Design of an Energy Efficient Windshield Defrosting System for Electric Transit Buses

Bachelor's Thesis 2019

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: A picture taken visualizing one of Nova bus' electrical bus.

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Summary

The focus of this bachelor thesis project is to reduce the energy consumption of modern electric buses by designing a new energy efficient windshield defrosting system. A current issue in these buses is the use of an outdated heating system which relies on excess heat present in traditional combustion engines, heat that in electric buses must be generated for the system to operate.

The aim of this project is to through a collaborative effort between Nova Bus, Polytechnique Montréal Technological University and Chalmers University of Technology develop a windshield defrosting and deicing system which is more efficient than the current outdated system or any alternative system available in today's market. In doing this, the project will create a more viable long term solution and help progress the integration of electrical buses into the modern market.

The project resulted in a concept containing an infrared heater which not only is more energy efficient than the currently used system, but is also cheaper to build and install. However, alternate issues such as high surface and windshield temperatures must be taken into account and further research must be done regarding how to minimize risk of injury before this system is ready to be fully utilized and implemented.

Sammandrag

I denna avhandlingen behandlas behovet av att i elektriska bussar tillföra ett nytt avfrostning och avimningssystem. Detta behövs för att det nuvarande systemet som finns i de elektriska bussarna är inte gjort för fordon som inte har motorer med mycket spillvärme och är därför väldigt ineeffektivt vid användning i elbussar.

Målet med detta projekt är att genom en kollaboration mellan Nova bus, Polytechnique och Chalmers hitta en lösning till att avimma och avfrosta rutor mer effektivt än vad nu är tillgängligt på marknaden och genom detta hjälpa integrationen av elbussar på marknaden och skapa en mer livskraftig lösning.

Projektet resulterade i ett koncept som använder sig utav infravärmare. Detta är inte bara mer effektivt än dess nuvarande motsvarighet men också billigare att bygga och installera i bussarna. Detta konceptet har dock inte bara fördelar, eftersom det

sitter i kabinen och kan bli väldigt varmt måste denna idé vidareutvecklas för att säkerhetställa att inga skador kan ske innan det integreras i de elektriska bussarna.

Keywords: IR, heating, electrical, vehicle, defrosting, windshield, HVAC

Abbreviations

HVAC Heating, Ventilation, and Air Conditioning

IR Infrared

CFD Computational Fluid Dynamics
FEA Finite Element Analysis
FEM Finite Element Method

PSD Power Spectral Density

FMEA Failure Mode and Effects Analysis
D-FMEA Design Failure Mode and Effects Analysis
Po Potential Occurrence of Failure
S Severity of Failure
Pd Potential Detection of Failure
RPN Risk Priority Number

Acknowledgements

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Contents

List of Figures

List of Tables

1
Introduction

With an ever-increasing demand for fossil free means of transportation, adaptations have begun with the recent launches of Nova Buses' [1] release of both hybrid electric and fully electric models. This means that more and more of the general public can choose further advances to living climate friendly, even in densely populated areas. However, with the arrival of electric vehicles, efficient use of the stored energy is a main issue. The heating, ventilation, and air conditioning (HVAC) systems represent a significant percentage of the total energy consumed, especially when the harsh northern climate comes into consideration. Due to the higher efficiency of the electric motors there is not enough excess heat generated to defog and deice the windshield. As a result, less efficient methods of heating glycol are currently used to control the climate in the buses. The disadvantages of current methods are that energy is being wasted on less effective means of heating the bus at the expense of driving range and therefore autonomy.

Nova Bus as a part of Volvo Group [2] are seeking, through this project, to design and develop an energy efficient windshield defrosting system that will replace the current unit. This new system must improve the energy consumption and efficiency of the existing ones, whilst guaranteeing the comfort of the driver and passengers.

1.1 Purpose

In partnership with Nova Bus and a team from Polytechnique Montréal the purpose of the project is to design and develop an energy efficient windshield defrosting system with the capabilities of replacing the current system utilized in hybrid and electric buses [3]. The current system being one that circulates heated ethylene-glycol through pipes and heat exchangers which heats air in order to warm the windshield. This is motivated by the fact that this auxiliary system for heating and defrosting the windshield consumes a significant part of the buses' stored energy and therefore reduces the autonomy, especially given the intensity of Nordic climatic conditions. By improving the windshield deicing system, the aim is to increase the operation range whilst improving visibility, operating conditions for drivers and reducing the environmental impact of the bus.

1.2 Project Setup

This project has been a cooperation between two different universities. Polytechnique, Montreal and Chalmers, Gothenburg. Ten students from Montreal and six from Gothenburg have worked together towards a common purpose, to develop a defrosting system for electric transit buses. This in partnership with Nova Bus, which is also located in Montreal.

In order to efficiently work as a large group of 16 people, despite the time difference and the distance, weekly meetings were held to plan and divide work responsibilities while also making important decisions regarding the project.

An aspect that added a degree of difficulty to the cooperation was that the students from Polytechnique began working on the project during their fall semester, which led to a preliminary concept already being chosen and presented to Nova Bus by the time the students from Chalmers joined the project. This entailed an extended integration time for the Chalmers team. An additional aspect worth noting is that, due to the varying yearly schedules between the two universities, the students from Polytechnique completed their part of the project on April 15th, while the Chalmers students worked for an additional month.

The Chalmers team began their work by reading reports written by the Polytechnique team and then re-evaluated the suggested concepts. Upon completing this, the teams were fully integrated with each other and the following project-tasks were cooperatively decided by all group members and distributed on a weekly basis.

1.3 Scope and limitations

Being part of an international project has both its limitations and advantages. The six hour time difference between the teams made it possible to work longer periods of time each day. While at the same time forcing communication to happen in a specific time window (between 2:00 p.m.-6:00 p.m., GMT+1). As for the final outcome of the project there were limitations concerning time. The time-frame for the students at Chalmers is set from 22nd of January to 16th of May.

The final decision regarding the concept and its design had to be in line with the client. Since this project aimed at developing a new defrosting system for Volvo Group, specifically Nova bus. This with concerns to how the concept handles the main issue and how it is to be integrated into the existing design. While simultaneously being manufacturable, lightweight and energy efficient.

The current system not only defrosts the windshield but also heats the surroundings, the driver and in some cases the passengers all in a safe way. This impacted the formation of the new product and limited it to methods of defrosting that are safe for the diver as well the passengers.

The environmental load was also a concern that needed to be taking in to consideration while choosing the final concept. It was deemed important to choose a concept that's equally or more energy efficient than the existing one.

This was a collaborative project between students at Polytechnique and Chalmers who worked throughout the project to create a unified project group. The team at Polytechnique started this project in September of 2018, and the Chalmers team began working on it in January when the project was already in motion. Because of this the Swedish part of the project group started with an evaluation of the concept created by the Canadian group and it took some time to integrate more into the current state of the project with the team at Polytechnique.

1.3.1 Ethics

During the project, the group has taken into consideration social and ethical issues that may arise. The most important guidelines followed have been the internal rules defined by the group with regards to their own ethical and moral grounds. In addition to this, the project has followed the values set by the institution of Chalmers, Polytechnique, Volvo Group and Nova Bus.

The guidelines included reducing potential harm to individuals, respecting trust and everything in-between. The final prototype is important but using appropriate means to reach it was deemed just as significant. Since the project regards electrical vehicles and reducing the energy consumed by them, the group considered it especially crucial to follow strict ethical rules to make sure that the work in this groundbreaking field was done correctly, both to make sure the public opinion regarding development in this field is strictly positive and also so that the group may feel proud for their contribution.

When developing the product several risks are still present, especially with regards to the systems placement inside of a moving vehicle. Since there is always the potential risk of a crash, the system must be secure enough to even out the risks.

During the project the group has taken into consideration several import dilemmas such as "what is most important? Sight or environment impact", on one hand there may be a direct improvement to human safety and on the other hand there may be a huge problem and an indirect threat to not only a few people but to the entire world. There are several legal requirements for both that needs to be taken into account.

The teams has also taken stands in regards to their personal integrity. When a party (for instance Nova or Volvo Group) wishes to put the project on a course that the students do not feel comfortable with, plans have been made as for how to act accordingly. The client has final say but the group will make sure to deliver their opinions clearly.

1.3.2 Environmental Aspects

This project is working towards lowering the energy consumption of electrical buses, by extension this will also help as to reduce the environmental load created by the buses. Although the task itself works as to reduce the load on the environment the team also has to make sure to not include the use of any harmful chemicals in the system that may impact the environment negatively in case of crash.

Overall the team has decided that the environmental impact is of high importance and will over all strive to create a system less harmful than the current one while also following any laws impacting the regions of use.

1.4 Outline

Chapter 2 contains theory and prior knowledge in order to confidently rely on the methods and software used for evaluating the outcomes of the project. Some necessary theory regarding the Canadian team's previous work is relevant. Together with the basic theory about heat transfer, computational fluid dynamics and finite element method it provides a basic understanding of the project. During the methodology chapter, chapter 3 the various methods that were used to obtain the projects results is presented in detail. In the results chapter, chapter 4 the different outputs from simulations, testing and risk management will be given. Also the final concept and its prototype is presented. In chapter 5, all tests and simulations is discussed and reflected upon leading to the final concept and the oncoming challenges before being able to fully incorporate the product into the market. To summarize the project and wrap up the report, a conclusion is presented in the last chapter, chapter 6.

2

Theory and Prior Knowledge

The following chapter contains theory and prior knowledge. The theory section will explain the theory behind some of the methods that were used and the prior knowledge section will present the work and concept proposals that the Canadian team created before prior to the Swedish team joining the project.

2.1 Concepts Created by the Canadian Team

At the time of the Swedish teams' inception to the project, the team at Polytechnique had already made a market study and from this defined a functional specification. From this functional specification the Canadian team then created seven concepts which they believed to have the potential to appropriately solve the primary task of this project. In this section the functional specification and the concepts will be presented. In order to evaluate the concepts created by the Canadian team. The functional specification and these systems have been designed to take into account the heating of the buses windshield, driver and cabin. Based upon feedback from Nova Bus to focus combined efforts towards the sole heating of the windshield, the concepts from Polytechnique will be presented in a way that reflects this restriction.

2.1.1 Functional Specification

From a market study together with the tasks from Nova Bus the following functional specification has been created. These specifications are divided into three categories. The primary functions, which can be seen in table 2.1, ensure the proper functioning of the system, the complementary functions are additional features that make the system more efficient and intuitive, meanwhile the constraints express budget, security, dimensional and environmental limitations. An importance factor K is then associated with each requirement, and the criteria for attaining it are detailed. Some of the criteria are defined according to the applicable industry standards and are therefore not detailed. The complete functional specification can be found in appendix A.

Table 2.1: A table of all primary functions

#	Function	K	Criteria	Level	Flexibility	Comments
1	Deice the windshield	5	Thickness of ice melted Thickness of ice on windshield during movement (with bus at full capacity):	SAE J381 A: 0 mm C: 2 mm	None None	According to bus drivers, respecting the norm is not sufficient to guarantee good visibility when the bus is in operation. Furthermore, after the bus had been prepped, no additional ice should accumulate while they are driving
2	Defog the windshield	5	Windshield surface cleared during movement (with bus at full capacity)	SAE J381 A:80% C: 99%	None	
3	Be integrable into LFSe buses	5	Power source voltage Encroachment on current bus design	600 V Same as current system	+ 0 % - 100 % + 25 % - 100 %	The current maximum voltage available is 600 V The new system should fit into the existing design of LFSe buses without taking too much additional space.
4	Be energy efficient	5	Maximum power consumption	20 kW	None	The new system should require a smaller power input than the current one

Concept 1 *Internal Heating*

1a) *Heating wires*

The following concept consists in installing microscopic tungsten wires on either face of the PVB film (Polyvinyl butyral). Said film is the interlayer between both layers of glass, creating safety glass, or more precisely, laminated glass. This type of glass is present in all windshields, as imposed by transportation norms. Passing electric current through the tungsten wires creates a heat source within the windshield.

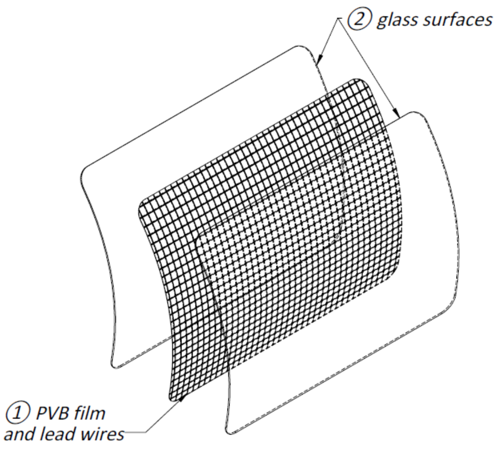

Figure 2.1: Concept 1a) Internal heating by heating wires

Table 2.2: Advantages and disadvantages of concept 1a

Advantage(s)	Disadvantage(s)
-Heat transfer is conductive, so the transfer speed is maximal, and the energy losses are minimal -Wires are inside the windshield, and therefore protected from degradation -Integrated to existing parts (windshield/door/mirrors) -Silent -Possibility to target heating area -Negligible weight	-Manufacturing methods to create such small wires are complex and expensive -Modify current manufacturing process of windshield will increase costs -Under specific lighting, the wires could become visible and hinder the driver visibility. -Larger exposure of external damage such as chips and cracks

1b) ***Metallic coating***

During the manufacturing process of the windshield, a conductive coating is applied by sputtering between the glass and the PVB layer. This method consists in the condensation of a metallic vapor on the glass. The thickness of the coating is measured in nanometers, which makes it transparent. With bus bars on opposite sides of the windshield, electrical current flows through the conductive layer and heats the glass by Joule effect. This concept can also be used as a low emissivity glazing by improving its thermal insulation, depending on the reflectivity of the conductive layer to the far IR. This system is integrated in the windshield, so the repair time is the time required to replace the windshield. It is a uniform coating, transparent to visible light, that would not hinder the visibility by affecting the driver's eye focus

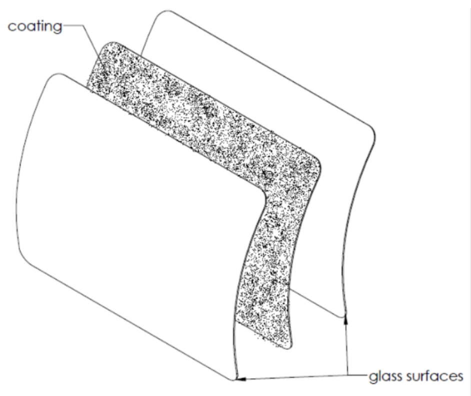

Figure 2.2: Concept 1b) Internal heating by metallic coating

Table 2.3: Advantages and disadvantages of concept 1b

Advantage(s)	Disadvantages(s)
-Multi-purpose: can defog and deice the windshield, the window, the door and the mirrors - Can be used as a low-emissivity glazing to help maintain the temperature of the bus - Also useful in the summer - Does not hinder visibility	-Existing patents - Availability of the manufacturing process - If not evacuated properly, water can freeze on the edges of the windshield or the wipers - Larger exposure of external damage such as chips and cracks

Concept 2 *Air Blown Through Resistive Heater*

This concept consists of a conductive heater, that warms up air and blows it on the windshield to warm it. Two variations of the concept are considered: the first one warms up the humid air that is already present in the bus, while the second one warms up the much drier air that is outside the bus.

2a) *Using interior air*

System description:
A turbofan draws ambient interior air into the system. This air then circulates through a resistive heating package. The hot air is then brought by flexible insulated air ducts to the flow distributor, which is placed right under the windshield. It is then blown onto the windshield.

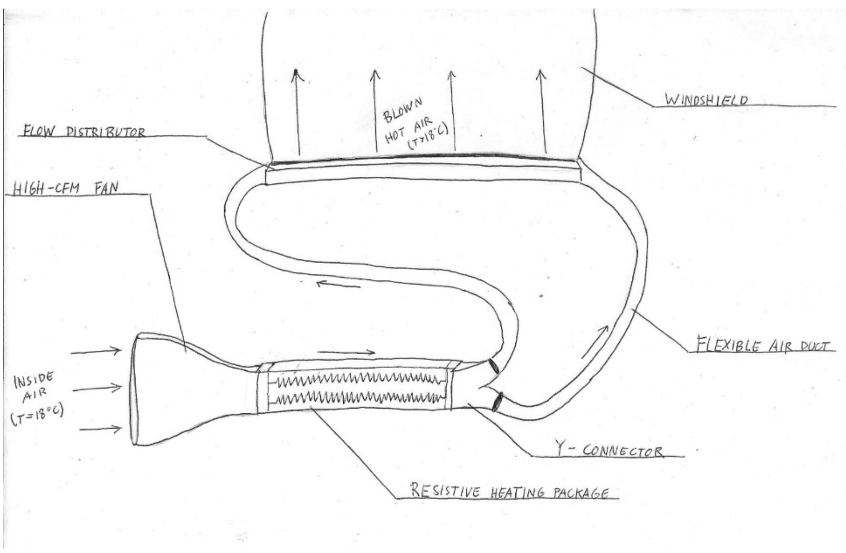

Figure 2.3: Concept 2a) Air blown through resistive heater using interior air

Table 2.4: Advantages and disadvantages of concept 2a

Advantage(s)	Disadvantages(s)
-Multi-purpose: de-icing, defogging, heating - Adaptable: Airflow and heating power can be adapted to provide desired results both for the windshield and the cabin - Similar to what exists now; little to no adaptation is required from bus drivers, and the concept of shooting hot dry air into the windshield has been proven to work on previous bus designs	-Large system: difficult to integrate to existing buses - Requires great airflow blown onto windshield, which might be uncomfortable for the driver - High velocities are required to deice the windshield - High levels of noise generated by the turbofan - Low energy efficiency compared to concepts for which heat is applied to windshield by direct contact

2b) ***Using exterior air***

System description:
A turbofan draws dry outside air into the system. The air flows through a heat exchanger (the hot fluid is exhaust air at 18 °C). The outside air is therefore partially heated, and then circulates through a resistive heating package. The hot air is then brought by flexible, insulated air ducts to the flow distributor, which is placed right under the windshield. It is then blown onto the windshield.

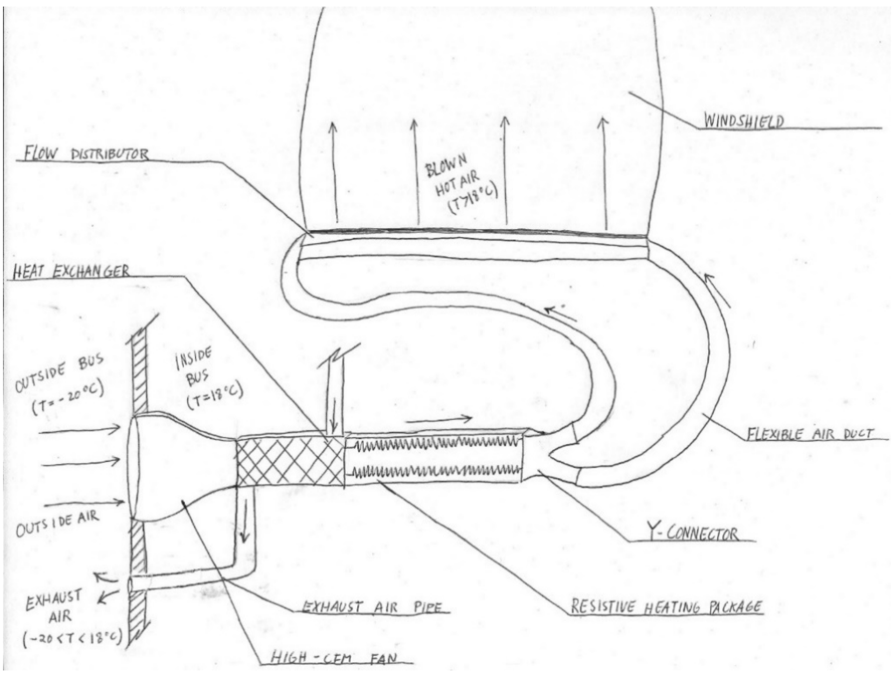

Figure 2.4: Concept 2b) Air blown through resistive heater using exterior air

Table 2.5: Advantages and disadvantages of concept 2b

Advantage(s)	Disadvantages(s)
Multi-purpose: de-icing, defogging, driver cabin heating - Adaptable: Airflow and heating power can be adapted to provide desired results both for the windshield and the cabin -Similar to what exists now; little to no adaptation is required from bus drivers, and the concept of shooting hot dry air into the windshield has been proven to work on diesel buses -Using dry outside air reduces the dewpoint	- Large system: difficult to integrate to existing buses - Requires great airflow blown onto windshield, which might be uncomfortable for the driver. - High velocities are required to deice the windshield - High levels of noise generated by the turbofan - Holeshave tobe made through bus wall in order to let outside air in and exhaust air out - Low energy efficiency compared to concepts for which heat is applied to windshield by direct contact

Concept 3 *Air Blown Onto Heated Rolled-up Curtain*

System description:

The system has two operating modes. The first mode consists of either interior or preheated exterior air that is blown over a rolled-up elastomer curtain containing heating resistances. The air temperature increases, and the hot air hits the windshield to defog it. In this mode, this concept is very similar to Blown air using interior air or Blown air using outside air (see technical sheets for concepts 2.1 and 2.2).The second mode is when the curtain unfolds on the windshield and heats it by direct contact, allowing for fast de-icing at rest.This mode is only possible when the bus is not in operation.

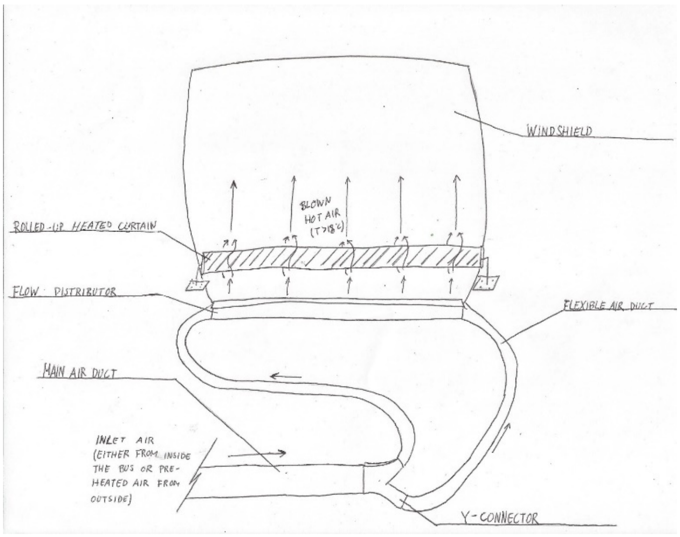

Figure 2.5: Concept 3) Air blown onto rolled-up curtain

Table 2.6: Advantages and disadvantages of concept 3

Advantage(s)	Disadvantages(s)
- Multi-purpose: de-icing, defogging, dehumidifying (if exterior air is used). - Adaptable: Airflow and heating power can be adapted to provide desired results. 2 modes: rapid de-icing and defogging during operation. - Similar to what exists now; little to no adaptation is required from bus drivers, and the concept of shooting hot dry air into the windshield has been proven to work on diesel buses	- Large system: difficult to integrate to existing buses - Very high temperatures are expected to be required inside the rolled curtain - Requires great airflow blown onto windshield, which might be uncomfortable for the driver - High levels of noise generated by the turbofan - Low energy efficiency compared to concepts for which heat is applied to windshield by direct contact - Very high temperature close to driver

Concept 4 *Radiant Heater*

System description: When infrared waves touch a surface, heat energy is released regardless of the surrounding air temperature. That heat energy excites the molecules in the object it meets which begin to vibrate, gain energy and warm up. All objects absorb and emit infrared and whether one is absorbing or emitting depends on the difference in temperatures between objects in an environment.The system suggested in this section takes advantage of this heat transfer phenomenon. It consists of an infrared heater that is mounted on the ceiling of the bus and that heats the entire cabin of the driver. The infrared heater will warm up the windshield, the window and the door to a temperature above the dew point while also heating the entryway to a temperature above the freezing temperature of water. This avoids the formation of fog and ice on the glass surfaces and keeps the floor ice free.

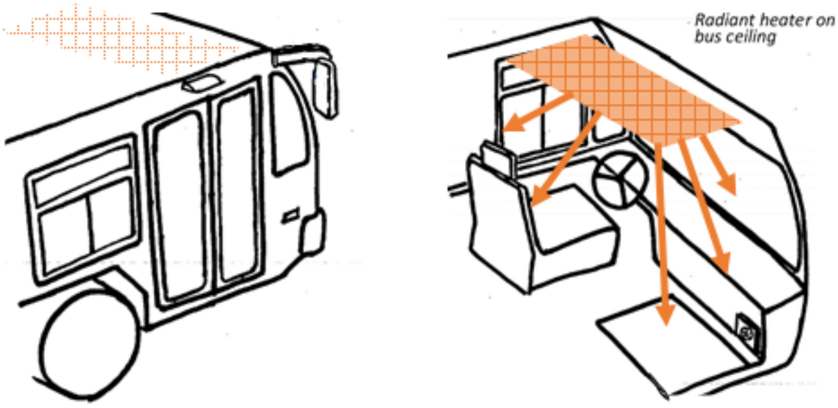

Figure 2.6: Concept 4) Radiant heater

Table 2.7: Advantages and disadvantages of concept 4

Advantage(s)	Disadvantage(s)
- A Radiant heater directly heats objects in an environment, not the air in between. Objects retain heat better than air, so residual energy maintains temperature in the environment for longer e.g. if a door is opened to a colder room, or when the thermostat turns off the heat source - Convection insufficiently warms surfaces of objects in a room and when the warm humid air meets a cold surface, condensation occurs. Infrared on the other hand warms the surfaces of objects without warming the air. The relative humidity in the air consequently remains low and when the air meets a warm surface, condensation does not occur - Infrared heaters are easy to install and they are less obtrusive than any other type of heater. They are typically wall or ceiling mounted. - Infrared heaters do not contain any moving parts so the product life is exceptionally long.	- Infrared heaters are not currently used in buses and choosing the design parameters can be difficult because no tests have previously been conducted and a lot of parameters are required to evaluate the consumption analytically - The settings of the heater could be more difficult to control with a thermostat because the air's temperature varies quicker than the surfaces' temperature - Safety measures need to be taken to manage the high temperatures avoid overheating and it's important to choose the right type of heater to avoid skin ageing and eye damage - Water absorbs the same wavelengths as human skin so it's necessary to evacuate snow to avoid,evaporating and increasing the humidity inside the bus

Concept 5 ***Heated Windshield Wipers***

System description:
The following system is used to deice the windshield wipers'rubber blade (in contact with the glass). Indeed, sometimes frost and ice remain attached to the wiper blade causing a bad wiping of the windshield. To remedy this, two heating films are attached to an aluminum plate along the wiper to create the heat necessary for defrosting. This aluminum blade is attached to the rubber of the wiper thus allowing conductive heat transfer to the rubber. Note that this is the only concept which does not defog the windshield.

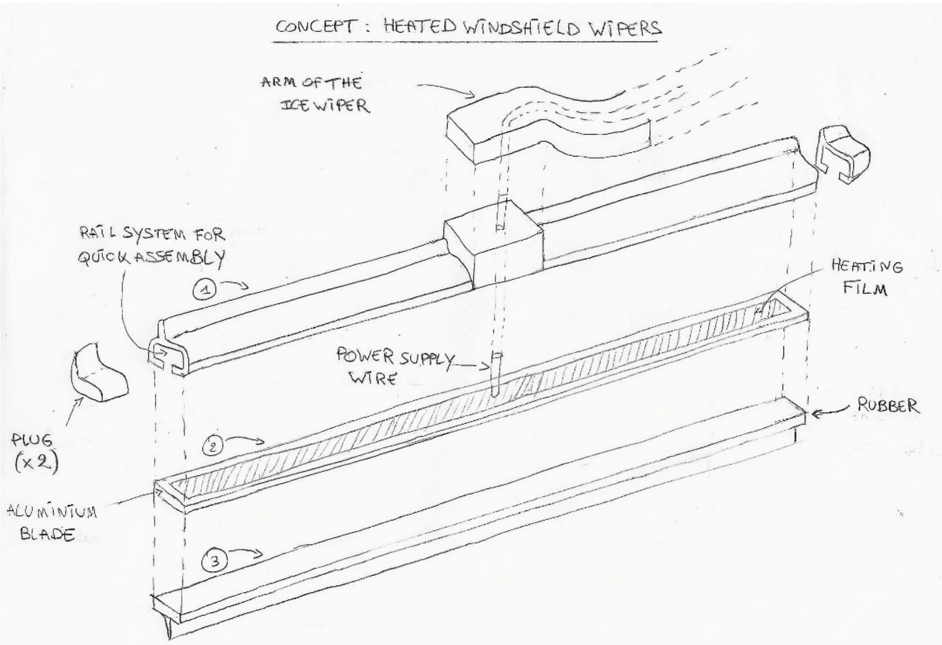

Figure 2.7: Concept 5) Heated windshield wipers

Table 2.8: Advantages and disadvantages of concept 5

Advantage(s)	Disadvantage(s)
- Improves the visibility of the driver - Low power consumption - Simple assembly of parts	- Requires a new windshield wiper design - Possible risk of prematurely aging the rubber on the wiper

2.2 Finite Element Method Analysis

Through the use of a numerical method called the Finite Element Method (FEM), complex engineering problems can be accurately approximated, as described in Introduction of the finite elements method [4]. These problems consist of mathematical differential equations which model physical phenomena that are of interest over a given region. With phenomena such as heat transfer, structural analysis, mass transport and fluid flow being among those most commonly of interest. With expressed boundary conditions for a one-, two- or three-dimensional region over which the physical problem wishes to be solved on, approximations can be found by numerically solving the differential equations. As is characteristic to the FEM, the region can be divided into number of smaller parts, which are known as *finite elements*, approximations can be found across each of these elements. By summarizing the solutions, a fair approximation can be found and expressed for the entire region.This method provides several advantages such as:

- Representation of complete and complex geometry
- Non-uniform material properties can be taken into account
- Simple approximations of the full solution
- Overview of regional effects from physical phenomena

2.3 Computational Fluid Dynamics Analysis

Computational Fluid Dynamics (CFD) is a bi-product of fluid mechanics that require the usage of numerical analysis and data structure to compute complex fluid flows. These computations are done to better prepare and depict the future reality of the given product. A CFD analysis could also be performed due to a problem being so complex that it would be impractical or even impossible to receive sufficient results through theoretical or experimental efforts alone.By using the finite element method to divide the domain into a so-called mesh and then time-stepping forward an approximation can be apprehended. These simulations are usually complemented by further testing as it is rarely possible to complete an entire project using solely CFD analysis. By using software to compute these simulations companies can save a countless number of man-hours and expenses by not having to perform extensive testing for different variations of prototypes.

2.4 Various Modes of Heat Transfer

To understand the issue of defrosting and defogging a Windshield it is important to understand the underlying theory of heat transfer. The presented theory is retrieved from the book Principles of Heat and Mass Transfer [5]. Whenever a temperature difference exists in a medium or between media, heat transfer will occur and must be taking into consideration. Where and how does the heat transfer impact the system? What type of heat transfer will or even can occur? This section will cover three different types of heat transfer.

2.4.1 Conduction

Conduction may be viewed as the transfer of energy between particles. A particle that has a higher energetic level than the one next to it will transfer energy to that particle in an effort to stabilize itself. Considering the cabin of the bus where the temperature will be higher than the temperature of the outside environment there will be conduction. The conduction will transpire within the walls, windshield and side windows. This is called conduction through a stationary fluid, note that a solid material is considered a stationary fluid. This phenomenon is illustrated in figure 2.8 where q'' is the heat flux meaning the heat transfer per unit area perpendicular to the direction of transfer.

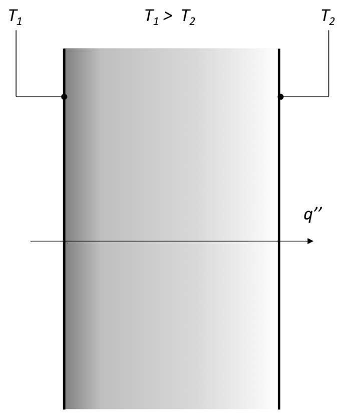

Figure 2.8: Conduction through a solid or a stationary fluid. The direction of the heat flux is shown to travel from the higher temperature to the lower.

2.4.2 Convection

When considering the convection there are two mechanisms that contribute to the heat transfer. The first being diffusion, the random molecular motion and the second mechanism being the energy transferred by bulk, microscopic motion of the fluid. For example, if a fluid flows over a heated bounding surface there will be a heat transfer, assuming there is a heat difference. The flow will develop a region where the flow at the boundary layer $y = 0$ varies from 0 to u_0. This is illustrated in figure 2.9, the convective heat transfer from diffusion dominates at the boundary layer. The contribution due to bulk originates from the region of the boundary layer growing as the flow progresses in the x-direction. The profile of the boundary layer is illustrated by the dotted line in the following figure.

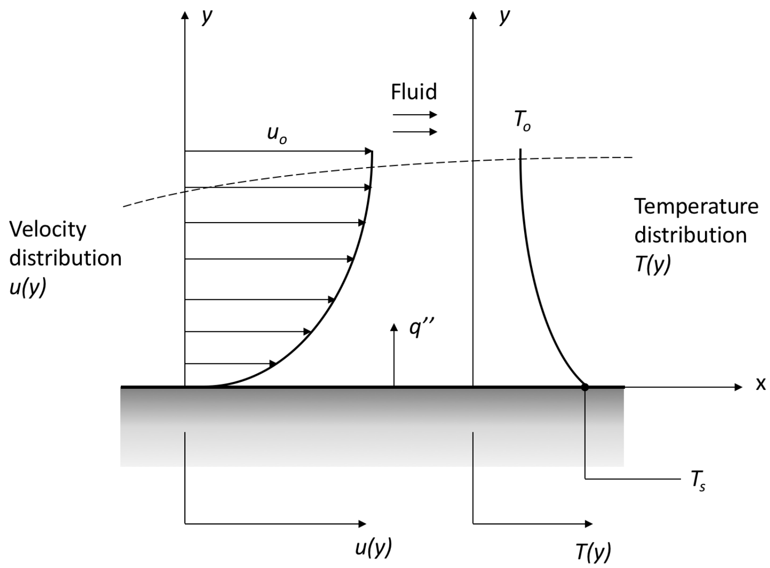

Figure 2.9: Illustration of the fluid flow over a heated boundary layer s. The illustration depicts how the temperature and flow changes over the y-direction. It also shows how the boundary layer develops in the x-direction.

2.4.3 Radiation

Radiation is a term that describes energy emitted by matter that is at a nonzero temperature. The emission may be related to the changes in electron configurations of the constituent atoms or molecules. The heat transfer differs from the previously explained methods since it does not require a medium to transfer heat. In fact the most optimal way to utilize radiation would be in a vacuum and when transferring through air there are almost no losses hence it is still a valuable way of heat transfer to consider for a defrosting system. In figure 2.10 a simple illustration of radiation is presented. The variable G represent how well the material absorbs radiation from the surroundings. E represent how well the material emits thermal energy. Both the absorption and emissivity are key factors when working with radiation and depend on the material as well as the finish of the exposed surface.

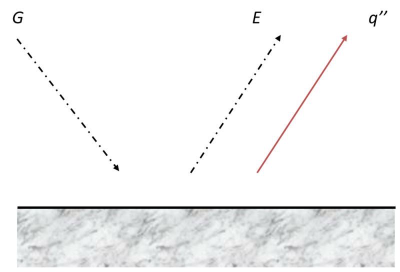

Figure 2.10: The variable G represent how well the material absorbs radiation from the surroundings. E represent how well the material emits thermal energy.

2.5 Infrared Heating

When infrared waves reach a surface, heat energy is released regardless of the surrounding air temperature. That heat energy excites the molecules in the object it meets causing them to begin vibrating, gain energy and heat up. All objects absorb and emit infrared radiation. Whether a surface at any time is absorbing or emitting radiation depends on the difference in temperatures between the given surface and objects in its vicinity. There are three relevant types of infrared heating which can be separated and classified based on their wave lengths.

“Near Infrared” or “Short wave” Infrared heaters operate between 0.75 and 1.4 microns and emit temperatures of 1300 °C or higher as well as a bright red visible light. Because of their high temperatures, near Infrared emitters are suitable for high intensity heat applications such as cooking, welding or the reforming plastics. However, the heat is not suitable for Comfort heating applications. Indeed, near Infrared is the most highly trans-missive but least absorbed in the skin (the skin reflects up to 35% of Near Infrared). Near Infrared can transmit into the fatty subcutaneous layer, penetrating through the dermis and heating nerves, hair follicles, oil and sweat glands and therefore it can age the skin and damage the eyes.

Medium Wave Infrared heaters operate between 1.4 and 3 microns, emit temperatures of 500 °C – 800 °C and produce a deep red light. Applications at this wavelength include manufacturing processes such as curing of glues and coatings, welding of plastic parts, print toner curing and industrial drying. Medium-wave Infrared transmits a bit into the lower epidermis, upper dermis layers but, does not transmit into the functional organs (sweat glands, nerves, etc.) carried by the skin. It is also well absorbed by the skin.

“Far Infrared” heaters operate in wavelengths above 3 microns. Far Infrared elements emit much lower temperatures, typically around the 100°C mark and no visible light. Human and animal skin absorbs Far Infrared specifically well, making Far Infrared a biologically significant heating wavelength for humans and animals. Far Infrared is the least trans-missive wavelength into the skin, but is actually the best absorbed by the blood and cells. This is sufficient for human comfort heating, and avoids any possible health and safety issues. Because of their lower temperatures, applications of Far Infrared heating include Domestic, Commercial and Public comfort heating applications. Far Infrared heaters use a number of different elements, with popular ones being nickel or Fe-Cr-alloy wiring or more recently carbon fibre. These recent emitters have an efficiency close to 100 %, which means that almost all of the energy consumed is transformed into energy output at the panel surface.

3

Methodology

The following section aims to describe the process and the methods that were used during the various parts of the project. These includes methods for concept evaluation, computational analysis, testing of the final concept and quality assurance.

3.1 Process

The planned overall process can be seen in figure 3.1. In its entirety the plan was to first integrate the Swedish and Canadian teams, which entailed the team in Sweden needing to familiarize themselves with the work already done by the Canadians. This work primarily included the generation and evaluation of feasible concepts. When the Swedish team had successfully been integrated, the teams began working together on analyzing the chosen concept. Following this there was once again a need to evaluate the concept with respect to the functional specification. Each step is further explained in the following subsections.

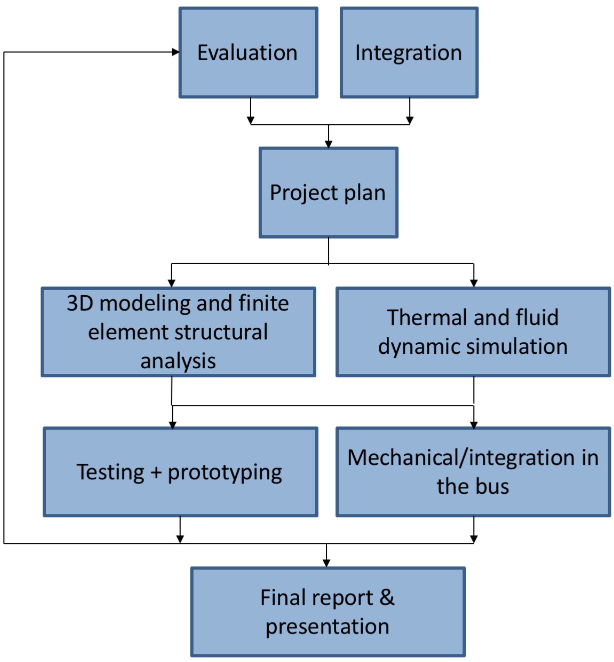

Figure 3.1: A schematic view of the overall process.

3.2 Concept Evaluation with Pugh Matrix

To further evaluate the concepts, in order to assess the previous work done by the students at Polytechnique, a Pugh matrix [6] was used. The criteria was primarily obtained from the functional specification created by the Canadian team, as can be seen in appendix (A). This specification also indicates the importance of each criteria, something that was then used as the basis for the importance values (K-score) ranging between 1 to 5. In addition, complexity and safety were split into three parts to make the assessment easier, more accurate and give more depth to the evaluation. These were given an importance value based on the group's experience. Furthermore, not all criteria was evaluated because some of them were considered too difficult to concretize. The different concepts were evaluated with the HVAC system currently used [3] as reference. Each criterion was deemed either better than, equal to or worse than this reference and received a corresponding comparison value as can be seen in table 3.1. These assessments were based on the team's engineering knowledge.

Table 3.1: Table of comparison values.

Comparison values	
1	Better than the reference
0	Equal to the reference
-1	Worse than the reference

The concepts were ready to be compared with one another once all of the criteria had been evaluated. Two different methods were used to gain two different values which together could be used to evaluate the concepts. The first method including adding the comparison's values to each other in order to obtain a total score. The second method entailed multiplying the comparison's values with the corresponding importance value and subsequently adding them together to receive a total weighted score. Once all of the concept received a total score and a total weighted score it became easy to eliminate concepts.

3.3 Prototyping with Computer Aided Design

When only one concept remained from the concept evaluation, it was designed through the use of the Computer Aided Design (CAD) tool, Catia-V5 [7]. This was done in order to be able to perform various analysis on the final prototype but also to confirm that the dimensions matched the dimensions of the bus cabin and how the heater would be mounted.

3.4 Computer Analysis

To reach a working prototype and furthermore verify the chosen concept, it was important to perform the necessary analysis of the systems before physically constructing them. To conduct these analysis, some arbitrary assumptions had to be made. For example, one of these assumptions was the size and position of the radiant heater. At a later stage in the project this would give a preliminary assessment on whether or not the concept was feasible or not. The following properties were examined within different simulation methods and software:

- Heat transfer
- Power consumption
- Durability
- Dimensions

3.4.1 Computational Fluid Dynamics

The defrosting and defogging phenomena which occur to any present liquid on the windshield of a bus when heated are complex and difficult to model and analyze. Due in part to the bus constantly being in a transient state in combination with the phenomena involving complex multi-phase interactions and multiple simultaneous phase changes. Furthermore, the chosen defrosting concept is based on the principle of radiative heat exchange, which is a wavelength and geometry dependent 3D phenomenon. All these parameters make it very difficult to predict the behavior and effectiveness of the suggested configuration of the heater without intensive computing. Computational fluid dynamics (CFD) analysis was therefore required to simulate the thermal phenomena which occurs in the bus during defrosting and defogging, to compare a desired heating configuration and optimize the chosen solution. For the entirety of this project, the Star CCM+ 13.04.011 R8 version [8] was used to perform CFD analysis. Due to the size of the simulations that needed to be run, a computational cluster was used. The used cluster was C3SE's Vera cluster which consists of a total of 196 compute nodes (total of 6200 cores) with a total of 23 TiB of RAM and 4 GPUs.

In order to maintain an organized structure to the thermal analysis, it was necessary to follow a methodical simulation plan and to validate the results obtained from performed computations. To do this, the heat exchange caused by the external convection was separately calculated and then added to a simulation computing the conjugate heat transfer phenomena which occurs within the bus cabin. Given that the phase changes occurring during the defrosting are complex, they require very fine meshes, long computational times, and very robust estimations of the simulation parameters and boundary conditions. To overcome these hurdles, the defrosting and phase changes per se were not computed, but were instead correlated to the windshield's surface temperature. To be clear, no water or ice was incorporated into either one of the simulations in any way due to the complexity that it would entail. This decision was made in combination with adopting the hypothesis that the wind-shield will be clear of ice and fog when the surface temperature is superior to 0 °C. This is also supported by the fact that in order to uphold safety regulations in accordance to SAE J381, the windshield would already be nearly free of ice. This in turn entails that the requirement on the heater would be to hinder the formation of new ice.

The general consensus when running simulations is that reality is very difficult to accurately replicate. Each mathematical correlation used within a CFD analysis inherently has a degree of error due to the fact that the correlation is merely a mathematical function which has been adopted to describe an observed behaviour in nature, such as a given form of heat transfer. Given this, the more mathematical correlations that are implemented into a simulation, the larger the inherent error of that simulation becomes and the less believable any results become. With this in mind, the choice to run two separate simulations was done so as to allow each simulation to only directly incorporate and focus on one mode of heat transportation, thereby simplifying each simulation. By reducing the inherent error of each simulation, the credibility of the simulations were increased and by default, the overall results of the CFD analysis. The two simulations were correlated by the assumption that the windshield could be treated as an isothermal object due to the windshield being so thin that the losses from the conduction are negligible. This entails that the windshield was treated as having such a high conduction that the relevant energy balance to solve in the analysis only took into consideration the radiative heating and the external convective chilling of the windshield.

The simulation regarding the external surface of the bus was done to obtain the convection coefficient of the windshield. This convection coefficient was used to model the chilling convective heat transfer which occurs between the windshield and the surrounding environment. The simulation regarding the internal surface of the bus was done to test if the windshield would reach the desired surface temperature when subjected to heating by the prototype heater and a chilling heat flux from the surrounding environment. Thereby, testing and confirming the viability of a far infrared heater as an alternative to the current defrosting system. The following sections provide detail regarding the computational fluid dynamics analysis, on both the interior and exterior of the bus. They present the simplified geometries, the mesh parameters, the chosen continua models and boundary conditions.

3.4.1.1 External Convection on Surface of Bus

As previously stated, convective heat loss accounts for a substantial heat flux between the bus and its vicinity. The external surface of the bus was simulated under the following conditions with the purpose of numerically solving the convection coefficient of the windshield. This in order to be able to calculate the average external chilling heat flux which affects the windshield. In terms of the scenario that was chosen to simulate, it was decided to adopt the external conditions which reflect the so called worst case environment and the average operation speed. This environment represents the harshest conditions, from the perspective of the chilling convective heat transfer affecting the windshield, that the bus would operate in. This specifically entails an air temperature of -20 °C and a driving speed of 15 m/s, where the speed of the bus and the temperature of the air combine to generate a high convection between the windshield of the bus and the environment.

A) Geometry

To conduct the external simulation, a wind tunnel was modelled from which the geometry of the bus was subtracted from. The subtracted geometry was the simplified 3D geometry of an LFSe bus that included the predominant external features and shapes of the bus.

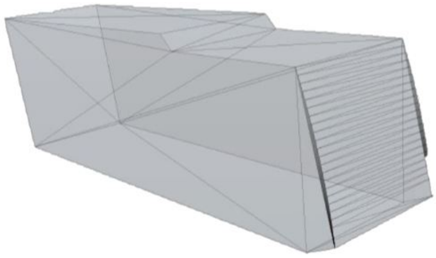

Figure 3.2: 3D geometry used for simulating the external convection on the bus.

B) Boundary Conditions

External air with a unidirectional flow was maintained at -20 °C through the tunnel at a speed of 15 m/s. The walls of the chassis were also represented as no slip walls, at a constant surface temperature of -5 °C. This thermal specification is an assumption, and therefore induces a point of uncertainty.

C) Continua

A new continuum was created and applied to the generated air region. The default properties of the air were maintained and supplemented by the following conditions:

- Three Dimensional
- Steady
- Gas
- Constant Density
- Cell Quality Remediation
- Turbulent (Reynolds-Averaged Naview-Stokes)
- K-Epsilon Turbulence (Realizable K-Epsilon Two-Layer, Exact Wall Distance, Two-Layer All y+ Wall Treatment)
- Segregated Fluid Temperature
- Segregated Flow (Gradients)

D) Mesh

Once the continua was set, an automated mesh operation was applied to the air region while selecting the surface remesher, the polyhedral mesher and the prism layer mesher. General parameters were applied to the domain, with the mesh in the immediate vicinity of the bus being further refined to ensure adequate results in areas of more advanced geometry or higher priority. The mesh's parameters were set to the following:

Default Controls	**General**	**Refined**
Base Size	0.3 m	0.3 m
Minimum Surface Size	30.0%	10.0%
Number of Prism Layers	2	5
Prism Layer Stretching	1.5	1.5

Table 3.2: Mesh parameters used in the general and the refined areas of the mesh.

This resulted in the following mesh:

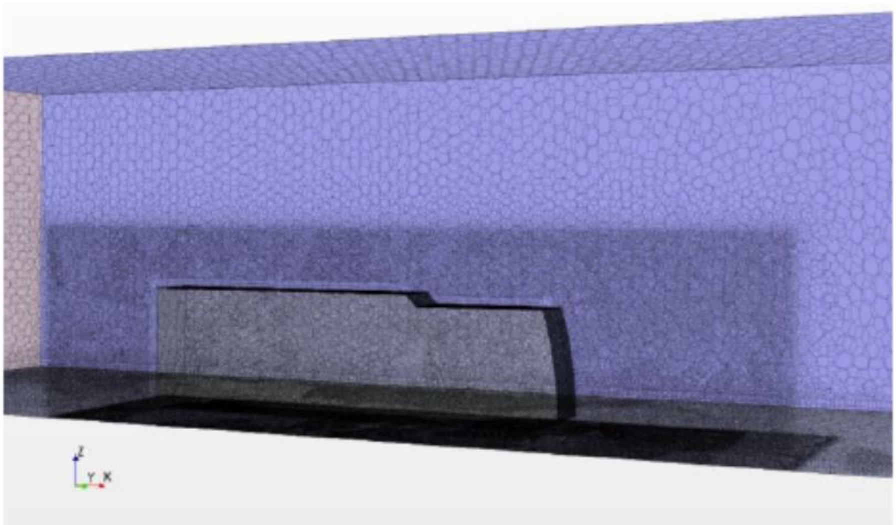

Figure 3.3: The resulting mesh used to simulate the external convective heat transfer on the windshield of the bus, notice the darker rectangle surrounding the bus due to the cells being more refined in this area.

Table 3.3: The number of cells, faces and vertices that comprise the resulting mesh.

# Cells	1 084 400
# Faces	6 686 690
# Vertices	5 426 654

3.4.1.2 Internal Radiation in Cabin of Bus

To test and confirm the validity of the proposed far infrared heater as a suitable replacement for the current heating system, the internal surface of the bus cabin was simulated. This was done with the specific purpose of measuring the surface temperature of the windshield as it is affected by the internal heating of the heater and an applied constant chilling heat flux. The chilling heat flux is based upon the resulting convection coefficient of the external simulation and surface area of the windshield. All of this to simulate the effect of the wind passing the bus without having to actively simulate the live interaction between the internal and external heat transfer on the windshield, as well as its internal conduction.

A) Geometry

In order to conduct the simulation, the internal geometry of the bus cabin was obtained from the team in Canada. The 3D CAD model was created based on physical measurements that were made in a LFSe bus. This internal model of the bus cabin was complimented by the incorporation and addition of the preliminary 3D design of the infrared heaters, according to the planned eventual integration of them into the existing LFSe cabin.

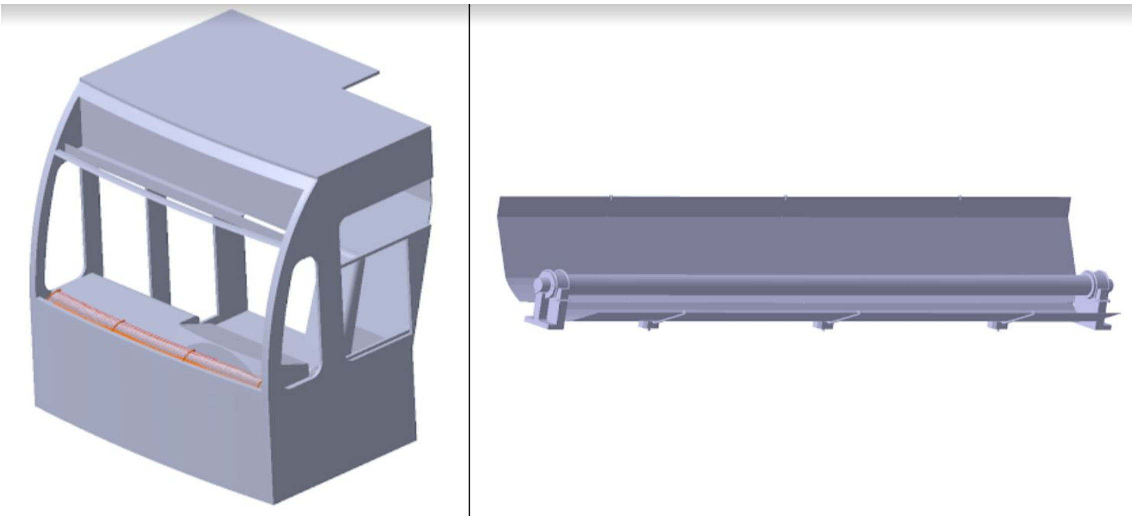

Figure 3.4: 3D models of the current cabin and designed heater.

B) Boundary Conditions

Appropriate boundary conditions were set to each internal surface of the bus cabin. Which boundary condition was applied to which surface was based on how relevant of an interaction the said surface would come to have with the radiative heat transfer between the heaters and windshield. All in all there were a total of four different boundary conditions created which were then applied to the various surfaces of the cabin.

The first boundary condition was applied to the windshield and included the following physical conditions and values:

Table 3.4: The physical conditions applied to the windshield's boundary condition.

Physical Conditions	**Type**
Custom Patch Angularity Specification	Use Region Values
Custom Patch Specification	Use Region Values
Radiation Flux Option	No Flux
Reference Frame Specification	Region Reference Frame
Shear Stress Specification	No-Slip
Specularity Option	Diffuse Reflection
Tangential Velocity Specification	Fixed
Thermal Specification	Heat Flux
User Wall Heat Flux Coefficient Specification	None
Wall Species Option	Impermeable

Table 3.5: The physical values applied to the windshield's boundary condition.

Physical Values	**Method**	**Value**	**Dimension**
Heat Flux	Constant	-220.52 W/m^2	Power/Length^2
Surface Emissivity	Constant	0.93	Dimensionless
Surface Reflectivity	Auto Calculate	N/A	Dimensionless
Surface Transmissivity	Constant	0.0	Dimensionless

The second boundary condition was applied to the emissive surface of the heaters. For this simulation the heater's were set to operate at a constant effect with no regulation. This is not entirely in accordance with reality, but was deemed suitable for the simulation as its purpose is to prove the concept of an infrared heater. The boundary condition for the emissive surface of the heaters included the following physical conditions and values:

Table 3.6: The physical conditions applied to the emissive surface of each heater's boundary condition.

Physical Conditions	**Type**
Custom Patch Angularity Specification	Use Region Values
Custom Patch Specification	Use Region Values
Radiation Flux Option	Diffuse Radiation Flux
Reference Frame Specification	Region Reference Frame
Shear Stress Specification	No-Slip
Specularity Option	Diffuse Reflection
Tangential Velocity Specification	Fixed
Thermal Specification	Adiabatic
User Wall Heat Flux Coefficient Specification	None
Wall Species Option	Impermeable

Table 3.7: The physical values applied to the emissive surface of each heater's boundary condition.

Physical Values	**Method**	**Value**	**Dimension**
Heat Flux	Constant	31830.0 W/m^2	Power/Length^2
Surface Emissivity	Constant	1.0	Dimensionless
Surface Reflectivity	Constant	N/A	Dimensionless
Surface Transmissivity	Constant	0.0	Dimensionless

The third boundary condition was applied to the reflective surface of the heaters and included the following physical conditions and values:

Table 3.8: The physical conditions applied to the reflective surface of each heater's boundary condition.

Physical Conditions	**Type**
Custom Patch Angularity Specification	Use Region Values
Custom Patch Specification	Use Region Values
Radiation Flux Option	No Flux
Reference Frame Specification	Region Reference Frame
Shear Stress Specification	No-Slip
Specularity Option	Diffuse Reflection
Tangential Velocity Specification	Fixed
Thermal Specification	Adiabatic
User Wall Heat Flux Coefficient Specification	None
Wall Species Option	Impermeable

Table 3.9: The physical values applied to the reflective surface of each heater's boundary condition.

Physical Values	**Method**	**Value**	**Dimension**
Surface Emissivity	Constant	0.0	Dimensionless
Surface Reflectivity	Auto Calculate	1.0	Dimensionless
Surface Transmissivity	Constant	0.0	Dimensionless

The fourth boundary condition was applied to the remaining internal surfaces of the bus cabin. Due to these surfaces not being directly involved in the heat radiative heat transfer between heater and windshield, they were set to have constant properties. The boundary condition applied to the remaining internal surfaces included the following physical conditions and values:

Table 3.10: The physical conditions applied to the remaining internal surfaces of the bus cabin's boundary condition.

Physical Conditions	Type
Custom Patch Angularity Specification	Use Region Values
Custom Patch Specification	Use Region Values
Radiation Flux Option	No Flux
Reference Frame Specification	Region Reference Frame
Shear Stress Specification	No-Slip
Specularity Option	Diffuse Reflection
Tangential Velocity Specification	Fixed
Thermal Specification	Temperature
User Wall Heat Flux Coefficient Specification	None
Wall Species Option	Impermeable

Table 3.11: The physical values applied to the remaining internal surfaces of the bus cabin's boundary condition.

Physical Values	Method	Value	Dimension
Static Temperature	Constant	15.0 °C	Temperature
Surface Emissivity	Constant	0.8	Dimensionless
Surface Reflectivity	Auto Calculate	N/A	Dimensionless
Surface Transmissivity	Constant	0.0	Dimensionless

C) <u>Continua</u>

There were two important factors to keep in mind when setting up the continua to be used. The first being the size of the 3D model on which the simulation was run on and the second being the simulations purpose of proving the concept of using a far infrared heater to heat the bus windshield. With these two factors in mind, it was decided that the simulation was to be run in steady state (Steady model) so as to simplify the simulation. In addition to this, the following models were selected to comprise the continua of the air within the cabin:

- Three Dimensional
- Gas
- Ideal Gas
- Laminar
- Gravity
- Gray Thermal Radiation
- Segregated Fluid Temperature
- Surface-to-Surface Radiation (View Factors Calculator)
- Segregated Fluid Temperature
- Segregated Flow (Gradients)

D) <u>Mesh</u>

The mesh needed to be fine enough to adequately cover the complex internal geometry of the bus cabin. Furthermore, the mesh needed to be especially fine when covering the areas of significant interest (the windshield, heaters and reflectors) in which the desired heat transfer will occur. Maintaining a high level of accuracy for the internal geometry was deemed important so as to make the simulation as similar to a physical test as possible. To accomplish this, an automated mesh operation was applied and the Surface Remesher, the Polyhedral Mesher and the Prism Layer Mesher were selected. In addition to this, the mesh controls were left at the default values with the exception of the following parameters:

Table 3.12: Non-default control values of mesh parameters.

Default Controls	**Value**
Base Size	1.0 cm
Minimum Surface Size	10.0 %
Number of Prism Layers	3
Prism Layer Stretching	1.5

The resulting mesh was the following:

Table 3.13: The number of cells, faces and vertices that comprise the resulting mesh.

# Cells	3 955 464
# Faces	24 326 456
# Vertices	19 914 894

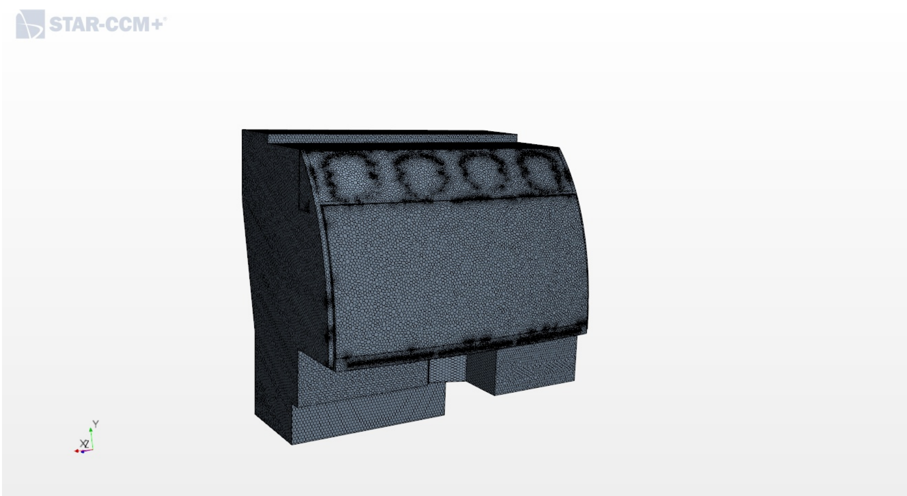

Figure 3.5: The resulting mesh used to simulate the radiative heat transfer in the bus cabin.

3.4.2 Structural analysis FEA

It is not possible to define a specific load case which can be said to accurately describe a bus in motion. This is due to varying road conditions and disturbances. Due to this a random vibration simulation was used to more accurately define and test how the suggested heater would handle being used in a bus in service. A random vibration test uses statistical methods to simulate the occurrence of disturbances on the road surface. The random vibration simulation was conducted using Finite Element Analysis (FEA) with the software ANSYS [9]. The simulation was used to calculate the structural responses such as stress levels, deformations and fatigue limits due to random, non-deterministic loads, in order to evaluate the expected lifetime of the suggested concept.

For the random vibration test data was used from the standard ISO 16750-3:2007 [10] as it is the one that Nova employs in their work. A random vibration analysis requires a geometry with determined materials, a modal analysis of the geometry which identifies the eigenfrequencies and eigenmodes, fixed supports where the geometry is fixed in space and an input power spectral density (PSD) acceleration data that states on which frequencies the loads are applied on the geometry. The values from the ISO-standard are shown in table 3.14 and figure 3.6.

Table 3.14: PSD and Frequency values from ISO 16750-3

Frequency Hz	**PSD** $(m/s^2)^2/Hz$
10	18
20	36
30	36
180	1
2000	1

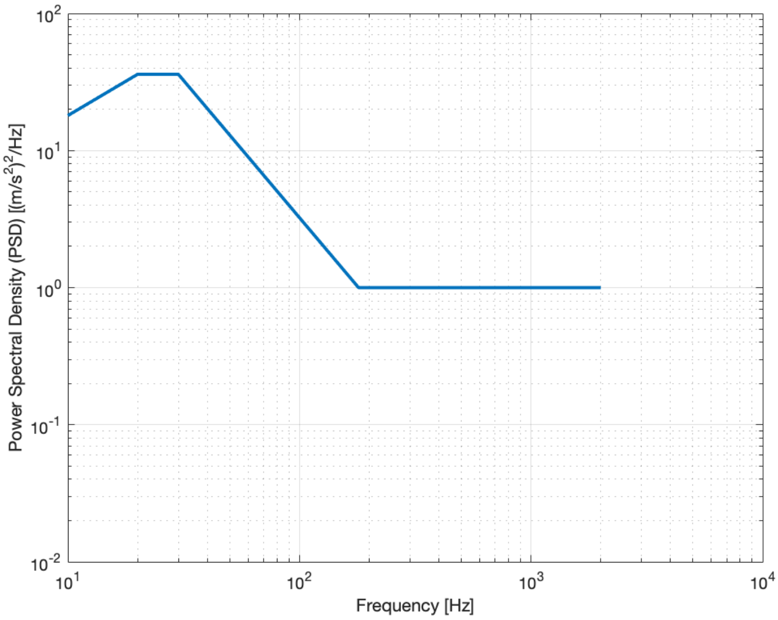

Figure 3.6: Graph of PSD acceleration versus frequency

In ANSYS the simulation began with importing the CAD model of the concept into a static structural module. Materials were chosen according the predetermined specifications of the different components. To select how the different parts were connected of the model the built in function auto contact was used and later on verified so to be sure that no connections were missed. An automatic mesh was applied over the whole model and was further refined along the heating element and reflector supports as they were of greater interest to thoroughly inspect. The engineering data and geometry were then linked to a new module for modal analysis. In order to evaluate the eigenfrequencies and corresponding eigenmodes of the model a maximum frequency needed to be chosen for the analysis. The ISO-standard states that the random vibration reach up to 2000 Hz. However these frequencies represent very small vibrations that are absorbed in the tires of the bus. It is therefore only necessary to include frequencies up to 1000 Hz when investigating road disturbances. The second most commonly occurring frequency in the ISO-standard is 180 Hz and according to the book Mechanical Vibrations [11] it would be necessary to include eigenfrequencies and corresponding eigenmodes up to twice as large as that frequency. Therefore 400 Hz was chosen as the limit. The five brackets connecting the heater to the bus were chosen as fixed supports. Following this, the first simulation to identify the nodes for the heater was run.

The simulation gave 11 eigenmodes and eigenfrequencies for the heater. The engineering data, geometry, model and solution was then linked to a random vibrations model. Within the random vibrations model PSD acceleration was chosen as data source for the test as they were stated in the ISO-standard, note that the 2000 Hz frequency was excluded here as well. The output of this simulation was chosen to be total deformation, equivalent stress and life expectancy with the fatigue tool. In order to get a better understanding of the fatigue of the different components they were simulated separately in the fatigue tool.

3.5 Testing and Quality Assurance

To ensure the quality and safety of the concept a FMEA was done. To be able to verify the concept, two separate tests were run. One was done in Canada and other one was done in Sweden. The Canadian team tested the fit a prototype into an actual LFSe bus and the Swedish team tested the prototype's ability to deice a windshield in a realistic climate.

3.5.1 Test of concept

The heater used in these tests was purchased at Infrared Heaters Direct and is produced by Herschel [12]. Its power is 1950 Watts and its dimensions are 760 mm x 100 mm x 166 mm. The heater emits wavelengths between 3 μm and 10 μm, which is in the far infrared range. In figure 3.8 the setup of test 6, which will be explained under the procedure section, is shown. The heater is positioned on the left and the windshield on the right of the figure.

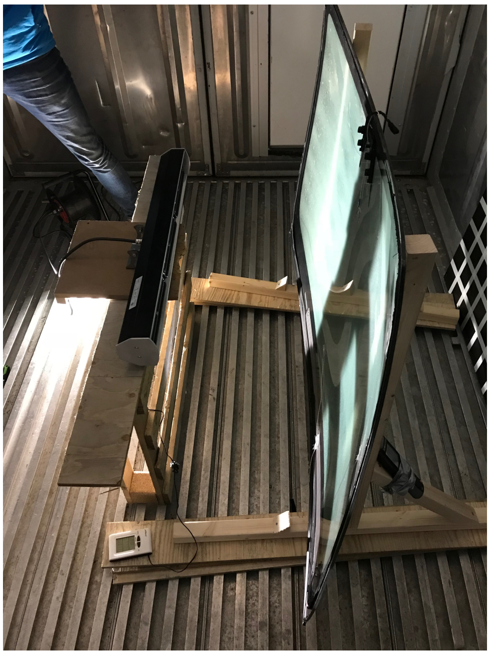

Figure 3.7: The test setup for test number six.

3.5.1.1 Objectives

The purpose of the conducted tests was to verify that the chosen concept, a far infrared heater, can defrost and defog a windshield. In total six tests were done. The environment was a freezer container which could be set to -20 °C.

Figure 3.8: The freezer container that was used for the tests.

The test was setup to simulate the standard procedure of bus windshield defrosting, called SAE J381. The same amount of water was sprayed on the windshield as in the standard, which is 0.05 mL/cm^2. Temperatures were measured on the vertical center line just as suggested and the same test time, 30 minutes, was used for all of the tests. However, the environment's conditions were not perfect. The cooling mechanism of the thermal chamber had to be switched off, thus the air on both the inside (to the left of the windshield) and the outside (to the right of the windshield) of the figurative bus was heated during the test. In reality only the air on the inside of the bus would get warmer while the external temperature would remain a constant -20 °C.

Furthermore, according to the standard, windshield wipers are permitted. This could not be included in the tests and led to longer defrosting times. There was also no way to compare the current defrosting system of LFSe buses in the same environment. This did not affect the test results, but it would have been interesting to compare the new concept with the one that is currently used under the same conditions.

3.5.1.2 Procedure

Firstly, the windshield was sprayed with water to form a layer of ice. This was repeated three times, so a total of three layers of ice were formed. When this was done the heater was turned on with an environmental temperature of -20 °C and then the cooling mechanism of the container was turned off. The reason for switching it off was to simulate the heating of the bus cabin, because a constant temperature of -20 °C on both the inside and the outside of the windshield would not give an accurate result. An issue with doing this is that the temperature on the outside of the windshield also increased. Ideally, the temperature on to the right of the windshield (outside of the bus) would have remained a constant -20 °C and while the area to the left of the windshield (which represents the internal cabin of the bus) would not have been cooled by the container, but this could not be accomplished. During the test, temperature was measured continuously on the inside of the windshield on two separate points, near the top and bottom of the windshield. The ambient temperature was also measured.

The setup of the heater was varied in six different ways. During the first five tests the heater was placed by the bottom of the windshield and aimed towards the centre of the windshield. For these first five tests the distance from the windshield was varied to be 0 cm, 25 cm, 50 cm, 75 cm and 100 cm. For the final test the heater was placed on a height equal to the centre of the windshield and with a distance of 50 cm from the windshield.

3.5.2 Verification of Placement in Bus

For this test a first prototype was built. It is referred to as P1.1 and is presented in this section. Figure 3.9 show P1.1 and its main components.

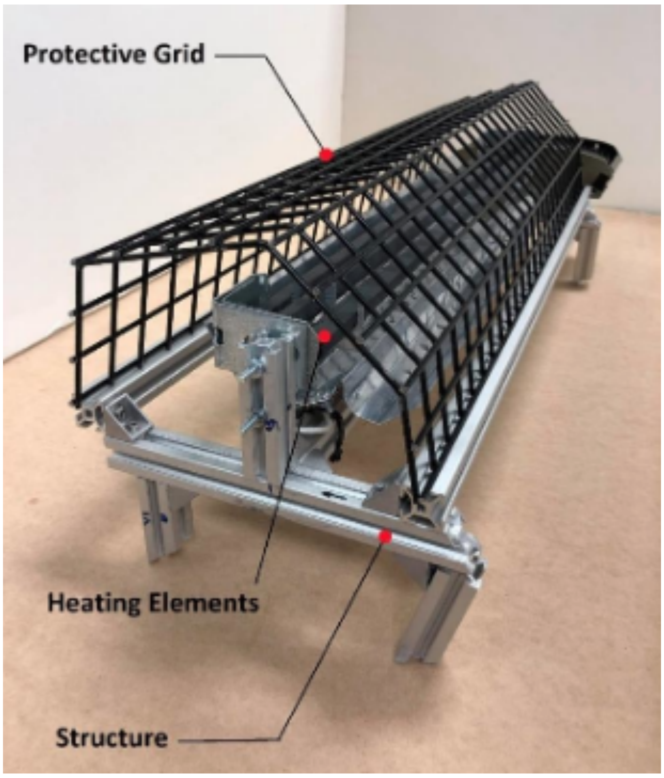

Figure 3.9: Side view of P1.1.

3.5.2.1 Objectives

The test was performed directly at the Nova Bus plant in Saint-Eustache. The objectives were to:

1) Check the geometric compatibility of P1.1 housing with the dashboard.

2) Evaluate the temperature of the heating elements and the protective grid and consequently the burn risks related to the safety of passengers.

3) Check that the temperature beneath the heater does not increase excessively so as to prevent damaging the plastic parts of the dashboard.

4) Measure the efficiency of purchased infrared heaters, i.e.:

a) Test the general efficiency of the heaters on the windshield (increase of the surface temperature of the windshield according to the zone delimited by the SAE J381 standard, defog and ensure fast evaporation of the melted water on the outer surface of the windshield).

b) Test the effectiveness of the reflectors to assess the radiation loss and to find the optimal orientation.

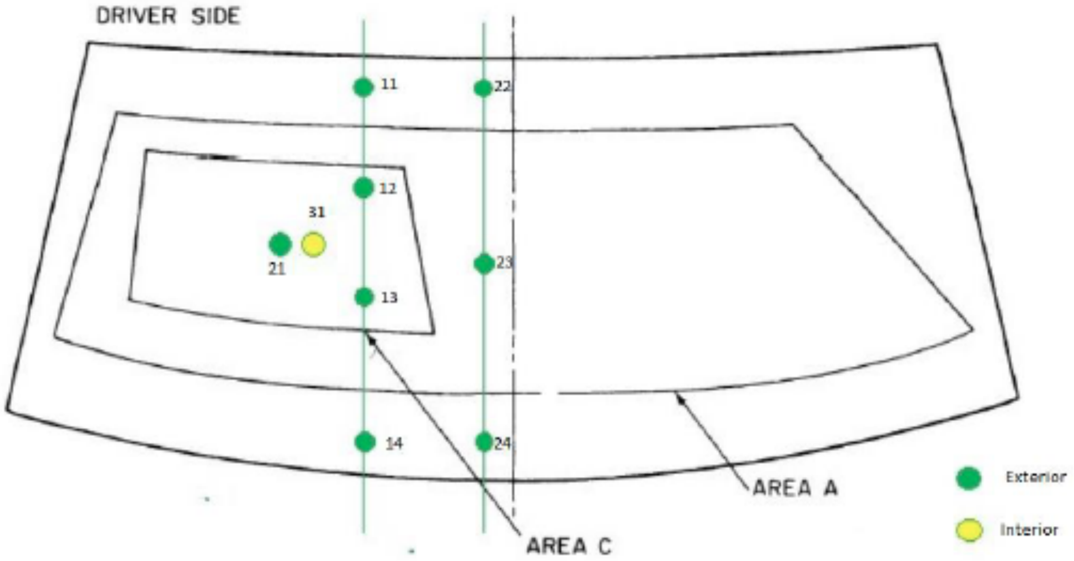

Figure 3.10: Position of the thermocouples on the windshield of the bus.

3.5.2.2 Procedure

For practical reasons, only half of the windshield was exposed to the radiation of the infrared heater.

1. Measured the following parameters:

- Ambient temperature and relative humidity
- Temperature inside the bus
- Relative humidity inside the bus
- Perpendicular heater-window distance

2. Placed the insulating welding blanket on the half of the dashboard on which the infrared heater was placed.

3. Placed P1.1 on the insulating cover,itself located on the dashboard.

4. Defined the different areas of SAE J381 with masking tape. The figures in SAE J381 Appendices was used to delimit the zones.

5. Installed the thermal camera inside the bus, facing the windshield and centered on area C defined by SAE J381 as shown on figure 3.10.

6.Installed the thermocouples according to the following picture and measured their exact x-y coordinates (origin is set at the bottom left corner of the tape-delimited area C).

3.5.3 Quality Assurance Supported by an FMEA

The Failure Mode and Effects Analysis (FMEA) is an effective way of detecting possible failures that may occur while using a given product. This risk assessment can be conducted in many different ways and the method that has been used in this project complies with the Volvo Group standard, STD 105-0005 [13] and follows the Design FMEA (D-FMEA) procedure. The standard also comes with an table which is a Volvo Group template [14].

To conduct an D-FMEA certain factors must be identified. At first, one requirement is to distinguish all the components within the product that could lead to a failure. Then the failure mode, the cause of the failure and the effect of the failure are listed. When all of these are specified one can, based on engineering knowledge, start to assess potential occurrence of failure (Po), severity of failure (S) and potential detection of failure (Pd). Each of these elements are graded on a scale from 1 to 10. The closer the grade is to 10, the more problematic the element is hypothesized to be. Then, the Risk Priority Number (RPN) is calculated by multiplying Po, S and Pd, yielding a value that can range from 1 to 1000. It is recommended to take action if the assessment leads to high RPN:s in order to lower the risk of failure occurring. When this action is done a new assessment can be conducted.

4
Results

In this chapter the results will be presented. First, the evaluation of the Canadian concepts will be presented and the decision regarding which concept that was chosen to be further developed. Following this the results from the computational simulations and the physical tests will be shown and finally the final concept and its characteristics are presented.

4.1 Concept Evaluation Using a Pugh Matrix

The following section will display the outcome of the re-evaluation of the Canadian teams concepts.

Table 4.1: Concept evaluation using a Pugh matrix

Pugh matrix 1										
Criteria		Importance (K)	Reference	Concepts						
				1a	1b	2a	2b	3	4	5
				Value	Value	Value	Value	Value	Value	Value
Perfromance	Electric power consumtion	5	x	1	1	0	-1	-1	1	-1
	Mass	3	x	1	1	-1	-1	-1	1	1
	Defrosting	5	x	1	1	0	0	-1	0	-1
	Defoging	5	x	1	1	0	0	-1	0	-1
Complexity	Number of parts	2	x	1	1	0	0	0	1	1
	Feasibility	5	x	0	-1	1	1	-1	1	1
	Impact on adjacent systems	3	x	-1	-1	0	0	-1	-1	-1
Maintenance	Accessibility of the parts	3	x	-1	-1	0	0	0	0	0
Safety	Temperature	5	x	1	1	0	0	-1	0	0
	Noise	5	x	1	1	-1	-1	-1	1	0
	Hinder visibility	3	x	-1	0	0	0	-1	0	-1
Availability	Unavailable or patented	4	x	0	-1	0	0	0	0	0
		Total: +		7	7	1	1	0	5	3
		Total: -		-3	-4	-2	-3	-9	-1	-5
		Total score:		4	3	-1	-2	-9	4	-2
		Total weighted score:		21	15	-3	-8	-39	17	-11
		Rank		1	3	4	5	7	2	6

As can be seen in table 4.1 concept 1a had the highest total score. This outcome contradicts the result of the Canadian team, which led to a new evaluation being done. With regards to their result concept 4 was chosen as the reference. Concept 2b, 3 and 5 were eliminated due to their low score.

Table 4.2: Concept evaluation using a Pugh matrix

Pugh matrix 2						
Criteria		Importance (K)	Reference #4	Concepts		
				1a	1b	2a
				Value	Value	Value
Perfromance	Electric power consumtion	5	x	1	1	-1
	Mass	3	x	1	1	-1
	Defrosting	5	x	0	0	0
	Defoging	5	x	0	0	1
Complexity	Number of parts	2	x	1	1	-1
	Feasibility	4	x	-1	-1	1
	Impact on adjacent systems	3	x	-1	-1	1
Maintenance	Accessibility of the parts	3	x	-1	-1	-1
Safety	Temperature	5	x	1	1	0
	Noise	5	x	0	0	-1
	Hinder visibility	3	x	-1	0	0
Availability	Unavailable or patented	4	x	0	-1	0
		Total: +		4	4	3
		Total: -		-4	-4	-5
		Total score:		0	0	-2
		Total weighted score:		2	1	-6
		Rank		1	2	2

When evaluating with concept 4 as reference both concept 1a and 1b came out ahead, see table 4.2. Concept 2a received a negative total score and was therefore eliminated. Despite none of the total scores of any of the concepts being favorable, the total weighted score was in favor of the internal heating concepts. Keep in mind that the internal heating concepts does not have the same opportunity to heat the driver, which favors concept 4. In addition, the technology of radiative heating is already developed, because this kind of system is widely used in the field of domestic heating. This all favors concept 4, the radiant heater. Even if further evaluation may be needed, the radiant heater was deemed to be a promising solution, therefore the team will follow the suggestion from Polytechnique and Nova Bus and continue developing this concept.

4.2 Computational Analysis Output

Results from the computational analyses are presented below. This includes results from the computational fluid dynamics and also results from structural analysis.

4.2.1 Computational Fluid Dynamics

The following subsection will present the results from the simulations run on the external surface of the bus and the internal surface of the bus cabin.

4.2.1.1 External Convection on Surface of Bus

After running the simulation for the external surface of the bus for 1 500 iterations, which corresponds to 73287.2 seconds or roughly 20 hours and 21 minutes, the following scalar views were obtained. The first figure depicts the temperatures across the wind tunnel and external bus surface.

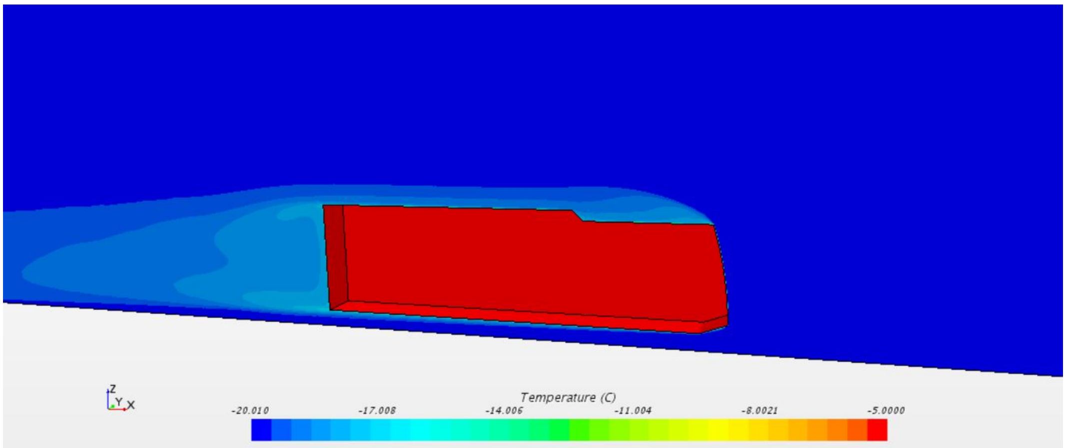

Figure 4.1: Temperature across the external surface of the buss and surrounding environment. Temperature ranges from -20.01 °C to -5 °C.

The second figure depicts the heat transfer coefficients across a symmetrical half of the bus windshield. Using these values, the average convection coefficient across the entire windshield was possible to calculate as $h_c = -11.02621$ W/m^{2}K. Using this, the chilling convective heat transfer which affects the windshield (and the infrared heater must counteract) was calculated as $\dot{Q} = h_c A(T_S - T_\infty) = -220.52$W/m^{2}K. To calculate this the assumed windshield temperature, external temperature, calculated convection coefficient and windshield area was used. This convective heat transfer was applied as the chilling effect on the windshield in the simulation of the internal bus cabin.

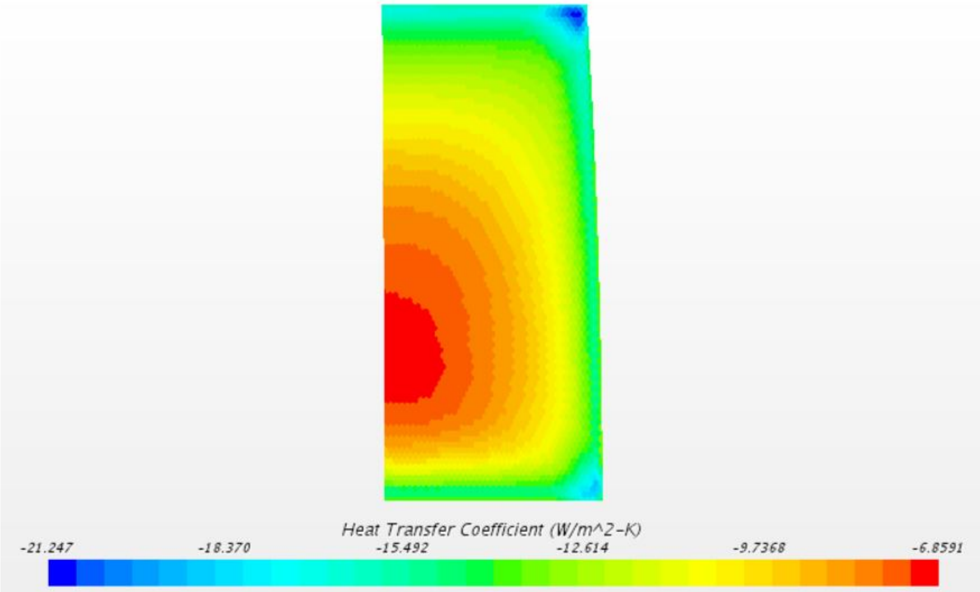

Figure 4.2: Heat transfer coefficients across the windshield of the bus. Coefficient ranges from -21.247 °C to -6.8591 °C.

4.2.1.2 Internal Radiation in Cabin of Bus

After running the simulation for the internal cabin of the bus for 30 000 iterations, which corresponds to 36938.7 seconds or roughly 10 hours and 16 minutes, the following scalar views of various parts of the cabin were obtained. They depict the varying temperatures across the cabin from two different angles, a cross section of the cabin and the windshield. Worth noting is that based on these results, only a marginal part of the windshield will remain at a subzero temperature.

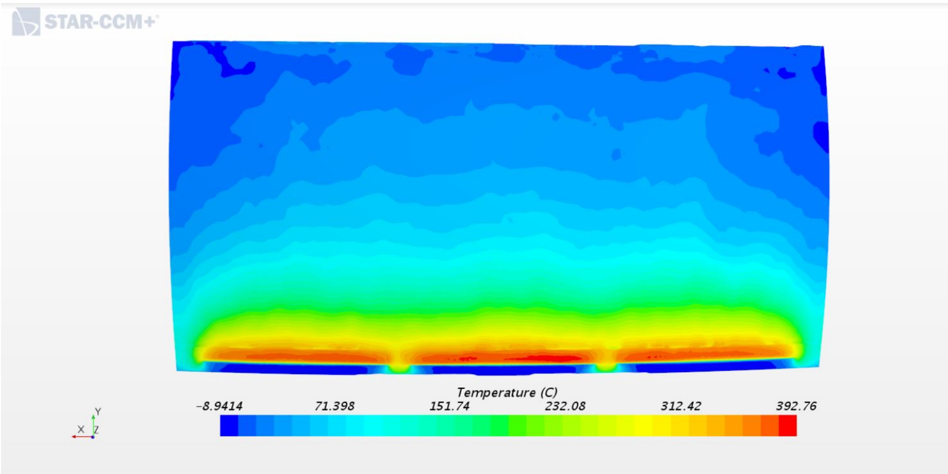

Figure 4.3: Surface temperature of windshield. Based on this the windshield will be almost completely defrosted. Temperature ranges from -8.9414 °C to 392.76 °C.

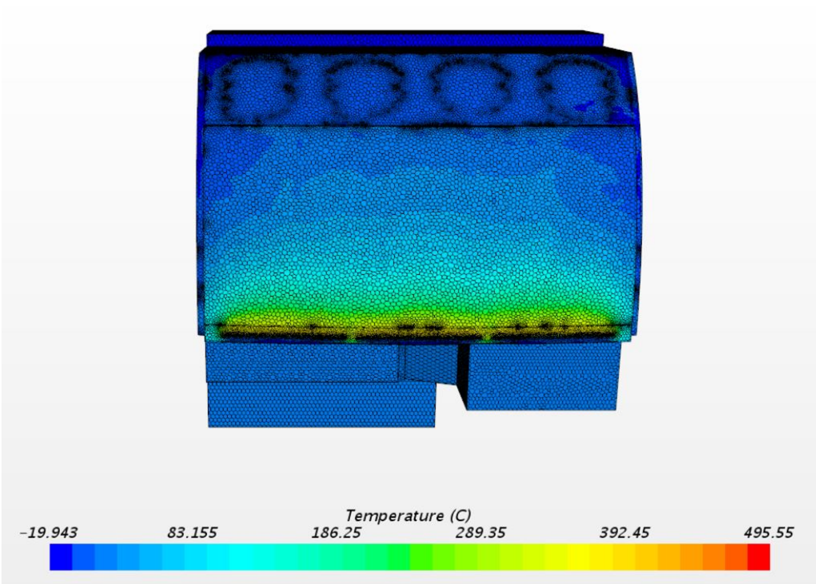

Figure 4.4: Surface temperature across the bus cabin, seen from a frontal view. Temperature ranges from -19.943 °C to 495.55 °C.

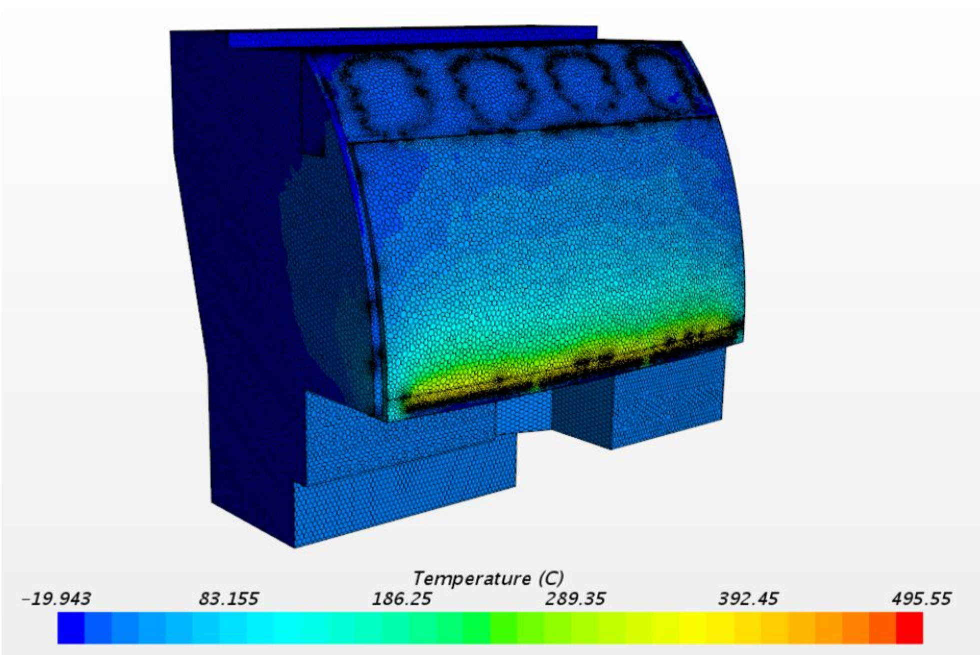

Figure 4.5: Surface temperature across the bus cabin, seen from an angle. Temperature ranges from -19.943 °C to 495.55 °C.

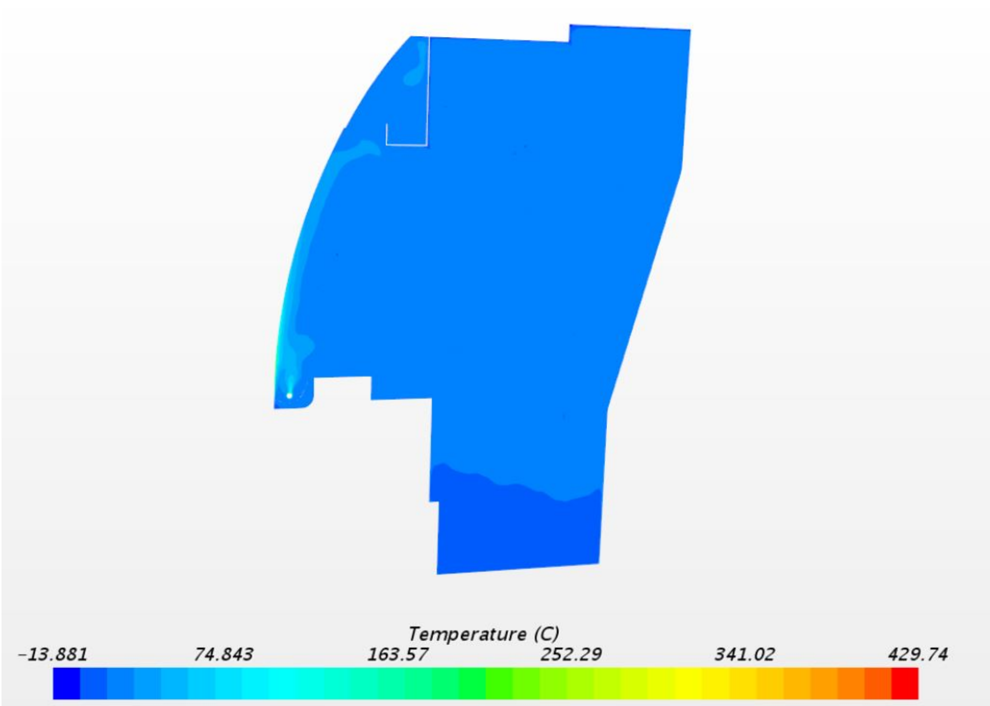

Figure 4.6: Temperatures along a cross section of the bus cabin. Temperature ranges from -13.881 °C to 429.74 °C.

4.2.2 Structural Analysis

The outcomes from the structural analysis shows that most parts of the heater will withstand usage according to the functional demands.

Firstly the outcome from the modal analysis resulted in 11 eigenmodes of resonance in the product. This is shown in table 4.3.

Table 4.3: Eigenfrequencies.

Eigenmode	Eigenfrequency [Hz]
1	109,19
2	125,13
3	137,32
4	168,71
5	185,02
6	229,73
7	241,92
8	244,34
9	303,43
10	306,60
11	378,34

Both Eigenfrequencies 168,71 Hz and 185,02 Hz are rather close to the 180 Hz frequency caused by random vibrations, seen in table 3.14. This can be contributed to an extra risk of fatigue of the affected components. The fifth eigenmode shows that when subjected to a frequency of 185 Hz the heating element will resonate, shown in figure 4.7. Notice that the eigenmode calculations does not take level of deformation into account, hence the large levels of deformation in the chart

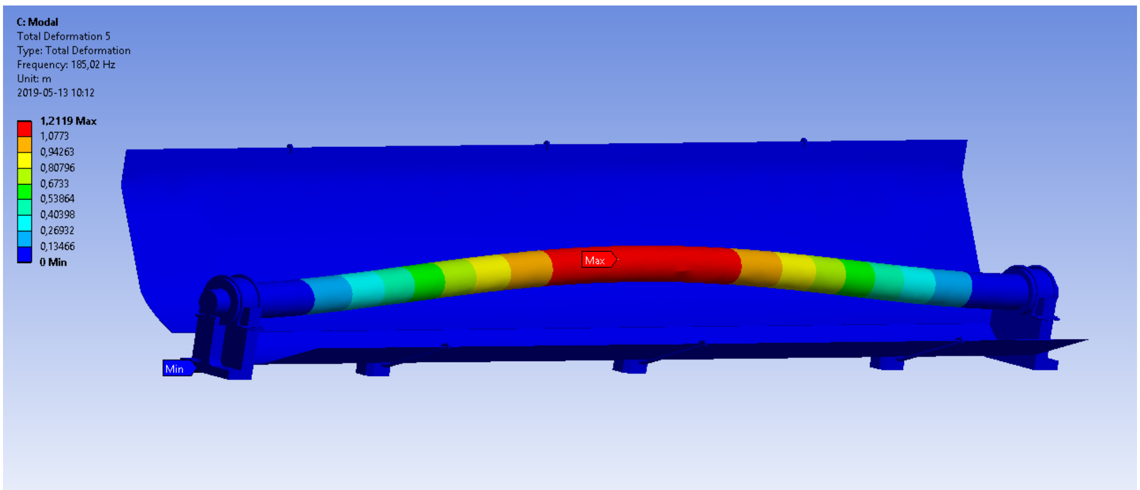

Figure 4.7: Eigenmode 5 of the heater assembly when subjected to a load with frequency of 185.02 Hz.

The directional deformation test in the Z-axis during random vibrations showed that the structure was stable in the direction of the vibrations and nothing would break initially.

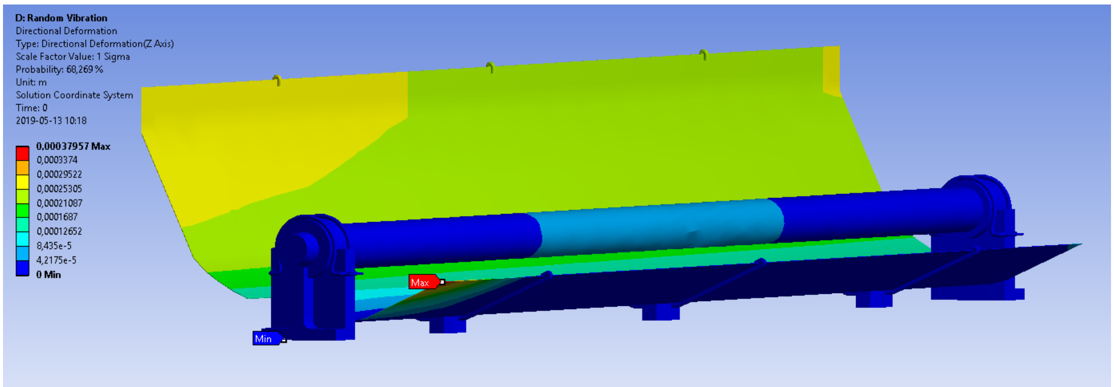

Figure 4.8: The colored chart shows that the maximum deformation of the heater subjected to random vibrations. It is calculated to be 0.37 mm.

The equivalent stress test resulted in satisfactory low levels of stress as well meaning that the structure would endure there as well.

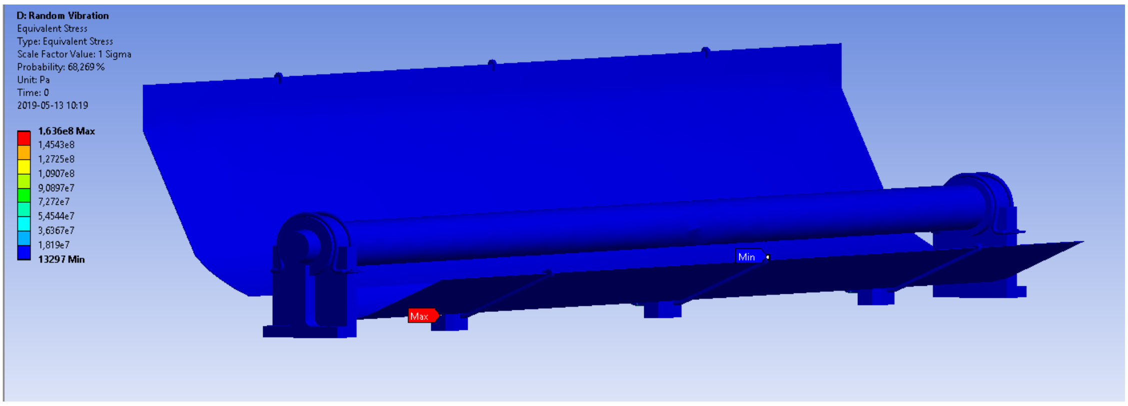

Figure 4.9: The results of the stress test when subjected to random vibrations. A maximum stress of 163 MPa is computed.

The fatigue analysis of the heating element showed that the element probably would endure 2.8×10^6 seconds, which equals to 777 hours. before breaking which is deemed satisfactory.

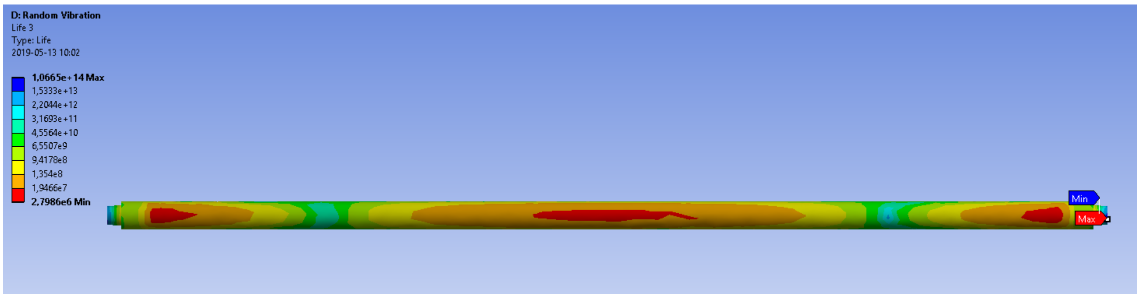

Figure 4.10: Fatigue analysis of the heating element when subjected to random vibrations. The colors represent calculated life expectancy.

The reflector was well in range of service life as well.

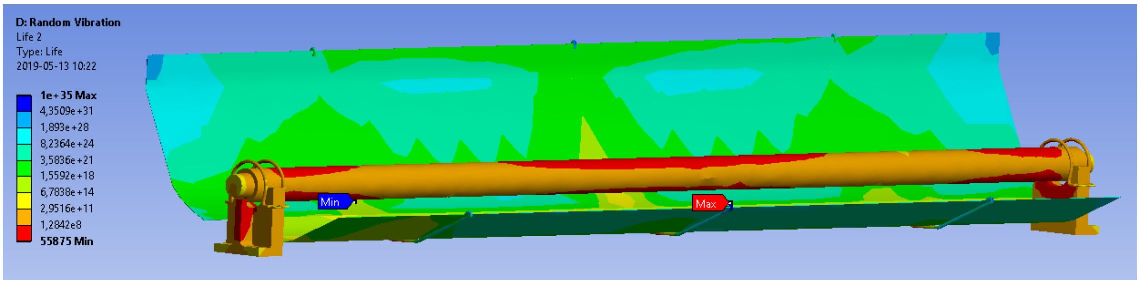

Figure 4.11: Fatigue analysis of the entire heater when subjected to random vibrations.

As seen in figure 4.12 the brackets holding up the heater will hold up for the planned service time.

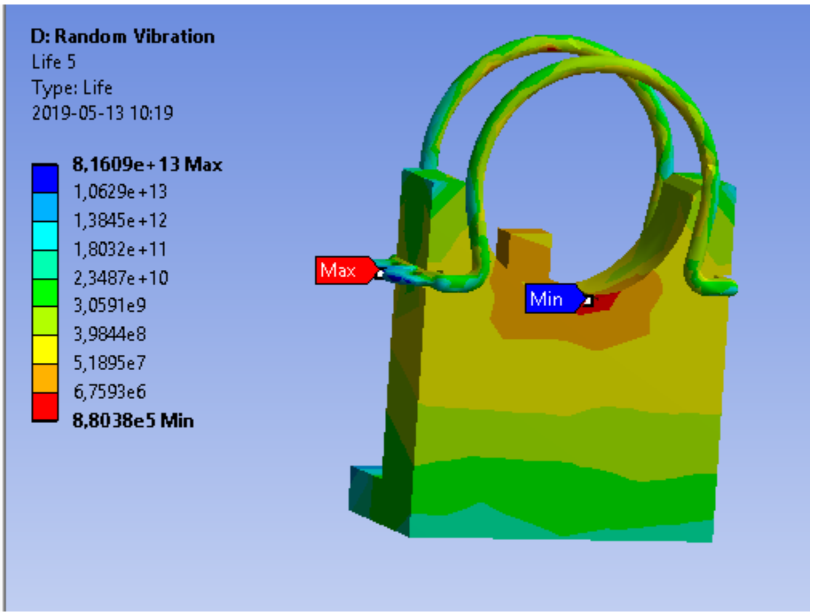

Figure 4.12: Fatigue analysis of the brackets holding up the heater assembly when subjected to random vibrations.

The analysis of the reflector supports were conducted with two different materials, steel and aluminum. The steel supports only withstood 12877 seconds. Therefore the material was changed to aluminum to see if this could solve the problem and increase durability. When it came to the supports for the reflector however the 2 mm thick aluminum wires also fatigued too quickly, only lasting for 55875 seconds, and need to be revised.

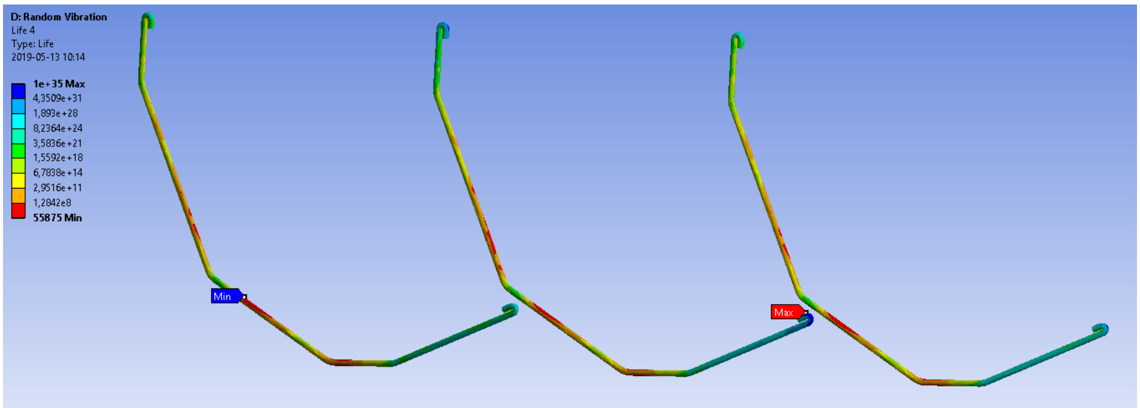

Figure 4.13: Fatigue analysis of the reflector supports in aluminum when subjected to random vibrations.

4.3 Test results

This section handles the output received from the two different tests conducted.

4.3.1 Test of Concept in Climate Chamber (Sweden)

The results from the test of the chosen concept is presented below. They are presented in the order that they were done and the last paragraph is a short summary.

4.3.1.1 Test 1 –0 cm

With the heater placed directly by the bottom of the windshield the defrosting results were good, but not optimal. After 30 minutes the central part of the windshield, the width that the heater covered, was fully defrosted. But the outer edges of the windshield, which were not directly covered by the heater, were not defrosted. There was also a large difference in temperature between the lower and the upper sections of the windshield. The lower part had a final temperature of 85.1 °C and the upper section had a final temperature of 8.6 °C. These big differences in temperature also meant that the lower part of the windshield was defrosted in about six to seven minutes while the upper part was not defrosted until 25 minutes in to the test. Due to this, the windshield was defrosted very unevenly.

4.3.1.2 Test 2 –25 cm

The second test gave similar results as the first. The centre part was fully defrosted and the outer edges still had some ice on them. There was still a difference in temperature, but not as big. The lower part of the windshield had a final temperature of 44.1 °C whilst the upper section had a final temperature of 6.2 °C. This entailed a somewhat more even defrost-procedure, but not good enough.

4.3.1.3 Test 3 –50 cm

The third test gave better results than the first two tests. After the 30 minutes had passed by the windshield was almost entirely defrosted. There was still some ice present on the outer edges but it could easily have been removed with the help of wipers. The temperature difference was also lower than in the two previous tests. The final temperature was at 24.8 °C on the lower section and 6.8 °C on the upper section. Because of this the time to defrost the lower section was somewhat extended compared to earlier test, but with the gain of defrosting now occurring at a more even pace across the windshield.

4.3.1.4 Test 4 –75 cm

With the heater placed on the ground 75 cm from the windshield the ice melted very poorly. Its defrosting was segmented and very poor. This was shown in that the ice near the outer edges of the windshield was melted but not the ice in the middle of the windshield. However, the final temperature of the lower section of the windshield was at 5.1 °C and on the upper section it was 1.2 °C. The reason for the ice not melting was most likely that the ice may have been thicker than it was in the previous tests.

4.3.1.5 Test 5 –100 cm

This test, surprisingly, gave better results than test 4. After the heater had been aimed towards the centre of the windshield from a distance of one meter for 30 minutes, the ice had melted on the entire windshield. It had not completely melted to water but it was melted enough to get rid of it with a couple of strokes with the wipers. The final temperature in the lower section and the upper section was exactly the same, -0.4 °C. Even though the temperature on the inside of the windshield did not exceed 0.0 °C, the heater managed to defrost it to a point where only a few strokes of the wipers were required to fully remove the ice.

4.3.1.6 Test 6 –50 cm, height=middle of the windshield

Unlike the five previous test the heater was placed in the centre of the windshield height wise, 65 cm from the ground, and with a distance of 50 cm from the windshield. The distance was chosen because at 50 cm distance the heater gave the best results. The heater was, as always, aimed towards the centre of the windshield and this test setup gave the best results. Unlike the five previous test this one could be finished after 25 minutes since the windshield had been completely defrosted in this time. The ice melted with a steady pace all across the windshield, but despite this there was a difference in final temperatures between the lower and the upper sections. In direct contrast to the previous tests, after this test the upper section was hotter than the lower section. The upper section was at 33.0 °C and the lower section was at 3.9 °C.

4.3.1.7 Summary of Testing the Concept

To summarize the six tests that were conducted, it was the clear that the last test gave the best result. What was made obvious was that the distance played a huge difference in a variety of ways. This is shown in figure 4.14. With the heater placed close to the windshield the temperature of the lower section of the windshield reached very high temperatures, which led to good defrosting in that area. The upper section of the windshield was not defrosted as effectively. Since the setup that was used in test number one is well correlated to the setup that is chosen for the final concept there is understandably a problem with the high temperatures in the CFD simulations. During test one the lower section of the windshield reached temperatures of 90.0 °C, which obviously can be dangerous for both the driver and the passengers as well potentially damaging the windshield.

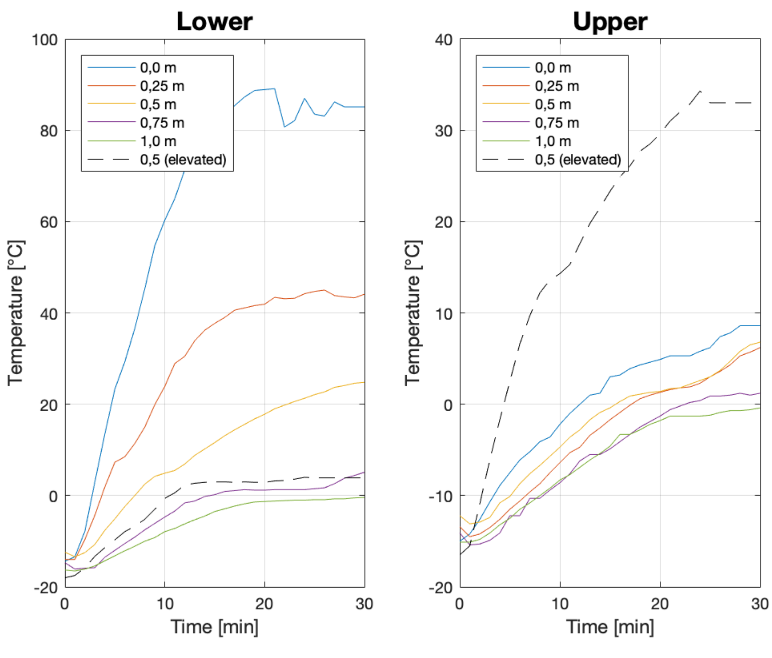

Figure 4.14: Lower and upper part of the windshield graphs of temperature vs time.

On the other hand, test number four and five did not give optimal results either. With a distance of 75 and 100 cm the defrosting was slow and the temperatures may have been too low. So, as mentioned before, 50 cm proved to be the optimal distance. It gave an even spread of the heat on the windshield and therefor an even defrosting procedure. It was also the distance that made the entire windshield defrost the in the shortest amount of time. Unfortunately, this configuration can't be accomplished in the bus. Neither the distance nor the height.

Worth mentioning is that there were always two humans in the container who approximately emit 100 watts each. This may have affected the test results.

4.3.2 Test to Verify Placement (Canada)

As per the SAE J381 standard, area C that is showed in figure 4.15 is critical and needs to be defrosted in less than 30 minutes to ensure sufficient driver visibility. The results of the tests were thus very conclusive. Indeed, after 25 minutes of testing, the temperatures measured by the different thermocouples increased significantly.

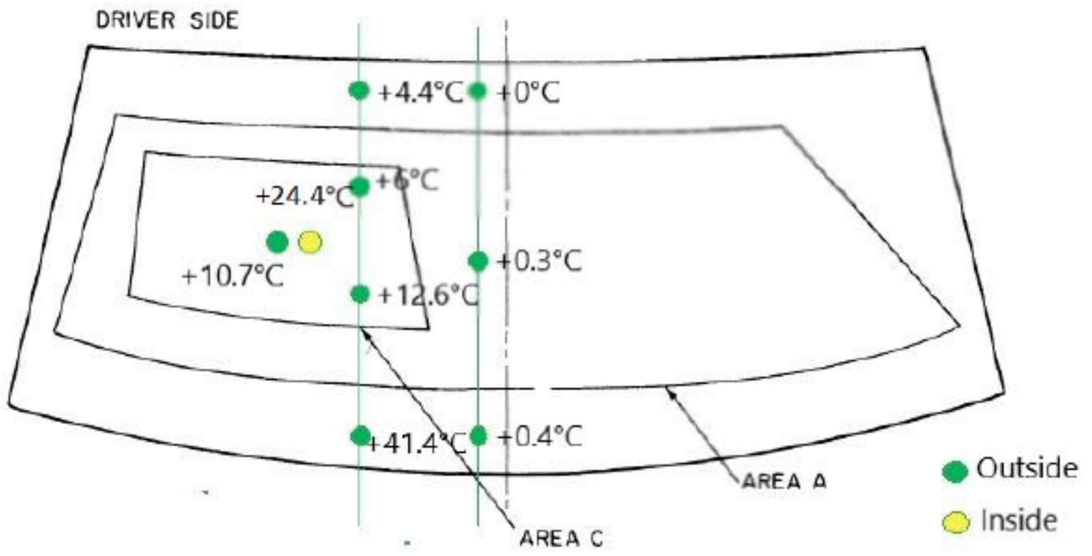

Figure 4.15: Temperature increase of each thermocouple.

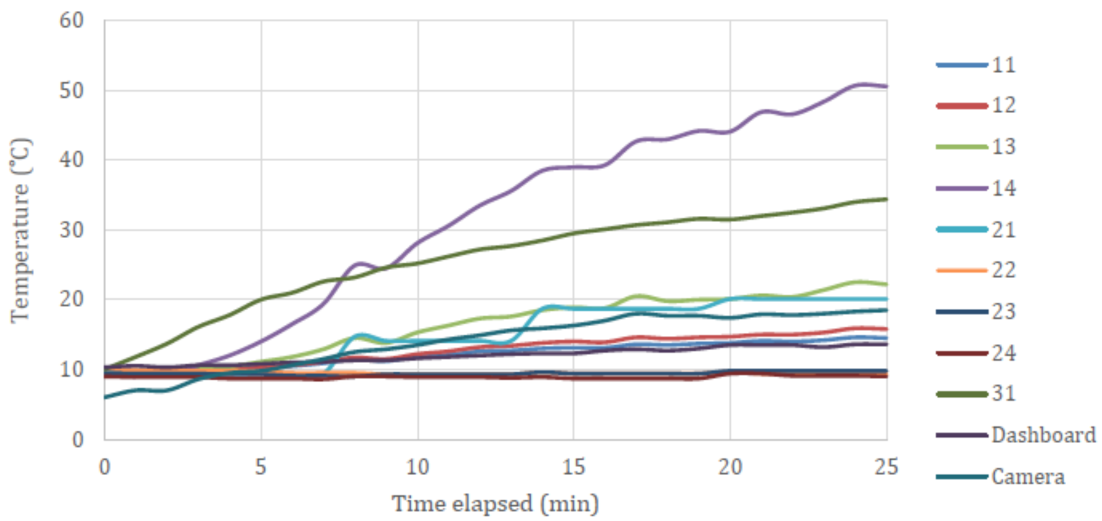

Figure 4.16: Temperature evolution of each thermocouple.

As shown in figure 4.16, a gain of more than 25 °C is detected in the main area to defrost, and an increase of 45 °C in the area nearest to the heater.

The reflector plays an important role in this temperature distribution: it scatters the beams across the windshield surface and redirects beams originally aimed towards the dashboard onto the windshield. The manufactured reflector is very efficient at doing so. Indeed, the thermocouple that was placed under the prototype, on the dashboard, only measured a 3 °C increase after 25 minutes of testing.

Furthermore, the used power source was of only 852 W instead of the available 1000 W because of the available voltage (208 instead of 240 V). If the system was used on a cold winter day (-20 °C) with maximum power, the targeted windshield area would definitely be defrosted in less than 30 minutes. However, the developed infrared heater would have to heat a surface that's approximately 5 times larger than the one on which the test was conducted, and at a distance further away from center point of the heater. This means that the power of the developed defroster will have to be adjusted and optimized to respect the criteria defined by the SAE J381 standard.

A concern that has been raised during the test on P1.1 is the fact that a heater placed on to the dashboard does not seem to be capable of causing a significant windshield temperature to increase far from the heater. Thus, if only dashboard heaters were to be used, this could be problematic as the driver could have trouble keeping the upper areas of the windshield clear. This lack of heating near the upper sections of the windshield is well illustrated by the Height on the windshield vs. Temperature at the tested zone center line in figure 4.17.

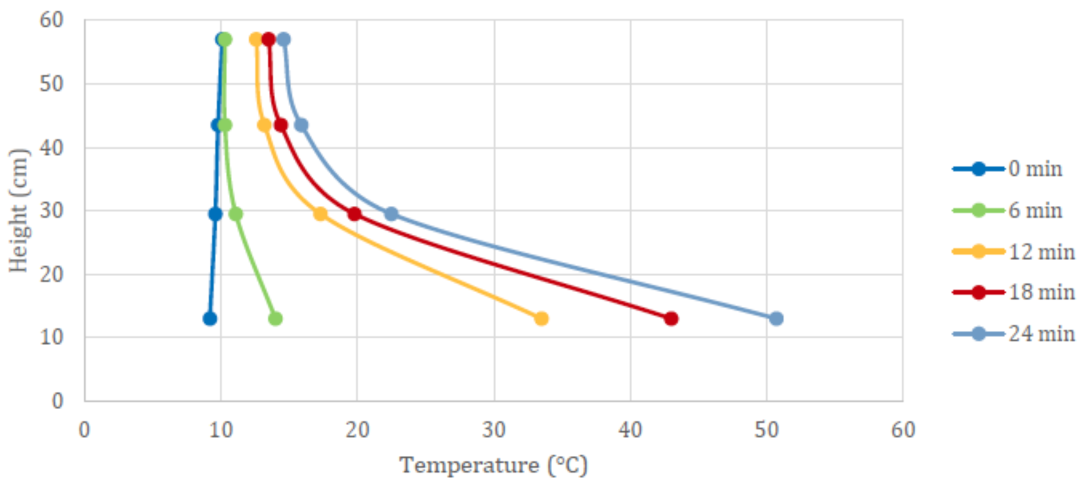

Figure 4.17: Height vs. temperature distribution on the tested area center line

The curves were extracted from the temperatures measured by thermocouples 11, 12, 13 and 14 (which all follow a straight vertical line) at different times. The maximum temperature gradient of the highest two thermocouples is rather low, while it is high for the bottom two. A simple solution to this low gradient would be to use complementary heaters positioned above the windshield to increase the temperature gradient of its upper region. This solution is detailed in Section 5.2–Configurations Management.

Furthermore, regarding driver visibility, the heating elements did not emit any visible light and no reflection was visible on the glass.

Finally, the temperature of the protective grid does not exceed 50.0 °C despite a much higher temperature of the heating elements. It is deduced that the installation of this type of heating is safe for the passengers in case of direct contact with the grid for a short time. However, the grid of the prototype P1.1 was black. To prioritize the safety, an aluminum grid could be used. Its temperature would be lowered, but some infrared rays would be reflected onto it, which would create a small loss of efficiency.

4.4 Risk Management

As a tool to assess the apparent risks with this prototype the team choose to use a Failure Mode and Effects Analysis (FMEA) to clearly show what parts of the radiant heater's life might present a risk to either people or equipment.

4.4.1 Failure Mode and Effects Analysis

The FMEA was constructed to detect potential hazards that may occur while using an infrared heating system instead of the ordinary HVAC system. The main focus for this FMEA will be to decrease the RPN but also decrease the numbers of 10 received in S which indicate that the radiant heating system can potentially lead to personal injuries.

As can be seen in Table 4.4, the main problem is overheating, which can lead to damage in the bus cabin or even worse personal injuries. Based on tests by the Swedish team, the heating system can reach temperatures up to 200 °C-300 °C, an important factor is therefore minimizing the risk of even higher temperatures. It is also crucial to minimize the probability of debris coming into contact with the heating element. Thus, it is important to build a product that prevents this problem. Likewise, it is important to feed the right amount of power to prevent overpowering the heating element which directly leads to an undesirable temperature level. Since the emitters can reach high temperatures, it is important to design a protection grid that prevents the bus driver or even the passengers from getting in contact with said element. This protection needs to be strong enough to withstand the stresses that occur while the bus is in operation and at the same time not block the emitters so that the windshield may still be defrosted and defogged.

Other components that could lead to personal injuries, if they malfunction, are the brackets and the fastening points. If the brackets are not strong enough to withstand fatigue the radiant heating system may move from its original position.

With mechanical analysis as a basis, the brackets should manage to endure both fatigue and static loads. Since this project does not have the mandate to change the fastening points, further investigation into causes of failure when implementing the radiant heating system falls on Nova bus to analyze. To minimize the concerns that have been raised some actions must be taken. When all of these planned actions are done, a new assessment will be conducted with simulations and testing as a basis.

Table 4.4: Risk Assessment supported by a Failure Mode and Effects Analysis.

FMEA - FAILURE MODE AND EFFECT ANALYSIS SYSTEM/DESIGN/PROCESS

Main system / Sub-system	Part/Operation name	Drawing-Part No.	Machine No.	Functional Specification-Technical Regulation (link if possible)	Supplier	
Radiant Heater	-	-	-	-	-	
Main Function / Operation	Date Performed	Date Time Updated	Status - Hardware/Digital modell	Issued by	Project	Issue
Defog/ deice windshield on a Nova LFSE Bus	2019-04-15	2019-05-15 13:19	-	Team Sweden	IMSX15-19-16	2

PART		CHARACTERISTICS OF FAILURE				1st RATING				ACTION-STATUS				2nd RATING				
No	Function / Part / Operation	Failure mode	Causes of failure	Undesirable customer effects Effects of failure on syst. / part / operation	Testing - Simulation	Po	S	Pd	RPN	Recommended action	Planned action	Responsible	Follow up date	Po	S	Pd	RPN	Verifications-Sign
1	Heating element	Fracture	Fatigue	Stops working	Ansys	5	9	2	90	Simulate lifecycle	Dimention the Heating element to withstand fatigue	Team Sweden	2019-05-09	1	2	2	4	Team Sweden
2		Over heating	Debris	Injury	CFD & Test	7	10	3	210	Prevent debris getting in contact with the heating elements	Design the final protoype to minimize the risk of debris getting in contact with the heating element	Team Sweden	-	7	10	3	210	-
3				Damage bus cabin	CFD & Test	7	7	3	147	Prevent debris getting in contact with the heating elements	Design the final protoype to minimize the risk of debris getting in contact with the heating element	Team Sweden	-	7	7	3	147	-
4			Overvoltage	Injury	CFD & Test	4	10	3	120	Analyse the heating element and modify to minimize the risk of personal injuries.	No action	-	-	4	10	3	120	-
5				Damage inventory	CFD & Test	4	7	3	84	Prevent overvoltage to occur	No action	-	-	4	7	3	84	-
7		Electricity	Power shortage	Inefficient deicing	CFD & Test	3	7	1	21	-	No action	-	-	3	7	1	21	-
8				Inefficient defogging	CFD & Test	3	6	1	18	-	No action	-	-	3	6	1	18	-
9				Insufficient heating	-	1	5	4	20	-	No action	-	-	1	5	4	20	-
10			Power failure	Stops working	-	2	5	1	10	-	No action	-	-	2	5	1	10	-
11		Blocking emitters	Debris	Inefficient deicing	-	3	5	1	15	-	No action	-	-	3	5	1	15	-
12				Inefficient defogging	-	3	5	1	15	-	No action	-	-	3	5	1	15	-
13	Protection grid	Fracture	Fatigue	Injury	Ansys	7	10	1	70	Analysis the protection grid with regards to fatigue	Design a protection grid strong enough to withstand fatiuge	Team Canada	-	3	4	1	12	Team Canada
14	Eletric wires	Wires break	Vibrations	Stops working	-	4	6	5	120	-	No action	Manufacturer	-	4	6	5	120	-
15		Assambly	Worngly assamblied	Do not work	-	1	4	5	20	Check for misstakes in assably line	No action	Nova Bus	-	1	4	5	20	-
16	Brackets	Fracture	Faitgue	Do not hold up heater	Ansys	4	10	1	40	Simulate lifecycle	Dimension the brackets to withstand fatigue	Team Sweden	2019-05-09	4	1	1	4	Team Sweden
17	Fastening point	Fracture	Fatigue	Do not hold up heater	Ansys	4	10	2	80	Simulate lifecycle	Dimension the fastening points to withstand fatigue	Nova Bus	-	4	10	2	80	-
18	Reflector	Fracture	Fatigue	Inefficient deicing	Ansys	1	6	2	12	Simulate lifecycle	Check if the assumption is correct	Team Sweden	2019-05-09	1	6	2	12	Team Sweden
19				Inefficient defogging	Ansys	1	6	2	12	Simulate lifecycle	Check if the assumption is correct	Team Sweden	2019-05-09	1	6	2	12	Team Sweden
20	Reflector supports	Fracture	Fatigue	Do not hold up the reflector	Ansys	10	6	3	180	Simulate lifecycle	Dimention the suports to withstand fatigue	Team Sweden	2019-05-09	5	6	3	90	Team Sweden

According to the FMEA table, the risk to mitigate in priority is the over-heating of debris that could fall under the grid near or directly onto the heating elements, possibly causing injuries of material damage.

4.5 Final Prototype

The CAD of the final prototype or P2 as its working name has been is shown in figure 4.18 or the drawings in Appendix B. It consists of three far infrared heaters to easier follow the curvature of the windshield. The final design also consists of reflectors to make sure that as much as possible of the infrared radiation hits the windshield. Finally to ensure user safety, there is a protective grid that is placed just above the heating elements.

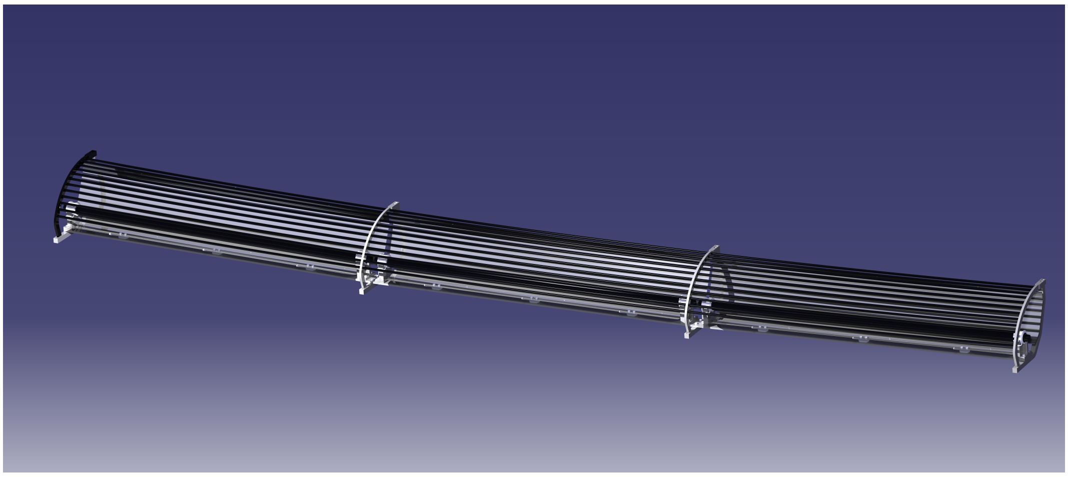

Figure 4.18: A CAD of the final prototype.

The heaters will be integrated to the dashboard below the windshield. This is shown in figure 4.19. The reason for placing it here is that it is the place near to the windshield that has most free space and also to make sure that visibility for the driver is not affected. The three heating elements are attached through brackets to the chassis of the system, which is attached to the chassis of the bus. Between these two chassis is a thermal insulation and a hood for closing the system with the rest of the dashboard.

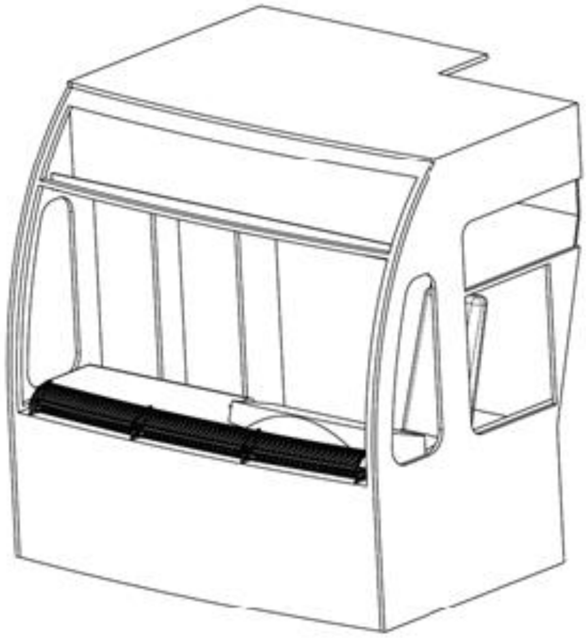

Figure 4.19: The final prototype integrated in the dashboard.

Table 4.5 summarizes the final prototype's main characteristics. These characteristics are for the whole prototype, meaning its 3 modules combined.

Table 4.5: Main characteristics of final prototype.

	Characteristic	Value
Dimensions	Overall Height	15 cm
	Overall Width	16.2 cm
	Overall Length	217.5 cm
Mass	Total Mass	9.1 kg
Power Source	Max Current	10 A
	Max Voltage	600 V DC
	Max Power Output	6000 W

4.5.1 Cost estimation and comparison with the current system.

This economic assessment consists of the life-cycle cost analysis of our system based on the results of the design analysis, the CFD simulations and qualified estimations in which the production cost, the operation cost and the maintenance cost will be evaluated. An economic assessment of different HVAC systems for electric city buses performed by the Technical University of Berlin as part of an International Electric Vehicle Symposium [15] has been used to compare the cost of the current system in LFSe and the suggested infrared system as shown in table 4.6.

Table 4.6: Cost estimation table.

	Current System(C$)	New System(C$)
Acquisition cost	2 000	733
Maintenance cost	5 000	3 290
Operation cost	15 218	2 949
Total cost	24 718	6 972

The acquisition cost represents the cost of purchasing of the defrosting system. Since we can only estimate the price of the whole HVAC system, the acquisition cost of the current defrosting system is based on an approximation provided by Nova Bus. This value is used to give an idea of the current acquisition cost to compare with the suggested system.

The acquisition cost of the suggested radiant system has been estimated by research regarding what a typical far infrared heater for private use costs. For instance, the heater that was used in the "verification of concept"-test cost 633 C$, but the heating elements would be custom made, and therefor their cost has been overestimated to keep a reasonable error margin.

The maintenance cost includes the price of replacement parts and the cost of labour, based on maintenance schedules. Infrared heaters require an annual maintenance inspection. Since our product would be integrated in a moving vehicle, it is safe to consider bi-annual preventive inspection and anticipate an additional maintenance operation for unexpected breakage.

Also, the heating elements could potentially need to be replaced once in the life span of the bus. An average time of 2 hours has been estimated for each maintenance procedure, and it should be performed by a qualified professional. The hourly wage of a journeyman electrician has been considered.

The operation cost has also been estimated with the economical assessment from the Technical University of Berlin, using the annual energy demand for a test reference year and multiplying it over a life span of 12 years. The current system has a fuel consumption of 4 L/hr and the cost of diesel has been averaged to 1.20 dollars/L, while the cost of electricity is 0.1008 dollars/kWh for a rate G9. The current HVAC system has a heating capacity of 30 kW, but the operation cost has been calculated for the defrosting system only, which is estimated at 20 kW. The operation cost of the suggested radiant system has been calculated for the same test reference year, with a heating capacity of 6 kW and an electric only energy demand.

4.5.2 Fulfillment of Functional Specification

After the simulations and the physical tests were done the final concept was created, a comparison with the functional specification was made. This was done in order to evaluate to which degree the concept fulfills the functional specification, which is found in Appendix A.

Regarding the primary functions, it is clear that all of them are fulfilled. Far infrared heating can deice and the defog the windshield. This was proved in both the CFD simulations and in the physical tests. Regarding the integration to the LFSe buses this is also fulfilled because of the fact of that it is designed with consideration to the bus dashboard. Finally, the energy consumption will also be lower than both the current one and the requirement of 20 kW. The designed system will consume 6 kW, 2 kW per heating element.

Most of the secondary functions and the constraints are also fulfilled. For an example the system is fully electric, it weighs only 9.1 kg, it is cheaper than 19500 C$ to manufacture etc.

The secondary functions and the constraints that are not fulfilled or not yet examined are listed below:

- Allow intelligent thermal management
- Allow manual takeover with simple controls
- Be integrable into LFShybrid buses
- Defrost the door, the driver's windows and the mirrors
- Comply with Volvo standards

5
Discussion

This chapter contains discussions regarding the concluded results from both physical tests and simulations as well as the final concept and further possible improvements to the system.

5.1 Computational Fluid Dynamics

The high temperatures that can be observed near the bottom section of the windshield following the completion of the simulation inside of the bus cabin can be attributed to two factors.

The first factor is the lack of any fluid being incorporated into the simulation. In reality, a certain amount of water and ice would be present when heating the windshield to deice and defog it. During this process a certain amount of the emitted radiative energy from the heater would go towards the heating, melting and evaporation of any water and ice present on the windshield. This would result in a lower surface temperature on the windshield as energy that in the simulation was used to increase its temperature would now have been used towards increasing the temperature of the fluid present.

The second factor is the lack of any regulative system in the simulation. A lack of such a system entails that the simulated heater operated at a constant effect throughout the duration of the simulation. The result of this being that a larger amount of energy was emitted from the heater than what would be in reality. In a more accurate simulation, and before actual installation into an LFSe bus, a regulation system would need to be developed and implemented. A regulative system with the capability to adjust the amount of emitted radiative energy from the heater based on what is needed at a given time, something that could perhaps be based upon the surface temperature of the windshield.

5.2 Final Concept

The final concept shows a functional but not completed prototype. Before the prototype can be properly implemented into a buss there are still a few parts that need to be considered for further development.

5.2.1 Analysis

Compared to the current system used in electrical vehicles the one designed by this collaboration is more energy effective while also being cheaper to build, install and maintain. However, the current system is still needed for heating the environment of the electrical bus and thus the new system loses some of it's value.

There are some safety concerns regarding having a hot heater inside of the bus which also needs to be addressed before actually implementing the system.

The fatigue analysis of the final concept showed that the design probably will withstand the load cases that comes form driving, with exception of the reflector supports.

5.2.2 Redesign

There are still a few parts that need design optimization. The current prototype needs to be adjusted to fit better onto the dashboard and it also needs to be shifted as to fit better together with the anchor points underneath the dashboard. The design needs some improvements that would increase safety such the implementation of a protective dome to hinder people from accessing it by mistake and hurting themselves. The high temperatures needed for defrosting the windshield was also highlighted as a problem in the FMEA table. This assessment predicted that the heat of the system together with debris getting in contact with the heating element could lead to damaging components of the heater and bus or, in the worst case scenario, lead to personal injuries. These risks and how to prevent them must be investigated before implementing the infrared heating system.

After testing the concept a problem regarding the temperatures on the windshield was found. With the heater placed directly under the windshield, the temperatures on the lower section got as hot as 85.1 °C while the upper part only got to 8.6 °C. This creates a slight problem in the form of uneven defrosting and perhaps too high temperatures on the lower section of the windshield.

A possible solution for this problem is to place heaters both underneath and above the windshield. This would give an opportunity to lower the effect of the heaters which would not give such high temperatures. Furthermore this would also give a more even defrosting procedure since the heat would be coming from two different directions and the distance would also be shortened.

If the dashboard could be custom made for fitting a heater, the chosen concept would probably be more efficient. This would give an opportunity to move the heater further away, lengthwise, from the windshield and this would give results more similar to test 2, as can be seen in section 4.3.1.2. Test 2 (0.25 m) gave better results than test 1 (0 m) in terms of not as high temperatures on the lower section of the windshield and also a more even defrost procedure. Meaning that the lower and the upper part of the windshield was defrosted almost at the same time.

5.3 Further Research and Development

Further research into this subject could and should be put towards making this system completely safe for use, since the cost of building, installing and using are lower than the current system being used. The largest point of concern for the suggested solution is its safety. Since the heater reaches very high temperatures during maximum load there should be more work put towards some kind of protection that separates the heater from its surroundings to limit the risk of any accidental contact with the heater. The prototype is also not fully ready for manufacturing so before it is possible to use on a larger scale there has to be some work put towards adjusting it and making it easier to manufacture.

There should also be more research put into checking if reflectors at the top of the windshield would have any effect on focusing the rays back towards the windshield and thus making it more effective in defrosting and defogging the upper section of the glass.

It is important to note that the prototype's electric components have not been studied at this point. However, the heaters would be powered by bus' batteries, which dispense a direct current of 600 V. Special care and further integration work will be necessary to ensure that heaters are safely installed and powered in an actual electrical bus.

In addition to the previous points, there always remains the possibility of finding new ways to further increase the safety and efficiency of the heater, and these possibilities should therefor be researched further.

From the concept evaluation not only the infrared heating system showed potential. Both the concept which incorporated integrated heating wires and a metal coating could been of interest to investigate the potential of. These concepts would likely not have the same issues with high temperatures that the radiant heater has and at the same time be as efficient. This type of heated windshields has also already been used in the car industry for a fairly long time. Even if a bus windshield could be too big for adapting these kind of system, their use in the defrosting and defogging of a partial section, for example the section A in the SAE J381 standard. If this section were to be deiced/defogged in a shorter time while using less energy than the radiant heater, a potential combination of several systems could then be used.

5.4 Setting

During this international project the Swedish team got the opportunity to travel to Montréal and meet both the Canadian team and also the people at Nova bus, this was a welcomed and valuable experience that was not only pleasant but also helped to integrate the two teams more into one unit.

In the initial stages of the project there were some difficulties regarding who should be responsible for a given task. There were sub groups created for each task so that everyone knew their role. Despite this, at times it remained quite difficult to work on each part knowing there are sixteen students working on the project. However after the aforementioned trip the teams felt much more secure with the communication and the sub groups managed to discuss among themselves how they wanted the work to continue which resulted in an overall better communication.

Since the Canadian team started the project in early fall it was hard to get started. The Swedish team had specific deadlines which needed to be done which somewhat hindered work to be done on the specified task during that time. In the future it might be helpful to start out a bit earlier and work longer but with a lower workload in this type of project. This would help to integrate the teams faster and get them on the same page right around the time that the Swedish team began their integration into the project during this iteration.

Overall the collaboration between the two teams worked quite well, with the good leadership and help from the Chalmers and Polytechnique teams supervisors in combination with very dedicated students from the Canadian team, it would have taken a lot of mistakes for the project to derail beyond the a recoverable point.

6
Conclusion

Through the performed tests and analyses, the concept of using a far infrared heater to deice and defog a bus windshield was proven to be viable. The suggested heating system may however not be as efficient as hypothesized to be, but despite this it is still found to be more energy efficient and have a lower energy consumption than the currently used glycol based system. While the initial predictions regarding the windshield's ability to absorb infrared radiation stands true, the Swedish team's performed tests indicated a certain degree of inefficiency due to reflection in the windshield.

However, due to the nature of infrared radiation and the lack of emitted light, this reflection of the rays will not in any way hinder the drivers visibility or compromise the comfort of them of any passengers. Worth noting is that the heating of the rest of the bus would be positively aided by the effect of the reflected radiation. Additional issues with the current solution that would need to be addressed before implementation include high temperatures towards the bottom of the windshield and an overall slightly uneven deicing. These two issues which could potentially be addressed by reducing the effect of the heaters while simultaneously adding additional heaters to the top of the windshield. Alternatively through the addition of reflectors at the top of the windshield that could redirect reflected radiation back towards the windshield as mentioned in section 5.2.2.

Revisiting the purpose of this project, it can now clearly be stated that a majority of it has been achieved. As explained above, an energy efficient windshield defrosting system has been developed. This system also meets all of the four primary requirements. This entails that the operation range for Nova Bus electrical buses would be increased by the implementation of this solution. With a more energy efficient defrosting system, more of the stored energy in the bus can be used towards propulsion. By increasing how efficiently energy is used in the defrosting and defogging of the windshield, the buses total environmental impact has been reduced.

To conclude, there is still a lot of possible future development. However this concept seems like a promising solution for the given problem.

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A
Functional specification

Table 1. Primary Functions

#	Function	K	Criteria	Level	Flexibility	Comments
1	Deice the windshield	5	Thickness of ice melted Thickness of ice on windshield during movement (with bus at full capacity):	SAE J381 A: 0 mm C: 2 mm	None None	According to bus drivers, respecting the norm is not sufficient to guarantee good visibility when the bus is in operation. Furthermore, after the bus had been prepped, no additional ice should accumulate while they are driving
2	Defog the windshield (stationary and in operation)	5	Windshield surface cleared during movement (with bus at full capacity)	SAE J381 (A: 80%, C: 99%)	None	
3	Be integrable into LFSe buses	5	Power source voltage Encroachment on current bus design	600 V Same as current system	+ 0 % - 100 % + 25 % - 100 %	The current maximum voltage available is 600 V The new system should fit into the existing design of LFSe buses without taking too much additional space.
4	Be energy efficient	5	Maximum power consumption	20 kW	None	The new system should require a smaller power input than the current one

Table 2. Complementary Functions

#	Function	K	Criteria	Level	Flexibility	Comments
1	Allow intelligent thermal management	3	Number of human interventions	0	None	The system should manage the conditions inside the bus without requiring any human intervention
2	Allow manual takeover with simple controls	4	Number of human interventions to override and control the system	3: - On/off switch - Manual/auto switch - Temperature control	+/- 2	If the driver wants to override the automatic control, they should be able to do so easily
3	Be integrable into LFShybrid buses	3	Power source Volume	600 V Same as current system	+/- 0 V + 0 % - 100 %	The system is mainly designed for electric buses, but integrating it into hybrid buses as well would be ideal
4	Ensure driver comfort	3	Driver area temperature	18˚C	+ 5 ˚C - 2˚C	
5	Defrost the door, the driver's windows and the mirrors	3	Surface cleared during movement (with bus at full capacity)	FMVSS 111 Small windows and mirrors: 90 % Door and driver's windows: 80 %	+/- 5 %	The small triangular windows on either side of the driver's cabin allow them to see the mirrors and are a security requirement, meanwhile visibility through the door and the side window add an element of comfort and security
6	Visibility	3	Number of elements that hinder the visibility	0	None	No visible parts or reflecting light should hinder the visibility at any angle or under any lighting conditions (day, night, oncoming headlights)

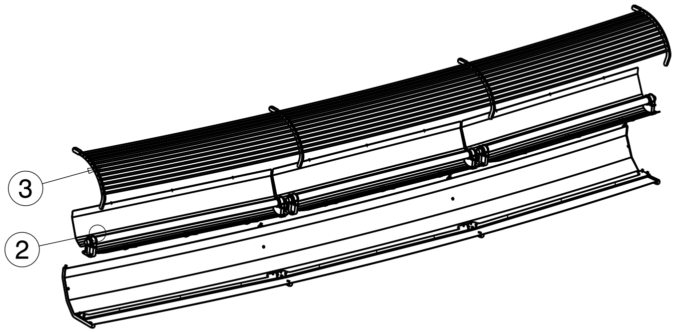
Table 3. Constraints

#	Constraint	K	Criteria	Level	Flexibility	Comments
1	Use electric energy exclusively	5	Power source	Not fossil	None	
2	Be manufacturable	5	Cost of the new manufacturing processes	Same as current system	+ 25 % - 100 %	Manufacturing and assembly processes should be easily integrated on the production line or provided by the manufacturer.
3	Reduce manufacturing costs	3	Price of parts and manufacturing processes or acquisition cost	19500 CAD	+ 20 % - 50 %	The manufacturing costs could be a bit higher, provided that the depreciation time is lower
4	Facilitate maintenance and repair operations	3	Accessibility of the parts Maintenance time and costs	With standard tools 1000 CAD / year	Without disassembling the entire system + 0 % - 50 %	 Maintenance time and costs reflect the complexity of the required operations
5	Maximize service life	3	Resistance to stress and vibration	No cracks should occur during Altoona Test ASTM D3580-95	None	Materials used must be in accordance with applicable ASTM standards, and no system failures must occur during the Altoona test.
6	Be lightweight	3	Mass	73 kg	+ 25 % - 100 %	
7	Minimize environmental impact during entire life cycle	4	Greenhouse gas emissions during manufacturing Percentage of recyclable materials	Same as current system 100 %	+ 0 % - 100 % + 0 % - 20 %	
8	Comply with Volvo standards	5	Volvo standards	None	None	
9	Do not compromise driver and passenger safety	5	ASTM E-162 ASTM E-662 APTA J1292	None	None	Surface Flammability of Materials Using a Radiant Heat Energy Source, Specific Optical Density of Smoke Generated by Solid Materials, Wiring distribution system harnesses to automotive vehicles.

B

Drawings

ITEM NO.	QTY.	DESCRIPTION	PART NUMBER	MATERIAL	MANUFACTURER
1	1	SUBASSEMBLY FRAME	P2-ST	-	-
2	3	SUBASSEMBLY HEATING SYSTEM	P2-RF	-	-
3	1	SUBASSEMBLY GRID	P2-OT	-	-



Vue isométrique
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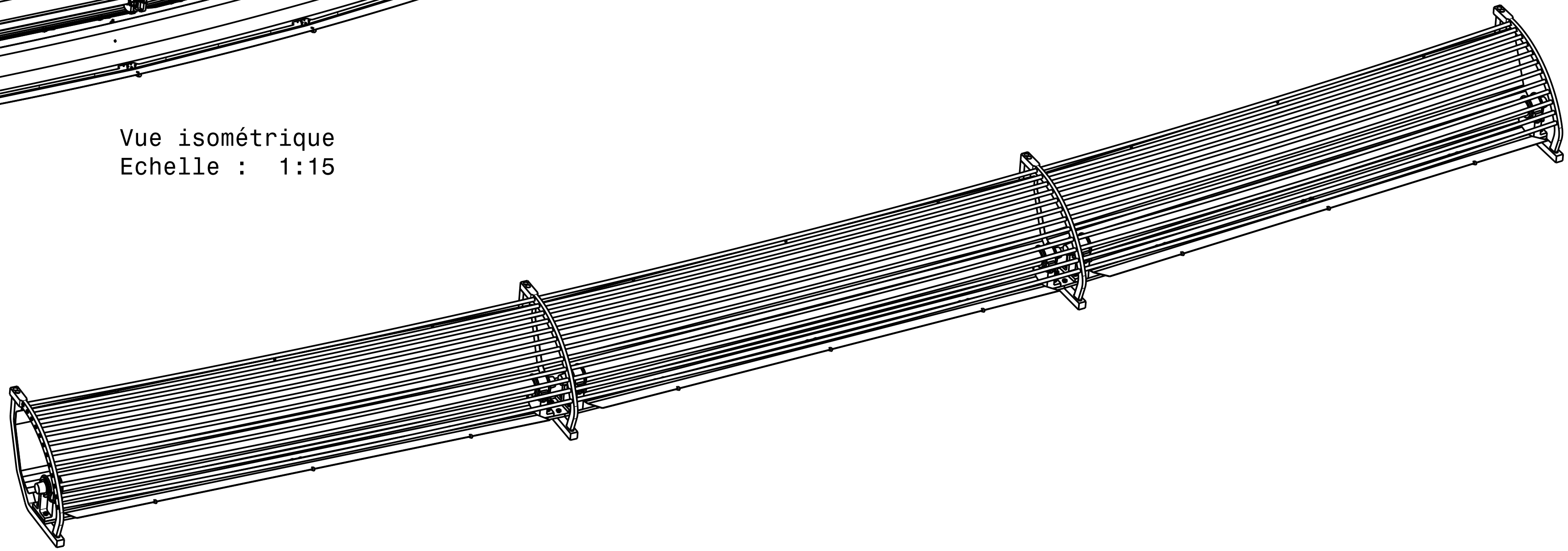
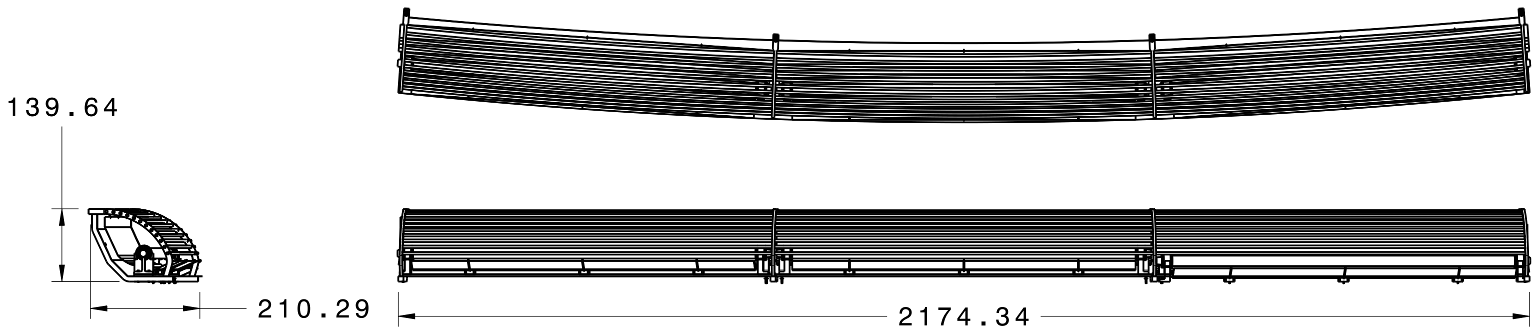




Vue auxiliaire A
Echelle : 1:10

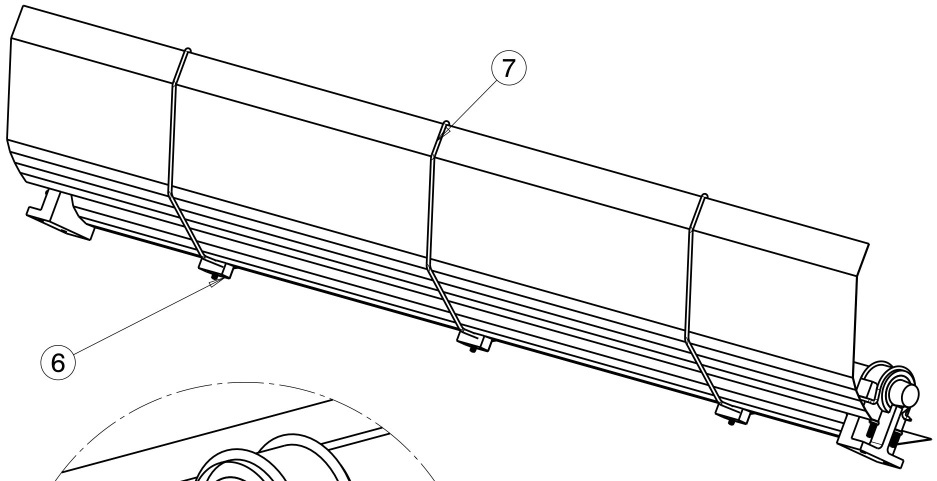
ÉCOLE POLYTECHNIQUE

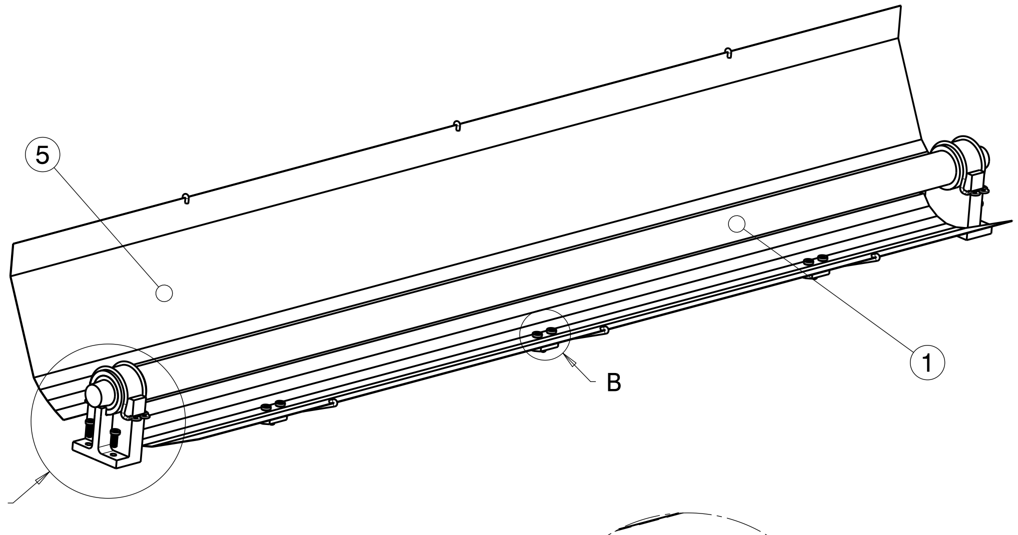
TITRE: COMPLETE ASSEMBLY

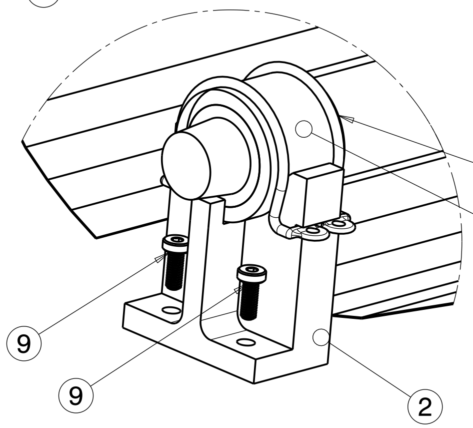
DESSINÉ PAR: TOM ALLART EQ.:
SIGNATURE:

DESSINÉ PAR: PAUL-ÉTIENNE CARRIER EQ.:
SIGNATURE:

DATE: 2019-04-12 | ÉCHELLE: 1:6 | NO.:







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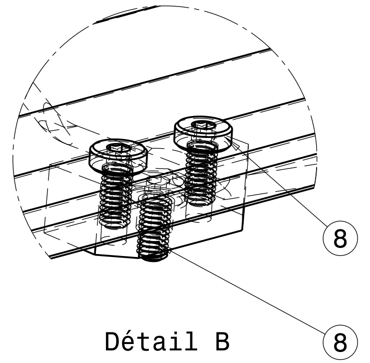


Détail B
Echelle : 2:1

ITEM NO.	QTY.	DESCRIPTION	PART NUMBER	MATERIAL	MANUFACTURER
1	1	HEATING TUBE	P2-HT-01-A	-	-
2	2	BRACKET LOW PART	P2-ST-01-A	ALUMINIUM	-
3	2	CIRCLIP	P2-SD-01-A	STAINLESS STEEL	-
4	2	CERAMIC SPACER	P2-HT-02-A	CERAMIC	McMASTER-CARR
5	1	REFLECTOR	P2-RF-01-A	ALUMINIUM	-
6	3	REFLECTOR SUPPORT BRACKET	P2-ST-03-A	ALUMINIUM	-
7	3	REFLECTOR SUPPORT	P2-ST-02-A	STAINLESS STEEL	-
8	9	LOW-PROFILE SCREW M3x0.5mm, 6mm LG.	90666A103	316 STAINLESS STEEL	McMASTER-CARR
9	4	LOW-PROFILE SCREW M3x0.5mm, 8mm LG.	90666A104	316 STAINLESS STEEL	McMASTER-CARR

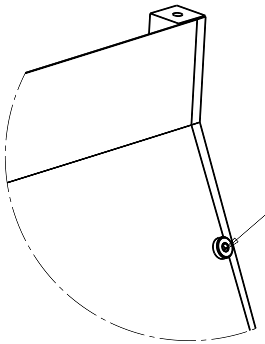
ÉCOLE POLYTECHNIQUE

TITRE: P2-RF : SUBASSEMBLY HEATING SYSTEM

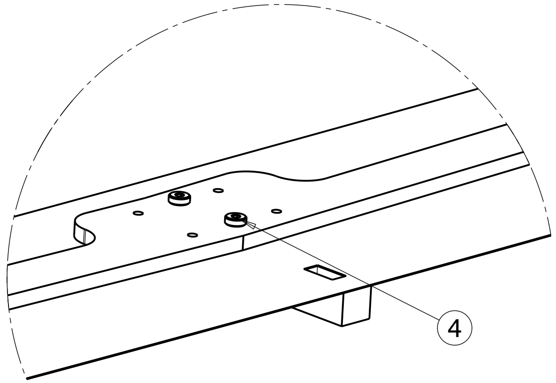
DESSINÉ PAR: TOM ALLART EQ.:
SIGNATURE:

DESSINÉ PAR: PAUL-ÉTIENNE CARRIER EQ.:
SIGNATURE:

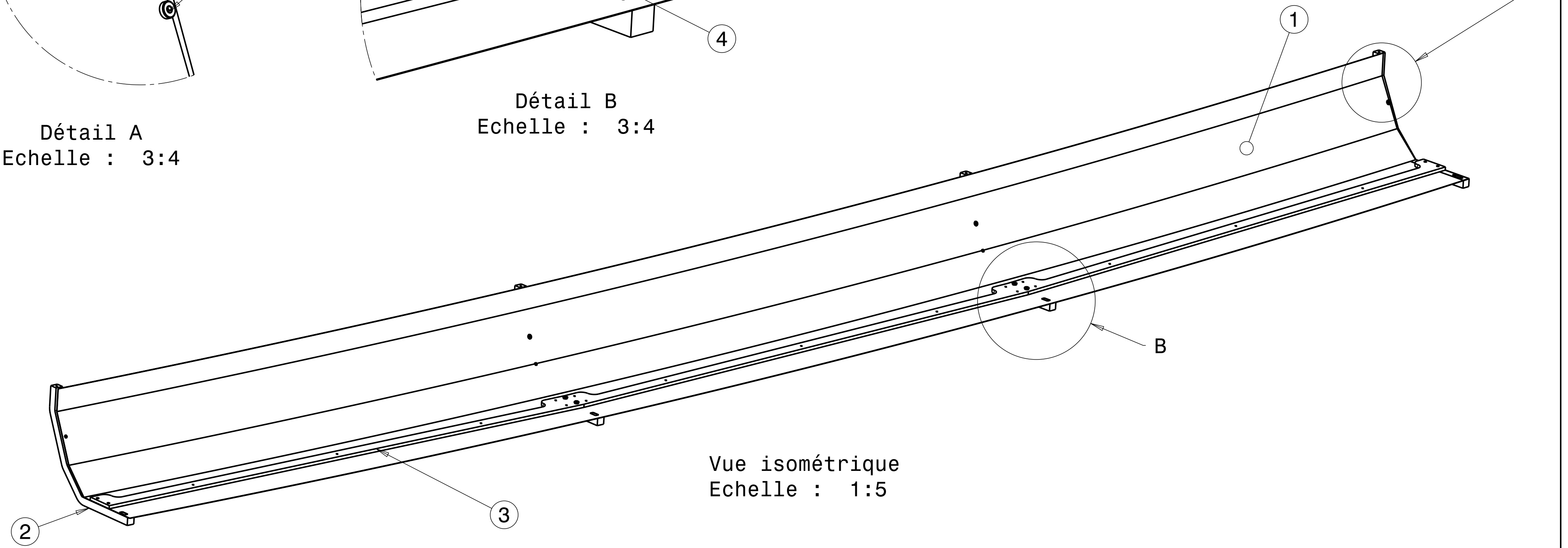
DATE: 2019-04-15 ÉCHELLE: 1:2 NO.:



Détail A
Echelle : 3:4



Détail B
Echelle : 3:4



Vue isométrique
Echelle : 1:5

ITEM NO.	QTY.	DESCRIPTION	PART NUMBER	MATERIAL	MANUFACTURER
1	1	HOOD	P2-OT-01-A	ALUMINIUM	-
2	4	GRID SUPPORT	P2-ST-06-A	ALUMINIUM	-
3	1	FRAME	P2-ST-04-A	ALUMINIUM	-
4	4	LOW-PROFILE SCREW M3x0.5mm, 6mm LG.	90666A103	316 STAINLESS STEEL	McMASTER-CARR
5	4	LOW-PROFILE SCREW M3x0.5mm, 20mm LG.	90666A106	316 STAINLESS STEEL	McMASTER-CARR

ÉCOLE POLYTECHNIQUE

TITRE: P2-OT : SUBASSEMBLY FRAME

DESSINÉ PAR: TOM ALLART EQ.:
SIGNATURE:

DESSINÉ PAR: PAUL-ÉTIENNE CARRIER EQ.:
SIGNATURE:

DATE: 2019-04-12 | ÉCHELLE: 1:5 | NO.: