



CHALMERS
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Development and Testing of Advanced Door Opening and Closing Function

Design, Implementation and Verification of Door Entry System

Master Thesis in Product Development

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

www.chalmers.se

MASTER'S THESIS 2026

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Master's Thesis 2026

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Cover: Opening interface for the user entry of the truck door.

Typeset in L^AT_EX

Printed by Chalmers Reproservice

Gothenburg, Sweden 2026

Abstract

The increasing electrification and digitalization of heavy-duty vehicles have created new opportunities to improve both vehicle functionality and aerodynamic performance. Reducing aerodynamic drag is an important criterion identified for lowering energy consumption and increasing vehicle range, and the integration of flush exterior components, such as door handles, can contribute to reducing surface discontinuities. This thesis investigates the development of a power-operated side-door system for a heavy-duty truck, with a focus on integrating power release, soft-close functionality and a flush exterior handle interface while retaining the existing latch mechanism and mechanical release as a backup.

A structured product development process was used to gauge the user needs and understand contemporary door entry systems to then develop and evaluate the prototype. The existing door system was integrated with an electric linear actuator in place of the door checker to enable a multi-functional solution. The actuator mounting geometry, required stroke, opening angle and operating forces were determined through kinematic and force calculations. Furthermore, a geared motor-driven mechanism was developed for power release and cinching. The multi-stage gear system was developed to provide the required output torque to the latch, and the drivetrain was verified using Romax. The housing, gears and opening interface were subsequently refined through several prototype iterations and functional testing. A preliminary communication and control system was also developed and tested using an Arduino-based setup to coordinate the different components and demonstrate the operating sequence.

The final prototype combined the developed actuator, latch interface, cinching and power-release functions, exterior handle interface and supporting test fixture into a functional system. The iterative development and testing process identified several practical limitations related to packaging, structural strength, electrical interface and component integration, which were addressed through successive design modifications. The results demonstrate the feasibility of integrating an electrically operated door system around an existing heavy-duty vehicle door, while the developed prototype provides a technical foundation for further refinement and integration toward a production-ready power-operated door system for heavy-duty vehicles.

Keywords: Heavy-duty trucks, advanced door system, power release, cinching, flush door handle, actuator, Arduino, prototyping.

Acknowledgments

We would like to express our heartfelt gratitude towards the team in Volvo TTI Doors & Closure for the opportunity to conduct this Master's Thesis. A very special thanks goes to our supervisors Filip Hjältn Wallborg and Magnus Gollungberg for their passion, contribution and dedicated support, always being available to provide guidance and answers. Furthermore, we would like to extend the thanks to Patrik Johansson from NVH who has gone above and beyond in providing support during the prototype and testing phase. Without our supervisors and Patrik, the thesis would not have matured at the pace that it did.

We would also acknowledge the feedback and knowledge from the rest of the team and stakeholders within Volvo TTI. Additionally, our thanks goes to the Doors & Closure manager Lena Almqvist Mogren for providing the opportunity and support in the project.

Finally, we would like to say thank everyone participating in the interviews. The users left us invaluable impression that greatly affected the trajectory of the project. Additionally, Lars Lindkvist our examiner and academic supervisor deserves credit. He gave us valuable feedback and the freedom to try our ideas out.

James Campo & Senthil Kumaran Ravi, Gothenburg, 2026

Disclosure of AI Use

AI tools were used to support the writing process, particularly for improving structure and grammar. In addition, AI-assisted tools were used for debugging the code related to Arduino. However, the ideas, analysis and conclusions presented in the thesis are the authors' own. AI was not used to generate reports or specific ideas. The authors have reviewed all AI-assisted material and assume full responsibility for the final content of the thesis.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BES	Battery Energy Storage
CAD	Computer-aided Design
DC	Direct Current
DER	Distributed Energy Resource
ECU	Electronic Control Unit
GND	Ground
MILP	Mixed-Integer Linear Programming
MG	Microgrid
NVH	Noise, Vibration and Harshness
LED	Light-emitting Diode
PSU	Power Supply Unit
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable-based Energy Sources
VCC	Voltage at the Common Collector

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1 Introduction

The purpose of the chapter is to outline the intent of report, moreover it also serves as a prologue for the subject, providing the core information of the thesis. Thus, the intended structure will include background, purpose, aim, scope, limitations and finally research questions.

1.1 Background

Volvo Trucks is a leading truck developer and manufacturer that aims to offer high-end trucks in a global market[1]. Achieving an overall reliable system and good quality impression is crucial to maintain the lead among the heavy-duty truck industry. The door and closure team at CAB in Volvo TTI aims to deliver and be leading at high performing door and closure system, with the focus on customer experience. The door represents the first point of interaction for the customer, thus the impression shapes the customers perception of the product.



Figure 1.1: Volvo Trucks Products [2]

1.2 Purpose

The thesis will focus on future implementation of advanced door features such as soft-closing function, automatic door opening and closure. Currently in the automotive industry there

exists features such as soft-closing using cinching mechanism in the latch [3]. The project will investigate the possibility to add the capabilities from the car industries and how we can adapt it to heavy duty trucks. The current door for heavy duty vehicles uses a mechanical door stop with grooves to set the position when you open it. Furthermore, the current handle is purely mechanical, additionally the latch generates a lot of noise when closing. The initiative of the change is to replace the current door handles to improve conveniences, functionality and safety. The aspiration is to provide the customer a premium offering that satisfies their needs and alleviates frustration of the current solution. Hence there needs to be an investigation on firstly what the customer needs are, in the context of doors and closure features. Subsequently, further investigation on the possibility to apply the aforementioned features through concept generation and prototyping.

1.3 Aim

1.3.1 Primary Aim

- Test, design, build a working prototype for the final advanced door concept. The aim is to use Technology Readiness Level rating system from NASA[4] to set a realistic expectation of the final door system prototype. The target is TRL 4, which means the prototype ought to be fully function and demonstrated briefly in a laboratory environment.

1.3.2 Secondary Aim

- Understand and investigate customer needs in terms of doors and closure function and experience.
- Evaluate the benefits and drawbacks of the different concepts and functions.
- Test and understand the mechanism between the different sub-components of the chosen concept.

1.4 Scope

The target of the project and scope revolves around advanced door mechanism. It will initially involve leveraging academic literature and benchmarking existing mechanical and electromechanical components. Furthermore, investigation in modern automotive door systems will be conducted to identify technological and methodological gaps. Based on the analysis, the project focuses on the design and development of a advanced door opening solution that distinguishes itself from the normative concept. Additionally, the project examines the integration of soft-close functionality and an electronic door stop within the existing system architecture. Finally, a set of comprehensive testing is conducted to evaluate the functionality, safety, and robustness of the proposed systems. The outcome of the aforementioned tests will be the basis of the final requirements list.

1.5 Limitations

The main limitations for the project are the following

- The project does not involve a full redesign of the door system. Instead, the work is limited to modifications and enhancements of the existing door structure to integrate new functionalities.
- The system architecture is fixed and cannot be changed in a radical extent in order to accommodate the new components.
- Long-term durability testing, full vehicle-level validation, aesthetic market competitive design and large-scale production considerations are outside the scope of this project.

1.6 Research question

Based on a preliminary pre-study, the following research questions have been formulated to specify the issues investigated in this project.

- **RQ1:** What is the present available knowledge/methods in regards to mechatronics and mechanical components for opening & closing heavy truck doors?
- **RQ2:** Identify requirements and customer needs for the product/solutions and how it affects scope, manufacturability, cost and legality?
- **RQ3:** What value does the product change have for the stakeholders?
- **RQ4:** How could we incorporate the changes in the current door system architecture?

2 Methodology

The chapter describes the methods used throughout the different stages in the project. The objective is to give an understanding in the structure and the underlying rationale on how and why certain decisions are made. The Figure 2.1 visualizes the order for different activities in the project. Furthermore, the design process is flexible, if any conflicting constraints or limitations emerges in the later stages then it should be encouraged to perform retroactive changes in the previous steps. The reasoning is due to enable the opportunity to pivot due new available information later on in the project.

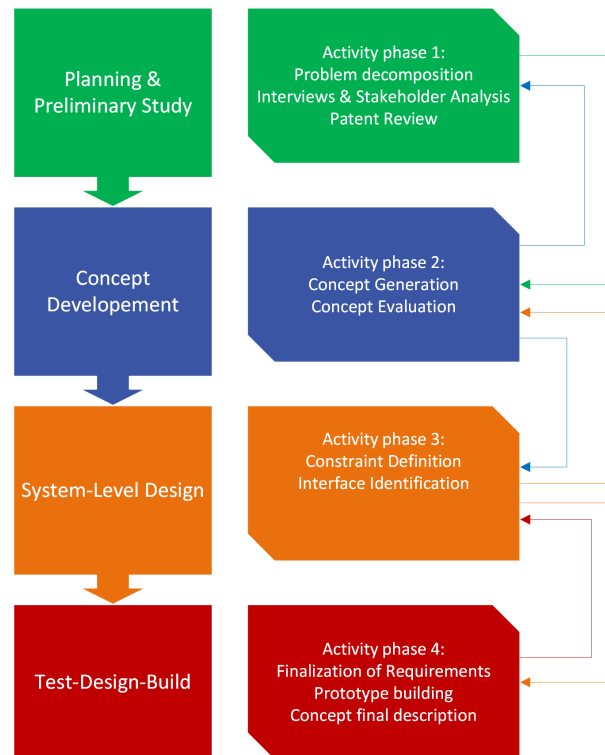


Figure 2.1: Design process.

2.1 Concept Development Processes

The Figure 2.1 describes the development processes for the project. The figure has four major stages that are conducted in chronological order and it also prescribes different methods used. The intention of the earlier methods is to gain leverage and information for the next phases

and insight on the product. The aim is to plan what methods should be used to realize the final product and at what stage. The spiral product development process is derived from the "Product Design and Development" by Ulrich et al.[5]. The final phase, namely production ramp-up, is being omitted due to being out of scope, since said phase is only relevant if the plan is to commercialize the solution. Furthermore, some of the stages are modified in order to adapt for the project scope, for example, pre-study is added during planning in order to highlight the use of literature studies, customer analysis and product benchmark early in the project.

2.2 Preliminary Study

The following section presents an overview of the problem with the current concept for door opening mechanisms and exploring potential solutions for said problems. Thus, a versatile array of methods were employed, which includes breaking down the concept and problem. Furthermore, there is an utilization of qualitative data collection through interviews, observations in clinics and reviewing existing patents.

2.2.1 Problem Decomposition

The intention with decomposing the problem is to divide the problems to smaller parts, which will allow for a deeper understanding on how the different components interact and affect each other. For this purpose, a function diagram in tangent with a system diagram will be used to illustrate the complete complexity. The need for an illustration can be attributed to the complexity of both the physical interaction and system capability. Furthermore, handling the problem in smaller parts allows for self-contained solution at the component level, allowing a diverse combination of potential solutions in the concept generation phase. Additionally, user function for the opening access will be conducted to explore potential scenarios and edge cases such as emergency after a crash.

2.2.2 Interviews & Stakeholder Analysis

The analysis was done by gathering quantitative and qualitative data. A clinic was held where internal stakeholders partook in viewing a door with cinching mechanism and switch-based release, observation was noted. Afterwards, a survey was then conducted with the same internal stakeholders to get their impression. However, utilization of quantitative data gathering was needed for customer needs, since the aim is to capture in depth frustrations, wishes and needs from the users. Therefore, the decision was to interview truck drivers to capture their impression of the door opening mechanisms. The qualitative and quantitative data will then be used to establish a requirements list.

2.2.3 Patent Review

A patent research study was carried out as an effective method for identifying concepts that are protected and must be avoided. The area of exploration was identified with the help of features that were deemed necessary from stakeholder analysis. Apart from this, an estimated 70% to 90% of technical knowledge is documented in the patents[6]. So, by analyzing

the patents, we can derive valuable sources of insight. Resulting in positive outcome for generating new ideas during our product development process.

2.3 Concept development

Initially in the concept development, decomposed sub-functions of the product will be outlined, this will enable concept generation of the sub-function, as opposed to generating the complete concept immediately. Thus, allows for a richer idea generation, which stems from the wider set of potential combinations. Previously obtained external searches such as patents, adjacent products will be utilized in the aim of brainstorming appropriate concepts for the sub-function. Thereafter, morphological matrices will be performed with the objective to generate the complete product concepts, this is done using the previously generated concepts in the sub-function as building blocks. In the subsequent step, Pugh and Kesselring matrices will be implemented to evaluate the final concepts.

2.4 System-level design

Identification of the product architecture and interfaces will be conducted by investigating the digital data of the product and the physical interface. A study on the geometrical constraint will also be conducted. Along with the physical interface identification there will also be a electromechanical interface illustration, this is to allow among other things, replication of the interaction between the control unit and components.

2.5 Test-Design-Build

The iteration of the physical prototype will be done in accordance with Test-Design-Build rather than the conventional Design-Build-Test due to shorter iteration cycle [7]. Therefore, it will allow for more tests and thus improving the learning opportunities. The outcome of the learning will be used to adjust the requirements list.

3 Pre-Study

This chapter presents the pre-study conducted to establish the basis for the development of the proposed door system. The study begins with a product analysis, including patent landscaping and benchmarking of existing vehicle solutions. This is followed by stakeholder and customer analyses to identify the relevant needs and expectations. Finally, the main components involved in the system are analyzed to understand their functions and constraints. Together, these studies provide the foundation for the subsequent concept development and design process

3.1 Product analysis

3.1.1 Patent Landscaping

Patent landscaping was conducted to investigate existing technological solutions related to vehicle door access, release, soft-closing and electronic control. The purpose was to identify relevant technological trends and working principles that could provide technical input and inspiration during the subsequent concept-generation process. A narrow and targeted approach was adopted, focusing on technologies relevant to the functions considered within the project scope.

The investigated patents covered technologies ranging from conventional mechanical latch arrangements to passive-entry systems and more recent electromechanical door architectures. To provide a structured overview, the identified solutions were grouped into four main areas : **access and passive-entry systems, electronic door release and emergency operation, system integration and power and soft-closing systems.**

3.1.1.1 Access and Passive-Entry systems

One development identified in the patent landscape was the transition from conventional key-operated access toward electronically assisted and passive-entry systems. These systems reduce the need for direct mechanical interactions by allowing the vehicle to detect an authorized user and initiate locking or unlocking functions electronically.

Early developments can be observed in [8], describing a system capable of automatically unlocking the vehicle when an operator carrying an authorized portable device approaches and subsequently locking the vehicle when the operator moves away. Similar approaches are presented in [9] and [10], which further demonstrate semi-passive and passive key-less-entry architectures and also the communication regions around the vehicle, shown in Figure 3.1. These systems demonstrate how user authorization and access functions can be trans-

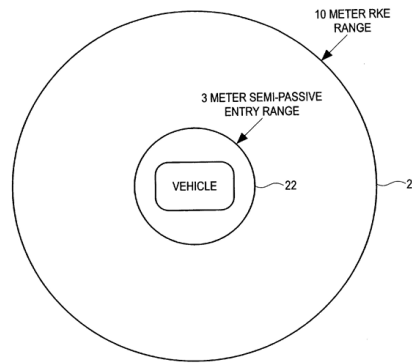


Figure 3.1: Semi-passive key-less-entry system illustrating the communication regions around the vehicle.[9]

ferred from a direct mechanical interaction to an electronically controlled system, providing alternative approaches for initiating vehicle access.

3.1.1.2 Electronic Door Release and Emergency Operation

Another significant development identified was the transition from mechanically linked door-release systems toward **electrically actuated release mechanisms**. In these systems, the normal user input can be provided through a switch or electronic interface, while an actuator performs the physical latch-release operation.

[11] describes an electrically actuated latch-release mechanism combined with an emergency mechanical operation member. The electrical actuator performs the normal release function, while an alternative mechanical path remains available when electrical operation is unavailable. A similar principle can be observed in more recent exterior-handle developments. [12] describes a flush-mounted vehicle handle incorporating an electronic opening device together with an emergency mechanical opening arrangement. [13] also incorporates electronic operation with a mechanism that enables mechanical accessibility following loss of electrical power.

These solutions highlight an important recurring principle: electronic operation can provide the primary means of door release while mechanical functionality is retained for emergency operation. This provided relevant inspiration when considering different approaches to user interaction and system redundancy during concept generation.

3.1.1.3 Power Release and Soft-Closing Systems

Power-assisted release and closing were particularly relevant technologies identified during the patent study. These systems introduce electromechanical actuation into the latch system to perform release and final closure functions that would otherwise depend on direct mechanical input from the user.

Earlier latch mechanisms relied predominately on mechanical components and linkages for release and locking. [14], for example, describes a mechanical vehicle-door latch in which the inside and outside release mechanisms are mechanically connected to the latch components. [15] demonstrates a more integrated side-door latch arrangement incorporating the ratchet,

pawl, release, and locking mechanisms within the latch assembly. These architectures provide a useful reference for understanding the mechanical functions upon which later powered systems are based.

More recent patents demonstrate the introduction of powered release and closing functions. [16] describes an automotive latch system incorporating power-operated release and cinching, combining electrical actuation, electronic control and mechanical latch functions. Different approaches to actuator integration were also identified. [17] describes a system in which the cinching actuator is positioned remotely from the latch and the mechanical input is transferred to the latch through an intermediate mechanism. In contrast, [18] and [19] incorporate power release and closing mechanism more directly within the latch assembly.

The investigated patents therefore demonstrate a progression from mechanically operated latch mechanisms toward power-assisted release and cinching systems, while also showing different possibilities for actuator placement and integration. These approaches provided technical inspiration for exploring alternative release and cinching principles during concept generation.

3.1.1.4 System Integration

As vehicle door systems become increasingly electromechanical, the integration of multiple functions within the overall door architecture becomes an important consideration. The investigated patents demonstrate different approaches to combining mechanical components, electrical actuation, sensing, and control within the door system.

[20] describes a modular door architecture in which several functional components are mounted on a common carrier. This approach allows multiple door-related components to be integrated as a single module, providing a more organized system architecture and reducing the need to install each component independently. [21] presents a different approach, focusing on the integration of an electric latch and its control system within the vehicle door.

These patents provided useful insight into how different door functions can be organized and coordinated within an electromechanical system and were considered as inspiration during concept generation.

3.1.1.5 Patent Landscaping Outcome

The investigated patents span several generations of vehicle-door technology, from conventional mechanical latches and early passive-entry systems to recent electronically controlled handles, power-release mechanisms and integrated cinching systems. Despite differences in implementation, several recurring technological developments were identified:

- **Transition from mechanical toward electromechanical operation.** Functions traditionally performed through mechanical handles, rods and cables are increasingly performed through sensors, switches, actuators and electronic control units.
- **Retention of mechanical redundancy.** Electronic release does not necessarily remove the mechanical release path. Several investigated systems retain an emergency mechanical function for conditions such as electrical power loss and accidents.
- **Increasing integration of functions.** Latching, release, cinching, sensing and control are increasingly combined within integrated latch or door modules rather than

implemented as independent mechanisms

- **Separation between user input and mechanical actuation.** Passive-entry systems, touch-sensitive interfaces and electronically activated handles demonstrate that the user's command no longer needs to be mechanically transmitted directly to the latch.
- **Growing importance of control and sensing.** As door systems become electromechanical, information concerning latch position, user command and system state becomes increasingly important for coordinating safe opening and closing operations.

These findings provided a broader understanding of the available technologies and working principles rather than defining a specific solution for the project. However, the applicability of these principles to heavy-duty trucks cannot be assumed directly due to different requirements and applications. Therefore, the patent findings were treated as technological inspiration whose suitability had to be evaluated against the requirements of the heavy-duty application.

3.1.2 Benchmarking

The benchmarking was conducted to investigate existing door technologies and identify solutions relevant to the development of an advanced door system for a heavy-duty truck. The study was divided into passenger vehicles and heavy-duty trucks. Passenger vehicles were used to investigate the implementation of individual functions such as electronic power release, soft closing, powered door movement, flush handles, and mechanical backup systems. The truck benchmarking then examined how similar principles are being introduced into heavy-duty vehicles, with particular focus on Tesla Semi and Windrose Electric.

The purpose of the benchmarking was not to directly transfer existing solutions to the proposed door system. Instead, it was used to understand how the different functions are implemented, the value they provide, and the design principles that could be adapted to the heavy-duty truck application.

3.1.3 Passenger Vehicle Benchmarking

Passenger vehicles were bench-marked because advanced door functions are already well established in this segment. The focus was placed on the individual functions relevant to this project: **power release, powered door movement, soft closing, flush exterior interfaces, and mechanical backup systems.**

3.1.3.1 Soft-close Functionality

Soft-close systems are commonly used in premium passenger vehicles to complete the closing operation after the door has been brought close to the latch. The current Mercedes-Benz S-Class, shown in Figure 3.2, uses a servo-closing function that pulls the door into the fully closed position after it reaches the initial latch position. A similar approach is also seen in the BMW i7 Series and Volvo ES90 where the Soft Close mechanism completes the closing operation smoothly.

The main value of these systems is improved user convenience and perceived quality. By



Figure 3.2: Mercedes Benz S-class[22]

allowing the door to be brought to the latch without the need to apply the full closing force, the system reduces the effort required from the user while ensuring a consistent and controlled closing operation. The controlled movement can also reduce harsh closing noise compared with slamming the door.

These systems were particularly relevant to the development of the cinching function in this project. The main principle taken from the passenger-car benchmark was that the closing operation can be separated into two stages: the user or the electric actuator brings the door to the initial latch position, after which a motor completes the final closing movement. This principle is especially relevant for a heavy-duty truck, where the larger and heavier door can require greater closing effort.

3.1.3.2 Power Release and Electronic Door Opening

The Volvo ES90, shown in Figure 3.3, provides a relevant example of how electronic door functions can be combined with a flush exterior design while retaining mechanical redundancy. The vehicle uses electronically integrated door operation as part of its overall access system, with flush-mounted handles contributing to a smooth exterior surface. The normal door operation is separated from the mechanical release mechanism allowing the user to interact with the door through an electronic interface while retaining a mechanical method of opening the door when required.

This approach provides several benefits. By separating the user input from a direct mechanical connection to the latch, the door interface can be designed more freely and integrated with functions such as key-less access and electronic vehicle control. The flush handle also contributes to a cleaner exterior design and supports the reduction of surface discontinuities. At the same time, retaining a mechanical backup provides redundancy in situations where the normal electrical release function is unavailable.

For the present project, this provides an important design principle that the normal user input can be separated from the mechanical release mechanism and used to initiate a power-release function, while the mechanical handle is retained as a backup. This approach allows the door interface to become more intuitive and integrated without removing the redundancy provided by the existing mechanical release system.



Figure 3.3: Volvo ES90[23]

3.1.3.3 Automatic and Power-Assisted Doors

The BMW i7, shown in Figure 3.4, demonstrates the use of powered door movement for all four doors, allowing them to be opened and closed electrically rather than relying entirely on manual operation. The system can be controlled through the vehicle interface and incorporates sensors to detect obstacles during operation.

The main value of this function is improved convenience, particularly for large and heavy doors. By assisting the complete opening and closing motion, the user does not need to apply the full force required to move the door. The controlled movement also provides a more consistent and refined user experience while integrating the door operation into the vehicle's wider electronic system.

For this project, the BMW i7 demonstrates the potential of using an actuator to assist the movement of the complete door. Although the heavy-duty truck door differs significantly in size, weight and operating conditions, the same principle applies that the powered door movement can reduce the effort required from the user. The benchmark therefore supported the development of an actuator-based system for assisting the opening and closing of the truck door.



Figure 3.4: BMW i7[24]

3.1.3.4 Passenger Vehicle Benchmarking Insights

The passenger vehicle benchmark demonstrated that the functions investigated in this project are already technically mature when considered individually. Electronic release, soft closing, powered door movement and flush exterior interfaces can be combined to improve convenience, perceived quality and user interaction.

However, these functions are generally implemented in passenger vehicles with different packaging and operating conditions than those of a heavy-duty truck. Therefore, the main outcome of the benchmarking was not the direct adoption of existing solutions, but the identification of the underlying principles that could be adapted to the truck door.

3.1.4 Truck Benchmarking

The development of electric heavy-duty trucks is changing the design priorities of the truck. While conventional trucks have traditionally focused primarily on load capacity, durability and functionality, the transition towards electrification has placed greater emphasis on aerodynamic efficiency. As aerodynamic drag directly influences energy consumption, reducing drag has become an important consideration for improving the range of electric heavy-duty trucks.

At the same time, electrification and increased digitalization are creating opportunities to improve the driver experience through mechatronic systems. Functions that were previously mainly associated with passenger vehicles, such as electronically controlled access, powered door operation and integrated user interfaces, are beginning to appear in new heavy-duty vehicle architectures. The door is therefore no longer considered only as a mechanical access system, but can also contribute to vehicle aerodynamics, user interaction and the wider electronic architecture.

Two relevant examples of this development are the Windrose E700 and the Tesla Semi.

3.1.4.1 Windrose E700

The Windrose E700, shown in Figure 3.5, demonstrates a design approach in which aerodynamic efficiency has strongly influenced the overall vehicle architecture. The truck uses a highly streamlined cab with a smooth front profile and integrated exterior surfaces. Windrose and industry reporting identify aerodynamic efficiency as a key part of the vehicle design, with the E700 reported to have a drag coefficient of approximately 0.275, which is considerably less than conventional trucks [25].

The approach was not limited to the cab shape alone. Windrose has also reduced exterior protrusions to create a smoother vehicle surface, including the use of a flush door handle. Unlike a conventional handle that is directly connected to the latch, the handle forms part of an electronically operated access system, while manual operation and an emergency release are retained as backups.

This makes the E700 particularly relevant to this project, as it combines aerodynamic considerations with improved user interaction. Although a flush handle alone has a limited effect on the overall aerodynamic performance of the truck, it contributes to the wider approach of reducing surface discontinuities. At the same time, its integration into an electronic access system shows how the conventional door interface can be developed into a mechatronic

system. This combination of a flush exterior design, electronic operation and mechanical backup directly supports the development direction explored in this project



Figure 3.5: Windrose E700[26]

3.1.4.2 Tesla Semi

The Tesla Semi, shown in Figure 3.6 demonstrates a similar shift in heavy-duty truck design, with a strong focus on both aerodynamic efficiency and driver experience. Its streamlined cab moves away from the conventional upright truck form, reflecting the increased importance of reducing aerodynamic drag to improve the efficiency and range of electric trucks.

Another notable feature is the centrally positioned driver seat. This differs from the conventional asymmetric truck cabin and creates a more centered driving environment with improved visibility and easier access. Although limited public information is available on the Semi's door and latch mechanism, the vehicle remains relevant to this project because it demonstrates the broader shift towards a more integrated and digitally focused driver environment. As the overall vehicle architecture changes, there is also an opportunity to develop the door beyond its conventional mechanical function by incorporating mechatronic features that improve user interaction and functionality.

3.1.5 Benchmarking Insights from Trucks

The Windrose E700 and Tesla Semi demonstrate a common direction in the development of future heavy-duty trucks. As electrification increases the importance of vehicle range, manufacturers are placing greater emphasis on aerodynamic efficiency to reduce energy consumption. At the same time, the overall vehicle architecture is evolving towards more integrated and digitally controlled systems that aim to improve driver interaction and functionality.

The benchmarking therefore showed that the proposed system aligns with these broader developments. The use of a flush-oriented exterior interface supports the wider effort to reduce surface discontinuities, while the integration of mechatronic functions such as power release, cinching and powered door movement explores how the conventional truck door can be developed to provide improved functionality and user experience



Figure 3.6: Tesla Semi[27]

3.2 Stakeholder and Customer Analysis

This section outlines the analysis of stakeholders and customers as a part of the thesis. The intention of the analysis is to examine and identify key stakeholders and customers pain-points and needs. Furthermore, the analysis also serves as building block for the requirement list which will aid concept generation and realization.

3.2.1 Stakeholder Analysis

A clinic with advanced door solutions in the automotive industry was conducted to get a first impression of the stakeholders internally. The rationale behind the clinic is to familiarize with the varied stakeholders and ensuring they are familiarized with the project. A first prototype with an latch with existing cinching feature from the automotive car industry was implemented to a heavy duty truck. Both an observation and an Volvo internal survey was conducted.

A wide array of internal stakeholders participated ranging from finance, project managers to feature leaders. Observation was conducted with minimal interference on how they interacted with the door, afterwards the stakeholders conducted a survey based on the experience. Due to the nature of the questions, the interview answers are omitted from the thesis. The participants gave valuable impression on improvements, potential implementation and direction of solutions for the door opening system to the heavy duty trucks. The explicit and implicit desired and wishes that do not reference Volvo's own internal requirements are then condensed in to the requirement list.

3.2.2 Customer Analysis

For the customer analysis, interviews with the focus group is conducted in order to assess frustrations and delights with the door mechanism. Customer for heavy duty trucks unlike passenger cars are varied, although single truck owners consist of 60%[28] of fleet owners, they only comprise of 20.8% of commercial driving license owners in the US. In other words, owners that uses their vehicle in a daily basis is only a minority in the trucking industry. Thus, the focus group needs to be narrowed down to daily users i.e. owners or employee truck drivers that use the vehicle and interact with it daily. Additionally, the decision is to perform a qualitative interview for a deeper depth of interpretation that would otherwise not be captured in a quantitative interview.

As a result, interviews are carried out across eleven different heavy duty vehicle drivers from different transportation sectors. Currently, women hold around 16% of the positions in the transportation industry and this includes the trucking industry. Notably, despite their relatively small number compared to men in the industry they provide additional insight and needs that could potentially differ. Furthermore, it was important to get truck drivers from a wide range of industries, everything from mining to goods transportation. The intention of the diversity is to capture the complete need profile across many transportation sectors and perspective. On other hand, since the interview is only conducting in Sweden, the need profile are limited to the market and there might be other needs in other markets that are not expressed in the thesis. The interview were held remotely due to the busy schedule of the drivers. The interviews held were between 20-30 minutes each.

Thematic analysis is an analytical framework specifically tailored towards qualitative data. The method is used to examine patterns resulting in themes for different datasets. The objective is to produce a transparent, coherent and convincing description of themes that shows the richness and complexity of the dataset. This is done by understanding the data, generate labels to section of the data. This description is then aligned with the research questions and the scope of the thesis as to only include patterns that are relevant to opening and closing mechanism. By virtue of executing a qualitative interview, the questions performed are open-ended and general, this is to avoid leading the focus group to bias a certain solution. However, most of the questions are standardized in order to have a comparative data, to ensure similar quality for each interview.

After completing the theme analysis and ensuring the relevance to the thesis subject, certain labels are prominent as seen in Figure 3.7. These labels through implicit and explicit means formed three themes for the complete analysis, namely:

- Noise, vibration and harshness.
- Inadequate usability
- Ergonomics

The themes will be used as the basis for the requirement list since it reflects on the need and frustrations of the primary users of the mechanisms. Furthermore, additional emphasis on the themes will be taken in to the account during the concept generation to ensure that the user's input shapes the product.

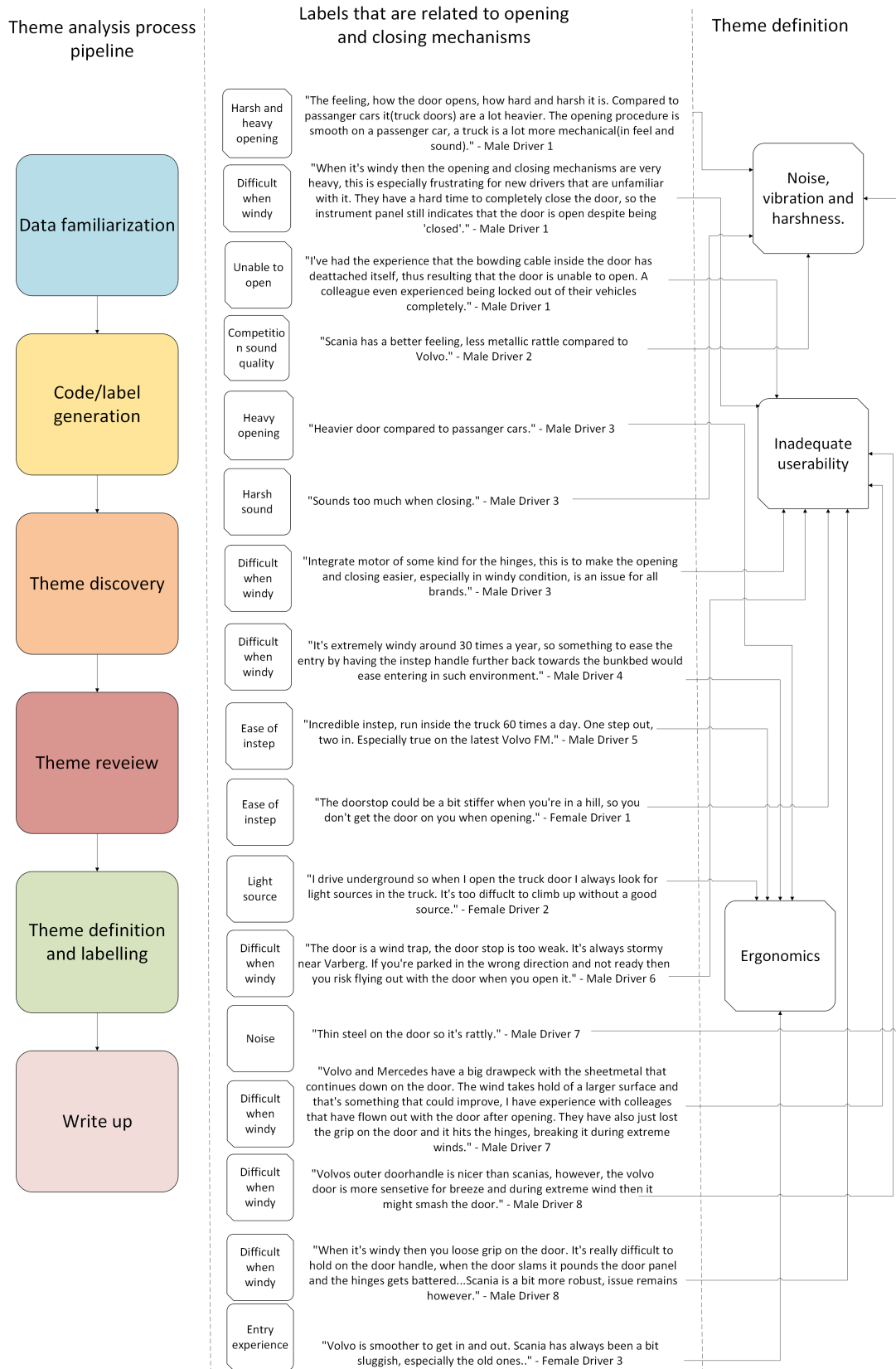


Figure 3.7: Theme analysis from focus group input.

3.3 Components Analysis

The intention of the sub-chapter is to give a comprehensive description and characteristics for the different components and their direct or indirect role at providing opening and closure function. The ambition is to give a fundamental understanding and potential limitations of the control unit that will be implemented, irregardless of concepts chosen.

3.3.1 Door Control Unit

This subsection will examine and describe the electrical control units that ought to exist in contemporary automotive door architecture for door function. Additionally, the aim is to understand what systems in the control unit incorporate the door entry feature and what can be excluded. Prevailing door control unit in the automotive industries are configured as seen in Figure 3.8 [29]. However, for commercial vehicles, more specifically, heavy duty

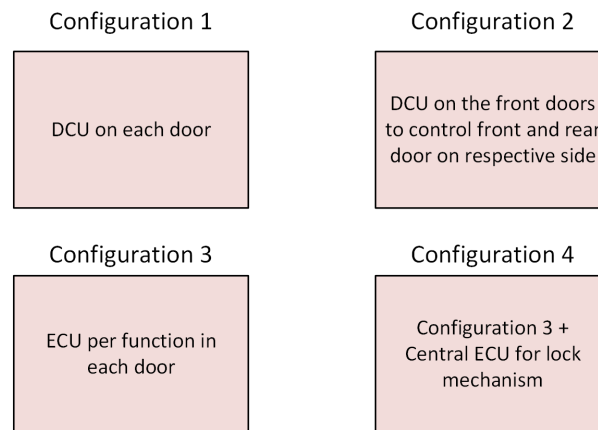


Figure 3.8: Conventional automotive control unit setup.

trucks are intentionally limited with the space on the cab. This is a deliberate dominant design in the industry, partly in order to comply for the length restriction [30] and maximize space for load. Furthermore, it stands to reason that a heavy duty truck is to transport massive load and not passengers and thus dis-incentivize designs that would bias the latter over the former. In other words configuration 2 in the Figure 3.8 is not applicable for heavy truck usage due to lack of rear doors in the standard heavy duty truck. Another key factor is that configuration 3 and to some extent 4 has a dedicated electrical control unit for each function rather than a single door control unit for all the function on each door. However, configuration 4 chooses to have a centralized locking control unit for the complete vehicle.

Upon close inspection at the control unit in Figure 3.9, the door control unit in fact consist of multiple interconnected modules. Additionally, the figure is adjusted to illustrate what is considered within the scope of the thesis in a large or small degree and what is completely out of scope. For instance, mirror and window lift adjustments are considered extraneous due to not directly contributing to the opening and closure mechanism and thus are highlighted.

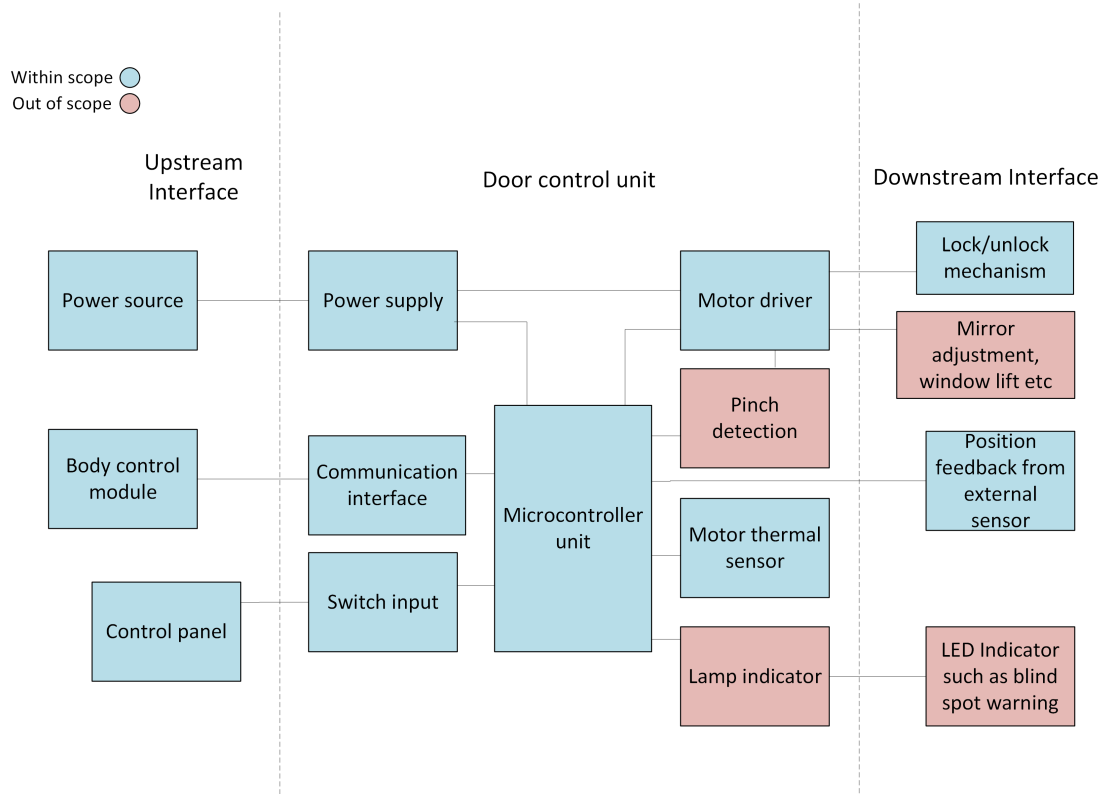


Figure 3.9: Conventional automotive control unit component scheme.

3.3.2 Voltage Regulator

The industry standard for voltages in batteries for heavy duty vehicles are 24V[31]. However, this poses issue for components that requires different amount of voltages to operate, especially in door control units that have a varied of modules interconnected in it. It follows that a solution is needed to adjust the output voltages. One way to achieve this could be through the usage of an buck-converter[32]. The buck-converter operates by converting a high input voltage from the battery to an appropriate output voltage for the component. This is achieved by adjusting the duty cycle D of the switch in the circuit. The buck converter is represented in Figure 3.10, it consists of a DC power supply, a switch, diode, inductor, capacitor and a resistor. The switch for a buck converter is an electronic switch such as an MOSFET.

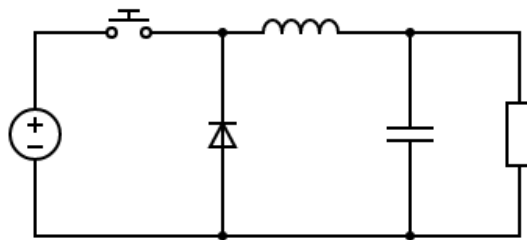


Figure 3.10: Buck Converter.

In the instance when the switch is activated, the diode acts as an off switch due to being reverse biased, causing the current to travel to the inductor, loading it. However, when the switch is disconnected to the power supply the current from the inductor continues through the diode. The Figure 3.11 illustrates the parameters of the inductor if the switch is on or off.

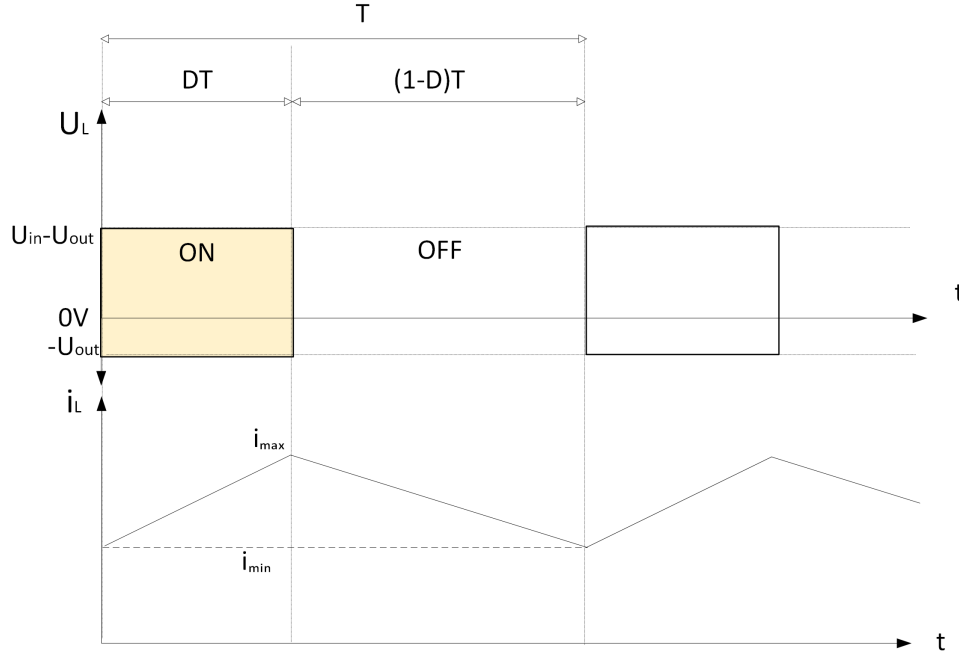


Figure 3.11: Buck Converter - Voltage and Current Graph for Inductor.

The current increases or decreases linearly in the inductor during the cycle when it's ON or OFF as seen in Figure 3.11.

The sum of the voltages in the system according to Kirchhoff's voltage law states that it must be 0 in a closed circuit.

$$\sum U = 0 \Rightarrow U_{in} - U_L - U_{out} = 0 \quad (3.1)$$

The load voltage U_L can be defined as the relationship with the load current I_L over time with the inductance L . [33].

$$U_L = L \frac{dI_L}{dt} \quad (3.2)$$

When the switch is on then the inductor is connected to the DC power source.

$$U_L = U_{in} - U_{out} \quad (3.3)$$

However, when the switch is off, the DC power is disconnected. Due to the continuity of the current in the inductor, a negative polarity is induced causing a negative voltage.

$$U_L = -U_{out} \quad (3.4)$$

This results in two states for the voltage induction during a cycle T.

$$U_L = \begin{cases} U_{in} - U_{out} & (\text{ON}) \\ -U_{out} & (\text{OFF}) \end{cases} \quad (3.5)$$

Assuming steady state, the inductor ends and start at the same current at each cycle T.

$$\Delta I_L = I_1 - I_2 = I_{min} - I_{min} = 0 \quad (3.6)$$

This implicates of the current is that the average voltage throughout the cycle T is 0 due to net change in a cycle is 0, thus the intended output voltage will be fixed for every cycle.

$$U_{L,average} = L \frac{dI_L}{dt} = 0 \quad (3.7)$$

To calculate the duty cycle needed for the desired output voltage, the ratio of U_L when it is ON and OFF needs to be calculated.

$$(U_{in} - U_{out}) \cdot D \cdot T = U_{out} \cdot (1 - D) \cdot T \Rightarrow U_{out} = U_{in} \cdot D \quad (3.8)$$

Thus, the electrical potential in the output has a clear relationship with the duty cycle relative to the voltage being supplied in a buck converter. It means for a 24V application it results in.

$$U_{out} = 24 \cdot D \quad (3.9)$$

3.3.3 Side door Latch

The side door latch system is a fundamental component in automotive door assemblies, responsible for ensuring secure door closure, occupant safety and controlled access to the vehicle. It functions as a mechanical retention device that interfaces with the striker mounted on the vehicle body and operates in tandem with internal/external handle mechanism, locking mechanism and electronic actuators. The importance of the latch system is particularly evident in crash scenarios, where it must prevent unintended door opening and maintain structural integrity. As a result, its design and performance should meet the stringent safety regulations mentioned in FMVSS 206 and ECE R11 [34][35].

A typical automotive side-door latch consists of numerous mechanical and electromechanical components that perform the locking, release and retention functions. Figure 3.12 presents an exploded view of a representative side-door latch, illustrating the complexity of the mechanism and the large number of interacting components required for its operation. Although the individual designs vary between manufactures, most latch system share the same fundamental operating principles.

3.3.3.1 Operating Principle

Despite the complexity of the complete assembly, the fundamental operation of a side-door latch is governed primarily by three components: **the striker, ratchet(fork bolt)(32) and pawl(detent)(28)**, illustrated in Figure 3.13.

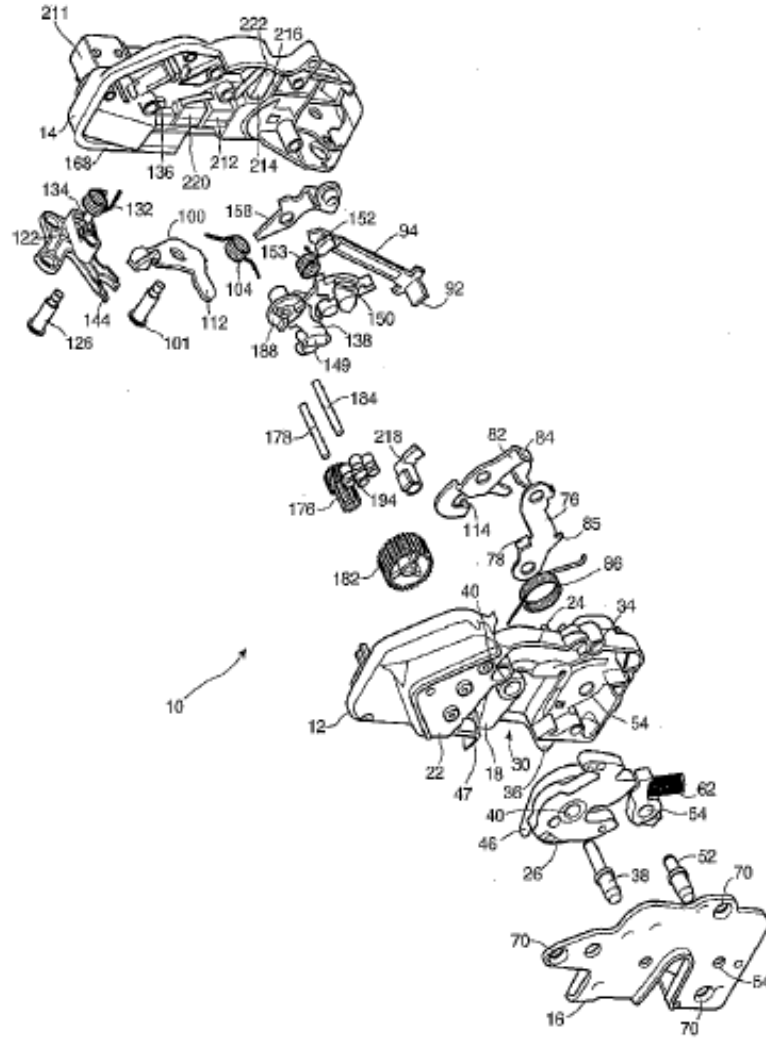


Figure 3.12: Exploded view of a representative automotive side door latch[15].

The **striker** is mounted on the vehicle body and enters the latch housing as the door close. As the striker enters the latch, it engages the **ratchet**, also referred to as the fork bolt, causing it to rotate about a fixed pivot [36]. This rotation converts the linear motion of the striker into rotational motion within the latch mechanism while allowing the ratchet to withstand the loads generated during door closing [37]. Once the striker reaches the required engagement position, the **pawl** engages with the ratchet profile, preventing reverse rotation and securely retaining the striker within the latch [36]. The geometry of the engagement between the pawl and ratchet is critical, as it determines the self-locking capability of the mechanism and ensures that the door remains securely latched under latched external loading conditions [38].

Most automotive latch systems incorporate two engagement positions:

- **Secondary latch position**, where the door is partially retained and prevented from unintentionally opening (Figure 3B in Figure 3.13).
- **Primary latch position**, where the door is fully closed and securely latched (Figure

3C in Figure 3.13).

The transition between these states is illustrated in Figure 3.13, where the ratchet rotates progressively as the striker enters the latch until the pawl engages the primary latch position.

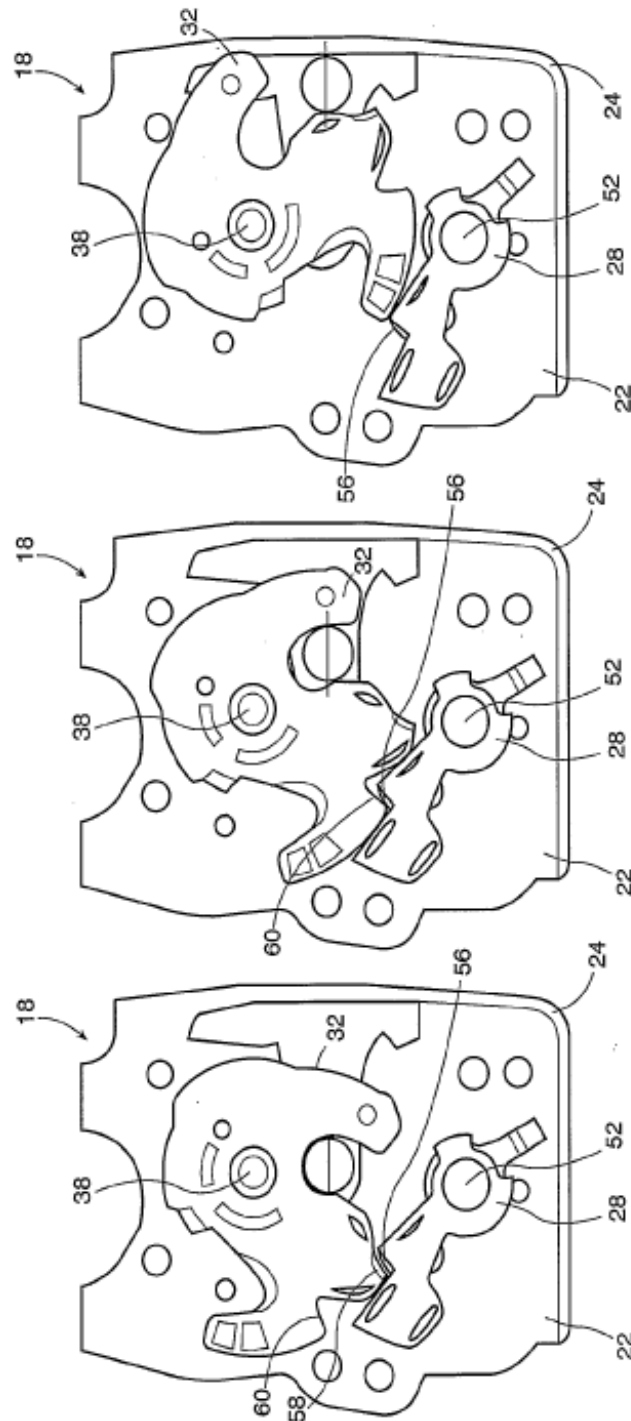


Figure 3.13: Operating sequence of a side-door latch[15].

3.3.3.2 Release Function

The release function of a side-door latch is achieved by disengaging the pawl from the ratchet, allowing the ratchet to rotate under the action of the return spring and release the striker. In conventional latch systems, this is accomplished through a release lever actuated by mechanical rods or Bowden cables connected to the interior and exterior door handles. When the release lever rotates, it applies a moment to the pawl, causing it to disengage from the ratchet. Once the pawl is released, the ratchet is free to rotate to its open position, thereby releasing the striker and allowing the door to open.

In modern electromechanical door systems, the fundamental release mechanism remains unchanged, however the mechanical input is replaced by an electric actuator. Rather than transmitting force directly from the door handle, the actuator reproduces the motion required to rotate the release lever and disengage the pawl from the ratchet. Consequently, the structural load path through the ratchet and pawl is also preserved while enabling electronic release and advanced door functions. Representative implementations of this principle are presented in [11] and [12], where electrically actuated release mechanisms are combined with independent mechanical emergency release paths to ensure door operation in the event of electrical failure.

3.3.3.3 Cinching Function

A cinching, or soft-close, function is incorporated in many modern vehicle doors to ensure complete door closure without requiring the user to slam the door. During closing, the striker is first captured in the secondary latch position, where the door is retained but not fully closed. A powered mechanism subsequently generates the additional force required to rotate the ratchet until the pawl engages the primary latch position, thereby completing the latching process. This reduces the manual closing effort while improving door-closing quality by minimizing impact loads, noise, and vibration.

Although different mechanical solutions exist, the operating principle remains the same. The additional mechanical work required to move the ratchet from the secondary to the primary latch position can be produced by an electric actuator acting directly within the latch assembly or remotely through an intermediate transmission mechanism. For example, [16] integrates the cinching actuator and drive mechanism within the latch assembly, whereas [17] employs a remotely mounted actuator connected through a mechanical transmission. Despite these architectural differences, all implementations share the same objective, which is to provide the additional torque required to move the latch from the secondary to the primary position automatically, thereby ensuring reliable door closure while reducing user effort and improving perceived vehicle quality.

4 Concept development

The chapter expresses the development and exploration of the different concepts and the methods used to achieve a final concept. The assessment is achieved by having a holistic understanding of the functions needed for the door opening and closure mechanism. As a result, the initial part of the chapter will explore the functions and system diagram. Furthermore, the knowledge acquired enables concept generation. Lastly, said concepts will be evaluated and eliminated using concepts such as Elimination Matrix, Pugh Matrix and Kesselring Matrix.

4.1 System Architecture & Specifications

The section exhibits the architecture of the system and function. Moreover, the user case will likewise be analyzed due to its proximity to the architecture with regard to usage knowledge. The additional dimension allows a deeper understanding of the architecture and a richer concept generation due to user consideration. In addition, the initial list of requirements will be presented, the requirements are derived from the interviews, internal surveys and future legal requirements.

4.1.1 Function-Means Diagram

The purpose of curating the function-mean diagram is to get a better understanding of the functionality of the product. This is done by breaking down the function of the existing products into multiple segments of sub-functions. These sub-functions describe a task without any explicit solution, the means are the mechanism used to carry out the function. Furthermore, the means in themselves can have multiple functions supporting it that can be further broken down. This enables for low-level view of the product, which can be leveraged in other methods and processes. The Figure 4.1 represent the function of door opening & closure and the recent advancement of means to achieve the function of advanced door opening & closure.

The project for the mechanism is scoped down to door braking, release system, control unit and the user interface. This is to avoid a too wide of a scope for the project time frame and thus reducing the uncertainty of delivering the project aim. Furthermore, the function-means diagram also lay the foundation of the system design where the interactions between components are illustrated. Additionally, functions in the Figure 4.1 is used to define the categories of sub-concepts in the concept generation later on.

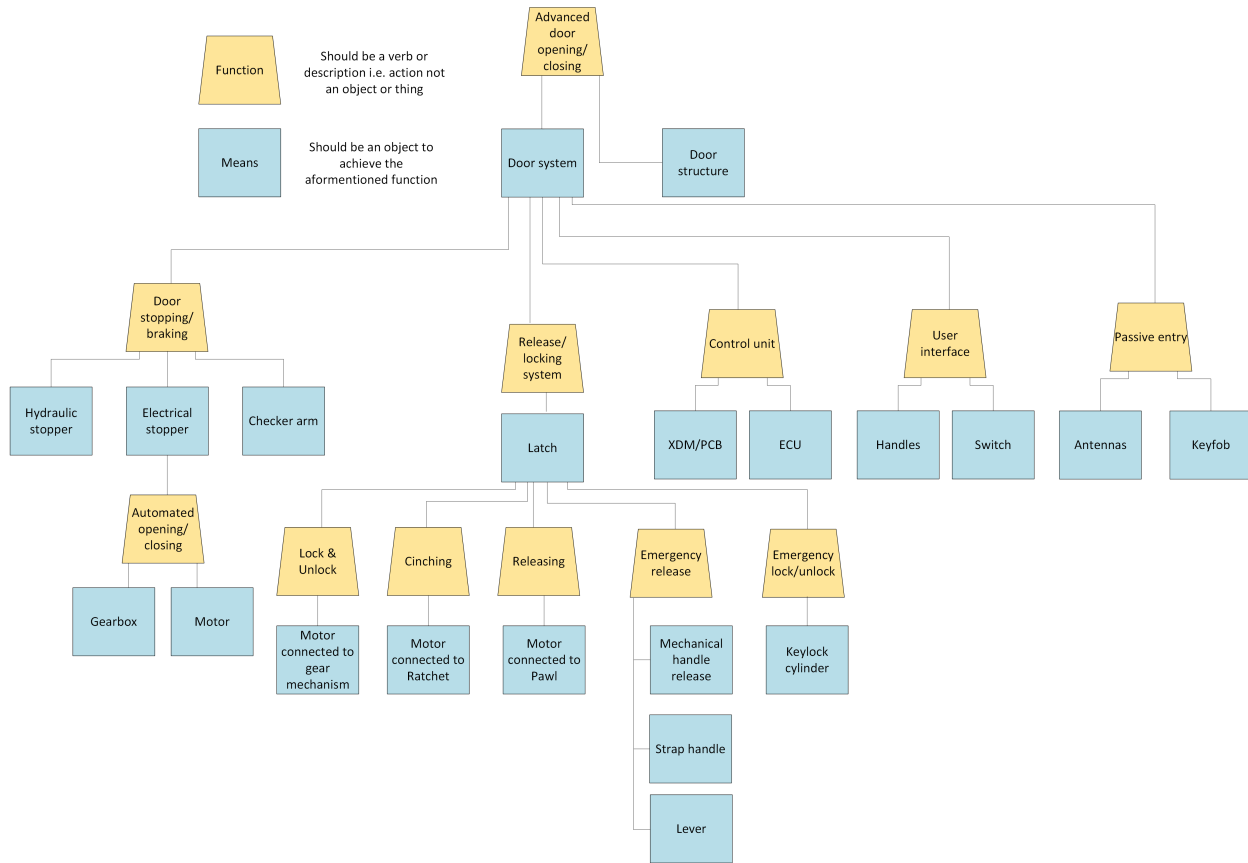


Figure 4.1: Function Diagram of opening and closure mechanisms.

4.1.2 System Diagram

The function diagram fails to demonstrate how the different sub-functions communicate with each other to achieve the holistic system capability. The door opening system is a complex system that has a myriad of different interfaces. This leads to the need of a system diagram, the framework describes the system in a high level and defines connections, constraints and areas of the system.

The diagram as seen in Figure 4.2 does not only show the individual components for the opening and closing function but also show how it is interfaced explicitly, either through physical interaction or communication. However, the Figure 4.2 only shows the component that are within scope of the project in detail, for the overall system interface as seen towards the overall door structure are an abstraction used to represent that the system will be somewhere in the door. The reasoning is two-fold, the first reason is to not reveal what door and where in the door the system will be installed in order to comply with the Volvo NDA and secondarily it is to support flexibility and not set a physical constraint in the system diagram.

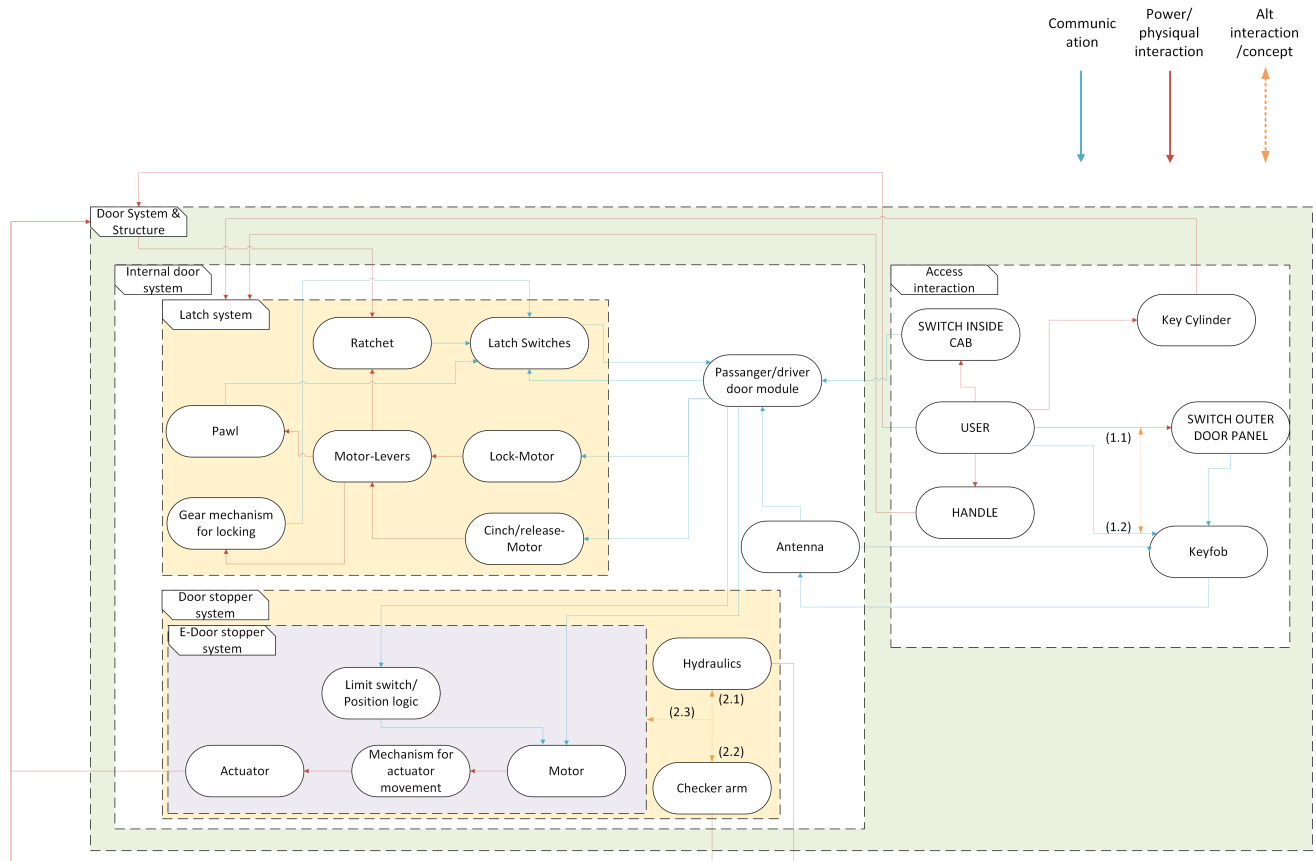


Figure 4.2: System Diagram of opening and closure mechanisms.

4.1.3 User Case

Establishing the function-mean and system diagrams shows how the system architecture and functions interact, however, it lacks the user experience as an aspect. Thus, the formulation of the user case is needed to illustrate how the end-user will interact with the product. The intention is to relate the aforementioned user case frameworks to usage in both normal conditions and in emergency situations. Furthermore, The user case allows illustration of different product state and how the customer interacts with the system in each mode. This is demonstrated in the Figure 4.3 that is categorized in five different cases, each case is paired up with potential ways to achieve the functionality. Moreover, the Figure also portrays how to interact with each case in an emergency situation. For instance modern OEM'S such as Hyundai[39] have air bag sensors that registers a high impact collision and unlocks the vehicle to allow a more seamless rescue operation.

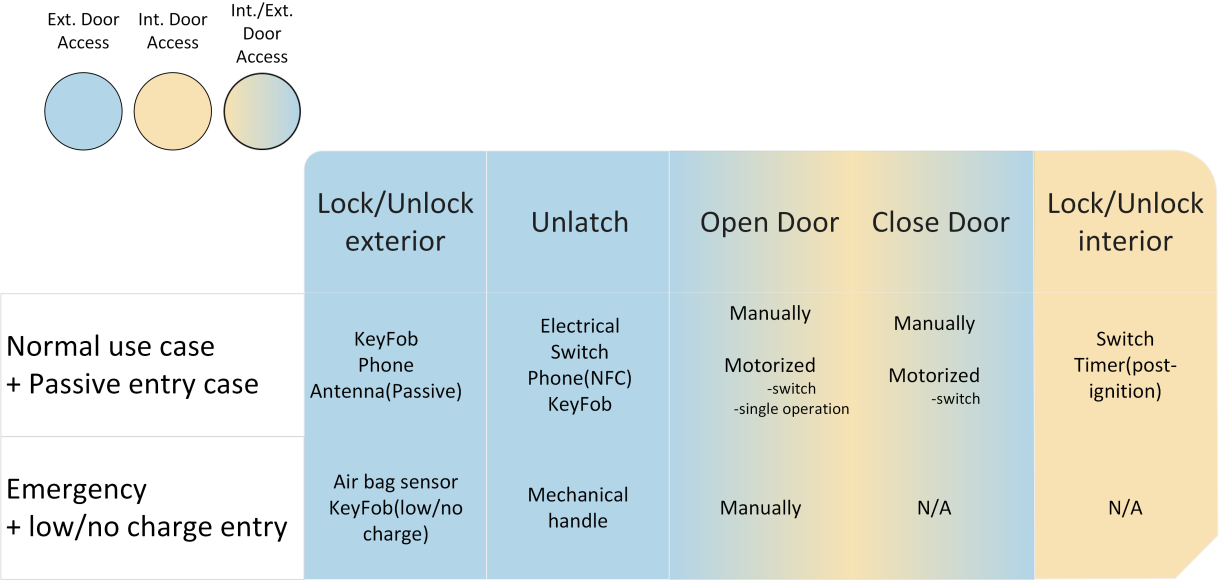


Figure 4.3: User case of opening and closure mechanisms.

4.2 List of Requirements

The purpose of the requirements list is to align features and capabilities that you ought and wish to reach with the product, it is gathered from a wide array of sources, primarily from legislation and implicit and explicit user needs and desires. Due to confidentiality and non-disclosure agreements, internal Volvo requirements are excluded. Thus, the project will only focus on presenting the product after the user requirements and legal requirements that are derived from public legislative demands or needs identified from the customer. The identified legislative demands are in regards to safety and integrity for the door lock system set by the European Commission in the form of ECE R11 [40] and the U.S. counterpart FMVSS 206 [41]. The aim of the legislation is to ensure that the integrity of the components for normal use and during crash. Additionally, the requirement to enable the application of the PIEK certification [42] is added, which is derived from a noise legislation[43] in the Netherlands which only allows maximum 60dB in city centers during certain times.

The projects initial requirements as seen in **Appendix A** are divided between five identified functions:

1. Door Braking
2. Latch System
3. ECU
4. User Interface
5. Passive Entry

The values in the were continuously updated throughout the project and adjusted based on internal feedback and legislative limits. However, the value in themselves does not reflect any requirements that Volvo has set internally rather it is based on what the findings and internal discussion has set initially in the project.

4.3 Concept Generation

The concept generation phase uses a multidimensional approach by leveraging the established function, system and user diagram as base of the concept generation. By using the constituents of the diagrams it facilitates the generation of relevant and high quality idea. This is achieved by using the sub-systems of the diagrams. The aim is to find solutions for the different functions that is anchored to the user needs through the requirement list generated. The ideas will then be funneled by using an elimination matrix and subsequently a morphological matrix will be applied to combined the ideas to a complete concept. The concepts will then be evaluated using different criterion to reach a final concept.

4.3.1 Idea Generation

As part of the initial phase of the idea generation is to view the segments of the function, systems and user diagram to get a sense of direction and boundaries for the idea. This is to avoid veering off too much from the topics of the project and leverage established findings to efficiently generate ideas. Following the initial stage follows brainstorming on each compartmentalized function, the ideas generated are then cross-referencing between each other to check for similarities. In addition, the solutions are also supported by results from the thematic analysis to see if any of the themes are addressed by the solution. This processes is limited to 5-15 minutes session on each sub-function in order mitigate diminishing return on the quantity of unique ideas. Following the internal searches, the external searches conducted on the pre-study, primarily the benchmarking and existing patents are compiled. This external data is then used to compare and anchor the feasibility of the ideas generated earlier. The aim with the approach is to reduce personal bias, internal assumption and identify proven solution. After internal reflection based on the external search, each sub-function is then revisited on a separate date for a similar time limit, with the goal of adjusting existing ideas or add new ones. This resulted in thirty unique sub-solutions as seen in **Appendix B**.

4.4 Concept Evaluation

The concept generation phase resulted in a wide range of solution ideas addressing the different functions identified during concept development. Since further development of every concept was neither practical nor necessary, a structured evaluation process was carried out to systematically narrow the design space and identify the most promising solution.

The evaluation consisted of three consecutive stages. First, an elimination matrix was used to remove concepts that did not satisfy the most critical project requirements. The remaining concepts were then combined into complete system solutions using a morphological approach. Rather than generating every possible combination, only technically feasible and meaningful combinations were considered. Finally, the resulting concepts were evaluated using the weighted Pugh matrix to identify the most feasible solution.

This structured approach ensured that the final concept was not selected based on individual preference but through a transparent and systematic decision-making process.

4.4.1 Initial Concept Screening using Elimination Matrix

The concept generation phase resulted in approximately thirty individual solution concepts, addressing each sub-functions of the advanced door system. While a broad solution is desirable during ideation, evaluating every concept in subsequent stages would have been both time-consuming and impractical. Therefore, an initial screening was performed using an elimination matrix. The elimination matrix, also called as concept screening matrix,[5] is a systematic method used during concept selection to compare alternative concepts against predefined evaluation criteria.

The purpose of the elimination matrix was to remove concepts that did not satisfy the minimum technical and project-specific requirements before investing additional efforts in their development. Five evaluation criteria were defined based on the project objectives:

1. Ability to improve door opening and closing functionality
2. Compatibility with the existing door architecture
3. Reasonable cost for the component
4. Novelty compared with existing market solutions
5. Technical feasibility

Each concept was assessed against these criteria using four possible outcomes. Concepts that fulfilled a criterion were marked positively (+), concepts that clearly failed were rejected and given (-), uncertain concepts requiring additional investigation were marked (?), while concepts showing potential but requiring integration with other solutions were marked (=). This allowed promising ideas to be retained without prematurely excluding concepts that could contribute valuable functionality when combined with other alternatives.

The elimination process reduced the initial 30 component concepts to 22 viable concepts addressing each sub-functions. These remaining concepts provided a sufficiently broad solution space while removing alternatives that were technically unsuitable or offered limited value. The complete elimination matrix is presented in **Appendix C**.

4.4.2 Concept Combination using Morphological Matrix

Following the initial screening, the remaining 22 solution concepts were organized in a morphological matrix. A morphological matrix is a systematic concept generation method in which a product is decomposed into its primary sub-functions, and multiple solution principles are identified for each function[44]. The purpose of the matrix was not only to visualize the available solutions for each sub-function but also to systematically explore complete system concepts through combinations of compatible components.

In theory, combining all remaining alternatives would have resulted in approximately 1,620 unique system concepts. Although the morphological matrix enables extensive exploration of the design space, evaluating every possible combinations would not have represented technically meaningful solutions. Therefore, a selective concept generation was adopted. Concepts were combined based on functional compatibility, technical feasibility and overall system efficiency. Particular emphasis was placed on ensuring that all identified sub-functions were represented in the generated concepts and the selected combination formed realistic and meaningful design solution. The process can be seen in **Appendix D**.

Based on these consideration, ten complete system concepts were developed from the morphological matrix. These concepts captured the most promising combinations while maintaining sufficient variation to enable a meaningful comparison during the subsequent evaluation stages.

4.4.3 Weighted Criteria

To ensure that the concept evaluation reflected the objectives and priorities of the project, the evaluation criteria were assigned relative weights using a pairwise comparison method. Each criterion was systematically compared against every other criterion to determine its relative importance before evaluating the concepts. During each comparison, a score of 1 was assigned when one criteria was considered more important than the other, 0.5 when both criteria were considered equally important and 0 when it was considered less important. The accumulated scores were then used to establish the weighing factors applied in the subsequent Pugh matrix. Figure 4.4 presents the resulting weighted criteria matrix. This approach ensures that the final concept selection reflects the relative significance of each criterion rather than assuming that all criteria contribute equally to the overall decision.

Criteria	Control simplicity	NVH	Cost	User safety	Ergonomic Performance	Reliability	Sum
Control simplicity		0,5	0,5	0	0,5	0	1,5
NVH	0,5		0,5	0	0,5	0	1,5
Cost	0,5	0,5		0	0,5	0,5	2,0
User safety	1	1	1		1	0,5	4,5
Ergonomic Performance	0,5	0,5	0,5	0		0	1,5
Reliability	1	1	0,5	0,5	1		4,0

Figure 4.4: Weighted Criteria.

The evaluation criteria were established based on the project requirements, customer needs identified during the pre-study, stakeholder discussions and engineering judgment. The selected criteria represent the technical, functional and user-oriented aspects considered most important for the development of an advanced door system.

User safety received the highest weighting because the primary function of the proposed system is to operate safely under all operating conditions without introducing hazards to the user or compromising vehicle functionality. In the automotive industry, safety is regarded as a fundamental design requirement that takes precedence over performance, comfort and cost considerations. Consequently, concepts that minimize the risk of unintended door movement and improve safe interaction with the door system were prioritized.

Reliability was assigned the second-highest weighting due to the demanding operating conditions of heavy-duty trucks. Door systems are subjected to frequent operation throughout the vehicle's lifetime while being exposed to vibration, temperature variations, dust and mechanical wear. Previous studies have identified reliability as one of the most important quality attributes for automotive door subsystems, directly influencing long-term functionality and customer satisfaction[45].

Cost was included to evaluate the feasibility of future implementation and was given the third highest score. Since the proposed concept should be suitable for production, assembly complexity, additional components and integration, costs must be considered alongside

technical performance. The cost of the considered components was a rough figure from the internet and exact values cannot be mentioned due to NDA.

Control simplicity evaluates the complexity of the required control architecture and system integration. Concepts requiring fewer electronic functions, simpler control logic and reduced integration effort were considered advantageous as they generally improve system robustness, simply maintenance and reduce potential failure modes. Product development literature also highlights that simpler solutions are preferred when comparable functional performance can be achieved[5].

Noise, Vibration and Harshness (NVH) was assigned a weighting of 1.5 because the primary objective of this project was to identify a feasible functional concept rather than optimize acoustic performance. While reducing door closing noise and vibration is an important design objective, improvements in NVH can be achieved during later development stages through refinement of the component geometry, sealing, damping materials and system tuning. Therefore, NVH was considered important but not a primary decision criterion during concept selection.

Similarly, *Ergonomic performance* was assigned a weighting of 1.5, although it contributes to user comfort and ease of operation, it was considered less critical than user safety, reliability and cost during concept selection. Moreover, from the stakeholder interviews, it become more clear that ergonomic performance was regarded more as a desire rather than a requirement. Consequently, ergonomic performance was given a lower weighting while still remaining an important factor in the overall evaluation.

The resulting weighting factors were subsequently applied in the Pugh matrix to evaluate the remaining generated concepts. By incorporating the relative importance of each evaluation criterion into the assessment, the matrix provided a structured and objective basis for comparing the concepts. The completed Pugh matrix and the resulting concept rankings are presented in the following section.

4.4.4 Pugh Matrix

Following the determination of the evaluation criteria and their corresponding weighting factors, the ten complete system concepts were evaluated using a weighted Pugh matrix. The objective of this evaluation was to provide a structured and transparent comparison of the concepts while accounting for the relative importance of each evaluation criterion.

The current door system was selected as the reference concept and assigned a baseline score of zero for all evaluation criteria. Each generated concept was then assessed relative to the reference solution with respect to control simplicity, NVH, cost, user safety, ergonomic performance, and reliability. The base scores ranged from -3 to +3, where +3 represented a significant improvement over the reference concept, 0 indicated equivalent performance, and -3 represented a significant deterioration. Intermediate values were also used to reflect smaller differences in performance.

To account for the varying importance of the evaluation criteria, each base score was multiplied by the corresponding weighting factor established through the pairwise comparison method. The weighted scores were subsequently summed to obtain the total score for each concept. In addition to the numerical evaluation, qualitative comments were documented

for every concept to justify the assigned scores and highlight their respective strengths and weaknesses. This ensured that the evaluation was supported by engineering judgment rather than relying solely on numerical results.

Only a single iteration of the Pugh matrix was conducted in this study. The current door system served as the sole reference concept against which all generated concepts were evaluated, thus eliminating the need for additional evaluation iterations with alternative reference concepts. Furthermore, the concepts had already undergone an elimination process and were developed from carefully selected combinations in the morphological matrix. Therefore, a single weighted Pugh matrix was considered sufficient to identify the most promising concepts for further development.

The completed weighted Pugh matrix is presented in **Appendix E**. The evaluation identified Concept 3 as the highest-ranked concept with a total weighted score of 29.75, closely followed by Concept 10 with 29.0. These concepts demonstrated the strongest overall performance against the weighted evaluation criteria and were therefore considered the most promising candidates for the final concept selection.

4.5 Concept Selection

The weighted Pugh matrix identified **Concept 3** and **Concept 10** as the two highest-performing concepts. Both concepts satisfied the project requirements and demonstrated strong performance across the weighted evaluation criteria, making them the most promising candidates for further development. As a result, these two concepts were selected for a more detailed development and assessment before determining the final concept for implementation.

4.5.1 Concept 3

Concept 3 consists of an electric actuator, ultrasonic sensor, modified side-door latch, switch based door release, mechanical emergency release and a dedicated ECU, which can be seen in Figure 4.5. The electric actuator provides the force required to open and close the door by extending or retracting when the system is activated. An ultrasonic sensor is incorporated to detect the presence of people near the door, providing an input to the system during door operation.

The concept then retains the existing side-door latch with some minor changes for attachments, while the power-release and soft-close functions are added as external units. This allows the additional functionality to be integrated without replacing the complete latch assembly, resulting in a more modular solution. Next, the door is activated to release using a switch integrated into the door during normal operation. The mechanical handle is retained as redundant means of operation, allowing the door to be opened mechanically in an emergency or in the event of an electrical system failure. Finally, a dedicated Electronic Control Unit (ECU) coordinates the operation of the actuator, latch and release-related functions. This ECU is then connected to the vehicle's overall door control system, allowing the door functions to be integrated with the existing vehicle architecture. Although this architecture provides modularity, discussions with the industrial supervisors indicated a preference for a single ECU controlling all door-related functions to simplify assembly and maintenance.

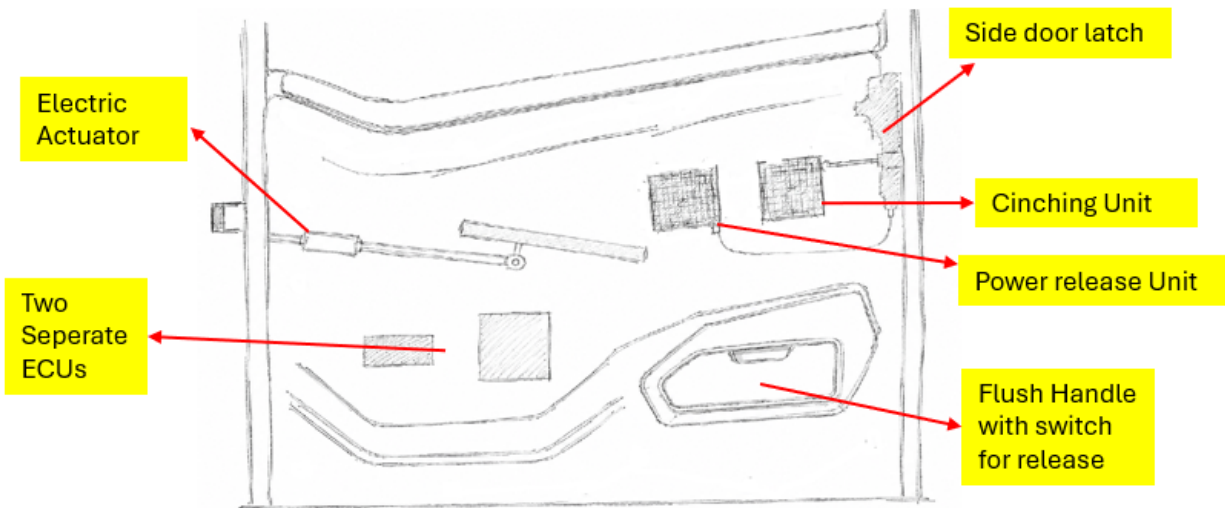


Figure 4.5: Sketch of Concept 3 architecture.

This limitation of Concept 3 is addressed in Concept 10.

4.5.2 Concept 10

Concept 10 incorporates a hydraulic stopper to control the door movement. The hydraulic stopper allows the door to be stopped and held at multiple opening positions, providing greater flexibility during operation. It also provides a braking function when the door moves at high speed, reducing uncontrolled movement and the risk of damage to the door and surrounding components.

The latch architecture and door handle arrangement remain the same as in Concept 3. The existing side-door latch is retained with the externally integrated power-release and soft-close functions, while the switch provides the primary means of electrical release. The mechanical handle is also retained to provide redundant operation in the event of an electrical failure.

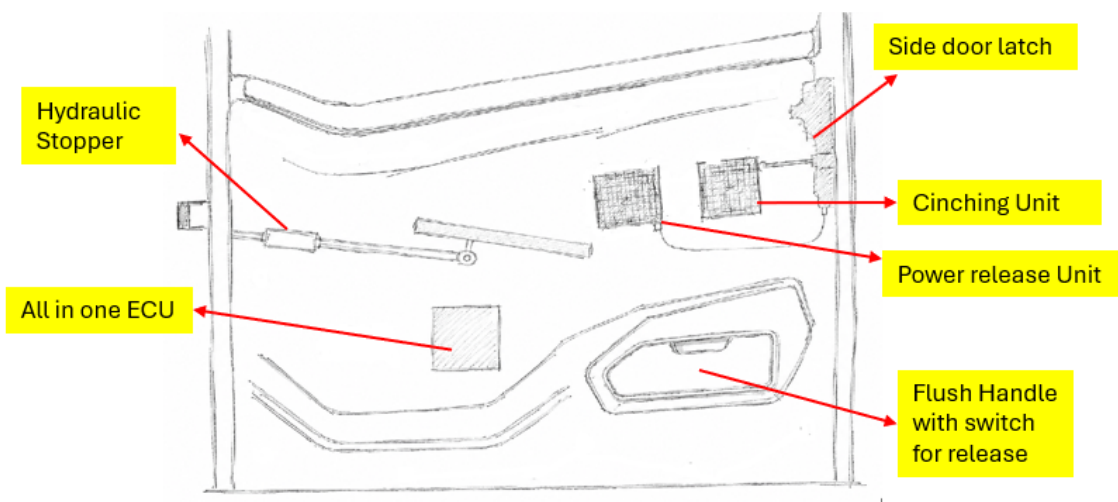


Figure 4.6: Sketch of Concept 10 architecture.

The main difference compared with Concept 3 is the ECU architecture. Instead of using a

separate ECU for the additional door functions, Concept 10 integrates the required control functionality into a single driver ECU module. This addresses the limitation identified in Concept 3 by reducing the number of separate control units and simplifying the overall system architecture. Concept 10 is shown in Figure 4.6.

4.5.3 Final Concept Selection

A final concept selection was therefore conducted by considering additional engineering and project-related factors that were outside the scope of the evaluation matrix. These factors included technical feasibility, compatibility with the existing door architecture, prototype complexity, availability of components and manufacturing resources, project time constraints, and the feasibility of validating the concept within the duration of the thesis. In addition, discussions with the industrial supervisors provided valuable engineering feedback regarding the practicality of implementing and testing the remaining concepts.

Although the integrated ECU architecture proposed in Concept 10 was preferred from an assembly and maintenance perspective, implementing this architecture would require additional development and components that were not readily available within the project time frame. In comparison, the architecture of Concept 3 could be implemented within the thesis time frame and provided a simpler approach for integrating and evaluating the required door functions.

Therefore, despite the architectural advantages of Concept 10, **Concept 3** was selected as the final concept for prototype development and validation. The decision was primarily driven by component availability, ease of implementation, and the possibility of testing the required functions within the available project resources and time frame. Concept 3 was subsequently developed in greater detail, integrated into the existing door system, and used for prototype development and experimental validation.

5 System Design, Prototyping & Testing Result

This chapter aims to illustrate the primary aim of the project, namely, building a digital and physical prototype in order to validate the chosen concept. Furthermore, the chapter will go in depth on how respective parts of the prototype are constructed and tested. However, owing to nature of the non-disclosure agreement the presentation will be limited in terms of showing the final product. However, due to test limitations and component availability passive entry is not able to be implemented in the test.

5.1 Chosen concept - component selection

During the preliminary phase of the prototyping after choosing the concept, a set of components were needed to procure to perform tests on and to build a prototype on. The criterion is that it ought to fit description on each subsystem on the chosen concept. Additionally, there needs to be a functional interface and integration between the included concept towards door and the adjacent subsystem.

5.1.1 Electrical actuator & Sensors

In this stage of the project, Volvo provided an motorized electrical actuator with two integrated hall sensors that is able to detect change of direction and speed. The given actuator utilizes six pins used for different functions.

- **VCC:** Powers the two hall sensors in the component with 5V.
- **GND:** Grounds the hall sensor in the actuator.
- **M+:** Positive terminal, applying positive voltage ranging from 3-27V forwards the motor in the actuator.
- **M-:** Negative terminal, applying positive voltage ranging from 3-27V reverses the motor in the actuator.
- **Hall 1:** Hall signal 1 sensor.
- **Hall 2:** Hall signal 2 sensor.

The sensor utilizes the multi-pole magnet attached to the actuator for this task. The operation relies on the 90 degree shift in the electrical phase between the two sensors [46] as

seen in Table 5.1, each shift gives the respective sensors different value based on if whether it senses the north or south pole.

Table 5.1: Hall signal sequence for each phase.

Position:	Hall Signal 1	Hall Signal 2
0°	0	0
90°	0	1
180°	1	1
270°	1	0

This opens the possibility to detect any sudden acceleration such as during heavy winds, enabling constraints on parts or the complete actuator movement as to mitigate the possibility of sudden pull of the door under such conditions. Furthermore, this allows accurate tracking on the actuator position by keeping a tally on the sensor pulses pattern. Moreover, detection of any directional changes are also tracked [47], this is visualized by the pulse signal being mirrored when the change of direction occurs as seen in Figure 5.1.

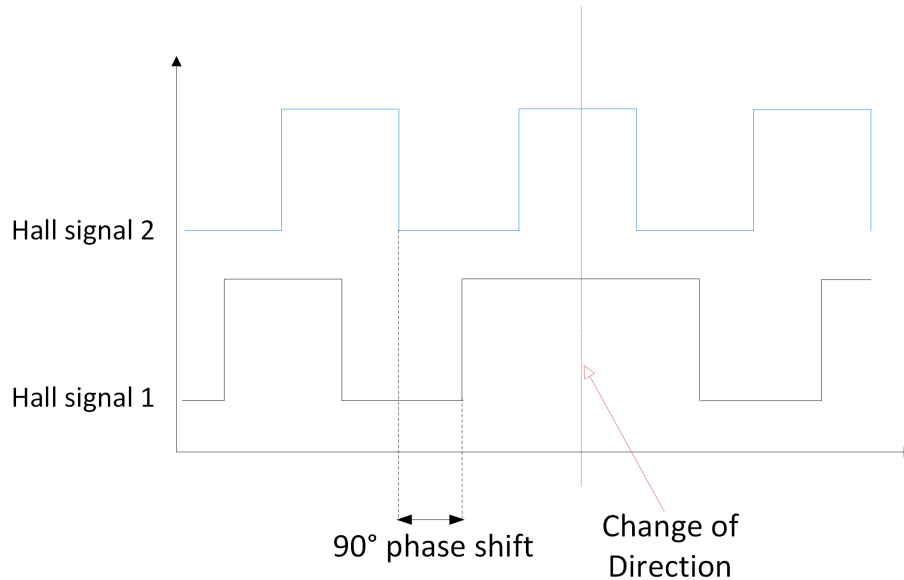


Figure 5.1: Phase shift defined by hall sensor positioning.

Given the nature of the actuator being motorized, it enables among other things the ability for automatic or assisted opening & closure. However, the actuator cannot detect any objects surrounding the door. Hence, during an automatic opening it could potentially open in such a way to cause damage to the door or an external subject. Thus, it is decided to also to implement a perception sensor that will complement the automatic opening of the door. Due to constraints in terms of availability, packaging, finance or available interface it was decided to go for an ultrasonic sensor. The sensor works by emitting sound waves that are greater than 20 kHz and contentiously emits and receive waves at the same pitch. The prototype will use the ultrasonic sensor HC-SR04 that has an effective emitting angle of 15 degrees and sends out around 40 kHz.[48]. The component utilizes four pins to achieve this result.

- **VCC**: Powers the two hall sensors in the component with 5V.
- **GND**: Grounds the hall sensor in the actuator.
- **TRIG**: The trigger that emits the sound waves.
- **ECHO**: Receives the emitted sound wave.

The distance of the object is calculated by multiplying the speed of the wave emitted by the transmitter multiplied by the time for the receiver to pick up the waves. Since the wave is bouncing from the object back to the receiver, the time is then divided by 2.

$$d = \frac{v \cdot t}{2} \quad (5.1)$$

Due to emitting ultrasonic waves, it operates on the speed of sound, which under standard atmospheric conditions is 343 m/s. However, HC-SR04 has an effective range of 0-3m meaning that for the project use, it ought to be adequate to anticipate any external individuals or objects.

5.1.1.1 Actuator Mounting and Kinematic Analysis

The actuator mounting was designed to provide the required door opening motion while remaining within the available packaging space. Since the actuator has a fixed closed length and a limited stroke, the mounting locations on the door and vehicle body had to be determined so that the actuator could accommodate the complete required door movement without reaching its mechanical limits. As the door rotates about its hinge-axis, the position of the door-side mounting point changes, resulting in a corresponding change in the distance between the two mounting points. Therefore, a kinematic analysis was performed to determine the actuator length at different door positions and to establish the maximum opening angle that could be achieved with the selected actuator.

The analysis was also used to determine the actuator force requirement based on the required door-opening torque and the actuator mounting geometry. Figure 5.2 illustrates the actuator mounting geometry and free body diagram for the door system.

5.1.1.2 Closed-door Actuator length

The initial actuator geometry was defined using the coordinates of the fixed body mounting point and the door mounting point in the closed-door position. The distance between the two mounting points was calculated using the *Euclidean distance formula*, derived from the Pythagorean theorem

$$L_0 = \sqrt{(x_{D_0} - x_B)^2 + (y_{D_0} - y_B)^2} \quad (5.2)$$

where L_0 is the actuator length in the closed position, B is the body mounting point and D_0 is the door mounting point when the door is closed.

The calculated closed length was then compared with the supplier's specified closed length for the selected actuator to ensure that the proposed mounting geometry was compatible with the available actuator.

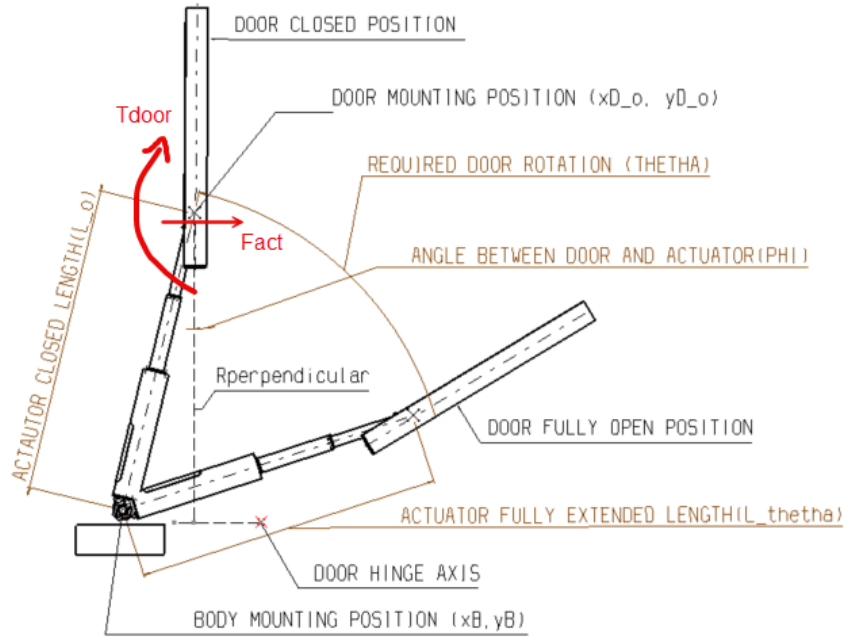


Figure 5.2: Actuator Mounting Geometry and Free Body Diagram.

5.1.1.3 Door Opening Kinematics

The door-side mounting point changes position as the door rotates about its hinge axis. The required door opening angle was defined based on the intended operating range of the door. In the present design, the target opening angle was specified as θ .

The new position of the door mounting point was determined using a *two-dimensional rotation matrix*.

$$\begin{bmatrix} x_0 \\ y_0 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_{D_0} \\ y_{D_0} \end{bmatrix} \quad (5.3)$$

which can also be expressed as

$$\begin{aligned} x_0 &= x_{D_0} \cos \theta - y_{D_0} \sin \theta \\ y_0 &= x_{D_0} \sin \theta + y_{D_0} \cos \theta \end{aligned} \quad (5.4)$$

where x_θ and y_θ describe the position of the door mounting point after rotation through the required opening angle. This transformation is based on the standard two-dimensional rotation transformation and was used to determine the actuator mounting geometry at the fully open position.

Once the rotated position of the door mounting point was obtained, the actuator length at the maximum door opening angle was calculated using the same Euclidean distance relationship:

$$L_\theta = \sqrt{(x_\theta - x_B)^2 + (y_\theta - y_B)^2} \quad (5.5)$$

The required actuator stroke was then determined from the difference between the actuator length at the closed and fully open positions.

$$S_{req} = L_{\theta} - L_0 \quad (5.6)$$

where S_{req} is the required actuator stroke.

The initial analysis was performed using the current door opening angle as the target condition. However, the actuator stroke required to reach this angle exceeded the available stroke of the selected actuator. Therefore, the target angle could not be achieved with the available actuator configuration. Rather than selecting a different actuator, the mounting geometry was evaluated to determine the maximum opening angle that could be achieved within the available stroke.

5.1.1.4 Determination of the Achievable Opening Angle

The maximum actuator length is determined from the actuator's closed length and available stroke.

$$L_{max} = L_0 + S_{max} \quad (5.7)$$

where S_{max} is the maximum available actuator stroke.

The maximum achievable door opening angle was then determined by finding the angle at which the actuator reaches its maximum length

$$L_{\theta_{max}} = L_{max} \quad (5.8)$$

Substituting the rotational transformation into the actuator length equation gives

$$L(\theta) = \sqrt{[x_{D_0} \cos \theta - y_{D_0} \sin \theta - x_B]^2 + [x_{D_0} \sin \theta + y_{D_0} \cos \theta - y_B]^2} \quad (5.9)$$

The maximum achievable opening angle therefore satisfies

$$\sqrt{[x_{D_0} \cos \theta_{max} - y_{D_0} \sin \theta_{max} - x_B]^2 + [x_{D_0} \sin \theta_{max} + y_{D_0} \cos \theta_{max} - y_B]^2} = L_0 + S_{max} \quad (5.10)$$

The resulting angle represents the maximum door opening that can be achieved without exceeding the available actuator stroke. Thus, the final opening angle was determined from the kinematic calculation rather than directly from the previous door opening angle. Finally, the mounting geometry was further fine tuned to achieve a considerable opening angle while also maintaining suitable packaging and actuator alignment.

5.1.1.5 Actuator Force During Door Opening

In addition to the kinematic analysis, the force required from the actuator to open the door was evaluated based on the torque required about the door hinge. The relationship between the actuator force and the resulting door-opening torque follows the fundamental moment relationship

$$T_{door} = F_{act} r_{\perp} \sin \phi \quad (5.11)$$

where T_{door} is the required torque about the door hinge, F_{act} is the actuator force, $r_{\perp}$ is the perpendicular distance between the hinge axis and the actuator's line of action and ϕ is the angle between the door and actuator.

The required actuator force can therefore be expressed as

$$F_{act} = \frac{T_{door}}{r_{\perp} \sin \phi} \quad (5.12)$$

Since the actuator mounting geometry changes as the door opens, the perpendicular lever arm $r_{\perp}$ also varies with the door opening angle. Consequently, the actuator force requirement is dependent on the instantaneous door position. The force analysis was therefore used together with the kinematic analysis to verify that the selected actuator could provide sufficient force throughout the required range of motion.

The final actuator mounting position was incorporated into the CAD model based on the calculated closed length, available actuator stroke, achievable opening angle, and force requirement. The resulting configuration provided the required door movement while remaining within the mechanical limits of the selected actuator.

5.1.2 Mechanical Latch with Motorized Release and Soft-Close

5.1.2.1 Existing Side-Door Latch

The proposed door system was developed around the existing Volvo side-door latch, shown in Figure 5.3, rather than developing the complete latch assembly. This approach reduced development complexity while maintaining the validated safety characteristics of the production latch. The latch already incorporates the primary locking mechanism, ratchet-pawl architecture and lock and unlock functionality. Therefore, the work was limited to integrating additional power-release and soft-close functions without modifying the fundamental locking mechanism.

The selected latch is capable of performing the following essential functions within the door system. It securely retains the door in both the secondary and primary latch positions through the ratchet-pawl mechanism while withstanding the loads transmitted from the striker during door closing and normal vehicle operation. The latch also provides the mechanical release function through the existing interior and exterior door handles and incorporates the production lock and unlock mechanism. In addition to these original functions, the latch serves as the mechanical interface for the proposed power-release and soft-close mechanisms developed in this thesis. Consequently, the existing latch architecture forms the foundation upon which the additional electromechanical functionality is integrated.

5.1.2.2 Motor Selection

To actuate the power-release and soft-close mechanisms, a HC675XLLG-101 brushed permanent magnet DC motor was selected. The motor was primarily chosen because it was readily available during the prototype development phase and satisfied the packaging constraints of the proposed actuator assembly. Furthermore, the motor is specifically intended for automotive latching and cinching applications, making it suitable for the operating conditions required in this project[49].



Figure 5.3: Existing Side-Door latch

The HC675XLLG-101 operates from a 12 V DC supply, which is compatible with the electrical architecture of passenger cars. The motor provides a high rotational speed while maintaining a compact package, allowing a reduction gearbox to be used to convert the available speed into the high output torque required for latch release and cinching. According to the manufacturer, the motor has a stall torque of 221.35 mNm, a no-load speed of 4706 rpm, a maximum output power of 27.28 W and achieves a maximum efficiency of approximately 71%. Under stall conditions, the motor draws approximately 9.71 A, while the no-load current is approximately 0.22 A. These characteristics are summarized in Table 5.2.

Table 5.2: HC675XLLG-101 Motor specifications.[49]

Parameter	Value
Rated Voltage	12 V
No-load Speed	4706 rpm
Stall Torque	221.35 mNm
No-load Current	0.22 A
Stall Current	9.71 A
Maximum efficiency	71%
Maximum output power	27.28 W
Operating temperature	-40° to 85° C

Brushed DC motors exhibit nearly linear torque-speed and torque-current characteristics over their operating range. As the output torque increases, the motor speed decreases approximately linearly, while the armature current increases proportionally. These characteristics make a brushed DC motor suitable for this application. The performance characteristics of the selected motor are presented in Figure 5.4. The figure illustrates the trade-off between output speed and torque and highlights the operating principle adopted in this work, where the high-speed output of the motor is converted into the high torque required at the latch

through the designed actuator.

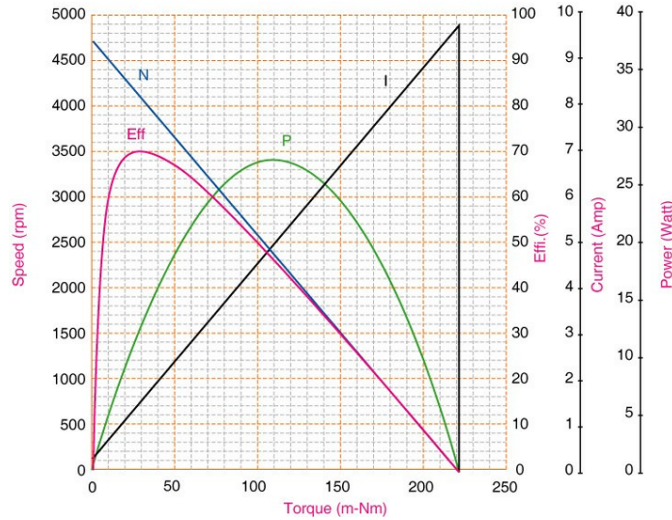


Figure 5.4: Performance characteristics of the HC675XLLG-101 DC motor[49].

Finally, although the selected motor satisfied the packaging, voltage, and speed requirements of the proposed system, its output torque alone was insufficient to actuate the latch directly. Therefore, a mechanical analysis of the latch was first performed to determine the required release and cinching forces. These calculated loads subsequently formed the basis for the actuator design and transmission ratio selection presented in the following section.

5.1.2.3 Force Analysis of the Latch Mechanism

A static force analysis of the production latch was carried out to determine the mechanical resistance that must be overcome during the release and cinching operations. The analysis considered the primary contributors to the resisting load, namely the door seal load, the ratchet return spring, the pawl spring and the friction generated between the ratchet and pawl contact surfaces. The required geometric dimensions were taken from the CAD model of the production latch.

Due to confidentiality agreements with Volvo Trucks, the proprietary dimensions and calculated numerical values cannot be presented. Instead, the analytical methodology and governing equations used during the design process are described. The Figure 5.5 illustrates the various forces acting on the production latch.

The seal pre-load acting on the striker generates a moment about the ratchet pivot,

$$M_s = F_{seal}r_s \quad (5.13)$$

where F_{seal} is the seal force and r_s is the perpendicular distance between the ratchet pivot and the line of action of the seal load.

The resisting moment generated by the ratchet spring was subsequently added to obtain the total moment acting on the ratchet,

$$M_{total} = M_s + M_r \quad (5.14)$$

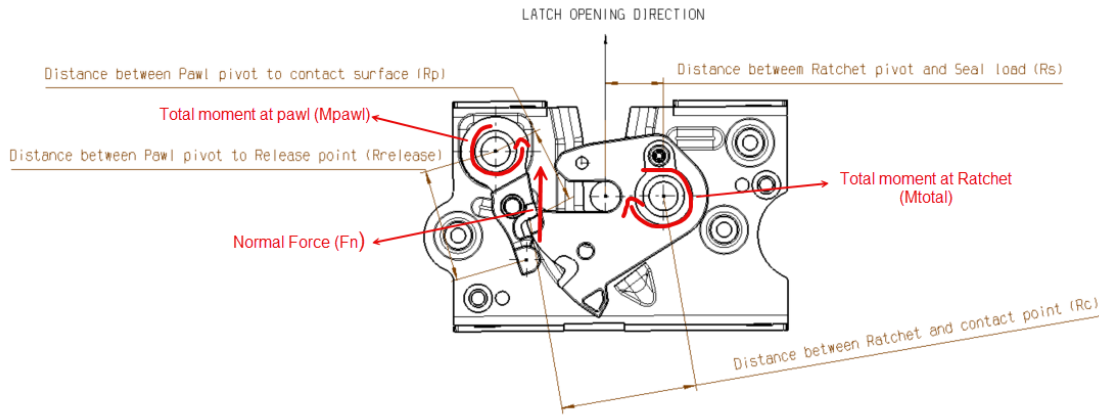


Figure 5.5: Latch dimensions and Free body-diagram.

Using static moment equilibrium, the normal force acting between the ratchet and pawl was determined as

$$F_n = \frac{M_{total}}{r_c} \quad (5.15)$$

where r_c is the distance between the ratchet pivot and contact surface.

The resulting normal force produces frictional resistance at both the engagement surface and the pawl pivot. The corresponding frictional moment is expressed as

$$M_f = \mu F_n r_p \quad (5.16)$$

where μ is the co-efficient of friction and r_p is the distance from pawl pivot to contact surface

The resisting moment generated by the pawl spring was then included to obtain the total resisting moment acting on the pawl

$$M_p = M_{spring} + M_f \quad (5.17)$$

Finally, the force required to disengage the pawl was calculated from

$$F_{release} = \frac{M_p}{r_{release}} \quad (5.18)$$

where $r_{release}$ represents the distance between the pawl pivot and the release point.

The calculated release force represents the minimum force required to disengage the latch under normal operating conditions. A design safety factor was subsequently applied to account for manufacturing tolerances, wear, and friction variations.

The same analytical procedure was then applied to determine the torque required for the cinching function, where the actuator must move the ratchet from the secondary latch position to the fully latched position while overcoming the seal compression and internal pawl resistance.

5.1.2.4 Actuator Box Calculations

The calculated release and cinching forces were then converted into actuator torque using the geometry of the release lever, which was determined based on the packaging space.

$$T_{act} = F_{release}r_{lever} \quad (5.19)$$

The travel of the lever was determined from calculating the angular travel of both ratchet and pawl. Next, the required angular displacement of the release lever also established the minimum output speed

$$\omega_{out} = \frac{\theta}{t} \quad (5.20)$$

where θ is the required angular travel of the release lever and t is the desired actuation time.

Finally, to satisfy both the torque and speed requirements, a three-stage reduction gearbox was designed. The transmission consists of an initial worm gear stage followed by two spur gear reduction stages. The overall gear ratio is given by

$$GR_{total} = GR_1GR_2GR_3 \quad (5.21)$$

The actuator output can therefore be expressed as

$$T_{out} = T_{motor}GR_{total}\eta \quad (5.22)$$

where T_{motor} is the motor output torque and η represents the transmission efficiency.

The selected transmission ratio ensured that the available gearbox output torque exceeded the calculated torque requirements for both the release and cinching functions while maintaining the required operating speed.

5.1.3 Combined door module and ECU

Contemporary Volvo trucks have the door module, comprised of sensors and motors, and the ECU which implements the control logic are treated as separate units. The aim is to simplify the solution by combining them. The existing Volvo ECU is developed and its software is handled and maintained by suppliers. Therefore, adding difficulty of modifying the existing architecture without the supplier. Thus, an micro-controller is used instead, namely an Arduino. For the purpose of the project, an Arduino mega 2560, the selection is motivated for it's extensive pin selection[50], thus allowing room and flexibility on how to build the architecture. The versatility of the pin selection mitigates uncertainty in the project by giving room to add additional components in the case the build pivots based on the test results.

The Arduino enables complete reign over the control logic of the project architecture and flexibility in regards to what can be interfaced towards the control unit. The existing ECU is only interfaced towards specific connectors and modifying it would add more time, cost and complexity added on top of the already existing uncertainty of configuration for the control logic. The prototype, developed using the ECU configuration 1 [29] owing to setup limitations and configuration of the fixture that the door is attached on. Furthermore, configuration 3 and 4 would introduce needless complexity in an already time-constrained project.

5.1.4 Switch and Mechanical handle:

The objective of the sub-system is to ease user interface towards the truck. The concept is has a dual interface, one being a mechanical handle that will be developed in CAD and the intended interface being an Alps Alpine Taktel switch. Hence, the switch, which requires a lot less effort, has an rated force of 1,57N [51]. However, the switch is electronically driven and connected to the latch motors, meaning that during an emergency situation it can cease to function due to lack of power. This results in the added redundancy of a mechanical handle which directly connected to the latch through an bowden cable, meaning the operation is entirely mechanical. Furthermore, it is also a more familiar solution for users that prefer the mechanical interface.

5.1.5 Auxiliary components selection

The prototype is not connected to a physical truck which results in the inability to harness the trucks internal components and systems. To address this, components outside of the concept scope is chosen to substitute essential functions from the truck. The first component is the battery, the heavy duty truck utilizes a 24V architecture, in it's stead, a DC power supply provided by Volvo is utilized. The particular PSU given is able to regulate both the current and voltage and uses banana cables to interact with components. With respect to the prototype, being able to test on a 24V power source is key to replicate a truck environment. However, not every component is able to utilize a 24V power supply, for example the Arduino is not rated for a 24V. Therefore, a buck converter needs to be added, the chosen converter utilizes DolaTek[52] DC to DC converter. The components allow input voltage of 24V to be converted to 5V as output, which aligns with the rated Arduino voltage.

Moreover, to regulate and define the motor operational logic in the different systems, a need for a motor driver is identified. This is due to the motors in the project in of themselves do not allow for speed regulation and directional input. The motor driver chosen is the BTS7960 [53]. Similarly, to the buck converter the driver uses switches for voltage regulator. What sets the two apart is the use of two sets of MOSFET switches for directional control as opposed to a single switch for voltage regulation. The motor driver utilizes the duty cycle, similar as the buck converter. However in this instance with the aim of configuring of direction and speed [54] as opposed to maintain a certain voltage. The chosen motor driver Direction is adjusted by powering either right PWM or left PWM, for either forward or reverse. Additionally, speed is adjusted by the aforementioned duty cycle, the higher duty cycle the faster the motor will move in chosen direction.

5.2 Sub-system prototyping and testing

The following section describes the development of the prototypes and the deployment used for testing. The development follows a test-design-build framework, in which the tests performed on the chosen and developed components informs on what type of architecture the final build will have. The objective of developing and testing the prototypes is to translate the chosen concept into a functional prototype that is used to evaluate said concepts to the user need. Furthermore, this anchors to one of the research questions, namely uncovering of hidden requirements that was not conceived in the initial project planning.

The development considered different aspects to ensure that the prototypes aligned with the requirements as closely as possible, any deviations are noted either due to time constraints or cost. The prototype is not expected to fully achieve all the requirements, rather it ought to aim the targets through iterations. However, due to constraints, the final build should be viewed as a first draft of a prototype that can be iterated for future improvements.

5.2.1 Auxiliary components

The testing begins with the auxiliary components, to ensure that the supporting components works before applying it to the essential components. This is not only to mitigate any future troubleshooting but also because some of these supporting components are needed to work to test the essential components. The primary supporting tool of the test is the laptop provided by Volvo and an multimeter. The first test is with the power supply, by using the multimeter, the different settings of the power supply could be verified. The second test is done by connecting the power supply input to a buck converter. Conversely, the output is connected to the multimeter. With the setting of 24V in the PSU, the readings of the output are confirmed to be 5V when utilizing the setup as shown in Figure 5.6. The following test,

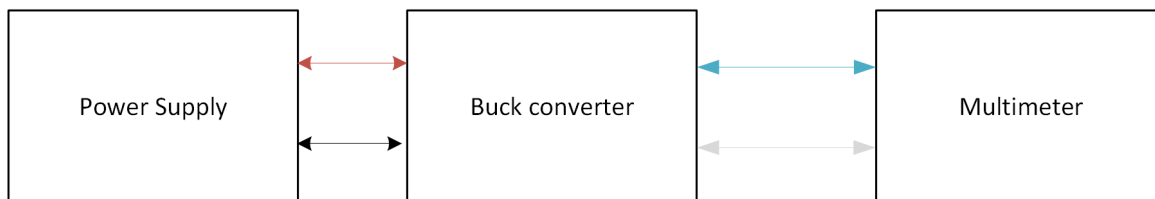


Figure 5.6: Buck converter test setup.

required the Arduino which in turn act as a two-fold test, one to confirm the function of the motor driver and the other the Arduino. The procedure begins with the Arduino connected to the laptop which provides a 5V source and in turn connects to the motor driver. Initially the 5V and GND connection is tested with a multimeter between the Arduino and driver with success. However, once the power supply is connected on the motor side, it started to give off odor of burnt plastic. Upon re-testing in an isolated test, namely the motor driver with only the power supply, it displays no signal on the multimeter. It is concluded that it short-circuited. The assumption is due to paint defects between the integrated heat sink and the driver it caused unintended contact between pins. Another possibility is the large heat buildup in the heat-sink due to the heat emitted from it after the initial test.

For the next test rather than just removing the heat sink and potentially cause heating issues, the decision is to use thermal pads made of graphene. The solution offers both a distance between the two surfaces and adds additional heat management capabilities. The second motor driver also show signs of minor defects along the heat sink surface but with the added thermal pad it displayed no signs of defects in an isolated test. Subsequently, the functioning motor driver is added to the full test setup is visualized in Figure 5.7.

The test uses Arduino IDE to adjust the PWM, the aim is to secure the function of forward and reverse drive. Furthermore, this test lays the foundation for latch and actuator functionality and their respective tests.

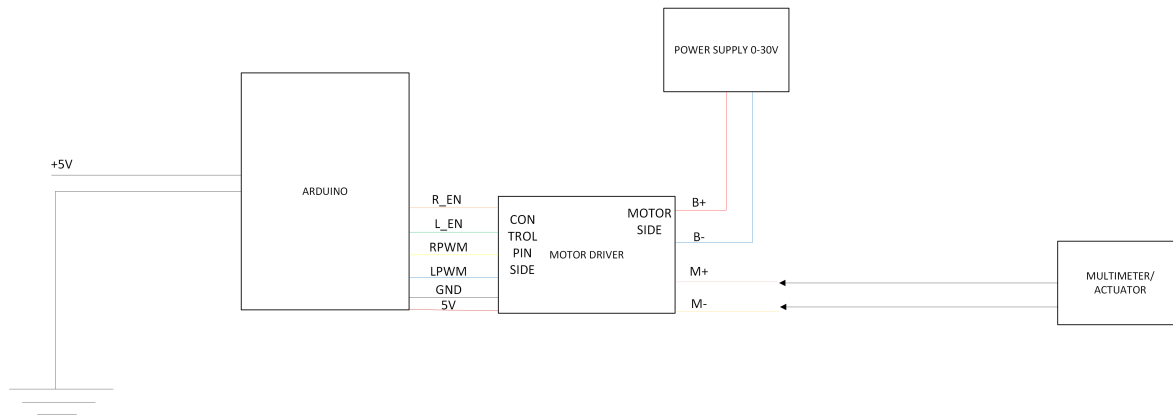


Figure 5.7: Motor driver test setup.

5.2.2 Actuator & Sensor

The actuator test builds directly from the motor driver test. However, at this stage of the project, the hall signals are unable to be tested appropriately. This is due to the sheer stiffness of the actuator requiring a sufficient leverage to move it manually. The aim with the hall sensors is to detect any unintended movement such as strong winds. This will yield the opportunity to counteract the wind by adjusting the PWM of the opposite direction of where the hall sensors are detecting spikes of speed, resulting in either slowing or stopping the slam. The adjustments of the PWM can be tested and verified physically by adjusting the motor direction and voltage.

The following test will be focused on just adjusting the PWM, where the power supply will provide electrical energy to the the motor pins on the actuator. The Figure 5.8 represents the test setup, the aim is to drive and reverse the actuator by manually adjusting through the power supply. In the test the actuator moves forward after connecting the motor+ pin to voltage supply and motor- to the ground, and vice versa for reverse, this confirms the basic functionality of the actuator.

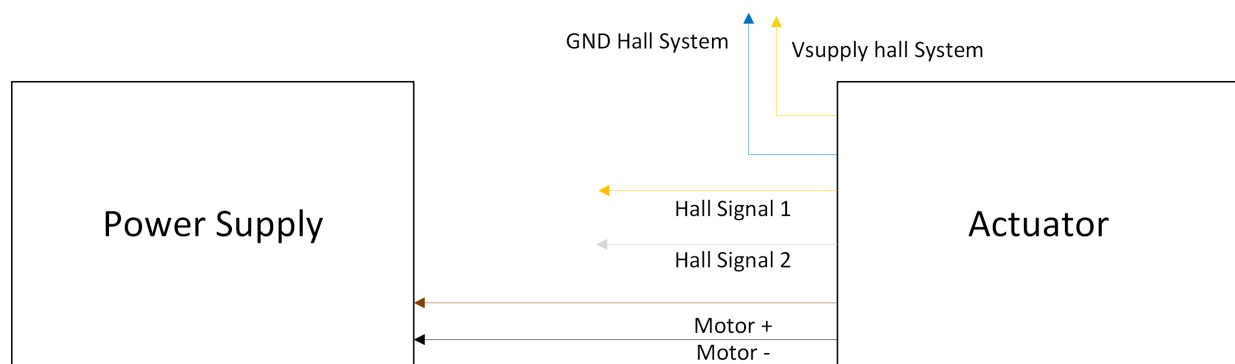


Figure 5.8: Actuator test setup.

The second test expands upon the first and involves the use of a switch to drive the motor. Furthermore, the Arduino and motor driver will be connected to the setup, this will facilitate control logic to the test. Therefore, moving the actuator position in different speed and

directions based on input conditions. For the test assessment, the target is to confer that the component interfaces work between the components and that implementation of control logic is possible. After the components are assembled, a test code is uploaded to the Arduino to check if the actuator drives forward in the first switch press and reverses at two presses. The test is illustrated in Figure 5.9 and the result can be viewed in **Appendix I**. The observation of the functionality and also verification using the multimeter between the interfaces shows that the test works as intended.

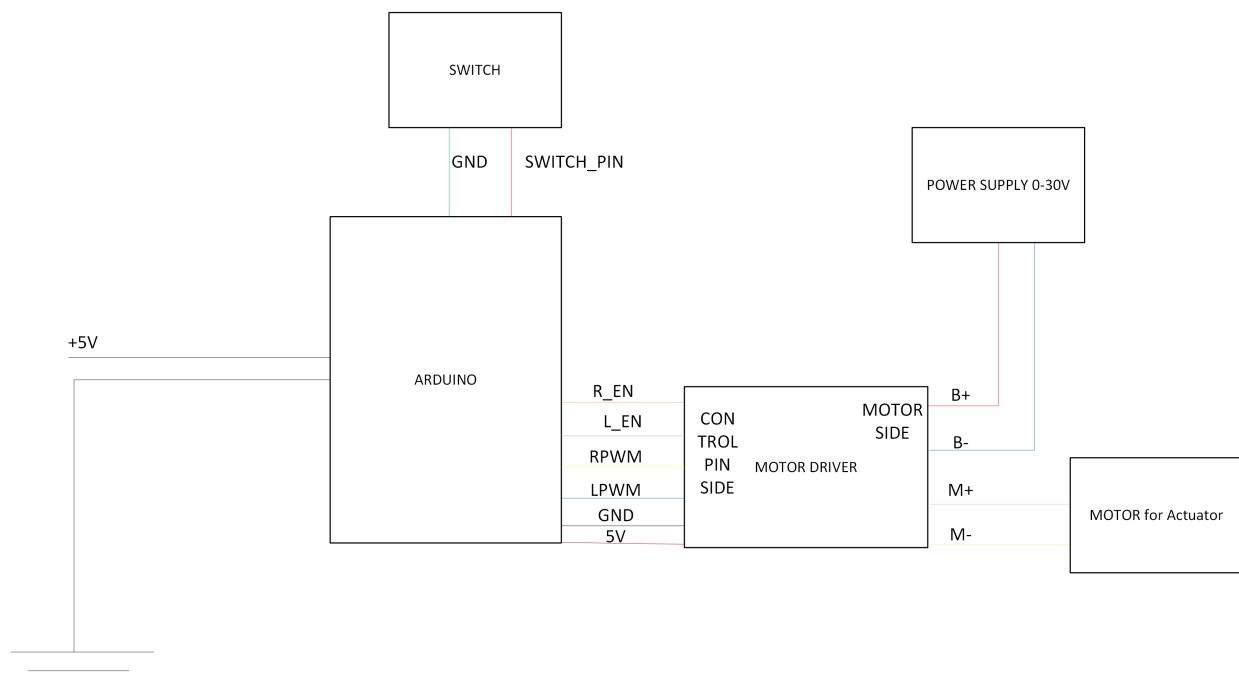


Figure 5.9: Actuator test 2 setup.

The actuator system will also include an external sensor, namely the ultrasonic sensor. The purpose of the sensor is to detect objects and inform the actuator of its relative position and stop if it comes too close. This test will use the same from the actuator test. However, the other components are not included, the reasoning for using an LED instead of the actuator is to isolate the performance of the ultrasonic and to reduce complexity in the test codes. For the test, it was agreed to check on two different arbitrary distances to represent when to capture diagnostic data and when the function will set in. Hence, once the object is detected on the farthest point, the LED will have pulsing illumination, this represent when the ultrasonic will start gathering data. The reasoning on why the total 3m that the ultrasonic is capable of is to reduce noise. However, once the object gets sufficiently close enough it will have a continuous illumination which represents when the function will occur i.e. actuator will be signaled to stop. For the purpose of the tests, different distances were used but for the prototype build. During the testing it was settled to have 10cm for the stopping signaling and 30cm for diagnostics due to being judged as sufficient for prototyping purposes and relevant data collection. The test setup and continuous illumination due to being near an object can be seen in **Appendix H**.

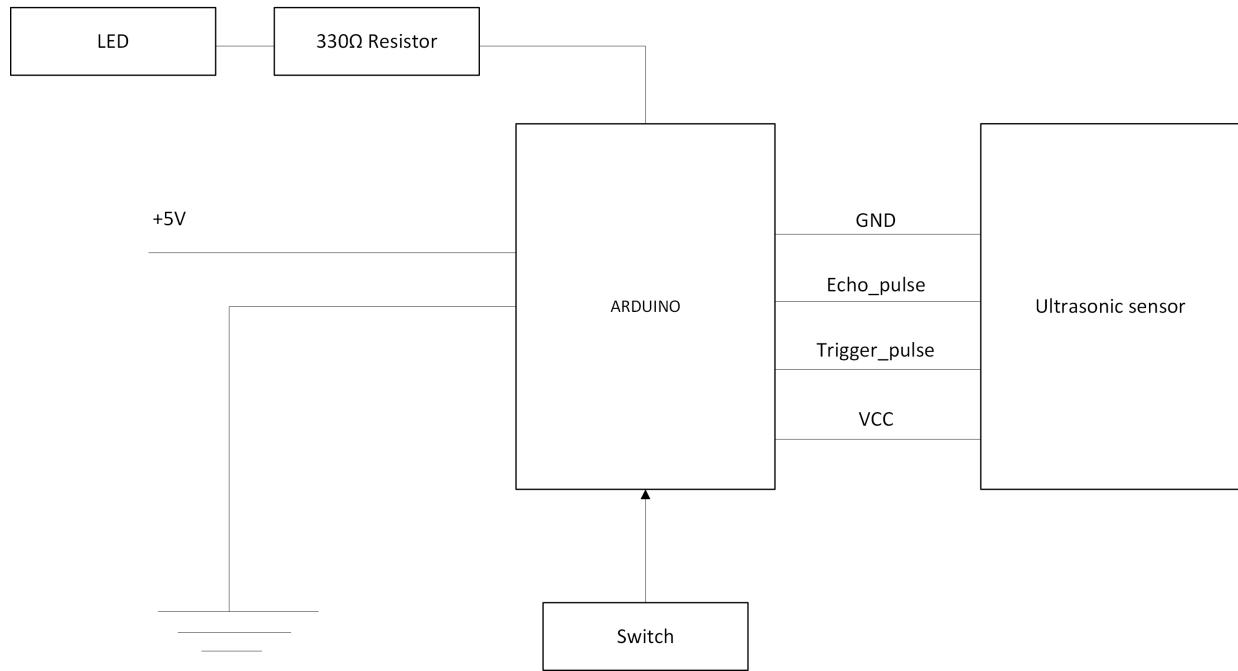


Figure 5.10: Ultrasonic test setup.

5.2.3 Latch

This sub-section will be divided by two parts, the first part will delve in to the verification, prototyping, testing and modification of the designed actuator boxes and also the current latch hardware and the second part will explore testing of the latch motors in terms of system interface and functionality.

5.2.3.1 Latch Verification Using Romax

Following the calculation of the required output torque and overall gear reduction ratio, the gear train was developed and verified using **Romax**. Romax is a specialized drivetrain simulation and analysis platform used for the modeling and assessment of geared electromechanical systems including gears, shafts and other transmission components[55].

The development process began by defining the available shaft locations and center distances within the actuator box. These dimensions were constrained by the packaging space, the dimensions of the selected motor and the arrangement of the surrounding components. Based on these constraints, a multi-stage gear arrangement was required, as the overall reduction ratio obtained from the previous calculations could not be practically achieved using a single gear pair system.

Since the selected motor already incorporated a worm on its output shaft, the first driven gear was configured as a worm wheel. The remaining reduction was achieved using a compound gear arrangement, where multiple gears were mounted on intermediate shafts. This allowed the required overall reduction to be distributed across several stages while maintaining a compact configuration within the available actuator box volume. The initial arrangement of the gear shafts and center distances is shown in Figure 5.11.

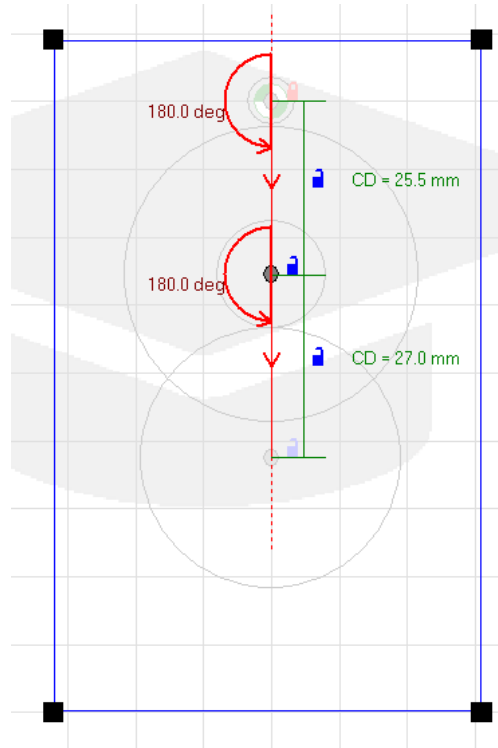


Figure 5.11: Initial Arrangement of the Gear shafts.

Next, The overall reduction ratio was then obtained from the product of the individual stage ratios.

$$i_{total} = i_1 i_2 i_3 \quad (5.23)$$

where i_1, i_2, i_3 represent the reduction ratios of the individual stages. These ratios were then incorporated in the Romax model, shown in Figure 5.12.

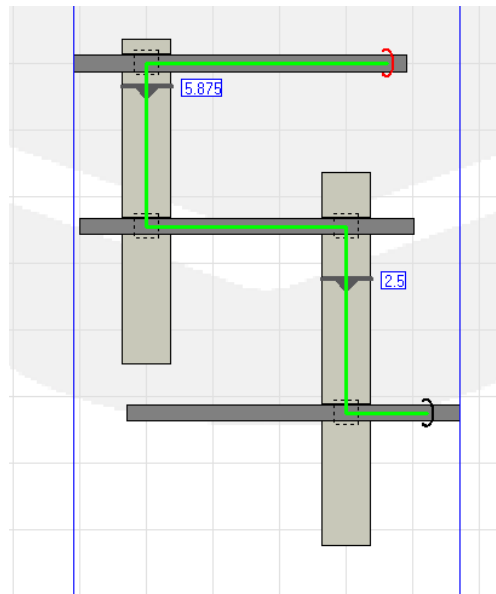


Figure 5.12: Reduction ratio across different stages.

After this, the gear module was selected separately based on the required gear dimensions and the intended manufacturing method. Since the gears were manufactured using 3D printing, the module had to provide sufficiently large and robust gear teeth while remaining compatible with the available center distances and packaging space.

Once the gear arrangement had been established, the complete drivetrain was modeled in Romax, as shown in Figure 5.13. The motor input torque obtained from the motor characteristics and the preceding calculations was applied to the model. The purpose of the analysis was to verify whether the selected gear arrangement and overall reduction ratio could generate the required output torque at the final gear stage. The output torque obtained from the Romax model was compared with the torque requirement previously determined from the latch force calculations. Due to NDA, the detailed Romax results including the output graphs and numerical values cannot be presented. However, the simulation was used as an internal verification step to confirm that the selected gear arrangement was capable of achieving the required output torque.

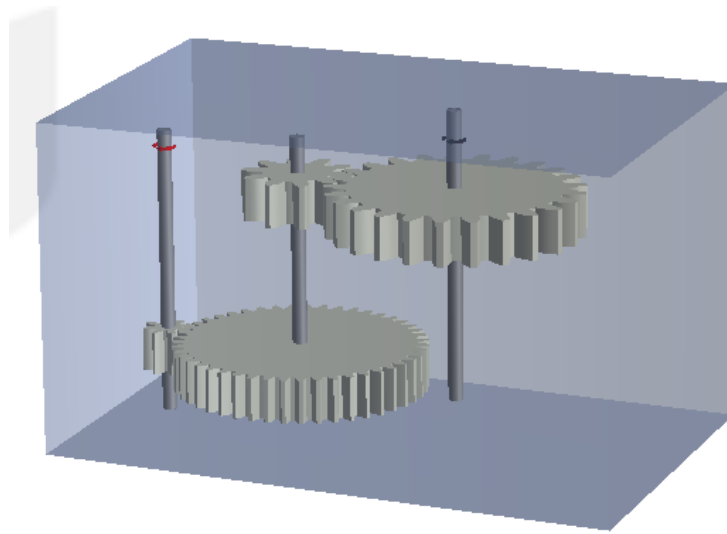


Figure 5.13: Complete gear train Modeled in Romax.

During the prototype development, the center distance between the intermediate and final gear shafts was revised to improve the physical arrangement of the gearbox. This required corresponding changes to the gear geometry and the Romax model. The revised center distance and updated gear parameters were therefore incorporated into the drivetrain model and the analysis was repeated to confirm that the modified arrangement continued to provide the required output torque. The Romax model showing the updated center distance is shown in Figure 5.14.

The verification confirmed that the revised multi-stage gear arrangement was feasible within the available packaging space and could provide the required torque transmission. The detailed development and subsequent iterations of the actuator box and individual gears, including the structural modifications identified during prototype testing, are discussed in the following section.

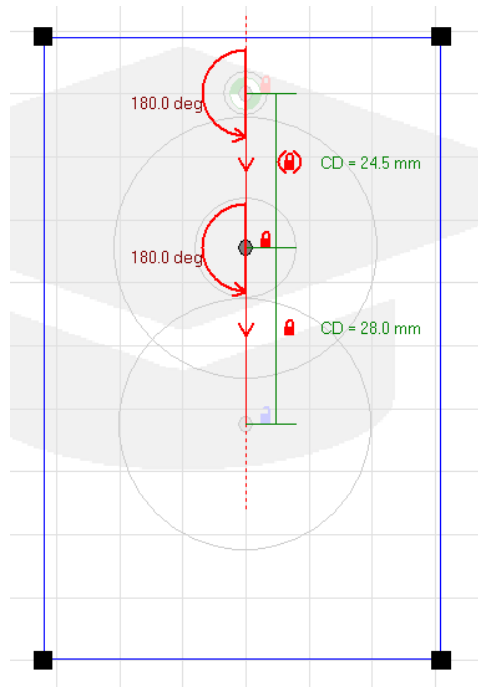


Figure 5.14: Updated center distance in Romax.

5.2.3.2 Latch prototyping

Following the drivetrain verification presented in the previous sections, the power-release and cinching functions were developed into a physical prototype. The prototype development focused on integrating the selected motor and gear mechanism with the latch through the Bowden cable interface. Since the proposed system involved the interaction of several mechanical and electrical components, the design was developed iteratively through CAD development, prototype manufacturing and functional testing.

The prototype development process focused on verifying the functional feasibility of the proposed mechanisms rather than directly producing a final production-ready design. Several iterations were therefore required to evaluate component packaging, gear operation, motor integration, cable attachment and the structural behavior of the actuator housing. Functional tests were conducted throughout the development process and the results from each iteration were used to identify limitations and implement improvements in the subsequent design. This iterative process resulted in the final prototype configuration used for the experimental validation.

5.2.3.3 Actuator box Design Iterations

The actuator box was developed to house and support the motor and gear mechanism used for the power-release and cinching functions. Its overall dimensions were primarily defined by the available packaging space within the door. The surrounding components particularly the window regulator were considered when defining the length and width of the housing. In addition, the maximum available height was constrained by the movement of the window glass during its downward travel. The internal dimensions were subsequently determined based on the size and arrangement of the selected motor, gears and associated shafts.

Figure 5.15 presents the four main iterations of the actuator box. Each iteration addressed specific functional or structural limitations identified during prototype development.

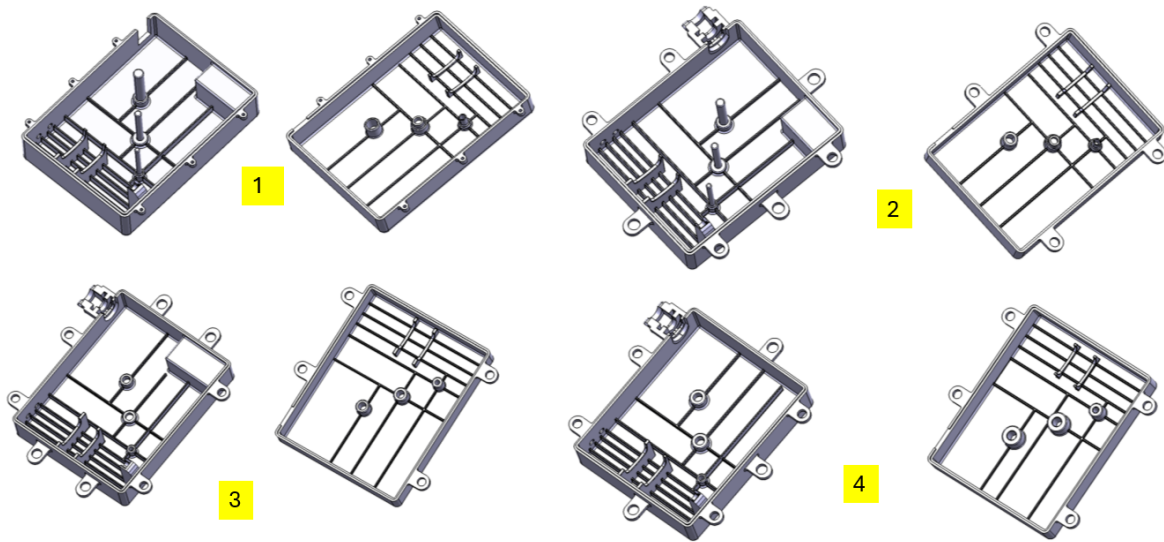


Figure 5.15: Actuator box iterations during the development stage.

Iteration 1 was primarily developed as an initial functional prototype. The main objective was to verify that the motor and gears could be accommodated within the available housing and that the designed compound gear arrangement operated as intended. This iteration therefore focused on validating the basic packaging and functional feasibility of the drivetrain rather than incorporating all final interfaces.

Iteration 2 introduced the cable attachment features required to connect the actuator mechanism to the latch through the Bowden cables. Different methods for closing the housing were also considered, including snap-fit features and screws. Although snap connections could simplify assembly, screws were ultimately selected as they provided a more secure and reliable method of closing the prototype housing while also allowing repeated access to the internal components during testing and development.

During extended testing of the second iteration, a structural limitation was identified. The 3D printed support poles used to support the rotating gear shafts began to fail due to the rotational loads transmitted through the gears. This indicated that the printed features were not sufficiently robust for repeated operation. To address the issue, **Iteration 3** replaced the printed support poles with steel rods. The steel rods were fixed within the actuator housing using super glue and provided a more robust support for the rotating components. This modifications significantly improved the structural behavior of the assembly, allowing the mechanism to operate repeatedly without the failure observed in the previous design. The use of steel rods therefore provided a practical solution for the prototype and enabled further functional testing of the mechanism. During the same testing phase, another issue was identified in the spacing between the shafts supporting the intermediate and final gears. The center distance between these shafts had initially been minimized to reduce the overall size of the actuator box. However, the limited spacing resulted in high loads on the gear features, causing the gear extrusion to fail during operation. The detailed investigation of this failure and the resulting modifications to the gear design are presented in the following

gear design section. As part of the actuator box development, the spacing between the corresponding shafts was increased to provide sufficient clearance and improve the robustness of the gear arrangement.

Finally, **Iteration 4** incorporated the results of the previous tests and represented the final actuator box configuration. Also, in the earlier designs, an over-travel slab was included as a physical stop to limit the movement of the mechanism. However, testing demonstrated that the required travel of the release lever could be controlled through the actuator control logic. Consequently, the physical over-travel stop was no longer required and was removed from the final design. This simplified the actuator housing and eliminated an unnecessary mechanical feature.

Through these iterations, the actuator box progressed from an initial packaging and functional verification model to a more robust prototype capable of supporting the motor, gear mechanism and Bowden cable interface during repeated operation. The final configuration incorporated the lessons obtained from the functional tests and provided the basis for the subsequent integration of the compound gear arrangement.

5.2.3.4 Gear Design

Following the development of the actuator housing, the individual gears were designed and refined for integration into the gearbox. The overall gear arrangement including the number of teeth and the corresponding gear geometry was initially established using the Romax model described in the previous section. These parameters provided the basis for creating the physical gear models used in the prototype. The gears were subsequently developed in CAD and manufactured for experimental evaluation.

The gearbox consisted of three main stages: a worm-wheel input gear, an intermediate compound gear, and separate final gear. Although the first two stages were common to both functions, the final stage was designed specifically according to the different functional requirements of power release and cinching

The **first gear** in the drivetrain was designed as a compound gear, as shown in Figure 5.16. The larger gear section acts as a worm wheel and meshes directly with the worm integrated into the selected motor. The smaller spur gear, incorporated into the same component, transmits the rotational motion to the intermediate gear. The gear geometry and tooth parameters were based on the results obtained from the Romax drivetrain model.

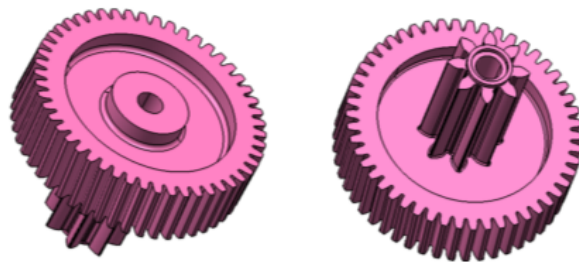


Figure 5.16: First gear CAD.

The **intermediate gear** was similarly designed as a compound gear, as shown in Figure

5.17. One gear section meshes with the smaller spur gear of the input stage, while the second gear section transmits the motion to the final output gear. The tooth numbers and other gear parameters for this stage were also obtained from the Romax model. This compound arrangement enabled the required overall reduction ratio to be achieved within the limited packaging space available inside the actuator housing.

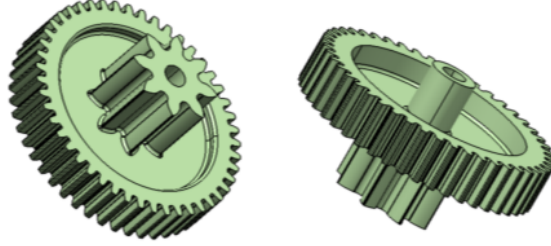


Figure 5.17: Intermediate gear CAD.

The **final gear** required separate designs for the power-release and cinching functions because the two functions required different interactions with the latch lever, which is illustrated in Figure 5.18. In addition, the module of the final gear was increased following a structural assessment using the **Lewis bending equation**. The bending stress at the gear tooth can be expressed as

$$\sigma_b = \frac{F_t}{bmY} \quad (5.24)$$

where σ_b is the bending stress in the gear tooth, F_t is the transmitted tangential force, b is the gear face width, m is the gear module and Y is the Lewis form factor, which depends on the tooth geometry.

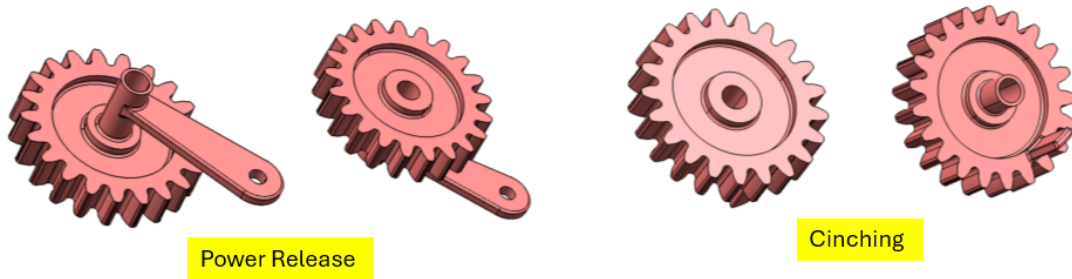


Figure 5.18: Final gear CAD for both functions.

The calculation was used to assess the bending capability of the final gear under the transmitted load. Based on this evaluation, a larger module was selected for the final gear to provide sufficient tooth strength for the prototype application. For the **power release function**, the output lever was incorporated directly into the final gear. Consequently, rotation of the final gear directly generated the movement required to actuate the latch release mechanism. This configuration provided a direct transfer of the gearbox output to the release lever. The

cinching mechanism on the other hand required a different arrangement. During door release, the cinching lever must be able to rotate freely and should not be continuously driven by the gear mechanism. The final cinching gear was therefore designed to engage the lever only during the closing operation. In a way such that, when the gear rotates in the cinching direction, a protruding feature engages the lever and rotates it to the required position. This geometry allows the lever to move independently without being continuously constrained by the gear. However, due to NDA, the exact gear parameters and calculated values are not presented.

5.2.3.5 Gear Design Iterations

Several iterations were required during prototype testing to improve the structural performance of the final gear components. During initial testing, the final gear used for the power-release mechanism experienced failure due to the rotational loads transmitted through the drivetrain. The integrated lever section was subjected to high loading and began to shear from the gear body. The sheared off gears are shown in Figure 5.19.

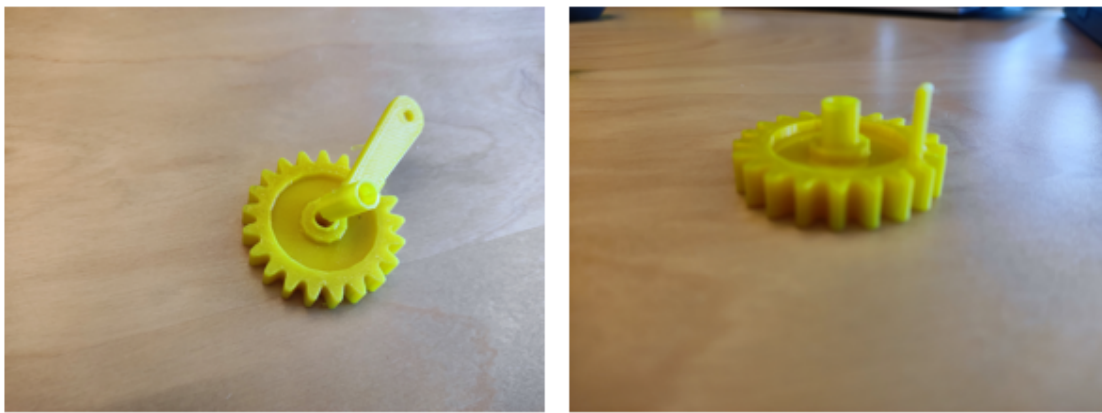


Figure 5.19: Sheared Prototyped gears.

To address this issue, the center distance between the intermediate and final gear shafts was increased. This modification provided additional space for increasing the thickness of the integrated lever section, thereby improving its structural stiffness and resistance to the applied rotational load. However, changing the center distance also required modifications to the gear geometry. The tooth numbers of the intermediate and final gears were therefore revised to accommodate the updated shaft spacing while maintaining the required gear interaction and overall drivetrain performance.

A similar issue was identified in the final cinching gear as well. The protruding feature responsible for engaging the cinching lever showed signs of failure during testing. The geometry of this feature was subsequently modified and reinforced to provide a more robust load path between the rotating gear and the cinching lever. Both modified versions of the final gear is illustrated in Figure 5.20.

Overall, this iterative process was necessary to develop a gear system that could not only achieve the required kinematic and torque characteristics but also withstand the loads encountered during repeated operation.

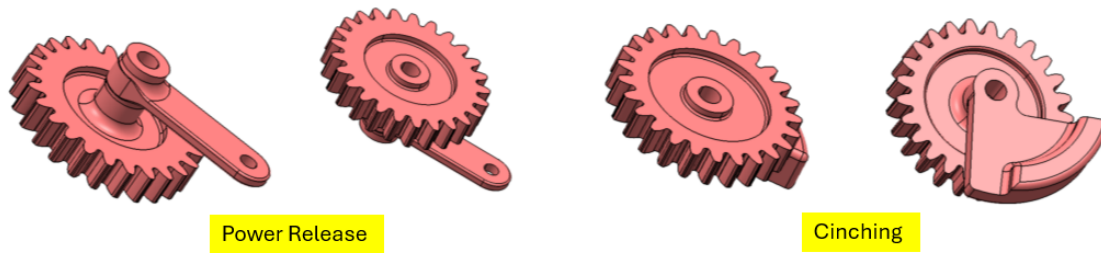


Figure 5.20: Modified Final gears.

5.2.3.6 Final Integrated Actuator System

The final stage of the latch prototype development involved integrating the refined actuator housing with the final gear system. As described in the previous sections, both the actuator box and the individual gears underwent several design iterations based on packaging constraints, functional requirements and observations made during prototype testing. The final design therefore represents the combination of these iterative developments rather than the initial gearbox configuration.

The final actuator box incorporates the selected motor, the worm-wheel input stage, the compound intermediate gear and the final output gear within the available packaging space. Figure 5.21 shows the final actuator box assembly CAD with the completed gear system incorporated into the housing and Figure 5.22 illustrates the 3D print version.

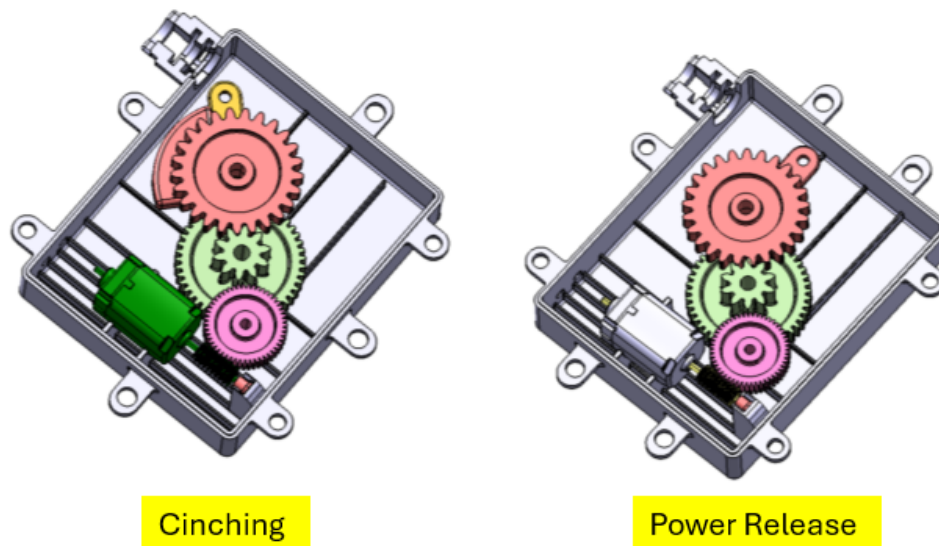


Figure 5.21: Final Integrated Actuator system CAD.

5.2.3.7 Latch motor test

The latch motor test utilizes a similar setup as the actuator. The difference lies in the utility, the aim of the release and soft-closing motor is to be active for the duration required to open

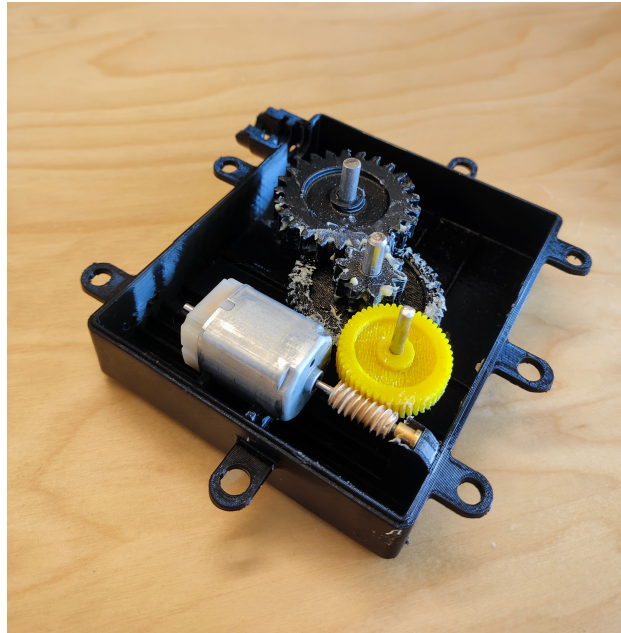


Figure 5.22: Final Integrated Actuator system - 3D printed.

or soft-close the door. Thus the verification are two-fold, the first is to use the system in isolation to see if the chosen motors work as seen in Figure 5.23.

The second verification method is to measure the time needed to open or close the claw, the difficulty with the former is that you have to include the door to get an accurate representation. The main contributor is the door weight, which adds additional force to the closing function and thus cannot be properly tested until the final setup. Thus, the test will primarily focus on the release of the latch motor, the cinching motor will also be tested in this manner. The setup requires a PSU, the latch and the motor in question is connected with a Bowden cable, the same Bowden cable is then connected to the pawl in the latch. The test physical setup is demonstrated in **Appendix G**. The resulting time is then measured, the test are done in repeat in order to obtain a larger sample and the longest measured time is selected to provide a conservative margin.

5.2.4 Opening interface

The development of the exterior handle interface focused on adopting the existing door-handle mechanism while incorporating the additional functions required for the proposed power-operated door system. The main objectives were to develop an interface that was as flush as possible with the outer door surface and next to integrate a user input for the power-release function, while maintaining comparability with the existing mechanical release mechanism and its mounting interfaces.

The design development progressed through several iterations, as shown in Figure 5.24. The initial concepts focused primarily on developing a *Class A surface* that matched the existing exterior door surface while incorporating a smooth transition to accommodate the flush handle. A major consideration during this stage was ensuring that the new interface was visually integrated and maintained an aesthetically pleasing appearance. Also, different

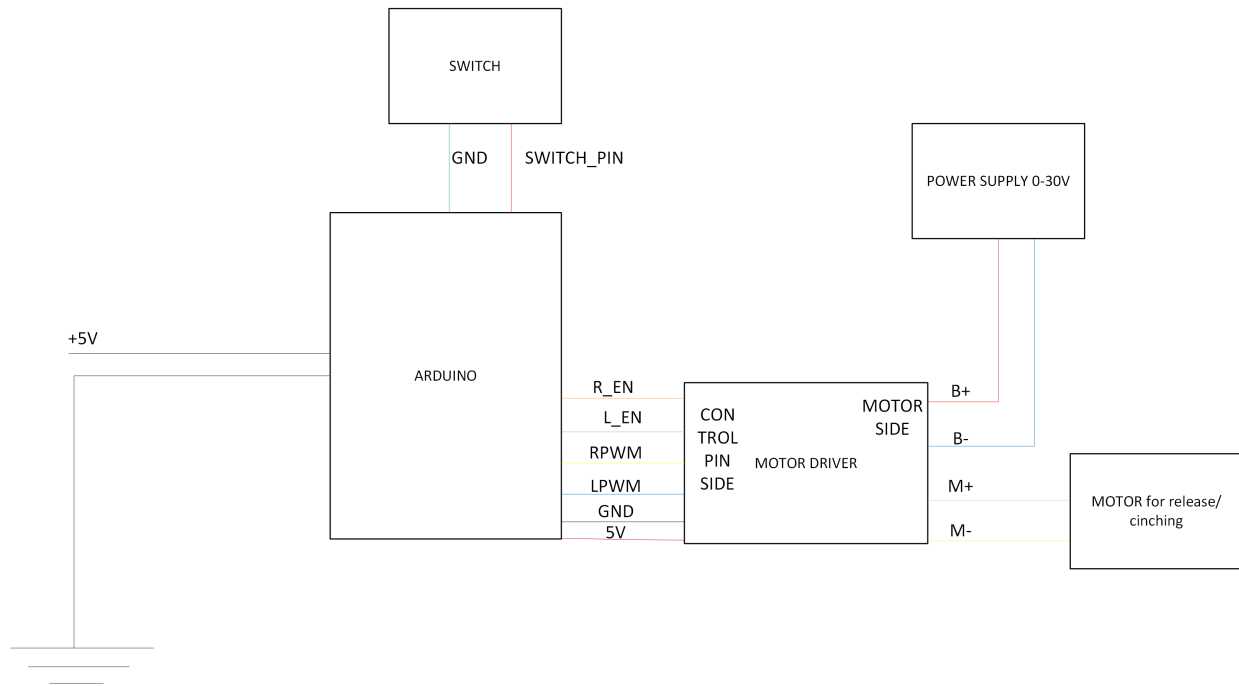


Figure 5.23: Latch motor test setup.

handle covers and packaging considerations were subsequently investigated to accommodate the mechanical handle, key cylinder and power-release switch interface.

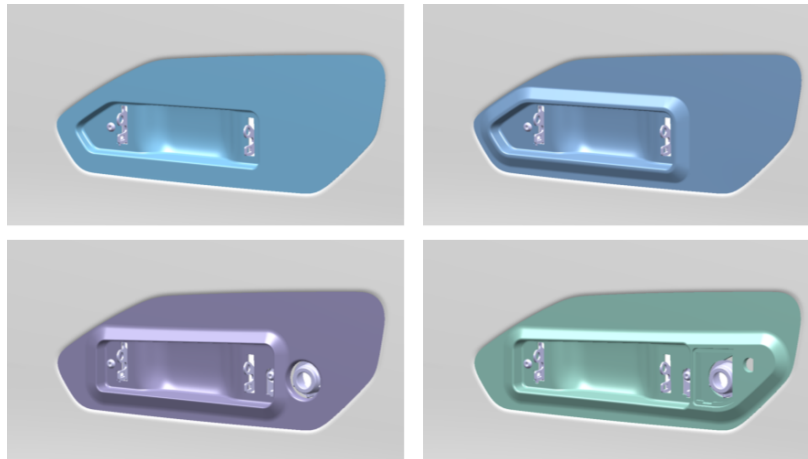


Figure 5.24: Opening interface iterations during the development stage

Initially, the handle interface was intended to integrate both the mechanical release function and the switch for activating the power-release function. The switch was planned to be positioned behind the handle, allowing both functions to be incorporated into a single interface. However during the packaging study, it was found that the available depth in the *y-direction* was insufficient to accommodate the switch behind the exiting handle mechanism. As a result, this configuration could not be implemented without significant modification to the handle geometry or the surrounding door structure. Following discussions with the industrial supervisors, the power-release switch was separated from the handle and placed separately.

This resulted in a clearer and more intuitive interface, with the dedicated switch serving as the primary user input for normal door operation.

The mechanical handle was subsequently retained solely as a backup means of operation. Initially, the intention was to position the mechanical handle in a hidden configuration, such that it would not be directly visible from the exterior of the door. However, the available packaging space and the geometry of the existing handle mechanism made a fully hidden configuration impractical. Therefore, the mechanical handle was made as visible one just for this study purpose.

The final design, shown in the Figure 5.33, consists of a cover surrounding the handle mechanism with several integrated features. A cut-out was introduced at the upper part of the handle to provide access for the user's fingers. The dimensions of this opening were defined by considering the approximate finger dimensions of a male user, while limiting access to three fingers. This provided sufficient space to operate the mechanical handle when required without unnecessarily increasing the size of the opening.

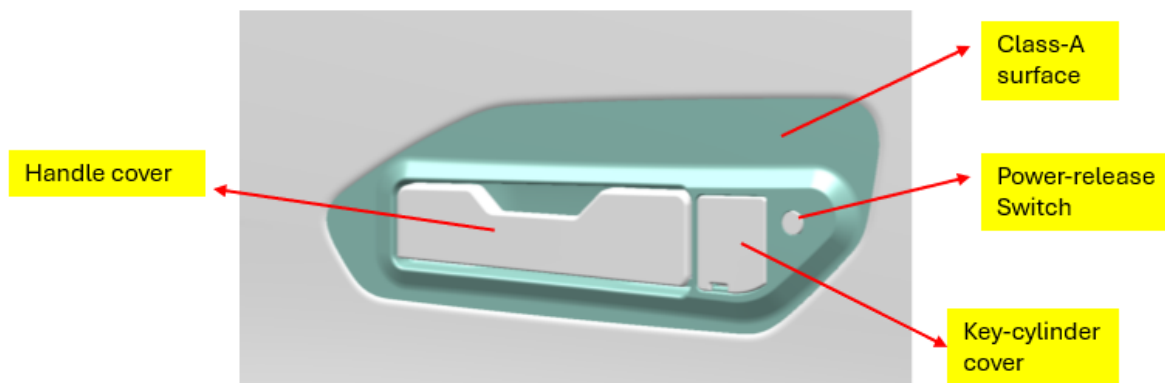


Figure 5.25: Final opening interface with integrated features

A separate cap was also incorporated to cover the *key-cylinder*, maintaining a cleaner exterior appearance while preserving access to the conventional key-operated function when required. In addition, the tactile switch used to activate the power-release function was mounted on an enlarged plastic interface. This increased the accessibility of the switch and also provided a more visually integrated and practical user interface.

Overall, the design evolved from an initial attempt to create a fully hidden and flush handle towards a more practical solution that balanced **packaging constraints, accessibility, mechanical redundancy and visual integration**. The final interface retained the existing mechanical handle as a backup, incorporated a separate switch for normal power release, and integrated the key cylinder and user controls within a single exterior cover design.

5.2.5 Prototype Fixture

To enable the testing of the door system in a real world setting, a special prototype fixture was developed to mimic the relevant structural interfaces of the truck cab. The fixture was designed as a simplified representation of the cab structure, focusing on the regions required for mounting and operating the door system.

A pallet was used as the base of the fixture, providing a rigid foundation for the structural frame. Aluminum extrusion profiles were then used to construct simplified representations of the *A-pillar* and *B-pillar*. The extrusion profiles provided a modular and adjustable structure, allowing the mounting positions to be modified during prototype assembly and testing.

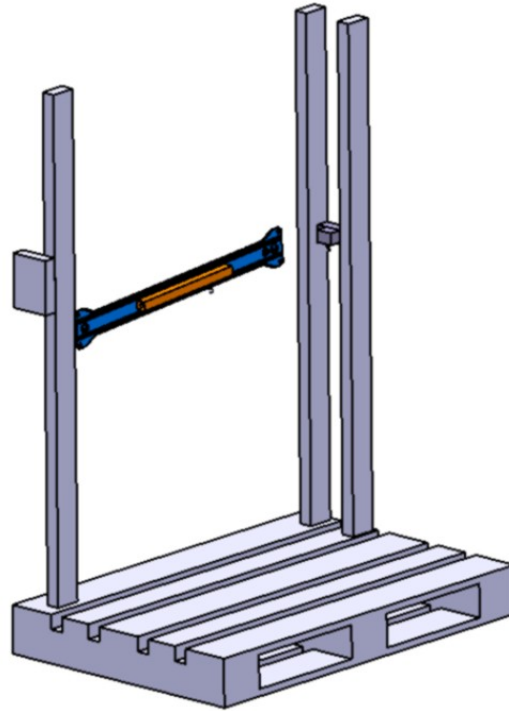


Figure 5.26: CAD model of the Prototype fixture.

The geometry of the fixture was adopted to account for the orientation of the original door hinges. Since the hinge axis was inclined rather than being completely vertical, the *A-pillar* was positioned with a corresponding inclination to reproduce the relevant hinge orientation. This was necessary to maintain the intended door kinematics and ensure that the door followed a representative rotational path during opening and closing. The inclination of the hinge also affected the position of the latch relative to the striker. Therefore, the *B-pillar* was slightly inclined to provide the required alignment between the latch and striker when the door was closed. Maintaining this alignment was important for ensuring correct engagement of the latch and reliable operation of the power-release and cinching mechanisms.

Additional brackets were incorporated into the fixture to accommodate the proposed actuator system. A dedicated bracket was mounted on the *A-pillar* to provide the fixed mounting point for the electric actuator. On the door side, a second mounting arrangement was attached to the *crash beam*, providing a structural connection for the actuator while also allowing it to move with the door. The relative positions of these mounting points were established based on the actuator kinematic analysis presented in **Section 5.1.1**.

The final CAD representation of the prototype fixture is shown in Figure 5.26. The fixture provides the required structural interfaces for the door, including the hinge, latch and striker locations., while also providing mounting provisions for the actuator system.

5.3 Design - Complete system

Once the testing on a sub-system level has been concluded comes the complete design of the prototype. Initially, the interfaces between the sub-systems and their respective voltage requirements will be identified. Additionally, the control unit logic will be defined for function validation of the final build and user needs.

5.3.1 Interface architecture

The interface architecture in Figure 5.27 defines the electrical hardware boundaries and the specific communication channels. However, the diagram shown is simplified to avoid congested view of the system relations. Furthermore, the added complexity in including specific pin channel connection adds to the congestion. The original interface diagram is created in KiCad and for a complete breakdown of the pin connections between the sub-systems view **Appendix J**.

The ECU in the architecture, in this the Arduino is the center piece of the complete system. Given that the primary function of the ECU is to receiving and send signals to the other sub-system. The PSU will be the only external component in the system due to not having access to the 24V truck battery, There will be two distinct voltage channels represented in red and green to represent components that require 24V and 5V respectively. The reason for this distinction is because components such as the Arduino and the latch motors are not rated to handle 24V. However, in order to fully utilize the motor speed in the actuator, it requires an application of 24V.

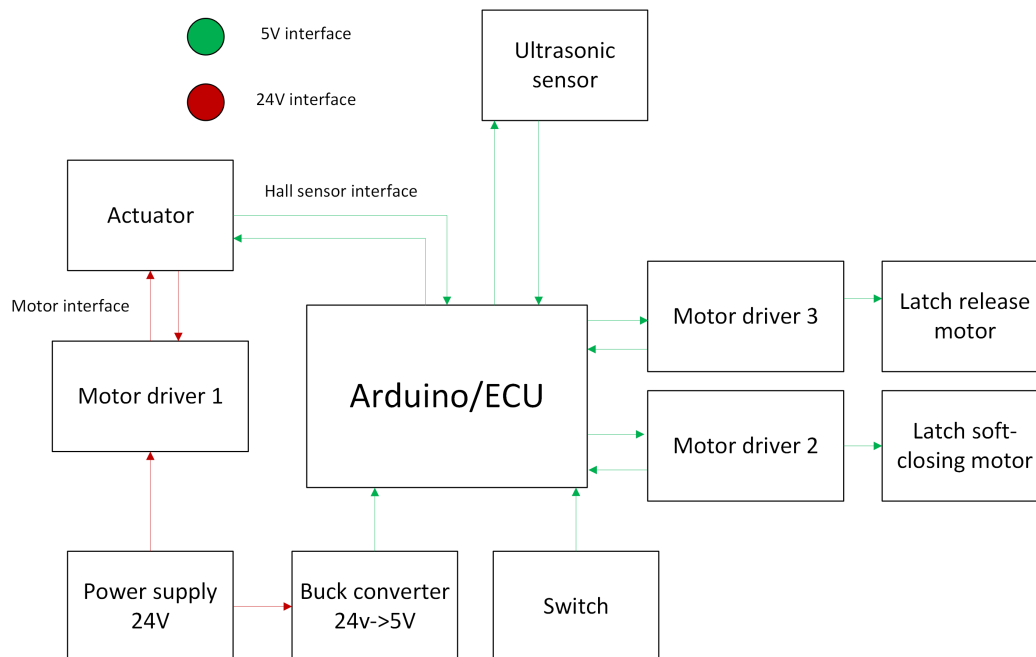


Figure 5.27: Simplified interface architecture of complete design.

5.3.2 Control unit & logic

The subsection illustrates what function that will be demonstrated at the final build and reflects the programmed logic. The system is written in C++ and Arduino IDE is used to write and upload the code to the micro-controller. The aim of the thesis is to demonstrate latch release and soft-closing i.e. cinching. However, the actuator is added owing to its ability to react to changes in speed, owing to the hall sensors. This utilization is added due to the user need of needing to mitigate harsh openings or closings that is caused by wind. Furthermore, this adds the opportunity for automatic and assisted door entry, this ought to mitigate the user remarks about the weight of the door.

The Figure 5.28 reflects the first iteration of the complete system logic. Initially, upon system activation, the Arduino initializes the variables before executing the control sequence. The system utilizes a baseline of 0 in the PWM to ensure that everything stays idle until the user interacts with the switch or door. The automatic closing will only work when the button is double pressed and initializing the soft-closing mechanism once it cause the latch to press the internal switch. The arrows and nodes represented by boxes in Figure 5.28 depict the relationship between system operations. Moreover, the diamond-shape box depicts the conditional decision block and the rectangular blocks correspond to operations occurring. The system operation has two distinct branches, automatic entry and manual handling of the door. The system will always aim to reach a state of idle, this is represented through returning to a state of idle in all the motors once the external input have been meet.

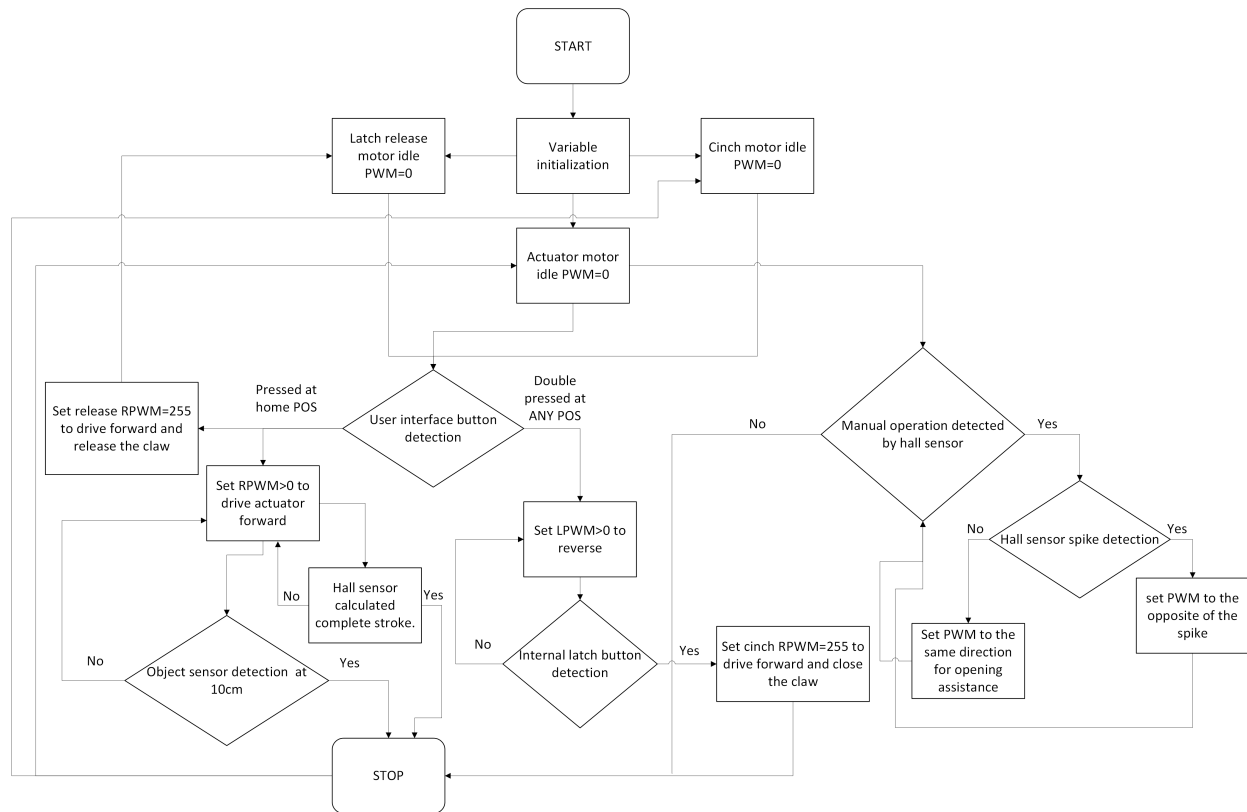


Figure 5.28: Initial control logic.

5.4 Build - Complete system

5.4.1 Realization - from test to build

The chosen concept will be realized in this section by utilizing the results from the previous tests. However, the complete build assembled on the door remains untested. Furthermore, the door has only clear interfaces for the already existing modified latch while the other components have to be added there in other ways. Thus, there is an added risk in terms of cost, time and quality when committing unexplored interfaces before ensuring that the electrical architecture and control logic works.

This led to building a complete prototype while attaching as few parts to the door as possible to address any potential issues without adding the complexity of assembling and potentially de-assembling the components. Once completed and confirmed that it works, the complete system will be installed on the door interface using existing or added interfaces.

5.4.2 Assembly

Assembling a complete prototype requires re-considerations of previous connections between components. One such major connection is wiring, banana connector has been utilized to replace some wiring for expedience, resulting in faster prototyping and testing. This involves enabling power from the PSU to any component dynamically which allows for quick re-adjustments when testing different components and thus reduces lead time. The rationale to replace them can be seen in Figure 5.29, the crocodile clips connected to the banana cables are exposed for dirt and water. Consequently, if by any chance the negative and positive cables touch each other while the PSU is on, it can create a short circuit, thus the aim is to minimize the cables. Thereby, the aim is to only use the banana cables where it is required, specifically the PSU for the final build.

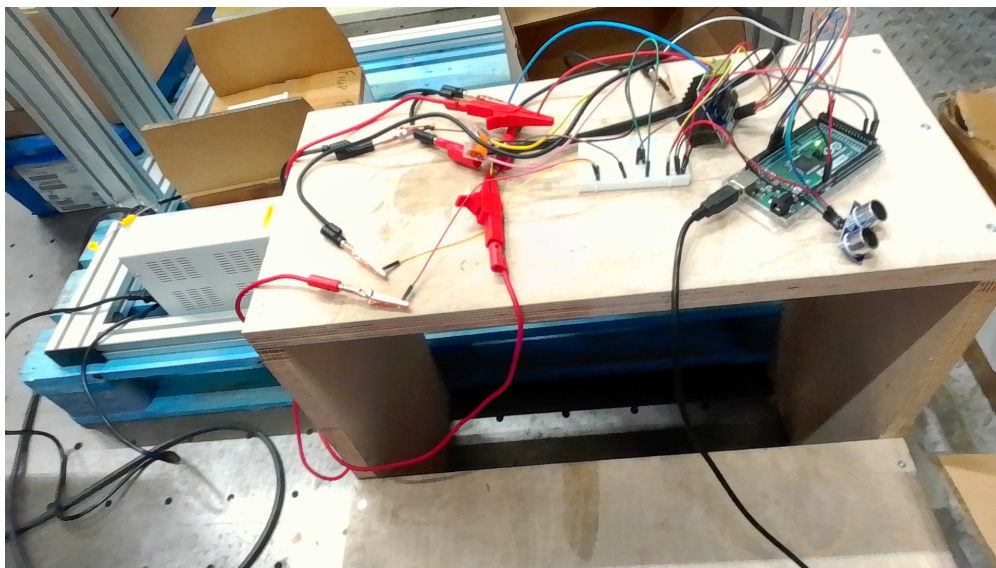


Figure 5.29: Early stages of assembling final build on the bench near the rig.

5.4.2.1 Wiring

As the banana cables were gradually replaced by normal wires, the resulting connections proved inconsistent. Initially the wiring were only tested on the switch and the PSU due to the availability of switches resulting in testing without risk of delaying the build. The result displayed erratic voltage load using the multimeter. The primary root cause is due to the quality of the soldering. The Figure 5.30 below illustrates different soldering connections and the standard that is expected to achieve is marked in red.

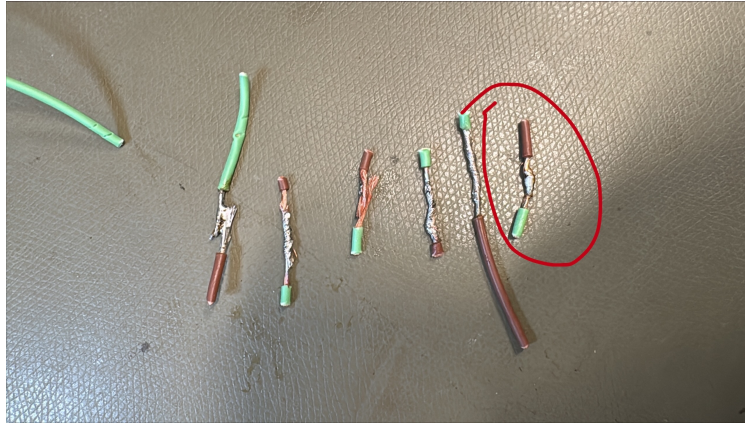


Figure 5.30: Iterative improvements on the electrical connections.

It should be remarked however that the wiring in the image are not what will be the final wiring. Once soldered it should be insulated with insulation tape in order to prevent short circuits and compromised performance by isolating the exposed wire from adjacent wires, dirt and water.

5.4.2.2 Assembly towards door

Once the bench prototype was finalized, the next stage was to integrate the system into the door assembly. This stage focused on fixing mounting locations for the actuator boxes, creating the required attachment features and resolving the packaging and cable-routing challenges that arose during the physical assembly of the system. The overall dimensions of the actuator boxes had already been defined during the packaging study considering the available space within the door. However, determining the overall allowable actuator size did not necessarily mean that the initially proposed mounting location was suitable.

Initially, both the cinching and power-release actuator units were planned to be integrated into the cover plate. However, during the physical packaging and assembly study, it was found that the available space within this specific region was insufficient to accommodate both actuator boxes and their associated attachments. Modifying the cover plate to create the required space was also considered, but this would have required additional design and manufacturing effort. Therefore, an alternative mounting location within the available door packaging space was selected. The actuator boxes were instead positioned on the inner side of the door outer panel. Since the outer panel did not contain suitable attachment features for the prototype, a dedicated mounting fixture was designed to provide an interface between the actuator boxes and the door structure. As shown in Figure 5.31, the fixture was designed to

conform to the available surface of the door outer panel while providing mounting locations for both actuator boxes. The fixture was glued to the door outer panel, after which both the boxes were screwed to them. This approach avoided extensive modification of the existing door components while providing a sufficiently stable mounting arrangement for prototype testing.

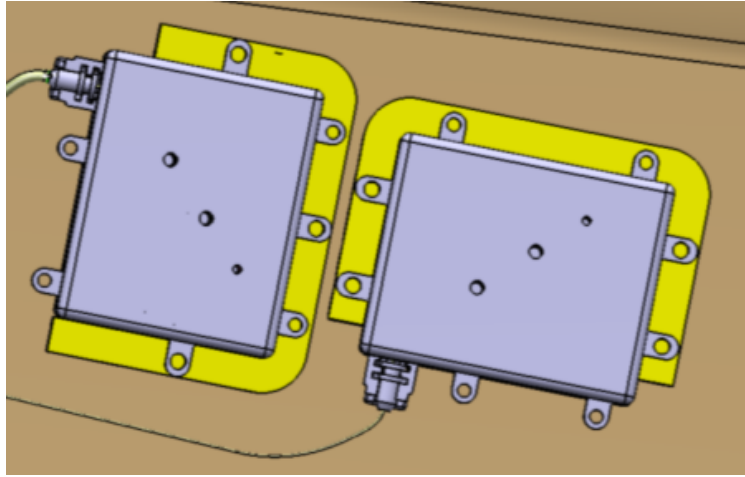


Figure 5.31: CAD of mounting Fixture glued to the Door outer panel.

Another thing that had to be designed for assembly into the door was the attachment of the power-release cable to the existing latch. The production latch did not provide sufficient available space to incorporate an additional cable attachment without modifying the latch itself. As the objective was to retain the original latch, a separate cable attachment was developed as a temporary solution. The attachment was manufactured as an independent component and was glued to the door structure as shown in Figure 5.32. Although this solution was not an ideal, it allowed for the complete power-release function to be evaluated during physical testing.

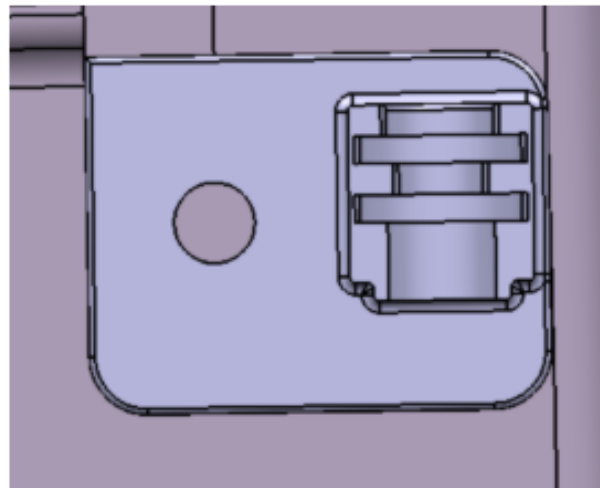


Figure 5.32: CAD of cable attachment for the Power release.

5.4.3 Final build - test

After the assembly, the user interface was tested with the control logic implemented. Initially, the opening is tested and it works. The first remark is the speed of the opening door opening, after re-adjusting the PWM, the speed reached an ideal state. However, the actuator emitted unacceptable noise level. Furthermore, the manual closing was not functional and did not operate as expected. The ultrasonic sensor works as intended. Although due to no hall sensor tracking the stroke length at full opening position it is instead set to idle based on timer that aligns with opening speed.

Once the opening is finalized and testing the soft-closing functionality by using automatic closing, The test revealed the possibility of pinching the user as it closes. Another remark is in regards to the user interface, a hidden mechanical handle would be more pleasant aesthetically and reduce the possibility of theft.

When trying to de-assemble to test for serviceability, some potential improvements were noted. The latch is glued directly on the sheet metal and is difficult to remove, a separate interface where you can screw it ought to be better for the service aspect.

5.4.4 Setbacks & adjustments

Concept development is an iterative process in which outcomes that are unexpected emerges during tests, design and build. And although the concept is developed methodologically in relation to a set of guidelines and parameters, the transition from a conceptual system to a fully realized physical prototype reveals unexpected outcomes. In the case of the advanced door entry, there were a few critical challenges that emerged during the final assembly.

5.4.4.1 Opening interface fitting

The opening interface, that is to say the mechanical handle and the door switch unit faced a critical geometric challenge. That being limited geometrical space and the tolerance towards the existing door handle interface despite aligning with the expected tolerance from 3D printing. Furthermore, the expected tolerance took in to the account of the rotation point which requires additional space of the handle and the underlying surface as to avoid clash. This results in the user unable to interact with the prototype unless fixed.

Rather than looking at the component at development, the investigation redirected to the interface itself and it's surrounding areas. By comparing the interface measurement with comparable doors through CAD and physical systems led to the revelation of misaligned interface. The specifics on the exact problem cannot be disclosed on the door side. For the handle, there were some structures that provided extra margin for support but were not critical that could be tweaked and re-adjusted in order to give even more room for the tolerance. The handle is then re-printed on a 3D printer in dark. The Figure 5.33 displays the new handle that fits the omitted interface.

Nevertheless, it is sufficient to state that by viewing on the larger picture and re-aligning adjacent tolerances and by doing minor tweaks on the handle, the interface managed to be secured.



Figure 5.33: Adjustment of geometries for opening interface.

5.4.4.2 Cinch switch engagement

The cinching function in the prototype utilizes a leaf-type switch integrated within the latch. The switch is intended to be activated only during the door-closing operation and should remain unactuated during door release. During the initial functional tests, the switch was activated independently to confirm that the cinching function operated as intended. However, during complete system testing including door closing and release, a potential issue was identified. The ratchet could come into contact with the switch lever during the release motion, creating a risk of unintended switch activation.

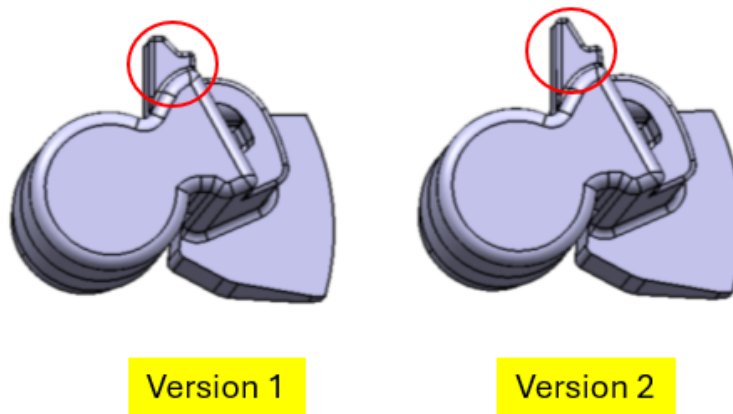


Figure 5.34: CAD model of Cinch lever versions.

To address this issue, two design iterations were developed by modifying the protruding feature highlighted in Figure 5.34. The first version incorporated a larger protrusion, while the second version had surface contact with switch lever. The purpose of these iterations was to ensure that the switch was activated at the required ratchet position during closing while preventing contact that could result in activation during release. As no suitable simulation

or analysis method was available to directly evaluate the switch activation, the two versions were assessed through physical testing.

The ratchet was moved through its operating positions, from the primary to the secondary position, while the switch state was monitored using a multimeter. Based on the multimeter reading, the 3D printed geometries were then manually removed bit by bit to further adjust the contact geometry. This allowed the exact point of switch activation to be identified. The test procedure conducted for this evaluation is presented in Appendix M. Through this iterative testing and modification process, the contact geometry was refined to achieve the intended operation of the cinching mechanism.

5.4.4.3 Cinching Cable routing

During the integration of the cinching mechanism, another setback was identified during the routing of the Bowden cable. The initial routing utilized an existing bushing in the latch. However, due to the limited packaging space within the door, this resulted in a relatively small cable bending radius, which we thought would not be a big issue. However, the resulting cable curvature introduced additional resistance and tension in the inner cable, which in turn affected the free rotation of the ratchet.

To address this issue, the cable bushing was modified from the previous version to the new one, as shown in Figure 5.35. The revised design provided a more suitable cable path and reduced the resistance caused by the tight routing. As a result, the tension acting through the cable was reduced, allowing the ratchet to rotate a bit more freely and improving the operation of the cinching mechanism.

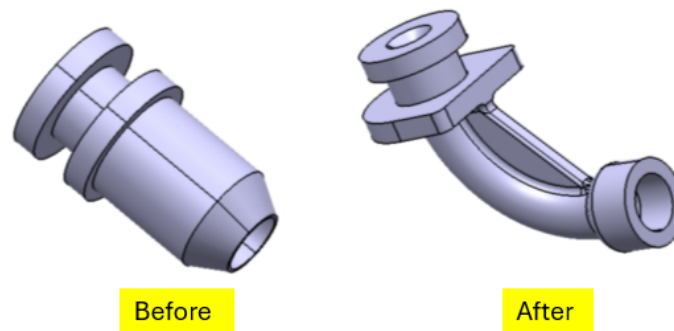


Figure 5.35: CAD of cable bushing.

5.4.4.4 Hall sensor damaged

When implementing the control logic to the assembly, the hall sensors displayed no function of response. Initially the assumption is that it was due to error with the control logic. However, after lengthy investigation and diagnostics, the issue still re-occurred. Resulting in re-framing the investigation to troubleshooting the hardware of the sensors. As a starting point, the voltage is being assessed to ensure that the sensors receive power. Yet, due to the square-wave output of the voltage, a multimeter will not suffice due its inability to capture rapid voltage changes. Therefore, an oscilloscope is used to determine the supply voltage since it can observe voltage changes over time.

The actuator is isolated and is only coupled to the PSU. The oscilloscope is connected to the actuators VCC and GND pins, however no output was detected. Because there is only one actuator available with the same setup there are no possibility to test it with the same component. Even so, a comparable component was used to the test that being a window lift regulator. The regulator uses hall sensors to determine the speed of the window on the door. During the test with the regulator same test setup as the actuator the oscilloscope displayed square waves of the the supply voltage, indicating a damaged sensor on the actuator.

5.4.5 Final build - pivot

The hall sensors are unavailable to the final build. This results in pivoting the coding logic as can be seen in Figure 5.36. Due to the short remaining lead time at this stage retrieving a new actuator with a functioning hall sensor was not an option and neither is opening up the actuator and replacing the integrated hall sensor. The prudent action is to check for alternatives. The specific motor driver BTS7960 employ current sensor, the forward pin is denoted as R_IR and one for reverse L_IR. A test is deployed utilizing the motor driver current sensor to see how much current is generated in the motor during manual handling. Current is generated through *Faraday's law* [56] by varying the magnetic flux in the motor. In the case of the test through mechanical means done by manually moving the actuator by using the door as a lever and thus rotating the motor inside. Furthermore, it during the test the movement is being observed by using diagnostics on sudden and normal closure to simulate the contrast between wind braking and average use case. Nevertheless, the results are noisy and overlap with each other. At the stage of the project it was decided to instead to omit the entire manual operation branch as to not lose time on building the final prototype on something that might work.

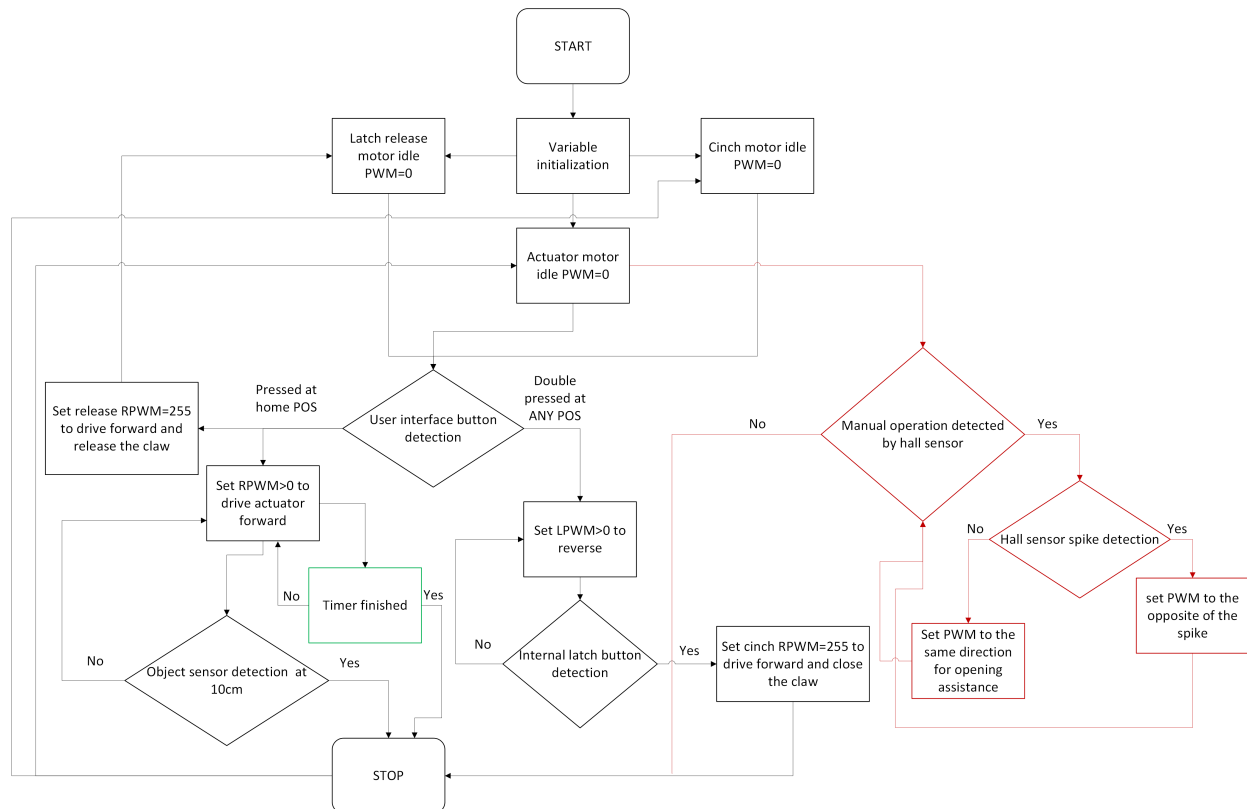


Figure 5.36: Control logic, green function is modified, branch in red are omitted due to the result from the oscilloscope test.

6 Project Findings

The aim of the thesis was to test, design and build a working prototype of an advanced door entry system suitable for a truck door. The chapter presents the main findings from the attempt.

6.1 Pre-study

During the pre-study a multi-faceted analysis involving patents, benchmarking, components and customer needs were performed. The findings shaped what, how and why the chosen concept were conceived. Across the complete analysis some important trends were identified and especially influential on decision-making for the rest of the project:

1. The automotive industry seems to have an emerging dominant design, namely the flush door handles and smart entry.
2. Ergonomics through ease of opening.
3. Reduction of harsh noises.
4. Leveraging electrification to achieve customer needs, for example improving NVH through implementation soft-closing function.
5. A more centralized control architecture.

6.2 Prototyping

The Table 6.1 below summarizes key findings of the prototyping outcome in regards to door opening

Table 6.1: Prototyping expectation.

Function:	Expectation	Outcome
Opening	Opening by pressing the button, stop when detecting an object, when stroke length is achieved stop.	Similar to the expectations but using a timer instead to estimate stroke length due to non functioning hall sensor that can keep a more exact positioning.
Closing	Double press the button, reverses the direction, hits the latch, the latch at the second position hits the internal switch, actuator stops and soft-closing is initiated.	Double press the button, reverses the direction, hits the latch, the latch at the second position hits the internal switch, actuator stops and soft-closing is initiated. However, big risk of pinching.
Manual use	When door is idle and not in home position. User ought to be able to press the door and with the hall sensor sensing direction of change and speed it helps the user to open/close the door, mitigating the heavy door experience. When sudden spike occurs outside of normal use cases the system ought to classify it as wind and mitigate the speed that door can travel.	Hall sensor is not functional, not able to test it.

6.3 Final Requirement List

The prototyping and integration activities provided several practical insights that were not fully captured in the initial requirement list. Since the main objective of the project was to develop and demonstrate a functional prototype, the requirements defined at the beginning of the project were not formally verified or validated through dedicated requirement testing. Therefore, the results of the prototype should not be interpreted as confirmation that the original requirements were fulfilled.

Instead, the prototype development process was used to identify additional requirements that would be important for the further development and future deployment of the system. These requirements were derived from the challenges and observations encountered during the development, testing and integration of the prototype.

As shown in Figure 6.1, the additional requirements cover different aspects of the system, including door opening, latch functionality, ECU integration, user interaction and component interfaces. Examples include considerations related to unintended door opening, door opening angle, modularity, anti-pinch functionality etc.,

Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
1	Door Braking					
	Actuator noise	R	Uneven noise during different opening speed	Measuring decibelmeter	40 dB	25 dB
	Door Opening Angle	D	Stroke Length	Physical measurement	85deg	90deg
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
2	Latchsystem					
	Modularity	D	Flexible latch setup suitable for different customer segments.	Digital and physical evaluation.	NA	NA
	Anti-pinch	R	Prevent pinching during soft-closing operation	Digital and physical evaluation.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
3	ECU					
	One complete system	R	Easier to assemble and saves geometrical space.	Digital and physical evaluation.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
4	User Interface					
	Hidden redundant user interface	D	Aesthetically pleasing and anti-theft measurement	Digital and physical evaluation.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
6	Interface					
	Wiring soldering quality	R	Mitigate loss of operation	Physical measurement	NA	NA
	Actuator positioning	R	Reduce geometrical impact and improve opening angle	Digital and physical evaluation.	NA	NA
	Latch positioning	R	Actuatorbox is on the sheet metal and to improve assembly and aftermarket, reposition it on a modular interface.	Digital and physical evaluation.	NA	NA

Figure 6.1: Additional requirements uncovered during the project.

The updated requirement list therefore does not serve as a final validation of the prototype against the initial requirements. Instead, it captures the lessons learned during the prototyping process and identifies the additional considerations required for the system to progress beyond the prototype stage. It can consequently serve as a starting point for the further development, testing and eventual deployment of the power-operated door functions.

7 Discussion and Future Work

This chapter will discuss regards the research questions, requirements, application of the methodology and also present the future work needed to be done to make the system production ready.

7.1 Research Questions

This section will answer the research questions from **Section 1.6** and refer to previous chapters for precise answers, if possible, the aim is to provide concise answers and avoid repetition. The objective is rather having a concise analysis and discussion around the answers presented earlier and limitations in regards to the aforementioned answers.

RQ1: What is the present available knowledge/methods in regards to mechatronics and mechanical components for opening & closing heavy truck doors?

There is a vast font of knowledge available for development in regards to door entry and closure for heavy truck doors. The **Section 3.1** introduces the most relevant mechanisms within the scope, including innovative capabilities from competitor trucks. However, the automotive industry is vast and all of competitors and patents could not be shown. One of the reasons being obsolete innovations or trucks, such as older models of trucks or simpler mechanisms where not presented due to misalignment with the goal of the project, that being advanced door opening and closure. Furthermore, it would be unfeasible to present every solution due to the extensive information available from different OEM. The approach chosen is by having a big enough of a sample size to see a trend among the more popularized brands and have an idea of where the innovation is going. The assumption is that the innovation is based on solving their customer needs, so by applying similar innovations it can allow for mitigation of unforeseeable user needs.

RQ2: Identify requirements and customer needs for the product/solutions and how it affects scope, manufacturability, cost and legality?

The initial requirements that are based on the pre-study are seen in **Appendix A** and is further expanded in **Section 6.3** as a result of the thesis project. Although the requirements have the customer needs incorporated, the method and a more expansive illustration of the needs are displayed in **Section 3.2**. Due to agreement with Volvo, the cost effect cannot be discussed in detail. However in terms of manufacturability and serviceability, the new requirements allow for easier and flexible customer offering and service. For example, the latch system being modular allows for different truck variants have different setups aligning with the customer usage and need. In contrast, the ECU being essential in every truck for

operating the electro-mechanism is required to be one complete system. This allows for faster cycle-time in terms of manufacturability due to reducing the amount of parts. Additionally, it allows faster service due to the control system of the door being localized in one component. The examples are just a few ways the components affect manufacturability, however, this also expands the scope and this is just a single dimension. In a multi-dimensional analysis where legal demands and cost is involved expands the scope immensely. This results in unfeasible verification of requirements in a single thesis project cycle. Which brings about high-level analysis and testing verification for the parts during the project cycle. For instance the prototypes and modification built on the latch ought to withstand the load that is mentioned in the legislation ECE R11 & FMVSS 206. But during the project it is not tested due to the resources in terms of cost and time required to conduct such test. Rather the thesis conducted only the tests possible for the prototype as is documented in **Chapter 5**.

RQ3: What value does the product change have for the stakeholders?

The proposed value comes in the form of addressing the customer and stakeholder need in **Section 3.2** with the solutions from the chosen concept in **Chapter 4** that best aligns with the aforementioned needs in form of requirements. Moreover, besides the mentioned stakeholders in the chapter, Volvo and the supervisors overseeing the project can utilize the information provided. Thus, it allows for a varied of different investigations that can be done internally to further flesh out the ideas explored. To give a concrete example, the hall sensor during the project turned out to be defective and could not rectify during the project stage. This opens up the opportunity for future investigations on how to incorporate it to the existing prototype in order to further generate value.

RQ4: How could we incorporate the changes in the current door system architecture?

Assembling the changes in the current door system is already explored in **Chapter 5**. However, to further explore and better enable the integration of the changes to the architecture, it would require dedicated interfaces ready for the components. This is to make it feasible for the manufacturing to assemble the components if it were in production. Having predictable placements with references instead of guessing where the components is suppose to be. This addition will allow for integration in terms of mass-production with predictable quality of the product. Furthermore, having a dedicated interface allows for an easier service for the aftermarket.

7.2 Application of Product Development Methods

The application of the methods used in **Chapter 4** were done systematically using criteria and weights. However, the criteria and weight used are just based on engineering judgment and to some extent customer need impression. Although it was optimized based on the available information, further investigation can be done on multiple markets to increase the accuracy of the assessment. However, based on the thesis time frame, the decision to only go with what was achieved in **Chapter 3 and 4** allowed enough time for the work in **Chapter 5**. So it was a balancing act of accuracy and a realized prototype.

During the prototyping the application of test, design and build was used. However, during the actual prototyping some of the tests were postponed due to no available door or rig at

the stage of the earlier tests. This resulted in the inability to test the full functionality. To give the most egregious example, of the hall sensors and moving the testing until the rig was finalized and door available. In retrospect, some testing of the hall sensors should be done earlier, even if the manual assist function could not be tested. The test with hall sensor calculating the stroke length should have been done early. This would allow us to earlier detect the defect in the actuator and enable us to perhaps get hold of a new actuator before the final build.

7.3 Future work

In this section, the future work required to further develop the proposed door system towards a reliable and production-ready solution. Although the prototype demonstrated the feasibility of the power-release and cinching functions, further development is required to improve the actuator, latch mechanism, packaging, reliability and system behavior under different operating conditions.

7.3.0.1 Actuator development and Testing

Further work is required to develop and validate the actuator under a wider range of operating conditions. One important area is the use of Hall sensors to monitor the actuator position and verify the system behavior during conditions such as wind braking and manual door closing. This would help determine how the actuator and control system should respond when the door movement is influenced by external forces or manual operation.

The actuator packaging should also be further investigated. A more compact actuator solution should be considered to reduce its visibility within the door and minimize its impact on the available packaging space. This would allow the system to be integrated more effectively into the existing door architecture.

In addition, the actuator should be tested under different environmental and vehicle conditions. For example, the effect of snow or ice accumulation on the door, as well as door operation when the vehicle or door is inclined, should be investigated. These conditions may influence the forces acting on the door and consequently the required actuator performance. Testing under such conditions would provide further input for refining the actuator design and control strategy.

7.3.0.2 Latch Mechanism Development

The present prototype of the latch still requires further development before the system can be considered ready for implementation. In the present solution, the cinching cable is attached directly to the ratchet, and there is no dedicated mechanism to reverse the cinching function in an adverse situation. A future latch design should therefore incorporate a suitable mechanism to allow the cinching operation to be reversed when required.

The current power-release solution also requires significant modification. In the prototype, the power-release cable acts directly on the pawl, effectively bypassing the existing locking mechanism. As a result, the latch mechanism must be redesigned to ensure that the power-release function cannot unintentionally release the door when the locking function is active.

The interaction between the power-release mechanism and the locking system should therefore be considered as part of the complete latch architecture rather than as a direct addition to the existing mechanism.

Another area requiring improvement is the cable end fitting attached to the ratchet. During prototype testing, the current end fitting was found to be insufficiently secure and could unintentionally detach, resulting in a loss of function. A more robust and reliable cable-end attachment should therefore be developed and tested to ensure that the connection remains secure during repeated operation.

Finally, the latch should be tested under representative environmental and operating conditions to assess its reliability and identify potential failure modes. Testing should include factors such as temperature variations, contamination, moisture, snow or ice and repeated operation. The results can then be used to assess whether the latch meets the requirements for further deployment and to identify areas requiring further improvement.

7.3.0.3 User Interface and Handle Development

The exterior interface was flush-oriented to optimize integration of the handle with the door surface and provide access to the power-release and mechanical backup functions. However, the final prototype was restricted by the packaging space and the existing handle mechanism.

Further work should look at a fully integrated handle solution from an earlier stage in the design process. This may allow for better packaging of the electrical switch, mechanical release and key access while further improving the flushness and overall appearance of the exterior interface and also making the handle hidden.

7.3.0.4 Control and Communication System

In the present condition, the communication and control system based on Arduino was developed to demonstrate the interaction between the different components. Future work should aim at developing a more representative vehicle-level control architecture. A key area for further investigation is the development or selection of a dedicated and fully integrated electronic control unit for the door system. The ECU should be designed to accommodate the required inputs, outputs, actuator control and communication interfaces within a single unit. In addition, the requirements for an automotive-grade ECU suitable for a heavy-duty truck application should be investigated, particularly considering the high-vibration, rugged and demanding operating environment.

Therefore, the future work should involve the testing and evaluation of the ECU and control system under conditions representative of the intended truck application. Based on the results of these investigations and tests, the requirements for a suitable integrated ECU can be identified and defined for the further development of the system.

Overall, the next stage should focus on developing the demonstrated prototype into a more integrated and reliable system. This includes refining the mechanical design, developing a representative control architecture, improving component integration within the door, and validating the system against clearly defined requirements. The lessons learned during prototyping and the updated requirement list provide a basis for this continued development.

8 Conclusion

The goal of this thesis was to investigate the possibility of integrating mechatronic functions in a heavy-duty truck. The work focused on developing and showing a working prototype of powered door motion, power release and cinching, and a flush oriented exterior interface while maintaining the existing latch mechanism and a mechanical back-up. Rather than developing a production-ready system, the objective was to demonstrate that these additional functions could be incorporated within the existing door architecture.

This was pursued through a structured process of pre-study, concept development, prototyping, testing, and physical integration into the door. The pre-study established the basis for the development by identifying relevant technologies, industry trends, customer needs, and technical considerations. Key findings included the increasing use of electrification, improved user interaction, soft-closing functions, and flush exterior components, which guided the development of the proposed system.

Based on these findings, the individual functions were developed and combined into a complete concept. The actuator was packaged to provide powered door movement, while separate mechanisms were developed for power release and cinching. The gear system, actuator housing, and latch interfaces underwent several iterations as testing identified challenges related to structural strength, packaging, cable routing, and component interaction. These findings were incorporated into subsequent design iterations, resulting in a functional prototype that demonstrated the interaction between the mechanical and mechatronic components.

The prototype was subsequently integrated into the truck door, demonstrating that the additional components could be incorporated into the existing architecture without a complete redesign of the door system. An Arduino-based communication and control system was also developed to demonstrate the interaction between the different functions and components.

The development process also provided answers to the research questions concerning available technologies, system requirements, potential value, and the integration of the proposed functions. In addition, the prototyping and testing activities identified several areas requiring further development, including actuator robustness and packaging, latch safety and reliability, cable attachments, environmental validation, and the development of an automotive-grade control system.

Overall, this thesis achieved its objective by developing a functional proof of concept and demonstrating that advanced mechatronic functions can be integrated into an existing heavy-duty truck door system. The prototype and the knowledge gained during its development provide a foundation for further refinement, testing and validation towards a more reliable and production-ready system.

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Appendix A

Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
1	Door Braking					
1,1	Wind Braking	R	Door braking mitigates wind from harsh or rapid opening.	Slam test to simulate wind.	resist 22km/h during opening and closing	resist 47km/h during opening and closing
1,2	Obstacle detection	D	Prevention of accidental crash during door opening	Physical measurement with ruler during door opening	10cm from detected object	10cm from detected object
1,3	Door Impact Tolerance	R	Withstand door slamming to a certain extent Avoids sudden crash or movement during door entrance.	Slam the door.	Rated load	Additional 10% on rated load
1,4	Maintain Position	R		Try different door angles to see if it stays put.	Minimum 1 position where it stops	Stop at any position
1,5	Environmental Sealing	R	Durability in outdoor conditions.	IP certification testing.	IP66	IP67
1,6	Emergency Stop	R	Safety critical feature for emergency situations	Functional testing of override mechanism on test bed	Physical or digital kill switch	Override due to current buildup
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
2	Latch system					
2,1	Load Requirements	R	Need to withstand a certain load put forward by ECE R11 & FMVSS 206.	Physical test as mentioned in the legislation documents.		
2,2	Door closing sound	R	To comply with PIEK certification	Measuring dB(A) with decibel meter tool on complete system.	67 dB(A)	Less than 67dB(A)
2,3	Environmental Sealing	R	Durability in outdoor conditions.	IP certification testing.	IP66	IP67
2,4	Emergency Stop	R	Safety critical feature for emergency situations	Functional testing of override mechanism on test bed	Mechanical redundancy	Mechanical redundancy
2,5	Latch closure effort	D	To ensure a pleasant effort in the spring for latch release.	Physical test with Dynamometer.	65N	45N
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
3	ECU					
3,1	Voltage requirements	R	Able to handle and interface a wide array of components that operates	Physical test with multimeter and oscilloscope	5V-24V	5V-24V
3,2	Current requirements	R	Able to handle and interface a wide array of components that operates	Physical test with multimeter.	1A to 5A	1A to 7A
3,3	Interface requirements	R	Interface to electrical architecture in the truck.	Physical test.	NA	NA
3,4	Environmental Sealing	R	Durability in wet and dirty conditions.	IP certification testing.	IP66	IP67

Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
4 User Interface						
4,1	Inside handle effort	D	Ergonomical effort for opening the door from inside.	Physical test with Dynamometer.	40N	20N
4,2	Mechanical handle backup and effort	D	The desire for functional mechanical backup during crash events, likely	Physical test.	70N	40N
4,3	Switch effort and engagment.	D	Switch ought to give actuation feedback and the effort ought to be easy	Physical test	5 N and 0.25mm travel	1 N and 0.25mm travel
4,6	Environmental Sealing	R	Durability in wet and dirty conditions.	IP certification testing.	IP66	IP67
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
5 Passive Entry						
5,1	Range of activation	R	Eligable entry of vehicle at a sufficient distance for convenient entry.	Physical and digital test.	2 m	2 m
5,2	Anti-theft	R	Prevent unauthorized access to system.	Physical and digital test.	NA	NA

Figure 8.1: Requirement list.

Appendix B

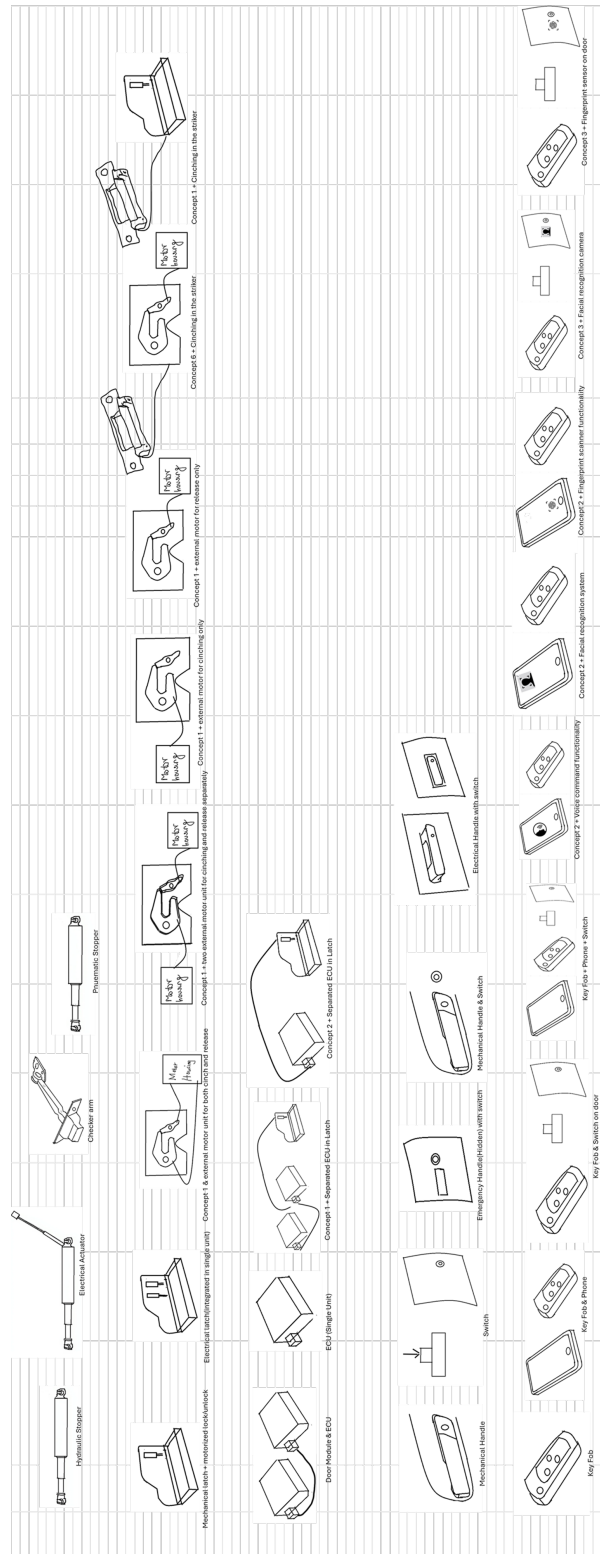
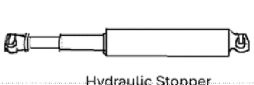
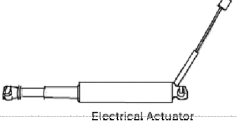
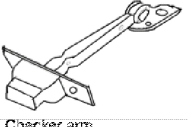
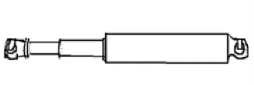
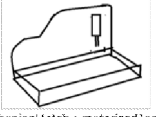
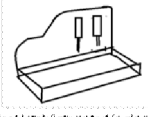
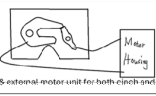
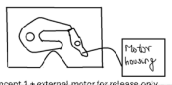
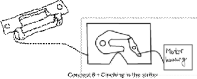
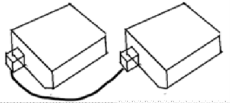
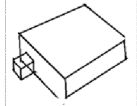
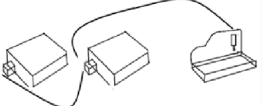
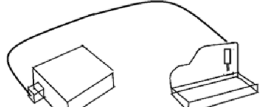
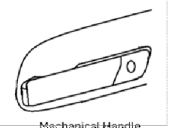
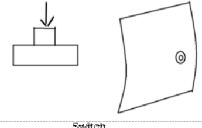
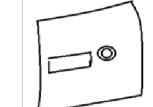
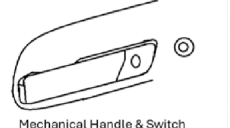


Figure 8.2: Sketches of the generated sub-function concepts in the concept generations.

Appendix C

Created: 2025-04-15 Elimination Matrix				Opening and Closure Features	Fits to current architecture	Reasonable Cost Estimation	Novel Enough	Elimination requirements: (+) Yes (-) No (?) More information needed (!) Check the product spec. Feasible under constraints Decision: (+) Proceed with concept (-) Eliminate the concept (?) More information needed (=) Got combined/Too similar		
Advanced Door Opening & Closure For Heavy Duty Application				Functionality	Size	Cost	Unique	Realizable	Comments	Decision:
Nr	Concept	Description	Image							
1	Door stopping: Concept 1	Hydraulic actuator for breaking the door speed/stopping it.	 Hydraulic Stopper	+	+	+	+	+		+
2	Door stopping: Concept 2	Electrical actuator for breaking the door speed/stopping it.	 Electrical Actuator	+	+	+	+	+		+
3	Door stopping: Concept 3	Mechanical arm for stopping door.	 Checker arm	+	+	+	+	+	Standard solution	+
4	Door stopping: Concept 4	Pneumatic actuator for breaking the door speed/stopping it, common in trunks.	 Pneumatic Stopper	-	+	+	+	+	Might fluctuate too much during temperature change for reliable door stopping.	-
5	Release and locking system: Concept 1		 Mechanical latch + motorized lock/unlock	+	+	+	-	+	Standard solution	+
6	Release and locking system: Concept 2		 Electrical latch (integrated in single unit)	+	+	+	+	+		+
7	Release and locking system: Concept 3		 Concept 1 + external motor unit for both clutch and release	+	+	+	+	+		+
8	Release and locking system: Concept 4		 Concept 1 + two external motor unit for clutch and release separately	+	+	+	+	+		+
9	Release and locking system: Concept 5		 Concept 1 + external motor for clutching only	+	+	+	+	+		+
10	Release and locking system: Concept 6		 Concept 1 + external motor for release only	+	+	+	+	+		+

11	Release and locking system: Concept 7		 Concept 7 - Caching in the pusher	+	-	-	+	+		*Too expensive due to additional motor integration on striker. *Negative effect on packaging space, will not fit unless modification.	-
12	Release and locking system: Concept 8		 Concept 8 - Caching in the pusher	+	-	-	+	+		*Too expensive due to additional motor integration on striker. *Negative effect on packaging space, will not fit unless modification.	-
13	Control unit: Concept 1		 Door Module & ECU	+	+	+	-	+		Standard solution	+
14	Control unit: Concept 2		 ECU (Single Unit)	+	+	+	+	+			+
15	Control unit: Concept 3	Additional ECU in the latch to only control the latch function	 Concept 1 + Separated ECU in Latch	+	?	-	+	+		* Too expensive due to additional latch variant and bigger latch due to ECU integration. *Negative effect on packaging space, don't know if it fits.	-
16	Control unit: Concept 4		 Concept 2 + Separated ECU in Latch	+	?	-	+	+		*Too expensive due to additional latch variant and bigger latch due to ECU integration. *Negative effect on packaging space, don't know if it fits.	-
17	User interface: Concept 1		 Mechanical Handle	+	+	+	-	+		Standard solution	+
18	User interface: Concept 2		 Switch	+	+	+	+	+			+
19	User interface: Concept 3		 Emergency Handle(Hidden) with switch	+	+	+	+	+			+
20	User interface: Concept 4		 Mechanical Handle & Switch	+	+	+	+	+		Novel in heavy duty truck but exists in passenger cars	+

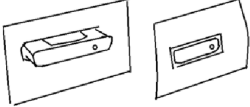
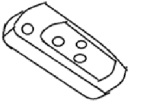
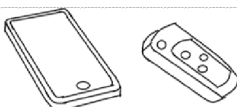
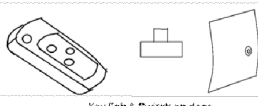
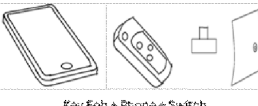
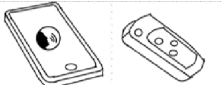
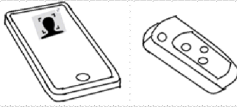
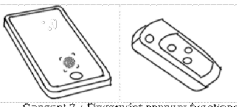
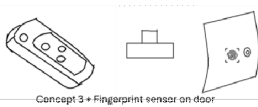
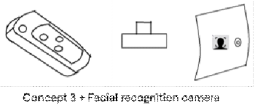
21	User interface: Concept 5	 Electrical Handle with switch	+	+	+	+	+	+	Novel in heavy duty truck but exists in passenger cars	+
22	Passive Entry: Concept 1	 Key Fob	+	+	+	-	+	+	Standard solution	+
23	Passive Entry: Concept 2	 Key Fob & Phone	+	+	+	+	+	+	Novel in heavy duty truck but exists in passenger cars	+
24	Passive Entry: Concept 3	 Key Fob & Switch on door	+	+	+	+	+	+	Novel in heavy duty truck but exists in passenger cars	+
25	Passive Entry: Concept 4	 Key Fob + Phone + Switch	+	+	+	+	+	+	Novel in heavy duty truck but exists in passenger cars	+
26	Passive Entry: Concept 5	 Concept 2 + Voice command functionality	+	+	+	+	+	+		+
27	Passive Entry: Concept 6	 Concept 2 + Facial recognition system	+	-	-	+	+	+	*Lacking packaging space for camera integration in door.	-
28	Passive Entry: Concept 7	 Concept 2 + Fingerprint scanner functionality	+	+	+	+	+	+		+
29	Passive Entry: Concept 8	 Concept 3 + Fingerprint sensor on door	+	+	-	+	+	+	Too expensive due to feature bloat.	-
30	Passive Entry: Concept 9	 Concept 3 + Facial recognition camera	+	-	-	+	+	+	*Too expensive due to feature bloat. *Lacking packaging space for camera integration in door.	-

Figure 8.3: Elimination matrix.

Appendix D

Sub-function	Description	Complete concept 1						
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
A	Door stopping	Hydraulic stopper	Electrical actuator+Sensor	Checker arm				
B	Release and locking system	Mechanical latch + motorized lock/unlock	Electrical latch (all functions motorized and integrated to latch)	Concept 1 + external motor unit for cinching and release	Concept 1 + two external motor unit for cinching and release separately	Concept 1 + external motor for cinching only	Concept 1 + external motor for release only	
C	Control unit	Door module + ECU(separate units)	Combined door module and ECU					
D	User interface	Mechanical handle	Switch	Switch + Mechanical handle(Only for Emergency/hidden)	Switch + Mechanical handle	Switch Integrated in Electrical Handle		
E	Passive entry	KeyFob	KeyFob+Phone	KeyFob+Switch	KeyFob+Switch+Phone	Concept 2 + Voice command functionality		Concept 2 + Fingerprint scanner functionality
Sub-function	Description	Complete concept 3						
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
A	Door stopping	Hydraulic stopper	Electrical actuator+Sensor	Checker arm				
B	Release and locking system	Mechanical latch + motorized lock/unlock	Electrical latch (all functions motorized and integrated to latch)	Concept 1 + external motor unit for cinching and release	Concept 1 + two external motor unit for cinching and release separately	Concept 1 + external motor for cinching only	Concept 1 + external motor for release only	
C	Control unit	Door module + ECU(separate units)	Combined door module and ECU					
D	User interface	Mechanical handle	Switch	Switch + Mechanical handle(Only for Emergency/hidden)	Switch + Mechanical handle	Switch Integrated in Electrical Handle		
E	Passive entry	KeyFob	KeyFob+Phone	KeyFob+Switch	KeyFob+Switch+Phone	Concept 2 + Voice command functionality		Concept 2 + Fingerprint scanner functionality
Sub-function	Description	Complete concept 5						
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
A	Door stopping	Hydraulic stopper	Electrical actuator+Sensor	Checker arm				
B	Release and locking system	Mechanical latch + motorized lock/unlock	Electrical latch (all functions motorized and integrated to latch)	Concept 1 + external motor unit for cinching and release	Concept 1 + two external motor unit for cinching and release separately	Concept 1 + external motor for cinching only	Concept 1 + external motor for release only	
C	Control unit	Door module + ECU(separate units)	Combined door module and ECU					
D	User interface	Mechanical handle	Switch	Switch + Mechanical handle(Only for Emergency/hidden)	Switch + Mechanical handle	Switch Integrated in Electrical Handle		
E	Passive entry	KeyFob	KeyFob+Phone	KeyFob+Switch	KeyFob+Switch+Phone	Concept 2 + Voice command functionality		Concept 2 + Fingerprint scanner functionality
Sub-function	Description	Complete concept 7						
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
A	Door stopping	Hydraulic stopper	Electrical actuator+Sensor	Checker arm				
B	Release and locking system	Mechanical latch + motorized lock/unlock	Electrical latch (all functions motorized and integrated to latch)	Concept 1 + external motor unit for cinching and release	Concept 1 + two external motor unit for cinching and release separately	Concept 1 + external motor for cinching only	Concept 1 + external motor for release only	
C	Control unit	Door module + ECU(separate units)	Combined door module and ECU					
D	User interface	Mechanical handle	Switch	Switch + Mechanical handle(Only for Emergency/hidden)	Switch + Mechanical handle	Switch Integrated in Electrical Handle		
E	Passive entry	KeyFob	KeyFob+Phone	KeyFob+Switch	KeyFob+Switch+Phone	Concept 2 + Voice command functionality		Concept 2 + Fingerprint scanner functionality
Sub-function	Description	Complete concept 9						
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
A	Door stopping	Hydraulic stopper	Electrical actuator+Sensor	Checker arm				
B	Release and locking system	Mechanical latch + motorized lock/unlock	Electrical latch (all functions motorized and integrated to latch)	Concept 1 + external motor unit for cinching and release	Concept 1 + two external motor unit for cinching and release separately	Concept 1 + external motor for cinching only	Concept 1 + external motor for release only	
C	Control unit	Door module + ECU(separate units)	Combined door module and ECU					
D	User interface	Mechanical handle	Switch	Switch + Mechanical handle(Only for Emergency/hidden)	Switch + Mechanical handle	Switch Integrated in Electrical Handle		
E	Passive entry	KeyFob	KeyFob+Phone	KeyFob+Switch	KeyFob+Switch+Phone	Concept 2 + Voice command functionality		Concept 2 + Fingerprint scanner functionality

Figure 8.4: Morphological matrix.

Appendix E

Reference: Current solution		CONCEPT 1		CONCEPT 2		CONCEPT 3		CONCEPT 4		CONCEPT 5		CONCEPT 6		CONCEPT 7		CONCEPT 8		CONCEPT 9		CONCEPT 10	
		Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted	Base score	Weighted
Criteria	Weight																				
Control simplicity	1.5	0	0	1.5	2.25	3	4.5	2.5	3.75	3	4.5	1	1.5	2	3	1	1.5	1	1.5	2.5	3.75
N/H	1.5	0	0	2.5	3.75	2	3	1.5	2.25	2.5	3.75	1	1.5	-1	-1.5	0	0	1	1.5	1.5	2.25
Cost	2.0	0	0	-1.5	-3	-3	-6	-1	-2	-1.5	-3	-2	-4	-2	-4	-0.5	-1	-1.5	-3	-2	-4
User safety	4.5	0	0	0	0	3	13.5	3	13.5	-1	-4.5	1	4.5	2.5	11.25	1.5	6.75	0.5	2.25	3	13.5
Ergonomic Performance	1.5	0	0	2	3	1	1.5	1.5	2.25	3	4.5	2.5	3.75	0	0	2	3	2	3	1	1.5
Reliability	4.0	0	0	-1	-4	2	8	2.5	10	0	0	1	4	-1	-4	2.5	10	1	4	0.5	2
Totalscores		0	0	3.5	2	8	24.5	10	29.75	6	5.25	4.5	11.25	0.5	4.75	6.5	20.25	4	9.25	3	6.25
				8	10	3	3	1	1	5	8	6	5	10	9	4	4	7	6	9	7
Rank																					
		Comment for concept 1: Easier to open with electrical handle, closing allows for quiet closing. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 2: Electrical actuator + switch also for actuating opening and closing. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 3: Control simplicity: Easier to open with electrical handle, closing with voice control. The actuator does not have "steps" that can be perceived as clunky. Compromise with faster opening with door braking. Occhinal allows for quiet closing and switch does not make much noise as an actuator. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 4: Very simple to open with a switch with integrated finger print integration. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 5: Check arm makes it very clunky however the voice control is a good idea. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 6: User releases the door mechanically and the handle is located near the handle and then the actuator is also activated. Voice command is also easy to N/H is worse because there are more separate parts thus more rattle. Costs heavily increased due to voice control. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 7: Simple to open due to only switch however due to the hydraulic system the door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		CONCEPT 8 Check arm makes it very clunky		Comment for concept 9: Similar door swing and bearing experience as reference. The door is being a 3. Due to automatic function it can be adjusted to allow for better N/H but it will allow for the separate the downside is the separate motors for release and clutch which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.		Comment for concept 10: Control simplicity: Easier to open with electrical handle, closing allows for quiet closing and switch does not make much noise as an actuator. The door is not as heavy as the current solution, which requires more components that will rattle. The door is not as heavy as the current solution, which requires more components that will rattle.	

Figure 8.5: Pugh Matrix

Appendix F

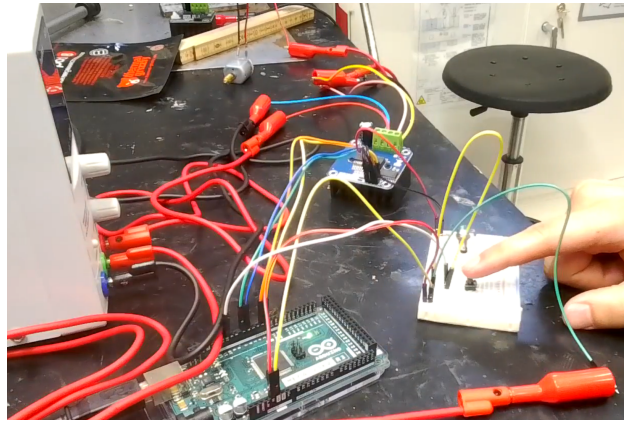


Figure 8.6: Test of motor spinning after pressing switch.

Appendix G

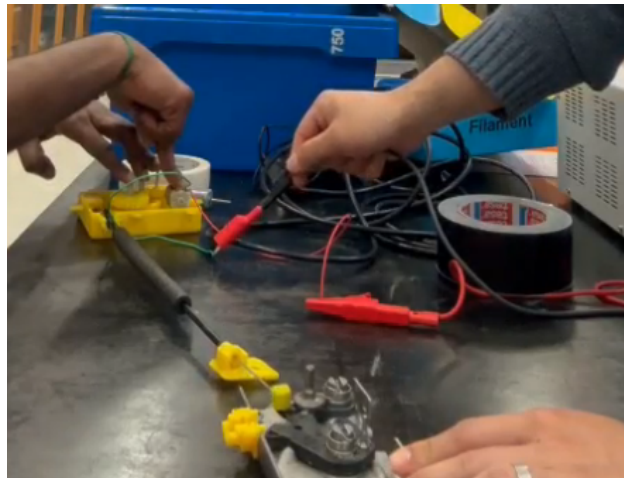


Figure 8.7: Test of motor opening the latch.

Appendix H

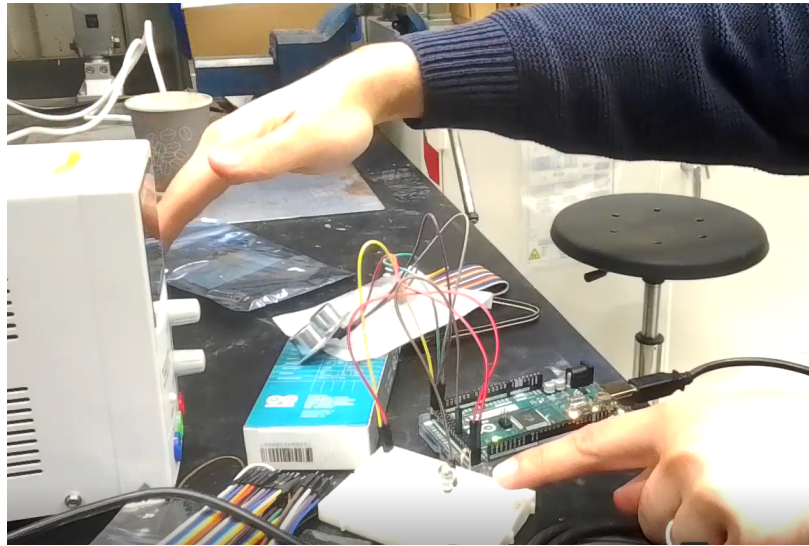


Figure 8.8: Test of ultrasonic.

Appendix I

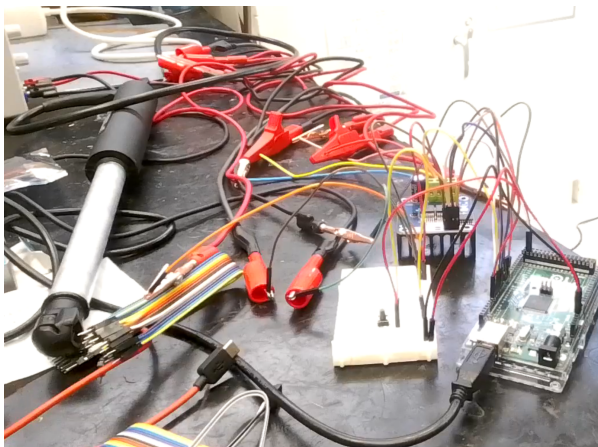


Figure 8.9: Actuator before pressing switch.

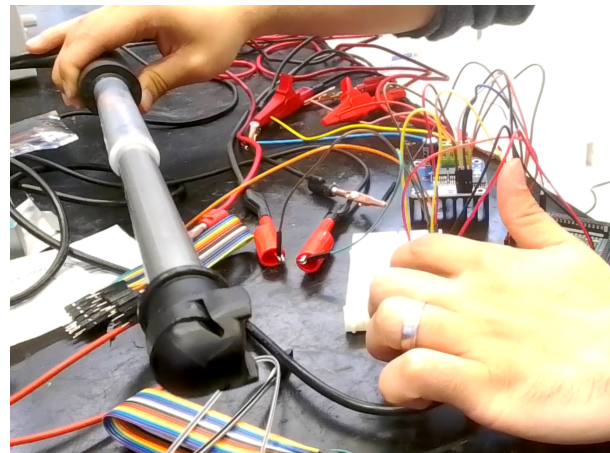


Figure 8.10: Actuator after pressing switch.

Appendix J

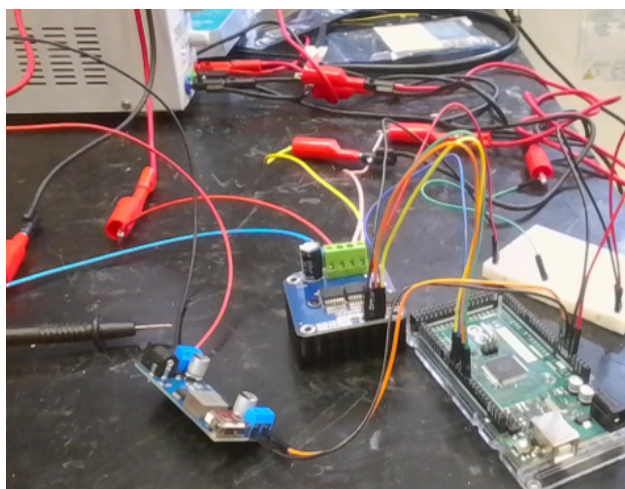


Figure 8.11: Test of motor opening the latch.

Appendix K

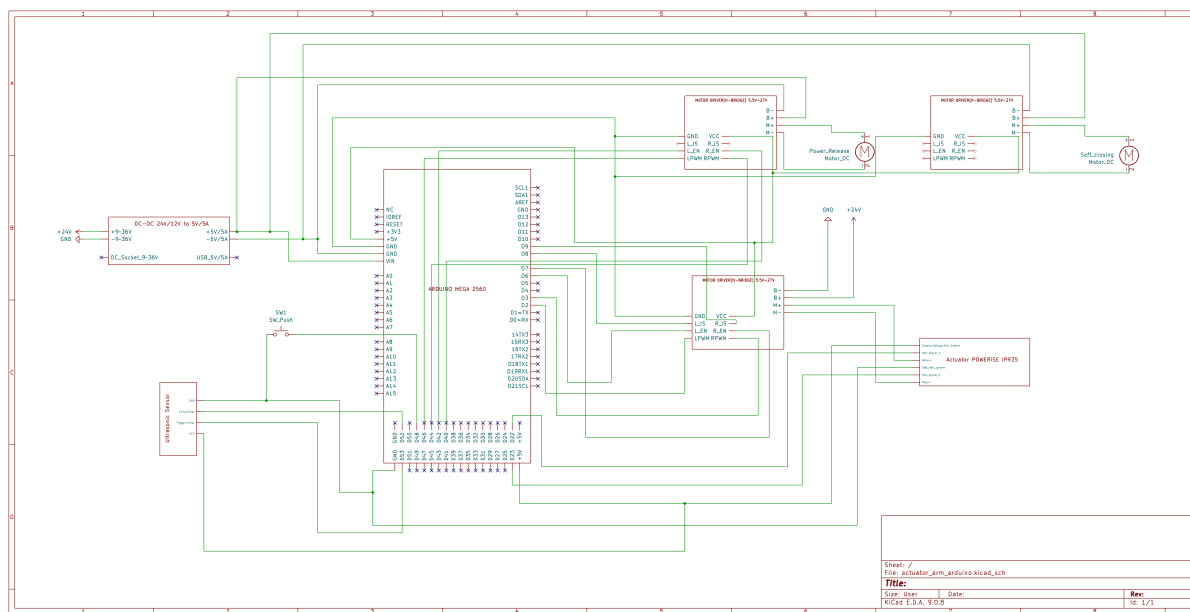


Figure 8.12: Interface architecture of the complete build.

Appendix L

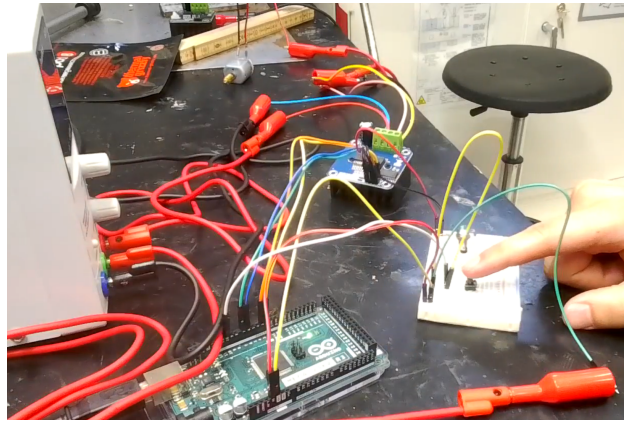
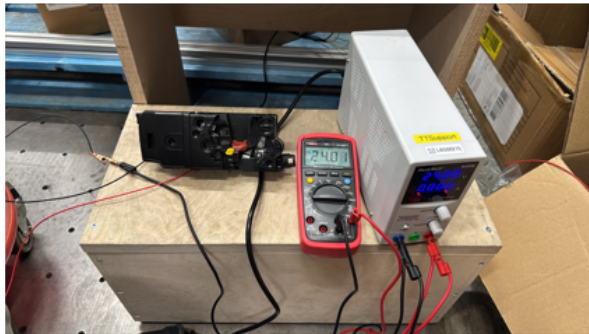
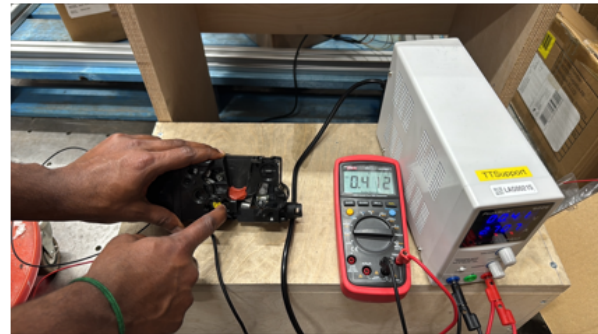


Figure 8.13: Test of motor spinning after pressing switch.

Appendix M



During Cinching



During Release

Figure 8.14: Test of cinch switch activation using multimeter.

Appendix N

Metric Number	Criteria/Functions	Requirements /Desires	Justification	Evaluation	Minimum value	Target Value
1	Door Braking					
1,1	Wind Braking	R	Door braking mitigates wind from harsh or rapid opening.	Slam test to simulate wind.	resist 22 km/h during opening and closing	resist 47km/h during opening and closing
1,2	Obstacle detection	D	Prevention of accidental crash during door opening	Physical measurement with ruler during door opening	10cm from detected object	10cm from detected object
1,3	Door Impact Tolerance	R	Withstand door slamming to a certain extent	Slam the door.	Rated load	Additional 10% on rated load
1,4	Maintain Position	R	Avoids sudden crash or movement during door entrance.	Try different door angles to see if it stays put.	Minimum 1 position where it stops	Stop at any position
1,5	Environmental Sealing	R	Durability in outdoor conditions.	IP certification testing.	IP 66	IP67
1,6	Emergency Stop	R	Safety critical feature for emergency situations	Functional testing of override mechanism on test bed	Physical or digital kill switch	Override due to current buildup
1,7	Actuator noise	R	Uneven noise during different opening speed	Measuring decibelmeter	40 dB	25 dB
1,8	Door Opening Angle	D	Stroke Length	Physical measurement	85deg	90deg
Metric Number	Criteria/Functions	Requirements /Desires	Justification	Evaluation	Minimum value	Target Value
2	Latch system					
2,1	Load Requirements	R	Need to withstand a certain load put forward by ECE R11 & FMVSS 206.	Physical test as mentioned in the legislation documents.		
2,2	Door closing sound	R	To comply with PIEK certification	Measuring dB(A) with decibel meter tool on complete system.	67 dB(A)	Less than 67dB(A)
2,3	Environmental Sealing	R	Durability in outdoor conditions.	IP certification testing.	IP 66	IP67
2,4	Emergency Stop	R	Safety critical feature for emergency situations	Functional testing of override mechanism on test bed	Mechanical redundancy	Mechanical redundancy
2,5	Latch closure effort	D	To ensure a pleasant effort in the spring for latch release.	Physical test with Dynamometer.	65N	45N
2,6	Modularity	D	Flexible latch setup suitable for different customer segments.	Digital and physical evaluation.	NA	NA
2,7	Anti-pinch	R	Prevent pinching during soft-closing operation	Digital and physical evaluation.	NA	NA

Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
3	ECU					
3,1	Voltage requirements	R	Able to handle and interface a wide array of components that operates	Physical test with multimeter and oscilloscope	5V-24V	5V-24V
3,2	Current requirements	R	Able to handle and interface a wide array of components that operates	Physical test with multimeter.	1A to 5A	1A to 7A
3,3	Interface requirements	R	Interface to electrical architecture in the truck.	Physical test.	NA	NA
3,4	Environmental Sealing	R	Durability in wet and dirty conditions.	IP certification testing.	IP66	IP67
3,5	One complete system	R	Easier to assemble and saves geometrical space.	Digital and physical evaluation.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
4	User Interface					
4,1	Inside handle effort	D	Ergonomical effort for opening the door from inside.	Physical test with Dynamometer.	40N	20N
4,2	Mechanical handle backup and effort	D	The desire for functional mechanical backup during crash events, likely	Physical test.	70N	40N
4,3	Switch effort and engagement.	D	Switch ought to give actuation feedback and the effort ought to be easy	Physical test	5 N and 0.25mm travel	1 N and 0.25mm travel
4,6	Environmental Sealing	R	Durability in wet and dirty conditions.	IP certification testing.	IP66	IP67
4,7	Hidden redundant user interface	D	Aesthetically pleasing and anti-theft measurement	Digital and physical evaluation.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
5	Passive Entry					
5,1	Range of activation	R	Eligible entry of vehicle at a sufficient distance for convenient entry.	Physical and digital test.	2 m	2 m
5,2	Anti-theft	R	Prevent unauthorized access to system.	Physical and digital test.	NA	NA
Metric Number	Criteria/Functions	Requirements / Desires	Justification	Evaluation	Minimum value	Target Value
6	Interface					
6,1	Wiring soldering quality	R	Mitigate loss of operation	Physical measurement	NA	NA
6,2	Actuator positioning	R	Reduce geometrical impact and improve opening angle	Digital and physical evaluation.	NA	NA
6,3	Latch positioning	R	Actuatorbox is on the sheet metal and to improve assembly and aftermarket, reposition it on a modular interface.	Digital and physical evaluation.	NA	NA

Figure 8.15: Final requirement list.

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