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Evaluation of a BLDC drive line and energy analysis for an electric Ultra Light Vehicle

Master of Science Thesis

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Göteborg, Sweden, 2011

Abstract

To achieve a better understanding of the vehicle a test bench was built using the same battery, controller and motor as the vehicle. With this test bench tests were conducted so that efficiency for the controller and motor could be measured for different speeds and torques. The result of this measurement gives an indication that the motor should preferably be driven at a speed between 250-600 rpm to achieve the highest efficiency. After the efficiency for the motor and controller was known it was used in a simulation model to estimate energy usage for the whole vehicle.

When all parameters and variables was gathered several simulations was run. All simulations where run with the ECE-15 drive cycle since this is commonly used in the automotive industry and also makes it easier to compare the results with other vehicles.

The result from each simulation, given in section 0, is shown with three values; energy usage [Wh/km], drivability [%] and distance [km]. Drivability is a comparison between the vehicles speed and the speed given by the ECE-15 drive cycle. If the vehicle speed doesn't match the drive cycle speed, due to motor limitation, its ability to perform isn't fully satisfied and this indication is given by its value of drivability. Distance is how far the vehicle can go with the given parameters and energy usage is basically how much energy the vehicle would consume per kilometer for the ECE-15 drive cycle. It is rather obvious that adding weight or having a different air drag coefficient and rolling resistance will affect the vehicle's performance and energy usage. But it's also noticeable how the battery's inner resistance or changing the auxiliary power, mostly consisting of lights, will also affect the energy consumption. Decreasing the inner resistance with 40mΩ and reducing auxiliary power with 50W will almost give an additional 6km driving distance.

All simulations are based on a case setup, given in section 4.13, which gives the values of 47.5Wh/km, 99.96% drivability and a distance of 28.58km. Since the vehicle is very light an increase of 2 passengers will change the values to 65.7Wh/km, 98.71% drivability and 20.68km.

Preface

Clean Motion was founded in 2010 with the idea of producing a three person BEV for urban areas and small communities. Their first prototype was created in the beginning of 2011 and has since then been developed before going into production in the first quarter of 2012.

The goal of the first product is to build something that is both practical and fun to drive, have no pollution using an electric driveline and at the same time be affordable. None of these challenges are easy to meet and therein lays the challenge of building a commercial BEV. It's also in the development phase this project comes in hand since knowing the energy usage will help in the process of deciding which parts need more development.

There are several people who have helped me with both ideas and information making it possible to finish this master thesis. At Chalmers I would like to thank Ali Rabiei who has been a great supervisor during the whole process from the beginning to the end. I also would like to thank Torbjörn Thiringer for being my examiner.

I also would like to thank Göran Folkesson, Peter Öhman, Hans Folkesson and Peter Helmroth for inspiration and giving me the chance of doing my master thesis with Clean Motion. I also would like to thank Magnus Nilsson at Clean Motion for helping me with the practical work of building the test bench used in the thesis.

Last but not the least I would like to thank Oskar Josefsson and Emma Grunditz at Chalmers for helping me with ideas.

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1. Introduction

If you read this you probably already know that the battery electric vehicle (BEV) has been around for more than a 100 years. Before the eminence of the internal combustion engine the BEV mainly competed with urban consumers not having the need for far travelling. Though due to the loss against vehicles with internal combustion engine the BEV has almost been nonexistent after the 1920's except for some commercial vehicles such as forklifts and golf carts and they have a different purpose than just personal transport.

During the oil crises in the 1970's the BEV for personal transport had a short revival but it wasn't until 1990's it really started to reemerge, and this partly because the state of California's interest pushing towards more environmentally friendly vehicles [1]. The environmental awareness combined with high oil price is probably the biggest reason for the increased interest of BEV's during the 21st century. This gets even more obvious since some governments in North America, Europe and Asia gives subsidies to consumers buying a low/non polluting vehicle [2][3][4][5].

All BEV's have in common to be as energy efficient as possible since this will reduce the need for a more power full electric motor and a bigger battery. To achieve this knowing where the energy is consumed is essential. The energy consumption can of course be measured with a power meter while driving the vehicle but this will only give the total consumption. By simulating the vehicles energy usage in each step in both the drive line and traction losses, more knowledge is gained. This information can then be used to improve the vehicles energy usage, and therefore become more efficient, by developing the parts that consume the most energy.

1.1 Purpose of the project

The purpose of this project is to do an energy analysis on Clean Motion's upcoming product known as the Z-Bee. This will be done by creating a simulation model evaluating the main components; motor, inverter and battery. It will also be used to analyze the impact of different parameters used as inputs for the simulation model.

The goal is to understand which impact each component has considering the energy usage. The model will also evaluate the impact of other parameters such as air drag coefficient, friction coefficient, weight, etc.

Following questions will be answered in the results of this report. This will also help the reader to understand the problems that this project is trying to solve. What happens if two motors are used instead of one? How much more energy is used when the vehicle is fully loaded compared to only having one passenger? What is difference using a battery with a high or low inner resistance? How big is the effect of having a low or high air drag coefficient?

2. The electric vehicle

The basic design of the Z-Bee reminds a lot of the three wheeled vehicle known as auto rickshaw or Tuk-Tuk. These vehicles are mainly used as taxis and can often be found in urban areas in India, Thailand and other places in Asia. But here the resemblance between the Z-Bee and the auto rickshaw stops. When a new auto rickshaw weighs 435kg and use a 2 or 4-stroke combustion engine [6] the Z-Bee is a pure BEV with the goal of weighing a third of the weight. A comparison between the two vehicles is shown in Figure 1.



Figure 1: Photo of auto rickshaw and concept design of the Z-Bee.

So why build a vehicle that weighs almost one third of a traditional auto rickshaw? As you probably already know a vehicles energy consumption is directly related to its weight. Besides the lower weight the less power is needed to accelerate and maintain speed. A less powerful motor, which is generally lighter, also needs less energy which means longer driving distance per energy unit.

All the reasons mentioned above are very important for a vehicle only using a battery as the energy source. Batteries are both expensive and limited in their energy storage capability. With a light vehicle it makes it possible for a BEV to achieve enough driving distance and cut cost to make it consumer friendly.

Except for the vehicle's weight the front area and air drag coefficient are also important. All these three factors will all affect the vehicle's energy consumption and will be evaluated in the simulation model created in this project.

So how is the drive line being built? As stated earlier the vehicle has three wheels; one front wheel and two rear wheels. Instead of having normal back wheels they are replaced with electric hub motors (see section 2.2.3). Each motor is connected to an inverter that controls the energy flow coming from the battery. Both inverters and motors are rated for the nominal voltage of 48 and they are connected to the battery. Except for the inverters a DC-DC converter is connected to the battery supplying the vehicle's lights, horn and dashboard. Figure 2 shows the basic setup of the driveline.

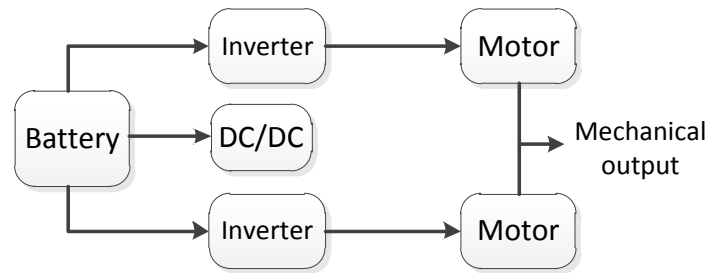


Figure 2: Driveline setup including battery, inverters, motors and DC-DC converter.

The figure above shows the energy flow going from the battery to the mechanical output. Though if regeneration is used the energy flow will be bidirectional and this is further explained in section **Error! Reference source not found..**

2.1 Similar vehicles to the Z-Bee

Even if the BEV has a long history it's mainly been used for specific areas such as forklifts and golf carts. Instead the idea of using a BEV as the main vehicle for personal transport has been very limited until the last 10 years. Though some BEV's are in production they are still very few running on roads today. Nevertheless a number of companies, both small and big, see the potential in the BEV. The following three subsections contain some of the vehicles that reminds of the Z-Bee being somewhere between a working prototype and production.

2.1.1 Electric Thai Tuk Tuk - Tuk Tuk Factory

The Tuk Tuk Factory is a Dutch company basically copying the traditional Tuk Tuk (autorikshaw). Its design reminds very much of vehicles found in Thailand and India with the difference of having an electric driveline instead of using a 2-stroke combustion engine. It has a capacity for three passengers plus driver with a range of 70-80km. The power rating is 6kW giving the 750kg vehicle a maximum speed of 50km/h [7].

2.1.2 Smite - Vehiconomics

Vehiconomics is a Stockholm based company with the goal of making energy efficient ultra light vehicles (ULV's). Their first product Smite has a design reminding of the Messerschmitt KR 200. It has capacity for two passengers and the range of somewhere between 80 and 120 km depending on the size of the battery which will be 3-8 kWh. The total weight is below 300kg and depending on the motor rating, which will be 4-7kW, the maximum speed will be up to 90 km/h [8][9].

2.1.3 Arcimoto SRK - Arcimoto

The Arcimoto SRK reminds more of Smite than the Z-Bee with two front wheels and one back wheel. The motor has the peak power of 62kW giving the vehicle a top speed of 105km/h. The curb weight is 770kg and depending on the type of battery the range will be between 64 and 128km on a full charge [10].

2.2 Main components

The vehicle being built by Clean Motion will have the most basic electric drive line containing battery, controller/inverter and electric motor. There will of course be lights and horn included in the drive line but they will all be included as an extra power drain known as the auxiliary power. Therefore focus will be on the three main components that are all described in further details in the sections below.

2.2.1 Battery

Using a battery as the main energy source in a vehicle is challenging due to limitations in its performance. In an ideal world the battery would have high energy density, high power density, low inner resistance, fast recharging and above all not be too expensive. This type of battery does unfortunately not exist and instead a choice has to be made between the commercial batteries available today. For a BEV it's important to have a battery that both have high energy and power density.

The energy densities for some of the more common rechargeable batteries are given in Figure 3 below. As shown their energy densities vary depending on the type of battery. But except for the energy density they also have different characteristics such as maximum current output, discharge cycles and inner resistance.

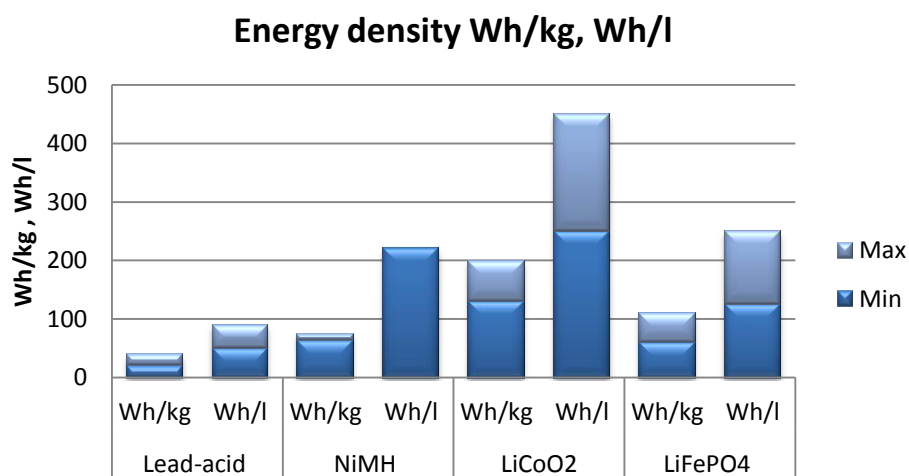


Figure 3: Wh/kg and Wh/l for some of the most common rechargeable batteries [11].

According to Figure 3 the best suitable battery would be the Lithium Cobalt Oxide (LiCO_2) battery since it has the highest potential energy density. But according to [12] the Lithium Iron Phosphate (LiFePO_4) battery can handle higher temperatures and overcharges without having the same risk of exploding or causing fire compared to the LiCO_2 battery. The LiFePO_4 also have more discharge cycles before reaching 80% of full capacity.

The other two battery types, Lead-acid and Nickel Metal-Hybrid (NiMH), can also be used in a BEV but they both have lower energy density and shorter life time than LiCO_2 and LiFePO_4 .

2.2.1.1 Battery used in the simulation

The battery type used in the Z-Bee is a LiFePO_4 and as mentioned in the previous section a lower energy density is met to achieve a safer battery having a longer life cycle. The backside of using this battery is the increase of weight to enable the same energy content. The battery used in the vehicle is shown in Figure 4 below.



Figure 4: The LiFePO₄ battery the simulation model is based upon.

The size of the battery used has a width of 160mm, height 214mm and depth 310mm. This gives the total volume of 0.0106m³ which is equal to 10.6 liters. Weight of the battery is 18.2kg and it has a nominal voltage of 48V and nominal capacity of 30Ah. According to the nominal values the energy content should be 1.440kWh. During a discharge test, see section 3.2.1.1, the real energy content was measured to be 1.698kWh with a capacity of 32.88Ah when a low discharge current was used. Even if the real energy content was higher the reader should keep in mind that the energy in the battery and energy provided by the battery is not the same. The energy provided by the battery highly depends on the discharge current and inner resistance due to I^2R losses.

Table 1 below gives a summary of the rated values for the battery.

Table 1: Summary of the rated values for the battery used in the simulation model.

Rated voltage	Rated capacity	Energy	Weight	Volume	Wh/kg	Wh/l
48V	30Ah	1.440kWh	18.2kg	10.6l	79Wh/kg	135.8Wh/l

2.2.2 Inverter and the Controller

The inverter is used to convert the DC voltage, from the battery, to a three phase voltage for the electric motor. This is possible by using MOSFETs, connected in a way shown in Figure 5 below switching with a frequency of 16.6kHz. The inverter can also handle all four quadrants making it possible to generate energy when the motor is used as an electromagnetic brake.

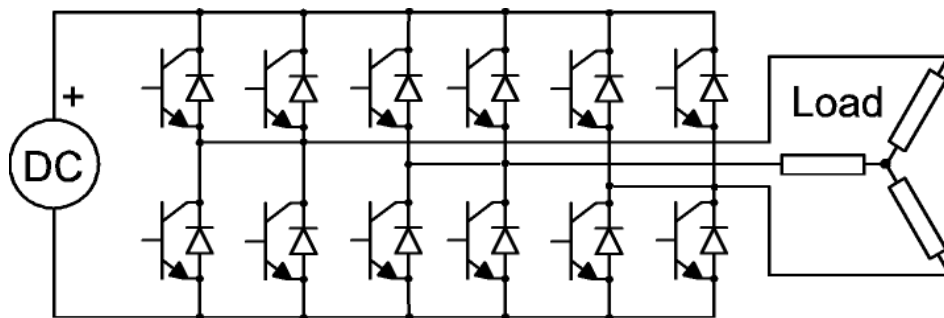


Figure 5: The setup of MOSFET's for the inverter that was used. Each phase have 4 MOSFET's making the total number of 12 MOSFET's.

The inverter used has the model number KEB48301 and is produced by the company *Kelly Controls, LLC*. The inverter, shown in Figure 6, is designed for a 48V BLDC motor with the power of up to 3kW.



Figure 6: 48V 150A 3kW Controller/Inverter model KEB48301.

The inverter also needs a controller switching the MOSFETs and this unit is combined inside the inverter. Except from handling the MOSFETs the controller also have other functions and some of them are given in Table 2 below.

Table 2: Some of the programmable functions for the KEB48301 inverter.

Function	Choice
Control mode	Torque, Speed or Balanced
Maximum battery current	0-100%
Maximum motor current	0-100%
Min/Max battery voltage	18-90V
Regeneration <ul style="list-style-type: none"> Release throttle Brake switch Brake sensor 	0-50% Fixed value 0-50% Fixed value 0-50% Variable
Motor temperature	Maximum temperature in Celsius

All values given in Table 2 can be changed by programming the controller using a standard PC and a USB cable. The ability of programming the inverter makes it possible to change some of the essential parameters improving the drive line for its specific use. For example the battery fuse might break due to over current and this can be avoided by limiting the current to the controller.

As for the driver he/she can control the inverter by giving three different signals, throttle, regeneration and reversing. The throttle signal will apply current to the motor making it accelerate. The regeneration signal can either be digital or analogue, braking the vehicle and transferring energy back to the battery. The reverse signal will tell the inverter to work in the 2nd and 4th quarter making it possible to reverse the vehicle.

As mentioned in this section the inverter and controller are combined in one unit. To simplify matters in this report the combined unit will onwards be known as the *inverter*, even if the controller is the topic.

2.2.3 Hub motor

There are two common types of motor setups in a BEV. Either the motor is connected to a shaft that may be combined with a gear box and then connected to the wheel/wheels directly or through a differentiator. The other setup instead uses a hub motor either on one of the wheels or on several wheels.

The Z-Bee uses the second setup replacing both back wheels with two hub motors. The hub motors are purchased from *Kelly Controls LLC*, though they are only the distributor and the manufacture is unknown and therefore information about the motor is rather limited. The hub motor used can be seen in Figure 7 below.

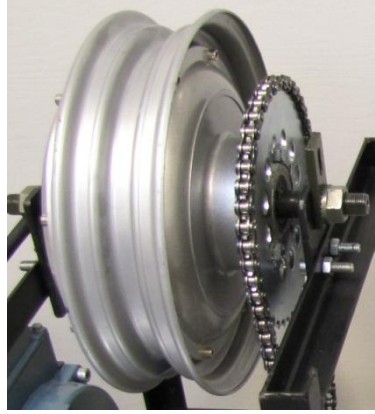


Figure 7: 48V 1.5kW Hub motor. Photo taken from test bench further explained in section 3.1.1.

The hub motor is a brushless DC-motor (BLDC) with a nominal power of 1.5kW and the rated voltage is 48V. It is mounted with 3 hall elements that are used by the inverter to measure the rotor position. According to the manufacturer the number of pole pairs is 17. However while measurements where conducted on the motor the number of pole pairs where calculated to be 23. This was achieved by measuring the electric frequency and the motor speed at the same time. The following equation was used to calculate the pole pairs.

$$p = \frac{60f}{n} \quad (2.1)$$

In the equation above f is the electric frequency (Hz) and n revolutions per minute (rpm).

Kelly Controls provide some performance data and a summary of the information is given in Table 3 below. This data can be used to extract an efficiency equation based on torque and speed. Though the data only gives one speed (RPM) per torque value which makes it hard to predict the efficiency for all speeds and torques the motor can apply.

Table 3: Performance data for a 48V, 1.5kW hub motor provided by Kelly Controls, LLC. [13]

Torque (Nm)	Voltage (V)	Bus Current (A)	RPM	Input Power (W)	Output Power (W)	Efficiency (%)	Speed (km/h)
0.1	48.07	4.412	744.4	212.1	5.56	2.6	53.5968
1	48.03	5.931	740.3	284.9	77.5	27.2	53.3016
...
38.3	46.63	55.72	546.6	2598	2191	84.3	39.3552
...
87.3	46.55	54.45	91.2	2534	834.1	32.9	6.5664

Instead of using the performance data an efficiency test was conducted using a test bench. The implementation of this test and the results is further explained in section 3.1.

2.3 Drive cycle operation for the BEV

The reasons why a drive cycle is used as an input is the results it gives by testing how the vehicle handle accelerations and also regeneration while braking. It also gives an opportunity to visualize results by plotting outputs gained by the model.

The main drive cycle used is called ECE15 and is generally used for light duty vehicles in Europe. It's a short drive cycle that includes three accelerations and four decelerations with the total distance of 0.9737km. The drive cycle can be seen in Figure 8 below [14].

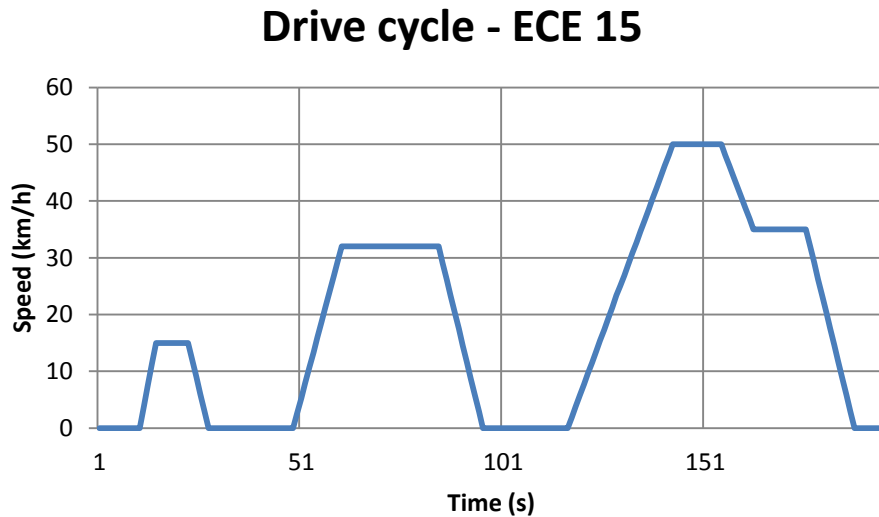


Figure 8: The ECE 15 drive cycle used for light vehicles in Europe.

The second drive cycle is called Braunschweig and was created to simulate bus driving in a city. Even if the drive cycle was meant for simulating city bus driving it is also suitable for the Z-Bee. It's more realistic than the ECE 15 drive cycle containing a total of 29 stops during a time of 29 minutes. Since there are a lot of stops during the drive cycle it's suitable to test the difference of using regeneration or not and to visualize changes in state of charge (SOC). The drive cycle, shown in Figure 9 below, has a total distance of 10.594km [15].

Drive cycle - Braunschweig

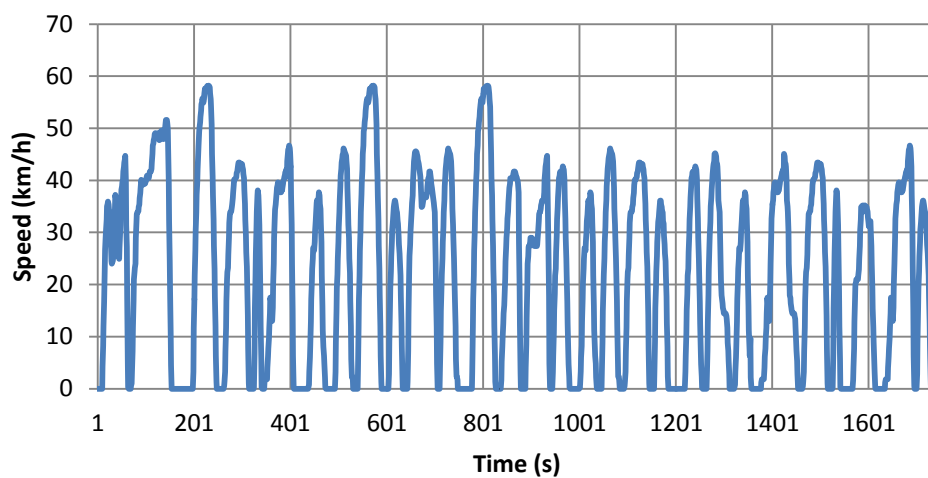


Figure 9: The Braunschweig drive cycle. Originally created for city bus driving.

The Z-Bee will be registered as an EU scooter and therefore both drive cycles will be capped at 45 km/h.

3. Modeling the main components

The model for the motor and the inverter is an efficiency map depending on torque and speed the vehicle has. So for each torque and speed relation the efficiency is known and therefore the losses, or energy usage, for the motor and inverter can be calculated. The efficiency for the motor and inverter is explained in section 3.1 and how the losses are calculated can be read in section 4.12.

For the battery a different model is used where the voltage changes during discharge. The voltage model is based on measurement conducted while discharging or charging the battery with a certain load. This is further explained in section 3.2.

3.1 Motor and inverter efficiency

The motor efficiency is preferable based on the torque and speed demanded by the vehicle. This can either be achieved by creating a look-up table or knowing enough about the motor so that an equation is used calculating the power losses based on torque and speed can be used.

To create a look-up table the motor will be tested using a torque sensor and a speed meter. The work process is based on measuring the efficiency for a fixed speed with different torques. Then gradually the speed is increased and at the same time measuring the efficiency for different torque levels. This will finally give a 3D matrix with torque and speed as inputs and efficiency as an output.

Another solution is to create a function where the efficiency depends on torque and speed. An example of this could be to calculate the power into the motor,

$$P_{in} = P_{out} + P_{losses}, \quad (3.1)$$

by using a function for the P_{losses} that is equal to

$$P_{losses} = P_{mech.losses} + P_{iron.losses} + P_{Cu.losses} \quad (3.2)$$

where the mechanical losses is relatively constant, the iron losses are approximately in relation with speed and speed squared and the copper losses are in relation with torque squared.

Both solutions, mentioned above, were carried out but in the end the lookup table was decided to be the most suitable solution. Since the values are based on real measurements this should be more realistic. Though when the efficiency was measured, the inverter was included for creating a lookup table containing efficiency for both the motor and the inverter.

3.1.1 Test bench

In order to measure the efficiency for each torque and speed relation a test bench had to be built. The test bench reminds a lot of how the drive line is built in the Z-Bee having the same battery, inverter and hub motor. Though different loads had to be applied to the motor and this was achieved by having a mechanical connection between the hub motor and a DC motor acting as a load. The DC motor is then speed controlled making it possible to apply different torques and at the same time maintain the wanted speed. In this way the wanted torques could be measured at different speeds making it possible to create a lookup table giving the efficiency by knowing the torque and speed.

Since the rotor is on the outside of the hub motor a direct connection with the DC motor wasn't possible. Instead a chain with two cogs were used to achieve a link between the hub motor and the

shaft that was connected to the DC motor. This is best explained by looking at the photo in Figure 10 below.

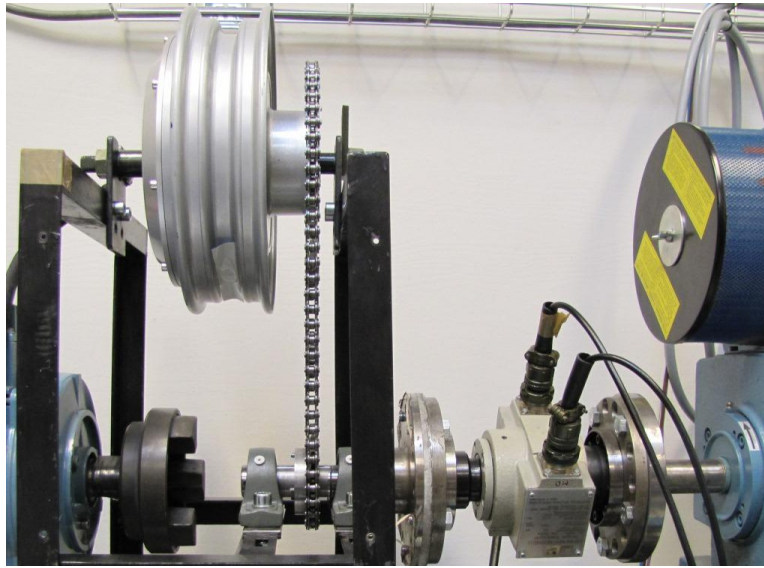


Figure 10: Part of the test bench showing how the hub motor is connected to the shaft with a chain. Part of the DC motor is shown in blue to the right.

To measure the output power from the hub motor a torque meter was connected in series with the shaft. The torque meter is the grey device with two cables connected, shown in Figure 11 below, and the optic speed meter is placed just below the adapter connecting the torque meter with the DC motor.

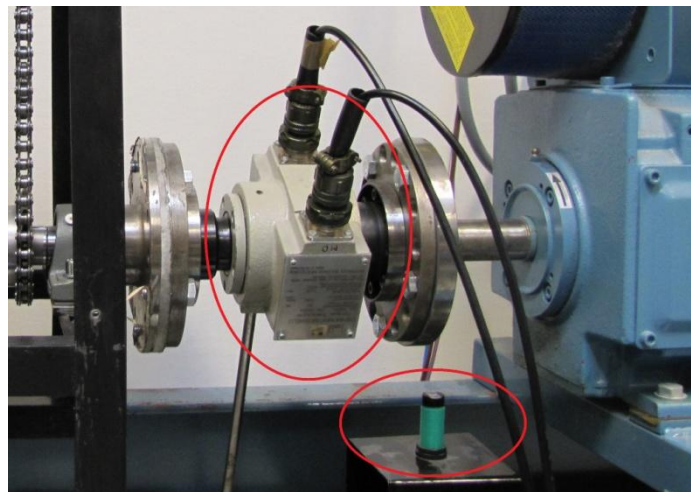


Figure 11: Torque and optic speed meter used in the test bench.

For the optic speed meter to work a reflected tape is placed on the rotating shaft making it possible to register revolutions per minute (rpm). This is then converted to angular speed using the equation below. The angular speed is then used to calculate the power output from the motor.

$$\omega = \frac{rpm 2\pi}{60} = rad/s \quad (3.3)$$

The combination of using a torque meter and an optic speed meter makes it possible to calculate the output power by multiplying the torque with the speed in radians per second.

$$P_{out} = \omega T \quad (3.4)$$

Simultaneously as the torque and speed is measured the input voltage and current is also measured with a power meter. The whole schematic setup, containing all components, is shown in Figure 12 below.

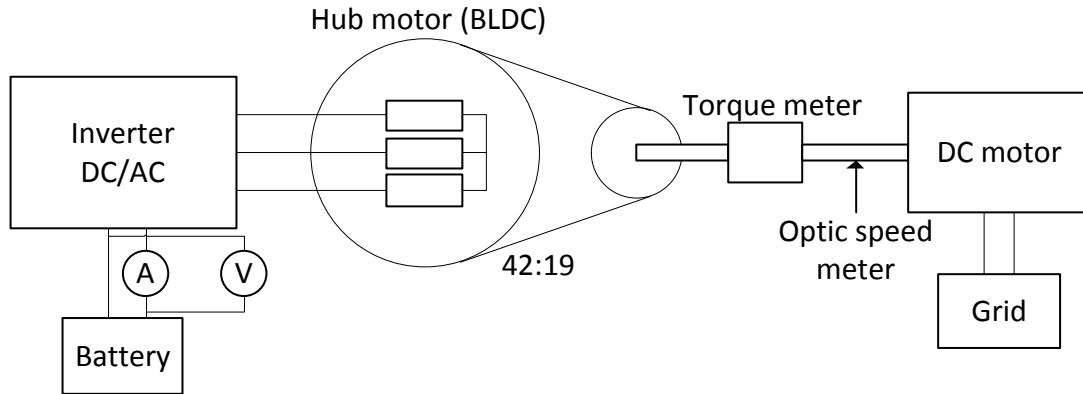


Figure 12: Schematic overview for the test bench.

Some components between the DC motor and the Grid have on purpose not been considered to simplify the schematic in Figure 12 above. The most important knowledge about the DC motor is that its speed controlled and therefore making it possible to run the hub motor with different torques without changing the speed.

3.1.2 Calibration of torque meter

The torque meter used in the test bench is of the model T30FN manufactured by the German company *HBM*. It has a nominal speed of 3000 rpm and nominal torque of 100Nm and therefore not being a limit for measuring the hub motor. Before measurements were started a calibration was conducted. By mounting a metal bar on the torque meter extending 50cm on each side, weights could be applied as shown in Figure 11 below.



Figure 13: Calibration of torque meter using a metal bar and two weights of each 5kg.

Weights of 5kg and 10kg were placed on one end of the metal bar to compare if the torque meter gave the same result as the mechanical equation would give. The difference between the calculated torque and the measured torque is given in Table 4 below.

Table 4: Results for calibrating the torque meter.

Test	5kg	10kg	5kg	10kg
1	24.81	49.20	0.00%	0.16%
2	25.07	49.20	1.05%	0.16%
3	25.00	49.20	0.77%	0.16%
4	24.85	49.22	0.16%	0.20%
5	24.84	49.17	0.12%	0.10%
6	24.86	49.38	0.20%	0.53%

The second and third column show the measured torque in Nm and the last two columns show the difference between the measured and the calculated values. Even if the difference is very small it's clear that the torque meter shows a slightly higher value than the calculated one. Even if one number shows a fault of 1.05% the conclusion of the calibration was to reduce the measured torque with 0.20%.

3.1.3 Measurements

As mentioned in section 3.1.1 there are four values measured for each data sample. These values are then used to create two matrixes and a speed vector; one matrix with the measured torques, one matrix containing the calculated efficiency and one vector containing the chosen speeds.

Since the DC motor can be speed controlled, using the optic speed meter as input, the speed was first set to a certain value before applying torque from the hub motor. The chosen speeds for the DC motor ranged from 100 rpm to 1550 rpm. For each set of speed different torques where applied between 1Nm up to 30Nm. This was done by using the equipment shown in Figure 14 below.

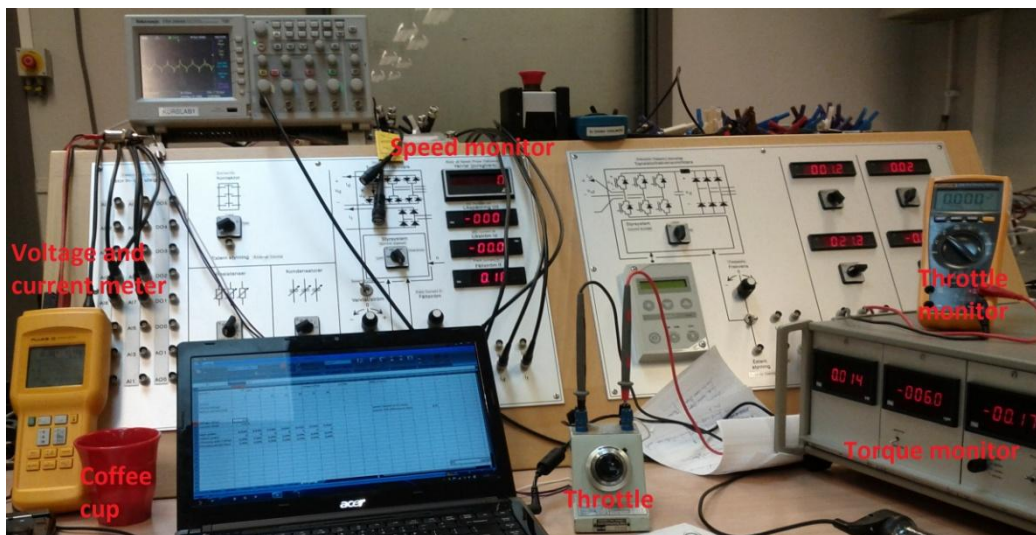


Figure 14: Equipment setup used to monitor the test bench.

Voltage and current was measured using a Fluke 39 Power Meter. The torque was measured using a HBM T30FN and the speed using an optic speed meter already in place in the lab.

First the speed was set with the help of the speed monitor. Then the throttle was used to apply a certain torque which was monitored with the torque monitor shown to the right. When wanted

torque was applied it was logged together with the input voltage and current. Knowing these four values the efficiency is calculated by using the following equation.

$$\eta = \frac{T\omega}{U_{in}I_{in}} \quad (3.5)$$

As mentioned above the maximum torque measured was 30Nm. This maximum torque value was set so that the DC motor wouldn't be overheated. Using the conversion ratio of 19:42, due to the chain, the maximum applied torque for the hub motor was approximately 66Nm. According to the performance data given by *Kelly Controllers* the maximum available torque is 87Nm. In other words the created matrix will not contain all values where the hub motor can be used. This is considered in the post processing of the data that is further explained in section 3.1.4.

3.1.3.1 Measuring the inverter

Except for mapping the efficiency for both the motor and the inverter another measurement was conducted to decide the efficiency for the inverter. To do this another set of equipment was used by placing a power meter between the inverter and the hub motor. The equipment, a *Yokogawa 2533*, used to measure the power between the inverter and the motor is shown to the left in Figure 15 below. On the top to the right is a *Norma D6100* measuring the battery power output and underneath is the monitor showing the value from the torque meter.



Figure 15: Equipment used to measure the efficiency for the inverter.

This setup would have been preferable for doing all measurements. Though a maximum current limit of 30A in the *Yokogawa 2533*, which was placed between the inverter and the hub motor, limited the measurements to only include some data points and therefore this setup couldn't be used for all measurements.

When the inverter is turned on without any load applied, the energy consumption is about 20W. This consumption is related to the controller inside that needs energy to run and leak currents.

The result of this test is shown in section 3.1.5 giving an idea of how well the inverter performs in the working points it could be tested.

3.1.4 Post processing of measured data

The results from the measurements are two matrixes containing torque and efficiency and one vector including the different speeds the tests were conducted. But the motor can operate at a wider range of torque and speed than measured and the matrix should therefore be expanded. So in order to use these values in the simulation model it's better to have a bigger matrix containing more data and therefore make it possible to extract a more accurate efficiency for the given torque and speed.

Increasing the data points in the efficiency matrix is done with interpolation by using the torque matrix and speed vector. The result of this can be seen in Figure 16.

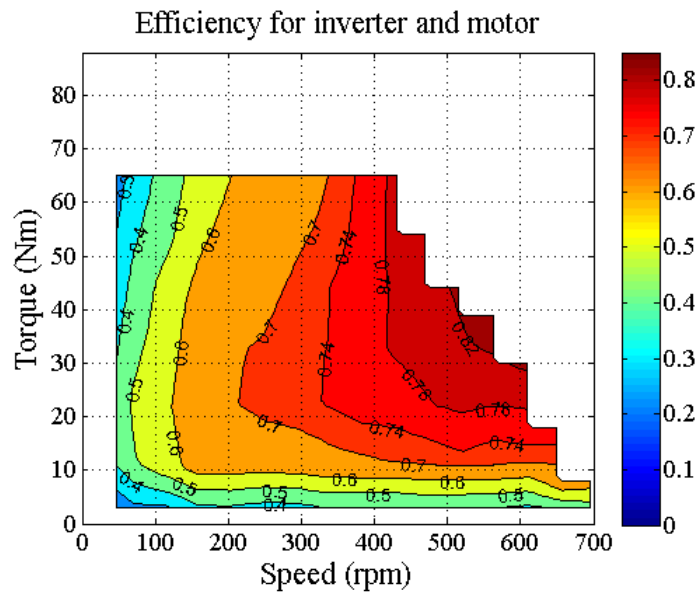


Figure 16: Efficiency for inverter and motor based on measurements.

Looking at the figure above the maximum torque is 66Nm, but as mentioned in section 3.1.3 the maximum torque given by the manufacturer is 87Nm. Therefore data points were taken from the performance data, given by the manufacturer, and then added to the efficiency map seen above. The new matrix was then interpolated and the result of this can be seen in Figure 17 below.

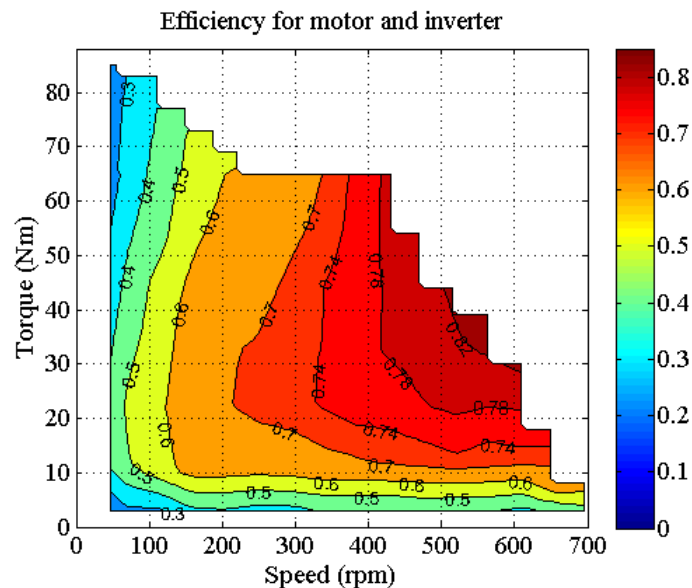


Figure 17: Efficiency for inverter and motor. Since higher torque is available more data points have been added.

Looking at the figure above there are still points which are not included in the table but they exist in the real operating machine. First there are the points where speed is below 50rpm and torque is below 3Nm. It's very clear that the motor can be used within these areas and therefore extrapolation have been used to add efficiencies for speeds lower than 50rpm and torques lower than 3Nm.

There are also some other areas where the motor should work and they can be found in the outmost part of the efficiency map looking like a staircase. It doesn't make much sense that the motor in reality would have cut-offs looking like this and therefore extrapolation have also been used to expand these areas. The final result of the efficiency map is given in Figure 18 below.

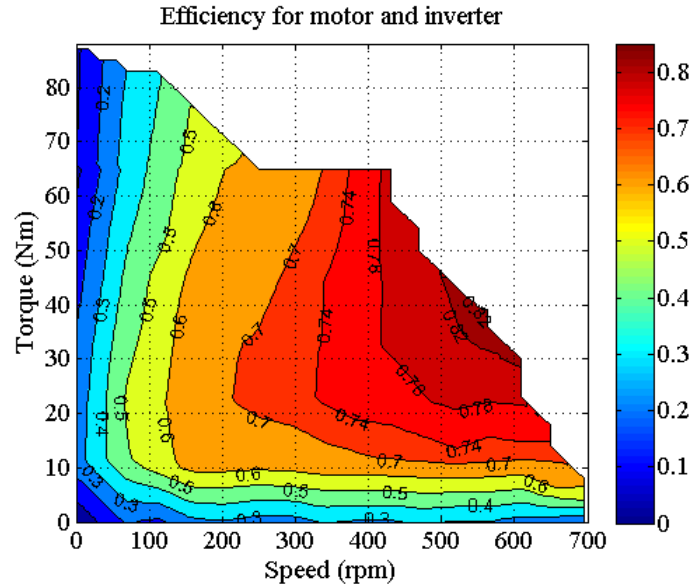


Figure 18: Efficiency for inverter and motor. Final result.

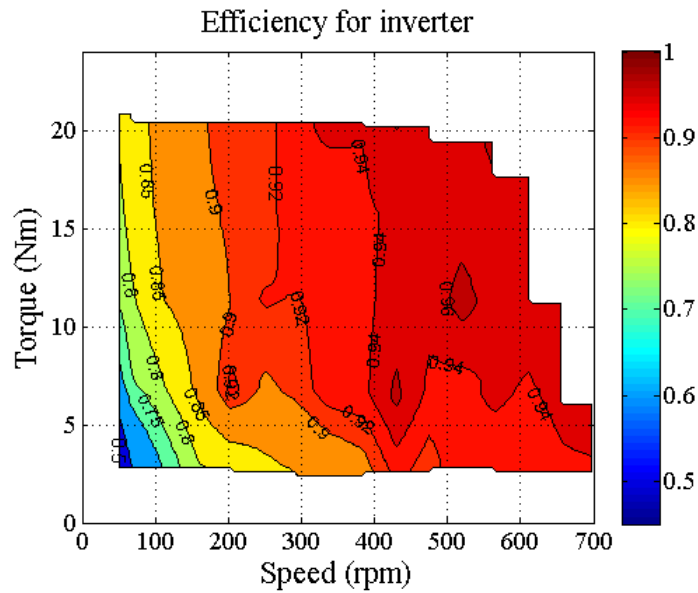
This is the efficiency map used in the simulation model. If the vehicle wants to be “outside” the colored area it will be limited to a spot where it actually can work. Therefore one of the limits in the vehicle is based on the efficiency map shown above.

3.1.5 Post processing efficiency data for the inverter

As mentioned in section 3.1.3.1 measurements were conducted for deciding the efficiency for the inverter. To do this a power meter was placed between the inverter and the hub motor. By doing this the output power from the inverter could be compared with the output power from the battery.

$$\eta_{inverter} = \frac{P_{out inverter}}{P_{out battery}} \quad (3.6)$$

Unfortunately the power meter could only handle 30A and therefore the applied torque was limited to no more than 9.3Nm. Comparing this to the other efficiency map, containing values for both the inverter and motor, number of data points is rather limited. This becomes clear looking at Figure 19 below where the y-axis, containing torque, only have values between 2.6Nm to 20.5Nm.



Looking at the efficiency map above it seems strange that the efficiency increase with higher speed and partly higher torque. This can partly be explained by the controller, inside the inverter, consuming about 20W. But even when the consumption from the controller is subtracted from the equation the inverter efficiency doesn't follow a clear trend decreasing with increased current. This could be that the MOSFETs have a fairly constant power loss and when the power increases the MOSFET losses will become proportionally less.

Even if the efficiency is partly uncertain, at least at lower torques, the inverter has an efficiency of at least 90% in most working points. Looking at the figures in the previous section the trend for the inverter and motor is that the efficiency increases up to 25Nm at low speeds and then starts to decrease. This is more likely because of the motor having stray losses but part of it could be the inverter having $R I^2$ losses.

Since the inverter efficiency map is not showing the torques higher than 20.5Nm it will not be used in the simulation model. Instead the efficiency map shown in Figure 18, will be used for both the inverter and the motor.

3.2 Battery voltage model

Instead of having a specific efficiency depending on the output current from the battery a generic battery model is used. The generic battery model is taken from the IEEE report [16].

In order to use the generic battery model some parameters must be extracted and then used in the following equation,

$$E_{nom} = E_0 - \frac{K \cdot Q}{(Q - Q_{discharge})Q_{discharge}} + Ae^{-BQ_{discharge}}, \quad (3.7)$$

where E_{nom} is the nominal voltage also known as the open circuit voltage (OCV). The other variables, in the function above, are explained in Table 5 below.

Table 5: Summary for parameters used in the generic battery model.

Parameter	Explanation	Equation
E_0 (V)	Start voltage with fully charged battery	Measured
Q (Ah)	Full charge in battery	Specified in data sheet
$Q_{\text{discharge}}$ (Ah)	Consumed energy	$Q_{\text{discharge}} = \int_0^t i(t) dt / 3600$
R (Ω)	Inner resistance in battery	Measured
A (V)	Voltage drop during exponential zone	$A = E_{\text{Full}} - E_{\text{Exp}}$
B (Ah) ⁻¹	Charge at the end of exponential zone	$B = 3 / Q_{\text{Exp}}$
K (V)	Polarization voltage	$K = \frac{(E_{\text{Full}} - E_{\text{Nom}} + A(e^{(-BQ_{\text{Nom}})} - 1)) (I_d t_d Q_{\text{Nom}})}{Q_{\text{Nom}}}$

By discharging the battery and at the same time measuring output voltage and current all other necessary parameters can be calculated.

3.2.1.1 Discharge test

To know the voltage characteristics for the battery a discharge test was conducted. The battery was first fully charged and then discharged with the current rating of 0.2C, or 6A, until depth of discharge (DOD) reached 100%. During discharge the current was measured and integrated so that the amount of Ah drawn was known. Simultaneously the voltage was logged with the aim of comparing the voltage level with DOD. The result from the discharge test, seen in Figure 23, was then used in the voltage model.

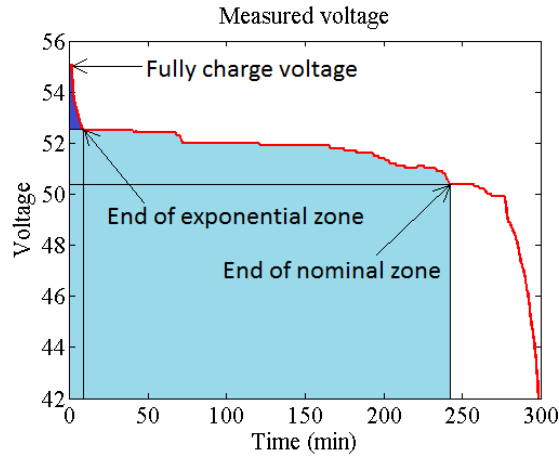


Figure 20: Result of discharge curve for a battery.

Values are taken from Figure 20 above that are then used to calculate the parameters in Table 5. E_{Exp} is taken from the end of the exponential zone and E_{Nom} is taken from the end of the nominal zone. Q_{Exp} is the charge at the end of the exponential zone, t_d is the discharge time, I_d the discharge current and Q_{Nom} is the total charge the battery contains.

When all parameters in Table 5 are known they are used in equation (3.7) and the result of this equation is shown in Figure 21 below.

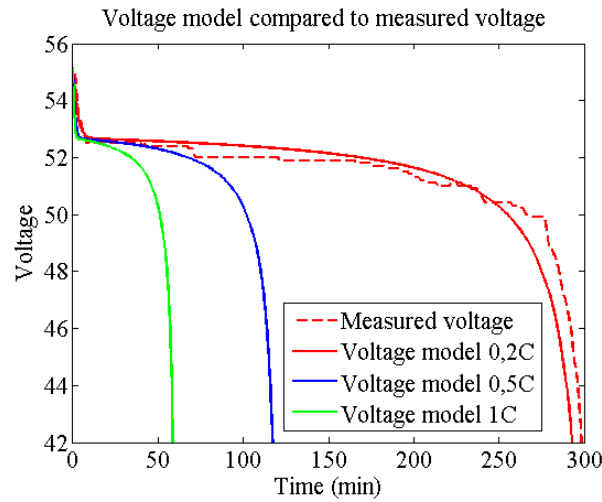


Figure 21: Result of the generic voltage model.

A summary for some of the measured values are given in Table 6 below. By comparing these with the values given by the manufacturer, shown in Table 1, we can see that the energy content has increased.

Table 6: Summary of measured battery values.

Rated voltage	Rated capacity	Energy	Weight	Volume	Wh/kg	Wh/l
51.9V	32.88Ah	1.698kWh	18.2kg	10.6l	93.3Wh/kg	160.2Wh/l

When the nominal voltage is known the battery current can be calculated. This process is further explained in section 4.8.

3.2.2 Battery simplification

There are several types of batteries that can be used in a BEV and the most common type store energy converting electric energy into a chemical structure based on a specific material setup. Simulating how energy is transformed between chemical storage to electric energy is not easy and simplified models are most often used. The goal is to simplify the battery model without losing too much of its accuracy and the model in this simulation is no exception. Therefore the battery model has been simplified according to Figure 22.

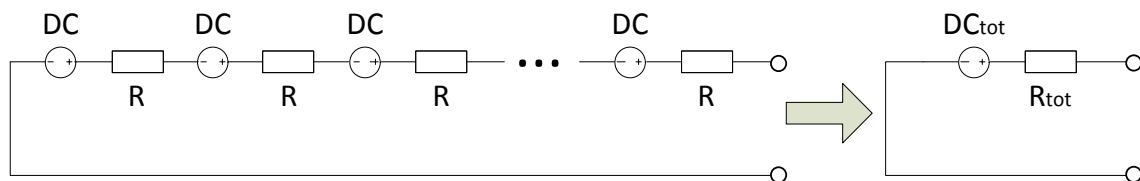


Figure 22: The battery cells are combined to a circuit only including one DC source with on inner resistance.

The figure above shows how the battery circuit is simplified by adding all single cells into one DC source with one inner resistance.

3.2.2.1 Battery's inner resistance

Except for logging the voltage and current during the discharge test the open circuit voltage (OCV) was also measured. The difference between OCV and discharge voltage is then divided with the current to decide the battery's inner resistance.

This test was carried through during the batteries constant voltage phase using an 800W load consisting of multiple effect resistors. As stated above the OCV was measured before connecting the load and then measuring the output voltage and current. With the results the inner resistance was calculated with the following equation,

$$\text{Inner resistance} = \frac{\text{OCV} - \text{Output voltage}}{\text{current}} \quad (3.8)$$

After doing this a few times the mean value of the results was conducted to be 100mΩ. This value was then be used for the inner resistance in the simulation model.

If the discharge current is increased the inner resistance will change. But since a variable resistance is one of the limitations of the battery model, see section 3.2.3, this isn't evaluated and therefore not considered in the simulation model.

3.2.3 Assumptions and limitations with battery model

Following assumptions and limitations should be considered when evaluating the battery model.

Assumptions in the battery model are the following

- The internal resistance is constant during both charge and discharge and doesn't vary with the amplitude of the current or temperature.
- The model's parameters are deduced from the discharge characteristics and assumed to be the same for charging.
- The capacity of the battery doesn't change with the amplitude of the current (Peukert's Exponent is said to be 1).
- The temperature doesn't affect the model's behavior.
- The Self-Discharge of the battery is not represented.
- The battery has no memory effect.

Limitations in the battery model are the following

- The minimum no-load battery voltage is 0 and the maximum battery voltage is not limited.
- The minimum capacity of the battery is 0 Ah and the maximum capacity is not limited. Therefore, the maximum SOC can be greater than 100% if the battery is overcharged.

4. The simulation model

As stated in the introduction one of the purposes of this project is to understand the impact on different components in the BEV. It is also interesting to know how different parameters, such as number of passengers and number of motors, affect the vehicles energy usage. To achieve these results a simulation model was created enabling to answer these questions.

All plots in Chapter 4 are only shown to explain the functions. They should not be considered as results.

4.1 Simulation tool and parameters of the vehicle

The simulation will be built by using MathWorks application Matlab© and of one the main inputs will be the two drive cycles, mentioned in section 3.2, so that the vehicle can be tested in different scenarios.

Since the model is built to test different parameters they can all easily be changed. In section 4.3 all inputs are listed to give an overview of what can be tested. The outputs given by the simulation are all stated in section 4.14.

4.2 Model assumptions and limitations

Building a realistic simulation model is about fully understanding the vehicle and its surroundings. This can be achieved by knowing the physics of the vehicle and physics of nature and then use mathematical expressions to simulate reality. Though it might be possible to copy nature itself it's very time consuming and therefore not reasonable. Instead assumptions are taken and limitations are met to the extent where the model is simplified without losing too much accuracy to reality.

The following list contains both assumptions and limitations that have been taken before building the simulation model.

- Constant temperature
- Constant humidity
- No change in elevation during drive cycles
- Energy usage while turning the vehicle are not considered
- Weather conditions are assumed to be zero wind and no rain
- Limitations in the battery model due to simplifications in the conversion between electrical energy and chemical energy. For more limitations in the battery see section 3.2.3.
- Auxiliary power usage (lights, horn, indicators) is constant
- Losses due to battery management system (BMS) is not included

4.3 Inputs to the model

The theoretic model has multiple inputs that all in different ways affect the calculations. This section keeps track on all available inputs that all can be changed to try different scenarios.

The inputs are divided into five categories, external, vehicle, battery, motor and inverter and other.

External

External inputs are either physical parameters or values that are specifically set for the vehicle.

- Gravity [m/s^2]

- Temperature [C°]
- Relative humidity [%]
- Air density [] (depends on temperature and relative humidity)
- Drive cycle [import file]
- Max speed [km/h] (the maximum speed for the Z-Bee is 45 km/h)

Vehicle

Parameters that all depend on the vehicle but don't depend on the three main components, battery, motor and inverter.

- Body weight [kg] (without load, battery, inverter and motor)
- Load weight [kg] (passengers plus other load)
- Drag coefficient [dimensionless]
- Front area [m²]
- Rolling resistance [dimensionless]
- Auxiliary power [P] (power used by lights, horn, windshield wiper etc.)
- Cable resistance [Ω] (total cable resistance between battery and motor)
- Wheel radius [m]

Battery

The voltage in the battery is calculated using a generic battery model according to the equation below. The battery model is further explained in section 3.2.

$$E_t = E_0 - \frac{K \cdot Q}{(Q - i_t) i_t} + A e^{-B i_t} \quad (4.1)$$

- Number of batteries (either 1 or 2)
- Weight per battery [kg]
- State of Charge [%] (Start value)
- State of Charge [%] (End value)
- Inner resistance [Ω]
- Battery model (depends on the following parameters)
 - Constant voltage [V] (E_0)
 - Voltage drop in exponential zone (A)
 - Charge in the end of exponential zone (B)
 - Polarization voltage (K)
 - Rated capacity per battery [Ah] (Q)
 - Depth of Discharge (DOD) [%] (Depends on Q and SOC)
- Energy content per battery [kWh] (based on mean voltage and rated capacity)

Motor and Inverter

- Number of motors and inverters (either 1 or 2)
- Weight per motor [kg]
- Weight per inverter [kg]
- Max power output [P] (depends on number of motors)

Other

Part from the parameters mentioned above it's also possible to run the simulation with the following choices.

- Distance adjustment [true/false] (see section 4.6)
- Regeneration [true/false] (see section 4.10)

4.4 Demanded force, power and torque

The drive cycle contains speed and time and by knowing these two parameters the demanded force, power and torque is calculated. The force is calculated by using the following equation,

$$F(t) = ma(t) + \frac{\rho C_d A_{front} v(t)^2}{2} + mg \sin \theta + f_r mg \cos \theta \quad (4.2)$$

where m is the total weight, a acceleration, ρ air density, C_d air drag coefficient, A_{front} front area, v speed of the vehicle, f_r friction coefficient and ϑ is the elevation angle.

The air density, ρ , is calculated by knowing the ambient temperature and the relative humidity. The temperature and humidity is run through an algorithm that calculates an approximate value of the air density that is then used in the equation above. The algorithm for calculating air density is given in

Appendix A [17].

The drive cycle is given in speed and time and the time increases with one second for each step. Therefore the acceleration is based on the speed change during one second with the following result.

$$a(t) = v(t) - v(t - 1) \quad (4.3)$$

To calculate the power the force is multiplied with the speed according to,

$$P(t) = F(t)v(t) \quad (4.4)$$

and this will give the following equation

$$P(t) = ma(t)v(t) + \frac{\rho C_d A_{front} v(t)^3}{2} + v(t)mg \sin \theta + f_r v(t)mg \cos \theta \quad (4.5)$$

Knowing the power, P , the torque is calculated with,

$$T(t) = \frac{P(t)}{\omega(t)} = \frac{P(t) \cdot r}{v(t)} \quad (4.6)$$

where r is the radius of the hub motor.

4.5 Real speed calculation

Since there is limitation in power output from the electric motor the speed in the drive cycle has to be recalculated from the demanded speed, $v_{dem}(t)$. By setting a limit for the power output a new speed is calculated and this will be known as the actual speed, $v_{act}(t)$.

The power output from the motor is based on limitations set while measuring the motor and inverter efficiency and also from the maximum output current from the battery.

Using power equation from the previous section and setting a limit for the power output an equation is given where all variables are known except $v_{act}(t)$.

$$P_{max}(t) = mv_{act}(t)(v_{act}(t) - v_{act}(t - 1)) + \frac{\rho C_d A_{front} v_{act}^3}{2} + mgv_{act}(t)(\sin \theta + f_r \cos \theta) \quad (4.7)$$

From this equation the actual speed, $v_{act}(t)$, is calculated by solving the cubic function. An example of how the speed changes can be seen in Figure 23 below.

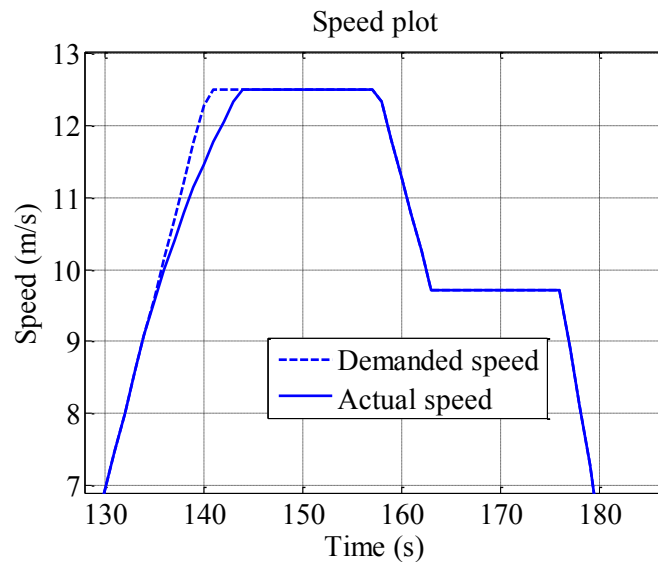


Figure 23: Demanded and actual speed during 50 seconds of the ECE 15 drive cycle.

4.6 Distance adjustment

Since the actual speed will be lower than the demanded speed due to limits in power output the total driving distance will be different. Therefore an input option is available to smooth out differences by having a higher actual speed compared to the demanded speed while braking. This is best explained by looking at Figure 24 below.

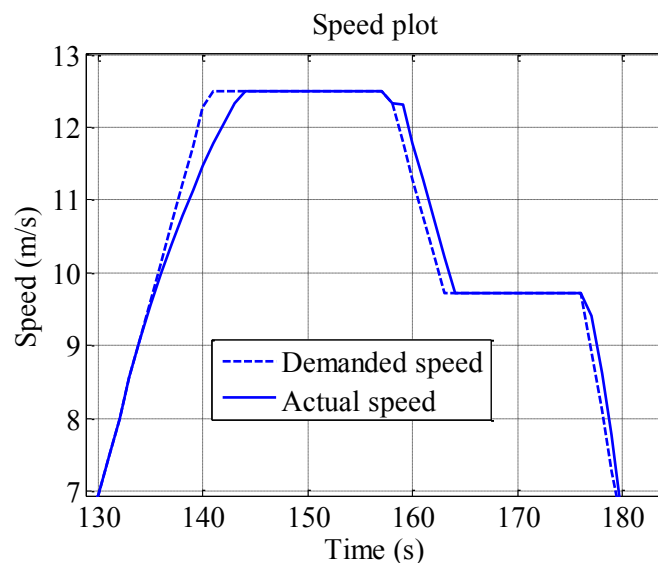


Figure 24: Demanded and actual speed during 50 seconds of the ECE 15 drive cycle.

As shown in Figure 24 the actual speed is compensated for the distance during braking for losing distance while accelerating. This can be compared to Figure 23 in section 4.5 that doesn't compensate for the lost distance during acceleration. If the two areas between demanded and actual speed, created while braking, are summed together they will have the same size as the area created when the vehicle is accelerating.

4.7 Actual force, power and torque

When the actual speed has been calculated, by solving the cubic in section 4.5, the actual force, power and torque is calculated using the same equations as in section 4.4.

An example of how the speed and power is changed due to power limitations is shown in Figure 25 below.

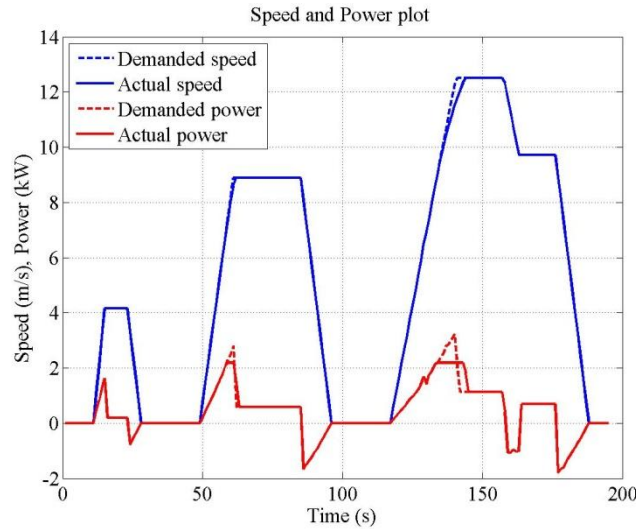


Figure 25: Example for speed and power with a maximum power output of 2190W.

In the first acceleration in Figure 25 above the vehicle have enough power to keep the speed demanded by the drive cycle. For the two following accelerations the vehicle reaches its power limit and therefore accelerates in a slower pace.

4.8 Calculating the battery current

With the voltage model explained in section 3.2 the nominal voltage is known and therefore the current in the battery can be calculated. This is done by knowing the nominal voltage and the amount of power the motor needs to drive the vehicle forward. By using Figure 26 below and going backwards the current is calculated by knowing P_{out} , efficiency for the motor and inverter, cable resistance, inner resistance and auxiliary power (P_{aux}).

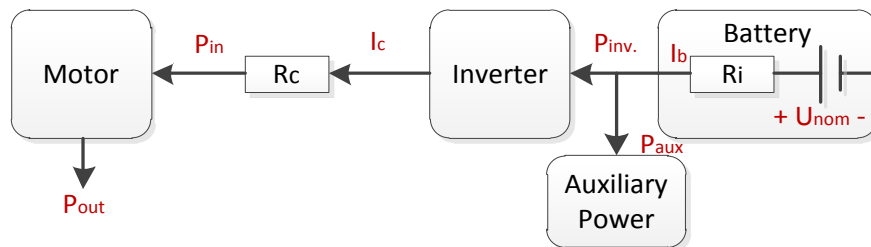


Figure 26: Block diagram for the driveline including power variables during discharge.

Even though the following equation will separate the motor and inverter efficiency the reader should be reminded that efficiency are combined for these components. In the simulation model the efficiency for the inverter is said to be 1 and instead the inverter efficiency is included in the motor efficiency.

First P_{in} is decided by knowing the motor efficiency and P_{out} .

$$P_{in} = \frac{P_{out}}{\eta_{motor}} \quad (4.8)$$

Then add the losses that depend on cable resistance, inverter efficiency and auxiliary power

$$P_{inv} = \frac{P_{in} + R_c I_c^2}{\eta_{inv}} + P_{aux}, \quad (4.9)$$

where the cable current is equal to

$$I_c^2 = I_b^2 - 2I_b I_{aux} + I_{aux}^2 \quad (4.10)$$

The final step is to calculate the power from the battery which is equal to the nominal voltage multiplied with the battery current and this gives the following equation.

$$P_{battery} = U_{nom} I_b = P_{inv} + R_i I_b^2 \quad (4.11)$$

In the equations above all variables are known except the battery current that can be calculated with the following quadratic equation.

$$I_b = \frac{U_{nom} \eta_{inv} + 2I_{aux} R_c}{2(R_c + R_i \eta_{inv})} \pm \sqrt{\left(\frac{U_{nom} \eta_{inv} + 2I_{aux} R_c}{2(R_c + R_i \eta_{inv})} \right)^2 - \frac{P_{out} + P_{aux} \eta_{inv} \eta_{motor} + I_{aux}^2 R_c \eta_{motor}}{\eta_{motor} (R_i \eta_{inv} + R_c)}} \quad (4.12)$$

The equation above is visualized in Figure 27 below where the current is shown together with the output and nominal voltage of the battery.

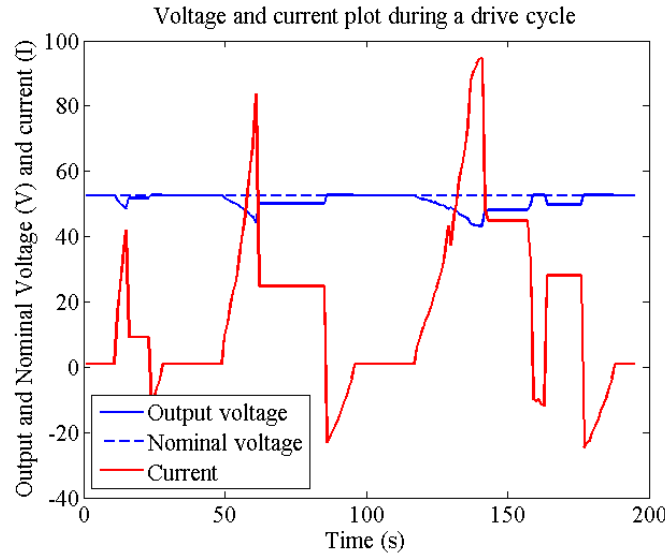


Figure 27: Current and voltage as a function of time.

Figure 27 above show the impact the current has on the output voltage. It's also obvious that the current is negative during deceleration and therefore the current is going into the battery. If regeneration is used the battery is charging during negative current. Regeneration during negative current is further explained in section 4.10.

4.9 State of Charge (SOC)

SOC_{start} is an input parameter that can be set to a value of up to 100%. When the simulation is run the SOC level in the battery will decrease or increase depending if the vehicle is using regenerative braking. The SOC level is calculated by knowing the nominal voltage and current which gives the input/output power from the battery during the whole drive cycle.

The battery input/output power is then transferred from W to kWh. When this is done the used energy is compared with the starting energy given by the battery size (kWh) and SOC_{start} . Now the SOC level can be decided for each step during the whole drive cycle and a typical result is shown in Figure 28.

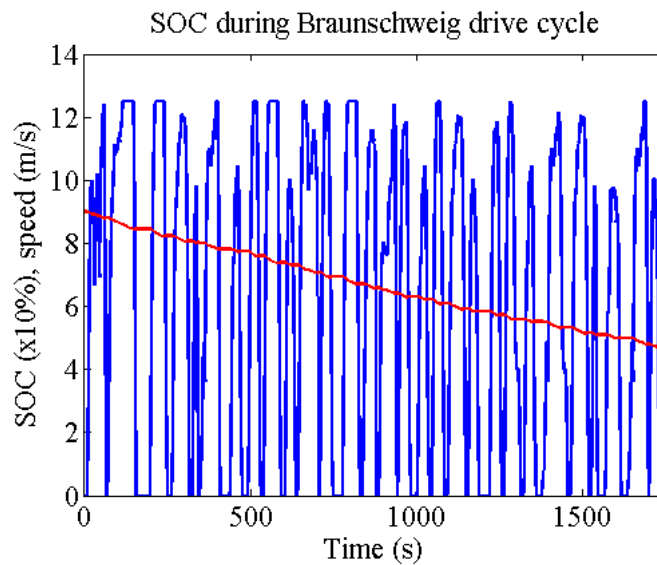


Figure 28: State of Charge for the Braunschweig drive cycle.

In Figure 28 above the input variable SOC_{start} is set to 80% and ends at 55.45%. During this drive cycle the vehicle has travelled a distance of 10.4km.

4.10 Regeneration

When the vehicle decelerates by braking the energy can be regenerated back to the battery. This function is optional in the model enabling comparison for when regeneration is used and not used. The flow of energy during regeneration is shown in Figure 29 below.

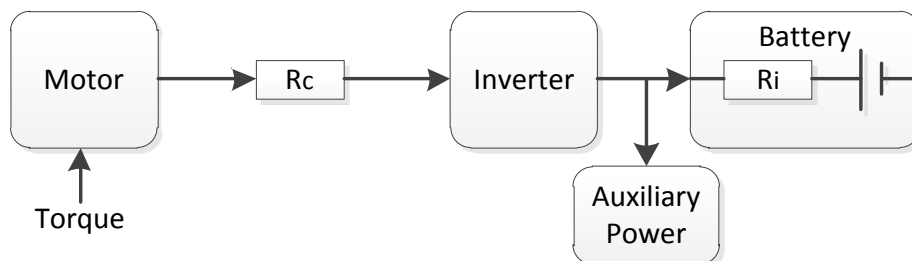


Figure 29: Energy flow during regeneration when the vehicle is braking.

Figure 30 below shows the affect of using regeneration during a 10.4km long drive cycle. In the end of the drive cycle SOC is 47.4% for regeneration and 40.2% without regeneration.

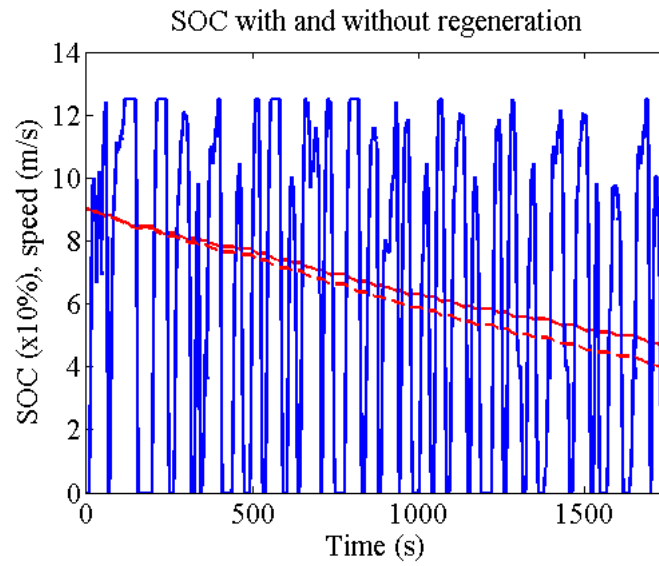


Figure 30: SOC level with and without regeneration for the Braunschweig drive cycle. The dashed line is without regeneration.

According to Figure 30 above regeneration is obviously more efficient since less energy is used. Subtracting the end value for SOC with the starting value of 90% the battery usage will be 42.6% for regeneration and 49.8% without regeneration. According to this the vehicle during the Braunschweig drive cycle use 16.9% less energy when regeneration is used.

4.11 Number of motors and batteries

One of the goals with the simulation model is to analyze the difference of using 1 or 2 motors and 1 or 2 batteries. Four different scenarios are possible and their setups are shown in Figure 31 below.

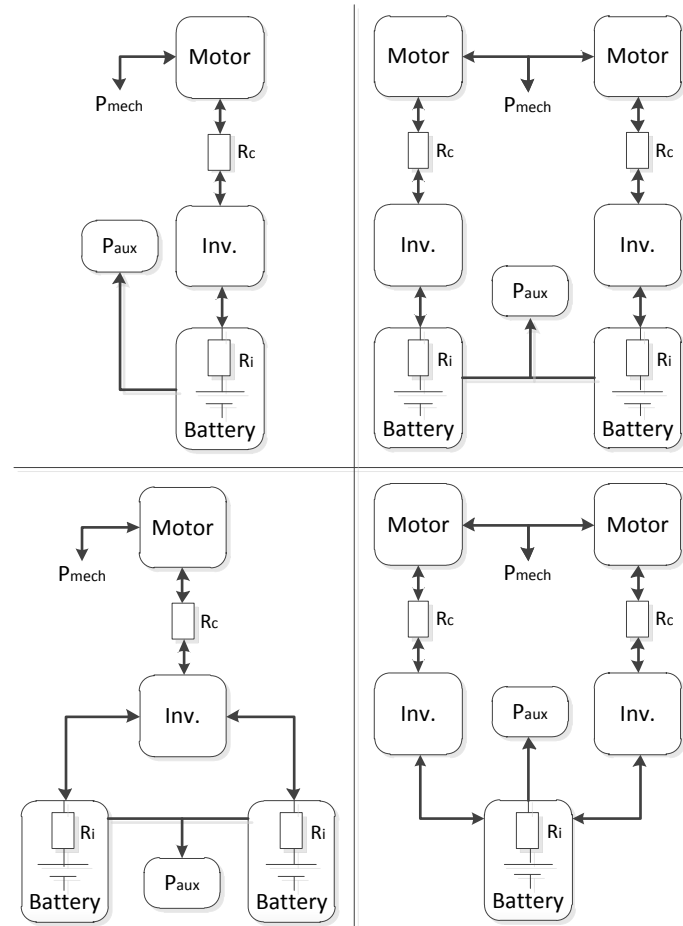


Figure 31: Four scenarios that's possible to test in the simulation model.

Two motors mean that more power is available. If only one battery is used there will be higher battery losses due to higher currents in the driveline. Using two motors will also affect the motor losses during lower speeds since the motors used have the highest efficiency when running close to nominal power and when two motors are used they will share the output power and therefore not be in nominal power as frequent as only having one motor. A summary of negative and positive affects for the different scenarios are given in Table 7 below.

Table 7: Summary of pros and cons from the different scenarios shown in Figure 31.

	1 Motor	2 Motors
1 Battery	<ul style="list-style-type: none"> • Lower weight • Medium efficiency • Lower power 	<ul style="list-style-type: none"> • Medium weight • Lower efficiency • Higher power
2 Batteries	<ul style="list-style-type: none"> • Medium weight • Higher efficiency • Lower power 	<ul style="list-style-type: none"> • Higher weight • Lower efficiency • Higher power

4.12 Losses in the drive line

When the vehicle is used there will be losses in the motor and inverter and losses due to resistance in cables and the battery. This simulation divides the losses into four components; battery losses, cable losses, motor losses and inverter losses. The motor and inverter losses depend on the efficiency explained in section 3.1 and will in the simulation be combined into one loss. Even though they are

grouped into one loss they are separated in the tables below. This battery and cables losses are both related to their respective currents and resistances.

A summary of all losses during discharge and regeneration is given in Table 8 and Table 9 below.

Table 8: Equations for calculating losses in the drive cycle during discharge.

Motors	Batteries	Battery losses	Cable losses	Motor losses	Inverter losses	Battery output
1	1	$R_i I_b^2$	$R_c (I_b - I_{aux})^2$	$P_{out} \left(\frac{1}{\eta_{motor}} - 1 \right)$	$U_{out} (I_b - I_{aux}) \left(\frac{1}{\eta_{converter}} - 1 \right)$	$U_{nom} I_b$
	2	$2R_i I_b^2$	$R_c (2I_b - I_{aux})^2$	$P_{out} \left(\frac{1}{\eta_{motor}} - 1 \right)$	$U_{out} (2I_b - I_{aux}) \left(\frac{1}{\eta_{converter}} - 1 \right)$	$2U_{nom} I_b$
2	1	$R_i I_b^2$	$2R_c \left(\frac{I_b - I_{aux}}{2} \right)^2$	$P_{out} \left(\frac{1}{\eta_{motor}} - 1 \right)$	$2U_{out} \left(\frac{I_b - I_{aux}}{2} \right) \left(\frac{1}{\eta_{converter}} - 1 \right)$	$U_{nom} I_b$
	2	$2R_i I_b^2$	$2R_c (I_b - I_{aux}/2)^2$	$P_{out} \left(\frac{1}{\eta_{motor}} - 1 \right)$	$U_{out} (I_b - I_{aux}/2) \left(\frac{1}{\eta_{converter}} - 1 \right)$	$2U_{nom} I_b$

Table 9: Equations for calculating losses in the drive cycle during regeneration.

Motors	Batteries	Battery losses	Cable losses	Motor losses	Inverter losses	Battery input
1	1	$R_i I_b^2$	$R_c (I_b + I_{aux})^2$	$P_{out} (1 - \eta_{motor})$	$(P_{out} \eta_{motor} - R_c (I_b + I_{aux})^2) (1 - \eta_{conv})$	$U_{nom} I_b$
	2	$2R_i I_b^2$	$R_c (2I_b + 2I_{aux})^2$	$P_{out} (1 - \eta_{motor})$	$(P_{out} \eta_{motor} - R_c (2I_b + 2I_{aux})^2) (1 - \eta_{conv})$	$2U_{nom} I_b$
2	1	$R_i I_b^2$	$2R_c \left(\frac{I_b + I_{aux}}{2} \right)^2$	$P_{out} (1 - \eta_{motor})$	$2 \left(0.5 P_{out} \eta_{motor} - R_c \left(\frac{I_b + I_{aux}}{2} \right)^2 \right) (1 - \eta_{conv})$	$U_{nom} I_b$
	2	$2R_i I_b^2$	$2R_c \left(I_b + \frac{I_{aux}}{2} \right)^2$	$P_{out} (1 - \eta_{motor})$	$2 \left(0.5 P_{out} \eta_{motor} - R_c \left(I_b + \frac{I_{aux}}{2} \right)^2 \right) (1 - \eta_{conv})$	$2U_{nom} I_b$

The main difference between discharge and regeneration is when the inverter losses are calculated. Comparing the two tables above will show that the inverter losses during discharge are calculated by using voltage and current and for regeneration by using the mechanical power (P_{out}) and motor efficiency.

Since the inverter efficiency was measured in combination with the motor efficiency the variable η_{conv} will be equal to one turning the inverter losses to zero. Instead the inverter losses are included in the motor losses since the variable η_{motor} contain the efficiency for both of them.

The battery output and input, included in the tables above, is the outgoing energy used by the drive line and the gained energy during regeneration.

4.13 Case setup

One of the goals with the simulation is to evaluate how different parameters will affect the vehicle's energy usage. This is done by running the simulation using a basic setup shown in Table 10. Then each parameter, which is of interest, will be changed to evaluate its impact on the vehicle. If more than one parameter is changed at the same time it's hard to make a conclusion not knowing which parameter made the certain impact on the results. Therefore only one parameter is changed per simulation and all other parameters keep their basic value. All simulation results, based on the case setup, are given in section 0.

Table 10: List of tested parameters.

Parameter	Basic setup
External <ul style="list-style-type: none"> • Temperature • Humidity • Drive cycle 	<ul style="list-style-type: none"> • 20°C • 50% • ECE 15
Vehicle <ul style="list-style-type: none"> • Passengers • Drag coefficient • Front Area • Rolling resistance • Auxiliary power • Body weight 	<ul style="list-style-type: none"> • 1 passenger • 0.4 • 1.68m² • 0.015 • 50W • 130kg
Battery <ul style="list-style-type: none"> • Quantity • SOC_{start} • SOC_{stop} • SOH • Inner resistance • Rated capacity • Energy content 	<ul style="list-style-type: none"> • 1 battery • 90% • 10% • 100% • 100mΩ • 32.88Ah • 1.36kWh
Motor <ul style="list-style-type: none"> • Quantity • Regeneration 	<ul style="list-style-type: none"> • 2 motors • Yes

4.14 Simulation outputs

Running the simulation will give multiple outputs that are used to evaluate some results. These outputs are all gathered in this section to provide an overview of which outputs are available.

Battery

- Battery current [A]
- Output voltage [V]
- Nominal voltage [V] – Voltage without having any load
- Battery losses [W] – Losses due to the inner resistance
- Output power [P] – Power used by the vehicle
- Input power [P] – Power gained by regeneration
- State Of Charge (SOC) [%]
- Energy consumed [kWh]
- Capacity used [Ah]

Motor and Inverter

- Efficiency [%]
- Motor and inverter losses [W]
- Torque [Nm]
- Power output [W]
- Angular speed [rad/s]

Other

- Cable losses [W] – Due to RI^2 losses
- Demanded speed [m/s] – Speed demanded by the drive cycle
- Actual speed [m/s]
- Demanded distance [m] – Distance demanded by the drive cycle
- Actual distance [m] – Distance the vehicle travelled
- Energy per km consumed [kWh/km]
- Maximum distance [km] – Based on kWh/km and usable energy in the battery

5. Analysis

The purpose of this project is to evaluate the vehicles components in the driveline and also do an energy analysis of the vehicle. In this chapter the results of simulations are provided and also an energy flow diagram showing where the energy is lost.

The results are given with the idea of understanding of what happens if the input parameters are changed. For example the questions asked in the introduction such as impact of having more than one passenger, using one or two motors and what is the affect of changing the battery's inner resistance will be answered.

5.1 Energy flows and losses

Since the Z-Bee is a plug-in BEV the energy will be taken from the grid and then used to give traction moving the vehicle forward. During this process there will be losses in each step and to simplify the overview a diagram is shown to give an idea of where the energy is used. Figure 32 below show all the steps in the drive train from energy uptake from the grid to energy losses during regeneration.

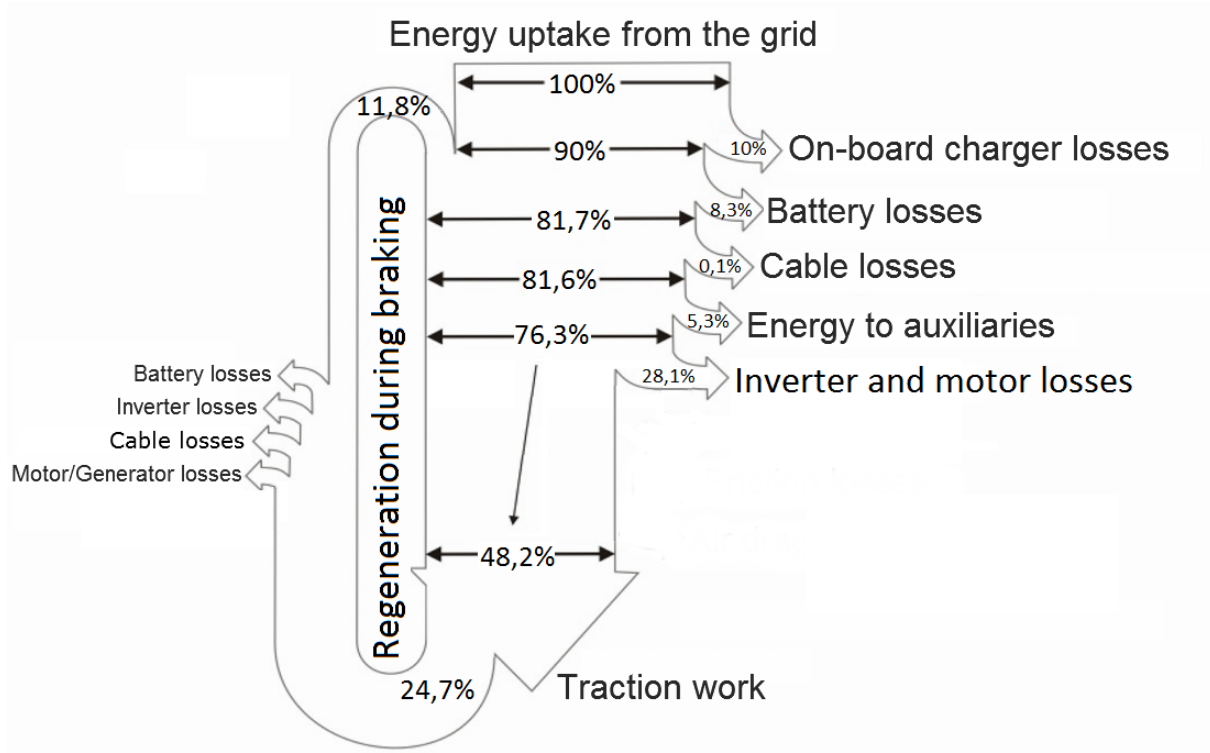


Figure 32: Energy flows and losses based on the simulation model. All values are given in percentage [%].

The *on-board charger losses* are based on a value measuring the losses while charging a lithium-ion battery. All other values are based on results from the simulation model.

5.2 Results from testing parameters

The following results give an example of how different parameters affect the vehicle. All tests will be run with the case setup, given in section 4.13, except for the parameter that will be changed. For the following tests the drive cycle ECE15 has been used and the result will be given in energy usage per km, for a given distance and drivability.

Energy usage per km basically means kWh/km and drivability is here defined as the distance the vehicle travelled compared to the distance demanded by the drive cycle. For example the drive cycle is, as mentioned in section 2.3, 0.9737km but the vehicle only travelled 0.9123km. According to the equation below the drivability is the following;

$$drivability = \frac{0.9123}{0.9737} = 93.69\% \quad (5.1)$$

Distance is how far the vehicle will go on a battery charge with SOC starting at 90% and ending with 10%. The battery's nominal energy level is based on a conducted measurement with the received value of 1.698kWh. With the assumption that the battery has an even energy distribution the potential energy will be calculated by the following equation.

$$Usable\ energy = (SOC_{start} - SOC_{stop})Energy_{battery} = 1.358kWh \quad (5.2)$$

5.2.1 Impact of motors, batteries and passengers

The vehicle's setup could be with 1 or 2 motors and with 1 or 2 batteries. If two batteries are used double amount of energy is accessible. How this affects the vehicle is shown in following table. Cursive values are the result of the case setup given in section 4.13.

Table 11: Result of the difference of using 1 or 2 motors and/or 1 or 2 batteries.

Number of motors and batteries	Energy usage (Wh/km)	Drivability (%)	Distance (km)
1 motor and 1 battery	34.5	98.78%	39.4
1 motor and 2 batteries	33.8	98.46%	80.26
2 motors and 1 battery	47.5	99.96%	28.58
2 motors and 2 batteries	40.9	99.92%	66.43

When 2 batteries are used the double amount of energy is available.

Tables 13 and 14 show the impact of using 1 or 2 motors and 1 battery with 1, 2 or 3 passengers. Each passenger will add an extra 80kg to the vehicles total weight.

Table 12: Result of having a load of 1-3 passengers with 2 motors and 1 battery.

Passengers	Energy usage (Wh/km)	Drivability (%)	Distance (km)
1	47.5	99.96%	28.58
2	56.1	99.58%	24.23
3	65.7	98.71%	20.68

Table 13: Results of having a load of 1-3 passengers with 1 motor and 1 battery.

Passengers	Energy usage (Wh/km)	Drivability (%)	Distance (km)
1	34.5	98.78%	39.4
2	40.9	96.73%	33.21
3	47.4	92.88%	28.64

Both tables show the impact of having more than one passenger. It's obvious that having more than one passenger will noticeably affect the energy usage for both setups and also the drivability for the setup only having one motor. The difference in drivability for both setups is shown in Figure 33 below.

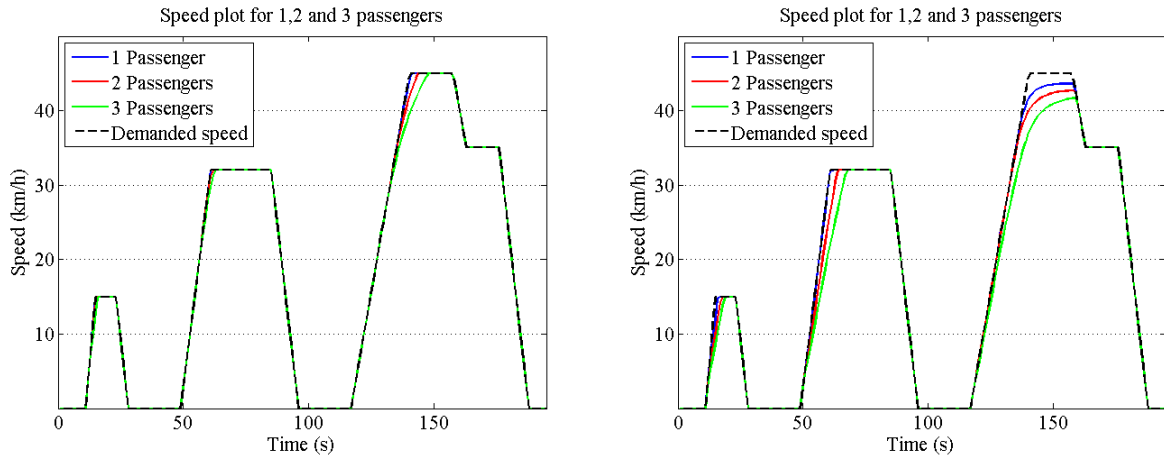


Figure 33: Result of drivability. The plot to the left is with 2 motors and the plot to the right is 1 motor.

5.2.2 Impact of air drag, front area, tire friction and air density

Except for the vehicles weight it's the following four parameters that has an impact on the force opposing the vehicle going forward. Cursive values are the result of the case setup given in section 4.13.

Table 15 show how the air drag coefficient decrease its energy usage from 41.9kWh to 35.5kWh when going from a coefficient of 0.5 to 0.3.

Table 14: Result of the air drag coefficient with the basic setup.

Air drag coefficient	Energy usage (Wh/km)	Drivability (%)	Distance (km)
0.3	44.0	99.99%	30.86
0.4	47.5	99.96%	28.58
0.5	51.0	99.90%	26.65

The Table 16 shows the impact of changing the front area. Since its part of the same equation as the air drag coefficient changing its value will have same impact on the energy usage.

Table 15: Result of the front area with the basic setup.

Front area m ²	Energy usage (Wh/km)	Drivability (%)	Distance (km)
1.3	44.4	99.99%	30.62
1.68	47.5	99.96%	28.58
2.1	51.0	99.90%	26.65

The Table 17 shows the result of changing the friction between tire and concrete.

Table 16: Result of friction coefficient with the basic setup.

Friction coefficient	Energy usage (Wh/km)	Drivability (%)	Distance (km)
0.010	42.6	99.99%	31.85
0.015	47.5	99.96%	28.58
0.020	52.2	99.90%	26.04

Since air density depends on the temperature and humidity. Table 17 shows the air density in the form of temperature and humidity. The difference between the results gives an extra energy usage of 1.4Wh/km.

Table 17: Result of temperature and humidity with the basic setup.

Temperature and humidity	Energy usage (Wh/km)	Drivability (%)	Distance (km)
Temperature = 0C, Humidity = 0%	48.5	99.95%	27.99
Temperature = 30C, Humidity = 75%	47.0	99.97%	28.89

5.2.3 Impact of auxiliary power, inner battery resistance and regeneration

Cursive values are the result of the basic setup given in section 4.13.

Impact of auxiliary power usage is rather linear. As a result it will approximately give an extra energy usage of 3Wh/km per 50W. If only lights are used, 50 Watts is a good approximation of auxiliary power.

Table 18: Result of auxiliary power between 0W to 150W.

Impact of auxiliary power (W)	Energy usage (Wh/km)	Drivability (%)	Distance (km)
0	45.0	99.96%	30.2
50	47.5	99.96%	28.58
100	50.1	99.96%	27.1
150	52.8	99.96%	25.73

Since the battery's inner resistance is constant Table 20 shows what happens if a higher or lower resistance is used.

Table 19: Result of battery inner resistance from 60mΩ to 140 mΩ.

Inner resistance in the battery (mΩ)	Energy usage (Wh/km)	Drivability (%)	Distance (km)
60	42.7	99.96%	31.65
100	47.5	99.96%	28.58
140	52.4	99.11%	26.07

Table 21 shows the impact of using regeneration and for the ECE15 drive cycle the vehicle could go an extra 3.36km. Regeneration would most likely have a bigger impact if the drive cycle also included elevation changes since more energy can be regenerated then compared to just braking.

Table 20: Impact of using and not using regeneration.

Impact of regenerations	Energy usage (Wh/km)	Drivability (%)	Distance (km)
With regeneration	47.5	99.96%	28.58
Without regeneration	53.9	99.96%	25.22

6. Conclusion

It is rather obvious when looking at the results in chapter 0 that weight has a big impact on the overall energy usage. Increasing weight will of course increase energy usage and this is the reason for building the chassis in composite material to keep the weight down, especially since the vehicle is designed as a scooter for the European market with the maximum speed of 45km/h. Even if the speed is of importance the air drag cannot be neglected. For example looking at the result in Table 14 the energy consumption increases from 44Wh/km to 51Wh/km when the air drag coefficient is increased from 0.3 to 0.5. Comparing the friction losses with the air drag losses using the case setup in 4.13 the air drag losses will exceed the friction losses at 9.1m/s, or 32.6km/h. Looking at the drive cycle used in the simulation the average speed is 26.6km/h which is close to the speed when the air drag losses is higher than friction losses. Since the vehicle is design for driving up to 45km/h it's likely it will be used at these speeds. Therefore reducing the air drag coefficient will have a noticeable impact on the overall losses. Reducing the air drag coefficient is easiest done by adding doors to the vehicle. Though this has to be done without completely cover the vehicle since then a ventilation system must be used and this will of course use even more energy. Without adding too much cost to the vehicle finding a way to covering the open areas enough without reducing the air quality for the driver might be the optimal solution for reducing the air drag losses. Also looking at the friction losses it's obvious from Table 16, where the energy consumption goes from 42.6Wh/km to 51Wh/km when the friction coefficient is increased from 0.1 to 0.2, that a lower friction will have a great impact. Reducing the friction losses without reducing weight could be achieved by using better tires having a lower friction coefficient.

Other than affecting the air drag coefficient and the friction some other actions are possible One of the easier changes to reduce the energy usage could be intelligent driver information. If information is given to the driver of how much energy that momentarily is being used it's more likely that the driver will use less energy per km. This information could also be completed with an algorithm calculating possible driving distance based on SOC for the battery and driver behavior. Even though this information is given to the driver it's not sure that he/she actually will use less energy. Also as a vehicle manufacturer you hand over responsibility to the driver in regards of smart energy usage. Instead some other measures could be addressed.

Let's start by looking at the results given in Figure 18 showing the efficiency for the drive line for every given speed and torque. This figure gives an indication of how well designed the driveline is in regards to the vehicle. E.g. a heavier vehicle with a lower air drag coefficient should have a driveline that has high efficiency at higher torques since this is the result of more weight and air drag coefficient. Instead a lighter vehicle with lower air drag coefficient would instead be more energy efficient with a driveline using higher efficiency at lower torques. Knowing this, the first step is to find a driveline that is the best solution for the specific vehicle. The vehicle in this report is rather light with one passenger and increases its total weight by almost 65% when two more passengers are added, for example this will increase the energy consumption from 47.5Wh/km to 65.7Wh/km. This will make it hard to optimize since small motors might be more efficient for on passenger but then the drivability could be affected when having a higher load. Finding a perfect solution might not even be possible just looking at the hardware. Instead it might be better using more powerful motors that are dynamic in its energy usage depending on how much torque should be applied depending on weight.

7. Future work

Below are some suggestions on future work that will improve the vehicle and the simulation model.

- What if the roof would be fitted with solar cells?
- How much further could the vehicle travel a sunny day and how long time does it take to fully charge the battery with solar cells?
- Is it reasonable to make the vehicle autonomous by using solar cells?
- If accuracy of model is high enough can an algorithm be used to estimate driving distance by using knowledge about driver behavior and SOC for the battery?
- Tweaking the model – By adding following components in the model accuracy can be increased.
 - Add power usage while turning
 - Use support for elevations
 - Use a better battery model having a variable resistance and variable SOH

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Appendix A

%This function calculates the air density (rho) by knowing the temperature
%in Celsius and the relative humidity.

```
function [rho] = air_density(T, relative_humidity)

%Constants
Rd = 287.05;      %Gas constant for dry air [J/(kg*deg(K))]
Rv = 461.495;    %Gas constant for water vapor [J/(kg*deg(K))]
P = 101325;      %Total pressure [Pa]

%The following section calculates the water vapor pressure
eso = 6.1078;
c0 = 0.99999683;
c1 = -0.90826951*10^-2;
c2 = 0.78736169*10^-4;
c3 = -0.61117958*10^-6;
c4 = 0.43884187*10^-8;
c5 = -0.29883885*10^-10;
c6 = 0.21874425*10^-12;
c7 = -0.17892321*10^-14;
c8 = 0.11112018*10^-16;
c9 = -0.30994571*10^-19;
p = (c0+T*(c1+T*(c2+T*(c3+T*(c4+T*(c5+T*(c6+T*(c7+T*(c8+T*(c9)))))))));

Es = eso/p^8;          %Saturation pressure of water vapor, [mb]
Pv = relative_humidity*Es*100; %Pressure due to water vapor [Pa]
Pd = P - Pv;          %Pressure due to dry air [Pa]
T = T + 273.15;       %Changing the temperature from C to K

%Air density is then calculated with the following equation
rho = Pd/(Rd*T) + Pv/(Rv*T); %Air density [kg/m^3]
```