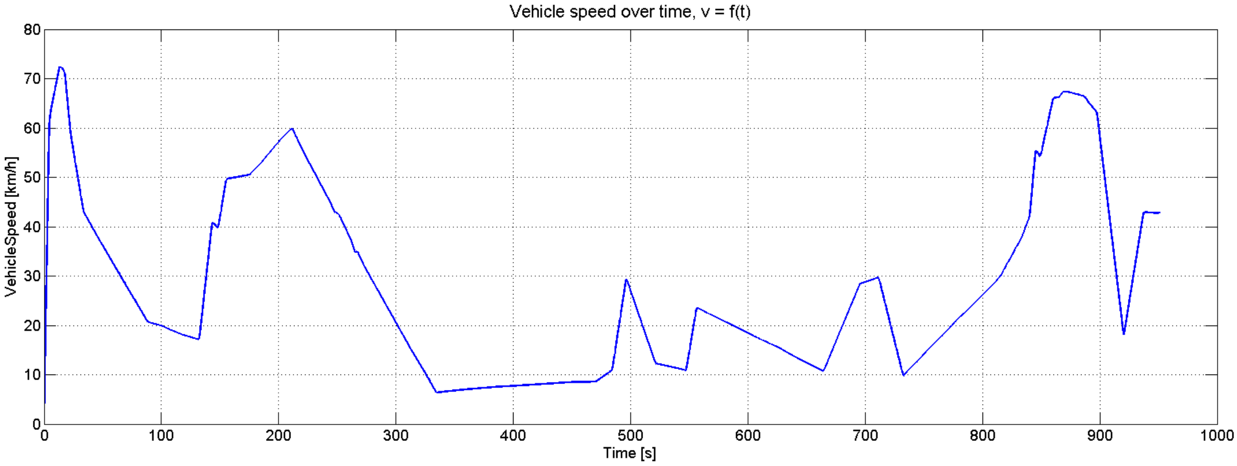
### 7.2.1 Simulation of measured driving cycle with road angle

Parsed data have been used for simulation in model VehDyn_v25 with EM efficiency calculation and the result energy consumption does take into account only the energy needed for propulsion (heating, electronics, lights and son on were not respected this time). There is a certain time deviation which is caused by no perfectly tuned PI regulator which represents the driver which is trying to follow the speed he is given and also that the vehicle used for measurement was totally different from the one which is represented by the model. Step time of the model is set to 1e-1 by default. The raw data are not relevant in that case. The results are shown below.

The calculated consumed energy was 1.31 kWh and the SoC at the end of the track was 94.54 % (MaxBatCapacity = 24 kWh).

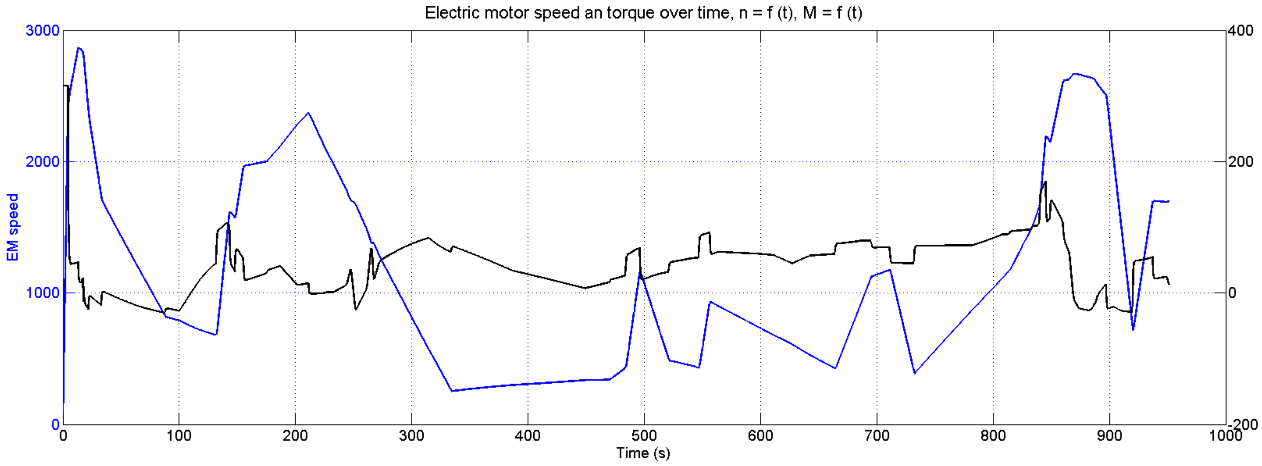


**Graph 7-1: Elevation profile of the driving cycle (GPS.gpx) used for simulation and follwoing optimization**

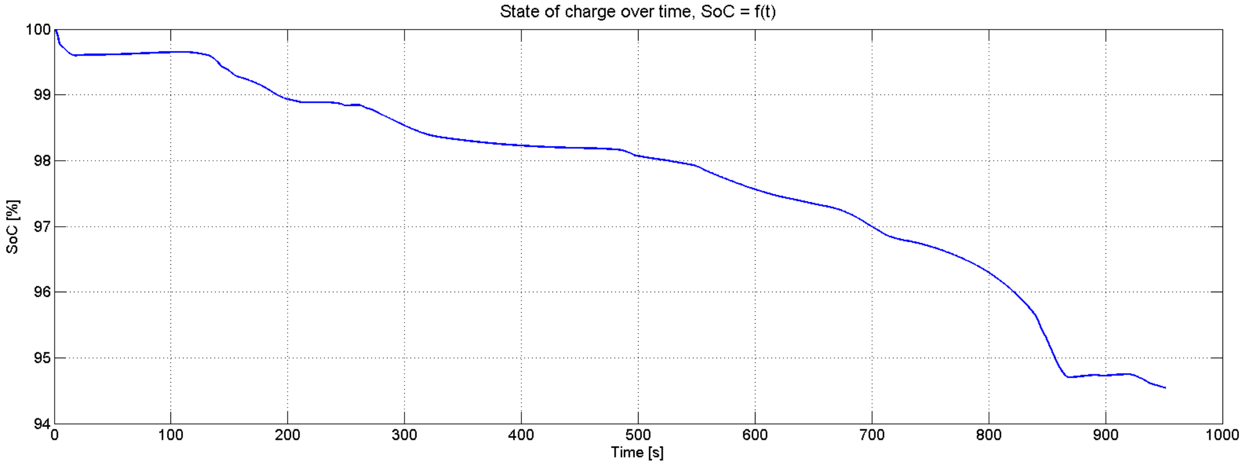


**Graph 7-2: Vehicle speed, non-optimized**

Time deviation is obvious because the original measured driving cycle lasts 1046 seconds while the modelled vehicle travels the same distance of 7.3 km in 951 seconds. This also can be caused by the myTracks app which automatically leaves out the points where the speed is zero so the car actually does not slow down in the simulation as it did in the real world.



**Graph 7-3: Speed and torque of the EM during the simulated driving cycle**



**Graph 7-4: State of charge of the simulated EV battery**

This time deviation seems to be a significant problem which would have to be solved by doing the measurement in the car that corresponds with the car modelled in the EV model. The speed points, which have its own time information in the original data, also have been taken at a specific travelled distance. The time deviation somehow breaks those connections between the speed, time, distance so it is not known if the car actually could be driving at the simulated speed on the precise part of the track. However the optimization of the simulated driving cycle could be still done.

### 7.2.2 Driving cycle optimization

After experimenting with the optimization function fmincon and its algorithms, it became clear that the settings and constraints of the function are crucial for getting some plausible results. Model VehDyn_v25 includes a pair of algebraic loops which seemed to cause problems but the optimization function could work even with them. So in the end the whole model, as it is described in the chapter 4.1, has been used.

Fmincon needs an object function for its functionality. The VehDyn_v25 model is called by this objective function and actually is the body of the calculation. Optimization function then checks the behaviour of the objective function and tries to input different combinations of the variables (speed points of the driving cycle). The constraints of the optimization, which limit the input values of the variables, are very important. We do not want to be told that the least energy consumption occurs when the car is barely moving so an interval of speed must be defined. These constraints are the linear ones and are marked as *ub* and *lb* (upper and lower bounds). Last constraint was a nonlinear equality marked as *ceq*. *Ceq* is defined in timeCondition function which ensures, that the optimized driving cycle will take the same time as the original one (simulated lasts 951.1 seconds). If this constraint was not defined, the optimization would just suggest to drive slower to lower the energy consumption.

timeCondition function:

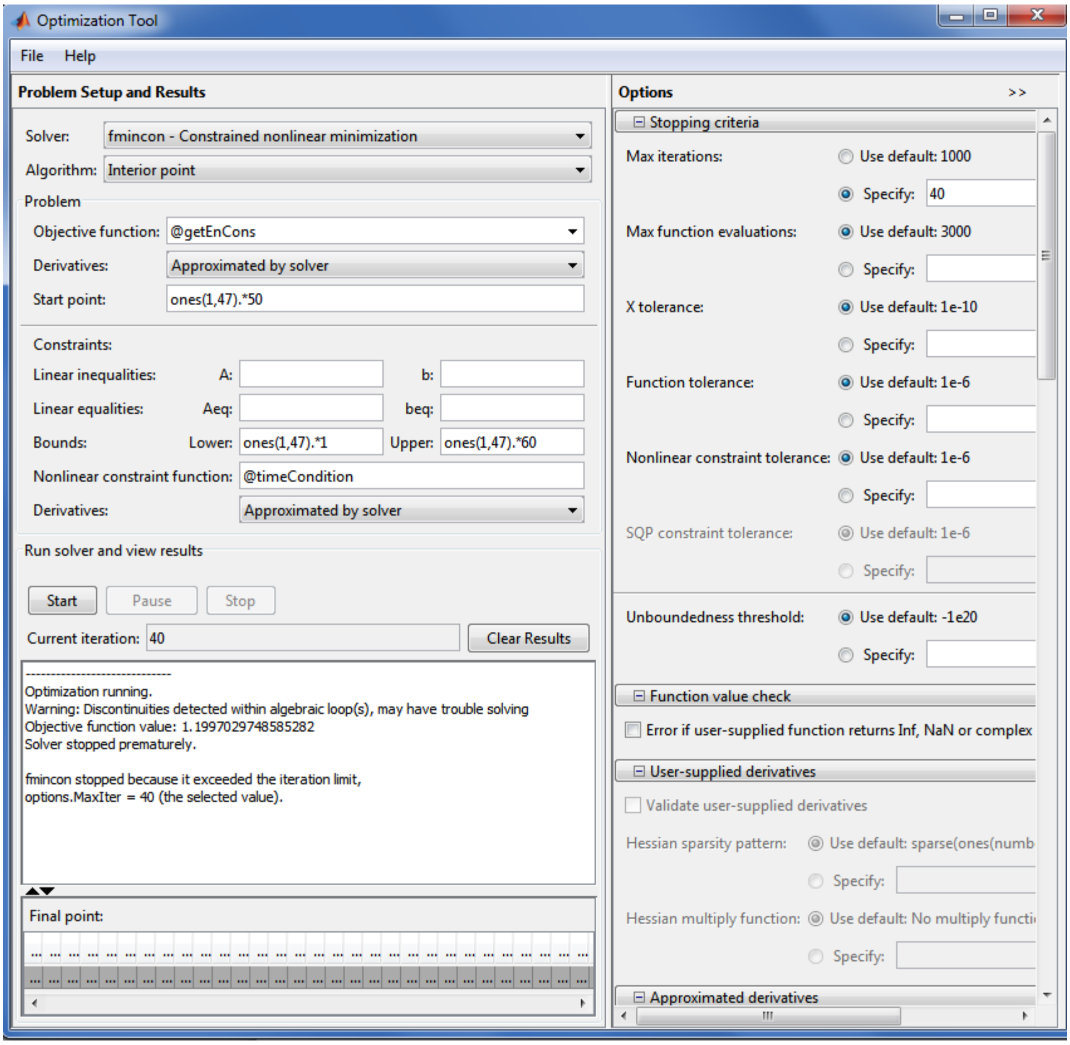
```
function [c, ceq] = timeCondition(Speedfcn)
    load('Input');  % loads saved workspace with the simulation
                      of non-optimized driving cycle
    Simout = sim('VehDyn_v25', 'SrcWorkspace','current');
    time=Simout.get('tout');
    time=time(end);
    c = [];
    ceq = [time-951.1]; % must be equal to zero
end
```

GetEnCons function serves as a transition between Simulink and Matlab workspaces so the optimization app (part of Matlab) can work with the model.

getEnCons function:

```
function consumption = getEnCons(Speedfcn)
    load('Input');  % loads saved workspace with the simulation
                      of non-optimized driving cycle
    Simout = sim('VehDyn_v25', 'SrcWorkspace','current');
    consumption = Simout.get('ConsEn').signals.values(end)
end
```

After running the simulation of the original driving cycle, an optimization part follows. We want to see, if the fmincon can adjust the speed points of the cycle based on the EV model so the energy consumption will decrease and the vehicle will still reach the end destination in the same time. The constraints were set from 1 to 60 km/h. That is the interval in which the optimization can change the speed points. The starting point is also needed to be defined in the optimization app so I thought that the constant 50 km/h could be just fine. It is just an estimation which can make the whole optimization process faster. Optimization tool can be found in the toolbar of Matlab (2013a) – Apps/Optimization. The vectors must have the same dimension as the time-speed structure of the parsed data of the non-optimized driving cycle. Interior point appeared as the most suitable algorithm for this application.



Solver: fmincon - Constrained nonlinear minimization
Algorithm: Interior point
Objective function: @getEnCons
Derivatives: Approximated by solver
Start point: ones(1,47).*50
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: ones(1,47).*1 Upper: ones(1,47).*60
Nonlinear constraint function: @timeCondition
Derivatives: Approximated by solver
Current iteration: 40

```
-----------------------------
Optimization running.
Warning: Discontinuities detected within algebraic loop(s), may have trouble solving
Objective function value: 1.1997029748585282
Solver stopped prematurely.

fmincon stopped because it exceeded the iteration limit,
options.MaxIter = 40 (the selected value).
```

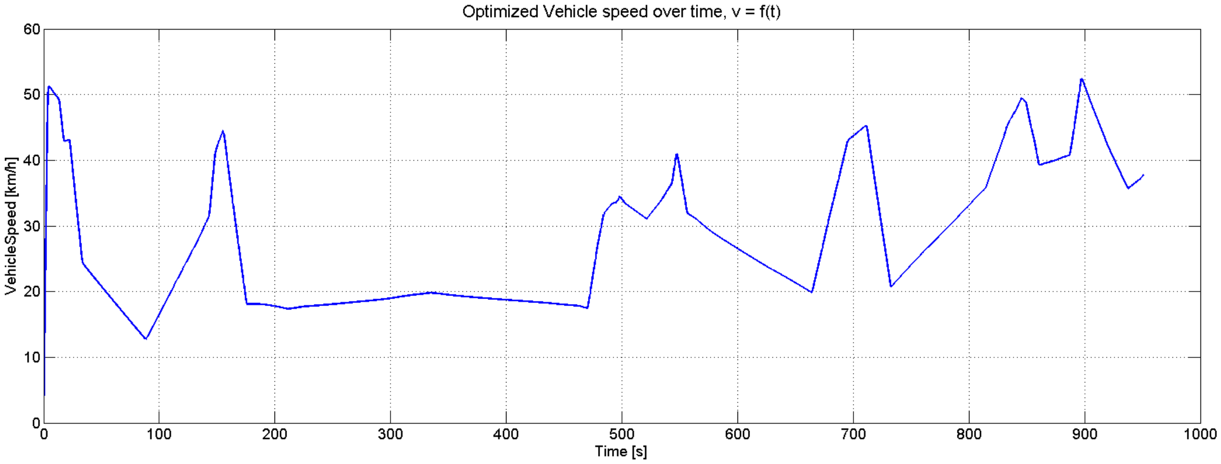
Max iterations: ○ Use default: 1000 ● Specify: 40
Max function evaluations: ● Use default: 3000 ○ Specify:
X tolerance: ● Use default: 1e-10 ○ Specify:
Function tolerance: ● Use default: 1e-6 ○ Specify:
Nonlinear constraint tolerance: ● Use default: 1e-6 ○ Specify:
SQP constraint tolerance: ● Use default: 1e-6 ○ Specify:
Unboundedness threshold: ● Use default: -1e20 ○ Specify:
☐ Error if user-supplied function returns Inf, NaN or complex
☐ Validate user-supplied derivatives
Hessian sparsity pattern: ● Use default: sparse(ones(numb ○ Specify:
Hessian multiply function: ● Use default: No multiply functi ○ Specify:

**Figure 7-1: Settings of the MATLAB Optimization Tool**

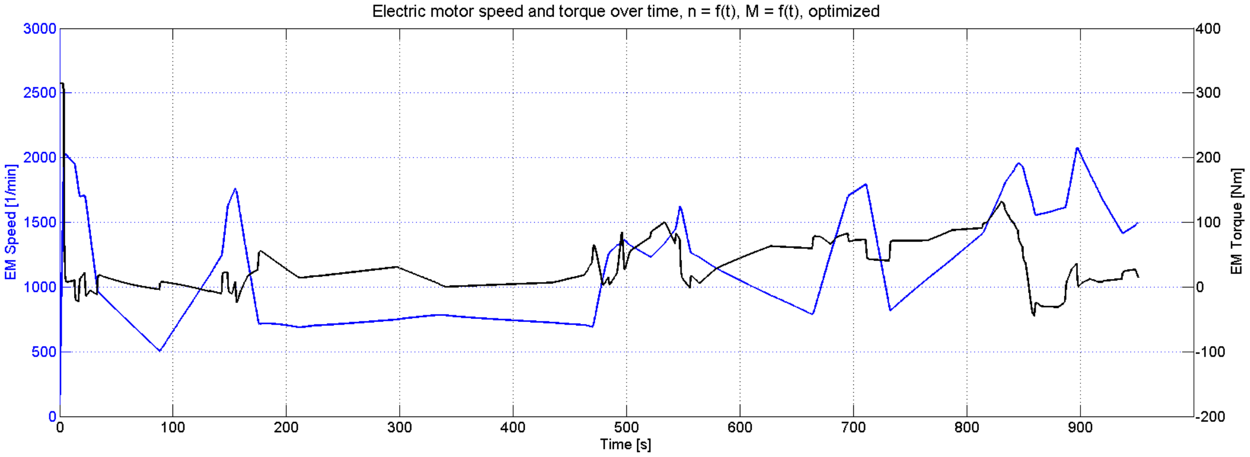
Iteration means that all speed points were tried out in a certain combination and fmincon searches for the combination that gives the minimum output as the consumed energy. The Max iterations parameter is set to 40 in this case, because Matlab can sometimes use a large amount of the RAM of the computer, which can cause the process to freeze. But it can be said that the more iterations the optimization do the better results will be.

I must mention that this is the earliest phase of testing these optimization algorithms and the whole process of 40 iterations took about an hour to finish. But the results are satisfying.

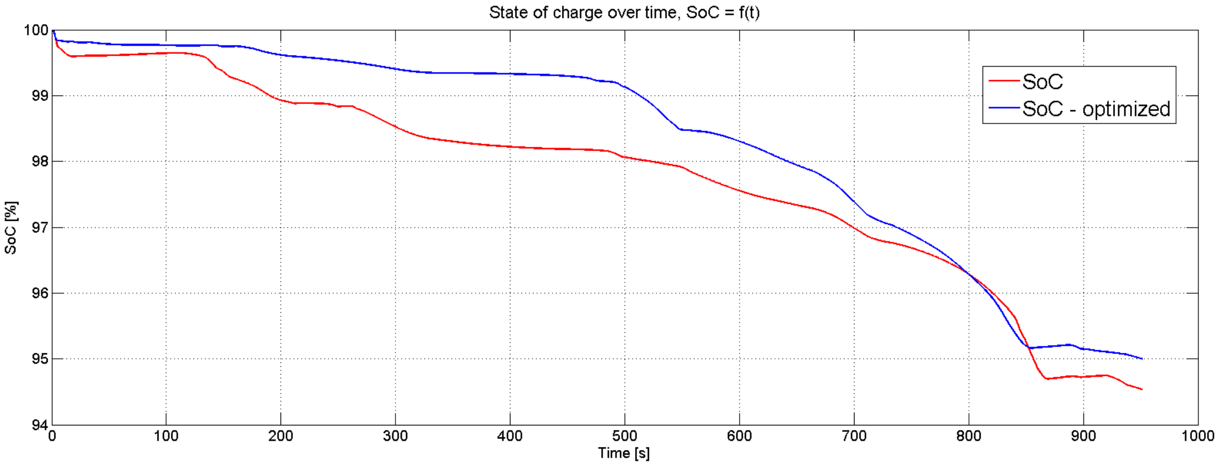
The calculated energy consumption was 1.2 kWh which is 0.11 kWh less than the original driving cycle. This means that the optimized driving cycle saved roughly about 8.4% of the energy originally consumed while keeping the same average speed of the vehicle.



**Graph 7-5: Vehicle speed, optimized driving cycle**



**Graph 7-6: Speed and torque of the EM during the simulated driving cycle, optimized driving cycle**



**Graph 7-7: State of charge of the simulated EV battery, comparison**

The optimization gave quite good results considering that the travelled distance is so short. However this energy saving is just theoretical and this driving cycle is just one of many. The optimized speed data could be feeding the adaptive cruise control or it can be somehow suggested to the driver on the dashboard of the EV. The optimization algorithm does not respect the traffic, corners etc. so it would always be up to the driver if the recommended speed is suitable for the current part of the track or not. But in my opinion this performed experiment shows that there is a certain room for improvement of the range of the EVs.

# 8. Conclusion

First part of this thesis is aimed to map the current technology of the electric vehicles and learn about the major factors which are most affecting the range of today’s EVs.

Second part is mainly practically based as it deals with the mathematical model of the electric vehicle and its implementation to the DS1103 controller. Designed interface board should provide a wide range of possible connections with the outer world but keeping a compact size at the same time. Primary use of the model and dSPACE controller should be in the VTP Roztoky and it was originally planned to do some physical measurements on the real electric drive too, but unfortunately the test-bench SW support is currently still in development. The optimization of the driving cycles is theoretically proven to work and I think that it shows that there can be even unconventional ways to prolong the range of the EVs.

The project of making a special test-bench suitable especially for the electric drives can expand also in many different fields of engineering and I think this thesis gives good directions in which the following steps should be taken. This applies mainly to the EV model which can of course be improved with many different individual models making the calculations and mainly the physical measurements more accurate in the future.

The idea of measuring custom driving cycles with road slope can also be improved by making a special data logger which could be easily installed into the EVs so the specific car type could be also represented by the mathematical model. However this solution would require actual electric vehicle for testing.

# 9. Bibliography

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# 10. Attachments

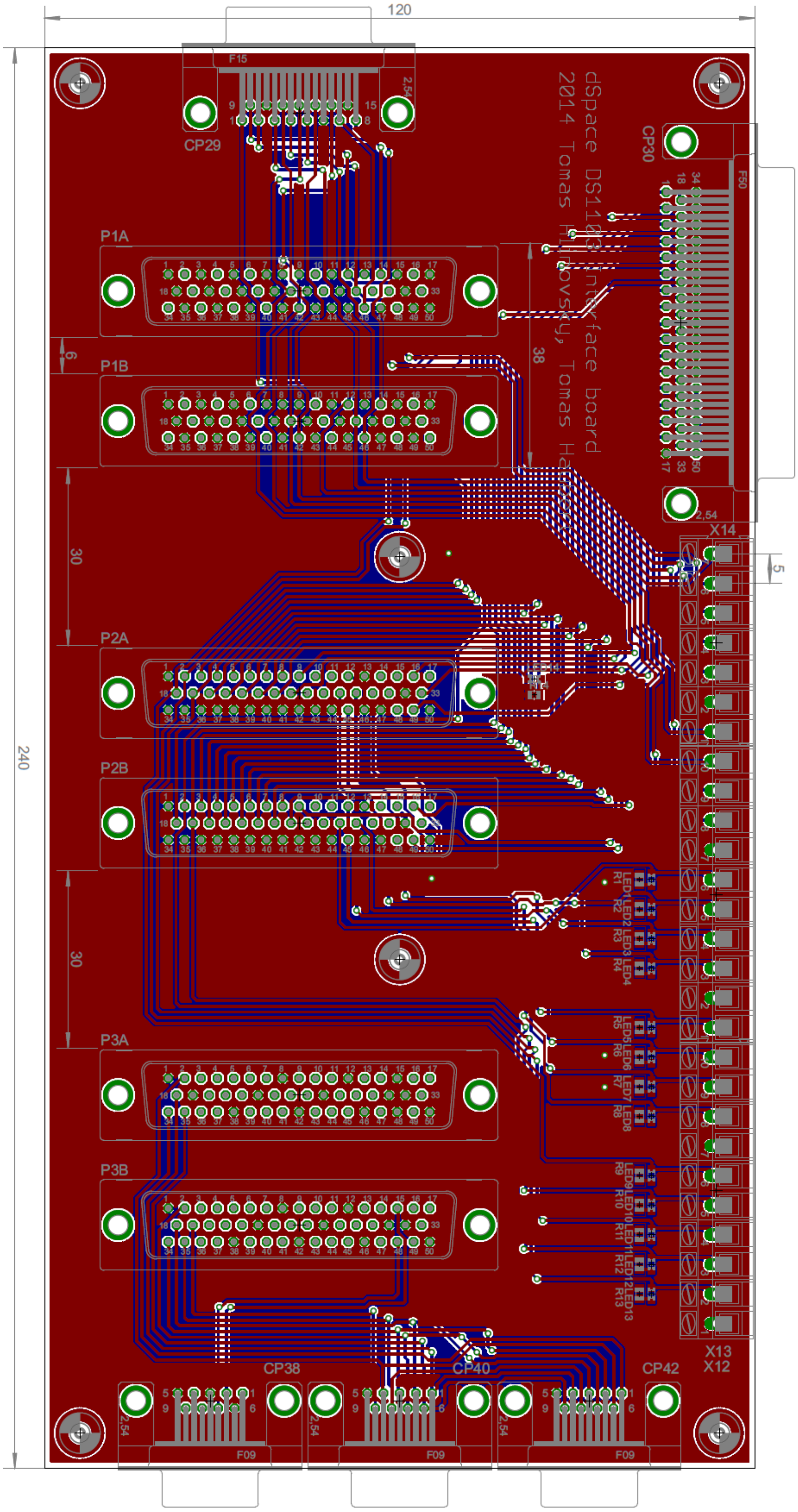

Figure 10-1: Interface board - design

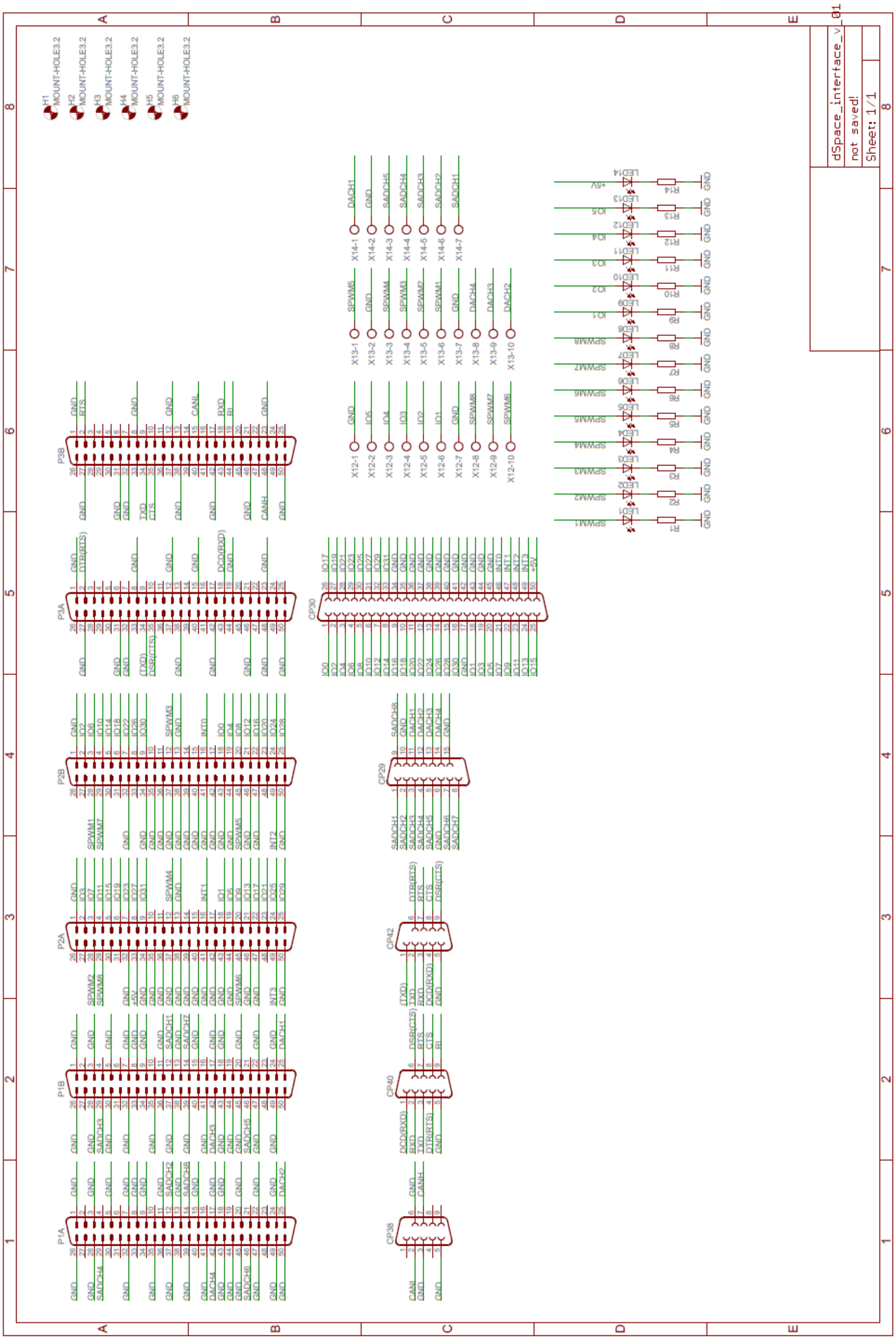

Figure 10-2: Interface board - pin connections

## 10.1 Content of the attached CD

**Model version for ‘normal’ (NEDC, Artemis) driving cycles:**
(CD\EV_model\VehDyn_NEDC)

- VehDyn_v25_NEDC.slx
- VehDynInit_v6_DCycle.m (Init. m-file – page 44)
- NEDC.m (NEDC driving cycle data)
- Eff_map_power_MotorData.xlsx (EM max power data)
- Eff_M_n_data_table.m (EM efficiency data)

**Model version for custom driving cycles:**
(CD\EV_model\VehDyn_v25(MainModel))

- VehDyn_v25.slx
- VehDynInit_v6.m (Init. m-file – page 44)
- EVOpt01_data_preparation.m (selection of the parsed GPS data – page 65)
- Eff_map_power_MotorData.xlsx (EM max power data)
- Eff_M_n_data_table.m (EM efficiency data)

**Functions for optimization application:**
(CD\EV_model\VehDyn_Optimization)

- getEnCons.m
- timeCondition.m
- Input.mat
- SpeedOptied_Data_GPS_sameLength.mat (Optimized driving cycle data – chapter 7.2)

**Driving cycles data**:
(CD\EV_model\DrivingCycles)

- saved .mat files with measured custom driving cycles

**ControlDesk project with dashboard layout:** (CD\EV_model\ControlDesk_project)

**Eagle project of the Interface board:** (CD\EV_model\Interface_board)

**Master’s Thesis .pdf file:**
CD\Optimal_Control_of_Mathematical_Model_of_the_Electrovehicle.pdf