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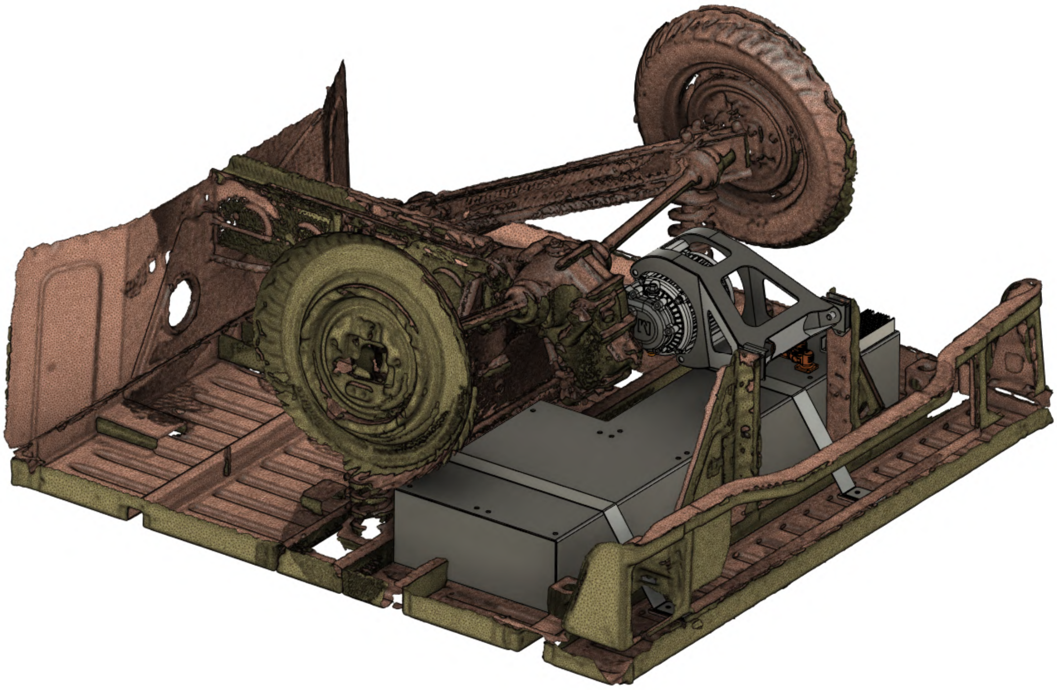

Powertrain Development of a Small Electric Cargo Vehicle

Master's thesis in Mobility Automotive Engineering

William Svensson & Alfred Wäpling

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

This thesis presents the development, manufacturing, testing, and evaluation of an electric drivetrain conversion kit for a Piaggio Ape cargo moped. The project was carried out in collaboration with Mint Engineering with the objective of developing an electric conversion kit for small cargo vehicles while minimizing modifications to the original vehicle.

The work included requirement definition, concept generation, component selection, reverse engineering, CAD-based design, manufacturing of custom Components, assembly, and prototype testing. Several drivetrain layouts and transmission concepts were evaluated with respect to packaging, manufacturability, installation complexity, cost, and vehicle performance. The selected concept consisted of a centrally mounted electric motor connected to the original differential through a custom-designed adapter and spline shaft while retaining parts of the original driveline.

Reverse engineering methods including 3D scanning, manual measurements, and CAD modeling were used to adapt the drivetrain to the existing vehicle geometry. Multiple custom components were designed and manufactured, including drivetrain interfaces, mountings, battery, and electrical integration into the original vehicle. The electrical architecture incorporated a battery management system, regenerative braking, CAN communication, and both high- and low-voltage systems.

Following manufacturing and installation of the developed conversion kit, the vehicle underwent functional testing, initial driving tests and troubleshooting. The testing verified the functionality of the electrical systems, drivetrain integration, regenerative braking, and overall vehicle operation. However, the vehicle exhibited significantly lower torque output than expected, resulting in limited hill climbing capability and failure to meet the specified torque requirement. Extensive troubleshooting, measurements, and analytical calculations were therefore conducted to investigate the source of the performance deficit. The investigation showed that the delivered motor differed from the specified model, as well as a mistake in motor controller selection where a controller with 200A peak amplitude phase current instead of 200A RMS was selected.

Despite the torque deficit, the project demonstrates the practical challenges and feasibility of converting lightweight cargo vehicles to electric propulsion using commercially available components combined with custom-designed mechanical interfaces. The work further emphasizes the importance of component verification, iterative testing, and system-level troubleshooting in electric vehicle conversion projects.

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We would like to thank our examiner Magnus Evertsson for his guidance and support throughout the project. We also want to thank our supervisors Henrik Hellström, Alexander Lewandowski and the rest of Mint Engineering for providing the opportunity, technical expertise and assistance during the entire thesis work.

William Svensson
Alfred Wäpling

Gothenburg, May 2026

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1
Introduction

This chapter introduces the project and defines its overall scope. It provides the background and motivation for the work, followed by the main objectives and the limitations that define the boundaries of the project. Together, these sections establish the context for the development of the electric drivetrain conversion presented in the following chapters.

1.1 Background

In recent years a global emphasis of sustainable transportation has grown. This has in turn led to a rapid increase in the adaptation of electric vehicles. At the same time popularity of small urban vehicles have also grown, particularly for small businesses such as mobile food and beverage vendors. Converting such vehicles from internal combustion to electric drive is a practical and environmentally friendly way to combine this. This approach both extends the service life of existing vehicles and is an affordable path to electrification without the need for new vehicle production. This project was carried out in collaboration with Mint Engineering and a costumer of theirs with the mission of converting a Piaggio Ape to electric drive.

1.2 Aim

The aim was to design and evaluate an electric conversion kit for a cargo moped that combines high quality components with reliability and ease of installation. A prototype electric drivetrain was developed and manufactured as part of the project. The mentioned drivetrain was thereafter fitted to the customer's cargo moped.

1.3 Limitations

The main limitation of the project is that the focus will be on the drivetrain and whats connected to it. While cargo compartments and further modifications like adding coffee brewers will be kept in mind they will not be part of this project.

The project will not include component design in terms of motor, inverter, battery segments or similar. Instead these types of complex components will be bought while things like brackets, adapters and other small parts will be designed. However, there will still be a focus on evaluating and choosing suitable components. The project will also be limited to only focusing on a Piaggio Ape vehicle since it is a very popular and available model.

2

Methods

This chapter presents the methods used in the project. It describes the overall approach for developing the electric drivetrain system, including concept selection, system design, and manufacturing.

The methodology combines requirement-driven concept development with iterative engineering design. This includes evaluating different system solutions, creating a system architecture, and selecting suitable components based on technical performance, cost, availability, and integration constraints.

In addition, the chapter covers the use of 3D scanning and CAD-based reverse engineering to adapt the design to the existing vehicle geometry, as well as the manufacturing strategy used to produce and assemble the final components.

2.1 Concept and Component Selection

To get to the point of selecting components, a concept has to be decided first. To start with, all requirements must be listed so that a concept that meets all vehicle requirements can be chosen. The requirements listing step takes input from multiple different parties such as the government, customer and developer and specifies them in a list with specific values to meet.

The concept is thereafter decided on by listing possible parts of concepts and weighing them against relevant criteria to find the best one. With the concept decided, a system architecture can be made. The purpose of the system architecture is both to be able to visualize the concept and system and to help in the design step by making it clear what components interact with each other and in what ways. For example, it shows where a cable is required, and whether that cable is a signal cable or power cable.

After concept development, the actual components could be selected. The system architecture and concept show what components are needed. Different alternatives for each component are listed with their specifications, and the best one is selected based on specification, price, availability and country of origin. The reason for including country of origin is that the customer wanted to prioritize European components. The components also need to be checked for compatibility, for example in terms of CAN protocol.

This structured approach ensures that the final system is both technically feasible and well integrated within the constraints of the existing vehicle platform.

2.2 Design

The mechanical design process is the largest part of the project in terms of work hours. The project covers multiple areas such as 3D scanning, reverse engineering, electrical design, both in terms of power transmission, signals, and component design. In general, the design process was iterative and closely linked to both manufacturing constraints and integration with the existing vehicle geometry.

2.2.1 3D Scanning

Designing parts for an already existing vehicle can be a time-consuming process in terms of packaging and integration of components. A fast way of recreating areas of interest into a usable computer model is by adopting 3D scanning. This enables accurate digital representation of complex geometries that would otherwise be difficult to model manually.

2.2.1.1 Scanner and Softwares Used

The scanner used was a Shining 3D Einstar; this was due to having one available at the university. The ExStar software was used to trim the point clouds by removing points from the surroundings such as the floor and floating segments. The point cloud was then exported to an open-source program called MeshLab to change the file format, enabling meshing to be done. The mesh could then be opened and used in fusion 360. The selected workflow prioritizes accessibility, compatibility between file formats, and sufficient accuracy for CAD-based reverse engineering.

2.2.1.2 Workflow

Several steps are required to obtain a usable 3D representation of a physical object. Firstly, several overlapping scans are performed. The raw scan files contain clouds of points that can rarely be opened or used in common CAD programs. Stitching the scan files together and converting the point cloud into a meshed surface allows it to be opened in most CAD systems.

When the rear suspension of the vehicle was dismantled for the original engine and transmission to be removed, a differential housing scan was performed. The differential and rear suspension were then put back in the vehicle, and the scan could thereafter be continued by starting at the differential and moving the scanner outward to cover other areas of the undercarriage. This meant that all sides of the differential housing could be included in the scan, although the upper part was difficult to reach while mounted in the chassis.

Eight different scanning actions were performed, all of which started at the differential. By doing so, the scanner managed to always recognize its orientation, facilitating smooth scanning execution. Also, by doing several smaller scans instead of one large one, re-scanning was possible when the scanner lost its track. This approach ensured a complete and geometrically consistent model of the scanned area while minimizing tracking loss and rework during scanning. One of these eight partial scans can be seen in Figure 2.1.

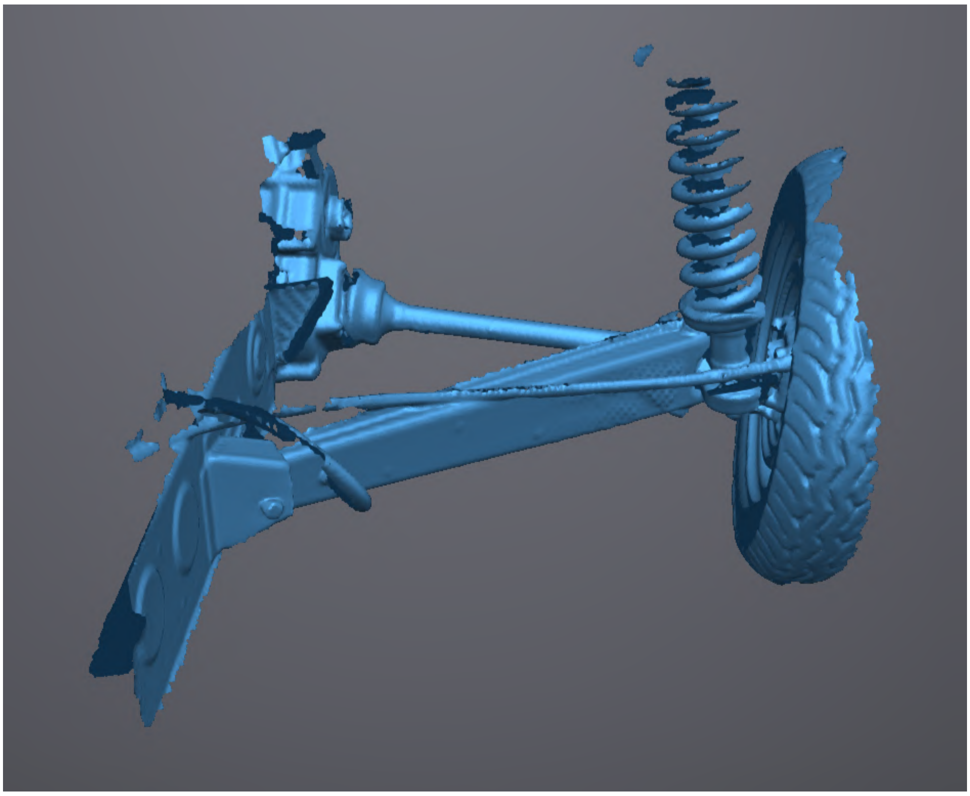


Figure 2.1: Partial 3D-scan point cloud

The Shining ExStar software was thereafter used to orient the scans in relation to each other by selecting a set of overlapping points in both the stationary scan and the scan intended to be moved. The resulting overlapping point clouds visualized in a single window can be seen in Figure 2.2.

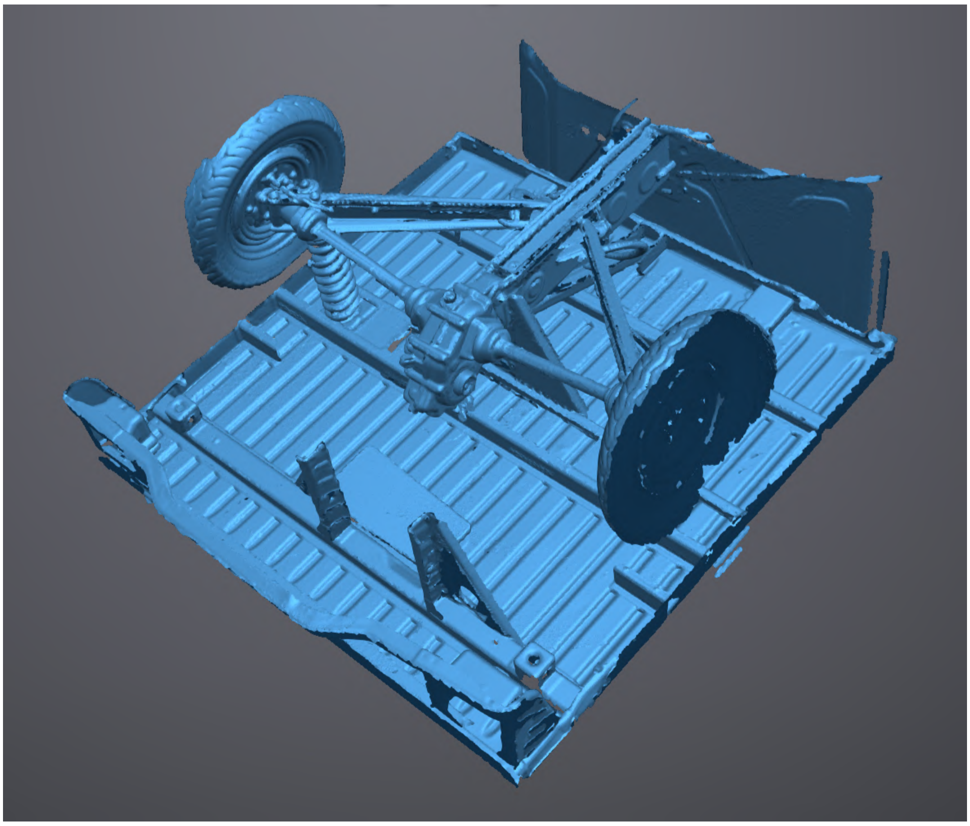


Figure 2.2: Complete undercarriage composed of multiple point clouds.

2.2.1.3 Post Processing

The ExStar software was found to require large amounts of RAM memory for stitching scans together and converting the point cloud into a mesh. Instead, another 3D scan processing program, called Revo Scan 5, was downloaded and used to post-process the scan. However, this software only supported .ply files, meaning that the .asc files had to be converted first. MeshLab, an open-source program, was therefore used to merge the individual scans and output the correct file format. The complete point cloud was then meshed in Revo Scan and put into CAD. This workflow enabled successful conversion from raw scan data to a usable CAD model suitable for further design work.

2.2.2 Component Design

The software used for the design in this project was primarily Fusion 360. The design process is done iteratively, where parts are made and assembled in subassemblies and finally in a full assembly which also includes the 3D scan of the vehicle. In the assemblies, eventual clashes or other issues are identified and fixed, which often results in other parts downstream also needing to be changed. The parts start as space claims used to set volumes for all parts. These space claims are changed until the final volume has been set and the part is finalized. During this design process, great emphasis is placed on the manufacturing method and assembly process to ensure that manufacturing and assembly is as easy and fast as possible. Focus on placement of electrical components is also necessary to ensure cables both fit with their needed bending radii and have a reasonable routing between components.

In a project like this where there already is an existing vehicle and some existing components, the design is less free than with a completely new design. For example, some interfaces like bolt patterns or splines are already set, which requires some reverse engineering to find the geometry when drawings cannot be found. One further and often easier way of doing this than 3D scanning is 2D scanning. This way a flat surface is easily scanned, imported and scaled in a CAD program where it can then be used as a reference to draw the geometry. The interface is then easily 3D printed and tested against the existing component to see if adjustments have to be made. This has been the workflow for several parts in this project where two interfaces are set and a part connecting them has to be designed. This iterative workflow ensured that the final design was both manufacturable and compatible with the spatial and functional constraints of the vehicle.

2.3 Manufacturing

The manufacturing in this project has been a combination of outsourcing and in-house manufacturing. Both have their place, for example, in-house manufacturing in a project like this for a prototype means the manufacturing can be more iterative and parts and fits are more easily tested. This is especially useful for reverse-engineered parts where the exact geometry is unknown and the design part is only an approximation. Outsourcing the manufacturing instead is often cheaper, faster and less work and is suitable for simpler parts. This project made use of many laser-cut and bent sheet metal parts which are easily ordered online at low cost. Parts like shafts with splines based on 2D scans were instead made in-house using a combination of CNC milling, manual milling and manual turning as well as sheet metal tools.

3

Concept and Component Selection

This chapter presents the development of the electric driveline concept and the selection of its main components. The focus is on evaluating different design alternatives and defining a final system architecture that fulfilles the functional requirements of the vehicle.

Several key design decisions are made regarding driveline layout, mechanical interfaces, transmission type, and placement of major components such as the motor, battery, and inverter. These decisions are based on a combination of packaging constraints, performance requirements, cost considerations, and compliance with Swedish regulations for Class 2 mopeds.

The result is a complete concept definition of the drivetrain system, which serves as the foundation for the detailed design and integration presented in the following sections.

3.1 Electric Driveline Requirements

Table 3.1 is a list of requirements both for the electric driveline and for the vehicle as a whole. It is divided into vehicle specifications, EV system, and reliability. The requirements are derived from different sources: some from Swedish legislation, some from the customer, some from calculations, and some from potential future customers.

Table 3.1: Specification of requirements for the system

Req ID	**Category**	**Requirement Description**	**Value / Target**	**Verification**
REQ. 01	Vehicle Specs.	The maximum vehicle speed may not exceed the specified value.	25 [km/h]	Data Sheet + calculation
REQ. 02	Vehicle Specs.	The vehicle range must exceed the specified value.	50 [km]	System Analysis
REQ. 03	Vehicle Specs.	The vehicle should meet the legal requirements of a class 2 moped according to Swedish regulations.	—	System Design + test
REQ. 04	Vehicle Specs.	The vehicle should have cabin heating and defrosting.	—	System Design
REQ. 05	Vehicle Specs.	The vehicle should have original instrumentation as well as state of charge indication.	—	System Design
REQ. 06	EV System	Nominal battery voltage may not exceed specified value.	60 [V, DC]	Data Sheet
REQ. 07	EV System	The minimum differential input torque must be no less than specified, at low motor speeds. Derived from a 20 percent gradient hill start.	110 [Nm]	Data Sheet
REQ. 08	EV System	The system architecture should allow 12 V auxiliary power to be output from the tractive battery.	400 [W]	System Design
REQ. 09	EV System	The system architecture should allow HV auxiliary power to be output from the tractive battery.	4 [kW]	System Design

Req ID	Category	Requirement Description	Value / Target	Verification
REQ. 10	EV System	The EV system must show equivalency to at least the specified IP rating.	IP65	System Analysis
REQ. 11	EV System	The maximum electric driveline weight shall be no greater than specified.	70 [Kg]	System Design + test
REQ. 12	EV System	The cost of the complete conversion kit must not exceed the specified value.	35,000 [SEK]	Bill of Material
REQ. 13	EV System	The EV system shall allow for regenerative braking.	—	System Analysis
REQ. 14	EV System	The system architecture must allow the original LV system to be powered by the tractive battery.	—	Design Considerations
REQ. 15	EV System	The conversion kit may be installed with no major modifications to the original vehicle chassis.	—	Design Considerations + Test
REQ. 16	EV System	The battery system shall include a Battery Management System (BMS) to protect against overcharge, over-discharge, and cell imbalance.	—	System Design
REQ. 17	EV System	The battery should not be able to charge or discharge at temperatures outside the operational range specified for the battery segments.	-	System Design
REQ. 18	EV System	The system shall allow for additional telemetry equipment to be installed.	-	System Design
REQ. 19	Reliability	The driveline shall achieve a minimum service life as specified.	10,000 [km]	Analysis

Since most of the requirements are self-explanatory, not all will be discussed here. However, the ones that require further explanation will be discussed. Only requirements that require additional justification or are directly derived from calculations or external constraints are further discussed in the following sections.

REQ. 07 comes from a calculation where a fully loaded vehicle with a total weight of 350 kg should be able to start with an acceleration of $0.5\,\mathrm{m/s^2}$ on a hill with a gradient of 20%. The required wheel force is the sum of hill-climbing force and acceleration force:

$$F = mg\sin(\theta) + ma$$

For a 20% gradient:

$$\sin(\theta) \approx 0.20$$

$$F = 350 \cdot 9.81 \cdot 0.20 + 350 \cdot 0.5 = 686.7 + 175 = 861.7\,\mathrm{N}$$

The required torque at the wheels is:

$$T_{wheel} = F \cdot r = 861.7 \cdot 0.215 = 185.3\,\mathrm{Nm}$$

The required torque at the differential input is:

$$T_{diff} = \frac{T_{wheel}}{i} = \frac{185.3}{1.68} = 110\,\mathrm{Nm}$$

REQ. 08 comes from the sum of constant power consumers of the 12 V system such as lights and phone chargers, but does not include things such as horns and turn signals. Only the constant power consumption and not peak values are considered since the vehicle will retain its 12 V battery to handle peaks.

REQ. 09 is derived from conversations with a coffee brewer and potential future customers about what machines would be suitable. The requirement is then the sum of the power of those machines.

REQ. 18 comes from the customer, who wants to be able to use additional battery telemetry on the vehicle. This project will not install such telemetry, but it will be considered, for example when choosing number of contacts on the battery.

Together, these requirements form the basis for all subsequent design decisions in the project and ensure the finished conversion kit and vehicle is satisfactory for all parties involved.

3.2 Driveline Concept

This section aims to decide a driveline concept in terms of placement of different components as well as the interface to the original vehicle, including which parts of the original driveline to keep. It will also decide what transmission type will be used. This will be evaluated to optimize the following parameters.

- Maneuverability
- Stability
- Weight
- Cost
- Ease of installation
- Compliance with legal requirements for a Class 2 moped in Sweden

3.2.1 Drive Layout

There are two clear possible drive layouts: driving on the front or the rear axle. Both have advantages and disadvantages. To decide on one of the two, a Pugh matrix was made.

Table 3.2: Comparison of front vs rear axle drive

Criterion	**Front Axle Drive**	**Rear Axle Drive**
Maneuverability	0	1
Weight	0	0
Cost	0	1
Ease of installation	1	0
Total	1	2

Since the drive shafts on the rear axle also act as control arms for the rear suspension, they and the differential cannot be removed without further modifications. See Figure 3.1 for the rear suspension. This means that in both scenarios, with front or rear axle drive, the differential and driveshafts will still be left. Because of this, weight and stability of both alternatives will be similar.

Figure 3.1: Underside of the vehicle before disassembly

Maneuverability will be better with the rear axle driven since most weight will be on the rear as well as the rear having two wheels instead of one in the front. Battery placement and cargo is also only possible close to the rear axle, which further puts weight on it, improving grip.

The one advantage of having the front axle driven is the ease of installation. The rear alternative requires more disassembly and is harder to access than the front.

3.2.2 Interface to Original Vehicle

Since the rear axle option has been chosen, the possible interfaces are all in the rear. The considered interfaces are in the wheel hubs, centrally with a new differential, directly on the original differential, on a differential with a transmission, or on the original engine/gearbox.

Table 3.3: Comparison of drivetrain conversion concepts

Criterion	**Rear Hub Motors**	**Central Motor with diff**	**Direct on Differential**	**Diff + Transmission**	**Original Engine / Gearbox**	**Complete Rear Axle Swap**
Maneuverability	2	1	–	1	1	1
Weight	0	1	–	1	0	0
Time to prepare kit	2	0	–	1	1	0
Cost	0	2	–	2	2	1
Ease of installation	1	1	–	1	0	0
Total	5	5	–	6	4	2

Having two hub motors without transmissions, one in each rear wheel, is good for maneuverability since the two driven wheels are decoupled and torque vectoring can thus be implemented. This concept is good in terms of ease of installation but requires two single-sided motors and two power electronics units. The absence of a transmission means that the motors need to deliver higher torque at lower operating speeds, resulting in larger motor alternatives being suitable. Large motors in combination with two inverters lead to unnecessary high costs and overall weight of the vehicle. In addition, unsprung mass is generally not desired in terms of vehicle dynamics.

A central direct drive motor would require modifications to the drive axles, which is bad in terms of ease of installation. A single high torque/low speed motor is needed as no transmission would be used in that case. A large motor means higher cost and might also have an impact on ground clearance. No differential action would lead to bad maneuverability and steering capabilities, especially for a one-wheel steered vehicle with weight balance towards the rear.

By retaining the original differential and final drive, a centrally mounted motor could be downsized compared to the concept with direct drive. A smaller motor with higher speed range can then be used, resulting in lower cost and similar weight. Installation would be fairly simple, but the differential has to be disassembled to allow the motor to be mounted since it is screwed from the inside of the differential housing. However, this concept is not possible since there is no motor small enough to be mounted directly on the differential without offset that will not make contact with the driveshaft as the suspension moves.

By keeping the differential and final drive and adding an additional transmission stage, further downsizing of the motor would be enabled, and this alternative was estimated to be the most cost-effective concept. The added transmission stage can be pre-mounted to the motor sub-frame, but the differential still has to be taken apart for mounting the extra transmission stage to the differential. The total weight will be similar to the option without an extra transmission stage, and so will the maneuverability.

Another option would be to disassemble the engine, remove all unnecessary parts and connect the motor to the original transmission. By having four gears, this concept could use the smallest motor out of all alternatives and still fulfill the requirements. However, this option requires a higher level of mechanical expertise during installation of the kit, which is not desired.

The last option would be to change the entire rear axle with a complete electric drive one. It would however be heavier, harder to install and require more parts and possibly modifications to the original chassis, all adding cost and difficulty for installation.

This evaluation ensures that the selected interface solution is compatible with both the existing drivetrain geometry and the chosen motor configuration.

3.2.3 Transmission Type

The transmission will be placed between the motor and the differential. Since the final drive ratio is only 1.68:1, a further reduction in the transmission is desirable. The need for more reduction comes from the limited distance between the input shaft of the differential and the drive shaft. This means large motors will not fit. For transmission types there are multiple options to choose from. For this driveline the choice is between chain, belt and gear drive. A further criterion is also added for this choice, that being noise level. This is added since it is desirable, especially in an electric vehicle, for it to be quiet, and the transmission is a part that can make a lot of noise.

Table 3.4: Comparison of drivetrain options

Criterion	**Chain**	**Belt**	**Gear**
Cost	1	0	2
Ease of installation	1	1	2
Noise level	0	2	1
Total	2	3	5

Since there are affordable motors available with transmissions already built in, it is cheaper to use gear drive than both chain and belt. This is because the complexity goes down when fewer parts are needed, as well as the subframe not needing features to hold or align such parts. The ease of installation is similar between all three types, but since gear drive requires fewer components (no chain/belt or tensioner), the gear drive gets a higher score. For the noise level criterion, a belt drive gets the highest score since it is quieter than both chain and gears. The gear drive scores slightly higher than the chain drive because it is built into a housing and runs in oil. It could also be argued that a gear drive whine is a more pleasant sound than a chain clatter.

The winning and chosen type is a gear drive transmission. The main reason for this is the price and simplicity of buying a motor with a built-in transmission. The transmission also offsets the output shaft from the centerline of the motor, giving more clearance to the drive shaft and putting the motor closer to the motor mounts on the frame. This selection ensures a suitable balance between efficiency, noise characteristics, and mechanical simplicity.

3.2.4 Battery Placement

Battery placement has many possibilities. It is theoretically possible to place it both above and under the bed, but for both aesthetic and practical reasons, under the bed is the most reasonable placement. Under the bed there are also different possible placements. The main being in front of or behind the rear axle. If placed in front of the rear axle there are also two further options, namely using one single battery box or two boxes split between left and right. The single box in front of the rear axle however has to be placed to the side as the frame is in the middle.

Table 3.5: Comparison of placement options

Criterion	In front of axle (one box)	Behind axle	Split left/right
Stability	0	2	2
Cost	2	2	0
Ease of installation	2	1	0
Total	4	5	2

For stability, both having a low center of gravity and having it close to the rear axle are beneficial. This is because the support polygon is the widest at the rear axle where there are two wheels as opposed to one in the front, meaning the vehicle can both take corners at greater speeds and stand at a greater angle without flipping over. This means that it is best to have the battery as far back as possible. It can however induce some understeer, but since the vehicle is not performance-oriented anyways, this can be disregarded.

For ease of installation, having one box in front is the easiest, both because it is fewer components and because it is placed in a spot with good accessibility. Having two boxes means more components and connections between boxes, which is harder and more work. It is comparatively easier to work in front of the rear axle since behind the rear axle there are other components such as the differential and motor. Therefore behind rear axle scores slightly worse.

Because of all of this, having the battery behind the rear axle is the chosen concept. It puts the center of mass close to the rear axle, improving both stability and traction. It also means having the weight central and only one box.

3.2.5 Inverter Placement

Since short motor cables and protection from water and dirt are important, there are two main options for the inverter placement. One is inside the cabin and one is inside the battery box close to the motor. There are also other things to consider, such as cable length to the battery and accessibility.

Table 3.6: Comparison of installation locations

Criterion	Inside Cabin	Inside battery box
Environmental protection (water/dirt)	2	2
Cable length to motors	0	2
Cable length to battery	0	2
Accessibility / serviceability	2	0
Total	4	6

Since placing the inverter inside the battery box shows multiple advantages, and the only disadvantage is accessibility, it was chosen as the final placement.

The selected driveline concept and component interfaces provide a balanced solution with respect to packaging constraints, performance requirements, and manufacturability, and form the basis for the detailed system design presented in the following sections.

3.3 System Architecture

The system architecture aims to visualize how parts of the driveline interact with each other and in what way in terms of electrical, mechanical, or signal interfaces. It also divides components into placement as far as if it is inside the cabin, battery box, or outside. This serves as a foundation for defining wiring, mounting locations, and system-level integration constraints.

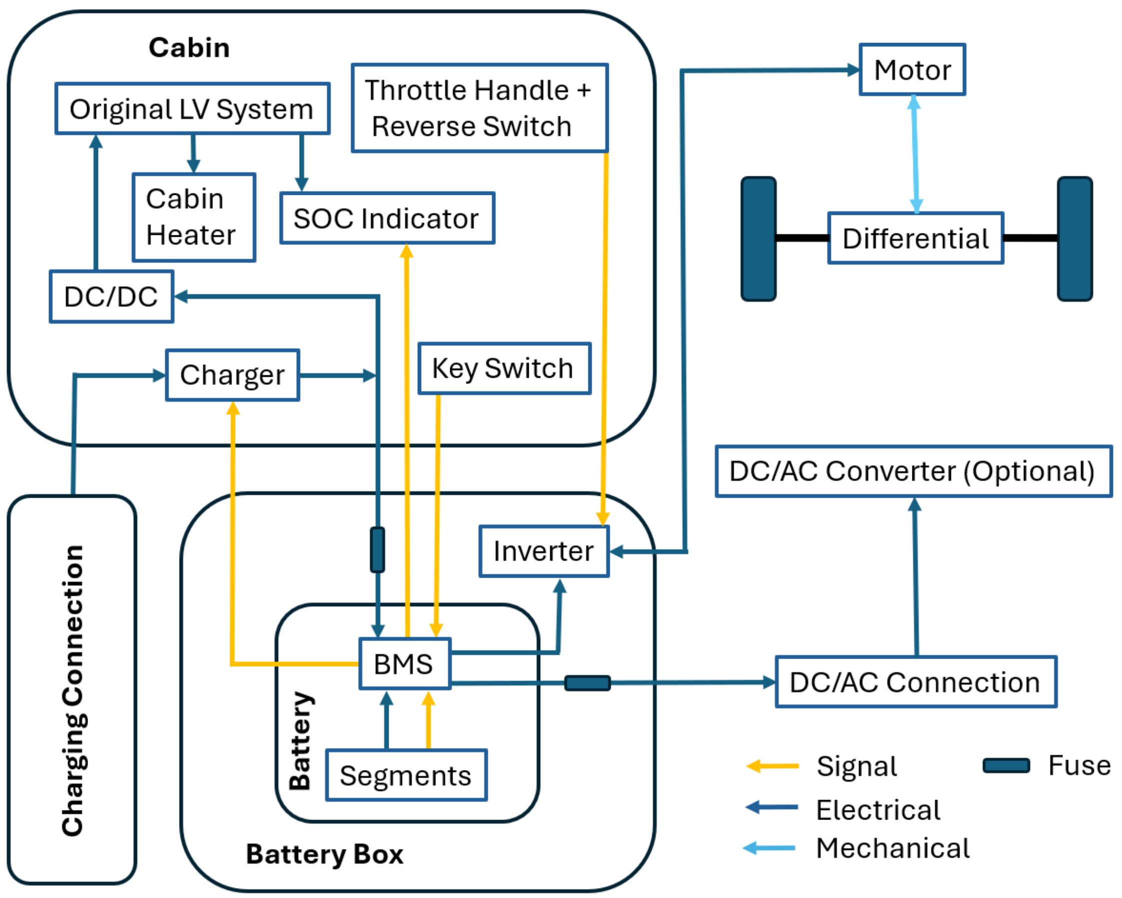


Figure 3.2: Schematic system architecture

The parts within the battery box are the segments, the BMS (battery managment system), and the inverter. The parts inside the cabin are charger, DC-DC, key switch for BMS, SOC (state of charge) indicator, throttle handle and reverse switch, heater, and the original 12v system. Everything that is connected to the segments is directly connected to the positive terminal and to the negative terminal through the BMS. The DC-DC and charger share cables between battery box and cabin and are

fused inside the battery box. The auxiliary DC-AC inverter is also fused inside the battery box. The inverter has no separate fuse; instead the BMS MOSFETs act as protection for it, as they are turned off in case the current exceeds specified values. All communication is done via CAN-bus between the BMS, charger, inverter, and SOC indicator.
The system architecture provides a clear overview of electrical, mechanical, and communication interfaces and ensures correct integration between all subsystems in the final design.

3.4 Component Selection

The following tables list components, their specifications and prices and aims to help in deciding components for the chosen concept. In general European components have been prioritized where possible. This was however not possible in most situations, both since there are fewer European alternatives and since Chinese alternatives are usually significantly cheaper. For example, European brands mostly make industrial or custom motors which either don't fit the application or the price range. The selected components together form a coherent system that satisfies the technical requirements while balancing cost, availability, and integration constraints.

3.4.1 Motor

The motors compared were two motors from QS, two from Sotion and one from Dana. The Dana motor does not have a built in transmission so it would require an extra one. It is however the only motor produced by a western country which was a priority for the kit. The QS138 70H motor was also considered early in the project, but, since its price was similar to the 138 90H and its mounting not as favorable as the 138 90H and 120 60H it was not considered further.

Table 3.7: Comparison of electric motor options

Criterion	QS120 60H	QS138 90H	Sotion FW10	Sotion FW16	Dana TM4 IPM-200
Cost	2200 SEK	3490 SEK	3040 SEK	3440 SEK	14495 SEK
Rated Power	2 kW	4 kW	5 kW	3.5 kW	3-18 kW
Peak Power	-	13.5 kW	10 kW	5.5 kW	5-35 kW
Max Speed	2800 RPM	2980 RPM	2645 RPM	2116 RPM	6750 RPM

The chosen motor was the QS120 60H. It was chosen since it was the cheapest and lightest motor, while still providing sufficient rated power and peak torque (120 Nm) for the application. It was also deemed as easy to mount both because of its size and its mounts. This selection provides a suitable compromise between performance, size, and integration simplicity.

3.4.2 Motor Controller

For motor controllers there were multiple European brands in the right power range. There was also one brand from the USA included, this being the Turntide controller.

Table 3.8: Comparison of motor controllers

Criterion	VESC Classic 100V	VESC Pronto	Silixcon TX	Turntide Gen 4, Size 2	NX Technologies P10
Cost	2100 SEK	2950 SEK	-	8730 SEK	12500 SEK
Rated current	160 A	150A	100 A	110 A	133 A
Peak current	200 A	200A	200 A	275 A	212 A
Size	100x48x19 mm	121x47x27	130x50x30 mm	187x165x71 mm	180x80x30 mm

From the specifications and the price the best suited motor controller for the application was the VESC Classic 100V but since it was sold out at the time the second choice was instead used, that being the VESC Pronto. The final choice ensures compatibility with the motor while maintaining sufficient current capability for the application.

3.4.3 Battery Segments

The initial plan of the project was to use second-life battery segments from Scania. These would be acquired through the customers contacts at the company. Later in the project, however, it became clear that those segments would not be received for this project. Because the battery box location and size and the nominal voltage of the full battery was already decided based on the Scania segments, the possible suitable segments were limited. On advice from Mint Engineering second life CATL segments were instead used. They were decided on because they have the same cell chemistry, dimensions and capacity and are easily available for purchase. The main difference between the battery segments is that the Scania modules are 12s while the CATL segments are 4s2p. This was however not an issue since the original plan was to use the Scania segments in parallel, resulting in a 12s configuration. The Polestar segments are instead arranged in series, which also results in a 12s pack. In the end, this makes the battery simpler since only one BMS is required instead of one for each segment in a parallel configuration. This configuration maintains the intended system architecture while ensuring practical availability of components. This gives a total battery capacity of approximately 6Kwh.

3.4.4 BMS, Charger and DC-DC

Based on advice and previous knowledge from Mint Engineering, A DALY BMS was chosen. After contact with DALY where a 200A 12s NMC bms was requested, they recommended a 200A 13s Li-ion BMS. Despite the fact that it is a 13s BMS it can be configured to 12s.

Also based on advice from Mint Engineering TC chargers were investigated and after checking that the CAN protocol was compatible with the daly bms it was decided it would be used. Required power for the charger was deemed to be around 2kw which would result in a charging time of about 3 hours. From this a 40A charger was chosen as this would result in $48\,\mathrm{V} \times 40\,\mathrm{A} = 1.92\,\mathrm{kW}$. A big reason for both the DALY BMS and the TC charger was the fact that Mint Engineering had previous experience using these brands and their assistance would be needed for installing and setting these parts up.

To be able to use the original 12V system a DCDC was required to keep the 12V battery charged. To choose a suitable DCDC all power consumers where listed with their respective power draw. Only constant power consumers such as lights or phone charging were included since peaks are handled by the battery. Table 3.9 shows the consumers and the total power draw

Table 3.9: Power consumers of the 12 V system

12 V power consumption	**W**	**Quantity**
Head lights	15	2
Tail lights	10	2
Parking lights	5	2
Phone charger	36	1
Interior lights	5	1
Windshield wiper motor	30	1
Cabin heater	300	1
Total	**431**	

It is important that the DC-DC converter provides a voltage above the nominal 12 V level (typically around 13.8 V) to ensure proper charging of the auxiliary battery system. With both required voltage and power specified a cheap enclosed DC-DC from AliExpress was chosen. It was specified to 414W and 13.8V. This is slightly below the calculated 431W, but was deemed okay since the difference is small. A 40 Ah 12 V battery corresponds to an energy capacity of $40 * 12 = 480Wh$ which at a continuous load of 17 W gives an operating time of $\frac{480}{17} \approx 28.2$ hours. The full consumption scenario is unlikely to occur frequently or for extended periods. The selected auxiliary components ensure safe operation of both the high-voltage and low-voltage systems while maintaining compatibility between subsystems.

4

Design

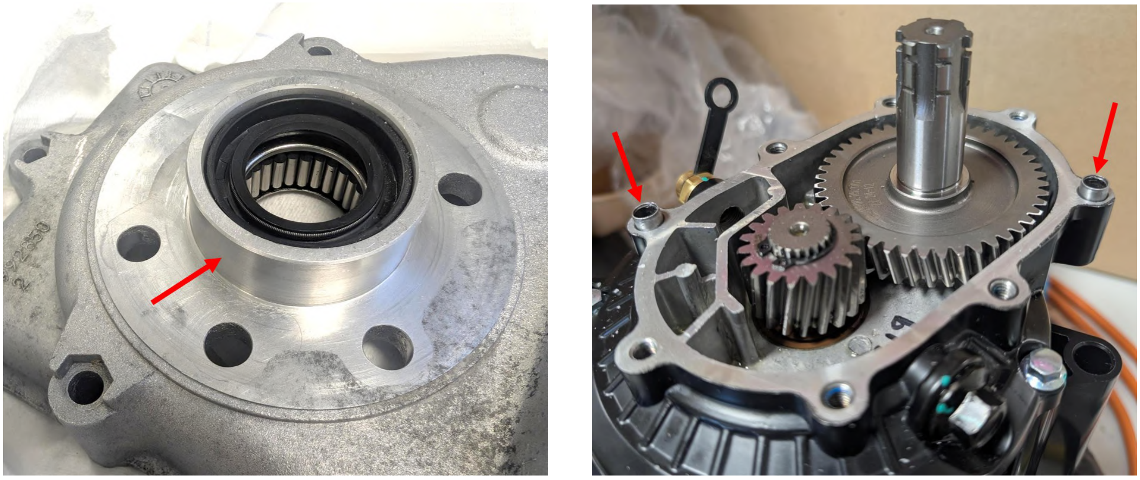
This chapter presents the detailed design of the electric drivetrain system and its integration into the existing vehicle. It covers the development of mechanical and electrical interfaces, component packaging, and subsystem design required to realize the selected concept.

The design work is based on the concept decisions made in the previous chapter and translates them into manufactureable and installable solutions. Special attention is given to reverse engineering of existing vehicle interfaces, structural constraints, and packaging limitations imposed by the existing chassis geometry.

The chapter also includes the design of key subsystems such as the motor and transmission integration, battery system layout, and driver compartment component placement. These designs are developed iteratively to ensure compatibility between mechanical, electrical, and spatial requirements.

4.1 Motor to Differential Interface

The interface between the motor and differential has two main functions, fasten the two components together and position them so that the transmission output shaft is concentric with the differential input. The differential has a cylindrical surface as locating feature around the center bore for the input shaft that can be used to position an adapter. This feature and the holes used to mount the original motor were also used for this adapter. On the electric motor there are motor mounts but no clear feature to use to position it concentric with the differential. To solve this, the original outer half of the gearbox housing was replaced by an adapter that acts as both an adapter between the differential and the motor and as a gearbox housing. This way the locating pins for the gearbox housing could be used to position the adapter on the electric motor. See figure 4.1 for interfaces and locating features on the two components.



(a) Differential housing locating features **(b)** Motor housing locating features

Figure 4.1: Interfaces and locating features.

4.1.1 Spline Shaft

As discussed, a custom shaft is needed to connect the transmission output shaft and the differential input gear. The original motor had a transmission output shaft with an external spline connected to the differential gear. Since this shaft was part of the transmission, a custom shaft had to be made. The electric motor also has an output shaft with an external spline. The initial idea was to replace the entire output shaft to accommodate the differential input gear without the need of having two separate shafts and two extra bearings, But it soon became clear that the motor shaft and its gear was manufactured as one part and could therefore not be separated. Because of this, it was decided that an adapter shaft with an internal spline in one end and an external spline in the other end would connect the electric motor output shaft to the differential input gear.

Two rolling bearings support each shaft radially, of which only one per shaft is axially fixed to allow thermal expansion. By having two bearings that carry each shaft, the spline connection between them is not vital for the concentricity of the system. The spline connection therefore only transmits torque, which means that some play is accepted.

The motor was designed to be mounted on a motorcycle frame, with the chain and sprockets transmitting torque to the rear wheel. With this in mind, the manufacturer placed a larger bearing on the output shaft to accommodate the chain forces. However, in this application, there are no radial chain forces present acting on the bearing. This meant that the mentioned bearing could be down-sized to reduce the axial length of the motor-differential package. To ensure that the new bearing would withstand the forces, the gear mesh forces were analyzed and translated into bearing reaction forces using moment equilibrium calculations. Since the motor gears are helical, both radial and axial loads occur. Gear mesh forces were derived using formulas from the Maskinelement text book [1].

Data derived from gear geometry:

$$\begin{aligned} d_{motor} &= 67.5\,\text{mm} \\ r_{motor} &= \frac{d_{motor}}{2} = 33.75\,\text{mm} \\ \alpha_n &= 20^\circ \\ \beta &= 15^\circ \\ T_{motor} &= 120\,\text{Nm} \end{aligned}$$

Transverse pressure angle calculation:

$$\alpha_t = \sin^{-1}\left(\frac{\sin(\alpha_n)}{\cos(\beta)}\right) = 20,74^\circ$$

Tangential force calculation:

$$F_t = \frac{T_{motor}}{r_{motor}} = 3555,6N$$

Maximum radial and axial forces:

$$F_{r,motor} = F_t \tan(\alpha_t) = 1346,4N$$

$$F_{a,motor} = F_t \tan(\beta) = 952,7N$$

With the maximum radial and axial forces calculated, the bearing reaction forces could be calculated using moment equilibrium. Figure 4.2 gives an overview of the the forces acting on the bearing.

$$\begin{aligned} L_1 &= 10.5\,\text{mm} \\ L_2 &= 12\,\text{mm} \end{aligned}$$

$$\begin{aligned} F_{r1} &= \frac{F_{r,motor}\,L_2}{L_1 + L_2} = 718,1N \\ F_{a1} &= F_{a,motor} = 952,7 \end{aligned}$$

The static load rating of a rolling bearing is generally lower than the dynamic rating. Since the tractive motor is supposed to deliver close to maximum torque at low speeds the static load is dimensioning for the system. The equivalent static bearing load for a single row groove ball bearing is calculated as follows, using the SKF Rullningslager handbook [2].

$$P_0 = 0.6F_r + 0.5F_a = 907N$$

Which is well below the static load rating of the bearing:

$$C_0 = 4.05kN$$

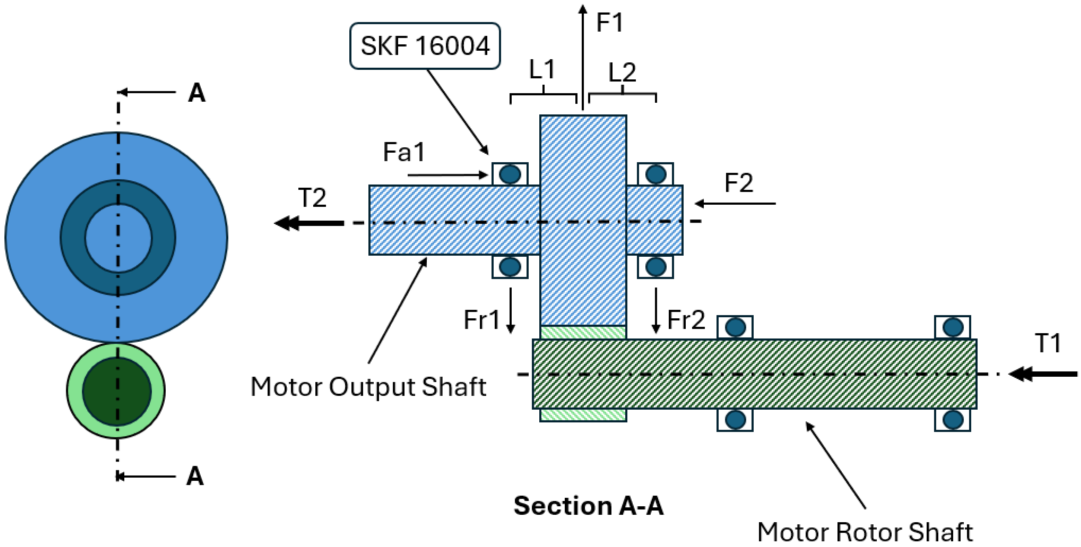


Figure 4.2: Motor gear reduction stage

A similar bearing reaction force evaluation for the final drive input shaft was conducted as follows.

Data derived from gear geometry:

$$d_{diff.} = 68\,\text{mm}$$
$$r_{diff.} = \frac{d}{2} = 34\,\text{mm}$$
$$\alpha_0 = 20^\circ$$
$$T_{diff.} = T_{motor}$$

Tangential force calculation:

$$F_{t,diff.} = \frac{T_{diff.}}{r_{diff.}/1000} = 3529,4N$$

Radial force calculation:

$$F_{r,diff.} = F_{t,diff.}\tan(\alpha_0) = 1284,6N$$

Using moment equilibrium, the bearing reaction forces could be calculated. Note that the final drive consists of two straight cut gears, which means no axial loads on the evaluated bearing. Figure 4.3 gives an overview of the the forces acting on the bearing.

$$L_3 = 21\,\text{mm}$$
$$L_4 = 22.5\,\text{mm}$$

$$F_{r4} = \frac{F_{r,diff}\,L_3}{L_4} = 1199,0N$$

Equivalent static bearing load calculation:

$$P_0 = 0.6F_r + 0.5F_a = 719.4N$$

Which is well below the static load rating of the bearing:

$$C_0 = 4.3kN$$

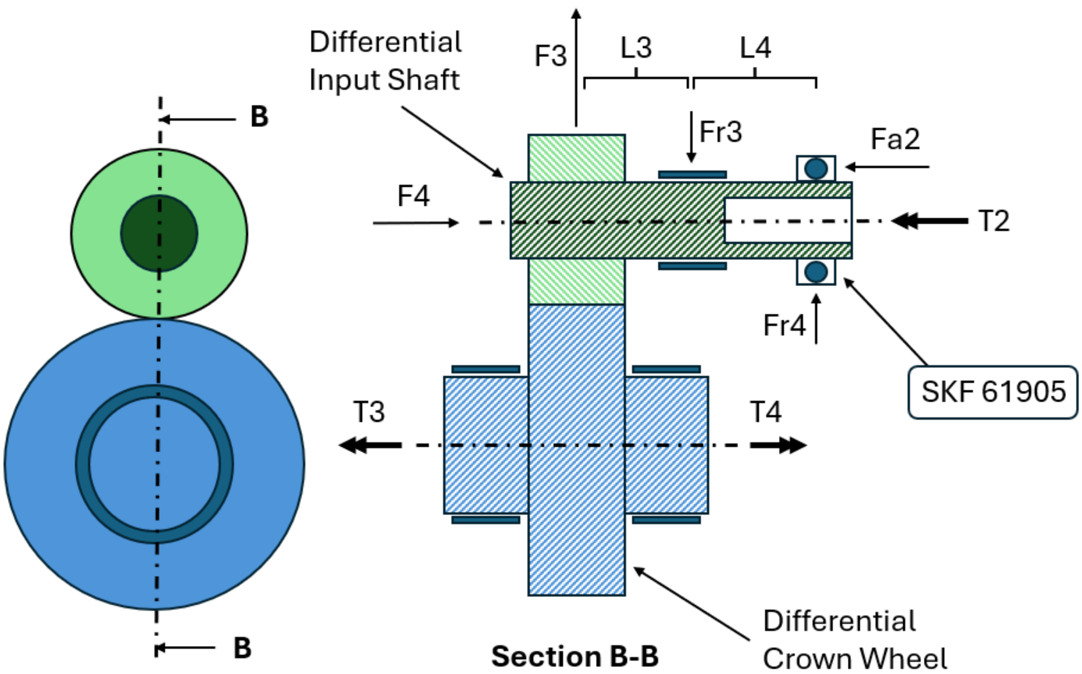
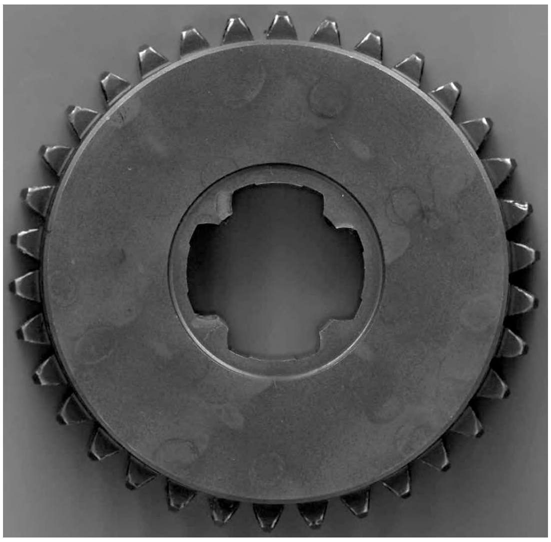


Figure 4.3: Final drive reduction stage

The final drive input spline had to be reverse engineered to replicate the cross section of its teeth. The input gear was scanned on a copier, put into the CAD software and scaled to the correct dimensions using measurements taken on the actual part. This 2D-scan could later be used to find an approximate shape of the spline teeth. The spline shaft was also measured using the measurement over pins method to obtain an accurate measurement of the original final drive spline shaft. Thereafter a gauge was laser cut from thin sheet metal for testing and tuning the profile, see figure 4.4. However, for the motor spline connection, a drawing with dimensions was found.



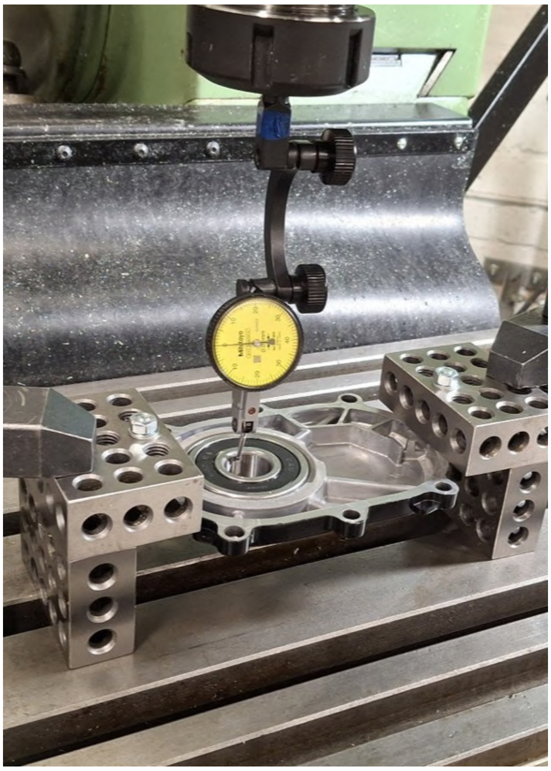
(a) 2D scan of the gear profile

(b) Spline profile gauge

Figure 4.4: 2D-scanned gear and spline profile gauge.

4.1.2 Adapter

A 3D CAD model was received from the motor manufacturer. This CAD model represented the outside of the motor without included internal features. The gearbox was therefore disassembled and measured using a vertical milling machine to obtain accurate measurements between the transmission bearing and the cylindrical pins locating the inner and outer gearbox halves in relation to each other. This was done to ensure concentricity between the two bearings. The old transmission lid was put on the copier to replicate the air-breather labyrinth of the mating gearbox half. See figure 4.5



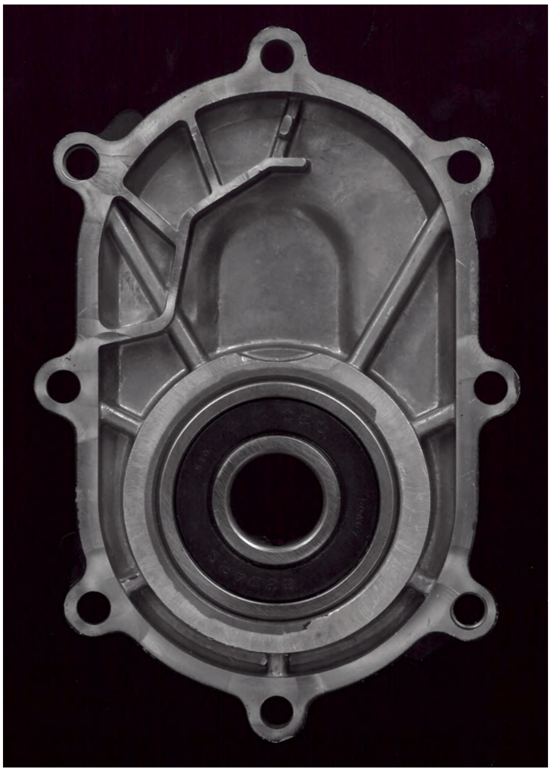


Figure 4.5: Reverse engineering of motor transmission cover

The complete custom gearbox half can be seen in figure 4.6. Note that the radial lip seal and needle roller bearing seats in the differential housing but were added to the figure anyways to better visualize the complete system. The radial lip seal separates the gearbox oil from escaping into the differential housing since the oil level of the gearbox is higher than the level of the differential oil. An additional O-ring seals the mating surfaces between the adapter and differential housing. Trelleborgs O-ring calculator was used to determine appropriate dimensions of the groove.

The adapter was designed to be machined using a 3-axis vertical milling machine, in two setups. and the Shaft was designed to be manually turned in two setups and shaped in a manual milling machine using a dividing head and shaper attachment.

The original drivetrain reversed its direction of travel by shifting the final drive input gear sideways, engaging the final drive output gear via another, free rotating, gear. The sifting was performed by engaging a shifting fork controlled by a spring loaded lever arm with a cable going into the cabin. Since the electric motor can be reversed electrically, there was no longer a need for the mechanical shifting assembly, so it was removed and replaced with cir-clips fixing the gear axially. The hole in the differential housing for the shifting fork shaft was plugged with an end cover. By not using the mechanical reverse gear the load on the bearings and spline shaft also reduces which was desired.

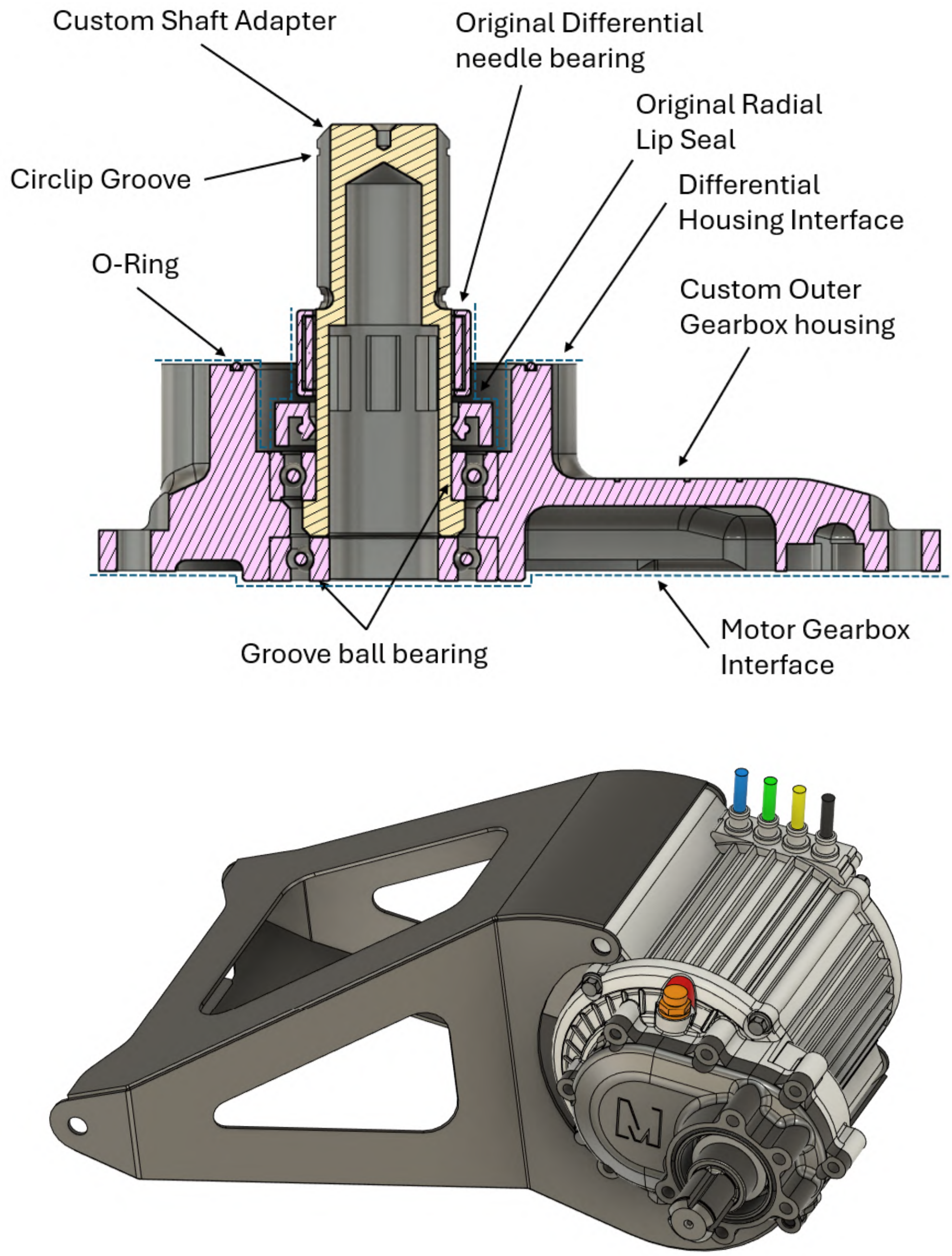


Figure 4.6: Transmission adapter and motor mount

By 3D-printing the adapter with shaft and putting everything together it could be ensured that it would fit before manufacturing the actual parts. It took a couple of design iterations before everything fit as intended and the end result can be seen in figure 4.7.

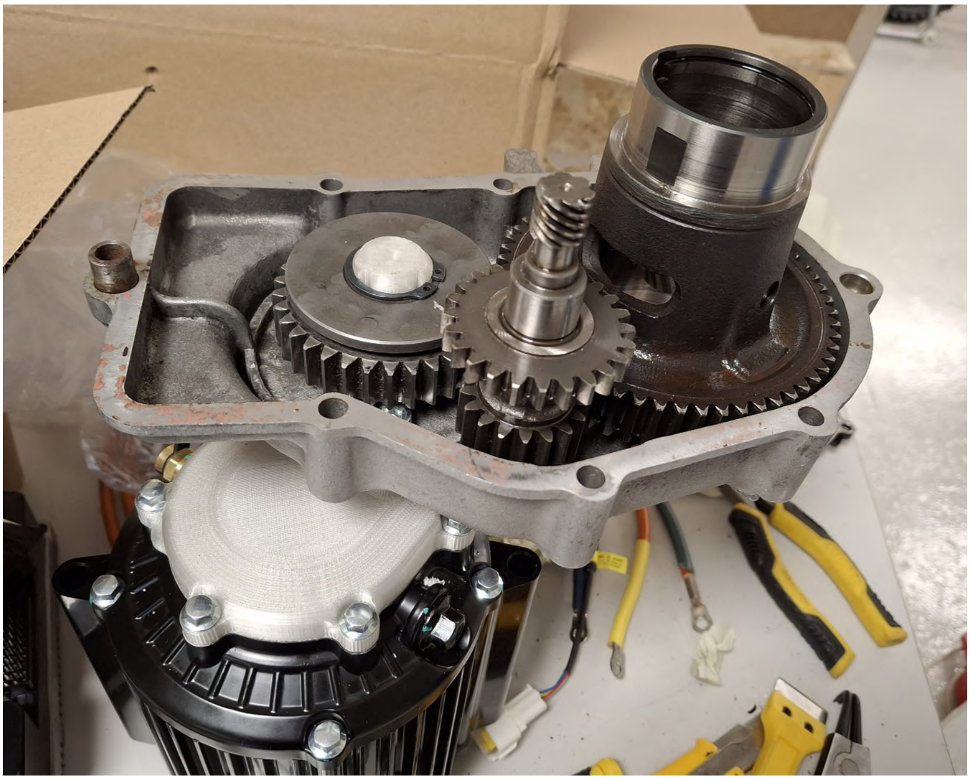


Figure 4.7: Motor and differential assembled with 3D-printed parts

4.2 Battery

The battery went through many design iterations. The first idea was to place as many components as possible inside the battery box to limit the number of connections to the box. However, there were size constraints on the box. They came from the fact that the battery would need to fit between the original beams under the bed, this because the box would otherwise clash with the motor. The box could therefore not be made wider than the spacing between the two rear beams. It was also constrained in length because the original rear fenders were to be used with their original mounts. Its shape was also constrained to an L shape as the middle of the battery had to be slimmer to not clash with the motor. A U shape would have been possible, but it was deemed to add unnecessary complexity for the manufacturing of the box. In the end the battery box was made as large as possible within these constraints. The charger was deemed not fit inside the battery box, it was therefore moved together with its type 2 charging connector to the cabin. Because there would need to be HV cables running to the cabin to the charger, the DC-DC was also moved to the cabin to reduce the number of cables and connections from the battery. Having the DC-DC in the cabin also reduces losses in cables since the long cables from the battery box to the cabin are higher voltage and lower current. The components left inside the Battery box were then the three segments, the BMS and the motor controller.

The connections required on the battery box were then specified as the following: motor cables, motor signal cables, auxiliary DC-AC, charger/DC-DC, key switch for BMS, throttle handle, charger/BMS CAN, display signal and extra telemetry. From this the number and type of connectors were chosen as two Deutsch DT 12 pin connectors for most signal cables, one Deutsch DT 6 pin connector for motor signal cables, and a total of seven Amphenol Surlok connectors for auxiliary DC-AC, charger/DC-DC and motor cables. All of these come with gaskets to seal their holes in the box. The surlok connectors were all chosen as the 16 mm^2 variants. The reason for this was to keep the different cables sizes to a minimum even though some of them could have been smaller.

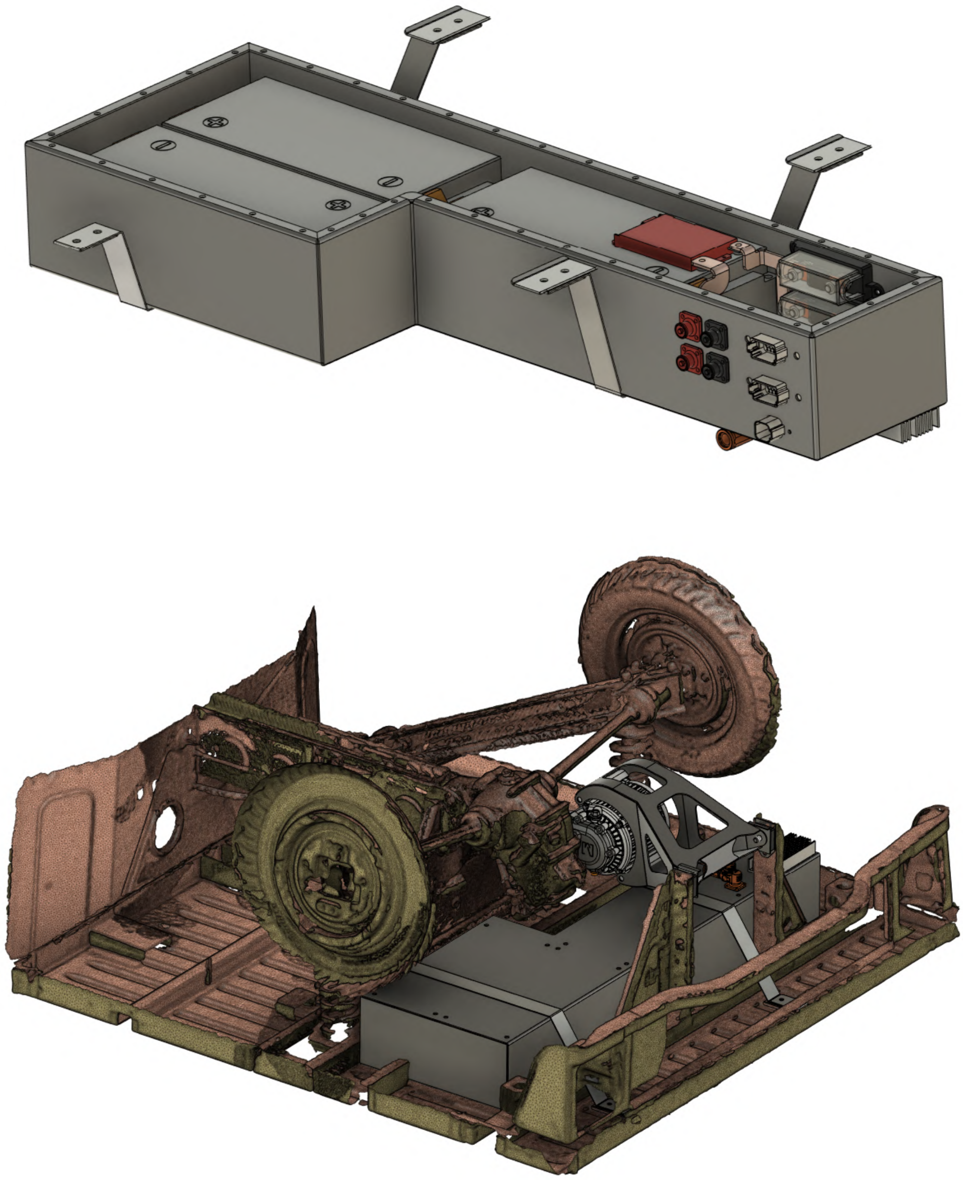


Figure 4.8: Battery design and mounting solution

The final battery design and how it will be mounted on the vehicle can be seen in figure 4.8. It also includes bus bars, battery mounts, heat sink for the motor controller, fuses as well as all holes required for mounting the components and the box lid. The BMS acts as fuse for the motor controller which is why there are only two fuses, one 100A for the auxiliary DC-AC and one 40A for the charger/DC-DC. Further the BMS is the negative terminal for all consumers, and the bus bar mounted on the floor of the box the positive terminal. These terminals will also have covers, and the rest of the bus bars heat shrink to protect against short circuiting the battery. Feet were also added to the underside of the box so that it could stand without hitting the connectors on the underside during assembly and future servicing.

Test panels were also cut to test fit connectors both to ensure that they fit and that they do not interfere with each other. Figure 4.9 shows one of the test panels. Test pices were also cut to test the bending to make sure the bends end up in the correct place and that the walls are the correct height.

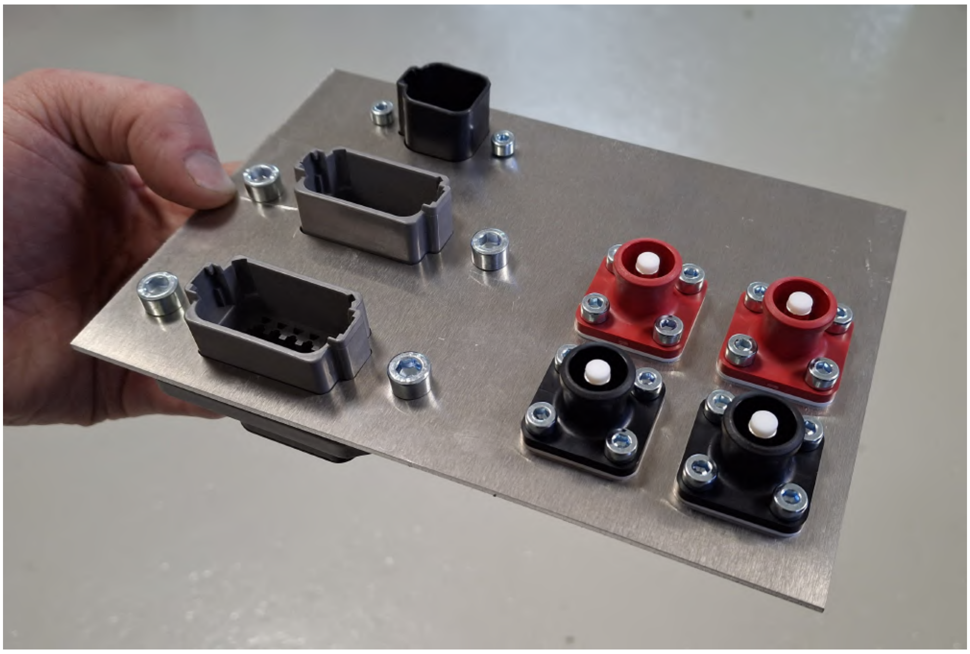


Figure 4.9: Connector fitment test panel

The final battery design achieves a balance between packaging constraints, electrical integration, and serviceability while ensuring safe operation and efficient system layout.

4.3 Driver Compartment

The components placed inside the driver compartment are the charger, type 2 charging connector, DCDC and SOC indicator. The DCDC has a rational space under the driver seat next to the 12v battery, since that is where it will be connected. This leaves the other side of the seat free for the charger. See figure 4.10a for a picture of the empty compartment, however do note that the battery is not installed in the picture. This also means that the Type 2 charging connector can sit on the rear of the cabin, which is easy to reach and out of the way of other things. The SOC indicator display is mounted on the dashboard, see figure 4.10b. However, this component is not discussed in further detail in this report, since it was the responsibility of Mint Engineering to design.

(a) Empty driver compartment

(b) Display

Figure 4.10: Driver compartment

Since the charger has a fan sticking out on its mounting side, see figure 4.11, standoffs are needed to mount it to a flat panel. to solve this 4 cylinders with trough holes were made to space the charger out from the rear wall of the cabin. Since the sheet metal in the cabin is thin and the charger heavy a 3d printed support was also made that the charger sits on which takes some of the load from the rear panel and places it on the floor instead.

Figure 4.11: Charger

Further, the electric heater was put under and in front of the seat. Both because it was one of the only locations where it fit and because the buttons to turn it on and of had to be reachable. Relays to turn BMS and heater on with the original ignition key was placed under the seat. This way everything turns on with the ignition key as everything powered by the traction battery gets power when the BMS is turned on.

5

Manufacturing

This chapter describes the manufacturing of the designed components and the assembly of the electric drivetrain system. It outlines how the design presented in the previous chapter is realized in physical parts through a combination of in-house fabrication and outsourced manufacturing.

The manufacturing strategy is based on balancing cost, time, and quality. Components are therefore either produced internally when flexibility and iteration are required, or outsourced when specialized processes such as laser cutting, bending, or surface treatment provide a more efficient solution where the time saved is worth the cost and iterations are not required.

The chapter focuses on the production of key subsystems including the motor-to-differential interface, battery system components, and supporting structures, and describes how these parts are manufactured and prepared for final assembly.

5.1 Motor to Differential Interface: Spline Shaft

The spline shaft was turned from SS2511 case hardening steel and nitro carburized to add wear resistance.

The manufacturing process started off by turning the outer and inner geometry to size in one single operation to ensure concentricity, see figure 5.1. During the machining it was accounted for the material growing a couple of hundreds of a millimeter diametrically during the heat treatment. The inner geometry was made larger to fit after heat treatment but the outer diameter was turned to spec. and ground back to spec. After heat treatment using abrasive cloth, to get a good surface finish for the lip seal and bearing raceway.

Figure 5.1: Spline shaft blank being turned in a lathe

A shaper attachment was available at Mint Engineering, but tools for both spline profiles had to be fabricated to fit the attachment, see figure 5.2. The tool holders were made from center-less ground bar, and the cutting edges from old HSS drill bits milled and ground to the desired shape.
The part was fixed in a dividing head and the machine spindle was centered over the axis of the part to be machined. The cutting tool was then aligned with the Y-axis of the milling machine. The part was clamped in a three jaw chuck for the first operation when the internal spline was to be cut. To make the external spline a mandrel was made, onto which the shaft was fixed with Loctite 641 to lock it in place while machining. The shaft and mandrel could later be dissasembled by heating it up in the oven.

Figure 5.2: HSS Spline cutting tools and spline shaping Process

The shaft was thereafter sent to Göteborgs Härdverkstad to be nitro-carburized. Figure 5.3 shows the finished shaft before heat treatment.

Figure 5.3: Spline shaft prior to heat treatment

The nitro-carburization heat treatment method is commonly used for parts that are sensitive to geometric changes as it has low impact on geometry. This method relies on relatively low temperatures in a carburizing atmosphere for a longer period of time to allow the carbon diffusing into the surface of the steel. According to Göteborgs Härdverkstad, a hardening depth of 0.5mm and hardness of 600-650HV was to be expected for the chosen material. Figure 5.4 displays the finished spline shaft together with the motor output gear and final drive input gear.

Figure 5.4: Spline shaft, motor output gear and final drive input gear

5.2 Motor to Differential Interface: Differential Adapter

The motor-differential adapter was milled in a conventional 3-axis vertical milling machine in two setups, see figure 5.5. Firstly the inside of the cover was milled, including milling of bearing seat reaming locating pin holes. It was then flipped and bolted into a jig for machining the other side, including features such as the other bearing seat, the O-ring groove as well as the differential centering bore and threaded mounting holes. The fixture had two centering features, one centering in the bearing seat and the other one for one of the locating pin holes. The fixture mounting threads were drilled out as the last step in the process. The bearing seats were machined to specification according to the SKF Rullningslager handbook [2].

Figure 5.5: Motor to differential adapter

5.3 Battery

Many parts in and around the battery were made from sheet metal. Instead of making them in-house they were sent to a company for laser cutting and bending. Figure 5.6 shows the pallet with cut and bent parts that was received.

Figure 5.6: Laser cut and bent sheet metal parts

When factoring in time, material, and gas to use the laser cutter at Mint it was cheaper to order the components finished. It also meant that the need for making test panels for bending was removed which greatly reduced price and time consumption.

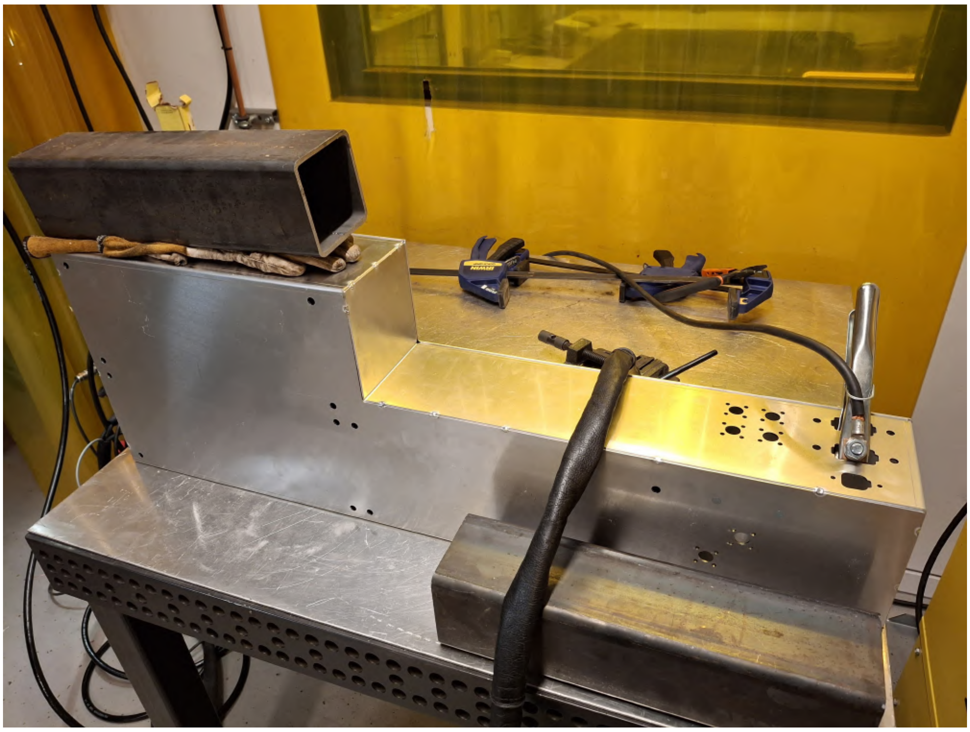


Figure 5.7: Spot welded battery box

Figure 5.8: Press studs and nuts being mounted

Both motor mount that can be seen in the bottom left corner of figure 5.6 and the battery box that can be seen in the top right corner of the same figure were then welded together to form the finished motor mount and battery box. After being welded, see figure 5.7 ,all press studs and press nuts were pressed into the cut holes in the battery box, see figure 5.8. The components could then be mounted inside and cables ran. All bus bars were made using the same method in 3mm aluminum sheet, see figure 5.9. These were then dipped in rubberized paint for insulation to avoid risk of short circuiting the battery.

Figure 5.9: Bus bars

Also the battery mounting bands and backing plates were ordered like this, see figure 5.10. The battery mounting bands were however bent a final time after receiving them to make the ends where they meet the bed double thickness.

(a) Battery mounting bands

(b) Battery mount backing plates

Figure 5.10: Battery mounting

This manufacturing approach enabled efficient production of structural and electrical battery components while maintaining sufficient quality, repeatability, and ease of assembly.

5.4 Motor Mount

The motor mount was welded similarly to the battery box. The motor mount however needed to be rolled into a round at the motor side of the mount since the company doing the laser cutting and bending did not do rolling. The motor was then used as a jig for welding both to align the 4 large pieces and to keep the mount from warping where it should fit around the motor. The mount was then powder coated for rust protection, see figure 5.11

Figure 5.11: Spot welded motor mount

5.5 Driver Compartment

A key focus of the driver compartment changes were simplicity, mainly because there was a need for the process to be quick. Because of this 3d printing was used for some parts. For example the brake lever made use of the throttle handle as a spacer on the handle bars, for this a 3d printed cylinder was used when the throttle handle was replaced with an electric one. Also the charger made use of a 3d printed mount in addition to being bolted to the rear wall of the driver compartment using aluminum cylinders as spacers, as can be seen in figure 5.12.

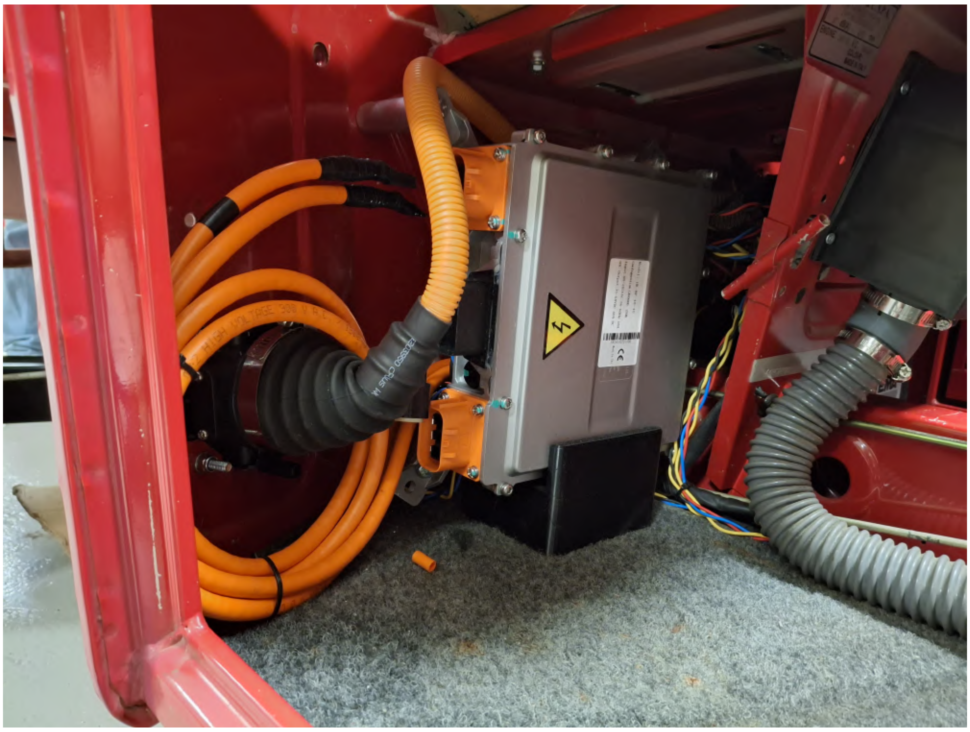


Figure 5.12: Charger mounted to the cabin under the seat

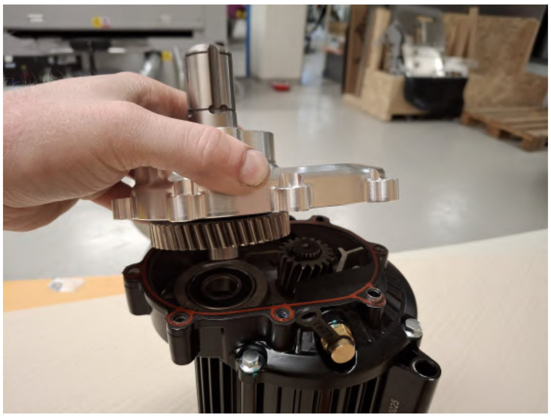
Overall, the driver compartment modifications focus on maintaining functionality while enabling quick integration and minimal modification of the original vehicle structure.

The electrical harness was manufactured on the vehicle by separating each function into its own wires that were then twisted together. these were pinned and inserted into the connectors for the battery and layed out on the floor to be taped together, see figure 5.13. during this process as well as during the battery wiring process a pin out was also made with wire colors in mind to make diagnostics of potential issues easier. This was then plugged into the battery and anchored in place. each function was then routed to its location and cut to length. Connectors where then put onto these ends and they were plugged in. The parts of the harness that did not go to the battery, for example switched 12v to the relays, were instead made one by one and combined into the harness.

Figure 5.13: Electrical harness first step

5.6 Powertrain Assembly

When all parts were acquired, the assembly of the powertrain was fairly easily completed. Two bearings and the spline shaft were mounted in the custom transmission cover. The complete unit could then be screwed onto the motor with the original gasket sealing between the mating surfaces 5.14a. The following step was to mount the radial lip seal and the needle roller bearing in the left differential housing half followed by mounting it to the motor with an o-ring to seal between the two. All differential internals were placed in the left half 5.14b, and then the right half could be mounted to the left half with a layer of flange sealant between the two.



(a) Transmission cover assembly

(b) Differential assembly

Figure 5.14: Powertrain assembly

With the motor and differential assembled, the motor mount and the rear suspension were added, forming a complete rear suspension unit to mount to the vehicle 5.15. Before adding this unit to the vehicle, the transmission and differential were filled with transmission oil.

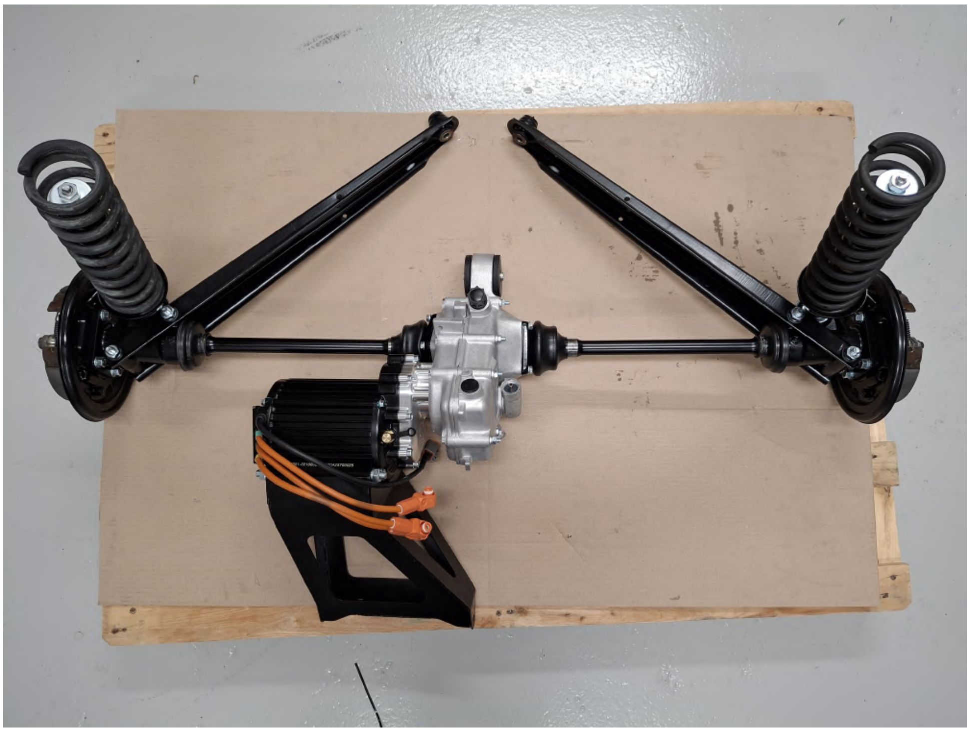


Figure 5.15: Complete powertrain with rear suspension

6
Results

This chapter presents the experimental results obtained during the development and testing of the project. The final result of the project is an electric conversion kit designed, manufactured, installed, and tested on a cargo moped. See figure 6.1 for two pictures of it installed. It begins with functional testing of the assembled driveline, suspension, and battery system, followed by an initial test drive to evaluate basic vehicle behavior and drivability. During these tests, several performance characteristics and issues were identified, most notably a significant deviation in expected motor torque output compared to observed vehicle performance. A series of diagnostic measurements and calculations were therefore carried out to investigate and isolate the cause of this. The chapter continues with a comparison between measured performance and theoretical expectations, as well as an evaluation of the system against the defined project requirements. The chapter then concludes with a design results section where the design is presented in terms of its result.

Figure 6.1: Installed Electric Conversion Kit

6.1 Testing and Troubleshooting

All tests were performed under dry road conditions with a fully assembled vehicle and a single driver unless otherwise stated. Key tests were repeated multiple times to verify consistency of observed behavior.

After physical installation of the driveline, suspension, battery and wiring a first test with wheels in the air was performed. This test showed that the system functioned largely as expected. The motor spun and turned the wheels, the accelerator handle controlled motor rotation in both directions, and regenerative braking functioned correctly. The only issue was the motor spun the wrong direction which was easily fixed in the motor controller by changing rotation direction.

After this a test drive was performed. The vehicle demonstrated stable and predictable driving characteristics and the driver inputs worked easily and smoothly. It was also apparent that the stability was better than expected from a three wheeled vehicle, probably because of the extra battery weight behind the rear axle somewhat improving the weight balance of the unloaded vehicle. The weight on each wheel was also tested and came out to $68kg$ front, $82kg$ RR and $84kg$ RL showing that the right to left balance was good.

One significant issue was identified. The motor appeared to produce significantly less torque than expected, preventing the vehicle from climbing steep hills. At first it was suspected that some setting in the motor controller was wrong, but after extensive testing of different settings this was ruled out. After this logging on the motor controller was done to make sure the controller was not giving large D currents which would oppose the permanent magnetic field and thus torque. This also showed slight negative D currents, large Q current and the phase current being at the maximum set value. After this the hall sensors were recalibrated with the reasoning that if the hall signals were wrong then the motor controller measurements of Q and D currents might be incorrect, resulting in reduced torque output. The hall calibration can be seen in figure 6.2

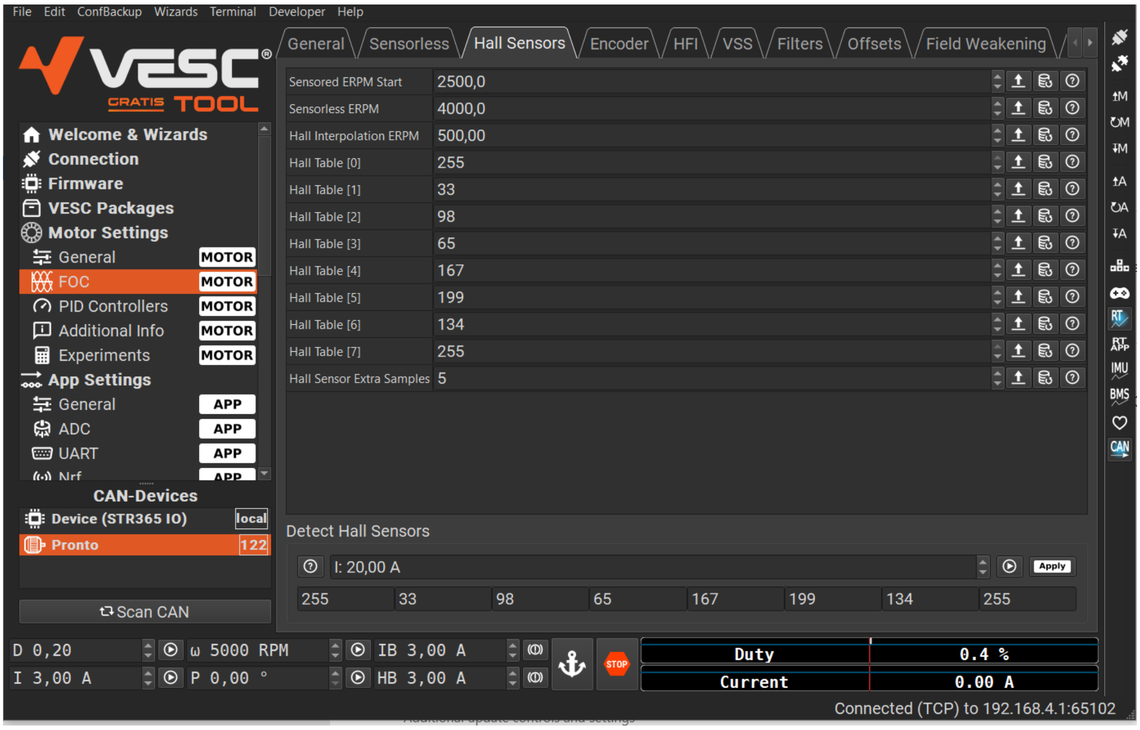


Figure 6.2: Hall calibration

This shows hall values ranging from 0 to 200 in roughly equal steps which suggests that the hall calibration and wiring are correct. The reason it ranges from 0 to 200 instead of 0 to 360 is that vesc represents degrees in this way where 0 represents 0 degrees and 200 represents 360 degrees.

After it was concluded that the Q current which is the torque producing part of the phase current was 200A and that the vesc values could be trusted some calculations were made. By using QS120 specified no load rpm and voltage, K_v and K_t were calculated to be 38.9 rpm/V and 0.246 Nm/A. At 200A this should give $K_t I_q = 0.246 \cdot 200 = 49.2\,\mathrm{Nm}$. With a total gearing of 3.97 this gives wheel torque of 195 Nm and with wheel radius of 210 mm gives a tractive force of $\frac{195\,\mathrm{Nm}}{0.210\,\mathrm{m}} = 928.6\,\mathrm{N}$. The vehicle with driver was weighed to 311 kg. Calculating the steepest climbable hill at constant speed gives $\sin^{-1}\left(\frac{928.6}{311 \cdot 9.81}\right) \approx 17.4°$. This assumes 100 percent efficiency but still suggests the vehicle should be able to go up steep hills.

The next test after this was max speed with field weakening turned off with wheels in the air to give the no load speed. The reason field weakening is turned off is to get the natural no load speed and not a speed that is increased by weakening the magnetic field. The test would ideally be done without the driveline connected since it takes some torque to spin, this torque is however low and therefore has little impact on the no load speed. The following analysis compares manufacturer-specified motor parameters with experimentally derived values. From the motor controller, the speed and voltage were observed to be 2496rpm and 42.9V. Calculating K_v and K_t from this gives 58.2 rpm/V and 0.164 Nm/A. comparing this to the QS120 specified values gives $\frac{0.164}{0.246} \approx 0.667$. The motor only produces 67 percent of the torque it should at a given current. This strongly suggests that the supplied motor differed from the specified model, which was further indicated by $\frac{72}{48} = 1.5 = \frac{0.246}{0.164}$ which suggests a winding configuration consistent with a lower voltage motor

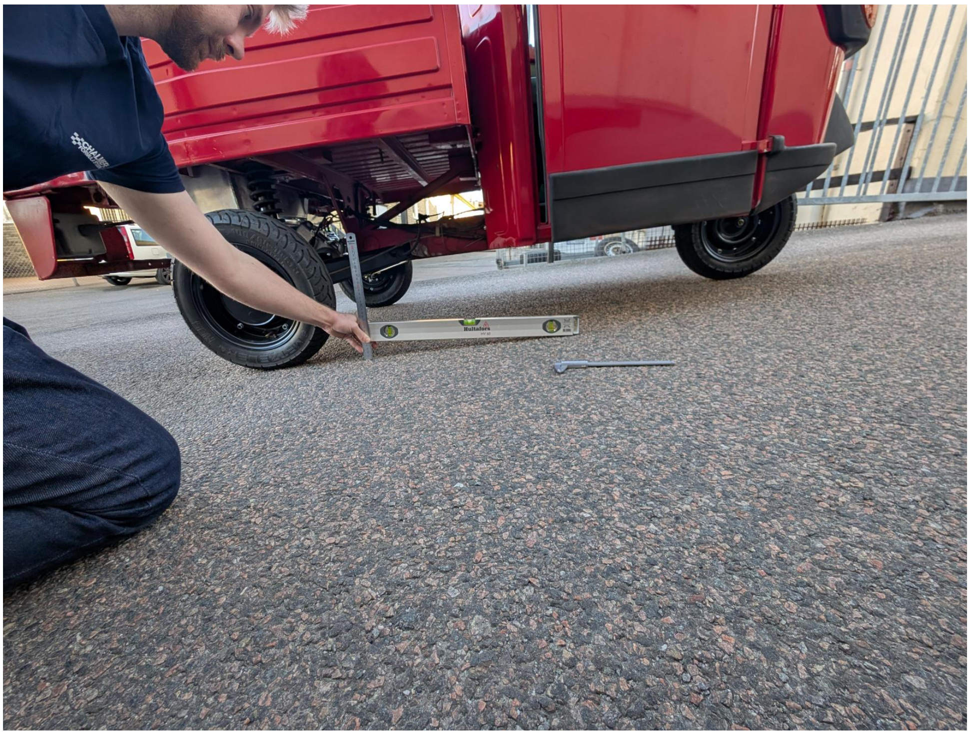


Figure 6.3: Hill test

A further test to find the actual motor torque was to find a hill that was exactly steep enough to where the vehicle would not accelerate up it. See figure 6.3. This hill was measured and calculated to be 5.17° which would require a tractive force of $311 \cdot 9.81 \cdot \sin(5.17°) \approx 275\,\mathrm{N}$ and motor torque of $(275 \cdot 0.21)/3.97 \approx 14.6Nm$. Using the derived K_t for the actual motor gives $0.164 \cdot 200 \approx 32.8Nm$. Since this calculated motor torque is more than double the required torque of $14.6Nm$ the vehicle should be able to accelerate up this hill. This doesn't take into account driveline efficiency but even assuming a low efficiency of 85% gives required motor torque of $14.6/0.85 \approx 17.2Nm$ which means the theoretical torque is still $32.8/17.2 \approx 1.9$ times what is required.

After this a test was performed to verify the motor controller current measurements. Since it is difficult to measure the AC current over the shielded phase cables the DC current was instead observed and compared against the DC current that the BMS reported. This was done by having the rear wheels in the air, handbrake pulled slightly and a constant accelerator handle. The test showed that both reported DC currents matched well. It is not the DC current that decides the torque but since DC current is either measured directly by the motor controller or derived from actual phase current measurements it shows the phase current is also correct. In the scenario where the DC current is measured the motor controller would compare it to the phase current and if they did not match it would trigger it to stop. This is because a difference in derived DC current form phase current and measured DC current indicates a short circuit. In the scenario where the controller does not measure DC current and only uses a derived value from phase current, if the controller and BMS currents match it means that the measured phase current should also be correct. The result of the test was therefore that the controller current measurements were correct.

Since the motor was running smoothly the idea that some motor parameters were wrong was unlikely but it was still investigated by running the motor parameter detection again which did change some values slightly, see figure 6.4 for the parameters, but did not result in a noticeable improvement in torque. It was further tested by manually changing some parameters slightly but this only resulted in the motor starting to stutter indicating that the detected parameters were correct .

Motor Resistance (R)	5,8 mΩ
Motor Inductance (L)	50,67 μH
Motor Inductance Difference (Lq - Ld)	22,67 μH
Motor Flux Linkage (λ)	17,265 mWb
Current KP	0,1013
Current KI	11,54
Observer Gain (x1M)	3,35

Figure 6.4: Detected motor parameters

In the end it was found out that the motor controller had a peak amplitude current of 200A and not 200A RMS which explains some of the lost torque. The rms valve instead becomes $200/\sqrt{2} = 141A$ which together with the low torque constant explains the low torque.

6.2 Requirements

This section aims to compare the result with the specified requirements. All requirements will however not be discussed, partly because the vehicle is not finished enough to test all requirements. For example time constraints meant the charging was not fully setup to test as well as legal requirements not being tested. The following requirements were considered fulfilled based on the implemented system design and were therefore not analyzed further: REQ.01, REQ.04, REQ.06, REQ.08, REQ.09 and REQ.13-18 most of these requirements being met follows directly from system design. The following requirements could not be fully verified within the project time frame: REQ.02, REQ.03, REQ.05, REQ.10, REQ.12 and REQ.19. REQ.02 was not tested since the charging was not completed and there was also not enough time to test this and the same applies to REQ.03 and REQ.10. REQ.05 was partially fulfilled since the original instrumentation is kept and the speedometer still uses a wire connected to the differential but the display to indicate SOC and range was not finished and tested. Further time would also be needed to make a complete bill of material to verify REQ.12. REQ.11 was verified by weighing the completed battery system. The battery mass was approximately 40 kg and, together with the 10 kg motor mass, resulted in a total added mass of approximately 50 kg, which is below the required limit of 70 kg. Finally the requirement which was tested and not met was REQ.07. This is presented in the previous chapter.

The main result from testing is that the system operates as intended in terms of drivability and control functionality. However, a significant deviation in motor torque constant compared to manufacturer specifications was identified and verified through multiple independent tests, indicating a likely mismatch between the specified and delivered motor.

6.3 Design Results

Several design choices were validated during the manufacturing and assembly of the system. The ignition-based relay system functioned as intended, enabling sequential activation of the battery management system, DC-DC converter, motor controller, and auxiliary heater through a single ignition input. This provided a simple and consistent startup procedure during testing.

The physical integration of the battery system into the vehicle frame was successful, and the overall packaging layout allowed all major electrical and mechanical components to be installed within the available space constraints. However, the use of individually routed internal battery cables resulted in a relatively complex assembly process, requiring significant manual routing and assembly, which makes future service more difficult. See figure 6.5 for the internal battery cable routing. Mechanical integration of the drivetrain components into the chassis was achieved, and all primary mounting points aligned as intended during assembly. The adapter

Figure 6.5: Finalized internal battery cable routing

shaft design includes a groove for a retaining ring, which introduces a stress concentration in the load path that reduces the torque capacity. This groove was also deemed unnecessary, since the gearwheel could instead have been allowed to bottom out against the spline shoulder. This is not an issue since the gears were straight cut, meaning very low axial forces.

Minimal modifications were made to the original vehicle chassis, but some mounting holes were deemed necessary, such as for the battery mouting and the charging port 6.6. There were also mounting holes made for the cabin heater, charger and for wiring anchors. Nothing of which could not be covered up in case of converting the vehicle back to its original form.

Figure 6.6: Modifications to the original chassis

Overall, the implemented design enabled successful assembly and integration of the electric conversion system within the vehicle, although certain aspects of the physical layout could be optimized from a manufacturing, assembly, and performance perspective.

7

Conclusion

In conclusion the project met the aim of designing, manufacturing and installing and testing a prototype electric conversion kit on a Piaggio Ape. The following Chapter discusses this and some findings further.
A key observation from testing was that the vehicle exhibited significantly lower torque than expected based on manufacturer specifications. This was identified through both hill-climb testing and no-load speed measurements. The independently derived torque values from these tests were however not consistent since the torque constant value suggested much higher torque than the physical hill test showed. The reason for this was not determined, however the no load test still showed that the motor received did not match the specified motor in terms of torque and speed constants. This strongly suggests that the motor received was not the specified model. Additional evidence supporting this conclusion was that the motor dimensions differed from available CAD models and drawings, with the received motor being approximately $25mm$ longer than expected.

The reduced torque resulted in limited hill-climbing capability compared to theoretical expectations. While the system was still operable under normal conditions, performance was noticeably affected when higher torque demand was required.

Two reasonable paths to address the observed torque limitation exist. Either the motor could be replaced with one with a higher torque constant, or the system could be modified by using a motor controller with a higher maximum current capability. Both approaches have practical implications. Replacing the motor with a unit matching the intended specifications would require either new motor mounts or spacers to enable compatibility with the existing motor mount. Alternatively, increasing the maximum current through a higher-rated motor controller would increase available torque without mechanical modification. However, this would increase system cost and introduce higher electrical and thermal requirements. It may also result in a higher-than-required maximum power capability for the intended vehicle application. Furthermore, the discrepancy between the experimentally derived torque constant and the observed hill-climbing performance could in the end be explained by the motor controller using peak amplitude phase current and not rms current. This means the current used to calculate torque should be $200/\sqrt{2} \approx 141A$. Combining this with the possibility the scales were not entirely accurate can explain the discrepancy. For example if the weight was 10 percent higher than what the scales showed the required torque would be $17.2/0.9 = 19.1Nm$, and using the new RMS current the expected torque is $141 \cdot 0.164 \approx 23.1Nm$. This difference of $4Nm$ could be explained by poor operation of electric motors at low speed

A positive outcome of the project was the implementation of a simple and practical user interface and power activation system. The original ignition key was used to control a relay system which enabled the battery management system MOSFETs and auxiliary electric heater. When activated, this sequence also powered the DC-DC converter and motor controller, allowing the system to be started in a single and intuitive step. Using a bidirectional accelerator handle also meant that the need for a switch to operate forward and reverse modes was removed.

An additional project limitation was delays in obtaining initial battery segments, which were later replaced with alternative segments. This affected the project timeline and reduced the available time for final system integration and requirement verification.

Overall, the project demonstrates that electric conversion of the cargo moped is feasible, while also highlighting the importance of verifying key component specifications during procurement, as deviations in motor parameters were shown to significantly affect overall vehicle performance and drivability.

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