Degree Project in Electrical Engineering
Second cycle 30 credits

Filling the gap Within Micromobility: Prototype of a Small Efficient Foldable Electric Vehicle With Long Range
The Suitcasecar

FREDRIK LIEN OSCARSSON
Filling the gap Within Micromobility: Prototype of a Small Efficient Foldable Electric Vehicle With Long Range

The Suitcasecar

FREDRIK LIEN OSCARSSON

Degree Programme in Electrical Engineering
Date: June 10, 2023

Supervisor: Mats Leksell
Examiner: Luca Peretti
School of Electrical Engineering and Computer Science
Swedish title: Prototyp av ett litet effektivt el-fordon som kan uppnå lång räckvidd
Abstract

Micromobility has been on the rise lately with a vast catalogue of electric vehicles reaching the market. Electric scooters, mopeds, bikes, one-wheelers and other vehicles have become the norm in everyday life. Most of these vehicles are meant to replace smaller modes of transport such as ordinary bicycles and skateboards. They are designed to complete the last part of one’s commute or for travelling shorter distances. There is; however, a gap within this segment. There is currently no electric micromobility vehicle on the market that is small and lightweight that has a long enough range to compete with ordinary two-tonne cars for longer commutes. This project aims to remedy this by presenting a solution as well as building a prototype of said solution. The electric vehicle that was built for this project is foldable. The design, when folded, is intended to resemble a large, rollable, suitcase. The overall size of the vehicle when folded is only 700x500x400 mm. When unfolded, it is large enough to seat one person fully enclosed. The top speed is limited to 25 km/h and the maximum range per charge is above 100 km. The prototype weighs 29 kg and is able to carry 95 kg. This thesis proves that it is possible to make small and lightweight electric vehicles that can rival traditional cars when it comes to commuting. These vehicles would reduce emissions, congestion and the need for parking space while also being a cheaper alternative for the end user.
Sammanfattning

Mikromobilitet segmentet har växt avsevärt de senaste åren. En stor samling av olika elektriska fordon så som elskotrar, mopeder, cyklar och enhjulingar, med fler, har blivit en del av vardagen. De flesta av dessa fordon är skapta för att tilryggalägga kortare sträckor. De är ämnade att ersätta cyklar eller att färdas till fot. Det finns dock ingen produkt inom det här segmentet tillgänglig på marknaden som är designad för att kunna tillyggalägga längre sträckor medan den fortfarande är liten och bärbar. Ett sådant fordon presenteras i denna avhandling som lösning på detta problem. Dessutom konstruerades en prototyp av det föreslagna fordonet för att bevisa att det är möjligt att göra små elektriska fordon med lång räckvidd. Prototypen som tillverkades i denna avhandling är vikbar, vilket gör den lätt att transportera när den inte är i bruk. Hela fordonet viks ihop till en resväskan som kan dras på bakhjulens. Den har en ihopvikt storlek av 700x500x400 mm, maxhastighet på 25 km/h och väger 29 kg. Detta fordon kan fullständigt innesluta en person när den är utfälld, bära upp till 95 kg och har en räckvidd på över 100 km per laddning. Fordon likt prototypen i denna avhandling kan hjälpa till med att minska utsläpp, minska behovet av parkeringsplatser och minska stockning på vägarna. Dessutom skulle ett sådant fordon också vara mer ekonomisk för slutanvändaren när det kommer till pendling jämfört med en traditionell bil.
iv | Sammanfattning
Key Words

Micromobility, Car, Electric car, Batteries, Electric motor, Efficiency, Foldable, Long range
Acknowledgments

I would like to thank my supervisor Mats Leksell and my Examiner Luca Peretti for taking on this thesis and in doing so allowing me to fulfil a personal dream. Mats also has my gratitude for all the experienced advice he has given me throughout this project. A special thanks also go out to Jesper Freiberg and Håkan Ferm for all their help and expertise in the workshop. Lastly, I would like to thank my parents and my brother for their unwavering support during my time at KTH and while doing this thesis.

Stockholm, June 2023
Fredrik Lien Oscarsson
Contents

1 Introduction 1
  1.1 Background ........................................... 1
  1.2 Problem ............................................. 2
    1.2.1 Original problem and definition ............... 2
    1.2.2 Scientific and engineering issues .......... 3
  1.3 Purpose ............................................. 3
  1.4 Goals ............................................... 3
  1.5 Research Methodology ............................... 3
  1.6 Delimitations ...................................... 4
  1.7 Structure of the thesis ............................. 4

2 Technical Description 5
  2.1 Brushless DC (BLDC) Motor ......................... 5
  2.2 BLDC Speed Controller .............................. 6
  2.3 Lithium-Ion Battery ................................ 6
  2.4 Lithium-Ion Battery Pack .......................... 7
  2.5 Battery Management System (BMS) ................. 8

3 Research Process 9
  3.1 Research ............................................ 9
  3.2 Design and Models .................................. 9
  3.3 Prototype Construction .............................. 10
    3.3.1 Welding ......................................... 10
    3.3.2 Fiberglass ....................................... 11
    3.3.3 Sewing ......................................... 11
  3.4 Simulation Validation ............................... 11

4 Current State of Micromobility 13
  4.1 Electric Vehicles .................................... 13
    4.1.1 Electric Scooter ............................... 17
# CONTENTS

4.1.2 Hoverboard .................................................. 18
4.1.3 Segway ......................................................... 18
4.1.4 Electric Bicycle .............................................. 19
4.1.5 Electric Moped ............................................... 19

4.2 Internal Combustion Engine (ICE) Vehicles ...................... 20
4.2.1 Moped ......................................................... 20
4.2.2 Microcar ....................................................... 20

4.3 Related work .................................................... 22
4.3.1 Mazda’s Suitcase Car ........................................ 22
4.3.2 The Impossible Bike ......................................... 23
4.3.3 The Peel P50 .................................................. 24

4.4 Summary .......................................................... 25

5 Prototype Process ............................................... 27
5.1 Vehicle Design .................................................. 27
5.1.1 Chassis Design ............................................... 27
5.1.2 Design of the Shell ......................................... 30

5.2 Software Implementation ....................................... 31
5.2.1 Motor Model ................................................ 31
5.2.2 Motor Heating Model ...................................... 39
5.2.3 Drag Coefficient Model ................................... 40
5.2.4 Energy Consumption Model ............................... 41
5.2.5 Chassis Strength Model ................................... 42

5.3 Hardware Implementation ....................................... 44
5.3.1 Battery Assembly .......................................... 44
5.3.2 Motor Model Validation .................................. 50
5.3.3 The Chassis ................................................ 51
5.3.4 The Seat ..................................................... 52
5.3.5 The Shell ..................................................... 53
5.3.6 Assembly of Prototype ..................................... 54

6 Results and Analysis ............................................. 59
6.1 Major results .................................................... 59
6.1.1 Motor Torque and Efficiency ............................... 59
6.1.2 Motor Heating ................................................ 62
6.1.3 Energy Consumption ....................................... 64
6.1.4 Prototype Performance ..................................... 65

6.2 Reliability Analysis ............................................ 66
6.3 Validity Analysis ............................................... 67
List of Figures

4.1 Average one-way commute distance per country (survey from 2014)[1] .......................................................... 14
4.2 Range and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project. ......................................................... 15
4.3 Battery capacity and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project. ......................................................... 15
4.4 Energy consumption and top speed of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project. ......................................................... 16
4.5 Energy consumption and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project. ......................................................... 16
4.6 Range and battery capacity of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project. ......................................................... 17
4.7 Smart Fortwo .......................................................... 21
4.8 Renault Twizy .......................................................... 21
4.9 Mazda Suitcase Car ................................................... 22
4.10 The Impossible Bike .................................................... 23
4.11 Smacircle S1 .......................................................... 24
4.12 Peel P50 ................................................................. 25
5.1 Extended chassis ......................................................... 28
5.2 Folded chassis .......................................................... 29
5.3 The three parts of the chassis ........................................... 29
5.4 The shell while folded ................................................... 30
5.5 The shell while unfolded ................................................... 31
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>Two Dimensional (2D) motor model with flux density</td>
<td>32</td>
</tr>
<tr>
<td>5.7</td>
<td>Start of building the geometry</td>
<td>33</td>
</tr>
<tr>
<td>5.8</td>
<td>Magnet array of the geometry</td>
<td>34</td>
</tr>
<tr>
<td>5.9</td>
<td>Geometry with stator core</td>
<td>35</td>
</tr>
<tr>
<td>5.10</td>
<td>Geometry with completed stator</td>
<td>36</td>
</tr>
<tr>
<td>5.11</td>
<td>The finished geometry</td>
<td>37</td>
</tr>
<tr>
<td>5.12</td>
<td>2D streamline of the velocity field from the drag simulation</td>
<td>41</td>
</tr>
<tr>
<td>5.13</td>
<td>Chassis stress with 950 Newtons of downward load</td>
<td>43</td>
</tr>
<tr>
<td>5.14</td>
<td>Chassis displacement with 950 Newtons of downward load</td>
<td>43</td>
</tr>
<tr>
<td>5.15</td>
<td>A defective battery pack</td>
<td>44</td>
</tr>
<tr>
<td>5.16</td>
<td>Balancing of a parallel bundle of 5 cells</td>
<td>46</td>
</tr>
<tr>
<td>5.17</td>
<td>The large battery pack</td>
<td>48</td>
</tr>
<tr>
<td>5.18</td>
<td>Battery pack top balancing</td>
<td>49</td>
</tr>
<tr>
<td>5.19</td>
<td>Torque measurement setup with the smaller battery pack</td>
<td>50</td>
</tr>
<tr>
<td>5.20</td>
<td>Chassis in its extended state with the fabric seat</td>
<td>52</td>
</tr>
<tr>
<td>5.21</td>
<td>Extruded Polystyrene (XPS) plug for the main fiberglass part of the shell</td>
<td>54</td>
</tr>
<tr>
<td>5.22</td>
<td>Motor controllers mounted directly to the chassis</td>
<td>55</td>
</tr>
<tr>
<td>5.23</td>
<td>Holes in the shell for motor mounts</td>
<td>56</td>
</tr>
<tr>
<td>5.24</td>
<td>The front of the chassis while unfolded</td>
<td>57</td>
</tr>
<tr>
<td>5.25</td>
<td>The finished prototype when unfolded</td>
<td>58</td>
</tr>
<tr>
<td>6.1</td>
<td>Torque validation: Simulated vs. Measured</td>
<td>60</td>
</tr>
<tr>
<td>6.2</td>
<td>Simulated efficiency map for two motors</td>
<td>61</td>
</tr>
<tr>
<td>6.3</td>
<td>Simulated losses at different operating points</td>
<td>62</td>
</tr>
<tr>
<td>6.4</td>
<td>Steady state temperature of the stator and coils at 840 Rounds Per Minute</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>(RPM) and 21 A peak current</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>Steady state maximum temperature at 840 RPM, from 1 to 21</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>A peak current</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>Four of the driving cycles, starting with nede/5</td>
<td>65</td>
</tr>
</tbody>
</table>
List of Tables

4.1 Weight, claimed energy consumption and top speed of some micromobility vehicles .......................... 26

6.1 Torque validation: Simulated vs. Measured .......................... 60
6.2 Simulated and measured energy consumption for different driving cycles .............................. 64
6.3 Component and vehicle weights ................................. 66
6.4 Torque measurement reliability ................................. 67
xvi | LIST OF TABLES
List of acronyms and abbreviations

2D  Two Dimensional
3D  Three Dimensional
AC  Alternating Current
BLDC Brushless DC
BMS  Battery Management System
CAD  Computer Aided Design
CC  Cubic Centimetre
DC  Direct Current
DIVA Digitala Vetenskapliga Arkivet
EMF  Electro-motive Force
FET  Field-Effect Transistor
ICE  Internal Combustion Engine
IEEE Institute of Electrical and Electronics Engineers
IGBT Insulated-Gate Bipolar Transistor
LiFePO4 Lithium Iron Phosphate
MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor
PCB Printed Circuit Board
RPM Rounds Per Minute
TIG Tungsten Inert Gas
XPS Extruded Polystyrene
Chapter 1

Introduction

This chapter contains a short description of the project as a whole. Some background and the project problem are stated here followed by a description of the work that was carried out and the surrounding delimitations.

1.1 Background

Micromobility has been on the rise for the last couple of years, especially within the electrically powered segment. Electric scooters, electric skateboards and longboards, electric one-wheelers and many other electric vehicles have become more and more prevalent. One of the reasons for this development is that lithium-ion batteries, which power most of these vehicles, have become much more affordable[2]. Therefore, these small electric vehicles can be mass-produced and sold relatively cheaply compared to 10 years ago. One problem with this is that a lot of these vehicles are made with sub-par quality and; therefore, break down quickly result in increased E-waste[3]. This project investigates a new segment of micromobility as well as the maximum range of small electric vehicles. Simultaneously, it is an attempt to prove that E-waste can be given a second life and that it is possible to construct a more suitable vehicle for commuting than traditional cars.

There are no fully enclosed vehicles within the micromobility sector that are light enough to be carried. This project is meant to create that segment. Furthermore, most electric vehicles within the micromobility segment are targeted as replacements for small and lightweight modes of personal transportation, such as bicycles. This project on the contrary is targeted as a replacement for traditional two-tonne cars. Therefore, the
intended range per charge is significantly higher than that of traditional vehicles within the lightweight micromobility segment.

The project that was carried out is a foldable, one-person electric car that, when folded is the same size as a large, rolling, suitcase. This vehicle is meant to be a substitute for a large portion of use cases with traditional cars. For example, those who use their five-seater car almost solely to commute, alone, to and from work. Using this electric vehicle as a substitute for a two-tonne ICE powered car would be cheaper for the user, both in acquiring cost as well as usage cost. It would also be more environmentally friendly as it is powered by electric propulsion with a small footprint. This would also result in less congestion on roads and remove the need for parking spaces since one simply folds it and takes it with them once they arrive at their destination. This thesis contributes to UN:s sustainable development goals 11, 12 and 13[4][5][6]. How it relates to these goals is explained further in the reflections section.

The scientific interest within this project is the investigation into what is actually possible to achieve within this segment of micromobility if the limits are pressed. What range is possible at which weight and size of an electric vehicle constructed with readily available materials and limited tools on a small budget?

1.2 Problem

There are currently no good alternatives available for, multi-purpose, single-person transportation for medium-range travel. Traditional cars are today mainly used for this kind of transportation, which results in other issues. Traditional cars are built to be able to carry multiple passengers as well as a lot of cargo. This results in cars being both large, heavy and incredibly oversized for a lot of use cases. Furthermore, most cars are powered by Internal combustion engines, which release emissions while in operation. These large vehicles also need a place to park while not in operation, which is most of the time. This leads to space congestion within cities and elsewhere.

1.2.1 Original problem and definition

Is it possible to construct an electric, foldable, vehicle that has the ability to transport one person, comfortably in any weather, a 100 km per charge that abides by the following constraints:
• 20 kg total weight, excluding the driver
• Maximum size when folded of 700x500x400 mm
• Load capability of 90 kg

1.2.2 Scientific and engineering issues

This project is limited by the materials and products that are currently available to the public. Mainly by the battery technology that currently exists. Furthermore, this is an optimization issue where the set constraints force one to find the most suitable balance between size, range, strength and weight for the vehicle.

1.3 Purpose

The purpose of this project is to investigate the possibility of a better alternative for personal commutes as well as to determine the maximum range for a lightweight, efficient electric vehicle.

1.4 Goals

The main goals of this project are listed below.

• To come up with a vehicle design that follows the aforementioned constraints.
• To analyze the energy consumption and possible range of said vehicle through simulations.
• To validate the results from the simulations with a functioning prototype.

1.5 Research Methodology

This project is conducted in three steps. Firstly, a scientific study is conducted to investigate what vehicles already exist as well as their inherent strengths and weaknesses. Then, a suggested solution is presented as an alternative for breaching the obvious gap within personal transportation. This solution is then simulated to evaluate the possible performance. The last stage consists of bringing this solution to reality by constructing a functioning prototype.
1.6 Delimitations

Due to a restricted monetary and time budget, as well as a lack of a suitable workshop, the prototype that was built for this thesis is in no way optimal. There are better and more lightweight materials available and better batteries do exist. Furthermore, the design can be improved by not having it as square as it is. However, this requires a lot of heavy machinery that was not readily available.

In addition, further improvements can be made if one has the option to construct the motors as well as the controllers from scratch to perfectly fit the intended application. This is not the case in this project. This project investigates what is possible for one person to achieve with limited tools and resources to incentivize future work within this area.

1.7 Structure of the thesis

This thesis is structured with eight chapters starting with this introduction. The second chapter goes through the background knowledge necessary for all components used in the project. The third chapter goes through the methods used. The fourth chapter contains background research on the micromobility segment. The fifth chapter describes the actual work that was carried out for this thesis. This is followed by the results obtained and the analysis of them. The last two chapters cover the discussion surrounding the outcome of the prototype and the conclusions with future work suggestions.
Chapter 2

Technical Description

A brief technical description of all components used in this project is presented in this section. The descriptions are meant to be explanatory enough to understand the rest of the thesis without the need for additional research.

2.1 BLDC Motor

A BLDC motor is a brushless Direct Current (DC) motor that turns by applying a three-phase alternating current to it. This is done with a speed controller that takes single phase DC as input and outputs a three-phase Alternating Current (AC). This is; however, not a perfect sinusoidal. The coils are located on the stator and therefore do not move while in operation. Because of this, no commutators are needed and hence the brushless nomenclature. The rotor is covered in permanent magnets and therefore the magnetic field of the rotor is fixed. The three phases of coils are distributed with a maximum of 120 degrees between each other. Rotation of the motor is achieved by supplying the coils with alternating current to achieve a rotating magnetic field on the stator side. The speed of the motor is controlled by varying the voltage across the coils. A low voltage results in a low speed and a higher voltage gives a higher speed[7].

BLDC motors can be controlled at max torque for different speeds making them much more efficient than traditional brushed DC motors. Furthermore, BLDC motors are more reliable and durable due to not having mechanical brushes[8]. The motors used in this project are two 350 W hub motors taken from a defective hoverboard. These BLDC motors consist of an outer rotor with 30 neodymium magnets, 15 pole-pairs. The stator has 27 coils, 9 coils per phase. 3 coils per phase are located next to each other and there is a 120
degree shift between every 3-coil bundle per phase. It is a three phase BLDC connected in a Wye configuration. However, these motors can be arranged in a Delta configuration as well. Doing so would increase the top speed with a factor of \( \sqrt{3} \) since this effectively increases the top voltage across each coil with the same factor.

### 2.2 BLDC Speed Controller

There are two types of BLDC Speed Controllers. Sensorless and those with sensors. The ones with sensors take data input from within the motor that keeps track of the position of the rotor. A hall sensor is commonly used for this data gathering. The sensorless ones get the information of the rotor’s position by measuring the back Electro-motive Force (EMF) for each coil and then calculating the distance to the closest magnet. The closer a magnet is the higher the back EMF.

The main purpose of the controller is to excite the coils at the correct time. For a three-phase BLDC, this is done with six Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET):s or Insulated-Gate Bipolar Transistor (IGBT):s and six Field-Effect Transistor (FET) drivers. A microcontroller determines when to energise the FET drivers and effectively switch each MOSFET. Three MOSFET:s are connected to the positive side of the DC voltage source and to one phase each. The remaining three MOSFET:s are connected to the negative side of the power source and to each phase of the motor respectively. To excite one phase, in a Delta configuration, two MOSFET:s are switched. One at the top side and one at the bottom side. If the motor is wired in a Wye configuration, two coils will be excited simultaneously for each pair of MOSFET:s switched[9]. The speed controllers used in this project have a peak power of 500 W each. One speed controller is used per motor.

### 2.3 Lithium-Ion Battery

Like all batteries, Lithium-ion ones consist of an anode, a cathode, an electrolyte and a separator. The anode in these batteries is typically made out of graphite and the cathode is usually a lithium cobalt oxide. The electrolyte is a combination of lithium salts and an organic solvent. The separator allows for lithium-ions to travel between the anode and the cathode but blocks electron
transportation.

Free Lithium-ions move from the anode towards the cathode through the separator during discharge. This leaves the anode with a net negative charge and supplies the cathode with a net positive charge. The negatively charged electrons are then drawn to the positively charged cathode. They cannot travel through the separator and must; therefore, go through the conductors and the load that is connected to the battery. Effectively driving a current through the load. During the charging of a lithium-ion battery, the opposite process occurs. A voltage slightly higher than that of the battery is supplied and electrons move from the cathode to the anode through the power source. The Lithium-ions move from the cathode to the anode through the porous separator.[10]

The voltage of a lithium-ion battery can range between 3 to 4.2 Volts, where 4.2 V is fully charged and 3 V is completely drained. The nominal voltage of these cells is typically between 3.6 to 3.8 V. The cells used in this project are of type 18650. These are cylindrical cells and the name describes the dimensions of the cell. They have a diameter of 18 mm and a height of 65 mm. These cells contain several layers of the anode, cathode and separator rolled up together. The top of the cells contain a safety feature called a Current Interrupter Device (CID)[11]. This is a diaphragm connected to the positive cathode that breaks the current pathway if the internal pressure within the battery becomes too high. Increased pressure is caused by a malfunction and the interruption of the current flow is a safety mechanism that is implemented to avoid thermal runaway.

18650 cells are popular because of their high specific energy and specific power. They can deliver a lot of power instantaneously and do so for a long time considering their low weight, usually 42g per cell. The best performing, commercially available, 18650 cells have a capacity of up to 3500 mAh[12] which is equivalent to 12.95 Wh at a nominal voltage of 3.7 V.

2.4 Lithium-Ion Battery Pack

For a lot of applications, 3.7 V is simply just not a high enough voltage. This is the case for this project as well. To get a higher voltage out of the 18650 cells than the nominal of 3.7 V several cells can be connected in series. This project requires a 48 V battery pack and to accomplish this, 13 cells are connected in series for a nominal voltage of 48.1 V. A larger capacity of the battery pack is
achieved by connecting multiple cells in parallel per series stage[13]. In this case, a battery with a capacity of 1500 Wh is desirable, this is equivalent to 31.25 Ah at 48 V. Nine cells in parallel with 3.5 Ah capacity each per stage will get these specifications. The battery would therefore consist of 13 series connections with 9 cells per stage, making it a 13s9p battery. The 13s stands for 13 series and 9p for 9 parallel, for a total of 117 cells. To manage the cells in the battery pack, a Battery Management System (BMS) needs to be used.

### 2.5 Battery Management System (BMS)

Since no cell is identical to another, the charge and discharge cycles of different cells will always vary. Sometimes by a small amount and sometimes by a lot. To keep all cells in a battery pack within the safety limits for Lithium-ion cells, a BMS is used. The BMS is connected to each series stage individually and can therefore measure the voltage for each stage. Furthermore, a BMS limits the current while charging and discharging as well as measures the temperature of the battery pack[14]. If the battery pack warms up beyond the temperature threshold, the BMS will break the current. If one series stage or more reaches above 4.2 V or below 3.0 V the BMS will break the current. This is a device that keeps the individual cells within safe operating limits.

Some BMSs also have balancing built into them. This is usually a resistive or capacitive circuit that equalises the voltage stages[15]. If one stage has a higher voltage than the other ones, current is drawn from this stage to charge up the other ones. This is done to keep all stages as close to equal as possible. Without balancing, there is a chance of not being able to utilise all of the stored energy within a battery pack due to the safety constraints employed by the BMS. If one stage is drained, and; therefore, at or below 3.0 V, the BMS will not allow the load to drain the battery pack further even if all other stages are fully charged. This is because the current drawn has the same magnitude at each stage, or very close to it. Power is available at all stages but one and can; therefore, not be utilised. A battery pack is only as strong as its weakest link.
Chapter 3
Research Process

The research process for this thesis consisted of gathering information about the current state of micromobility. What vehicles were available on the market and their respective performance. Followed by the design process and modelling. Finally, a prototype vehicle was built and used to validate the models.

3.1 Research

The first step of this project was to gather information surrounding the current state of micromobility as well as what constitutes as a micromobility vehicle. This was done through online research using portals such as Digitala Vetenskapliga Arkivet (DIVA) and Institute of Electrical and Electronics Engineers (IEEE). Furthermore, a lot of information on what vehicles are available on the market as well as their specifications was gathered from resellers of said vehicles.

Time was also spent researching how to implement the different techniques required to build the prototype. These included: learning how to Tungsten Inert Gas (TIG)-weld, learning how to work with fiberglass and learning how to build plugs for the fiberglass parts.

3.2 Design and Models

Once sufficient knowledge of the current state of micromobility, and the shortcomings within this segment, was obtained the next step was to dimension
and design a vehicle that was meant to address those shortcomings and effectively bridge the gap within micromobility. The dimensions and weight constraints were set by examining what an average person can lift for a short period of time and size limitations for transport on flights and trains as well as storage. The design of the vehicle and its folding mechanism was developed with Computer Aided Design (CAD) and Three Dimensional (3D) printing. Several iterations of the design were modelled in CAD and then 3D printed, on a 1:10 scale, and assembled to assess what worked and what did not. After several iterations, the final design was decided.

Several simulation models were built to assess the expected performance of the prototype. A 2D motor model of the hub motors was made in COMSOL as well as a model for the static strength of the chassis under max load. Furthermore, one more COMSOL model was imported and altered to estimate the drag coefficient of the vehicle in its extended state. This model was available at comsol.com and used an Ahmed Body to model the expected drag coefficient. Only the geometry of the body needed to be changed in this simulation file and there was; therefore, no need to build such a model from scratch. Similarly, an already-made MATLAB script and Simulink file were used, with alterations, to estimate the energy consumption of the prototype for different driving cycles.

### 3.3 Prototype Construction

The prototype was built using a lot of different methods, ranging from welding to fiberglassing. The different methods are used most prevalently in different occupations and areas of expertise. Fiberglass is mainly used in boat building and the best knowledge is found with experienced boat builders. Welding is mainly used in industry and electronics, which also is a big part of this project, is a completely different field. Building a prototype like this requires a broad set of techniques that are seldom related to each other and; therefore, forces one to gather expertise from different parts of the skill spectrum.

#### 3.3.1 Welding

Both TIG-welding, spot-welding and soldering were used in this project. TIG welding was the method used for welding together aluminium square tubing to make the chassis structure. Spot welding was used when building the battery. The individual battery cells were connected to each other using a spot
welder and nickel strips. Soldering was also used when building the battery packs, where the BMS leads were soldered to the aforementioned nickel strips. Furthermore, soldering was also used to connect all of the electronics as well as altering the motor controllers.

3.3.2 Fiberglass

Fiberglass and polyester were used to make the shell for the vehicle. Several plugs, also known as moulds, were built to plaster the parts on. These moulds were made out of XPS, attached together with spray glue, and spray foam that was later sanded down to get the desired shape of the fiberglass parts. The individual fiberglass parts were then attached to the chassis using rivets and bolts. Hinges were also used between the fiberglass parts that are foldable.

3.3.3 Sewing

The seat is made out of fabric and required some sewing to make. Both hand stitching and a sewing machine were used to make the seat. Furthermore, eyelets were needed which were attached with a press set.

3.4 Simulation Validation

The simulations were validated with the finished prototype or with individual parts of the prototype. The energy consumption simulation was validated by driving the prototype vehicle for a set distance and measuring the total energy consumption. The motor model was validated by measuring the torque of one of the motors used in the prototype.
Chapter 4

Current State of Micromobility

The micromobility segment can be divided into two distinct categories. Vehicles powered by electricity and vehicles powered by fossil fuels through an ICE. Some examples for both categories are presented here for a look into the current state of micromobility. Micromobility vehicles can be very useful for different applications, one of which is commuting to and from work or school. A study covering average one-way commute distances in different countries is presented in Figure 4.1.

4.1 Electric Vehicles

The micromobility segment is mainly dominated by electric vehicles. These include but are not limited to Scooters, Bikes, Hoverboards, Mopeds, Skateboards, Longboards and One-wheelers. It is a versatile segment of transportation with a lot of different choices. This might be because there are different definitions for micromobility. Small cars can sometimes even be considered to belong to this segment.

Some vehicles are compact and light others are larger and heavy. Whether big or small they all share the characteristic of being unable to cover a long range per charge. Those vehicles that can reach a somewhat longer range are instead inherently large and heavy. There is currently no lightweight and small option on the market with the ability to travel a long range per charge. This is demonstrated in Figure 4.2. Furthermore, Figure 4.2 displays a somewhat linear relationship between increased range and increased weight. Additional comparisons for the same vehicles can be seen in Figures 4.3, 4.4, 4.5 and 4.6.
Average one-way commute distance per country (survey from 2014)[1]
Figure 4.2: Range and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project.

Figure 4.3: Battery capacity and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project.
Figure 4.4: Energy consumption and top speed of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project.

Figure 4.5: Energy consumption and weight of some electric micromobility vehicles on the market. The red dot represents the prototype made in this project.
4.1.1 Electric Scooter

One of the most prominent micromobility vehicles is the electric scooter. This vehicle is usually manufactured with a hub motor design. However, some come with traditional motors and drive belts. Most electric scooters have two wheels connected by a platform on which the rider stands, or in some cases sits if there is a saddle. The front of the vehicle is equipped with a handlebar that is used to steer the vehicle. All necessary controls are also most often located on the handlebar such as the accelerator, brake lever and front light. The Xiaomi MI M365 Pro is a popular scooter with a hub motor. It weighs in at 14.2 kg and is powered by a 474 Wh Lithium-Ion battery pack. The manufacturer claims that a range of up to 45 km is possible with this scooter.

A group of researchers put this claim to the test[16]. They tested the scooter with 65 kg of weight on it on a flat surface, with zero degrees of inclination. The scooter could, with these conditions, reach a range of 45 km. When max speed was set to 25 km/h the total energy consumption was 476 Wh. However, if the max speed was limited to 20 km/h or 15 km/h, the energy consumption was only 362 and 324 Wh respectively for the same range. That
is an average of 10.6 Wh/km at 25 km/h and an average of 7.2 Wh/km at 15 km/h.

From these results, one could conclude that the advertised range is correct. However, these tests were performed under quite optimal conditions. The payload was fairly low, 65 kg, and most importantly there was no change in inclination or acceleration and retardation after the initial acceleration to the set top speed. A higher payload, a heavier rider, for example, would decrease the range. Furthermore, driving this vehicle with more starts and stops as well as changes in speed would also decrease the actual range.

4.1.2 Hoverboard

These vehicles have two wheels abreast. Each wheel is a hub motor and they are connected through a platform on which the rider stands. The balancing of the board is achieved with a gyroscope and it is driven by the rider shifting its weight in the direction they want to go. Each individual hub motor is usually rated for a constant power between 250-350 watts. However, there are models available that have more and less powerful setups.

One popular hoverboard is the Denver HBO-6750[17]. This vehicle has two hub motors rated at 350 W each. It is powered by a 36 V, 4 Ah battery which equates to 144 Wh. The total weight of this particular hoverboard is 10.6 kg. With this battery it has the potential to reach 15 km per charge. That is an average of 9.6 Wh/km if that range is actually reached. The Hoverboard was first invented by Shane Chen and introduced to the public in 2013[18]. Shane Chen is also the inventor of the solowheel.

4.1.3 Segway

The Segway was invented in 2001 by Dean Kamen[19]. It is a self-balancing vehicle with handlebars. The design can be compared with the hoverboard; although, a lot larger and with the addition of the handlebar.

The Segway i2[20] is one of the standard models. It weighs in at 48 kg and has a top speed of 20 km/h. The vehicle is powered by a 73.6 V battery pack with 5.3 Ah of capacity. This is equivalent to 390 Wh. With this setup, the company claims that the range per charge is between 26 and 39 km. That is 10 Wh/km if 39 km is achieved on one full charge.
4.1.4 Electric Bicycle

Electric bicycles can be purely motor powered but they can also be pedal-assisted. The ones only powered by the motor are similar to electric mopeds and thus merit no further explanation. The pedal-assisted electric bicycles; however, are quite different from the other vehicles previously mentioned. As it is powered by a combination of electrical power from the motor and human pedalling, power from the rider. The combination of power sources usually results in a longer range per battery capacity.

One research group that set out to optimize the energy consumption for a heavily loaded delivery bicycle[21] were able to reach an electric energy consumption of 23.3 Wh/km. However, this was done with a pedal-assisted bicycle that weighs 67.8 kg and had a payload of 128.6 kg for a total weight of almost 200 kg. Furthermore, the route that was used for these tests was very demanding with 150 full stops in only 2.4 km in an area with a lot of inclination.

This can be compared to an ordinary, pedal-assisted electric bicycle. The Batavus Harlem E-Go[22] has a battery capacity of 396 Wh and a promised, assisted, range of 40 to 80 km. That is equivalent to 10 Wh/km and 5 Wh/km respectively for a vehicle that weighs 19.2 kg excluding the battery. With the weight of the battery, it is closer to 23.7 kg.

4.1.5 Electric Moped

Electric mopeds are similar to purely electric bicycles. The differentiating factors are usually that the mopeds are more powerful and heavier with a higher battery capacity. Another difference is that the legislation for mopeds is more strict in most countries. In many cases, they have to be registered. Most of the models available are two-wheeled with one or more electric hub motors. However, there are models with both three and four wheels as well.

A two-wheel model, the Eloped ES1[23] weighs 80 kg and has a top speed of 45 km/h which makes it required to be registered in Sweden for example. It is powered by a 72 V Lithium-Ion battery pack with 20 Ah of capacity. That equates to 1440 Wh and can reach a range per charge of up to 60 km. That is an average energy consumption of 24 Wh/km.
4.2 **ICE Vehicles**

There are also a couple of vehicles powered by fossil fuels that are sometimes counted as being part of the micromobility segment. There are ICE powered longboards and scooters as well as bicycles. However, these are quite unusual and seem to have been outmanoeuvred by their electric counterpart. Two categories where ICE powered micromobility vehicles are still prominent are mopeds and microcars.

4.2.1 **Moped**

The traditional moped usually has a 49 Cubic Centimetre (CC) ICE and a small form factor designed for carrying one person at a maximum speed of 45 km/h. They are small and nimble compared to cars and in some countries marketed for juveniles. In Sweden, for example, the age requirement for driving a moped is 15 and requires a licence. The ones with a top speed of 45 km/h also need to be registered, taxed and insured in Sweden[24]. If the max speed instead is 30 km/h it falls under a different category which does not require registration and hence no tax. However, a licence and insurance are still needed for these slower mopeds. The rules are the same for electric mopeds. The legislation surrounding mopeds in Sweden, and many other countries, make them more expensive to own than the electric vehicles previously mentioned, with the exception of the electric moped.

4.2.2 **Microcar**

Microcars are in most countries classified as cars. However, there are some countries, such as Sweden, where they can be classified as motorcycles, even with four wheels. Microcars were somewhat popular in the 50s and 60s[25] with classics such as the Mini and the Peel P50. However, as time progressed, cars appear to have become larger and larger in general and the small cars almost completely disappeared[26]. It is only in the last two decades that small and micro cars seem to have done a reemerging within the market. Smart cars led this charge with their first model being released in 1998[27] as seen in Figure 4.7.

Although there are a few options of micro cars with ICE to choose from, most of the newly developed vehicles within this category are electrical. The ones powered by fossil fuels are mainly vintage cars from the 50s and the 60s.
One example of this type of newer electric microcar is the Renault Twizy[28] as seen in Figure 4.8.
4.3 Related work

There has never been a product or prototype quite like the one in this project. However, inspiration and ideas have arisen from studying different vehicles with similarities. The most impactful of these are presented below.

4.3.1 Mazda’s Suitcase Car

The basic foundation of the idea to build an electric, foldable suitcase car originally came from the concept suitcase car from Mazda[29] which can be seen in Figure 4.9. This concept car was built by seven engineers from the Manual Transmission Testing and Research Group in 1991 for the company’s in-house competition "Fantasyard". The aim of the competition was to design and make a prototype of the most innovative and creative "Moving Machine". The car was built from a Samsonite suitcase with a width of 75 cm and a height of 57 cm. The engine is a 33.6 CC gasoline engine from a pocket bike. It has a top speed of 30 km/h and can be assembled/disassembled in under a minute. All of the necessary parts for the vehicle are contained within the suitcase.

Figure 4.9: Mazda Suitcase Car
There is limited information available for this vehicle as it never made it to production. According to Mazda, two prototypes were built and unfortunately only one remains with the company. The original was accidentally destroyed in 1991.

### 4.3.2 The Impossible Bike

The Impossible Bike is a great example of an electric vehicle that tried to push the limits of what was considered possible. It was designed to fit within a standard backpack with a total weight of only 7 kg and the design can be seen in Figure 4.10. The company claimed that it had a maximum range of 30 km with a 104.4 Wh battery pack. That is a, impossibly, low energy consumption of 3.48 Wh/km[30]. The Impossible Bike never managed to launch which eternalized its name and it might have been because it promised more than it could deliver.

![Figure 4.10: The Impossible Bike](image)

However, a very similar vehicle is available on the market. It is the Smacircle S1[31] seen in Figure 4.11. This vehicle is based on the Impossible Bike but is a little larger and heavier. The S1 weighs 10.9 kg and has a 201 Wh battery. The maximum range per charge is stated as 20 km for this particular model, which equates to an average energy consumption of 10 Wh/km. The Smacircle S1 is more feasible than the Impossible Bike with stated values that are comparable to other electric vehicles and that might be the reason why this is actually a real product that one can currently buy.
4.3.3 The Peel P50

The Peel P50 is registered in the Guinness Book of World Records as the smallest production car ever made. It was originally made between 1962 and 1965 and the original had a total weight of 59 kg. It is 137 cm long, 99 cm wide and powered by a 49 CC two stroke engine. It has a top speed of 60 km/h through a three-speed gearbox with no reverse. The car is made out of fiberglass and was marketed as a vehicle that could carry one person and a shopping bag[32]. A picture of the Peel P50 can be seen in Figure 4.12.

In 2010, a company started to make replicas of the original Peel P50. The replicas are made with fiberglass moulds that have the exact same dimensions as the original moulds did[33]. The replicas are sold in two different variations. There is a gasoline-powered one with a 49 CC engine. Then there is also the EV alternative, which is an electrically powered Peel P50 replica. This version uses a DC motor and Lithium-Ion batteries and has a maximum range per charge of 400 km. The battery that they claim can deliver this range has a capacity of 3.2 kWh. If the claims are true then that is an average energy consumption of 8 Wh/km.
4.4 Summary

Micromobility is a wide concept and there is disagreement about what vehicles actually are micromobility vehicles. There are many different kinds of vehicles to choose from, both electric and others. The focus of this project is on the electric segment since the prototype that was built is electric. A table of some electric vehicles and their corresponding weight and claimed energy consumption per kilometre can be seen in Table 4.1.
Table 4.1: Weight, claimed energy consumption and top speed of some micromobility vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Vehicle Weight</th>
<th>Claimed Energy Consumption</th>
<th>Top Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI M365 Pro</td>
<td>14.2 kg</td>
<td>10.6 Wh/km</td>
<td>25 km/h</td>
</tr>
<tr>
<td>HBO-6750</td>
<td>10.6 kg</td>
<td>9.6 Wh/km</td>
<td>15 km/h</td>
</tr>
<tr>
<td>Segway i2</td>
<td>48 kg</td>
<td>10 Wh/km</td>
<td>20 km/h</td>
</tr>
<tr>
<td>Eloped ES1</td>
<td>80 kg</td>
<td>24 Wh/km</td>
<td>45 km/h</td>
</tr>
<tr>
<td>Impossible Bike</td>
<td>7 kg</td>
<td>3.48 Wh/km</td>
<td>20 km/h</td>
</tr>
<tr>
<td>Smacircle S1</td>
<td>10.9 kg</td>
<td>10 Wh/km</td>
<td>20 km/h</td>
</tr>
<tr>
<td>Peel P50 E</td>
<td>105 kg</td>
<td>8 Wh/km</td>
<td>40 km/h</td>
</tr>
<tr>
<td>Boosted Mini S</td>
<td>6.8 kg</td>
<td>8.8 Wh/km</td>
<td>29 km/h</td>
</tr>
<tr>
<td>Microlino</td>
<td>530 kg</td>
<td>60.9 Wh/km</td>
<td>90 km/h</td>
</tr>
<tr>
<td>Zero SR/S</td>
<td>235 kg</td>
<td>76 Wh/km</td>
<td>200 km/h</td>
</tr>
<tr>
<td>Renault Twizy</td>
<td>474 kg</td>
<td>67.8 Wh/km</td>
<td>80 km/h</td>
</tr>
</tbody>
</table>
Chapter 5

Prototype Process

This chapter goes through all of the stages involved to build the prototype. The design of the prototype is presented, and then the software and modelling stage is described. Ultimately ending with how all of the parts of the prototype were made and the final assembly of the vehicle.

5.1 Vehicle Design

A lot of thought was put into the overall design of the vehicle since it needs to follow a set of constraints while still being strong, durable and somewhat comfortable to drive. The folding mechanism needs to work with minimum inconvenience for ease of use, but still be strong enough to support the weight of the driver. The max weight of the vehicle is also of importance as it should be easy to handle for most people while having it folded up. Therefore, the design process became an optimization problem for finding a good balance between Weight, Strength, Size and range. The possible range is connected to the weight since it is limited by how heavy the battery pack can be, e.g. how many battery cells that can be used.

5.1.1 Chassis Design

It was early on decided to make the chassis out of aluminium square tubing because it is reasonably priced, readily available and has a high strength-to-weight ratio. The chassis consists of two parts that are not fixed together. The front, which contains the front wheel steering mount and the back which includes the structure for the driver seat. The front part of the chassis is mainly made out of 25 mm aluminium tubing. The reason for this is that the front part
needs to be able to slide freely inside the back part, which is made out of 30 mm tubing with a thickness of 2 mm. This gives a clearance of 0.5 mm on each face when the 25 mm square tubing is inserted into the 30 mm square tubing. A CAD model of the chassis in its extended state can be seen in Figure 5.1 and in its folded state in Figure 5.2.

![Figure 5.1: Extended chassis](image)

The main body of the rear part of the chassis is made out of two 67 cm long 30 mm squares running alongside each other. Between these, there are two pieces of 44 cm long squares of the same dimension attached perpendicular to the longer tubes. One is connected at the very rear end and the other is attached 21 cm from that same end. Four 22 cm tubes are attached to the top of the base oriented straight up. These make up the structure and anchoring points for the seat, which is made out of fabric. The two 67 cm lengths are kept completely open throughout the whole length of the tubes so that 25 mm tubing can slide within them.

The front part of the chassis consists of two 67 cm 25 mm square tubes separated by a distance of 44.5 cm. These slide into the two 67 cm long 30 mm squares in the rear part. Between these lengths, of 67 cm 25 mm tubing, the steering is connected. The steering comes from a kick-scooter with an inclination change on the steering mount. This is connected between two 43 cm long 30 mm tubes running alongside the 67 cm 25 mm tubing. These tubes are separated by 20 cm with a 25 mm tube attached at the absolute front of the
front part of the chassis. Lastly, there are two 33 cm long 25 mm square tubes attached vertically at each corner front of this part of the chassis. These are for mounting the front part of the shell to the chassis. These are not included in the CAD designs shown in Figures 5.1, 5.2 and 5.3

Furthermore, there are two 67 cm long, 25 mm tubes that are a part of the chassis but not fixed anywhere. These slide freely in the middle between the front part and the back part of the chassis. These can also be extended outside of the front part of the chassis when folded to be used as extension arms for a handle. The freestanding tubes are clearly visible in the centre of Figure 5.3.
5.1.2 Design of the Shell

The shell is designed so that it looks like a suitcase when folded and gives full coverage for the driver once unfolded. To achieve this, the shell is also split into two parts. The back part of the shell is the most rigid. It is solid for 70 cm in length with attached sides and back, going vertical for 47 cm. On top of this, there is a lid which is 3 cm high and matches the bottom part in other dimensions. Both the bottom and top parts are open in the front to allow for the front part of the shell as well as the unfolding function. The top and bottom parts are hinged in the back so that the top part can swivel 90 degrees and act as a back support when unfolded. On the bottom side of the top part, there is a piece that can slide up and out 90 degrees. This part acts as the roof when unfolded.

The front part of the shell consists of a plate that covers the front, mounted to the aforementioned points on the chassis. On top of this, another lid is attached to hinges. This lid is slightly smaller than the lid of the back part so that it can slide under that one. The front lid is two-layered, and the outer layer is attached to the chassis. However, the inner layer can slide freely. This part extends upwards and contains a see-through window. The shell design can be seen unfolded in Figure 5.5 and folded in Figure 5.4.

Figure 5.4: The shell while folded
5.2 Software Implementation

The software used and models built for this project are presented here. COMSOL, MATLAB and Simulink were the software programs used in this project.

5.2.1 Motor Model

COMSOL was used to build a simulation model of the hoverboard motor. This model was implemented as a 2D representation of the three-dimensional motor. To accomplish this, measurements of one of the hoverboard motors were taken manually with a ruler and callipers. The number of poles and coils was visually inspected by opening up the motor. The geometry of the motor with flux density for an operating point of 4.2 rad/s and 1 A peak, phase, current is displayed in Figure 5.6. Furthermore, the number of turns per coil was also visually examined and approximated. This resulted in sufficient knowledge of the motor to reverse engineer a 2D model of it in COMSOL.
Constructing Motor Geometry

When the physical motor had been inspected and dimensioned, the following parameters were retrieved for the BLDC motor:

- Poles = 30
- Coils = 27
- Turns per coil = 14
- Motor depth = 42 mm
- Stator Radius = 53 mm
- Rotor inner Radius = 54 mm
- Rotor outer Radius = 64 mm
- Air gap = 1 mm
The geometry of the motor was implemented by adding and subtracting basic shapes from each other. Adding shapes together in COMSOL is done through a Union command and subtracting shapes from each other is done through a Difference operation.

The first shape was a circle with a radius of 9.5 mm which represents the central shaft of the motor. Another circle with a radius of 15 mm was then added and centred on the first one. This second circle represents the inner attaching circle of the stator as can be seen in Figure 5.6. Two more circles were then added with radiiuses of 56 and 54 mm. These circles represent the permanent magnets. However, this 2 mm thick array needs to be split into 30 separate shapes to represent the 30 permanent magnets. This was done by adding a line segment with a length of 112 mm that spanned from one side of the magnet ring to the other. This line segment was then copied and rotated by 12 degrees. This was done 14 times to get the 30 magnet segments. The resulting geometry after these steps can be seen in Figure 5.7.

All the line segments and the larger circle with a 56 mm radius were then added together with a Union. The smaller circle, with a radius of 54 mm, were
then subtracted from the aforementioned Union using a Difference operation. The geometry for the magnet array was then completed. The geometry of the magnet array can be seen in Figure 5.8.

![Figure 5.8: Magnet array of the geometry](image)

The geometry for the stator was then made. A circle with a radius of 53 mm was added to the geometry and centred on everything else. This circle represents the outer dimensions of the stator core. Another circle with a radius of 31 mm was created and subtracted from the one with a radius of 53 mm using a Difference operation. The resulting circle as well as the first two that were created represents the stator core. However, there are three legs missing from the stator core at this point and these were added as 3 rectangles with a width of 7 mm, rotated 120 degrees respectively. All of these shapes that comprise the stator core were then joined together through a Union, the resulting geometry can be seen in Figure 5.9. At this point, the general shape of the stator was completed, but the coils and tooth gaps were yet to be implemented.
The coils and the teeth of the stator were created simultaneously. Three rectangles were used to create a stator slot. The centre one is 8 mm wide and 15 mm long. This rectangle is almost identical to the actual stator slots of the motor. However, to get a correct representation, the rectangle has to taper off towards the bottom with an angle of 6.66 degrees on each side. This was done with the other two rectangles. The two rotated rectangles were then subtracted from the centre one using a Difference operation. A line segment was then added to the middle of the resulting shape through a Union, effectively splitting the shape in two. This represents the two parts of a coil within each stator gap. One for current going into the screen and one going out of it. This general shape of a stator gap was then rotated 26 times by 13.33 degrees to get all of the stator slots and coils. All of these stator slots were then removed from the stator core using a Difference operation. However, this time the objects subtracted were kept by selecting the option: Keep objects to subtract. The only thing that was left to do for the stator at this point was to add the tooth gaps. This was done by implementing a rectangle with a width of 1.5 mm and a height of 3 mm at the top centre of the original stator slot. This was then rotated as the stator slots and all the resulting rectangles were subtracted from the stator core using a Difference operation. The stator was then completed.
and can be seen in Figure 5.10.

![Figure 5.10: Geometry with completed stator](image)

The geometries containing air as well as the air gap boundary pair were then created. Two concentric circles with radii of 54 and 53.5 mm were added and the smaller one was subtracted from the larger one using a Difference operation and once again keeping the subtracted geometry. This represents the boundary pair in the middle of the air gap that is needed for torque calculations. The stator core and the coils were then subtracted from the circle with a radius of 53.5 mm using a Difference operation and keeping the subtracted geometries. All of the needed geometries were then implemented and the final geometry could be finalized. The final geometry can be seen in Figure 5.11.

The geometry was finalized by adding all objects within the identity boundary together with one Union and all objects outside of the identity boundary together in another Union. This creates two parts: the stator part and the rotor part, separated by the identity boundary. The last step was to connect both parts with a Form Assembly command. This operation automatically creates the boundary pair.
Materials

When the geometry is finished, all different parts of the geometry have to be assigned a material with respective material properties. The materials that this motor consists of are Air, Copper, Neodymium magnets and silicon steel. All of these materials were found in the internal material library in COMSOL. Air was assigned to the air gap as well as the hollow parts within the stator core. The stator slots were assigned copper as their material. All 30 magnets were set as Neodymium (N50) magnets and the stator core was assigned silicon steel.

Physics

Different physical attributes and formulas could then be added to the model and this is done via domain selection. A domain is a geometry surface, such as a magnet, half a coil, the stator core etc.

Moving mesh: A rotation of the rotor as well as the outer air gap was added through a rotating domain, contained in the Moving Mesh physics selection. The rotation angle is defined as a variable angular rotation speed multiplied by
a time interval. The point of rotation is origo, which the geometry is centred on.

**Ampere’s Law, Remanent Flux Density:** The Remanent Flux Density physics is applied to all of the 30 magnets. This is done through two separate Ampere’s Law physics since the orientation of the magnets is inverted to its neighbours, creating 15 pole pairs. Therefore, 15 of the magnets are assigned a Remanent Flux directed in the positive radial direction, with one magnet between each chosen magnet. The remaining 15 magnets are assigned the Remanent Flux in the negative radial direction.

**Ampere’s Law, B-H Curve:** The physics for the stator core is implemented as a B-H curve that comes preloaded with the previously mentioned material selection of Silicon Steel.

**Coils:** The coil physics is divided into three separate coil implementations since this is a three-phase machine. Each phase has three coils in a row with three coil bundles for a total of nine coils per phase. Each bundle of coils is separated by six coils from the other two phases. This is equivalent to 120 degrees of rotation between each coil bundle per respective phase. The conductor model for all of the tree coil physics is chosen as a Homogenized Multiturn Conductor since all coils consist of more than one turn. In this case, the number of turns per coil is 14. The coil current is set to a variable representing the peak value of the current multiplied by the cosine of 15 times the rotation previously described for the Moving Mesh. This motor is a 15 pole pair machine and; therefore, needs the electrical rotation to be 15 times faster than the mechanical to work properly.

The remaining two phases are implemented in the same way. The only change is that the current inputs are phase shifted with 120 and 240 degrees respectively. For coil physics to work properly, a reversed current direction has to be assigned for each coil to represent the direction of the current in each coil. This is done for all phases where half of the domains are chosen as having the reversed current direction so as to simulate the circulating current for each coil.

**Arkkio Torque:** The last physic that was implemented was the Torque calculation. In this case, Arkkio Torque is used since it is more exact than the ordinary Force Calculation physic. The Torque is calculated in the air gap between the rotor and the stator. More precisely, it is calculated across
the previously mentioned boundary pair within the air gap. Therefore, the domains that are chosen for the Arkkio Torque physic are the two halves of the air gap.

**Study**

The study is set up with a parametric sweep and two study steps, one stationary and one time dependent. The sweep uses the peak coil current and the rotational speed as parameters. They were set up to sweep from 40 to 840 RPM with increments of 40 RPM. The peak current was set to sweep from 1 to 21 A with increments of 1 A. This resulted in results for 441 different operating points.

The study itself which is executed 441 times first solves the stationary physics in the model with the stationary study step. The second study step, the frequency dependent one, then uses the results from the stationary study to solve for time dependent variables.

**5.2.2 Motor Heating Model**

Once the motor model was working it was extended to also simulate the heating of the stator in the motors. This was done in the same COMSOL simulation file using a Heat Transfer in Solids physics, a multiphysics node and an additional study.

To implement the heating model one needs to start with adding the Heat Transfer in Solids physics. In this case, it was only applied to the geometries of the stator and the coils since the heating in the rotor is of lesser interest. This heat transfer model uses convection to the air to simulate the heating of the motor. The flux type chosen is Convective heat flux using two heat flux nodes. One is applied to the inner stator boundary that is in contact with the air domain. The other one is applied to the outer stator boundary that is also in contact with air. The heat transfer coefficient for both of these nodes was set to 20 W/m2K.

For Multiphysics, Electromagnetic Heating physics was used. This couples the Electromagnetic Rotating Machinery with the Heat transfer in solids physics. The study setup that was used to simulate the heating in the stator consists of two study steps. The first step is a Time to Frequency Losses study step. This uses the results from the motor model as input study and has a user
defined time interval from 0 s to 1/\omega s with 12 harmonics. This study step is only applied to the Rotating Machinery physics selection. The second study step is a stationary step that is applied to the Heat Transfer in Solids and the Multiphysics coupling.

### 5.2.3 Drag Coefficient Model

The simulation model used for assessing the drag coefficient was not built from scratch. An already-made COMSOL file for simulating the drag coefficient over an Ahmed body was imported and altered to fit the geometry of the vehicle in this project. An Ahmed body is a benchmark for aerodynamic simulations. In this simulation, only half of the geometry is simulated and then mirrored to save on computation.

The only change that was made to get this simulation to work for this project was to replace the geometry of half of an Ahmed body with half of the geometry of the intended vehicle in this project. To do this, the Ahmed body geometry was deleted and the body of the intended vehicle was built from 9 rectangles, called blocks in COMSOL, that were arranged and merged with a Union to get the shape of a wedge which can be seen in Figure 5.12. This is a 2D view of the 3D geometry.

After changing the geometry of the vehicle in the simulation, all physics that were previously set up in the simulation file was assigned to the corresponding faces of the new geometry. The last change that was made was to change the inlet velocity, in the Parameters, to 7 m/s. This is equivalent to 25.2 km/h and therefore gives the estimated drag coefficient at the vehicle's intended top speed. The simulation was then run and the estimated drag coefficient could be retrieved.
5.2.4 Energy Consumption Model

An efficiency map was retrieved from the motor model and the drag coefficient was calculated using the drag model. These values were then used in a MATLAB script that originally was meant for calculating fuel consumption for parallel hybrids. However, this script can also, with a few adjustments, estimate the power used by a purely electric vehicle. The changes that were needed for this are listed below:

- Change ICEpower to 1 Watt
- Turn Hybrid operation on (Hybrid=1)
- Turn battery depletion on (Depletion=1)

These changes will effectively remove the impact of the ICE. When this was done, the vehicle parameters were put into the script. The following are the values that were set:

- Final gear ratio 1:1, since hub motors are used (gr2 = 1)
- Vehicle and driver weight was set to 95 kg, 20 kg for the car and 75 kg for the student performing this project ($M_v = 95$)

- Wheel radius of 8.40 cm, which is the radius of the hub motors with rubber tire ($r_w = 0.0840$)

- Drag coefficient of 0.43, retrieved from simulations in COMSOL at 25 km/h ($C_d = 0.43$)

- Roll resistance coefficient of 0.006. Bicycle tyres on asphalt have a coefficient of 0.004 which was multiplied by 1.5 ($C_r = 0.006$)

- The projected front area of the vehicle is 0.55 m wide and 0.8 m high ($A_v = 0.55 \times 0.8$)

- Max speed of 25 km/h ($v_{max} = 25/3.6$)

- Battery capacity of 500 Wh ($W_{batt} = 100 \times 3600 \times 5$)

The efficiency map was imported from COMSOL as a Table and adapted to the MATLAB script through some lines of code that can be seen in Appendix A. Different driving cycles are applied to get a plethora of outcomes. All of which had a top speed of 25 km/h.

The actual simulation is then performed with the Simulink file: Parallel-V21-R2018b. The current driving cycle is chosen and the Simulink file is run. The state of charge is examined once the simulation has finished. The energy consumption is calculated by taking the difference in SOC from start to finish multiplied by the capacity of the battery. This value is then divided by the total distance travelled to get the energy consumption per distance, in Wh/km.

### 5.2.5 Chassis Strength Model

The geometry of the chassis in its extended state was modelled in CAD software and then imported to COMSOL for strength analysis. For simplicity, all of the domains were assigned aluminium as the material. The physics for this simulation is a Solid Mechanics physics selection where the three wheels are fixed in place with a Fixed Constraint on these domains. The seat is loaded with 800 Newtons of downward force with a Boundary load and another boundary load is applied to the chassis directly with 150 Newtons for a total of 950 Newtons of downward load. This is to simulate the max load of the vehicle. The stress as well as where the chassis wants to bend during this
load can be seen in Figure 5.13. The actual chassis displacement during this simulation can be seen in Figure 5.14.

Figure 5.13: Chassis stress with 950 Newtons of downward load

Figure 5.14: Chassis displacement with 950 Newtons of downward load
Contact Pairs were then specified between the inner and outer square tubes that are in contact but not welded together. This specification results in COMSOL treating the touching aluminium tubes as non-transparent. Meaning that they can not go through each other while bending. A continuity was applied to all of these Contact Pairs in the physics section. The Study in this case is a stationary study step as the resulting data that is of interest is the static stress and displacement of the chassis during max load.

5.3 Hardware Implementation

The following sections explain how the practical work was carried out as well as how the prototype was made.

5.3.1 Battery Assembly

Two battery packs were made for this project. One smaller 13s5p pack for testing and as a backup in case the larger 13s10p pack failed. Both battery packs were made from used 18650 lithium-ion cells taken from defective battery packs, one of which can be seen in Figure 5.15. The smaller pack consists of 75 individual cells and the larger one has 131 cells for a total of 206 cells used in this project.

![Figure 5.15: A defective battery pack](image)
Disassembly of Defective Battery Packs

When disassembling battery packs, it is of utmost importance not to short any of the series connections. Lithium-ion batteries have a high power density and are prone to combustion during thermal runaway. Furthermore, defective battery packs often have one or more cells that have been punctured and therefore leaked. The electrolyte within these batteries can cause skin and eye damage. If the electrolyte mixes with water or ignites it becomes even more harmful.

Safety equipment should always be used when disassembling lithium-ion battery packs, such as safety glasses, gloves and non-flammable clothing.

All cells within a battery pack consisting of 18650 cells are spot welded together with nickel, or nickel-plated, strips. These connections need to be broken in order to separate each series bundle of cells from each other. This was done by prying up the nickel strips with a small screwdriver so that a scissor blade could fit between the strip and the cells. The strips were then cut with the scissors.

Once all of the series connections are removed and one is left with bundles of cells only connected in parallel, each bundle was measured with a volt meter. All packs that showed a voltage above 2.5 Volts were kept and the other bundles were discarded. The 206 cells needed for the two battery packs were scavenged from 4 different defective packs. The 75 cells for the smaller battery were taken from a 13s9p battery pack. Therefore, all of the cells for this pack are from the same batch. The cells for the larger battery pack were taken from three different 10s5p battery packs. Two of these packs were built with the same type of cells. Only 4 series bundles out of a total of 43 from these defective packs showed a voltage of zero.

Balancing and Matching of Battery Cells

To get the most out of each battery pack it is necessary to arrange the cells so that all parallel bundles have as close to the same capacity as possible. Therefore, each parallel bundle taken from the defective battery packs were charged and then fully discharged to measure the capacity. This was done with a balance charger that records the capacity going in and out of the battery. This setup can be seen in Figure 5.16
This was done for each parallel bundle and the capacities were written down and taped on each corresponding bundle. The parallel connections were kept intact from the defective battery packs since these cells already are matched.

When all of the capacities were measured the matching could begin. The bundles were matched in parallel so that each series got approximately the same capacity. No parallel bundle was comprised of different types of cells since this can result in the current drain being uneven because of the differences in internal resistance between different cells. Therefore, the larger pack was arranged with nine series of the same type of cells and four series of a different cell manufacturer. The smaller pack only uses one type of cell.

**Assembly of the Battery Packs**

Once the cells were matched they needed to be connected to each other. As described in the disassembly section, this is done with a spot welder and nickel strips. The spot welder that was used in this project is a timing and
current limiting board connected to a 12 volt, 200 Ah, Lithium Iron Phosphate (LiFePO4) battery that has a maximum discharge of 200 A, limited by its BMS. The timing board needs a high current discharge to function properly and the connections need to be sound in order to carry that amount of current.

The parallel stages were welded together first. When each parallel stage was completed, with 10 cells for the large pack and 5 cells for the small one, the parallel bundles could then be connected in series to each other. This was done with an alternating orientation of the parallel bundles to make compact battery packs. During the assembly of the larger pack, it was noted that one of the 10 cell bundles did not hold its charge. It was self-discharging faster than it should. Due to this, the whole bundle was replaced with 11 cells of the cell type used for the smaller battery pack to not mix cell types per stage. This stage got 11 cells instead of 10 as they could not hold the same capacity as the other ones used in the larger battery. This bundle of 11 cells was placed as the topmost bundle in the pack, e.g. as the main positive terminal connection so that it is easy to replace once a suitable 10-cell bundle can be found. Therefore, this battery is not a true 13s10p pack. All of the 13 series stages contain 10 cells except for the last one which has 11, effectively resulting in a 131-cell battery pack. A picture of the large pack can be seen in Figure 5.17 and the smaller battery pack can be spotted in Figure 5.19.

Once all of the parallel and series connections were done, a nickel strip was spot welded to the main negative of each battery pack. This nickel strip was then soldered onto the negative input terminal of the BMS. The balance leads of the BMS were then soldered onto each positive stage of the series connections. The leftmost balance wire is connected to the positive terminal at the lowest potential, the first stage, and the rightmost is connected to the main positive pole, the last stage.
Top Balance of the Battery Packs

Top balancing is done after assembling the packs because of the risk of accidentally shorting a section while assembling. If this were to happen, it would be much safer to be handling completely discharged batteries than fully charged ones.

This kind of balancing is good to utilise on used cells and cells of different types since it means charging each parallel bundle to its maximum voltage individually with a balance charger. This is advantageous since the BMS only can balance each stage above 4.18 V and with a current of 25 mA. The different series stages will not discharge at the same voltages since they have slightly
different capacities; therefore, it is better to start the battery off with all cells fully charged. The BMS will then limit the battery once one stage reaches 3.0 V while discharging instead of once one stage reaches 4.2 V while charging. This will lead to an overall more balanced battery pack during normal use, e.g. not only complete discharges before charging.

The easiest method to use is to charge the whole pack with a 48 V charger until the charging is stopped by the BMS due to one series stage reaching 4.2 V. All series stages are then measured with a multimeter and each stage that is not at 4.2 V is then charged individually to 4.2 V with a balance charger. As depicted in Figure 5.18

Figure 5.18: Battery pack top balancing
50 | Prototype Process

5.3.2 Motor Model Validation

Once the small battery was completed, motor torque validation could commence. The input current of the motor was measured at different torques to compare to the results of the COMSOL motor model. The current was measured with an, clamp, Ampere metre and the torque tests were implemented by tying weights to string and lifting them vertically with one of the motors. The radius of the actuating arm was 8.26 cm and the resulting torque was calculated. The test setup can be seen in Figure 5.19.

![Torque measurement setup with the smaller battery pack](image)

Figure 5.19: Torque measurement setup with the smaller battery pack

The stator shaft of the motor was fixed in place with a vice and the vice itself was attached to a table with a suction cup. This setup was rigid enough
to conduct tests with up to 10 kg weights.

When a few torque and corresponding current measurements had been taken a comparison was made with the results from the motor model. The model corresponded quite well with the actual tests, but it was realised that the number of turns per coil in the model might have been guessed too low. Changing this number from 13 turns to 14 and running the simulations again resulted in a model that very closely resembled the measurements.

5.3.3 The Chassis

The chassis is made out of aluminium. The most appropriate method for welding aluminium, especially thin aluminium, is TIG welding. TIG stands for Tungsten Inert Gas. The name describes the welding method, the electrode is made out of tungsten and an inert gas, usually argon, surrounds the arc so that the weld does not react with oxygen and other gases while welding.

Aluminium was chosen for the chassis as it has a high strength-to-weight ratio. The material used was 30 mm square tubing and 25 mm square tubing with respective thicknesses of 2 and 1.5 mm. All of the chassis material came from two, two meters long 30 mm square tubing and two, two meters long 25 mm square tubing. The aluminium tubing was cut up into pre-decided lengths on a metal band saw. Each edge was then filed with a metal file to get a flat finish.

The aluminium square tubing used for this chassis is very thin. A low amperage limit is needed when welding these thin aluminium materials to not burn through the material. In this case, a current limit of approximately 60 A was set when welding the 1.5 mm square tubes and approximately 90 A limit for the 2 mm aluminium welds. Furthermore, when the steering wheel, as well as the motor mounts, were welded to the chassis the current limit was set to approximately 140 A. This was done because of the higher aluminium thickness of these parts.

Before joining two parts together with a weld, both of the surfaces have to be clean for a good bond. If there were paint or anodized aluminium where the welds were intended, this was filed down until pure un-anodized aluminium was visible for at least one centimetre away from the edges that were to be welded. The areas that were to be welded were then brushed with a wire brush.
to remove any debris. Once all parts are clean, the welding can be done.

The actual welds are done by first heating up a small area of the two materials that are to be bonded so that a small pool of floating aluminium is formed. This is done with the TIG torch, adjusting the amperage with a foot pedal. Once a pool has formed and starts to sink into the material, extra aluminium is added from the filler material. This process is repeated as the welding area is traversed until an edge is reached. Aluminium heats up rather quickly and; therefore, the heat usually needs to be adjusted down once an edge is approaching. This is done by easing up on the foot pedal. The chassis and the seat can be seen in their extended state in Figure 5.20.

![Figure 5.20: Chassis in its extended state with the fabric seat](image)

5.3.4 The Seat

The seat is made out of Nylon fabric and four eyelets. Fabric was chosen for the seat for three reasons. It is lightweight, it is removable and it gives a bit of dampening. There is no other dampening on the vehicle. The Nylon fabric
was folded to get a double layer. It was then sewn around the edges as well as a cross pattern, with a sewing machine, across the whole seat which measures 50x46 cm. A hole was made in each corner and the eyelets were inserted accompanied with fabric glue. Each eyelet was then hand stitched from the centre and outwards to the fabric to strengthen the attachment of the eyelets to the fabric.

The seat is attached to the chassis by placing each eyelet over the four pins that are screwed into the vertical aluminium square tubes on the rear part of the chassis. This is displayed in Figure 5.20. It is locked in place at the rear pins with 3D-Printed disks so that it is easier to handle and does not fall off by itself.

5.3.5 The Shell

The shell consists of fiberglass and nylon fabric. There are 6 individual fiberglass pieces that make up the shell. The back base is the largest one. This one is attached to the back part of the chassis with bolts. The top back part is attached to the previously mentioned fiberglass part with hinges. There is a third fiberglass part connected to this one with hinges as well. The front part of the vehicle also has three fiberglass parts. The front plate is connected to the front part of the chassis with rivets. A fiberglass lid is attached to this part with hinges and the last fiberglass part slides within the lid. All fiberglass parts can be seen in Figures 5.24 and 5.25.

The fiberglass was laid on plugs made out of XPS and spray foam, the plug for the main part can be seen in Figure 5.21. The surface of the plug where the fiberglass was supposed to go was sanded and painted with water-soluble paint to get a smooth surface and to prevent the polyester from reacting with the XPS. A gelcoat was then applied on top of the paint. This was let to dry until it got sticky. The first layer of polyester was then applied on top of the gelcoat with a brush. A layer of fiberglass was put on the polyester and another layer of polyester was brushed into the fiberglass. An aluminium roller was used to flatten the fiberglass and ensure even distribution, and no oversaturation, of the polyester. This process was repeated to add additional layers of fiberglass to the parts. Some of the parts were made with one layer, some with two layers and some with a mix of both. Extra layers were added where needed to strengthen the shell in critical points while keeping the total weight as low as possible.
5.3.6 Assembly of Prototype

The Printed Circuit Board (PCB) boards of the motor controllers were removed from their casing and all wires for functions not used were removed. The PCB:s were then directly mounted to the aluminium chassis by drilling holes in the chassis and screwing the heat sinks for the IGBT:s directly to the chassis. This can be seen in Figure 5.22.
Two holes were then cut in the main part of the shell so that the motor mounts could protrude it. This was done with an oscillating multi-tool and the results can be seen in Figure 5.23. All the fiberglass parts were then cut to shape and sanded for a better finish. All parts were painted with alkyd paint once the finish was deemed satisfactory.

The fiberglass parts were mounted to the chassis with rivets and bolts. Rivets were used on parts that have no need to be removed in the future. Bolts were used on the parts that should be removable. Hinges were used to attach all the folding parts to each other, such as the fiberglass lids. A polycarbonate sheet was used as the front window. This was attached to a flat piece of fiberglass as an extender and then attached to the front lid with hinges so it can fold into the front lid. A picture of the front lid and the extended window unfolded can be seen in Figure 5.24. The back lid was also attached to the main body part with hinges and acts as a backrest when unfolded. This lid also has a hinged extender made out of fiberglass. All of these folding parts of the shell can be seen unfolded and how they attach to each other in Figure
The shell holds itself up by the two extended parts pressing against each other. However, when first testing this it was realised to be too weak. Therefore, the two strings that can be seen in Figure 5.25, as well as two 3D-printed backstops attached to the back lid, were added. The backstops press on the main fiberglass part when the back lid is opened 90 degrees. The strings act as a counterforce to the window part pushing the back lid backwards. Furthermore, two strips of wood were added to the sides of the window with rivets to strengthen it as it was bending too much. These can also be seen in Figure 5.25. The space between the front and the main part of the shell is covered with nylon fabric. This fabric is currently attached with tape but will be sewn into the fiberglass parts by drilling small holes in the fiberglass and hand sewing between them.
A 3D printer was invaluable during the assembly process as no parts actually fitted well together. Small spacers and mounts were designed and printed to desired geometries to get these parts to fit nicely together. The seat mount also got 3D-printed spacers between the aluminium tubing and the seat so that it does not rip against the sharp edges. The previously mentioned backstops were also 3D-printed and more parts will be made on the printer to get everything to work more smoothly, such as a handle for pulling the suitcase when folded and more.
Figure 5.25: The finished prototype when unfolded
Chapter 6

Results and Analysis

All of the relevant results from this project are presented in this section. The energy consumption and motor torque are touched upon as well as the performance of the finished prototype. All results from the various simulations are also presented here. The section ends with a validity analysis.

6.1 Major results

The results from simulations and practical testing are presented here.

6.1.1 Motor Torque and Efficiency

The motor model is used to estimate the efficiency of the hoverboard motors. The torque produced by the model at different peak winding currents was compared to measurements at the same peak currents for the actual motor to validate the model. The model was first set up with 13 windings per coil. However, during the validation of the torque it was realised that 14 windings per coil corresponded much better to reality. Since this was an estimated value from the start, it was changed from 13 turns to 14 turns. The simulated torques at different currents can be seen in Table 6.1 and Figure 6.1, for 14 turns, with the corresponding results from the measurements. It is important to note that the torque measurements were measured with very unreliable techniques and can, therefore, contain some errors. There is, however, a clear correlation between the simulated and measured values. Only diverging at higher currents, which indicates that the model might be understating the efficiency at higher currents.
### Table 6.1: Torque validation: Simulated vs. Measured

<table>
<thead>
<tr>
<th>Peak Line Current</th>
<th>Torque - Simulated</th>
<th>Torque - Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.84 A</td>
<td>0.70Nm</td>
<td>0.65Nm</td>
</tr>
<tr>
<td>3.40 A</td>
<td>1.31Nm</td>
<td>1.24Nm</td>
</tr>
<tr>
<td>4.95 A</td>
<td>1.92Nm</td>
<td>1.86Nm</td>
</tr>
<tr>
<td>6.51 A</td>
<td>2.51Nm</td>
<td>2.48Nm</td>
</tr>
<tr>
<td>8.35 A</td>
<td>3.21Nm</td>
<td>3.50Nm</td>
</tr>
</tbody>
</table>

With the model validated, an efficiency map could be derived from the model. This efficiency map can be seen in Figure 6.2. These motors have a maximal efficiency of 88.74 % according to the motor model. This peak efficiency is reached at approximately 80 rad/s and 1.5 Nm of Torque for both motors e.g. 0.75 Nm of Torque for one motor. At this operating point, the electric power is 135 W and the resulting mechanical power is 120 W.
Comparing these two plots, one can conclude that efficiency is not everything. It is clear that operating the motors at low speeds and high torque is not preferable since the efficiency is low and the losses are high. However, one could be fooled to believe that it is advantageous or at least not disadvantageous to operate the motors at high power, e.g. both high torque and velocity. The efficiency is still good at these operating points but the losses are high. It was concluded from this simulation that the best operating point is at high speeds and low torque.

The maximum AC peak current, per phase, measured during testing was 50.1 A. This current was measured at full throttle going up a steep hill. Using this current in the motor model resulted in an average torque of 13.5 Nm per motor. This is close to the motor specifications, but actually a bit higher than the specified maximum torque of 12 Nm. The DC current at the same time was 19.9 A at a voltage of 50 V. That results in an instantaneous power of approximately 1000 W. The highest DC current overall was measured at 21.8
A for a total power of 1090 W.

![Electrical machine Losses](image)

Figure 6.3: Simulated losses at different operating points

### 6.1.2 Motor Heating

The heating model was simulated for all peak currents ranging from 1 to 21 A. However, only the results from the highest rotational speed of 840 RPM are included here since the heating increases with speed and current. Therefore, this is the worst case scenario and can be seen in Figure 6.4. The simulated temperature reaches a peak of slightly above 200 degrees celsius. The temperature is lowest in the centre of the stator and highest in the excited coils and surrounding metal of the stator. The temperature for each peak current preset was plotted and can be seen in Figure 6.5.
Figure 6.4: Steady state temperature of the stator and coils at 840 RPM and 21 A peak current.

Figure 6.5: Steady state maximum temperature at 840 RPM, from 1 to 21 A peak current.
6.1.3 Energy Consumption

The efficiency map was used to simulate the energy consumption of the vehicle for different driving cycles. Three of these cycles are standardized cycles, these are IdealMotion, nedc and CycA10 cycles. However, these cycles are used for traditional cars and all include top speeds above 25 km/h. Therefore, the speeds of these cycles were divided by integers so that the max speed of each driving cycle is approximately 25 km/h. The speed of the nedc cycle was divided by 5, IdealMotion by 2 and CycA10 by 3. The three other cycles were created for this project. Two cycles with constant speeds of 20 km/h and 25 km/h, these were given the names ConstantCycle20 and ConstantCycle25 respectively. The last driving cycle, named RealisticCycle, is designed according to how this vehicle would most likely be driven. The simulated energy consumption for all driving cycles can be seen in Table 6.2 with accompanied average velocity per cycle.

Table 6.2: Simulated and measured energy consumption for different driving cycles

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>Energy consumption (Wh/km)</th>
<th>Average Velocity (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nedc/5</td>
<td>9.78</td>
<td>6.61</td>
</tr>
<tr>
<td>ConstantCycle20</td>
<td>10.92</td>
<td>20.16</td>
</tr>
<tr>
<td>IdealMotion/2</td>
<td>11.01</td>
<td>15.95</td>
</tr>
<tr>
<td>ConstantCycle25</td>
<td>13.69</td>
<td>25.20</td>
</tr>
<tr>
<td>RealisticCycle</td>
<td>14.57</td>
<td>21.15</td>
</tr>
<tr>
<td>CycA10/3</td>
<td>15.58</td>
<td>10.56</td>
</tr>
<tr>
<td>Completed prototype</td>
<td>16.38</td>
<td>16.11</td>
</tr>
<tr>
<td>First test</td>
<td>16.74</td>
<td>16.17</td>
</tr>
</tbody>
</table>

The different driving cycles can be seen in Figure 6.6. It depicts the driving cycles in the order they are presented in Table 6.2, starting with nedc/5 and ending with CycA10/3. ConstantCycle20 and 25 are excluded from this figure as they are constant speeds.
6.1.4 Prototype Performance

A first test was conducted once the chassis as well as all of the electronics were ready. The controllers and the battery were taped to the chassis as well as a power meter and some controls for accelerating and braking. A 7.05 km test run was conducted with this setup, e.g. without the shell. This distance was travelled with an average speed of 16.17 km/h. This included a four-minute long full stop. This test had a total energy consumption of 118 Wh for an average of 16.74 Wh/km. This run is presented in Table 6.2, labelled First test, for comparison with the simulations. The electronic braking used during this test is of a dynamic type, more specifically plug braking. This reverses the field in the motor to achieve strong brake action. This type of braking consumes power and puts a lot of stress on the motors.

A final test run was conducted with the vehicle completed with the shell as depicted in Figure 5.25. This test run followed the same route as the first test run and was therefore 7.05 km long. With the completed prototype, this test run had a total energy consumption of 115 Wh for an average of 16.31 Wh/km, which is slightly better than without the shell. However, the average speed for this run was slightly lower at 16.11 km/h and plugging was still used as the only form of braking. This run is also included in Table 6.2, labelled Completed prototype.

The battery pack came in at a weight of 6.7 kg with cables and enclosure.
This was a little heavier than expected. However, where the weight differed the most from what was expected was for the fiberglass parts. All of these combined, with the polycarbonate window, weigh almost 9 kg. A breakdown of the weight of all components as well as the finished vehicle with different setups can be seen in Table 6.3. Barebone represents the finished prototype without any shell. This is how the vehicle was used during the First Test. The completed prototype with all of the fiberglass parts needed for the full enclosure is labelled Full Shell and came in at a total weight of 29 kg. However, the total weight of the vehicle if the extending fiberglass parts, as well as the front lid, are removed is only 26.1 kg. This leaves the prototype with all the necessary parts to protect the battery and chassis from debris and water coming from underneath. Furthermore, it is also what is required to make the vehicle look like a suitcase when folded. This is labelled Necessary Shell in Table 6.3.

Table 6.3: Component and vehicle weights

<table>
<thead>
<tr>
<th>Part</th>
<th>Expected Weight (kg)</th>
<th>Actual Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Battery</td>
<td>6</td>
<td>6.7</td>
</tr>
<tr>
<td>Chassis and steering</td>
<td>7</td>
<td>7.8</td>
</tr>
<tr>
<td>Controllers</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Fiberglass and window</td>
<td>2.5</td>
<td>9</td>
</tr>
<tr>
<td>Barebone</td>
<td>17.5</td>
<td>19.7</td>
</tr>
<tr>
<td>Full Shell</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>Necessary Shell</td>
<td>19</td>
<td>26.1</td>
</tr>
</tbody>
</table>

The battery pack, with 131 cells, that is used in the vehicle has a capacity of 20 Ah at a 1C discharge rate. This is equivalent to 962 Wh at a nominal voltage of 48.1 V. Driving this vehicle with the same energy consumption as in the tests would result in a max range of 58.7 km. Furthermore, the size of the prototype is 700x500x380mm while folded, excluding the protruding back wheels. These can, however, be removed and placed inside of the vehicle.

6.2 Reliability Analysis

The reliability of the torque measurements is questionable since the setup used was very crude and somewhat unstable. Furthermore, hitting the sweet spot on the throttle where the motor just started and continued rotating during the
tests was very difficult. However, three runs were made for each load while measuring the torque and the average peak current of the runs was chosen as a comparison to the simulated values. The results of all the measurements can be seen in Table 6.4. Taking the average peak current of each torque measurement smooths out the underlying reliability problems in the torque measurements.

Table 6.4: Torque measurement reliability

<table>
<thead>
<tr>
<th>Torque</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Average Peak Line current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65 Nm</td>
<td>1.73A</td>
<td>1.86A</td>
<td>1.94A</td>
<td>1.84 A</td>
</tr>
<tr>
<td>1.24 Nm</td>
<td>3.55A</td>
<td>3.44A</td>
<td>3.21A</td>
<td>3.40 A</td>
</tr>
<tr>
<td>1.86 Nm</td>
<td>5.03A</td>
<td>4.86A</td>
<td>4.98A</td>
<td>4.95 A</td>
</tr>
<tr>
<td>2.48 Nm</td>
<td>6.10A</td>
<td>6.39A</td>
<td>7.03A</td>
<td>6.51 A</td>
</tr>
<tr>
<td>3.21 Nm</td>
<td>8.59A</td>
<td>8.54A</td>
<td>7.93A</td>
<td>8.35 A</td>
</tr>
</tbody>
</table>

6.3 Validity Analysis

The measured motor torque corresponds very well with the simulated motor torque as can be seen in Figure 6.1 for low torques. It was not possible to measure higher torques with the setup available. Therefore, the validity for higher torques could not be determined for the model. However, the strong correlation for lower torques was deemed sufficient to validate the motor model. Furthermore, the validity of the heating model could not be validated.

The actual average energy consumption of the prototype was somewhat higher than the simulated span of energy consumption for different driving cycles. The measured energy consumption was closest to the simulated CycA10/3 driving cycle with 15.58 Wh/km. The best measurement for the prototype came in at 16.38 Wh/km which only is a difference of 0.8 Wh/km. The simulated average energy consumption seems to have been somewhat optimistic; however, the results from the simulations are close enough to the measured data to deem it a good tool for estimating energy consumption.
Chapter 7

Discussion

The prototype built in this project met all goals set in the beginning with a minor overdraft of the vehicle weight. The total weight of the vehicle was about 9 kg heavier than the 20 kg max weight set in the beginning. The range, with this battery pack, is about 58.7 km. However, this pack was built with used cells that on average had a capacity of 2000 mAh. There are 18650 cells available, to anyone, with a capacity of 3500 mAh at the same cell weight. The battery pack built in this project has a capacity of 20 Ah, equivalent to 962 Wh at nominal voltage. If it were built with new cells at 3500 mAh of capacity each, it would have a total capacity of 35 Ah, which is 1684 Wh. Such a battery pack would weigh the same as the one used in this project and have the same size; however, it would allow for a range of 102.4 km based on the tests that were performed. The tests were; however, done on a demanding test circuit with a lot of braking, accelerating and tough inclination. The price difference between new and used, discarded, cells is huge, which is why used cells were used in this project.

The total weight goal of 20 kg might be possible to reach if different materials are used. The chassis could have been made in carbon fibre if the time and monetary budget would have been larger. Furthermore, using carbon fibre for the shell would also have saved on weight. The motors, if built specifically for this vehicle could also have been made lighter. The dimensions and outer casting of the motors are unnecessarily thick for this project. Also, if one is satisfied with a range of 100 km for mixed driving, 9 cells in parallel would be sufficient for the battery pack if cells with 3500 mAh of capacity are used. This would result in a battery pack with 117 cells instead of 131, saving 588 grams of weight. The range per charge would then be 92.2 km with
such a battery at 1512 Wh capacity. It is important to note that all capacities here are given at a 1 C discharge rating. Meaning that this is the capacity if continuously discharged at 1 C. For 9 cells in parallel at a capacity of 3.5 Ah that is 31.5 A. Such high currents are almost never reached with this vehicle and the average current draw is significantly lower. Therefore, it is fair to assume that the capacity will be higher than stated as capacity increases with lower discharge currents for lithium batteries. That is why I state that a 13s9p pack would probably be sufficient to reach a range of 100 km with this vehicle if the cells have a capacity of 3.5 Ah each. Furthermore, the actual range with the current battery pack is probably higher than 60 km due to the same reason. I have driven approximately 16 km in total since the battery pack was last fully charged and the resting voltage of the battery is currently at 49.83 V, which is a decline of 4.77 V from the fully charged battery at 54.6 V. The voltage is not a perfect indicator of how much capacity is left, but it is correlated and after driving approximately 16 km, the voltage is not even at the nominal of 48.1 V

A heat rating could not be found for the motors that were used in this project. The maximum heat tolerance of a motor is defined by the insulation rating of the copper as that is what melts first. The insulation classes range from 130 to 180 degrees Celcius. Assuming that these motors have the lowest insulation class, B, of 130 degrees Celcius it was still considered safe to operate them at 48 V for this application. Looking at Figure 6.5 one can see that the highest simulated temperature of the stator and coils is 200 degrees Celcius at steady state. However, this is if the motor is run at this operating point for a long period of time which is not reasonable. This operating point is probably never reached as it is the max speed and max torque simultaneously, resulting in incredibly high power. The average electrical power while driving is only about 80-130 watts and the peak DC current measured while testing the prototype was only 21.8 A for a fraction of a second. That is 1090 W peak electrical power for a very short time. Actually being able to hold one’s hand on the motors after driving for several kilometres further supports the claim that there is a low risk of overheating. An average person can hold something for a longer period of time at a maximum of 65 degrees Celcius. However, this is the rotor that is somewhat warm to the touch which indicates that the stator should be even hotter.

The efficiency difference between the complete prototype and the prototype without the shell is small. The energy consumption for the whole prototype was 16.38 Wh/km and without the shell, it was 16.74 Wh/km. This difference
could be attributed to better aerodynamics with the shell but it could also be
due to the slightly lower average speed. It could also have been more wind
during one of the tests and more braking used on the other. In other words, the
difference in energy consumption is so small that aerodynamics seems to have
little effect on the efficiency at these low speeds. At least with consideration
to the added weight of the shell at approximately 9 kg. Because of this, and
the shell structure being very flimsy and awkward to operate, it was decided
to strip off some of the body parts. The parts that were left on the vehicle were
the parts that made it look like a suitcase while folded. Those are the main
part of the shell, the back lid and the front plate. This makes the unfolding
much easier and quicker as well as removes some weight but it removes the
posibility of full enclosure. However, it is possible to build and fit all parts
necessary for a fully enclosed foldable vehicle as proven in Figure 5.25 that
can fold into a suitcase of the previously specified size. Although, it might not
be the most practical solution.

From this project, I can say that these small hoverboard motors are well-
built and can actually deliver above their specifications. The motors used in
the project were rated at 12 Nm of max torque at a power rating of 350 W
each. Using the motors and the simulation model, it seems that the motors
actually were able to deliver a max torque of 13.5 Nm. They are designed to
be powered by a battery with a nominal voltage of 36 V. In this project, 48 V
were used and no problems were discovered. Assuming that the currents are
the same for a 36 V battery pack and a 48 V battery pack, that would mean
that the power rating at 48 V should be 467 W per motor. Running the motors
at 48 V will of course increase the heat in the motors, as they can rotate faster,
but they seem to be able to handle it.

During testing, it became clear that larger wheels are necessary for this
vehicle. Not for speed or efficiency but for comfort. These small, hard rubber,
hoverboard wheels give almost no dampening. Therefore, this prototype is
only pleasant to drive on really smooth pavement. As soon as the ground
becomes uneven or rougher the ride is almost unbearable. Most of the
dampening is needed on the back wheels since most of the weight is there.
Fortunately, it is possible to mount air-inflated tires on the hoverboard wheels
with a slightly bigger radius. Doing so would significantly improve the comfort
while riding the vehicle and probably even lower the energy consumption by
eliminating a lot of the vibrations in the whole vehicle, but mostly in the hub
motors.
Discussion
Chapter 8

Conclusions and Future work

The conclusions from the theoretical and practical work performed for this thesis are presented in this chapter. The limitations that arose during the project are addressed and future work on this project is suggested. The chapter ends with some reflections on the environmental and ethical aspects of this thesis.

8.1 Conclusions

The first fiberglass parts were laid directly on the XPS which resulted in the polyester and gelcoat reacting with the XPS. This resulted in bent and undersaturated fiberglass parts since the polyester sank into the XPS. This problem was easily solved by painting the XPS before plastering. Fortunately, the parts that were made directly on the XPS could be salvaged by removing them from the plug while still malleable and letting them dry out completely on flat surfaces, as both parts were just flat sheets. In addition, a release agent should be used as the first layer to get the part to release from the plug easier once it has hardened. This was not used and; therefore, the parts were very hard to remove from the plugs. The largest plug had to be dismantled to get the part to release from it.

Furthermore, it is very hard to weld thin aluminium. One will get burn through and the material will bend from the heat. Therefore, I would in hindsight have chosen material with more clearance between the inner and outer parts of the chassis. While welding these, the two parts locked up and had to be separated with a hammer which bent the front of the chassis. Even with several hours of sanding, filing and bending, the two parts still have too
much resistance while extending and collapsing the chassis. A lot of force is needed to pull it out to the extended state; which could have been avoided or mitigated if the material had better clearance.

It is possible to build a foldable electric vehicle with a range of 100 km that can fit and fully enclose one person and fold into the size of 700x500x400 mm. However, with the materials available today it might not be possible to do so while keeping the total weight of the vehicle, including the battery, below 20 kg. Furthermore, improvements need to be made to the folding mechanisms to make this vehicle more user-friendly. In its current state, it is not worth the hassle of folding and unfolding the vehicle for making shorter trips and will therefore not be used anymore until this and the riding comfort are resolved.

As a prototype, this vehicle did not end up being a vehicle that I would want to drive because of the shortcomings mentioned. However, as a proof of concept it performed remarkably and with some changes could be a vehicle that I and others would want to use.

8.2 Limitations

This project was severely limited by the resources and time available. Since this project was self-financed, the materials chosen were not only determined from the perspective of best fit. The cost of the material also played a big role in choosing what to use. Furthermore, the amount of material that was purchased was always just as much as needed or sometimes even less. This resulted in no room for errors and spillage of material. For example, there was not enough aluminium tubing to make the mounting plate for the steering wheel. The base of the scooter that was used for the steering wheel was instead cut into three pieces and welded together to bridge the gap where the mounting of the steering wheel was supposed to be. Furthermore, there was not enough polyester to make the fiberglass parts as thick as desired. This resulted in the shell being somewhat flimsy.

With better equipment and a lot more time, one could have made motors from scratch that are a lot more suited for this vehicle. This would have added the possibility to save on space and weight as well as improve efficiency. Furthermore, the design of the vehicle could have been made better with suitable machinery.

The time set aside for this project also proved limiting. Fortunately, the
design of the vehicle was already decided on before the project actually started. This helped a lot in completing the project on time. However, some parts of the building process were rushed to finish on time which resulted in subpar parts.

The longevity and durability of the prototype could not be determined since it was completed only one week before the deadline. There was simply not enough time to test the prototype over a longer period of time. Furthermore, more energy consumption measurements should have been made to get a better understanding of the actual average energy consumption for all different driving conditions. However, once again there was not enough time to do so.

8.3 Future work

All things that were set out to be done for this project were done. Some of the goals were met and others were overdrafted. Future work could include analyzing the design of the prototype to decide where it can be improved for usability, size, drag etc. In addition, motors could be made specifically for this particular vehicle that better suits it. It would be interesting to see how big of an impact such a change would have on the overall energy consumption.

Future work could also include getting this vehicle classified as a moped or a motorcycle so that the top speed can be increased. With motorcycle classification, one could remake this vehicle in a version that can travel at 90 km/h. Then it would really rival traditional cars as a commuting vehicle. However, legislation is slow and other improvements should probably be prioritized. The ultimate goal would be to have a functioning vehicle based on this prototype that can replace regular two-tonne cars for personal commutes.

A safety analysis of the vehicle should be made. All vehicles that are classified need to comply with different safety regulations depending on the classification of the vehicle. After having driven the prototype, I can say that I would not feel comfortable driving it faster than 50 km/h as it stands now. I do not think that it would handle a crash without severe damage to the vehicle and the driver in its current state. However, one has to remember that this is a proof of concept prototype that had no regard to safety.

Lastly some advice, something will always go wrong in a project like this
and one will have to rethink the plan. Things break and the practical work will take a lot more time than expected. Therefore, I would only recommend undertaking such a project with a heavily exaggerated time budget. It does not hurt to have an inflated monetary budget either.

8.4 Reflections

One of the most important aspects of this project is the proof that it is possible to build an electric vehicle that can rival traditional cars when it comes to commuting. For those who use their car solely for commuting and shorter distance travelling without cargo, this vehicle could be a suitable substitute if improved and classified so that it is allowed to travel at higher speeds and stable enough to comfortably do so. This vehicle would be much cheaper to buy, own and operate than a traditional car. Furthermore, since it is an electric vehicle built from used parts. It is much more environmentally friendly than its two-tonne, fossil fuel powered, counterpart. Furthermore, this prototype also reduces E-waste by repurposing discarded batteries as well as electronics. This vehicle could also help reduce congestion on roads and reduce the need for parking spaces as it is much smaller than a traditional car. Moreover, once you arrive at your destination you simply fold it up and take it with you. Therefore, no parking space is necessary at all. This would allow for more housing or green space within cities.

This thesis contributes to UN:s sustainable development goals 11, 12 and 13. The sustainable cities and communities goal, 11, is addressed by the possibility to reduce parking space within cities. Furthermore, it allows for "clean" transportation both within cities and allows for better communications between neighbouring cities.

The responsible consumption and production goal, 12, is mentioned because of the reuse of batteries and E-waste. The raw material of Lithium is currently very limited compared to the demand for lithium batteries, mainly from the electric car sector. Reusing discarded batteries and giving them a second life is a viable method to reduce waste and save on limited resources.

The climate action goal, 13, is related to this thesis as the vehicle presented can help reach the goal of being carbon dioxide neutral by 2050. The transportation sector has to take a more aggressive shift towards electrification in order to reach this goal. Maybe the solution is not replacing traditional cars.
with electric cars of the same size and design considering the lack of suitable batteries. A better solution could be to replace them with smaller electric vehicles that are more efficient and requires a lot less battery capacity and other materials.
Conclusions and Future work
References


Appendix A

MATLAB code

```matlab
%**********************************************************
% * This file sets the parameters for the Simulink program
% * "Parallel" and must be run prior to running simulations.
% * 170329, 170521, 171111
% *
% clear all

% Load driving Cycles

load nerc;
load us06;
load IdealMotion;
load braun;
load brotur;
load CycA10;
load CycFIGE;
load CycFTP;
load CycHFET;
```
load CycNYC;
load li85;

Table1 = readtable('C:\Users\P\Downloads\efficiencymap.dat');
Table2 = readtable('C:\Users\P\Downloads\effmap2.dat');
Table3 = readtable('C:\Users\P\Downloads\table3.txt');
Table4 = readtable('C:\Users\P\Downloads\table44.txt');
Table3([1,2,3],:) = [];
Table4([1,2,3],:) = [];

nedc(:,2) = nedc(:,2)/5;
IdealMotion(:,2) = IdealMotion(:,2)/2;

% nedc1 = nedc(1:900,1);
% nedc2 = nedc(1:900,2);
% nedctemp = [nedc1 nedc2];
% nedc = nedctemp;

us06 = CycA10;
us06(:,2) = us06(:,2)/3;

Table_temp = Table1;
Table1 = Table4;
Table3 = Table4;
ICEconventional=1;

acceleration = [0 0 0 0 0 0 0 0.2 0.3
 0.4 0.5 0.6 0.7 0.8 0.9 1 1.2 1.4 1.6
 1.8 2 2.4 2.8 3 3.2 3.4 3.6 3.8 4 4.2
 4.4 4.6 4.8 5 5.2 5.4 5.6 5.8 6 6.2 6.4
 6.6 6.8];
retardation = flip(acceleration);
retardation = retardation;
constant = [7 7 7 7 7 7 7 7 7 7 7 7 7 7 7].

NewCyc = IdealMotion;
tempCyc = [acceleration constant retardation acceleration constant constant constant retardation];
tempCyc = [tempCyc tempCyc];
tempCyc = tempCyc(1:1191);
NewCyc(:,2) = tempCyc';
constant = [constant constant constant constant constant constant constant constant constant constant constant constant constant constant constant];
constant = constant(1:1191);
constant = constant;
%NewCyc(:,2) = constant'
us06 = NewCyc;

avg1 = mean(nedc(:,2))*3.6
avg2 = mean(us06(:,2))*3.6
avg3 = mean(IdealMotion(:,2))*3.6
avg4 = mean(nedc(:,2))*3.6

% Specification when simulating a hybrid vehicle
ICEpower=1; % Default is that the ICEpower + EMpower should be 100kW
EMpower=1600;
TorqueEMmax=28;
% Vehicle type
+++++++++++++++++++++++++++++

Fuel = 1; % Gasoline (Fuel = 1), Diesel (Fuel = 2), Ethanol (Fuel = 3)
Hybrid = 1; % 0 for conventional, 1 for parallel hybrid
Depletion = 1; % 0 for Charge Sustaining mode and 1 for depletion mode
StopAndGo = 0; % 1 if stop & go is on
Speedy = 0; % 1 for "sporty" driving

% ICE parameters ++++++++++++++++++

if Fuel == 1 | Fuel == 3, % Gasoline or Ethanol
load EtaICE_OTTO;
EtaICE = EtaICE_OTTO;
elseif Fuel == 2, % Diesel
load EtaICE_DIESEL;
EtaICE = EtaICE_DIESEL;
else
    'Erroneous fuel choice'
end

[value, row] = max(max(EtaICE'));

Pice_max = ICEpower*Hybrid + ICEconventional *(1-Hybrid);
if Fuel == 1,
   wice_max = 6000*2*pi/60;
elseif Fuel == 2,
   wice_max = 4500*2*pi/60;
else
    'Erroneous fuel choice'
end
wice_min = 700*2*pi/60; % 700 rpm idle speed
Tice_max = Pice_max/(wice_max*row/(length(
EtaICE) -1));

[PtoT, Tice, Wice, Tlim_ice, FuelConsICE] = CreateICEmap (Pice_max, wice_max, Tice_max, EtaICE);

% Ratio for the final gear between the traction motor and the wheels
*************

gr2 = 1;

% Mechanical parameters
++++++++++++++++++++

Mv = 95; % Vehicle curb weight + 250 kg passenger and cargo
rw = 0.084 * 1; % wheel radius (m)
Cd = 0.43; % @25 km/h
            % air_resistance. (Sports Car 0.3-0.4,
            % Ecomony Car 0.4-0.5, Pickup Truck 0.5,
            % Tractor-Trailer, with fairings 0.6-0.7,
            % Tractor-Trailer 0.7-0.9)
Cr = 0.005; % roll resistance
            (0.006...0.008 for low roll resist tires
            . 0.01...0.015 ordinary tires)
Av = 0.5 * 0.80; % Front area, Width*Hight
                (2.57 m²)
rho_air = 1.225; % Air density [kg/m³]
grav = 9.81;

Pvehicle_max = (Cr*Mv*grav + 1/2*rho_air*Cd*
                Av*vmax^2)*vmax;

% Gearbox +++++++++++++++++++++ utvx =
            (speed of ICE)/(speed of wheels) incl.
final gear
utvx_max = wice_max / ((vmax / 5) / rw); % "First gear". Arbitrary, it is assumed that top speed of gear 1 is at 1/5 of max speed
utvx_min = wice_max / (vmax / rw) / 1.3; % "Fifth gear". Under the assumption that top speed of the engine and the vehicle "coincides"

Number_of_gears = 5;

Utvx_vect = zeros(1, Number_of_gears + 1);
Utvx_vect(1, 1) = utvx_min;
Utvx_vect(1, length(Utvx_vect(1, :))) = inf;
for i = 2: Number_of_gears,
    Utvx_vect(1, i) = Utvx_vect(1, i-1) * (utvx_max / utvx_min)^(1 / (Number_of_gears - 1)));
end

% Electric machine parameters
++++++++++++++++++
Pem_max = EMpower * Hybrid + 2000 * (1 - Hybrid);
    % Peak continuous power
Tem_max = TorqueEMmax * Hybrid + 10 * (1 - Hybrid);
    % Peak continuous torque
wem_max = wice_max; % EM mounted on cranc shaft

% [EtaEM, Tem, Wem] = CreateEMmap(Pem_max, wem_max, Tem_max);

Wem = 0:83.776 / 20:83.776;
Tem = Table1(421:440, 4);
Tem = table2array(Tem);
Tem = Tem';
Tem = [0, Tem];
Tem = Tem * 2;
E1 = Table1(1:20, 8);
E2 = Table1(22:41,8);
E3 = Table1(43:62,8);
E4 = Table1(64:83,8);
E5 = Table1(85:104,8);
E6 = Table1(106:125,8);
E7 = Table1(127:146,8);
E8 = Table1(148:167,8);
E9 = Table1(169:188,8);
E10 = Table1(190:209,8);
E11 = Table1(211:230,8);
E12 = Table1(232:251,8);
E13 = Table1(253:272,8);
E14 = Table1(274:293,8);
E15 = Table1(295:314,8);
E16 = Table1(316:335,8);
E17 = Table1(337:356,8);
E18 = Table1(358:377,8);
E19 = Table1(379:398,8);
E20 = Table1(400:419,8);

E1 = table2array(E1);
E2 = table2array(E2);
E3 = table2array(E3);
E4 = table2array(E4);
E5 = table2array(E5);
E6 = table2array(E6);
E7 = table2array(E7);
E8 = table2array(E8);
E9 = table2array(E9);
E10 = table2array(E10);
E11 = table2array(E11);
E12 = table2array(E12);
E13 = table2array(E13);
E14 = table2array(E14);
E15 = table2array(E15);
E16 = table2array(E16);
E17 = table2array(E17);
E18 = table2array(E18);
E19 = table2array(E19);
E20 = table2array(E20);

E1 = [0.01; E1];
E2 = [0.01; E2];
E3 = [0.01; E3];
E4 = [0.01; E4];
E5 = [0.01; E5];
E6 = [0.01; E6];
E7 = [0.01; E7];
E8 = [0.01; E8];
E9 = [0.01; E9];
E10 = [0.01; E10];
E11 = [0.01; E11];
E12 = [0.01; E12];
E13 = [0.01; E13];
E14 = [0.01; E14];
E15 = [0.01; E15];
E16 = [0.01; E16];
E17 = [0.01; E17];
E18 = [0.01; E18];
E19 = [0.01; E19];
E20 = [0.01; E20];

null =
[0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;

EtaEM = [null, E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, E12, E13, E14, E15,
E16, E17, E18, E19, E20];
EtaEM = EtaEM./100;
EtaEM = EtaEM';

MaxEff = max(EtaEM,[],"all")
MaxEff2 = max(EtaEM)

% LossMap
E1 = Table3(1:20,12);
E2 = Table3(22:41,12);
E3 = Table3(43:62,12);
E4 = Table3(64:83,12);
E5 = Table3(85:104,12);
E6 = Table3(106:125,12);
E7 = Table3(127:146,12);
E8 = Table3(148:167,12);
E9 = Table3(169:188,12);
E10 = Table3(190:209,12);
E11 = Table3(211:230,12);
E12 = Table3(232:251,12);
E13 = Table3(253:272,12);
E14 = Table3(274:293,12);
E15 = Table3(295:314,12);
E16 = Table3(316:335,12);
E17 = Table3(337:356,12);
E18 = Table3(358:377,12);
E19 = Table3(379:398,12);
E20 = Table3(400:419,12);

E1 = table2array(E1);
E2 = table2array(E2);
E3 = table2array(E3);
E4 = table2array(E4);
E5 = table2array(E5);
E6 = table2array(E6);
E7 = table2array(E7);
E8 = table2array(E8);
E9 = table2array(E9);


E10 = table2array(E10);
E11 = table2array(E11);
E12 = table2array(E12);
E13 = table2array(E13);
E14 = table2array(E14);
E15 = table2array(E15);
E16 = table2array(E16);
E17 = table2array(E17);
E18 = table2array(E18);
E19 = table2array(E19);
E20 = table2array(E20);

E1 = [0.01; E1];
E2 = [0.01; E2];
E3 = [0.01; E3];
E4 = [0.01; E4];
E5 = [0.01; E5];
E6 = [0.01; E6];
E7 = [0.01; E7];
E8 = [0.01; E8];
E9 = [0.01; E9];
E10 = [0.01; E10];
E11 = [0.01; E11];
E12 = [0.01; E12];
E13 = [0.01; E13];
E14 = [0.01; E14];
E15 = [0.01; E15];
E16 = [0.01; E16];
E17 = [0.01; E17];
E18 = [0.01; E18];
E19 = [0.01; E19];
E20 = [0.01; E20];

null =

[0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01;0.01]
Appendix A: MATLAB code

LossEM = [null, E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, E12, E13, E14, E15, E16, E17, E18, E19, E20];

LossEM = LossEM';

LossEM = LossEM*2;

figure(2)
clf
% mesh(jCOMP)
% contour([-w(length(w):-1:1) w(2:length(w))],[-Tref(length(Tref):-1:1) Tref(2:length(Tref))],EtaEM',[0.2:0.05:1])
surfc(Wem,Tem,EtaEM')
axis([0 max(Wem) 0 max(Tem) 0 1])
xlabel('Speed [rad/s]')
ylabel('Torque [Nm]')
title('Electrical machine efficiency')

figure(5)
clf
% mesh(jCOMP)
% contour([-w(length(w):-1:1) w(2:length(w))],[-Tref(length(Tref):-1:1) Tref(2:length(Tref))],EtaEM',[0.2:0.05:1])
surfc(Wem,Tem,LossEM')
axis([0 max(Wem) 0 max(Tem) 0 400])
xlabel('Speed [rad/s]')
ylabel('Torque [Nm]')
zlabel('Power loss [W]')
title('Electrical machine Losses')

% Power electronics efficiency (preset)

EtaPE = 0.96;
% Fuel energy density [MJ/liter]
if Fuel==1, % Gasoline
  Density = 32e6;
elseif Fuel==2, % Diesel
  Density = 36e6;
elseif Fuel==3, % Ethanol
  Density = (85*19.6e6 + 15*32e6)/100;
else
  'Erroneous fuel choice'
end

% Battery parameters ++++++++++++++++++
Wbatt = 100*3600*5; % 100 Wh/kg, 13 kg
[EtaBATT, Pbatt] = CreateBATTmap(Pem_max, Wbatt);
SOC_batt_ref = 70; % [%]
OnOffMin = 30;
OnOffMax = SOC_batt_ref - eps; % ML: In order to start the simulation correctly

% SuperCap parameters ++++++++++++++
% Wsc=2e5;
% Psc_max_discharge = Pem_max;
% [EtaSC, Psupercap, Wsupercap] = CreateSuperCapMap(Psc_max_discharge, Wsc)
% SOC_sc_ref_value = 90;

% Controller parameters
  ********************************************

  Tau_charge = 1;
  ksoc = max(Wbatt)/400/Tau_charge;

% Auxiliary load power
  *********************
Paux = 0; % Without AC