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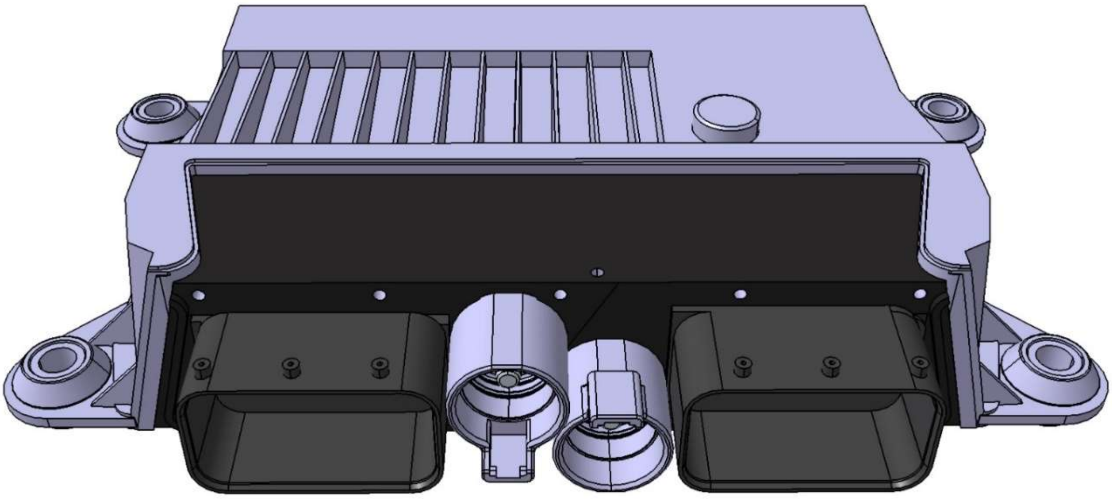

Mechanical concept development of new flexible ECU enclosure

Master‘s thesis in Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
CAD model of a new flexible ECU enclosure.

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Abstract

Electronic Control Units (ECU) are electronic devices that build up a vehicle network. These devices read sensor data and control various functions in a vehicle, such as engine control, speed, transmission, brakes, and lights. They are essentially small computers consisting of a printed circuit board (PCB) and they are scattered all across the vehicle. On a truck, there are three of these ECUs on the chassis. All of them are designed and built for a specific function, depending on the need for that specific truck, meaning they are usually not suitable to be placed anywhere else, or on a different truck or a bus. This is very inflexible, both in terms of these usage but also for new development.

The idea of the project that this thesis is a part of, is to introduce more commonality between ECUs and create a more generic design that can replace current chassis ECUs. This would mean reusing the same ECU for all of these, which would reduce development time and costs. The new ECU will also have enhanced computing power, which puts more demands on cooling. Because of the exposed positioning of the ECU, there are also concerns regarding sealing and vibrations.

This thesis has been an integrated product development project. Major areas of the development centered around concept design and heat transfer. In the ECU, the heat is created due to power dissipation in electronic components. The heat then migrates down to the base of the components, though the PCB that they are mounted on, through a thermal interface material between the PCB and the aluminium casing, through the casing, and then dissipated into surrounding outside air. Calculations for each of these stages have been made and conclusions are that the resulting temperature at equilibrium can be within safety limits to ensure a long lifetime. The proposed design does not utilize these results fully however.

The proposed design increases flexibility by introducing a design that can house two PCBs. The PCBs can be exchanged depending on the need, but the core idea is to have a base PCB shared between all the variants of the chassis ECUs. The enclosure will also be shared, eliminating the need for different enclosure design for the chassis ECUs. Other concepts were also proposed that should be investigated further.

Keywords: ECU, Heat Transfer, Product Development

Preface

This work has been done at Volvo GTT and acknowledgements goes out to everyone at the GION team for making me feel a part your team. Thanks to Abhineet Singh Tomar for always bringing lunch and being a companion during this work. Special thanks to supervisor Roy Johansson for letting me do this thesis, and for helpful insights and discussions, and being the general highlight of everyone's day. Also thanks to Professor Johan Malmqvist for being my examiner at Chalmers University of Technology.

Acronyms

ECU – Electronic Control Unit
RCIOM – Rear Chassis Input/Output Module
CCIOM – Center Chassis Input/Output Module
FCIOM – Front Chassis Input/Output Module
PCB – Printed Circuit Board
I/O – Input/Output
GION – Generic Input/Output Node
IP6K9K – International protection standard of sealed unit (Highest rating in ISO 20653)

Table of Contents

1 Introduction

The contents of this report will start with an introduction into the background of this thesis. The thesis concerns the development on a new product. The background will explain the current product and its uses and then formulate the need for a new product development project. The purpose and specific goals of the project will also be explained. An outline of the report can be found in the end of this chapter.

1.1 Background

The advances in the electronics industry and imposing government regulations have been a driving force for the development of vehicle network technology.

An Electronic Control Unit (ECU) is an embedded electronic device used as the basis for this network. These devices read various sensor input data and control many different functions in a vehicle. This functions include engine control, door control, seat control, speed control, transmission control and many other. Modern vehicles can have as many as 80 ECUs.

An example of an ECU is the RCIOM (Rear Chassis Input/output Module) that is used in Volvo trucks, which is located on the cross member behind the gearbox on a truck, see Figure 1. It controls a multitude of components including (RCIOM2, 2016):

- Rear lights and side marking lights
- Reverse warning
- Trailer lights
- Brake switches
- Rear differential lock, which is used to lock both wheels at the same rotational speed.

Because of its positioning, the component is exposed to harsh weather and operation conditions. This included high vibration levels, high temperature, solar radiation, fluids including grease, oil and water, gases, and other components of the road, such as dirt and road salt.

The ECU itself consists of a Printed Circuit Board (PCB) and Input/output (I/O) connectors inside a mechanical enclosure. This thesis will concern three different types of these enclosures. The RCIOM, seen in Figure 2, will be used as a reference in the future. The FCIOM (Front Chassis Input/Output Module), as seen in Figure 3, is a similar ECU that is positioned in a front location of a truck. The third type is the CCIOM (Center Chassis Input/Outout Module), which is located at the center of a truck. It looks similar to the RCIOM.

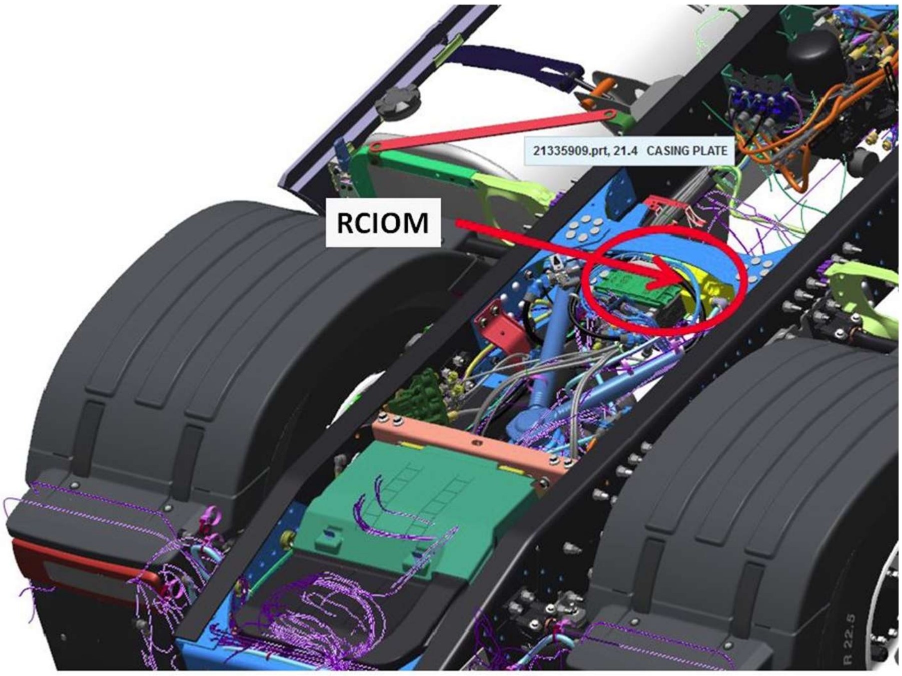

Figure 1. The RCIOM is positioned in an outside environment, exposed to weather and operation conditions (RCIOM2, 2016).

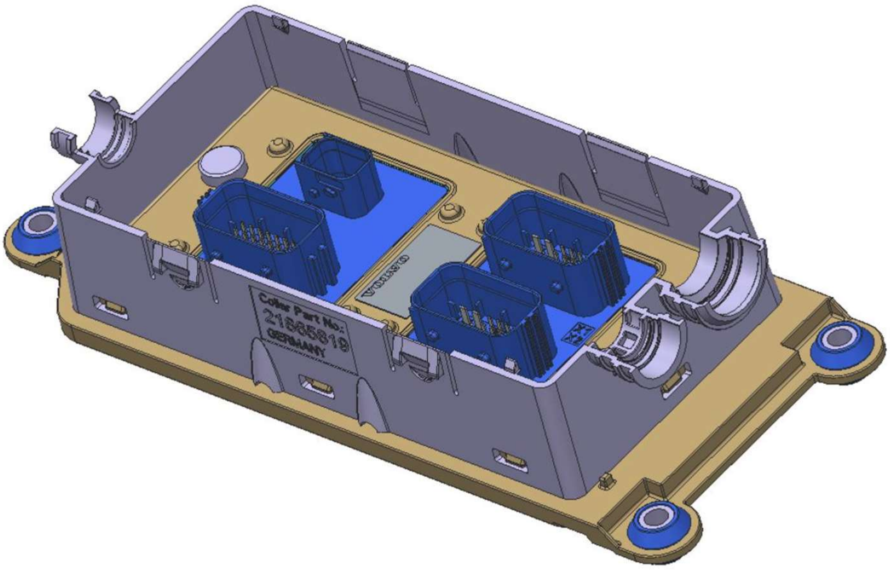

Figure 2. CAD model of the RCIOM, with I/O connectors and enclosure showing, and with the PCB inside (RCIOM2, 2016).

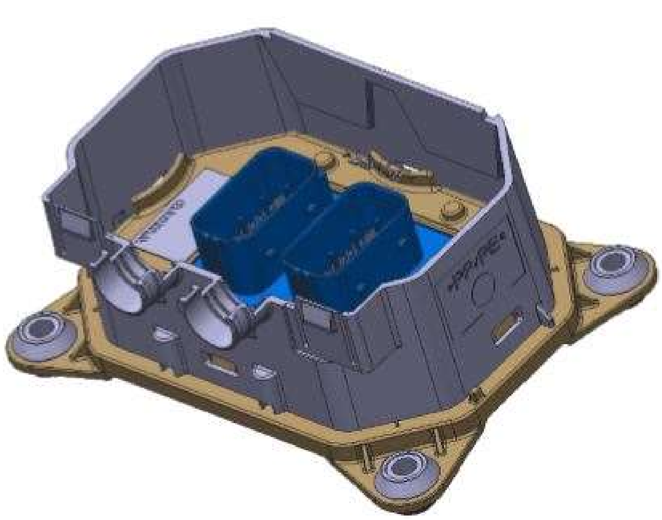

Figure 3. CAD model of the FCIOM, with I/O connectors and enclosure showing, and with the PCB inside (FCIOM2, 2016).

The PCB is placed inside the housing, with waterproof cutouts for the connectors. Underneath there is a bottom plate that seals the PCB from the outside and on top there is a plastic cover and collar that provides basic protection for the connectors. There is also a vent for equalizing the pressure inside and grommets for shock and vibration mitigation. The housing is made from aluminium, an inexpensive material with low cost and good heat transfer properties.

These three ECUs (RCIOM, CCIOM, and FCIOM) also come in different varieties by changing the PCB to fit different applications. This creates products with various differential value, but not with much commonality between them. As it is now, the ECUs are specialized depending on their applications. This is disadvantageous because of the many different part numbers that must be produced and tested. It is also difficult to reuse the design and components. By creating more commonality between the ECUs, it is possible to improve the ECUs in various ways in regards to generic design and increased I/O nodes.

The ECU design will be common across the product range and can be tested once and then used in many different applications, as opposed to a customized ECU which needs to be tested for each unique part number. This will also reduce the development cost and cost for the aftermarket by reusing the same part number already developed. This new ECU is called GION (Generic Input/output Node). Generic refers to the fact that it is not customized.

The principle of building a modular idea that fits within different applications can also be applied to many other ECUs as well.

A major part of this modularity is to create flexibility in the GION by using multiple PCBs. That way, all the different variants of the RCIOM, CCIOM, and FCIOM can be replaced with only two PCBs. One will be a base PCB that is shared across all three ECUs and one will be an extender PCB that covers the needs of the higher demanding ECUs.

Because of the new electronic design there is risk of a higher heat buildup inside the GION. Heat management will be an important part. There is also the challenge of ensuring seal integrity in a flexible product. In the current customized ECU, the seals are integrated into the design permanently.

1.2 Purpose

The project was closely coordinated with the PCB development team as well as another student working with PCB design. The purpose was to investigate flexible design options and design an enclosure for the PCB and suitable connectors.

1.3 Goal

The aimed outcome of this project was a functional prototype enclosure that incorporates a next generation PCB with connectors in a way that is flexible and robust. Important product specification goals are as follows (RCIOM2, 2016):

- Weight is requested to be less than 1.5 kg.
- The degree of protection shall be at least IP6K9K according to ISO 20653 (ISO 20653, 2006), which is the higher protection level. IP stands for International Protection. 6K signifies that it shall be dust tight and 9k indicates that it is safe from high-pressure water jet washing.
- Requirements concerning mechanical strength, corrosion, heat transfer and vibration must be met.

The embodied design would be complete with 3D CAD models and 2D drawings for prototyping and product presentation, as well as a specification of requirements that is expected to be fulfilled. One or more prototypes would be built for showcasing and testing.

The prototype would undergo testing as part of the product verification. The complete and final test cycle includes many different and extensive tests, such as high/low temperature, high vibration, electrical loads, chemical loads, mechanical shock, permeability, free fall, salt spray test, gravel bombardment and IP classification tests. Some of these could be performed tentatively in order to prove concept feasibility. Which ones would be decided at a later stage.

1.4 Delimitations

The scope of this project will mainly concern enclosure development and although it will not touch much upon elements outside of this, it will have design considerations and limitations brought on by the parallel development of the PCB. This will be handled by working closely with the student responsible for working with the PCB. More specific chosen delimitations are as follows.

This project will not treat PCB or software development.

Extensive user studies will not be made, mainly because many technical requirements are already specified and also because it will not be a frequent user interactive product. Concern will however be taken considering assembly and manufacturing.

The project will be more research oriented than production ready.

1.5 Report outline

This introductory chapter has hopefully provided all the information needed to understand what this project is about. The structure of the rest of the report will be explained here.

In chapter 2 *Method*, the adopted development process for this project will be explained, with the different steps that accompany it. It discusses the approach towards the research that concerned the project. Then the developments process will be clarified, along with the detailed design and the prototype and testing. The methods described are the ones that were used up until the conclusion of the thesis.

The targets for the project are defined in chapter 3 *Requirement Specification*. These are the requirements that are defined for the final design that goes into production, but were still used as a guideline. Some of the important requirements are explained further.

Chapter 4 *Concept Development* concerns the development of the enclosure design and also includes the breakdown of the ECU into important function, where the enclosure is one of those.

The connectors and how they integrate into the enclosure design is described in chapter 5 *Connector & Enclosure Integration*, which also includes power connectors. This chapter also deals with alternative concepts that were also promising.

The proposed design that a prototype was built from can be found in chapter 6 *Developed Design*.

Heat dissipation is dealt with in chapter 7 *Thermal Resistance*. This chapter deals with heat transfer through multiple parts in the ECU, all the way from inside the electronic components out into the surrounding air.

Chapter 8 *Discussion* will discuss the results of the thermal resistance chapter and many other things of importance that concerns the project and the process.

Finally, chapter 9 *Conclusion* will conclude the report with the important things to take away from this work and what should be done in the next iteration if the work continues.

2 Method

The product being developed can be described as a Market-Pull product and the generic product development process (Ulrich & Eppinger, 2012) will be used accordingly, with some modifications. The development of the enclosure is made concurrently with the development of the PCB and introduces the considerations that come with it. To reduce the risk of design changes at the later stages of development, concurring engineering should be applied with increased focus on the beginning of the development process (Maylor, 2010).

Figure 4 shows the process used for this project. There was a feedback loop between the research and the detail development because of the new information that came into play and new areas of study. Likewise, there was some research that didn't come to use but is still important for a final design before production.

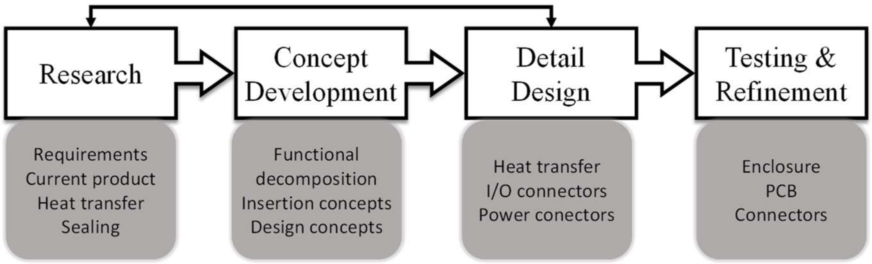

Figure 4. Product development process used in the methodology.

2.1 Research & Requirements Elicitation

The first step of the front-end process was to establish the requirements through a target specification. Information required for this could be elicited from provided documentation and also from converting expressed customer needs into measurable requirements.

Data from the current product could be organized to create a reference for future concept screening. This data was available as physical products and drawings, but a better model of how it actually performed would have been better.

It is also useful to investigate competitors’ solutions and available technologies. This process was ongoing throughout the concept development phase. However, for the purpose of this project there was not too much information that proved to be useful. Information regarding IP6K9K was too simple, and information about heat transfer and vibration was mostly unavailable.

Information concerning testing procedures was available, which could translate into further requirements for the target specification.

The theory of heat transfer was studied by textbook and was modified and applied to fit the purpose of the project. Heat transfer properties of electronic components was found from catalogues.

2.2 Concept Development

A structured approach to concept development was desired in order to provide clarity and facilitate an efficient development process. The first step of this approach was to create a functional decomposition of the GION using a black box description as a basis. The existing product was helpful in describing the subfunctions and resulted in a function-mean-tree. The subfunctions created could then be seen a subproblems to be solved. Some critical subproblems that related to the most important requirements was focused on initially, but ultimately all the subproblems need to have a means of solution.

The *Enclosure* subproblem was divided into two parts for efficiency. First, the enclosure solution was separated into the different ways of inserting the PCB into the enclosure. This was because there are already a number of different ways this could be done available on the market. It was also interesting to see what else could be done. These concepts were then screened in a concept screening matrix, (Ulrich & Eppinger, 2012). Second, the results of the first step were used to formulate more developed concepts that could potentially be used in the final design and for future work. These were also screened in a concept screening matrix. The selection criteria of these comparison matrices originated from the requirements and expressed needs of the product.

2.3 Detail Design

The I/O connectors and power connectors that are to be used on GION were first chosen. They had to be changed from the current ECU because of new technical requirements from the electrical side.

The resulting concept from the concept development stage was further developed into something that may represent a final design. This included integrating the connectors into the design. The results of the functional decomposition should be used at this stage and to some degree it was.

Detail calculations and estimates of heat transfer were done at this stage. This could be done by assuming passive cooling and looking at the transfer of heat through the entire system. This involves the transfer from inside the semiconductors, through the PCB, through the out casing and into the atmosphere. Some interesting data was found from these investigations.

2.4 Testing & Refinement

Physical prototypes are important in order to test the functionality and feasibility of the product. The prototypes will need to be manufactured then undergo testing as part of the product verification.

3D printed models were made and used together with the PCB and connectors to test the integration of the connector package with the enclosure.

Tests concerning IP6K9K performed according to ISO 20653 (ISO 20653, 2006) and tests for mechanical loads described in ISO 16750-3 (ISO 16750-3, 2007) are important tests that need to be done on a complete model. They are not suitable for weak structured 3D printed model.

Thermal tests according to ISO 16750-4 (ISO 16750-4, 2010) will also require a complete prototype and was not performed for this project at this time.

3 Requirement Specification

Requirements for the target specification in Table 1 has been largely defined by technical requirement documents provided by Volvo GTT and international standards, see reference tab in the table. These documents are specified in the reference section. Some explaining of the table is in order in order to fully understand and make use of it. *Criteria* refers to a function or specification that the final product is to fulfill. *Target value* is the value or aim that defines the criteria. Some of the criteria are of more importance than others. They can therefore be classified by the level of focus they should receive in development. The classification in divided into *demands* and *wishes* (*D/W*). This can be further specified by a *value* ranging from 1 to 5, where 1 is of little importance and 5 is of high importance. The method used to verify how the criteria fulfill their target values is defined in *verification*. Finally, *reference* describes the source of the criteria and also includes a reference to the method of testing, when relevant.

Table 1. Target specification for the product. Includes target value and method of verification. Reference refers to the maker of the requirement. In the case of verification by testing, the testing procedure is defined by the reference.

	Criteria	Target value	D/W	Value	Verification	Reference
1	Tools required for maintenance	Common tools or no tools	D		Concept testing	Volvo
2	Recycling	Suited for recycling	W	4	DFR	Volvo
3	Environmental impact	Minimize	W	4	DFE	Volvo
4	Time to assemble	Minimize	W	3	Assembly test	Volvo
5	Time to disassemble	Minimize	W	2	Assembly test	Product planning
6	Time to mount	Minimize	W	4	Assembly test	Product Planning
7	Cost of manufacturing	Minimize	W	4	Cost estimate	Product Planning
8	Mass production	Suited for mass production	D		Production	Product Planning
9	Color of plastic parts	Black	D		Visual	Volvo
10	Appearance	Premium, robust	D		Visual	Volvo
11	Weight	<1.5 kg	D		CAD model	Volvo
12	Height	<97 mm	D		Drawing	Volvo
13	Length	<313 mm	D		Drawing	Volvo
14	Width	<136 mm	D		Drawing	Volvo
15	2D Drawings specification	Format: Tiff/Cal (or pdf) Minimum three views Section view with part list Materials specified Other acc. to Volvo STD	D		Drawing	Volvo
16	3D Model specification	Format: CATIA V5/Pro Engineer (or STEP)	D		CAD model	Volvo
17	Functional operating temperature	-40°C < T < +85°C +100°C for 2 hours	D		Temperature test	Volvo ISO 16750-4

18	PCB maximum temperature	130°C	D		Temperature test	Volvo Shockman (2010)
19	Withstand mechanical shock	500 m/s^2	D		Mechanical shock test	Volvo ISO 16750-3
20	Withstand dropping	1 m	D		Free fall test	Volvo ISO 16750-3
21	Withstand random vibrations	2000 Hz r.m.s. 18.4 g	D		Random vibration test	Volvo ISO 16750-3
22	Withstand continuous vibrations	100 Hz 10.2 g	D		Sinusoidal vibration test	Volvo ISO 16750-3
23	Withstand rapid cooling	T_{max} into 0°C to +4°C	D		Ice water shock test	Volvo ISO 16750-4
24	Withstand humidity	+65 ± 3°C 93 ± 3 %RH	D		Damp heat, steady state test	Volvo ISO 16750-4
25	Withstand corrosion (salt)	Normal performance Markings, labels visible	D		Salt spray test	Volvo ISO 16750-4
26	Withstand corrosion (gas)	H_2S, NO_2, Cl_2, SO_2	D		Mixed gas test	Volvo ISO 16750-4
27	Withstand chemicals	Urea, washer chemicals, Denatured alcohol etc	D		Chemical load test	Volvo ISO 16750-5
28	Dust shall not penetrate	Arizona A2 Fine test dust	D		IP6K9K	Volvo ISO 20653
29	Water shall not penetrate	High pressure jet 15 l/min, 9000 kPa, 80°C	D		IP6K9K	Volvo ISO 20653
30	Withstand gravel bombardment	Gravel size 9 to 16 mm	D		Stone chip resistance test	Volvo STD 1024,7132

The criterion 18 *PCB maximum temperature* is defined to protect the semiconductor connections on the PCB from melting, causing failure. In order to prevent a reduced life time and effects such as discolored PCB and brittle components, the maximum acceptable operating temperature has to be set in relation to expected life time. This is expressed by the following equation (Shockman, 2010):

$$T_{hours} = 6.376 \times 10^{-9} \times e^{\frac{1154.267}{273.16+T}} \tag{3-1}$$

where T_{hours} is the time to 0.1% failure rate and T is the stable operational temperature. Table 2 shows the expected time of continuous service until a failure rate of 0.1%. The maximum acceptable temperature is often considered to be 140°C, since this predicts a lifetime of one year. Volvo GTT has chosen a temperature of 130°C (RCIOM2, 2016), which gives a lifetime of two years. Note the dramatic decrease in life time with rising temperature as a result of equation 3-1. There is a lot to be gained by reducing the temperature inside the ECU.

The criteria 28 *Dust shall not penetrate* and 29 *Water shall not penetrate* are important demands that need to be solved in order to fulfill IP6K9K rating. The electronics inside the ECU will have to be protected from any dust or water that may cause a short-circuit. This rating is needed for the harsh operating condition the ECU will be exposed to. Many of the other requirements are a consequence of these same conditions.

Verification methods DFR (Design for recycling) and DFE (Design for environment) can be used for evaluation of the respective criteria. The chapter *Discussion* will go through the tests that have been performed for the requirements and which haven't.

Table 2. Time to a failure rate of 0.1% at a given temperature (Shockman, 2010).

Temperature (°C)	Time (Hours)	Time (Years)
80	1,032,200	117.8
90	419,300	47.9
100	178,700	20.4
110	79,600	9.1
120	37,000	4.2
130	17,800	2.0
140	8,900	1.0

4 Concept Development

Concept development is a part of the product development process. This phase investigates ideas to solve important problems. The requirements for the new product will first be listed. Then, the main function of the product will be divided into several subproblems which can usually be solved independently. The most important of these subproblem, the generalization of the enclosure, is included in the following chapters.

4.1 Functional Decomposition

The mechanical design development of the ECU is focused of the enclosure. The enclosure exists for a specific purpose and does not simply consist of a box for the PCB, but incorporates much more complex design features. In order to facilitate an efficient and comprehensive development, it is important to identify the core functionality of the enclosure and then divide this into several, more simplified, subproblems (Ulrich & Eppinger, 2012). It is then possible to achieve clarity of the product and its functions that need to be incorporated into the final design. This project will use a function-means-tree that divides the core functionality into subfunctions. These subfunctions each have a correlating design solution that will represent the basis for choosing how to realize the functions.

4.1.1 Function-means-tree

The core functionality of the ECU divided into the five subfunctions *Protect PCB*, *Provide I/O signals to PCB*, *Enable assembly of parts*, *Ensure robust enclosure* and *Mount to frame*. These are further divided as can be seen in Figure 5. The design solutions for each of these can be found at the end of the respective branch.

Because of the number of design solutions to the subfunctions, it is important to first choose the critical design solutions that have the most effect on the success of the product. Since the functions are more or less dependent on each other, there is a logical approach of choosing the order of which the design solutions should be solved.

The main function of the ECU enclosure is to protect the PCB from the environment. This is expressed by the function *Protect PCB* and its subsequent subfunctions. The function that has the most impact on the flexibility of the product and its overall success is *Contain PCB* with its design solution *Enclosure*. The enclosure solution is linked to many of the requirements and also determines the possible design solutions to other functions. Some of the most important requirements are realized through the functions *Ensure waterproof* and *Ensure dustproof*. These functions relate to the fulfillment of the requirements for IP6K9K. The design solution will be a sealing capable of operating in the given environment specified in the requirements. The function *Heat transfer* is an important part given the thermal buildup in the PCB in combination with the not so cold environment and the drastic effect that temperature has of the lifetime of the PCB components. The function is realized with a *Heat transfer system* which will be a combination of a heat transfer structure and a thermal material capable of transferring heat from the PCB to said structure. The function *Equalize pressure* is used for correct sensor readings and to prevent condensation inside the enclosure, and it uses a *Pressure equalization system*.

The function *Provide I/O signals to PCB* is the connection from the sealed enclosure to the outside electrical system. The subfunction *Connect I/O signals* will be using a *Connecting system* as a design solution. The male part of this connector will be chosen from a supplier, depending on the number and type of I/O signals needed. The female part will however need to fit into the enclosure and sealing system and will be designed as needed. The function *Protect I/O connectors*, with emphasize on protection from the environment, is realized with a *Protection system* which will probably be included with the male connector.

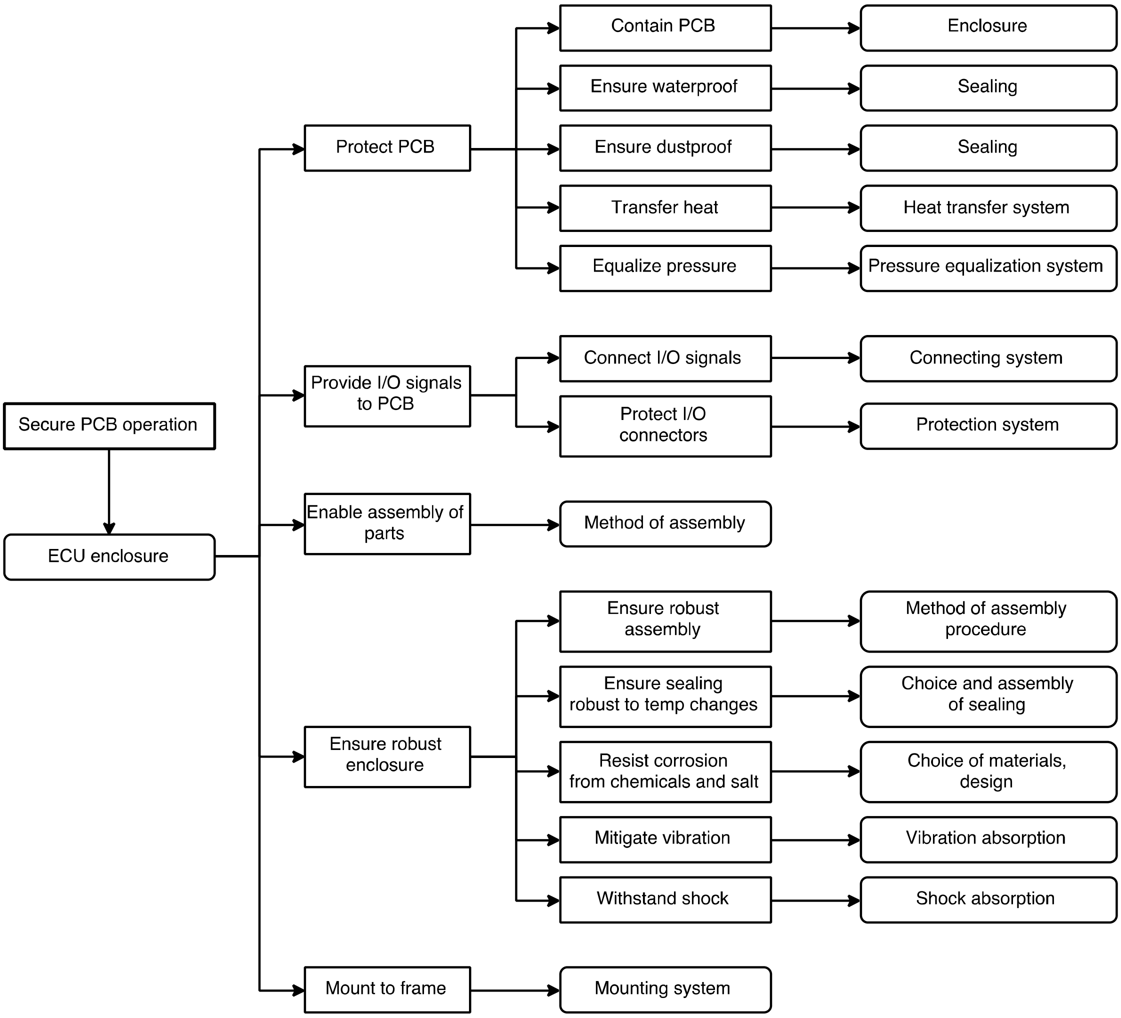

Figure 5. Function-means-tree showing sub functions that need to be solved for a successful completion of the main task.

The different parts of the design solutions will be assembled into the final ECU through the function *Enable assembly of parts* and its design solution *Method of assembly*. The assembly method will need to cover all parts of the assembly and take into consideration the requirements for assembly time.

In order to ensure a functioning product throughout its lifetime, it needs to withstand changes in its environment. The function *Ensure robust enclosure* addresses these issues. The subfunction *Ensure robust assembly*, with its design solution *Method of assembly procedure*, looks at the correct way of assembling the product to ensure correct tolerances, especially along the split lines of the assembly. Because of varying temperatures around the ECU, the function *Ensure sealing robust to temperature changes* is needed to protect against the thermal expansion of different materials in contact with each other. The design solution *Choice and assembly of sealing* is related to the sealing solution previously mentioned, but also takes into consideration the force of assembly of said sealing. The subfunction *Resist corrosion from chemicals and salt* deals with the environmental fluids that may come into contact with the ECU when placed on the chassis. The design solution *Choice of materials, design* addresses this problem by looking into the properties of materials of interest and also ways to protect for instance the sealing line from most of the fluids. Because of the positioning on the chassis, the ECU is subjected to mechanical load that propagates from the chassis, through the mounting mechanism, and onto the ECU. The subfunctions *Mitigate vibration* and *Withstand shock* deals with ways to protect mainly the electrical components and the connectors. The design solutions *Vibration absorption* and *Shock absorption* are the methods of realizing this.

Lastly, the function *Mount to frame* determines the method and positioning of the mounting to the chassis. There are some requirements concerning the type of screws used for mounting and the design solution *Mounting system* will deal with how these are positioned on the ECU.

4.2 Enclosure Insertion Concepts

The flexibility and success of GION largely depends on the Enclosure design solution. The enclosure is the most critical element and determines the course on the project and the formulation of the other design solutions. When gathering ideas for the enclosure, it is useful to divide them into methods of PCB insertion. In the current ECU, the PCB in inserted from the bottom and the connector is fitted into a hole in the base structure. A bottom plate is then used to complete the seal. The ways of insertion include *Top*, *Bottom*, *Front*, *Back, and Side*.

In addition to the different ways of insertion, the connection design solution is closely integrated into the enclosure. This is because there are two different ways of attaching the connector to the PCB. The pins going from the connector are joined with the PCB through either soldering or press-fit. These pins are the ones transferring electrical current to the PCB. These pins can in turn be either straight or perpendicular to the direction of the connector.

Because of the many design alternatives that originates from the combination of these, it is necessary to perform some rough tentative screening of realistic concepts. Beginning with the *Top* concepts, it is evident that there are some major concerns with the implementation. Figure 6a and b illustrates two concepts using the straight connector. In the first one, "Top plate", the PCB and the connector is inserted from the top into the base structure. A top plate is then put on top, with the connector going through a hole in the plate. This setup introduces concerns both regarding sealing across all the edges of the plate and the heat dissipation from the PCB. Also, if the plate is too thin it would not be mechanically reliable. Moreover, there are issues with how to fasten the connector to the plate, since fastening it from above would be problematic and create complex sealing solutions. The second concept, "Top plate+" is similar to the above but different in that the PCB and connector is fastened to the top plate and then inserted together into the base structure. This allows for the PCB and connector to be fastened to the plate in an easier way. It is also possible for the connector to be integrated into the top plate, eliminating the need for a sealing solution in the interface of the connector and plate. The concept "Top side", shown in Figure 6c, has a 90 degrees connector which in inserted from the top together with the PCB and is sealed by a plate on top. A sideways connector such as this is superior to a straight connector in that the seal for the connector is integrated into the main sealing and there is less need to fasten the connector to the other structures in additional ways. Having the support plate on the top is however not ideal for reasons of sealing and heat transfer.

For the *Bottom* concepts, Figure 7a shows the concept "Bottom plate" which is the one currently used for the RCIOM. The PCB has a straight connector which is inserted from below into a hole in the base structure. The connector is fastened and sealed around the hole. When it comes to flexibility and the ability to use two PCBs, this concept has some limitations. The concept "Bottom plate+" in Figure 7b is similar with the exception of attaching the PCB to the base plate before moving the connector through the hole. This comes with the same issues as with the "Top plate" concept in finding ways of fastening the connector and ensure seal integrity. Figure 7c shows the concept "Bottom side" which is similar to "Top side" with the difference of inserting the PCB from below which is more beneficial for sealing and heat transfer.

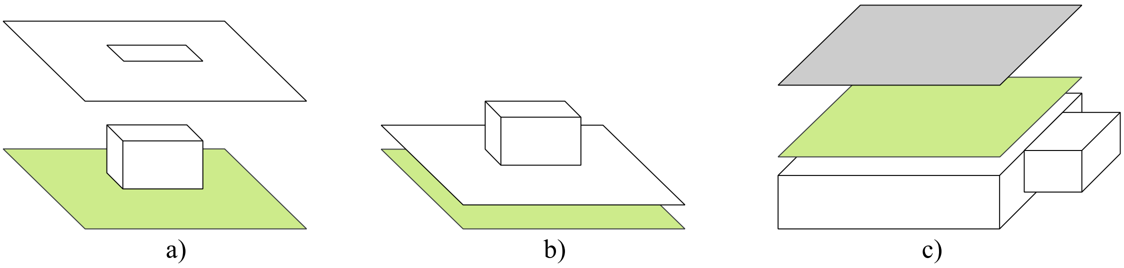
a) b) c)

Figure 6. Simple illustration of the Top concepts. (a) "Top plate", (b) "Top plate+", (c) "Top side".

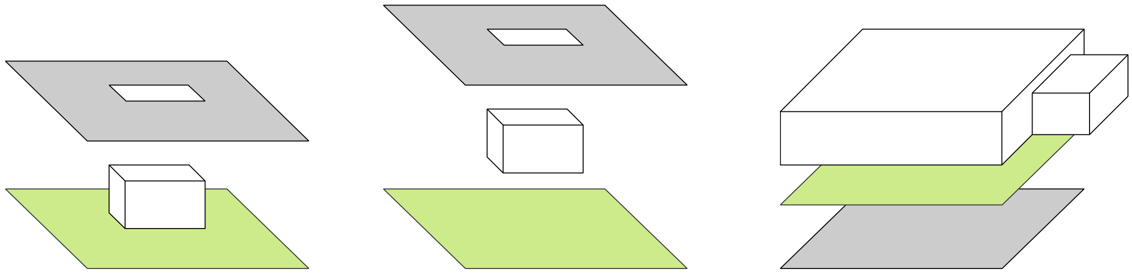
a) b) c)

Figure 7. Simple illustration of the Bottom concepts. (a) “Bottom plate”, (b) “Bottom plate+”, (c) “Bottom side”.

Lastly are the Front, Back, and Side concepts. The “Front plate” in Figure 8a consists of a 90 degrees connector and PCB, inserted from the front into a hollow base structure and sealed by a plate with a hole for the connector. This concept suffers from being overly complex and not reliable and it also carries the same issues as “Top plate” and “Bottom plate+” when it comes to fastening the connector. The concept “Front plate+” in Figure 8b illustrates an alternative that tries to eliminate these issues. With the connector integrated into the plate, the area of sealing required decreases. Figure 8c shows the concept “Back plate”, where the PCB is inserted from the back and the connector goes through the hole in the front. This is beneficial in the amount of sealing that can be eliminated. There are however problems with the fastening of the connector to the base structure, with the manufacturability, and the overall flexibility. As for the side concepts, no feasible solution has been found.

The insertion concepts can be compared with each other in a tentative concept screening matrix (Ulrich, & Eppinger, 2012), see Table 3. This is done in regards to a reference concept, which will be the “Bottom plate” concept, since this represents the current ECU in the form of the RCIOM. A number of criteria are used to compare the concepts to this reference. These criteria embody the most important requirements and purposes of the GION.

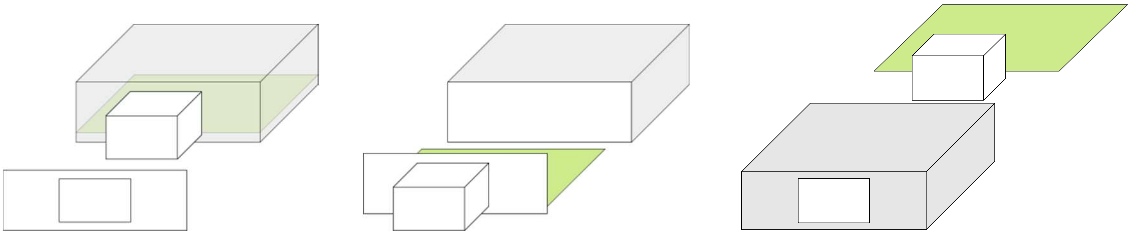
a) b) c)

Figure 8. Simple illustration of the Front and Back concepts. (a) “Front plate”, (b) “Front plate+”, (c) “Back plate”.

For the criteria *Manufacturing (cost)*, three concepts performed poorer than the reference. “Front plate” requires the cover plate and connector to be manufactured separately, as well as the hollow enclosure. This hollow enclosure could prove to be problematic in manufacturing. “Front plate+” has an integrated cover plate with the connector, but also has the hollow enclosure. “Back plate” has a hollow enclosure, in addition to a complex opening.

For the criteria *Assembly (cost)*, three concepts performed poorer than the reference. “Top plate” has a more complicated assembly process, where the cover plate needs to be fastened around the edges of the enclosure as well as around the connector. Doing this in one step could be problematic. “Bottom plate+” also has assembly issues with many steps having to be performed at the same time. “Front plate” will require many operations in assembly to fasten the connector and ensure seal integrity. Two concepts performed better than the reference. “Front plate+” eliminates many assembly steps with an integrated connector. “Back plate” eliminates even more assembly steps with an enclosure hole that can fit the connector. This concept probably performs the best from an assembly point-of-view.

For the criteria *Thermal dissipation (performance)*, three concepts performed poorer than the reference. “Top plate” uses a plastic cover which is a bad heat conductor, meaning it only transfers heat from the bottom. “Top plate+” uses a plastic cover as well. “Top side” uses an aluminium cover on the top. Having it on the bottom in contact with the PCB would be better. One concepts performed better than the reference. “Bottom side” has the cover plate on the bottom, and because the connector uses so little space, there is a lot of surface area that can be used for cooling.

For the criteria *Shock and vibration (performance)*, there was not enough information available to make an educated assessment of which concepts performed better or worse than the reference

For the criteria *Sealing (performance)*, six concepts performed poorer than the reference. “Top plate” has a sealing line that goes around the entire enclosure, as well as around the connector. Having the seal on the top, along with a plastic cover, makes this worse than the reference. “Top plate+” eliminates some of the sealing issues with its integrated connector, but the other problems remain. “Top side” also has the sealing on the top, which makes it too unprotected. “Bottom plate+” introduces complex sealing solutions when it comes to fastening the connector from the outside, as opposed to from the inside. “Front plate” has many sealing lines that run too close to each other which makes it complicated and redundant. “Back plate” has a complex sealing solution as well, since the connector will need to be fastened from the outside. Two concepts performed better than the reference. “Bottom side” combines the connector sealing line with the bottom plate sealing line, reducing the complexity. “Front plate+” minimizes the sealing by using integrated connectors. Because it is inserted from the front, the area that needs to be covered with sealing is also smaller in comparison.

Table 3. Comparison of insertion concepts

Selection Criteria	Top plate	Top plate+	Bottom plate (REF)	Top side	Bottom side	Bottom plate+	Front plate	Front plate+	Back plate
Cost									
Manufacturing	0	0	0	0	0	0	-	-	-
Assembly	-	0	0	0	0	-	-	+	+
Performance									
Thermal dissipation	-	-	0	-	+	0	0	0	0
Shock and vibration	0	0	0	0	0	0	0	0	0
Sealing	-	-	0	-	+	-	-	+	-
Form									
Size	0	0	0	0	0	0	0	0	0
Functionality									
Flexibility	0	0	0	0	0	0	+	+	0
Scalability	0	0	0	+	+	0	+	+	+
Sum +	0	0	0	1	3	0	2	4	2
Sum 0	5	6	8	5	5	6	3	3	4
Sum -	3	2	0	2	0	2	3	1	2
Score	-3	-2	0	-1	3	-2	-1	3	0
Rank	9	7	3	5	1	7	5	1	3
Selection Criteria	Top plate	Top plate+	Bottom plate (REF)	**Top side**	Bottom side	**Bottom plate+**	Front plate	**Front plate+**	Back plate

For the criteria *Size*, it was not yet clear how the concepts would perform compared to the reference. “

For the criteria *Flexibility*, two concepts performed better than the reference. “Front plate” can use different number of connectors as well and different sized connectors, without affecting the enclosure. The size of the plate also means that this change only needs to be minor. “Front plate+” also has these advantages, with the added fact that with an integrated connector, only one part needs to be changed.

For the criteria *Scalability*, five concepts performed better than the reference. “Top side” can manage two PCBs slightly better than the reference. “Bottom side” does it likewise. “Front plate”, “Front plate+” and “Back plate” can all use both multiple PCBs as well as different sized PCBs. They are much easier to customize than the reference.

The result from screening the methods of PCB insertion gives a first guideline to possible enclosure design solutions. The highest ranked concepts are “Bottom side”, “Front plate+”, “Bottom plate”, and “Back plate”. However, the “Back plate” concept has more issues with manufacturability than what the screening suggested. Since the purpose of the screening was to be a rough tentative screening of realistic concepts, the relative weight of each criterion was not included. If this type of concepts scoring was made, the manufacturing criteria would have gotten a higher focus. Because of the higher problems associated with it, the “Back plate” concept will not be considered.

4.3 Enclosure Design Concepts

The results from the insertion concepts screening are three different ways of insertion, namely “Bottom side”, “Front plate+” and “Bottom plate”. They can now be used to further develop the Enclosure design solutions. These shall then in turn be compared with each other in a similar screening matrix.

The concepts are described in the text with numbers that reference to the figures to help understand the different parts and how they function. They are presented in separate pages for clarity.

4.3.1 Rails

This concept is derived from “Front plate+” and uses an extruded profile to create a straight-walled base structure (1), see Figure 9. This kind of design is not easily made possible by cast manufacturing because of draft angles. This fact adds to the uniqueness of this particular concept. With rails (2) incorporated on the inside of the profile, it is possible to slide the PCB (3) in from the side. By using a side connector (4) solution, this allows for fast assembly. Multiple rails enable multiple PCBs to be installed. Connectors can sit on one PCB or multiple PCBs (5). If multiple connectors are to be possibly used, they should be integrated into a connector package (6). This will allow faster assembly, but is also crucial for ensuring a correct seal (7), which is located between the housing and the assembled connector. This would also mean that the connector package accounts for the product variance, along with the PCBs. Basically, as long as the interface between the connector package and the base structure remains the same, in order to ensure the sealing, any type of connectors can be used. Because of the extruded nature of the base structure, it is very simple to change the length of it to account for larger PCBs, meaning the scalability is high.

Heat transfer is enabled through the use of thermal pads (8) on the rails. The pads also help with vibrations and mechanical shocks, by holding components in place. A soft, not so sticky pad should allow for the PCB to slide across it, preferably compressing it in the process as to increase thermal conductivity. The easy assembly of the PCB and connector is however only possible if the pads are assembled in advance, which evens out the gains in total assembly time. For outside thermal convection, it is very easy to add fins (9) to the extruded profile.

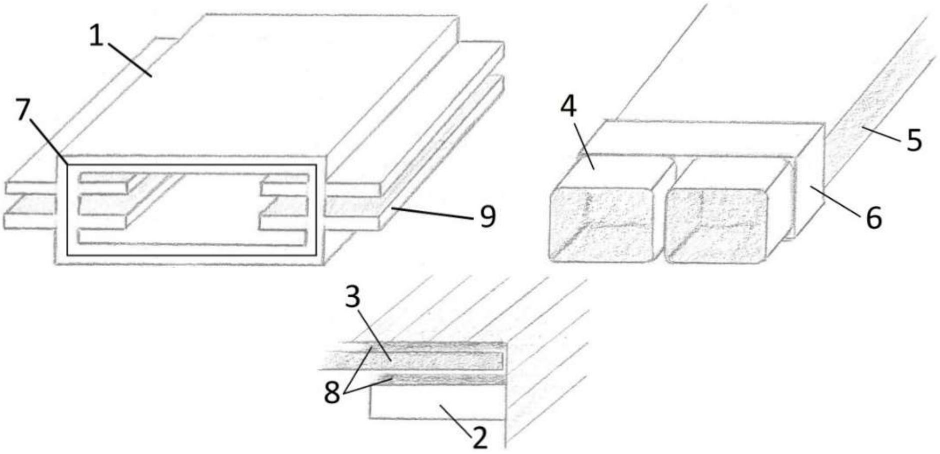

Figure 9. Different elements in the rail concept.

4.3.2 Bottom Side

“Bottom side” can be directly translated into a concept consisting of a cast housing (1) which defines the top with possible heat sink elements (2), see Figure 10. The connector (3) is fastened to the PCB (4) and then inserted from the bottom into the housing. Bottom insertion provides a good protection for the underside sealing line. The PCB can be thermally attached to the roof of the housing if it is attached to the connector as in (5). The bottom plate (6) is connected from below and sealed across its sides (7). Prior to this the connector is sealed along a path (8) that seals the connector and the housing. The connector is then sealed with the bottom plate.

To incorporate multiple connectors, a connector system (9) is used. This can have different variants, but the overall dimensions define the interface. A second PCB can be placed on the bottom plate with the correct tolerancing. The PCBs would be attached to each other by a support (10), which could also represent an internal connection between the PCBs. This is the case of using the connectors for each PCB. Using connectors on only one PCB enables use of a shorter connection (11) and less distance between PCBs. The size of the enclosure is however not governed by this distance, but by the overall size of the connector itself.

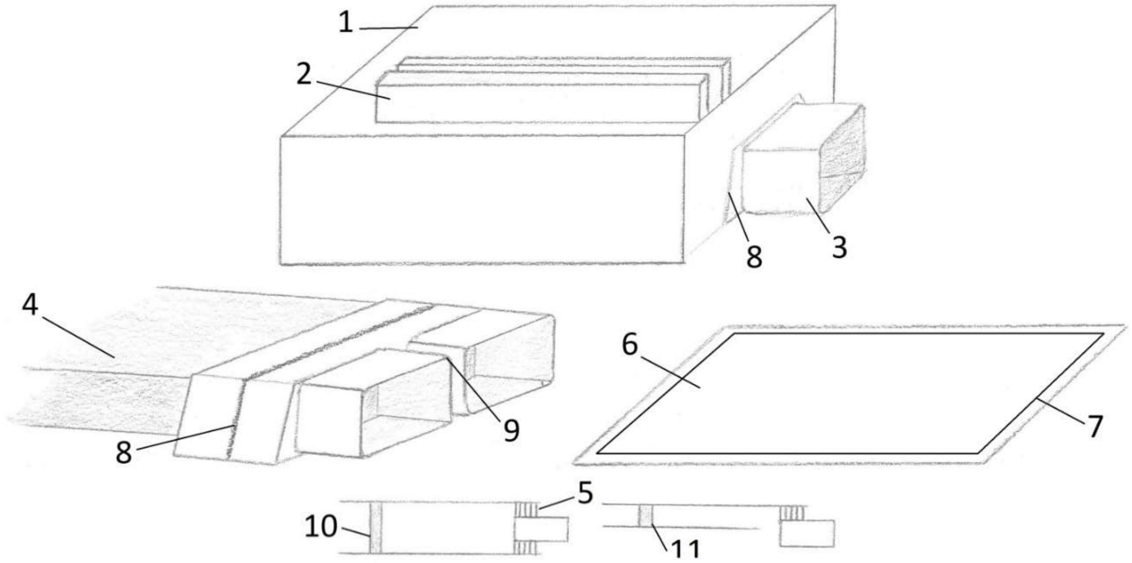

Figure 10. Different elements in the bottom side concept.

4.3.3 Side Hole

Combining “Back plate” and “Bottom side” enables a concept that makes the former more feasible, while keeping many of the advantages. It consists of a cast base, see Figure 11, with sides (1) included. One of the sides has a pocket (2) that is used for inserting the PCB (3) and contain the connector (4). Once inside, the PCB is connected to the base top (5) with thermal material and possibly other means of fastening. The connector package (6) is sealed on the side (7) and a bottom plate (8) finishes the seal. Alternatively, the connector package with PCB could be inserted from below and the connectors seal along the inside of the side pocket. This requires the base structure to be somewhat longer to make space for the extra length created by the connectors at insertion. It does however create the possibility of a better seal positioned on the inside. Although the increased length and ways of fastening could still cause more issues than it solves.

A second PCB and connector could also be integrated. The second PCB could connect thermally to the bottom plate, provided the correct tolerancing. Because the PCB is inserted from below, there are no direct issues with draft angles, although the second PCB would preferably need to be a bit larger so that the sides of it could rest against the sides of the higher draft angles.

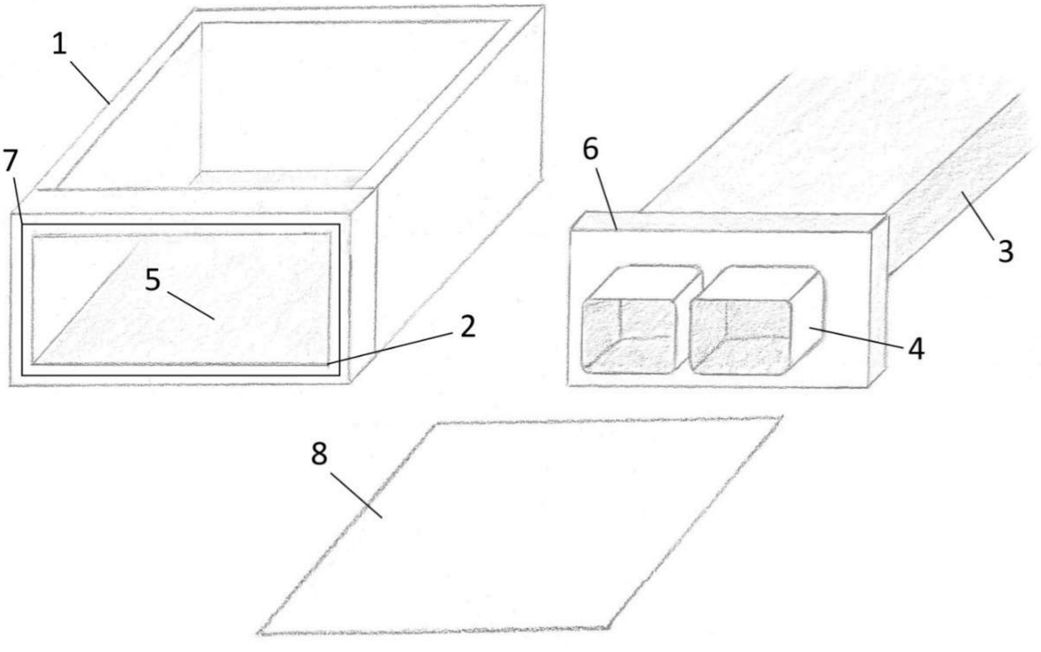

Figure 11. Different elements in the side hole concept.

4.3.4 Top Connect

Reusing the principles of “Bottom plate”, it possible to examine how the existing solution may be modified for the new requirements. The PCB (1) is inserted through the bottom of the housing (2) and the connector (3) on the PCB is placed through the hole (4) on the top of the housing, see Figure 12. Another PCB can be placed underneath the first and a long connector (5) then goes through a second hole (6) in the housing. It is possible for this hole to only exist in the low version with only one PCB and then added if needed. It could also be closed with a blind plug if no connector is needed to occupy that place. The PCBs would will as mentioned have an internal connection (7) which also acts as a support. The bottom PCB could also be placed against the bottom plate to compliment this.

The first PCB could end short as in (9), or extend as in (10). This works well if the housing is made flat on the top, with the connector placed vertically parallel with each other. Another alternative is to have a housing according to (8), which would allow all the connectors to use short connector pins. This would simplify the design of the PCB and use of connectors, but would possibly create unused space within the housing. Using two PCBs, however, creates this problem either way.

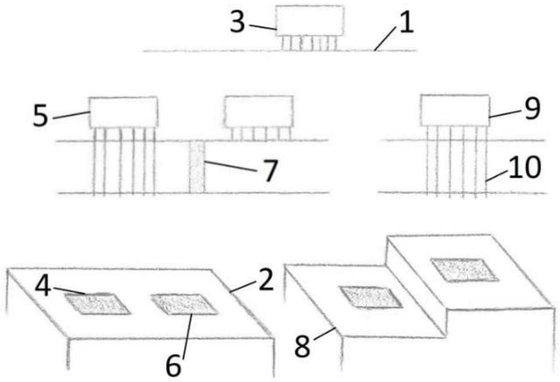

Figure 12. Different elements in the top connect concept.

4.3.5 The L

Merging “Bottom side” and “Bottom plate” gives rise to this flexible combination. The PCB is inserted from below together with connectors, see Figure 13. The connector package is formed in such a way that it can be turned to allow the connectors to be positioned either on the side or the top. This form follows a double sloped surface. The sealing line follows the edges of the pocket in the housing and connects to the connectors accordingly. In the case of the connectors pointing upwards, the pins will be vertically straight. When the connectors are pointing to the side, the pins will be perpendicular.

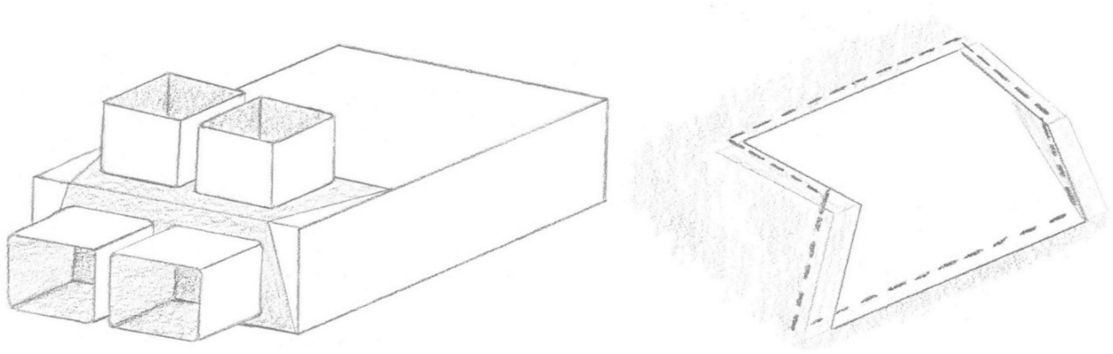

Figure 13. Different elements in the L concept.

4.3.6 Comparison

The final enclosure concepts can be compared with each other in a concept screening matrix as before (Ulrich & Eppinger, 2012), see Table 4**Error! Reference source not found.**. This is done in regards to a reference concept, which will be the RCIOM that represents the current ECU. The criteria used to compare the concepts are the same as previously. However, it is easier to get meaningful data at this time when the concepts are more developed and easier to understand.

For the criteria *Manufacturing (cost)*, one concept performed poorer than the reference. “Side Hole” will be complicated to manufacture and will not be cost efficient in mass production, or even for prototyping for that matter. One concept performed better than the reference. “Rails” has an easily manufactured extruded profile, with can produce many units in a short time and in an uncomplicated and not expensive way.

For the criteria *Assembly (cost)*, one concept performed poorer than the reference. “Side Hole” has a complex way of assembly. It also creates extra unused space at the back, which ties together with the manufacturing. Two concepts performed better than the reference. “Bottom Side” requires a minimum of assembly steps and is a popular method among many other ECUs. “The L” is similar in idea, but needs more investigation in practice.

For the criteria *Thermal dissipation (performance)*, four concepts performed better than the reference. “Bottom Side”, “Side Hole”, “Top Connect and “The L” utilizes the top side for cooling which can be more efficient. The reference does not make full use of this as it is.

For the criteria *Shock and vibration (performance)*, there was not enough information available to make an educated assessment of which concepts performed better or worse than the reference.

For the criteria *Sealing (performance)*, there was indications of how this would look and perform, but not enough to make any comparisons. The reference also didn’t have any problems in the regard

For the criteria *Size*, four concepts performed better than the reference. “Rails”, “Bottom Side”, “Side Hole” and “Top Connect” all have possibility of being made smaller than the reference. “The L” is more uncertain because it may require a bigger size to function. “Bottom Side” and “Side Hole” may also turn out bigger than expected due to the use of two PCBs, but possibly not enough to make than bigger than the RCIOM.

For the criteria *Flexibility*, three concepts performed better than the reference. “Rails” can use different sized connectors, different number of connectors and different PCBs, all providing they follow the interface laid out. “Top Connect” can also change between the connectors in a similar way, although somewhat more limited. “The L” is the same, and can also change the orientation of the connectors, providing more flexibility.

Table 4. Comparison of concepts

Selection Criteria	RCIOM (REF)	Rails	Bottom Side	Side Hole	Top Connect	The L
Cost						
Manufacturing	0	+	0	-	0	0
Assembly	0	0	+	-	0	+
Performance						
Thermal dissipation	0	0	+	+	+	+
Shock and vibration	0	0	0	0	0	0
Sealing	0	0	0	0	0	0
Form						
Size	0	+	+	+	+	0
Functionality						
Flexibility	0	+	0	0	+	+
Scalability	0	+	0	0	0	0
Sum +	0	4	3	2	3	3
Sum 0	8	4	5	4	5	5
Sum -	0	0	0	2	0	0
Score	0	4	3	0	3	3
Rank	5	1	2	5	2	2
Further development	No	**Yes**	No	No	**Yes**	**Yes**

For the criteria *Scalability*, one concepts performed better than the reference. “Rails” outperforms all others by being able to change the size of the enclosure quite easily in production, enabling the use of different sized PCBs and also opening up for future use in other places besides the chassis.

The results show that the performance of the RCIOM can be improved by choosing a similar concept than enables the use of two PCBs or a new one that can be improved additionally. Furthermore, it shows that the “Side Hole” concept will not be considered. The “Bottom Side” concept and the “The L” concept are quite similar. The latter is however more interesting than the other, since the “Bottom Side” concept is quite common among other ECUs. The “Bottom Side” concept will therefore not be developed further.

5 Connectors

This chapter will go into the choices for the design solution Connecting system. The connecting system for the I/O signal and the connecting system for the power supply will be discussed. How these connectors will integrate into the enclosure is also important.

5.1 I/O Connector

Housing the PCB is a major function of the enclosure. The previous enclosures used one PCB of varying designs depending on the application. The new ECU will use up to two PCBs in order to cover the range of existing versions. These will be two unique PCBs, compared to the multiple ones used before. Another major function of the ECU is the connection of I/O signals to the PCB. Connectors that provide these signals will be integrated into the design and used together will the rest of the enclosure.

In order to account for the previous versions it was important to choose connectors with enough pins to cover the required I/O signals for the new ECU. A connector that fulfilled the requirements was a 58-pin connector from TYCO (Modular Connector – Product Specification). This connector had dimensions 55.6 mm x 31.6 mm and a depth of 23.5 mm.

Some of the concepts featured side connectors with perpendicular pins. The idea for incorporating these was to position the two connectors, one for each PCB, next to each other and pointing in opposite direction. This gave a measure for the possible distance between PCBs that are stacked on top of each other. Some guidelines were taken from a different application which is visualized in Figure 14.

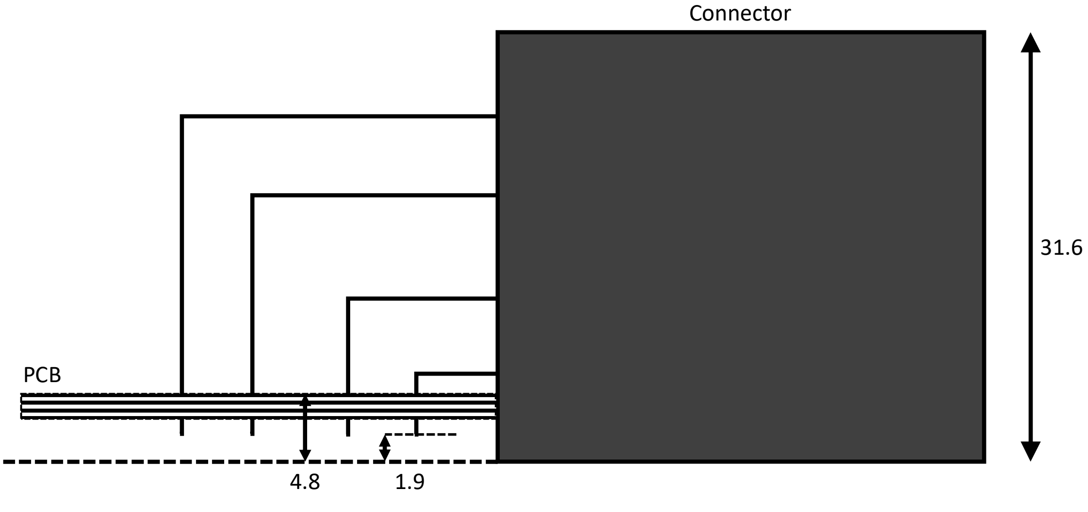

Figure 14. Important parameters that show how the 58-pin connector interacts with the PCB.

There are four rows of pins exiting the backside of the connector and going down into the PCB. The guideline was to have a distance of 4.8 mm from the inside of the PCB to the end of the connector. With two connectors in parallel, this give 31.6 – 4.8 x 2 = 22 mm between PCBs.

5.2 Power Connectors

The current ECU uses 2-pin power connector that handles a maximum of 30 ampere each. Looking at the number of high-side drivers that is used for GION, the required current is up around 200 ampere for both PCBs. Even with two old power connectors the total current supply will only be 120.

It was decided to use a DTHD04-1-4P for the receptacle and a DTHD06-1-4S for the plug from DEUTSCH. They support a current of 100 ampere and can mounted on a PCB by soldering the pin. If one for each PCB is used, it will cover the power supply for a PCB at maximum performance and also serve as a backup if one of the power supplies fail.

Together with the 58-pin connectors, the power supplies will influence the size of the enclosure. The 58-pin connector length was 55.6 mm. With two connectors, the length adds up to 111.2 mm. As for the power connector, the pin will be soldered to the PCB. With a distance of 22 mm between PCBs, this creates a restriction for the positioning of the powers connectors. If the diameter of the power pin is 8.76 mm and the diameter of the power shell is 26.54 mm, then the angle and width of two power connectors in tangent can be calculated, and with them the length can be determined. Figure 15 shows the setup for the connectors and Table 5 the exact values. Calculation can be found in Appendix C.

Table 5. Values for the angle, length, and width of two power connectors together. Comparison to a distance of 20 mm.

PCB_dist	Angle	Length	Width
20.0000	25.0565	50.5823	37.7800
22.0000	29.9252	49.5416	39.7800

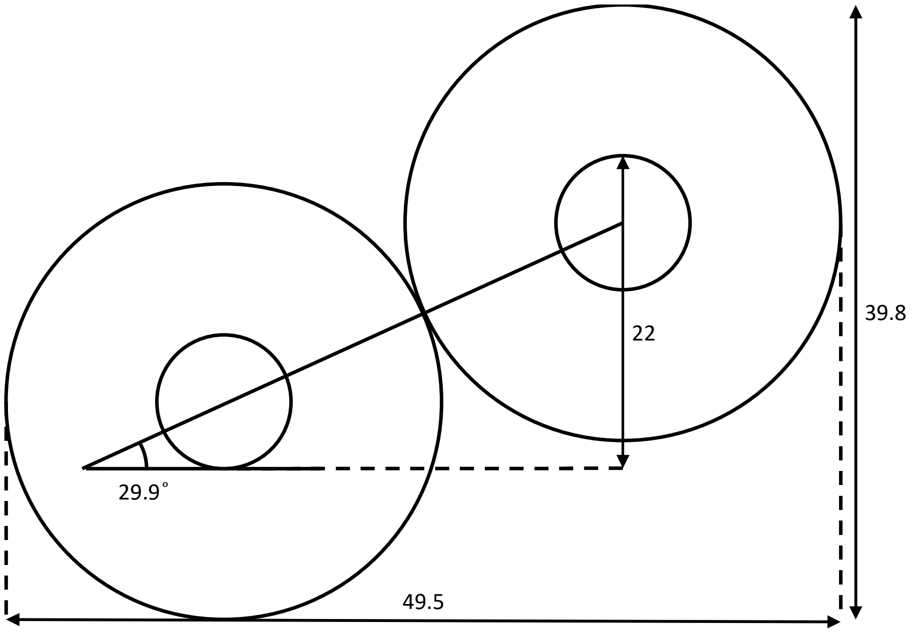

Figure 15. Positioning of two power connectors next to each other. With a distance between PCBs of 22 mm, this is the most efficient way to reduce the total length of the connector package.

6 Alternate concepts

According to Table 4, there were three concepts that seemed promising and were considered for further development. Ultimately, it was decided that The L concept would be developed for a prototype. However, the other two remaining concepts, Rails and Top Connect, were interesting enough to justify this chapter that will explain what needs to be done to make these concepts successful.

6.1 Different Concepts – Rails

The perpendicular side connectors can be used for the Rails concept, se Figure 16. The 22-mm distance between PCBs gives the necessary information for the inner dimensions. Information about the other dimensions makes it possible to translate into dimensions for the enclosure that fits with both the connectors and the PCBs. This concept was developed further after the initial design. Several adjustments are needed for a successful integration.

The heat transfer would not occur from the sides. The available space is too small for the area and number of switches on the PCB. Instead, heat transfer would occur over a larger area in the middle of the PCB, where the semiconductors would need to be positioned. A semi liquid thermal interface material would be used across the face instead of thermal pads as originally intended.

The inner flanges of the enclosure could be smaller to simply allow the PCB to rest on its edges. One side of the ceiling would need to be hollowed out a bit to allow room for the pins exiting the other side of the PCB, as well as other pins that goes through the PCB.

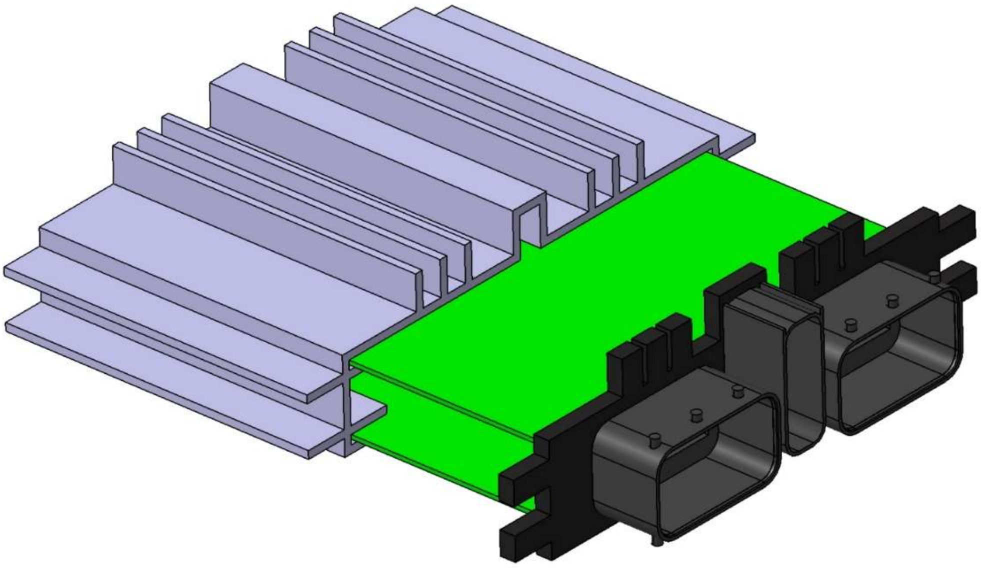

Figure 16. Early developed rail concept

For consistency, the connectors would be integrated into a single package and would not be separable.

Rough measurements of this concept are as follows; length is 214 mm, width is 162 including connectors, and height is 69 mm.

6.2 Different Concepts – Top Connect

A version of the concept is in Figure 17. The use of straight pins for the connectors is a valid one and probably the least space consuming. The extra space required for dual PCBs is the only concern. The 58-pin connector that was available uses perpendicular pins exclusively. Therefore, for the sake of the prototype, it was not possible to use this type of connector. It would have been possible with the use of a different connector. However, the connectors that were available that had approximately the same number of pins, were vastly oversized and less compact in pin density. Still, this concept was developed further after the initial design and some adjustments could be made for a successful integration.

The connectors would be more appropriately arranged to allow for the maximum area for heat transfer. Dimensions of fins for heat dissipation would be free of restrictions.

Fasteners could be properly used to secure PCBs along with connectors.

The connectors are divided into two parts, with one for each PCB. Positioning the connectors on different levels would allow for the use of the same pin length for both connectors.

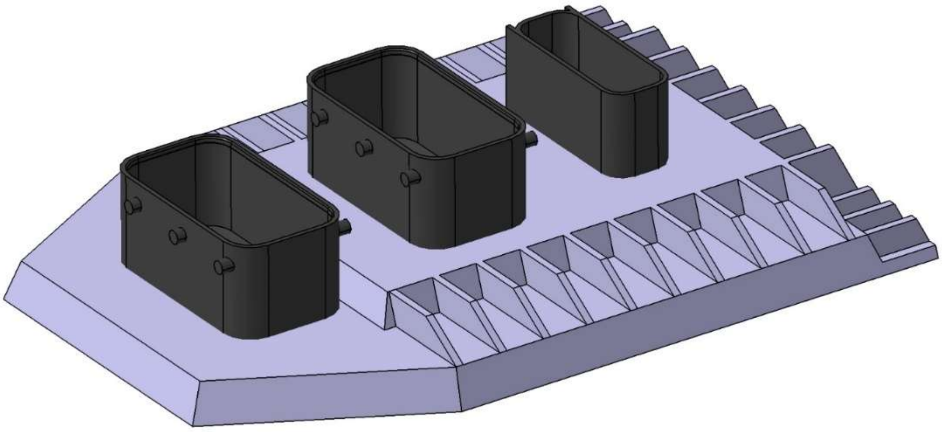

Figure 17. Early developed top connect concept.

7 Developed Design – The L

The L concept was first pursued due to its unique properties. The connectors can change orientation by turning them along two planes. This allows for them to be positioned or either the top or the side and this is believed to have value in increased flexibility. Depending on the surrounding environment on the truck, there may the other objects that introduce restrictions on how to place the ECU. This idea is to circumvent that by changing the connectors orientation prior to assembly. See Figure 18 and Figure 19 for the different ways of assembly.

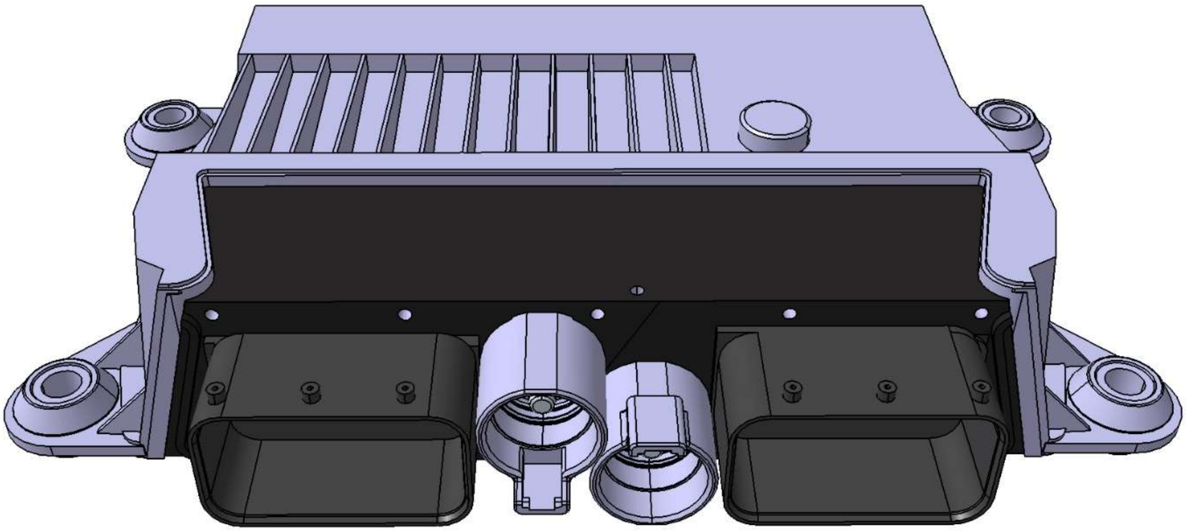

Figure 18. The connectors are orientated along the side.

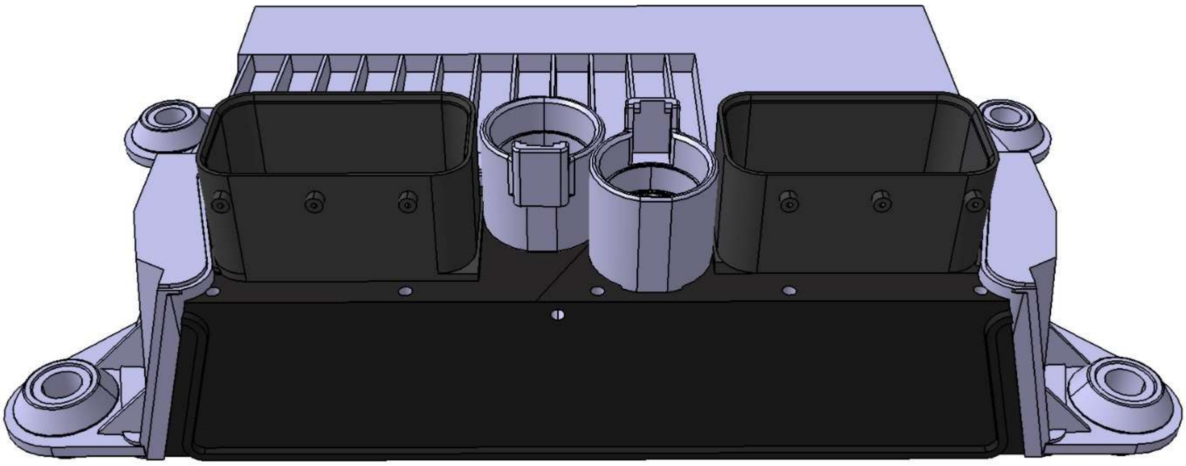

Figure 19. The connectors are orientated on the top.

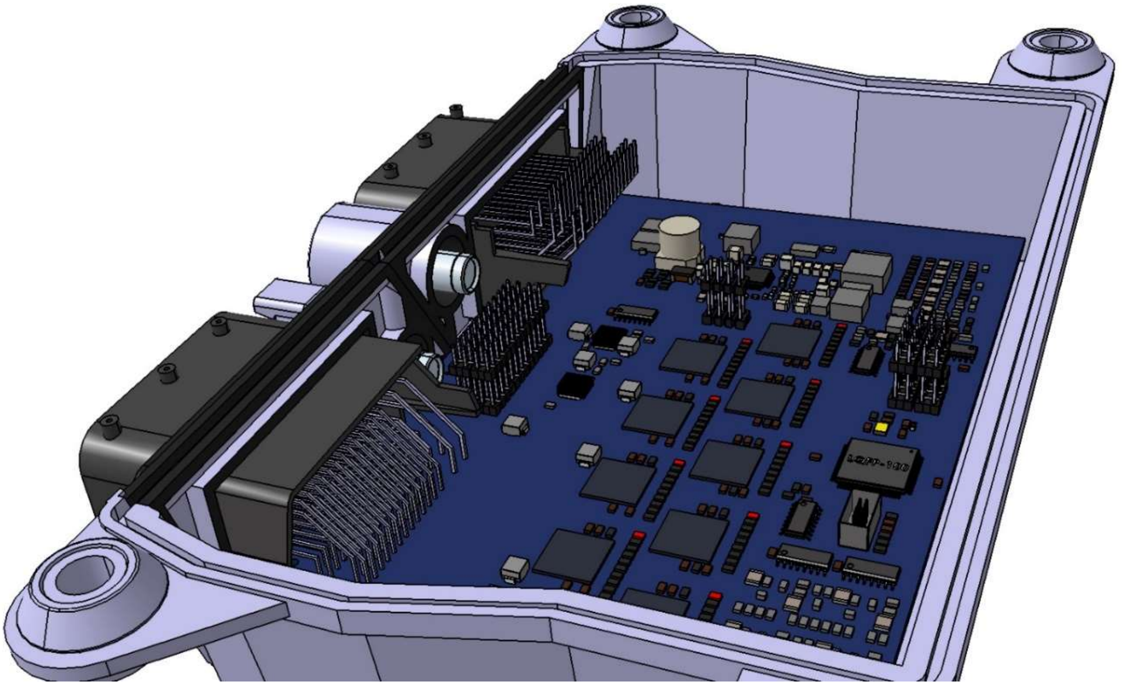

Figure 20. Inside of the enclosure showing the PCB with the 58-pin connector.

The first PCB is placed with the underside against the roof of the enclosure, see Figure 20. It will be connected to one of the 58-pin connectors and a power connector. The semiconductors that require cooling will need to be placed together with no pin or object on the opposite side, to allow for a flat surface. A second PCB can be placed on top and connected by the other 58-pin connector, power connector and internal pins to connect the two boards.

The underside of the enclosure has a groove running along its edge which continues across the connector package. This groove will be in contact with a bottom side. The bottom side will be a sheet metal plate with curved edges that enter the groove. The groove is prior to assembly filled with a liquid sealant that acts as glue, similar to the current ECU. The bottom side will also need to be formed in such a way that part of its side comes into contact with the second PCB, to enable heat transfer on that side.

The prototype that was made can be seen in comparison to the FCIOM in Figure 21, which is one of the lower versions of the current ECU. A comparison to the higher version RCIOM can be seen in Figure 22. With regarding to size, this version of GION is definitely smaller in size compared to its older counterpart. However, with the complete model the difference gets less apparent. This is in part due to the two PCBs, which create more empty space inside of the ECU, and part due to the use of side connectors which increase the space outside the ECU.

Rough measurements of this concept are as follows; length is 272 mm, width is 171 mm including connectors, and height is 55 mm not including the connectors. This iteration of the PCB has length of 178 mm and width of 119 mm.

Figure 21. GION prototype next the FCIOM. Compare to previous figures.

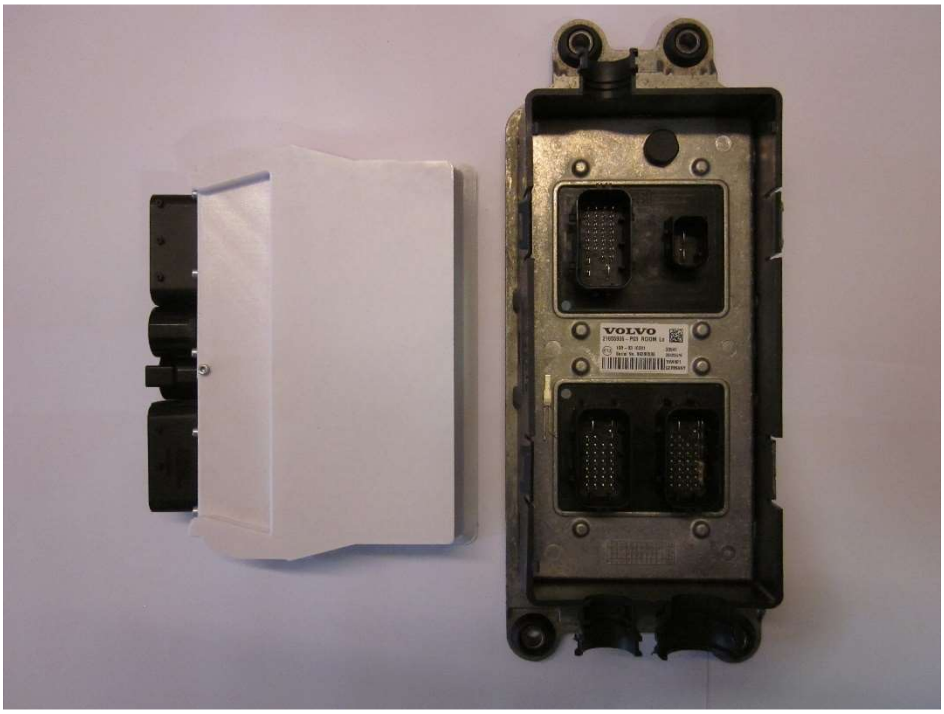

Figure 22. GION prototype next to the RCIOM. Compare to previous figures.

8 Thermal Resistance – Heat Transfer Design Solution

The heat transfer of the ECU can be seen as a heat transfer through a system of parts. The heat originates from the junction inside the high-side-driver components. It then migrates through the PCB, through the TIM, through the outer casing, and into the outside atmosphere. This process through the different layers will be explained in this chapter. The discussion later will tie all the parts together. This chapter is valid for a general configuration, and not necessarily part of a specific concept. It is up to the concept itself how well it can incorporate the designs that are suggested in this chapter.

8.1 Enclosure Thermal Resistance

The nature of the ECU developed requires a power consumption that is far from negligible. With a fixed voltage supply, power in the switches is directly proportional to the ampere needed in each individual switch. This power is power that will be used in the switches and dissipated as heat. If the temperature due to this heat rises too much, it risks damaging the junction die inside the switch and reduce the expected life time.

Referring to the requirements, it was shown that for each ten degrees increase in temperature the life time of the switch is reduced by half. For electronics, the biggest obstacle for increased performance is the inevitable temperature increase. For this reason, many high-power electronic devices use fans for cooling. However, the exposed positioning of the ECU on the chassis does not allow for the use of fans, since this would compromise the sealing required to keep out dust and water and other fluids. This fact creates the need for passive cooling through the ECU housing. Passive cooling is done solely by natural heat transfer into surrounding environments.

8.1.1 Heat Transfer and Thermal Resistance

Passive cooling uses natural heat transfer through materials and into a passing fluid. Heat transfer is a measurement of the speed of heat transport across materials. This rate can be expressed by (Heat Transfer, 2002)

$$q = -kA\frac{\partial T}{\partial x} \tag{8-1}$$

where q is the heat-transfer rate, k is the thermal conductivity of the material, A is the area of the transfer and $\partial T/\partial x$ is the temperature gradient in the direction of the flow.

The thermal conductivity defines the transfer of heat through a material. This process can be explained by lattice vibrations and movement of free elections in solids. This means that materials with good electrical conductivity usually has good thermal conductivity as well. The process that defines the transfer of heat between a material and a fluid is the thermal convection, which can be expressed as (Heat Transfer, 2002)

$$q = hA(T_w - T_\infty) \tag{8-2}$$

where h is the convection heat-transfer coefficient. Convection heat-transfer is dependent of the boundary layer that forms between a wall and a moving fluid. Because of this, it is often necessary to determine the convection factor experimentally. The process of convection can be explained by the movements of molecules of a fluid and is also dependent on the viscosity and density of the fluid. For instance, water has a lot higher convection rate than air. Furthermore, a higher temperature simply means a higher activity of molecules in a solid of fluid. This means that the conductivity and convection factor increases with increased temperature, although the increase is understandably higher for fluids compared to solids.

The thermal conductivity, thickness of a material, area of effect, and convection to a surrounding fluid, may be viewed a resistance to the flow that is the heat-transfer rate. From equation (8-1), the thermal resistance for conduction can be expressed as

$$R = \frac{\Delta x}{kA} \tag{8-3}$$

and from equation (8-2), the thermal resistance for convection is

$$R = \frac{1}{hA} \tag{8-4}$$

8.1.2 Heat Sink Optimization Model

If looking at an extruded surface in the shape of a fin, see Figure 23, the energy from the base is equal to the energy going out through the material and the energy that is dissipated from the surface. Simply put, it is the combination of conduction through the material and convection into the surroundings. In order to calculate the total thermal resistance of a fin, it is necessary to consider the fact that the transfer-rate is not completely efficient. For a simplified case, the fin efficiency, η_f, can be expressed as

$$\eta_f = \frac{\tanh mL_c}{mL_c} \tag{8-5}$$

where

$$mL_c = \sqrt{\frac{hP}{kA_b}}L_c \tag{8-6}$$

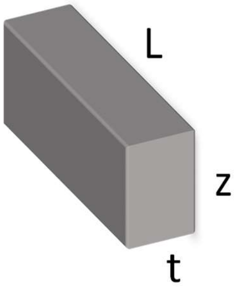

Figure 23. Dimension of an extruded surface.

P is the perimeter or circumference of the fin expressed as

$$P = 2z + 2t \tag{8-7}$$

where z is the depth and t is the width of the fin. L_c is a corrected length of the fin defined by

$$L_c = L + t/2 \tag{8-8}$$

A_b, the cross section area of the fin is

$$A_b = zt \tag{8-9}$$

Putting these together and the fin efficiency can be seen as

$$\eta_f = \frac{\tanh mL_c}{mL_c} = \frac{\tanh\left(\sqrt{\frac{h(2z+2t)}{kzt}}\left(L+\frac{t}{2}\right)\right)}{\left(\sqrt{\frac{h(2z+2t)}{kzt}}\left(L+\frac{t}{2}\right)\right)} \tag{8-10}$$

The thermal resistance of a section of a system of fins can divided into several parts. The resistance through the wall beneath the fin, R_{wf}, the resistance through the fin into the atmosphere, R_f, the resistance through the wall between the fins, R_{wo}, and the resistance from the wall between the fins into the atmosphere, R_o. The total resistance of the heat sink from the base through the fin into atmosphere can then be expressed as

$$\frac{1}{R_{tot}} = \frac{1}{R_{wf} + R_f} + \frac{1}{R_{wo} + R_o} \tag{8-11}$$

From equation (8-3) and (8-4), the respective resistances will then be

$$R_{wf} = \frac{\Delta x}{kA_b} \tag{8-12}$$

$$R_f = \frac{1}{\eta_f A_f h} \tag{8-13}$$

$$R_{wo} = \frac{\Delta x}{k A_o} \tag{8-14}$$

$$R_o = \frac{1}{h A_b} \tag{8-15}$$

The fin efficiency factor is included in the thermal resistance for the fin. The surface area of the fin is shown as

$$A_f = P L_c \tag{8-16}$$

and the surface area between the fins as

$$A_o = z L_o \tag{8-17}$$

The optimization goal will be to minimize the total thermal resistance of a system of fins. The optimization model for a system of one fin is then expressed as

$$\min R_{tot} \tag{8-18}$$

and the model of a given number of fins as

$$R_{tot,fins} = \frac{1}{\frac{n}{R_{tot}}} \tag{8-19}$$

The mass of a fin will be considered as well and can be expressed as

$$mass = tLz \tag{8-20}$$

8.1.3 Results

See Appendix A for these calculation in MATLAB.

For slower air flow speeds, the convection factor can be expressed by (The Engineering Toolbox)

$$h = 10.45 - v + 10\sqrt{v} \tag{8-21}$$

For a speed of $v = 0.5$ m/s, the convection factor $h \approx 17$ W/m^2 K.
For aluminium, an average conduction value of 200 W/m K can be used.

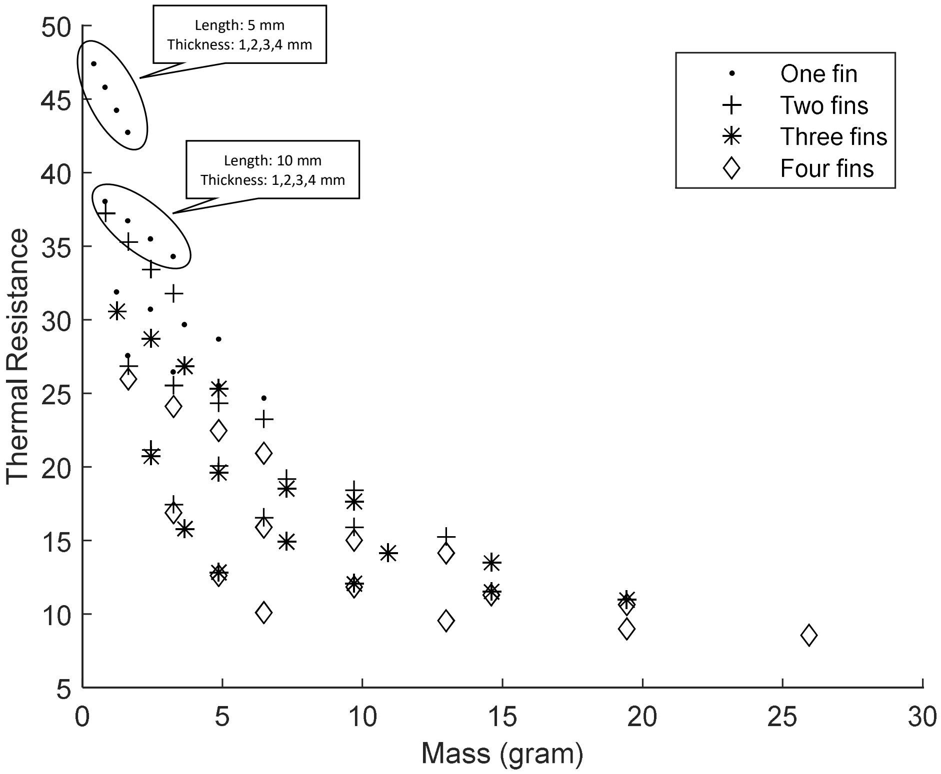

Figure 24 Plot of thermal resistance for a combination of different properties.

First made is a comparison between different number of fins in a given area and how this affects the thermal resistance. The system of fins under consideration is a 3 x 3 cm area of one to four fins. The base thickness is $x = 2$ mm. By changing the values of the fin thickness t and fin length L, the graph in Figure 24 can be plotted.

The important parameters to look at is the thermal resistance and the mass, since this will affect both the cost and the weight. What is important at this stage is to create a correlation between the design parameters and the resulting thermal resistance. This is still a necessary step, because this is but one part of the total thermal resistance.

The fin thickness values vary between 1,2,3, and 4 mm and represents the results in a group of values that can be seen in the plot. The fin length values vary between 5,10,15, and 20 mm and represents a bigger change of group values in the plot. The thermal resistance can be seen to decrease rapidly with increased number of fins, but not so much with increased thickness. This is because the convection heat transfer depends on the surface area of the fin. Adding a fin doubles the surface area but increasing the thickness by a few millimeters does not have as much effect. In this case, increasing the length gives more result.

This overall representation can be further examined in order to display the effects on the system by a change of values. Figure 25 shows the change in thermal resistance based on fin thickness, using a constant fin length of 15 mm.

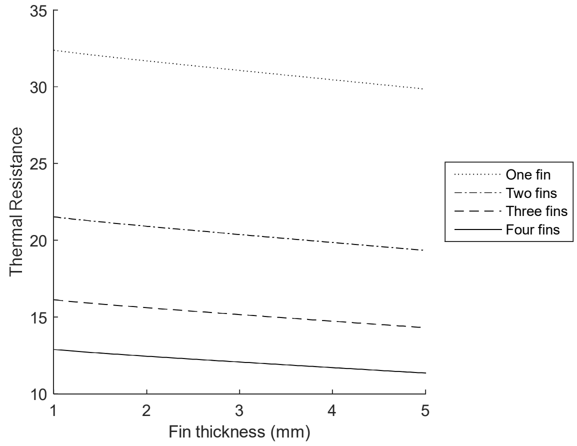

Figure 25. Plot of the thermal resistance depending on thickness of the fin.

The resistance changes significantly with increased number of fins, but only negligibly with increased thickness. Indeed, as shown before the thermal resistance is largely dependent on the surface area. Increasing the number of fins increases the total surface area much more than increasing the thickness would.

Figure 26 shows the change in mass based on fin thickness, again using a constant fin length of 15 mm.

The mass increases clearly with increased thickness, as well with the number of fins. Comparing with Figure 25, it is not justifiable to increase the thickness in order to reduce resistance.

Looking at the effects of fin length, Figure 27 shows its effects on the resistance for a constant thickness of 2 mm.

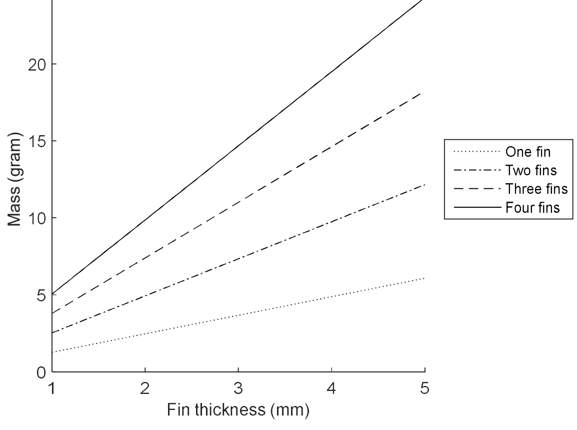

Figure 26. Plot of the mass depending on thickness of the fin.

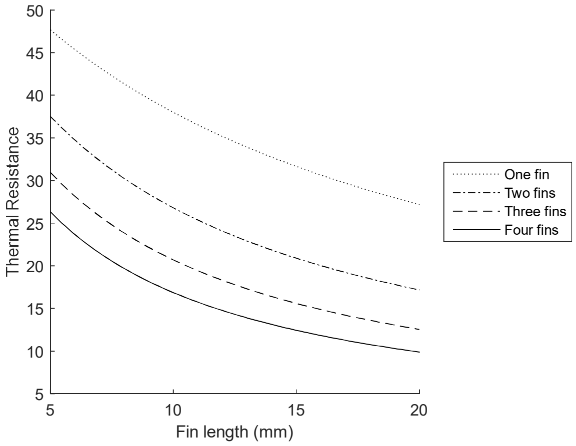

Figure 27. Plot of the thermal resistance depending on length of the fin.

Fin length definitely has a greater effect of reduced thermal resistance than thickness has. There is however not as much gained from an increased number of fins. As can be seen, there is also a somewhat exponential increase in resistance with decreasing fin length. A higher length would be preferable.

Figure 28 shows the change in mass based on fin length, again using a constant fin thickness of 2 mm.

An increase in fin length also shows an increase in mass. The conclusion to draw from all of this, is that it is important to estimate the maximum thermal resistance that the system can handle and then choose the parameters that results in the least amount of mass. Since the thermal resistance of the enclosure is only one part of the total thermal resistance of the system, it is not obvious what maximum value should be put on the resistance. This will be dealt with in the discussion later. However, with three fins, a length of 15 mm, and a thickness of 1.5 mm, a thermal resistance of 15 °C/W can be achieved. Since the enclosure holds the biggest resistance, this would be a good value.

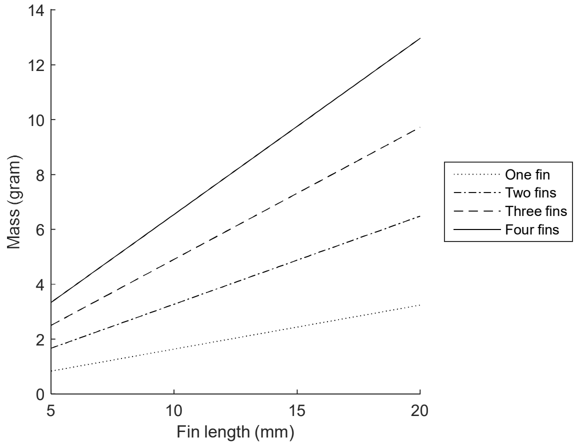

Figure 28. Plot the mass depending on length of the fin.

8.2 PCB Thermal Resistance

The previous section explained the necessity of proper cooling for the switches on the PCB. Passive cooling is used by transferring heat through the shell and by dissipation into surrounding atmosphere. In order to get a correct estimate of the temperature rise in the switches, it is required to know the thermal resistance of all the different elements along the way. Thermal resistance is often expressed with the symbol θ and the total resistance of the system can be expressed as (Thermal Design Basics. 2009)

$$\theta_{JA} = \theta_{JC} + \theta_{CA} \tag{8-22}$$

where θ_{JA} is the thermal resistance from junction to atmosphere, θ_{JC} is the resistance from junction to case, and θ_{CA} is the resistance from case to atmosphere. The previous section dealt with the resistance from case to atmosphere. This section will find an expression for resistance from junction to case.

A PCB is usually constructed in several layers, see Figure 29. Common materials used in the layers and their respective thermal conduction values are shown is Table 6 (Johnston, 2015).

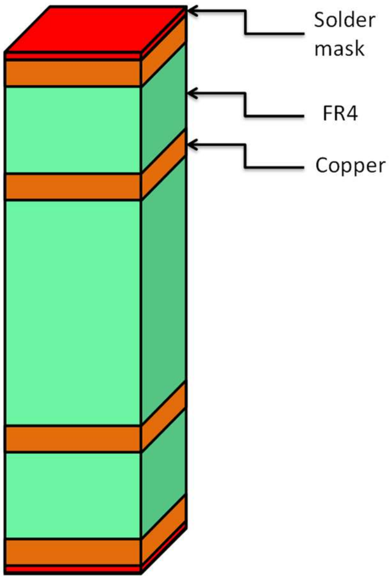

Figure 29. View of the layers in a PCB.

Table 6. Components of a PCB and thermal conductance.

Component	k	W/m·K
Air	k_{Air}	0.0275
Copper	k_{Cu}	355
FR4	k_{FR4}	0.25
Solder mask	k_{Sm}	0.21

As noted before, the thermal conduction through a material can be expressed as

$$\theta = \frac{\Delta x}{kA} \tag{8-23}$$

By adding the resistances of the multiple layer together a combine resistance through the PCB can be found as

$$R_{\theta PCB} = \frac{\Delta x_{Cu}}{k_{Cu}A_{Pads}} + \frac{\Delta x_{FR4}}{k_{FR4}A_{Pads}} + \frac{\Delta x_{Sm}}{k_{Sm}A_{Pads}} \tag{8-24}$$

where Δx_{Cu} is the total thickness of the copper layers in the PCB, Δx_{FR4} is the thickness of the FR4 layers, and Δx_{Sm} is the thickness of the solder mask layers. A_{Pads} is the area on the underside of the switch where heat is allowed to transfer from the junction to the PCB (PQFN, 2016).

In order to transmit current through the layers, PCB manufacturers add holes in the board with copper plated walls. These holes, called vias, are also used to transfer heat from one side of the PCB to the other. Figure 30 shows a via that extends through all of the board. The copper plating is usually quite thin, with an outer radius r2 and inner radius r1, see Figure 31.

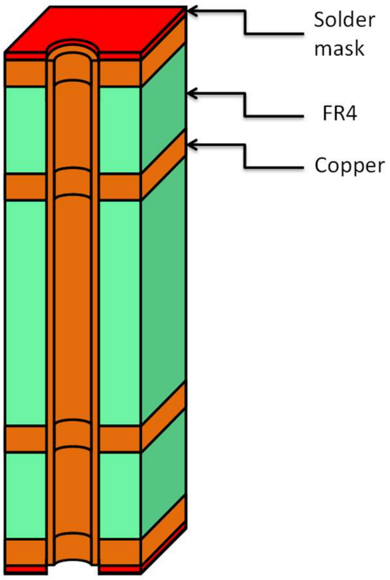

Figure 30. View of a via in a PCB.

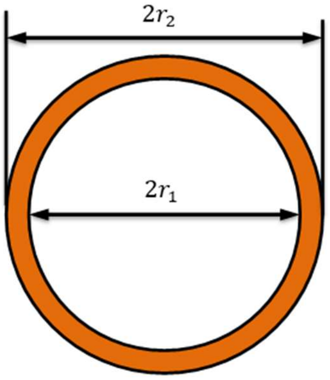

Figure 31. Area of the layer of a via.

From equation (8-23), the resistance through a single via can be determined by

$$R_{\theta Via} = \frac{l_{PCB}}{k_{Cu}\pi(r_2^2 - r_1^2)} \tag{8-25}$$

where l_{PCB} is the thickness of the board. Since the vias run parallel with the PCB thickness, an expression can be made for the thermal resistance of any number of vias within the given area. This can be written as

$$R_{\theta PCBplus} = \frac{1}{\frac{1}{R_{\theta PCB}} + \frac{1}{R_{\theta Via}} + \cdots + \frac{1}{R_{\theta Via}}} = \frac{1}{\frac{1}{R_{\theta PCB}} + \frac{n_{Via}}{R_{\theta Via}}} \tag{8-26}$$

where the 'plus' in $R_{\theta PCBplus}$ indicates the addition of vias. The resistance can be calculated using $l_{PCB} = 1.6$ mm, $A_{Pads} = 86.3$ mm^2, $\Delta x_{Cu} = 426$ µm, $\Delta x_{FR4} = 1125$ µm and $\Delta x_{Sm} = 50$ µm. Table 7 displays the resulting resistance depending on the number of vias. $R_{\theta PCBplus2}$ also takes into consideration area of the PCB that is occupied by vias, but as can be seen the difference is negligible. Even with their small size, the vias affect the resistance considerably. Figure 32 visualizes this effect better. See Appendix B for these calculations in MATLAB.

Table 7. Thermal resistance depending on number of vias.

n_{Via}	$R_{\theta PCBplus}$	$R_{\theta PCBplus2}$
0	54.8702	54.8702
1	41.8615	41.8971
2	33.8389	33.8855
4	24.4626	24.5114
8	15.7400	15.7803
16	9.1878	9.2153
32	5.0137	5.0300

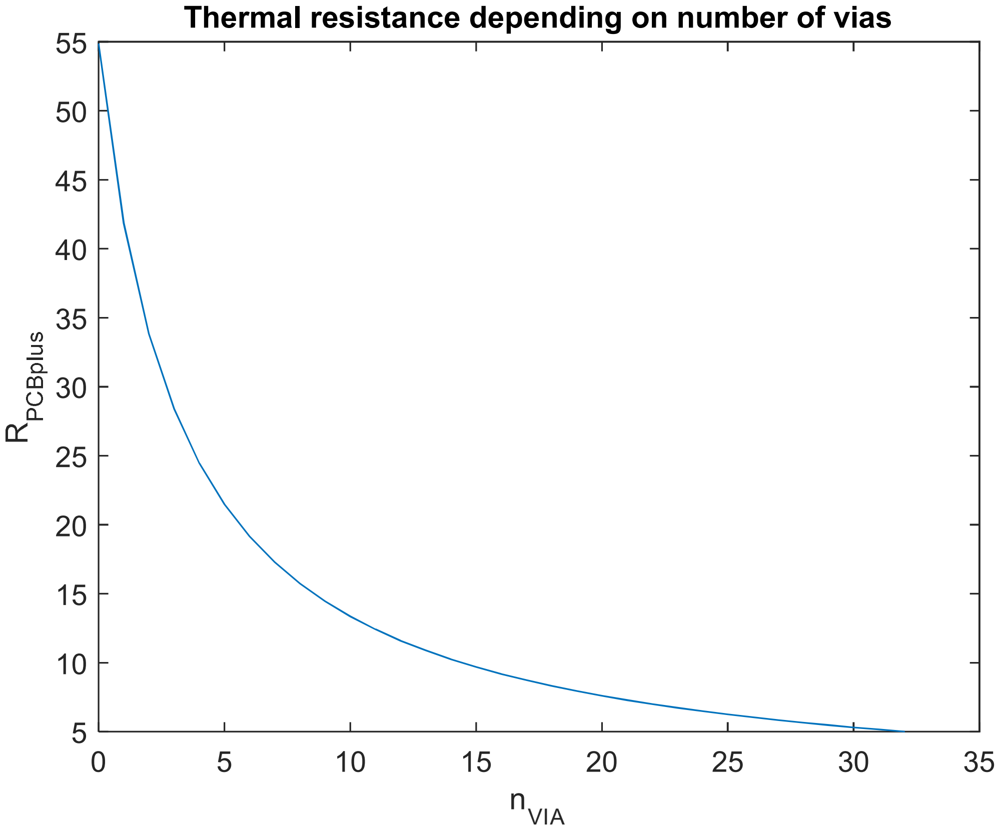

Figure 32. Plot showing the thermal resistance depending on number of vias.

Some important variables to consider are the thermal resistance values that come with the semiconductor package. The first is the measured thermal resistance from the junction to the casing. If a heat sink is mounted on top of the package, then the value from the junction to the top of the case is of importance. In this case, the interesting value is the resistance from the junction to the bottom of the case. The symbol for this is $R_{\theta JC}$ (PQFN, 2016).

The second variable is the measured resistance from the junction to a horizontal spread on the PCB. The value is taken from the top surface of the board. The symbol is $R_{\theta JB}$.

These values can now be used to get a more accurate estimate of the junction temperature rise. The previous value $R_{\theta PCBplus}$ concerned the resistance directly beneath the semiconductor exposed pads. The thermal resistance through the surrounding PCB can be expressed as

$$R_{\theta PCB2} = \frac{\Delta x_{Cu}}{k_{Cu} A_{Board}} + \frac{\Delta x_{FR4}}{k_{FR4} A_{Board}} + \frac{\Delta x_{Sm}}{k_{Sm} A_{Board}} \qquad (8\text{-}27)$$

where A_{Board} is the effected area of board not in contact with the thermal pads of the chip.

Table 8. A more accurate calculation of the thermal resistance depending on number of vias.

n_{Via}	$R_{\theta PCBtotal}$
0	8.3363
1	7.9665
2	7.6293
4	7.0368
8	6.0995
16	4.8376
32	3.4632

This area can be calculated as

$$A_{Board} = A_{PCB} - A_{Pads} \tag{8-28}$$

where A_{PCB} is the area extending out from the chip to cover area between adjacent chips.

The various resistances can now be added together to yield the total resistance from junction to opposite side of the PCB. Total thermal resistance becomes

$$R_{\theta PCBtotal} = \frac{1}{\frac{1}{R_{\theta JC} + R_{\theta PCBplus2}} + \frac{1}{R_{\theta JB} + R_{\theta PCB2}}} \tag{8-29}$$

The equation can be solved using $A_{PCB} = 900\ \text{mm}^2$, $R_{\theta JC} = 0.32$ C/W and $R_{\theta JB} = 4$ C/W. Depending on the number of vias, the resulting resistance can be seen is Table 8.

Since the thermal resistance do not increase notably with more vias after 32, it is reasonable to choose a number that do not exceed this too much. This would of course depend on the thermal resistance desired and also the potential increase in cost that comes with so many vias. 30 vias should still be enough and this process can be referenced to in the future if more resistance is needed.

8.3 Thermal Interface Materials

Effective heat dissipation relies on methods to transfer heat from electronic devices to ambient air. Often this means developing electronics with high thermal conductivity and designing heat sinks which together transfer heat from the device junction to the passing air flow. However, an important factor to consider is the transfer of heat from the device to the heat sink to allow for efficient heat dissipation. What comes into play here is the contact resistance between two joining surfaces. No surface is completely smooth and sometimes a surface can be relatively rough, with many microscopic cavities. When two surfaces are joined, the only contact will be at the tip between these cavities. The cavities in turn will form air-filled voids, which can reduce the contact surface area with more than 90 percent [A]. Because of the low conductivity of air of 0.027 W/m°C (Liu & Chung, 2006), there is a need to use a connecting element to facilitate heat transfer. That element is thermal interface material (TIM).

The current ECU uses a grease that conforms itself to the PCB and metal when exposed to mounting pressure. There are some advantages to this, but also several disadvantages. It is difficult to control the thickness, it is messy and it can contaminate other components when it starts flowing. Being a liquid, it is also very susceptible to shearing forces. A TIM that can overcome these drawbacks are thermal pads. Thermals pads can come in many forms but the common denominator is that they arrive at the assembly as solids. Their size can be controlled to cover the area that is needed, and they can be handled with ease. Some pads also have a phase-change characteristic, with allows them to melt at 50-80 °C and fill the air-filled voids, which is one of the benefits with thermal grease. However, because of their thickness they usually have a lower thermal resistance put together than thermal grease does, which will be the price for better control (Sarvar, 2006).

Choosing TIM will be a matter of cost and application. The best way is to investigate just how much thermal resistance is needed and then make a decision on the justified cost. Figure 33 shows a general comparison on the cost for some thermal pad materials taken from two dealer websites (Digikey, 2017)(Mouser, 2017). Properties have also been taken from a catalogue (Thermal Interface Material, 2015). A material with a thermal resistance of ~5 °C cm^2/W is best considering the increase in price beyond that.

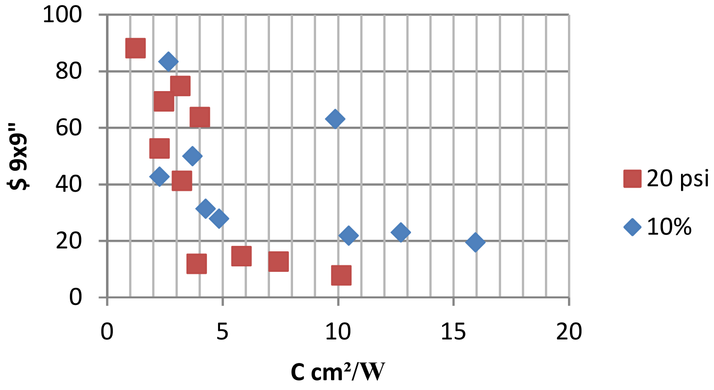

Figure 33. Cost vs performance for a number of thermal pads on the market.

8.4 Application of thermal results

The total heat resistance of the ECU is a combination of the resistance of the different parts along the heat transfer path. From the inside of an electronic component and through the PCB, the heat resistance was determined to be ~3.5 °C/W. From the backside of the PCB and though the TIM, the approximated resistance was ~5 °C/W. Through the aluminium enclosure and dissipation into the surrounding air, the resistance was ~15 °C/W. This adds up to 20.5 °C/W for the entire system. Now, it was important to note that this is done assuming the configuration specified. The results are independent of any concept design. It cannot be easily applied to any concept. For instance, the Rails concept can easily apply all of these specifications into its design. Not using any fins resulted in a thermal resistance of ~65 °C/W.

These results were also verified by numerical simulation. A simple model was made in CATIA V5 and analyzed in ANSYS Workbench, with Steady State Thermal settings, see Figure 34. The total model was 100x100 mm. The spacing between fins was ~3 mm, the fin thickness and shell thickness was 2 mm, and the fin length was 15 mm. The heat convection factor was the same as previously stated.

The result of the simulation was a total thermal resistance of ~1.3 °C/W across the whole area. The result of the analytical calculation presented so far, was ~1.5 °C/W with similar configuration. The simulation yielded slightly more favorable results. This is because the simulation considers the entirety of the model, while the manual calculation only considers a smaller area at a time.

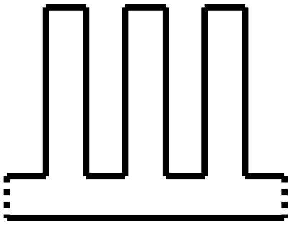

Figure 34. Example of the configuration for the simulated model.

9 Discussion

The requirement 18 *PCB maximum temperature* puts an upper limit of the inner temperature of the high-side-drivers of 130 °C. In combination with requirement 17 *Functional operating temperature*, this means that for any chosen design, the temperature difference between the drivers and the surrounding air shouldn't be higher than 30 °C. The thermal resistance of the different parts in the ECU can be put together in series to yield a total value of the resistance. Going from the outside and in, the system consists of the enclosure, the thermal interface material, the PCB, and the high-side-driver. The results of these stages have already been determined and will be repeated below, followed by a discussion of them.

Looking back at chapter 7.1.3, it can be seen that with a fin length of 15 mm and a thickness of 1.5 mm, a thermal resistance of 15 °C/W can be achieved, with wind speeds of only 0.5 m/s. Looking at Figure 24, it can be concluded that using this kind of structure yields much better results in terms of thermal resistance for high power application, than only using a flat plate.

Looking at chapter 7.2, it can be seen that the combination of the high-side-driver and the PCB gave a thermal resistance of around 3.5 °C/W, using 30 vias for each driver. It is important to remember than the thermal resistance is inversely proportional to the area. Cutting the area in half doubles the resistance. The value used is still a good approximation, but can be improved in the future.

As seen from chapter 7.3, a TIM with around 5 °C cm^2/W is a standard choice. Using the area of the previous sections, the thermal resistance can be estimated to around 2 °C/W.

Overall, the thermal resistance sums up to 15 + 3.5 + 2 = 20.5 °C/W. This means that for each watt in the high-side-driver, the temperate difference in relation to the atmosphere is 20.5 °C. With the driver dissipating closer to 0.5 watts, the temperature difference will be around 10 °C, which is lower than the 30 °C needed by the requirements. This would result in four times longer lifetime according to Table 2. Important to note is that these calculations were done by looking at a single high-side-driver and a small area around it, and then going up through the enclosure. It does not take into account surrounding high-side-drivers and areas. This should however mean that this is done as a worst-case scenario. Taken into accounting the whole system, the total area increases since the heat will migrate to the sides. With a rough computer simulated heat transfer, it was found that the numerical simulation actually results in a smaller resistance than the analytical. This is likely because of the increased area that is taken into consideration in the model. More information regarding this is still needed however, and a real-life test is the best way to get an accurate figure on the thermal resistance.

The results of the thermal analysis showed that cooling the PCB with only a plate may be insufficient. With two PCBs, it would be better to use an enclosure that uses extended fins on both side, to maximize the heat transfer for both PCBs. With this in mind, it would be worth making a prototype of the rail concept as well, in order to get a better comparison of that and the current prototype.

The requirements 12 *Height*, 13 *Length*, and 14 *Width* had expressed limits of 97 mm, 313 mm, and 136 mm, respectively. From the results of The L, the height is 55 mm, the length is 272 mm, and the width is 171 mm. This means that the height and length are smaller. The width however, is larger. This isn't too much of a concern, since the project had the freedom to change the size requirement. However, with a PCB width of 119 mm, the width of The L at 171 mm is definitely in excess. With a PCB length of 178 mm, the length of The L at 272 mm is far too much. Ideally, the size of the enclosure shouldn't be much different than the size of the PCB, because everything else is wasted space and material. As for the Rails, its height is 69 mm, length is 214 mm, and width is 162 mm. The length is smaller than The L, but the width is still outside of the requirement range. This is because of the use of side connectors, which the RCIOM did not use. In return, the height of both The L and Rails is shorter.

With regards to many of the requirements, it was not possible perform any of the tests. Theoretically, the requirements concerning temperature have been met, but still need to be tested. The length requirements were not deemed to be too important, but are estimated to be somewhat fulfilled. The rest of the requirements are left as is.

Looking at the goal of this project, the architecture of the ECU does allow for a flexible design. The enclosure will act as the platform and the connector package as one of the modules. The connectors can be changed depending on the number of PCBs and application. The sealing lines will then represent the interface that is shared among all the connector modules. Using this setup, it is possible to utilize the advantages that come with a modularized product. These include better tailored products, shorter development time and costs, and reduced system complexity.

Using a sealing material in the form of a rubber gasket was the goal from the start, but could not be realized with the pursued concept. However, going with either of the two alternative concepts would open this possibility. It would then be possible to do calculations on the pressure required to create a sufficient seal and also to dimension the screws needed in the design.

The current designs rely of screws for some of the assembly. Instead of screws it could also be possible to use snap fasteners to create the seal and assemble the parts. Such a design is preferred in the requirements. However, the elasticity and strength required from such a material cannot be gained from a 3D printed prototype, and would have to be included when designing for injection mold production.

The mounting system can also be dimensioned in a more thorough way. If the total weight can be approximated then the stress on the mounting screws can be calculated. From the requirements, the ECU can be subjected to accelerations of 500 m/s^2. With four mounting holes, the force can be calculated and the screws dimensioned correctly.

As far as the process is concerned, it seems correct to have used the method of developing insertion concepts to start with. This eliminated several of the options, leaving more detailed concepts to emerge from the remaining ones. Still, this step should have been done sooner and faster, to give time for more detailed development. The thermal analysis, although important, also took more time than anticipated. Faster decision-making would have helped this project to advance further and a more comprehensive prototype could have been made. The thermal analysis was still very successful and turned out to be a core chapter in this project. A simplified computer simulated analysis has been made, and indicated that the analytical calculations are mostly correct, and only slightly off from the simulated values. The simulated version actually had a lower thermal resistance than the one resulted from the analytical one. A complete simulation of the final design would still give more substance to the work. Going back to the function-means-tree, there are several subproblems that remain. However, this sort of functional decomposition was much more useful than a functional flow type, because it simply expressed the functions within the system, without the need of complicating it by expressing the dependencies between them. The dependencies that did exist were easily identifiable and did not cause any kind of problems. Looking at the requirements, the goal of flexibility could have been expressed better. It was not included since the requirements were taken from the RCIOM and were not necessarily fully translated into the requirements of GION. That's because GION was more of research-oriented project and there was more freedom in regards to the fulfillment of certain requirements, such as weight and dimensions.

10 Conclusions

The purpose of the ECU is to protect the electronics from the outside environment and surrounding. This gives rise to important requirements, such as sealing, heat resistance, vibration resistance, and shock resistance. It needs to be able to perform to expectations during a long time, which give demands on heat dissipation. It also needs to accommodate multiple PCBs and different connectors, which creates the need for a flexible design. Hopefully, this design will not only be able to replace the current ECUs on the chassis, but also on other parts of a truck.

The heat calculations reveal that a PCB that is cooled passively with a fin structure, is going to perform better than just using a plain plate, possibly with a thermal resistance of up to 35 °C/W lower. This is important to increase the lifetime.

The developed concept “The L” has a familiar design where the PCBs can be mounted from the bottom side. It supports two PCBs on top of each other and it has a 58-pin connector and a 100-ampere power connector for each PCB. All the connectors are integrated into a connector package which defines the connector interface. Its unique feature is based around the connector package, which is symmetrical in design and can be turned to support connectors pointing both up and to the side.

However, with “The L”, there are some problems with how the fin structure can be implemented. It would indicate, that as far as heat problems are concerned, this concept has its flaws. The size is also a problem. The connector package takes up much more space than anticipated. The use of a bottom insertion method is good for a concept such as “Top Connect”, but for “The L”, the required use of draft angles and sealing flanges, along with mounting structure, introduces too much extra space and unnecessary dimensions. The required distance of 22 mm between PCBs is part of the source to this. In a concept such as “Top Connect” that uses straight pins, there are no immediate restrictions on the distance between PCBs.

Along with a number of other issues, it can be speculated that the alternative concepts “Rail” and “Top Connect” are still viable solutions to satisfy requirements. The concept “Top Connect” has many advantages, but could not be pursued further, because the 58-pin connectors use did not have straight pins that were required for the prototype. In order to fully evaluate this concept, it is necessary to have straight pin connectors available, so as not to put limits on what is possible and not have restrictions on solutions. The “Rails” concept consists of an extruded aluminium profile, which has rails inside it for sliding in the PCBs. It is easier to incorporates outer fin for thermal dissipation and to seal the enclosure. The “Rails” concept could be the more appropriate direction to go, although it does have certain concerns when it comes to the thermal interface material between the enclosure and the PCB. The design introduces restrictions on the PCB design. These restrictions are as follows:

- All high-side-drivers must be on one half of the PCB.
- Connectors and pins that go through the PCB must be on the other half.

This kind of configuration has some disadvantages. The drawbacks can be these:

- There will be need for long copper wires across the PCB.
- These will take up a lot of space on the PCB and possibly complicate the design.

The connector package still has some considerations when it comes to assembly, which is a consequence of connecting two PCBs before assembly into the enclosure. However, there are many advantages, both when it comes to heat dissipation, and also when it comes to size. The stability and robustness can be improved in a big way as well.

In conclusion, a new ECU design has been developed. In retrospect, however, in may not be the optimal design.

11 Action plan for future work

For future work, it is recommended that the use of fin structure continues to be a part of the design. It is not existing in the current RCIOM, but with the increase in power usage, due to automated vehicles for instance, there will be higher demands on heat dissipation than there was previously. A more detailed heat calculation also needs to be made in order to verify the theoretical results.

The “Rail” concept should be investigated further, since it could be a more viable solution to GION, especially if using two PCBs with high demands on cooling. The enclosure needs to be updated to allow for the connector pins to fit. The PCB needs to be remodeled to have all the high-side-drivers on one side, and all the pins on the other side. The connector package can then be equipped with a sealing gasket and screws for tightening it to the enclosure. A phase-change TIM is probably the best choice, because of the absence of a pressing force to press the PCB to the enclosure.

A prototype of a straight pin connector could also be made, both to open up the possibility of the “Top connect” concept, and to utilize the concept “The L” fully.

Some additional work can be done if staying with “The L” design. The enclosure will need screw holes to fasten the PCBs, and also a flange to support the extender PCB. The connector interface along the sealing line needs to be verified that is sufficient. The connector package will also need some rework to function properly.

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Appendix

Appendix A. MATLAB – Enclosure Thermal Resistance

```
close all
clear all
clc

%Thermal convection depending on air flow
v = 0.5;
h = 10.45-v+10*sqrt(v);
% h=17;
%Thermal conduction
k=200;

for j=1:4
%t:Fin thickness
for t=1:4
% t=2;
   t=t*1e-3;
%for z=50:10:100
%z:Fin length
z=30;
z=z*1e-3;
%L:Fin height
for L=5:5:20
   L=L*1e-3;
%L_o:Length between fin walls
L_o2=[30-t 30/2-t 30/3-t 30/4-t];
L_o=L_o2(j)*1e-3;
%x:Wall width
x=2;
x=x*1e-3;

%Fin perimeter
P=2*z+2*t;
%Fin added height
L_c=L+t/2;
%Fin area
A_f=P*L_c;
%Fin base area
A_b=z*t;
%Wall area between fins, open area
A_o=z*L_o;

mL_c=sqrt(h*P/(k*A_b))*L_c;
n_f=tanh(mL_c)/mL_c;
```

```
%Thermal resistance, wall to fin
R_wf=x/(k*A_b);
%Thermal resistance, fin to ambient
R_f=1/(n_f*A_f*h);
%Thermal resistance, wall to open area
R_wo=x/(k*A_o);
%Thermal resistance, open area to ambient
R_o=1/(h*A_o);

%Thermal resistance, fin to ambient (Simplified formula z>>t)
R_f2 = 1/(z*sqrt(2*h*k*t)*tanh(L_c*sqrt(2*h/(k*t))));


%Thermal resistance, Total per fin
Rtot=1/(1/(R_wf+R_f )+1/(R_wo+R_o));
Rtot2=1/(1/(R_wf+R_f2 )+1/(R_wo+R_o));
mass(t*1e3,(L*1e3/5),j)=(j*t*z*L)*2700*1000;

Rtot_fins(t*1e3,L*1e3/5,j)=1/(j/Rtot);

end
end
end
l=0;
for i=1:4
   for j=1:4
      for k=1:4
         l=l+1;
         Rmass(l,:) = [Rtot_fins(k,j,i) mass(k,j,i)];
      end
   end
   hold on

end
n=21;
i=ceil(n/16);
n1=n-16*(i-1);
j=ceil(n1/4);
k=n1-4*(j-1);
[k j i]

figure(1)
scatter(Rmass(:,2),Rmass(:,1),'c')

figure(2)
scatter(Rmass(1:16,2),Rmass(1:16,1),'.','k')
hold on
scatter(Rmass(16+1:2*16,2),Rmass(16+1:2*16,1),'+','k')
```

```
hold on
scatter(Rmass(2*16+1:3*16,2),Rmass(2*16+1:3*16,1),'*','k')
hold on
scatter(Rmass(3*16+1:4*16,2),Rmass(3*16+1:4*16,1),'d','k')
xlabel('Mass (gram)')
ylabel('Thermal Resistance')
legend('One fin','Two fins','Three fins','Four fins')
find(Rmass(:,1)<=13 & Rmass(:,1)>=12 & Rmass(:,2)<=5 & Rmass(:,2)>=4)
```

Change L

```
clear all
clc

for j=1:4
for i=1:100
t=2;
L_o3=[30-t 30/2-t 30/3-t 30/4-t];
L_o2=L_o3(j);

L=5+i/100*15;
z=30;
x=2;

t=t*1e-3;
z=z*1e-3;
L=L*1e-3;
L_o2=L_o2*1e-3;
x=x*1e-3;
L_o=L_o2;
v = 0.5;
h = 10.45-v+10*sqrt(v);
k=200;

P=2*z+2*t;
L_c=L+t/2;
A_f=P*L_c;
A_b=z*t;
A_o=z*L_o;
mL_c=sqrt(h*P/(k*A_b))*L_c;
n_f=tanh(mL_c)/mL_c;

R_wf=x/(k*A_b);
R_f=1/(n_f*A_f*h);
R_wo=x/(k*A_o);
R_o=1/(h*A_o);
R_f2 = 1/(z*sqrt(2*h*k*t)*tanh(L_c*sqrt(2*h/(k*t))));
```

```
Rtot=1/(1/(R_wf+R_f)+1/(R_wo+R_o));
Rtot2=1/(1/(R_wf+R_f2)+1/(R_wo+R_o));
mass(j,i)=(j*t*z*L)*2700*1000;%+(x*z*(L_o+t)))*2700*1000;

Rtot_fins(j,i)=1/(j/Rtot);

end
end
figure(11)
hold on
L=linspace(5,20,100);
plot(L,Rtot_fins(1,:),'linestyle',':','color','k')
plot(L,Rtot_fins(2,:),'linestyle','-.','color','k')
plot(L,Rtot_fins(3,:),'linestyle','--','color','k')
plot(L,Rtot_fins(4,:),'linestyle','-','color','k')

xlabel('Fin length (mm)')
ylabel('Thermal Resistance')
legend('One fin','Two fins','Three fins','Four fins','location','eastoutside')

figure(12)
hold on
plot(L,mass(1,:),'linestyle',':','color','k')
plot(L,mass(2,:),'linestyle','-.','color','k')
plot(L,mass(3,:),'linestyle','--','color','k')
plot(L,mass(4,:),'linestyle','-','color','k')

xlabel('Fin length (mm)')
ylabel('Mass (gram)')
legend('One fin','Two fins','Three fins','Four fins','location','eastoutside')

figure(13)
hold on
[hAx,hLine1,hLine2] = plotyy(L,Rtot_fins(3,:),L,mass(3,:));

ylabel(hAx(1),'Thermal Resistance')
ylabel(hAx(2),'mass(gram)')
```

Change t

```
clear all
clc

for j=1:4
for i=1:100
t=1+i/100*4;
```

```
L_o3=[30-t 30/2-t 30/3-t 30/4-t];
z=30;
L=15;
L_o2=L_o3(j);
x=2;

t=t*1e-3;
z=z*1e-3;
L=L*1e-3;
L_o2=L_o2*1e-3;
x=x*1e-3;
L_o=L_o2;
v = 0.5;
h = 10.45-v+10*sqrt(v);
k=200;

P=2*z+2*t;
L_c=L+t/2;
A_f=P*L_c;
A_b=z*t;
A_o=z*L_o;
mL_c=sqrt(h*P/(k*A_b))*L_c;
n_f=tanh(mL_c)/mL_c;

R_wf=x/(k*A_b);
R_f=1/(n_f*A_f*h);
R_wo=x/(k*A_o);
R_o=1/(h*A_o);
R_f2 = 1/(z*sqrt(2*h*k*t)*tanh(L_c*sqrt(2*h/(k*t))));

Rtot=1/(1/(R_wf+R_f)+1/(R_wo+R_o));
Rtot2=1/(1/(R_wf+R_f2)+1/(R_wo+R_o));
mass(j,i)=(j*t*z*L)*2700*1000;%+(x*z*(L_o+t)))*2700*1000;

Rtot_fins(j,i)=1/(j/Rtot);
end
end

figure(21)
hold on
t=linspace(1,5,100);
plot(t,Rtot_fins(1,:),'linestyle',':','color','k')
plot(t,Rtot_fins(2,:),'linestyle','-.','color','k')
plot(t,Rtot_fins(3,:),'linestyle','--','color','k')
plot(t,Rtot_fins(4,:),'linestyle','-','color','k')

xlabel('Fin thickness (mm)')
ylabel('Thermal Resistance')
```

```
legend('One fin','Two fins','Three fins','Four fins','location','eastoutside')

figure(22)
hold on
t=linspace(1,5,100);
plot(t,mass(1,:),'linestyle',':','color','k')
plot(t,mass(2,:),'linestyle','-.','color','k')
plot(t,mass(3,:),'linestyle','--','color','k')
plot(t,mass(4,:),'linestyle','-','color','k')

xlabel('Fin thickness (mm)')
ylabel('Mass (gram)')
legend('One fin','Two fins','Three fins','Four fins','location','eastoutside')
```

Appendix B. MATLAB - PCB Thermal Resistance

```
clear all
clc

%Thermal conductance
k_Air = 0.0275;
k_Cu = 355;
k_FR4 = 0.25;
k_Sm = 0.21;

%Dimensions
A_Pads = 86.3e-6;
x_Cu = 71e-6*6;
x_Sm = 25e-6*2;
x_FR4 = 1.6e-3-x_Cu-x_Sm;
L_PCB = 1.6e-3;

%Thermal resistance through PCB
R_PCB = x_Cu/(k_Cu*A_Pads) + x_FR4/(k_FR4*A_Pads) + x_Sm/(k_Sm*A_Pads);

%Radius of Via
r_1 = 0.3e-3/2;
r_2 = 0.35e-3/2;

%Thermal resistance through a via
R_Via = L_PCB/(k_Cu*pi*(r_2^2-r_1^2));

%n = Number of Vias
n = [0 1 2 4 8 16 32];
%Thermal resistance through PCB depending of number of vias
for i=1:7
   A_Pads2 = A_Pads-n(i)*pi*r_2^2;
   R_PCB_2 = x_Cu/(k_Cu*A_Pads2) + x_FR4/(k_FR4*A_Pads2) +
x_Sm/(k_Sm*A_Pads2);
   R_PCBplus2(i) = 1/(1/R_PCB_2+n(i)/R_Via);
   R_PCBplus(i) = 1/(1/R_PCB+n(i)/R_Via);
end
%Thermal resistance depending on number of vias
x = 0:32;
y = 1./(1./R_PCB+x./R_Via);
figure(1)
plot(x,y)
xlabel('n_V_I_A')
ylabel('R_P_C_B_p_l_u_s')

%C/W - Thermal resistance from junction to bottom of case
R_JC = 0.32;
```

```
%C/W - Thermal resistance from junction to area around board
R_JB = 4;

%Area extending out from chip to cover area between chips
A_PCB = (30e-3)^2;

%Effected area of board not in contact with thermal pad from chip
A_Board = A_PCB - A_Pads;

%Thermal resistance through surrounding PCB
R_PCB2 = x_Cu/(k_Cu*A_Board) + x_FR4/(k_FR4*A_Board) +
x_Sm/(k_Sm*A_Board);

%Total thermal resistance through PCB
R_PCBtotal = 1./(1./(R_JC+R_PCBplus)+1/(R_JB+R_PCB2));
R_PCBtotal2 = 1./(1./(R_JC+R_PCBplus2)+1/(R_JB+R_PCB2));

k_TIM = 5; %W/m*K
x_TIM = 1e-3;
%Thermal resistance through TIM
R_TIM = x_TIM/(k_TIM*A_Board);

%Thermal resistance from case to heat sink
R_CH = R_PCBtotal + R_TIM;
R_CH2 = R_PCBtotal2 + R_TIM;
```

Appendix C. MATLAB - Power Connector Position

```
clear all
clc

Y=[20 22];

for i=1:2
%Distance between PCBs
PCB_dist = Y(i);
%Diameter of inner connector pin
Connect_inner = 8.76;
%Diameter of outer connector shell
Connect_outer = 26.54;
%Distance from outer shell to edge of pin
Shell_to_Pin = (Connect_outer-Connect_inner)/2;
%Width of both connectors
Width = PCB_dist+Shell_to_Pin*2;
%Distance from point of contact between connectors to outer shell - width
Point_to_shell_width = Connect_outer-Width/2;
%Width of triagonal line between connectors
Width_inner = Width-Point_to_shell_width*2;
%Angle of connectors
Angle = asin(Width_inner/(Connect_outer*2)); %pi
%Distance from point of contact between connectors to outer shell - length
Point_to_shell_length = Connect_outer/2-cos(Angle)*Connect_outer/2;
%Length of both connectors
Length = sqrt((Connect_outer*2)^2-Width_inner^2)+Point_to_shell_length*2;

x(i,:)=[PCB_dist Angle*180/pi Length  Width];
end

disp('  PCB_dist  Angle     Length    Width')
disp(x)
```