Design and Analysis of an Optimized Defroster Plenum

MECH 4860 ENGINEERING DESIGN

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Executive Summary

Our team was tasked with redesigning and optimizing the front windshield defroster plenum for the Xcelsior coach, manufactured by New Flyer Industries. As part of New Flyer's continuous improvement group, the goal was to reduce waste associated with manufacturing the defroster plenum, as well as improve its performance. The defroster plenum is an air chamber that redirects hot air from the blower fan to the windshield, which melts frost and evaporates fog.

Our redesigned defroster plenum has a total cost of [redacted] per part, with a payback on machinery after [redacted] coaches. With an improved low end outlet velocity of 15.4%, a decreased velocity range of 4.5 m/s, and improved thermal conductivity, our plenum will decrease the time required for defrost to less than 30 minutes. Improving the uniformity of the velocity profile will also lead to a decrease in peak noise levels. By having our design in one piece, containing pre-drilled holes and using pushpin rivets as fasteners, we will reduce the installation time by 10 to 15 minutes. Our defroster plenum can be installed by one technician, at one location on the process line. The new design will be manufactured from ABS plastic, which leads to a final mass of 2.6 kg.

Our new design will outperform on the following target specifications: cost, payback on machinery, installation time, defrost time, number of parts, noise, and weight. We will maintain the same number of technicians required for installation and number of locations on the assembly line where the plenum can be installed. We recommend that our final design should be moved forward for prototyping and testing at New Flyer industries. We are confident that our redesign of the defroster plenum will solve all the key problems associated with the current model.

1 Introduction

New Flyer Industries is the leading heavy-duty bus manufacturer in North America. The Winnipeg based company has many parts manufactured across Canada and the United States. The Winnipeg facilities are one of the locations at which the buses are assembled. The company is constantly looking to improve efficiency of the production line and the overall production process. The large volume of buses being produced allows small changes in efficiency to save large amounts of money and time.

As a leading manufacturer, New Flyer Industries is constantly re-evaluating their methods to ensure that the technology they implement is cutting edge. New Flyer Industries has a continuous improvement group that reviews and refines the current manufacturing processes. With a focus on Lean manufacturing, the goal is to be constantly improving and reducing waste. Our student design team, as part of the engineering design course, worked as part of the continuous improvement group.

For our design project, we focused on analyzing and redesigning the front windshield defroster plenum. The plenum is designed to control and direct hot air towards the windshield. This is done to remove and prevent fog and ice from forming on the windshield. Fogging and ice forming on the windshield can cause a lack of visibility for the driver, which creates dangerous driving conditions. In regions where climates reach sub-zero degree Celsius temperatures, the windshield defroster system is essential. The plenum is currently fabricated in three pieces. The plenum is not manufactured by New Flyer Industries; rather it is purchased from a vendor and installed in the Winnipeg facility. The current plenum design is shown in Figure 1. The actual defroster plenum is shown in green, while the dash close-outs which sit on top of the plenum are shown in red and blue.

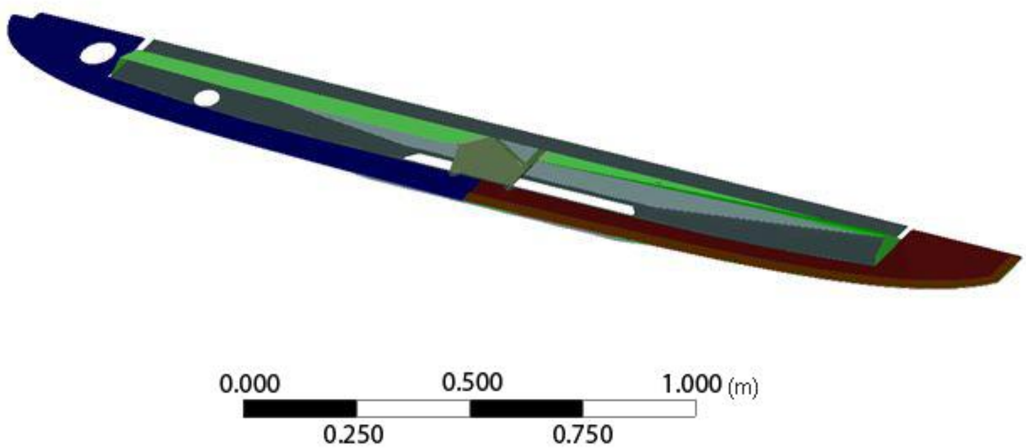


Figure 1: The original 3D view of the defroster plenum from the bus [1]

The defroster plenum is located underneath the dash of the bus among various other pieces of equipment, such as wires and cables. The actual defroster is below the plenum, where coolant lines from the engine run to the front of the bus and a fan blows air over a heat exchanger and into the defroster plenum. The position of the defroster and the surrounding components is shown in Figure 2.

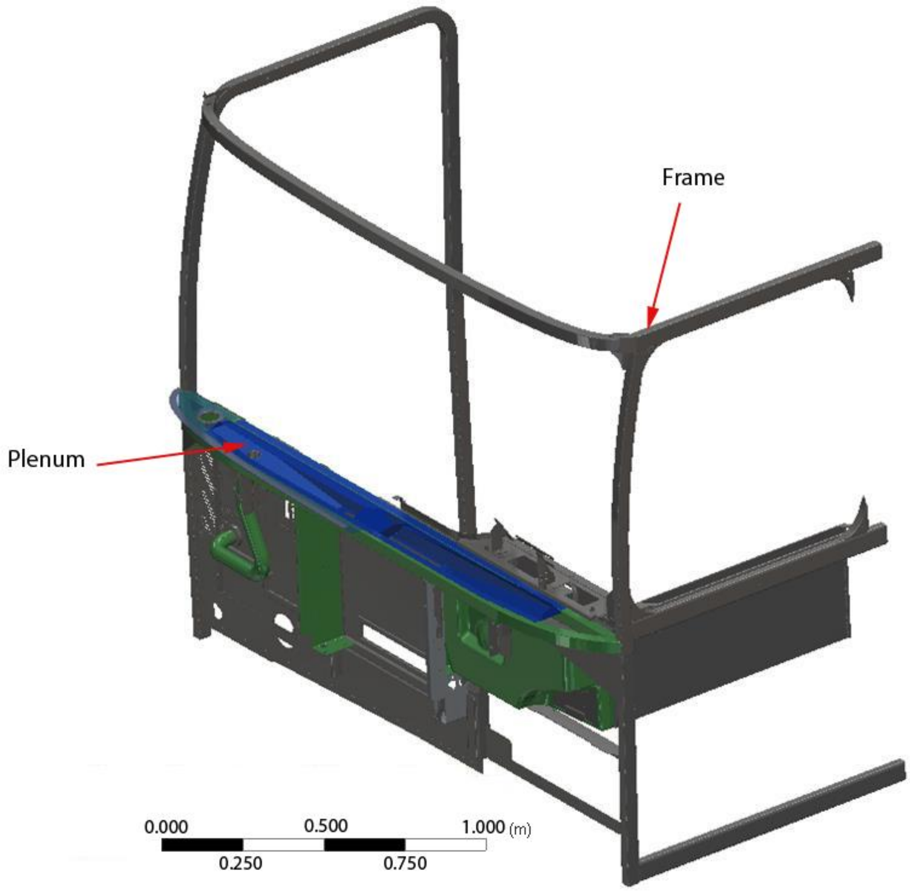


Figure 2: The position of the defroster and its surrounding components [1]

The main issue with the current defroster plenum is that it is relatively expensive in comparison to other parts on the bus [1]. The current part is made of galvanized steel, which is shaped and spot welded together. The welding ends up being a large percentage of the total cost of production of the part. During installation, the plenum is installed first and then two aluminum dash closeouts are installed on either side of it. The plenum is installed by one technician. The installation requires measuring, drilling holes, installing a hose and the addition of a rubberized edge to the plenum. This process has a total installation time of around two hours. Also, the installation can only be done when the dash panel closeouts have not been installed yet, which can be limiting. Our team has been tasked with redesigning a defroster plenum that will address the issues with total cost and installation. Additional objectives are discussed in Section 1.2.

1.1 Objectives

We focused mainly on reducing product cost, to increase profitability for New Flyer Industries. This was accomplished by analyzing the current manufacturing process, installation process and material selection. We could then develop a new design that would reduce cost in all three of the aforementioned aspects of the design.

Another important goal is to reduce the installation time for the new design. Reducing the installation time will also save money for New Flyer, in the form of reduced labor costs. The current plenum can easily be installed by one technician; therefore, our newly designed plenum must be installable by one technician as well.

Other than the cost and the installation time, an effective air distribution of the plenum is crucial. Increasing airflow distribution to the window will lead to improved defrosting time of the windshield. Furthermore, if airflow distribution is improved, the defroster fan speed could be reduced; this would lead to a reduction in the noise created in the defroster plenum.

There is no single problem to solve for this particular project. The goal is to optimize aspects of the production process as well as maximize the part`s performance. Consequently, the focus of the objectives is to design a new defroster plenum that will reduce the overall costs associated with the part, while reducing the manpower required to install it and at the same time, improve the plenum`s performance. Identifying the objectives of the project allowed us to develop constraints and limitations and target specifications.

1.2 Constraints and Limitations

The constraints and limitations identify the minimum acceptable requirements associated with this design. They can be broadly categorized as size, safety, performance, manufacturing, and installation constraints. The constraints and limitations can be seen as the design boundaries of a project.

1.2.1 Safety and Performance Constraints

The safety and performance constraints are primarily governed by a series of codes and standards. Several standards and testing requirements were identified, which set minimum performance and safety constraints on the plenum. The standards and tests listed below dictate the safety requirements for flammability, as well as air flow and heat transfer requirements for the windshield, passenger compartment and driver’s area. Furthermore, there is a brief listing of additional internal performance constraints set by New Flyer, which are not governed by standards or performance testing.

These standards rely on specific tests to confirm whether the standard is being met, which must be completed following the development of the part. Since the design is conceptual, and no prototypes will be available for testing, it will be impossible to use these tests to confirm if the standards will be met. Instead, literature or comparison with current designs will be used to demonstrate that the design meets the current standards, with the understanding that New Flyer will conduct the relevant tests following the extent of the team’s involvement.

1.2.1.1 Society of Automotive Engineers (SAE) - J381 [2]

The SAE - J381 standard ensures that the windshield defrosting systems used on the bus meet certain performance requirements. It is taken as the best practice in the industry, and is recognized by New Flyer as the method of testing the windshield defrosting systems, for which the plenum is a part.

To perform this test, the windshield is coated with 0.05 mL/cm^2 of water in a -18 degree Celsius chamber, to create a uniform cover of ice on the windshield. Using the defrosting systems, the ice must be cleared from the front windshield and side windows in less than 30 minutes. In order to maintain consistency among tests, regulations are applied to the use of the defrosting systems, including engine load, flow of heater defroster system coolant, temperature of coolant, air velocity, windshield wipers, defroster/heater system air, and vents on the bus.

While the plenum is only one part of the defrosting systems utilized in the test, this is the governing performance standard for windshield defrosting systems, and therefore the plenum design must work with the current systems in the bus to continue to defrost the windshield in under 30 minutes. The defrost test cannot be performed until a prototype of the plenum is created. Consequently, to estimate if the windshield will be defrosted in less time than with the current plenum design, we will use computational fluid dynamics analysis of the air flow from the redesigned plenum, in comparison to air flow measurements from the current plenum.

1.2.1.2 Federal Motor Vehicle Safety Standards (FMVSS) – 302 [3]

The FMVSS - 302 standard pertains to the flammability of interior materials for passenger cars, multipurpose passenger vehicles, trucks, and buses, by measuring the burn rate of the part. This standard affects the plenum material selection, as the plenum is within 13 mm of the occupant compartment of the bus. Adhering to this standard will reduce deaths and injuries to bus occupants as a result of fires originating from the interior of the vehicle (e.g. cigarettes or matches).

To test if the plenum material meets this standard, a horizontal flammability test is used. The part is mounted in a test chamber and subjected to a flame; for a given burn time, the distance of burnt material is measured, allowing the burn rate to be determined. In order to meet the requirements of the test, the plenum must not burn at a higher rate than 4 inches per minute [4].

For the purpose of the current design process, the burn rate of the selected material will be looked up (not tested directly), as the complete part will not be constructed during the design phase.

1.2.1.3 American Public Transportation Association (APTA) TS - 54.2 [5]

The APTA TS – 54.2 standard regulates the air flow from the climate control systems to the driver's area, of which the plenum is a part. At least 100 cubic feet per minute of air must be provided to the driver's area when operating in the ventilating and cooling modes. When heating, if less heat is required, the airflow to the driver's area can be reduced proportionally to the reduction of airflow to the passenger area. Furthermore, the defroster and interior climate control systems must be capable of diverting heat towards the driver's feet and legs, while maintaining visibility through the driver's side window.

The plenum design must work with the current systems in the New Flyer Xcelsior coach to continue to meet these requirements. Computational fluid dynamics analysis of the air flow from the redesigned plenum was used to determine if these requirements were being met. In regards to defrosting of the side window, a comparison of the amount of air flow from the redesigned part to the current part will be used to estimate if the side window will be still be defrosted. This will suggest that the standard will be met when tested in conjunction with the other parts of the defrosting system.

1.2.1.4 Testing Requirements [6]

Certain test results are required to meet New York City Transit requirements. This is due to the fact that many of the buses assembled in Winnipeg will be sold in New York. The results from these tests are affected by the plenum design, and therefore performance in these tests must be considered in the redesigned part. The plenum will affect the results of the following two tests: the “New York Driver’s Area Heating Test,” and the “New York Passenger Area Heating Test”. A brief summary of the test conditions and the analyzed parameters is presented below.

The “New York Passenger Area Heating Test” ensures that the driver area defroster is capable of heating the driver’s area to 60 degrees Fahrenheit within 60 minutes, while the doors are cycled, after the interior has been left at 6 degrees Fahrenheit for 5 hours. Lastly, the “New York Passenger Area Heating Test” ensures that the heating system can heat the passenger area to 60 degrees Fahrenheit within 60 minutes, while the doors are cycled, after the interior has been cold soaked at 20 degrees Fahrenheit for 5 hours. Furthermore, the windshield is sprayed with water in the manner described in SAE J381.

Since these tests are affected significantly by additional defrosting equipment that the team does not have access to, it will be impossible to perform the standardized tests to ensure that the requirements are met. Therefore, computational fluid dynamics analysis of the heat transfer and air flow from the redesigned plenum, in comparison to air flow and heat transfer measurements from the current plenum, will be used to suggest that the testing requirements will be met when tested in conjunction with the other parts of the defrosting system.

1.2.2 Size Constraints

The redesigned plenum must fit into the bus frame, such that none of the neighboring parts in the bus will require dimensional changes. Furthermore, a snug fit (such that the plenum will not shift upon placement in position) is required. The defroster plenum and the surrounding devices are shown in Figure 3.

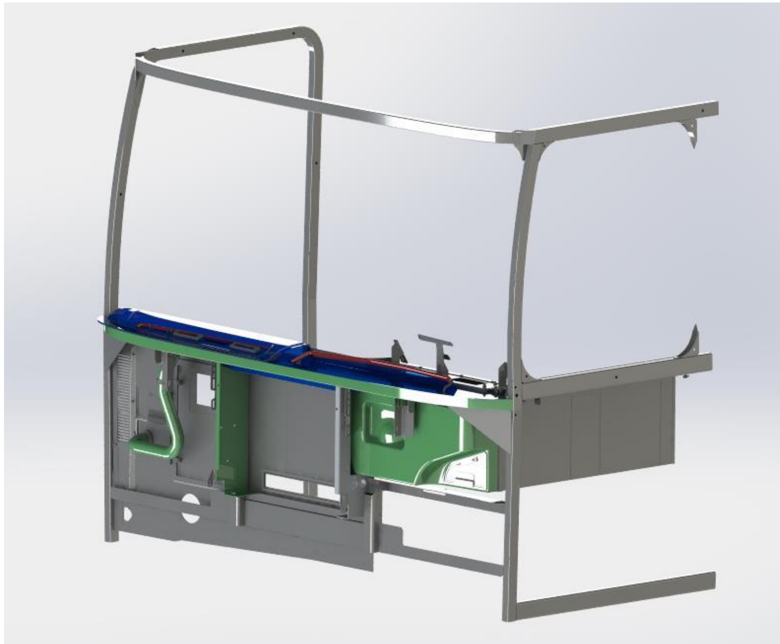


Figure 3: The position of the defroster plenum and its surrounding components [1]

The green components, shown in Figure 3, are directly connected to the defroster plenum, the plenum is shown in blue, and grey components are not directly connected to the defroster plenum. Since the defroster plenum is required to be able to sit and remain stable on the green frame structure, the size of the defroster plenum is constrained.

The original defroster plenum is shown in detail in Figure 4. It is composed of three parts: right secondary closeout (red), left secondary closeout (blue), and the base. The closeout plates are composed of aluminum, while the base is welded from four pieces of galvanized steel, which are marked by green, yellow, white and grey. While the design of the plenum will change, this figure is used to show some of the basic constraints for the defroster plenum. It requires two holes in the bottom, so that the pipe with hot air flow can be connected. Furthermore, it requires slots in the top of the defroster plenum, so the hot air can be transferred to the windshield.

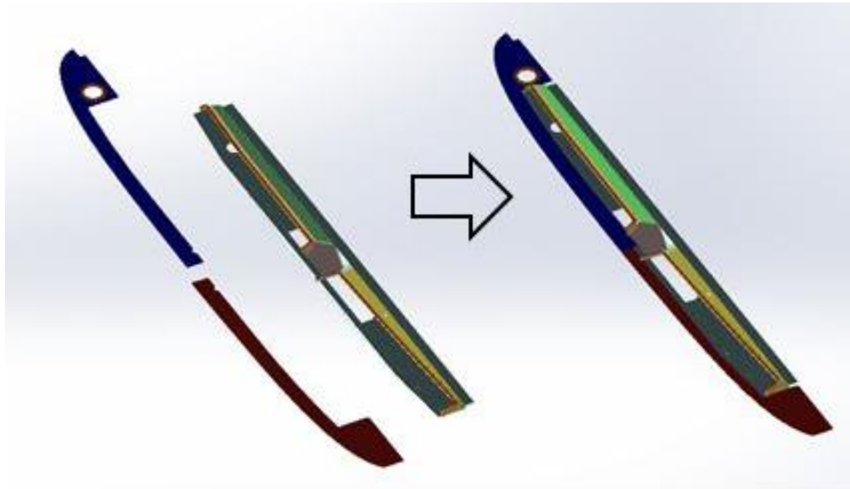


Figure 4: The original 3 D view of the defroster plenum assembly [1]

The dimensions of the support frame are shown in Figures 5 and 6. Figure 5 shows the dimensioned top view of the support frame structure, while Figure 6 shows a dimensioned front view of the support frame. The support frame determines the maximum length and width of the defroster plenum.

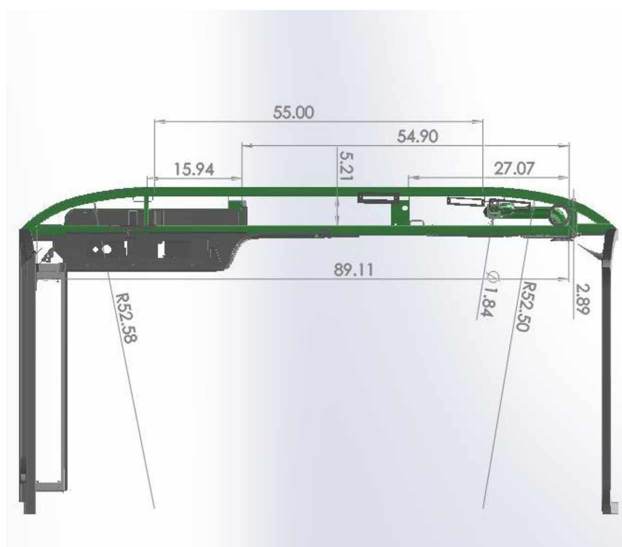


Figure 5: Top view dimension of the frame structure [1]

As can be seen in Figure 5, the size of the defroster plenum is limited to a trapezoid area. The short base is 55 in., the long base is 89.11 in., and the width is 5.21 in. In order to fit the defroster plenum into the frame structure, the long base length of defroster plenum must be less than 89.11 in., and short base must be less than 55 in., the width should be less than 5.21 in. A hole in the defroster plenum with an approximate diameter of 1.84 in. is also required, which is used to connect to a pipe with hot air flow.

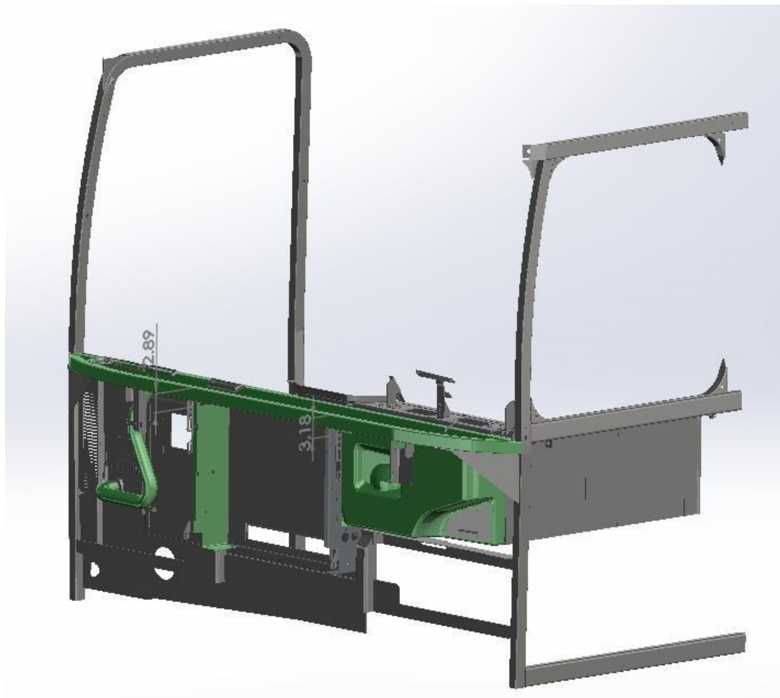


Figure 6: Front view dimension of support frame structure [1]

Figure 6 details the height constraints on the defroster plenum. The depth of the slot in the central part of frame structure is approximately 3 in., which indicates the defroster plenum height should be less than 3 in. In addition to the size constraints there are numerous manufacturing and installation constraints, which are contained in Section 1.3.3.

1.2.3 Manufacturing and Installation Constraints [1]

The manufacturing and installation constraints consist of cost, time, and availability. There are two primary concerns related to availability: the selection of the material and selection of the fabrication process. When creating the plenum design, the fabrication processes required to produce the plenum must be considered, as the set of vendors available to New Flyer must be able to perform these fabrication processes. Furthermore, the plenum material must be available to these vendors, and must be able to be shaped with the available fabrication processes. The vendor must also be able to produce the required production volume of 2000 parts per year. Lastly, the plenum must be produced for less than the current cost of $268. Any overhead costs associated with adjusting the design must be paid back within one year, for the given production of 2000 parts per year.

For installation constraints, the plenum must be able to be installed in under 2 hours, which is the current install time. The installation must be able to be completed by one person. During the time allotted for installation, the plenum must be set-up and secured to the bus frame [5].

TABLE I summarizes the constraints on the plenum design. For the constraints related to meeting test requirements, other components of the bus have an impact on the results of the test. Therefore, the plenum performance is not directly limited by the performance constraints detailed in these tests. This means that although the defrost system as a whole must meet these testing requirements, our plenum ultimately will not greatly affect the results. The constraints related to these tests are listed in the first section of the table labeled as standards, while constraints that only impact the plenum design are listed in the remaining two sections.

TABLE I: CONSTRAINTS AND LIMITATIONS

Constraints Related to Tests and Standards		
Standard	**Testing Procedure**	**Required Test Results**
SAE-J381 **[2]**	At -18^{o}C, 0.05 mL/cm^2 of water applied to windshield	Ice must be defrosted from windshield in <30 min
FMVSS-302 **[3]**	Part set on fire, burn rate determined	Burn rate < 4 inches/minute

Standard	**Testing Procedure**	**Required Test Results**
Driver's Area Heating Test **[6]**	Interior set to 6°F, doors cycled	Defroster heats driver's area to 60°F in <=60 min
Passenger Area Heating Test **[6]**	Interior set to 20°F, doors cycled, 0.05 mL/cm^2 of water applied to windshield	Defroster heats passenger's area to 60°F in <=60 min
APTA TS-54.2 **[6]**	Air flow to driver's area is measured	Air flow > 100 cfm, must be air flow toward driver's area, must maintain visibility through the driver's side window
New Flyer Industries Constraints [1]		
Requirement	**Required Level**	
Manufacturing process Availability	Must have an available vendor that can perform required manufacturing processes	
Material Availability	Material must be available to vendor	
Production Volume	2000 parts/year	
Plenum Cost	<$268	
Payback Period	<1 year	
Installation Time	<2 hours	
Installation Personnel	1 person	
Sizing Requirements [1]		
Requirement	**Required Level**	
Fits within the current bus frame	Secure fit with frame. Detailed dimensions of the frame structure of the front of bus can be found in Section 1.3.2.	

Once the constraints and limitations of the project were identified, the target specifications were developed.

1.3 Target Specifications

Target specifications describe the quantifiable needs of the client that we aimed to achieve. Some of the specifications carry more importance than others, and consequently the specifications were split into two categories. The first category includes the essential specifications that our design must meet. The other category contains the secondary specifications that we attempted to meet. If it was not possible to meet the secondary specifications, the new design at minimum maintained the same quality as the current model.

1.3.1 Essential Specifications

Our primary goal with the design is to reduce cost by at least 100 dollars per plenum [1]. Because of the large volume of buses that are produced at the facility (2000 per year), this will lead to substantial savings for New Flyer Industries.

The second specification is to reduce installation time by 20 minutes. Since it takes two hours to install the current defroster plenum, our goal is to have the design installed in 1 hour and 40 minutes or less [1]. This reduction in installation time will also lead to indirect savings since the technicians will have the ability to do more work in the day with the extra time gained.

The defroster plenum will be one piece with no additional parts. The client and the installation technician both voiced concerns about the fact that the current defroster plenum currently must be installed in multiple parts. The plenum itself is galvanized steel sheet metal that is welded together from four separate pieces. Then, once in place, two aluminum secondary closeouts are placed around the plenum. If the whole plenum assembly is in one piece, it will be easier to install, which will save time.

Any initial costs involved in changing the manufacturing of the defroster plenum must have a payback period of less than one year [1]. This means that if New Flyer Industries has to purchase a tool or mold to be able to install or manufacture the part that we design, it will have to cost less than the overall savings per year from the new plenum design.

1.3.2 Secondary Specifications

Our redesigned defroster is specified to reduce current windshield defrost time by 5 minutes. The SAE-J381 standard requires that it takes 30 minutes for the defroster to clear the window. Therefore, we aim to defrost the window in 25 minutes with our new design. If the performance of the defrost system can be ameliorated, it would mean that in the future the fan speed could be reduced, which would reduce noise levels [1].

Another specification of our redesign will be to reduce the noise produced by the plenum by 2 dBA [1]. Although the current plenum produces acceptable noise levels, it is always better to reduce white noise if possible. Less noise will keep the passengers and the driver more comfortable.

The secondary specifications are not just limited to performance. It is important that the installation can be done by one person. Currently, one technician installs this plenum alone. Our design needs to be light enough and easy enough to maneuver that one person can still install it. Also, the defroster plenum can only be installed at one particular stage on the assembly line [1]. For some flexibility and freedom in terms of assembly, the new plenum should be designed in a way that it can be easily maneuvered and installed, even if other components have already been installed on the dash. Multiple installation points is particularly helpful if there is a part shortage, as the assembly line can keep on moving and the part can be installed at a later stage.

Furthermore, the new design must be equal to or less than the weight of the current model. Our goal will be to produce a part that has a lower weight than the current defroster plenum. This is a very low importance specification, however, since the weight of the plenum is not a major concern [1].

1.3.3 Summary of Target Specifications

Table II is a summary of the specifications listed above. The client assigned a value of importance for each of the target specifications on a scale of one to five, five being the most important. This importance scale gave our team better focus when creating the design, because the problem was clearly defined and the specifications were effectively prioritized.

TABLE II: TARGET SPECIFICATIONS SUMMARY

Imp	Metric	Units	Ideal	Marginal
5	Manufacturing cost	[CDN dollars/unit]	<168	268
5	Installation time	[Minutes]	100	120
4	Number of parts in the plenum	[Parts]	1	3
4	Have a short payback time for tooling	[# of Coaches]	<2000	N/A
3	Defrost time	[Minutes]	25	30
2	Noise reduction	[dBA]	2	0
5	Installed by a limited number of technicians	[Technicians]	1	N/A
2	Number of locations where plenum can be installed in assembly line	[Locations]	2	1
1	Low weight plenum assembly	[kg]	<=4.15	4.15

2 Design Generation

During the design generation phase, the team produced a defroster plenum design that met all the target specifications while remaining within the constraints and limitations. To produce the design, it was necessary to create numerous concepts, then screen and score each concept to determine which concepts best met the target specifications. Aspects from each of the concepts that scored well were integrated to produce the final design, which will be recommended to the client.

2.1 Design Methodology

The design generation process began with the evaluation of both patented designs and competitors' designs. By looking at designs that are currently in use, the team was able to see the wide range of concepts that are currently available. Looking at other's designs sparked the team's creativity, allowing the team to progress to the development of unique concepts. The team's concept development phase began with the use of the TRIZ methodology, to identify the generalized solutions needed to meet the design objectives. Using the generalized solutions that were recommended by the TRIZ methodology, numerous concepts were generated during the brainstorming stage. The concepts generated during brainstorming were mostly small changes that focused on meeting one or two customer needs; these brainstormed concepts were carried through to the concept analysis phase.

Concept analysis began with concept screening, which was a rough analysis that identified a shortlist of concepts that best met the customer's needs. To perform concept screening, the individual concepts were organized into categories, based on the aspect of the design that was focused on. The categories of concepts were then screened using individualized criteria. Following concept screening, the individualized criteria were weighted according to prioritization of the client objectives. The weighted criteria were used in preliminary scoring of the shortlisted concepts; preliminary scoring was undertaken to determine an initial listing of ideas that would be taken to the concept integration stage. To ensure client satisfaction with the integrated design, the accuracy of our preliminary concept scoring was discussed with our client. If the scoring of certain criteria was in question, a sensitivity analysis was conducted. The sensitivity analysis used detailed research from additional sources to re-score the concepts and created a finalized scoring matrix. The concepts that proceeded through the finalized scoring matrix were integrated into a complete design. This procedure was followed to ensure that our final design will be the best choice, based on what the client needs and wants, with the highest accuracy possible.

The results of the concept generation stage, as well as concept screening and preliminary concept scoring, are included in Appendix B for brevity. The sensitivity analysis and final scoring matrix is included in the detailed concept analysis.

2.2 Detailed Concept Analysis and Selection

During concept screening and scoring, the concepts were split up into four categories:

1) Methods to fasten the plenum to the frame of the bus.
2) Material to produce the plenum.
3) Manufacturing process to produce the plenum.
4) Physical plenum designs.

By separating the ideas into categories, the team could focus on developing ideas that directly related to specific project needs, instead of trying to solve many issues at once. Sections 2.2.1 to Section 2.2.3 detail the finalized concept scoring for each category. The sensitivity analysis is also included, if it was conducted.

2.2.1 Material and Fabrication Process Concept Selection

The material and fabrication process are critical in reducing the cost, installation time, number of parts, and payback time for the defroster plenum design. Since the cost and installation time are the primary objectives of the design, significant time was dedicated to selecting the optimal material and fabrication process.

2.2.1.1 Final Material Scoring and Concept Selection

The materials that proceeded through concept screening and preliminary scoring are contained in TABLE III. Letter identification is maintained from initial screening and scoring in order to maintain consistency.

TABLE III: MATERIALS THAT PROCEEDED TO FINAL CONCEPT SCORING

	Concept	Picture and/or Description
C	Stainless Steel	N/A
G	Polycarbonate (PC) [7]	N/A
H	Acrylonitrile Butadiene Styrene (ABS) [8] [7]	N/A
I	Fiberglass	N/A
J	Acrylic/Polymethyl Methacrylate (PMMA) [9] [7]	N/A
K	High Density Polyethylene (HDPE) [7]	N/A

The preliminary scoring of the materials was deemed sufficient by the client to proceed to material selection. Therefore, no sensitivity analysis was needed prior to the finalized concept scoring. The final concept scoring matrix it contained in TABLE IV. Refer to Appendix B for justification of the weighting of the scoring criteria in each category.

TABLE IV: FINAL CONCEPT SCORING OF MATERIALS

Criteria	Weight	C	G	H	I	J	K
Density	0.10	3	4	4	3	4	5
Thermal Expansion [10] [11]	0.10	5	3	2	4	1	2
Strength	0.10	4	3	4	5	3	3
Thermal Conductivity	0.30	2	3	4	4	4	4
Cost	0.40	1	3	4	2	2	2
Total		2.20	3.10	3.80	3.20	2.80	3.00
Rank		6	3	1	2	5	4
Proceed?		No	No	Yes	No	No	No

Fiberglass, although having a high strength, has inherently high costs in production. Furthermore, HDPE and PMMA were found to have high raw material costs. The heavy weighting of the criteria towards cost significantly reduced the scoring of fiberglass, PMMA, HDPE, and stainless steel. Criteria weighting towards the thermal conductivity further reduced the score of stainless steel. From the concept scoring matrix, ABS plastic emerged as the clear material choice. While the thermal expansion coefficient did not match closely with the metal frame, this criterion was weighted very lightly. In all other categories, ABS exceeded the current material. Therefore, the material that proceeded to concept integration is ABS.

2.2.1.2 Final Fabrication Process Scoring and Concept Selection

The fabrication processes that proceeded through concept screening and preliminary scoring are contained in TABLE V. Letter identification is maintained from initial screening and scoring in order to maintain consistency.

TABLE V: FABRICATION PROCESSES THAT PROCEEDED TO FINAL CONCEPT SCORING

	Concept	Picture and/or Description
G	Reaction Injection Moulding [12] [13] [14]	Moulds are constructed of part, and then thermoset is poured into mould. Lower pressures are needed than injection moulding as plastic sets inside mould. Part can be produced in one piece, or separate moulds may be used, and pieces are bonded together.
H	Vacuum Forming [15] [16] [17]	Moulds are constructed of part, and then plastic is poured into hot mould. Plastic is compressed by suction to form part shape. Can be produced in 3 parts (deflection panels (2), then rest of part), then parts are bonded together.
I	Rotational Moulding [18] [19]	Moulds are constructed of part, and then plastic is poured into hot mould. Part is rotated until plastic planes out on mould walls. Part is produced in one piece, and then holes are cut out from part.

For the fabrication process, preliminary scoring was not conclusive. Rotational moulding, reaction injection moulding, and vacuum forming were all determined to be viable possibilities for the fabrication process. Since all fabrication processes are compatible with ABS plastic (the recommended material), material considerations were not a factor. Therefore, in consultation with the client, the team determined that a sensitivity analysis was needed. To perform the sensitivity analysis for fabrication process selection, additional information was obtained on each of the three processes. The industry contact for the project, Ben Chao, was also consulted. He provided us with industry experience on which manufacturing processes are low cost in practice, as opposed to the theoretical costing of the manufacturing process. In addition, he provided the team with the contact information of New Flyer's preferred vendors for all three manufacturing processes. The vendors were consulted to provide the part cost and overhead costs that would be necessary to produce the old plenum design. Since the new physical design was being developed simultaneously, the old design was provided to ensure consistency among the vendor's cost estimates. Since New Flyer's preferred vendors were used, the cost estimates from these companies have been determined to be accurate.

For rotational moulding, Centro Inc. was consulted. The old design could be produced as one piece, and would cost [redacted] per part [19]. The mould was estimated to cost between [redacted] while the fixture that is required to hold the part during production would cost between [redacted] [19]. Together, the overhead (one time) costs for rotational moulding would be between [redacted].

For reaction injection moulding, Romeo Rim was consulted. The old design could be produced in two parts, and depending on material selection would cost [redacted] per part [14]. The two halves would be bonded together with rivets or screws. The tooling (mould) costs for the two piece mould would be between [redacted] per part [14]. Tooling costs would be a one-time cost.

For vacuum forming, Plasticom Inc. was consulted. The old design would be produced in two parts, and would cost [redacted] per part [17]. The two sections would be bonded together using Plexxus. The tooling and fixture (overhead) costs would be [redacted] [17].

The cost estimates for each of the three processes were used to revise the concept scoring; revised scoring is shown in TABLE VI. Refer to Appendix B for justification of the weighting of the scoring criteria in each category.

TABLE VI: FINAL CONCEPT SCORING OF MANUFACTURING PROCESSES

Criteria	Weight	G	H	I
Overhead Costs	0.3	2	5	4
Part Cost	0.4	3	3	5
Tolerance	0.1	5	4	3
Post Processing Needed	0.1	5	2	3
Adequate Production Volume	0.1	5	3	4
Total	1	3.3	3.6	4.2
Rank		3	2	1
Proceed?		Yes	Yes	Yes

From the revised scoring, rotational moulding emerged as the suggested fabrication process. Centro Inc. was consulted again to provide more accurate costing for the revised plenum design. The revised plenum design included additional features from the old design and integrated in the dash closeouts, such that the entire plenum assembly could be sent to New Flyer in a single piece.

With the addition of the new features, [redacted] Consequently, the group shifted focus to producing the part using vacuum forming, which was the second highest scoring concept.

Plasticom Inc. was again consulted to provide a cost and feasibility assessment of the new physical design, including the dash closeouts. Plasticom Inc. stated they could produce the plenum design at a cost that was comparable to the initial estimate. Therefore, vacuum forming was selected as the finalized process for producing the defroster plenum. Using vacuum forming as the fabrication process will be the concept that is taken forward to the concept integration stage.

2.2.2 Final Fastening Method Scoring and Concept Selection

The fastening methods that proceeded through concept screening and preliminary scoring are contained in TABLE VII. Letter identification is maintained from initial screening and scoring in order to maintain consistency.

TABLE VII: FASTENING METHODS THAT PROCEEDED TO FINAL CONCEPT SCORING

	Concept	Picture and/or Description
A	Plastic Rivet [20]	Plastic pin technician pushes in with thumb which secures it into place.
D	Double Sided Tape	Tape that has adhesive on both sides.
E	Velcro	Velcro bonded to the plenum and the frame.
F	Screw with Template	Still use screws but use a template instead of measuring each hole to drill.

During preliminary scoring, the scoring of the fastening method was not conclusive. Multiple designs had very close results. Furthermore, in consultation with the client, concerns were raised about the ease of removal and profile of certain designs. The part must be removable in order to allow for repairs, while the profile of the fastening method must be low enough that the plenum fits underneath the dash. The concepts were re-scored with additional consideration placed on the ease of removal and profile of the concept. The finalized scoring matrix is included in TABLE VIII. Refer to Appendix B for justification of the weighting of the scoring criteria in each category.

TABLE VIII: FINAL CONCEPT SCORING OF FASTENING METHODS [1]

Criteria	Weight	A	D	E	F
Cost	0.3	4	5	4	3
Time	0.1	5	3	3	2
# of parts	0.1	4	4	3	4
Noise	0.1	4	4	4	4
Low Profile	0.4	4	3	2	4
Total	1	4.1	3.8	3	3.5
Rank		1	2	4	3
Proceed?		Yes	No	No	No

Following the finalized concept scoring, pushpin rivets received the highest score, followed by double sided tape. Velcro and double sided tape did not score as well because they have a high profile. Therefore, using pushpin plastic rivets was the concept that proceeded to the design integration stage.

2.2.3 Final Physical Design Scoring and Concept Selection

To define possible physical design changes (concepts), plenum features are identified according to the nomenclature contained in Figure 7.

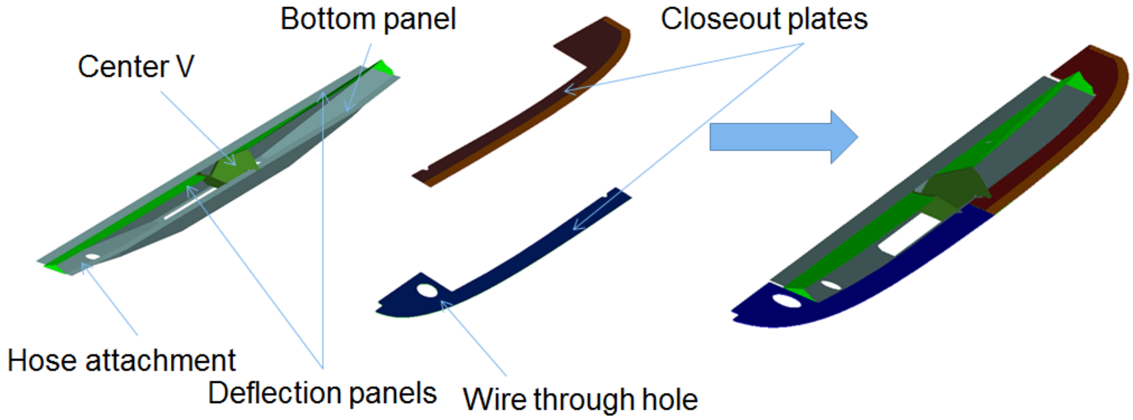
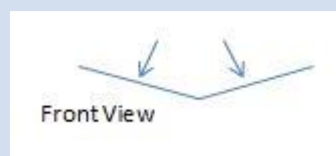
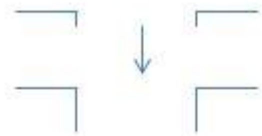
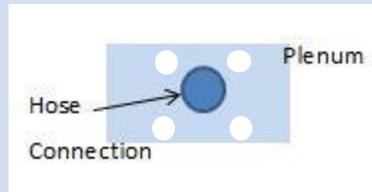


Figure 7: Exploded view of the defroster plenum

The physical designs that proceeded through concept screening and preliminary scoring are contained in TABLE IX. Letter identification is maintained from initial screening and scoring in order to maintain consistency.

TABLE IX: PHYSICAL DESIGN CONCEPTS METHODS THAT PROCEEDED TO FINAL CONCEPT SCORING

	Concept	Picture and/or Description
A	Flatten centre ‘V’	
C	Curve centre ‘V’	
F	Curve Deflection Panels	
L	Curve Bottom Panel	

	Concept	Picture and/or Description
P	Increase Area of Hose Connection	
R	Predrill Holes and use Plastic Rivets for Hose Connection	

The preliminary scoring of the materials was deemed sufficient by the client to proceed to selection of a physical design. Therefore, no sensitivity analysis was needed prior to the finalized concept scoring. The final concept scoring matrix it contained in TABLE X. Refer to Appendix B for justification of the weighting of the scoring criteria in each category.

TABLE X: FINAL CONCEPT SCORING FOR PHYSICAL DESIGNS

Criteria	Weight	A	C	F	L	P	R
Cost to Produce	0.222	3	3	3	2	3	3
Time to Manufacture	0.167	2	2	2	2	3	3
Time to Install	0.194	4	4	4	4	4	5
# of Parts	0.139	4	4	4	4	3	3
Heat Transfer to Sides	0.111	3	3	4	4	3	3
Heat Transfer to Middle	0.083	3	4	4	4	3	3
Noise	0.028	4	4	4	4	3	3
Assembly Line Locations	0.028	2	2	2	2	3	3

Criteria	Weight	A	C	F	L	P	R
Weight	0.028	4	4	4	4	3	4
Total		3.20	3.28	3.39	3.17	3.19	3.42
Proceed?		Yes	Yes	Yes	Yes	No	Yes

Since many of the improvements to the physical design can be integrated independently of one another, only one concept was eliminated during the final concept scoring phase. Predrilling the holes to the plenum greatly improved the installation time, and required almost no increase in manufacturing cost. Since increasing the area available for hose attachment provided only moderate improvements to the installation time, it was eliminated.

Following the finalized scoring of the design shape and structure concepts, the following changes were taken forward to concept integration: the centre 'V' was flattened, curves will be added to the centre 'V,' bottom panel, and deflection panels, and holes around the site of hose attachment will be predrilled, with screws suggested as the form of attachment of the hose to the plenum.

2.3 Concept Integration

The complete design that moved forward to the analysis state is a combination of all the leading concepts that we determined in the design subsections (Sections 2.2.1 to 2.2.3). These subsections include fabrication and material selection, fastening method, and physical design.

The new defroster plenum will be formed using ABS plastic with a vacuum forming process and will be fastened using plastic pushpins. The physical design will remain similar to the current plenum, but will also include a rounded and flattened center 'V,' and all inside sharp edges will be rounded as well (bottom panel and deflection panels). Rounding off all the sharp edges acts to reduce pressure loss of the airflow as it flows across the plenum. Six holes will also be predrilled on the back lip (for the plastic pushpins) and four holes will be predrilled around the hose connection site. The revised features in the plenum design are detailed in Figure 8.

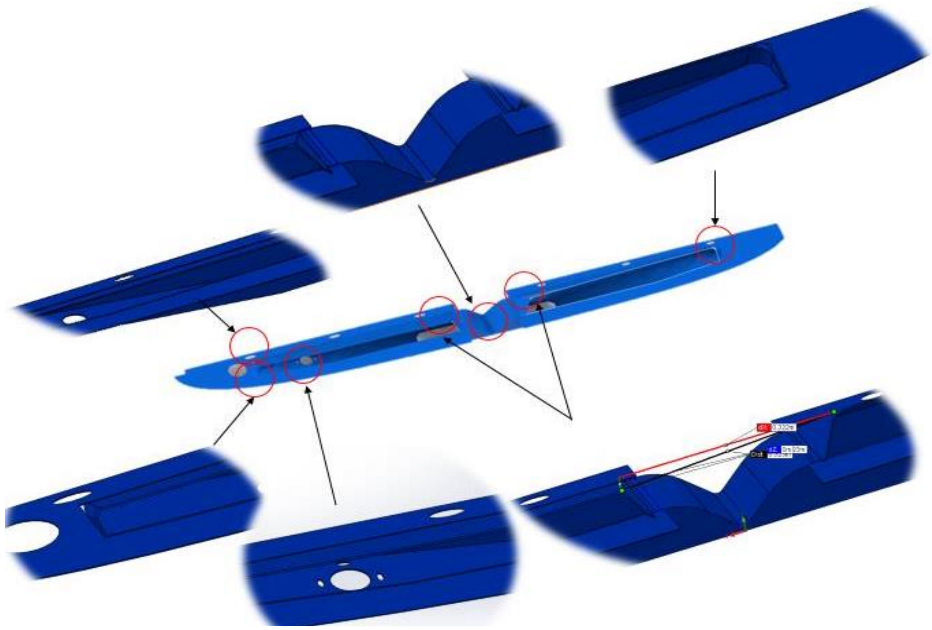


Figure 8: Complete design showing added physical features

The completely integrated concept, suggested from the concept screening and scoring phase, is shown in Figure 9.

Figure 9: Complete design using integration of leading concepts

Following the development of the concept, analysis on the concept was performed to ensure that the revised defroster plenum design met the objectives outlined by the client. To aid in understanding of the analysis, a detailed description of the final design is presented prior to the analysis. The analysis contains a detailed description of how the addition of certain features quantitatively met the client’s objectives.

3 Details of Final Design

Following the integration of the leading concepts into a complete design, the general structure of the design was known. To determine the exact dimensions of the physical features, a computational fluid dynamics (CFD) optimization of airflow and noise performance was performed. Following the CFD analyses, all features from the integrated design were carried forward to the final design; several additional features were added following the CFD optimization procedure. The CFD optimization procedure is detailed in Section 4.1.2. The final design that resulted from the optimization process is described in Section 3.1. Detailed engineering drawings of the design are contained in Appendix A.

3.1 Overview of the Design

The final defroster plenum design combines the dash closeouts and central plenum into one entire part, instead of three separate pieces. The dash closeouts and exterior of the central plenum have the same fundamental shape as the original plenum; however, features have been added to improve the performance of the design with respect to the client's objectives. Added external features are that there are six pre-drilled holes on the back lip of the plenum, and four pre-drilled holes on the bottom left hand side where the auxiliary heating hose connects. The deflection panels have also been smoothed out, instead of a double-planed design.

In the interior chamber, the defroster plenum will have a curved center V section, along with smoothed edges leading to the plenum outlet. The edges of the centre ''V' have been extended outwards, such that the centre 'V' profile has been flattened out. Furthermore, sharp edges in the bottom panels have been smooth out. This smooth continuous design reduces air drag and improves air flow at the outlet. The shape of the center V section of the defroster plenum was also angled to cause more airflow to reach the outer louvers, which improves uniformity in the flow. To improve airflow to the windshield on the hose-side of the plenum, the plenum area has been reduced. Figure 10 shows the redesigned defroster plenum and all the key features that have been modified.

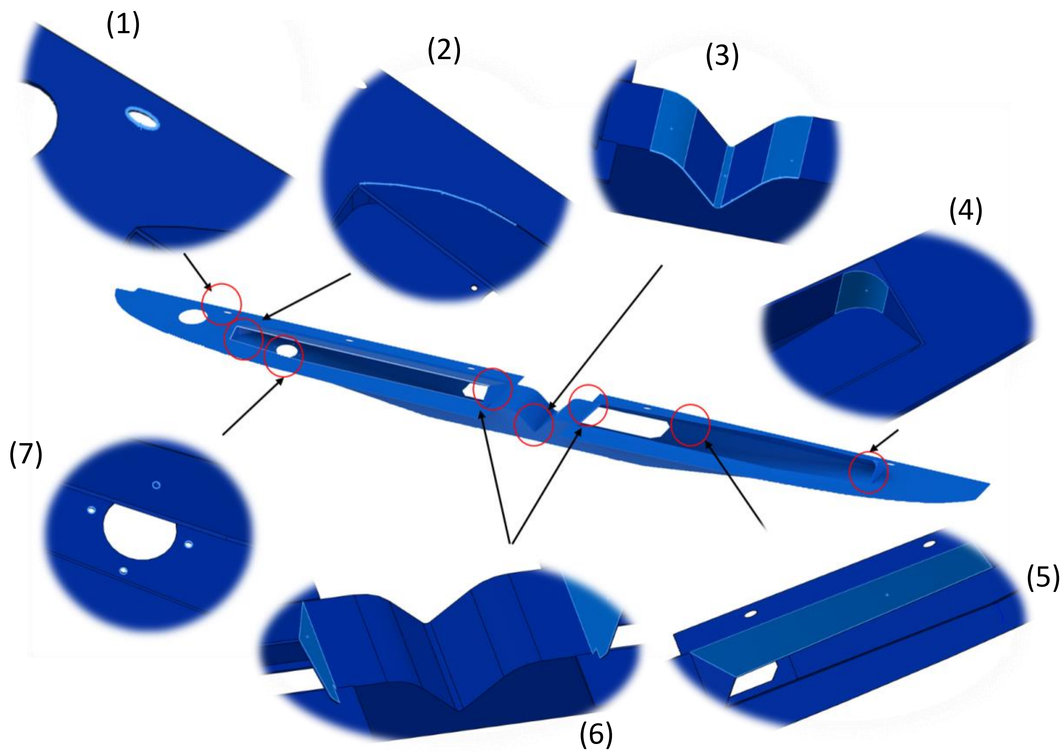


Figure 10: Final design with expanded view and numbering of key features

A summary of the features that were added to the final plenum design, including the reason for the feature change as well as a reference to the feature on Figure 10, is included in TABLE XI.

TABLE XI: ADDED FEATURES IN FINAL PLENUM DESIGN

Feature	Function	Figure 10 Reference
Combined Dash Close-outs with Central Plenum	Reduce # of Parts	Central Image
Six Pre-drilled holes for Frame Attachment	Reduce installation time	1 → Only one hole is pictured
Four Pre-drilled holes for Hose Attachment	Reduce installation time	7
Curved Central 'V'	Improve airflow, reduce noise	3
Flatten Central 'V' Profile	Improve airflow, reduce noise	6 → Distance between two edges was reduced
Curved Bottom Panels	Improve airflow, reduce noise	4 → Edges of bottom panels are shown
Reduction of Hose-side Plenum Area	Reduce backflow → improved airflow	2
Curved Deflection Panels	Improve airflow, reduce noise	5→ Double planed bend in deflection panel was removed

The changes to the plenum design are not just limited to physical changes. Changes were also made to the fabrication process and material selection as well as the fastening method, which are outlined in Sections 3.1.1 and 3.1.2.

3.1.1 Material and Fabrication Process of Final Design

The final design will be produced using ABS plastic. ABS plastic offers a number of advantages over galvanized steel (the current material). Namely, it is a low cost plastic that meets the required safety standards, while providing several other key advantages.

It has a low thermal conductivity, which will reduce temperature losses as air passes through the plenum; it is lightweight, but is has sufficient structural stiffness to maintain its structure during operation; it is also compatible with vacuum forming, which is advantageous for producing the plenum design.

Vacuum forming entails laying a sheet of plastic over a die. When suction and heat are applied, the plastic sheet forms to the shape of the die. The process produces parts at a low cost, and can meet the manufacturing demands of 2000 coaches per year. The plenum will be made in 3 sections and bonded together; however, when the defroster plenum is sent to the New Flyer Industries facility, it will be in one complete piece. To streamline the fabrication process, the gaps between the dash closeouts and central plenum were removed. A redundant hole in one of the deflection panels was also removed. An image of the features that were changed is included in Section 3.1.3.

3.1.2 Fastening Method

The defroster plenum will be fastened to the frame of the bus using pushpin plastic rivets, at the location of the predrilled holes on the plenum. These pushpins are cheap, easy to use and easy to remove. Pushpin fasteners are used at various locations on the bus; therefore, New Flyer Industries will already have these fasteners available for the technicians. In addition, the technicians are already familiar with their use. The pushpins are considered one time use. This means that if the defroster must be removed, new pushpins are recommended to be used instead of the old ones.

The complete listing of sections that were changed in the old design, factoring in the changes that were required to improve performance, streamline the fabrication process, improve the installation time, is presented in Section 3.1.3.

3.2 Summary of Changes to Old Plenum Design

Section 3.1 details the new plenum design and describes the features that were added. To aid in understanding of the effect these changes have on the old plenum structure, the sections of the old design that were changed are highlighted in Figure 11. Detailed images of the original sections of the plenum that were affected by changes are labelled by number. Images labelled in orange (Sections 1 – 7) are the sections that were affected by the changes described in detail in TABLE XI; these sections were changed in order to meet certain client objectives. Sections 8 and 9 were changed to streamline the plenum design for vacuum forming. The changes made to sections 8 and 9 are described in detail in TABLE XII.

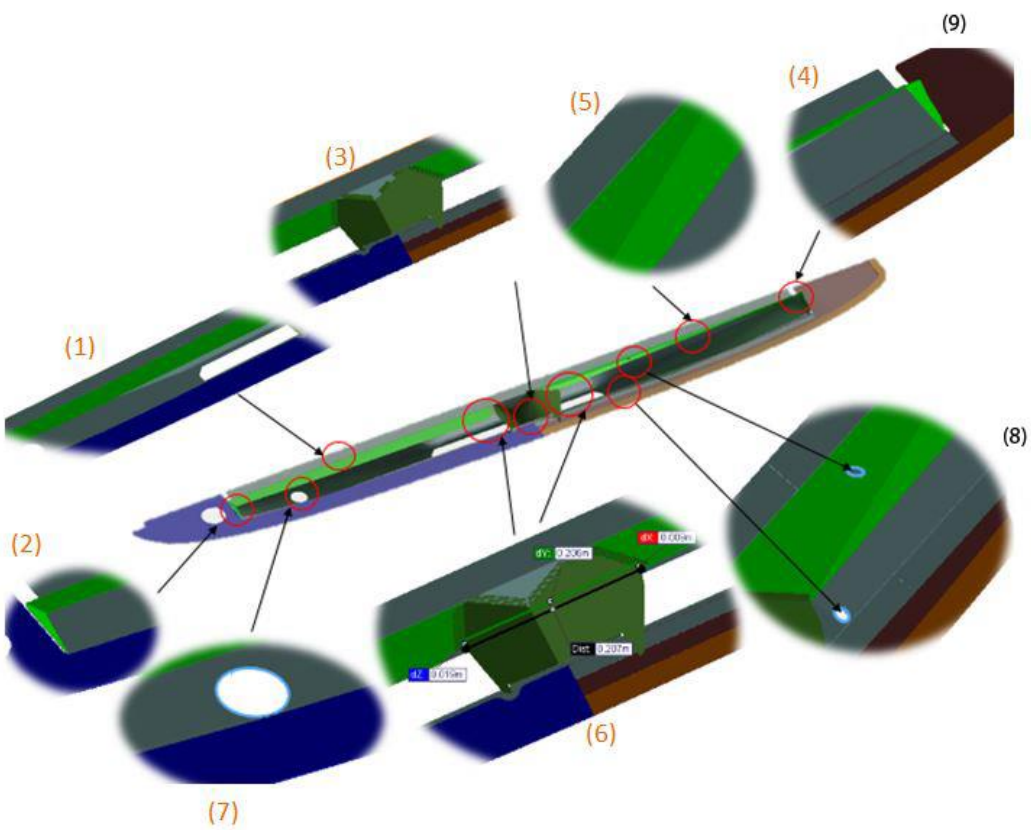


Figure 11: The old plenum design

TABLE XII provides a brief description of the changes to sections 8 and 9; these changes were made in order to tailor the plenum design for vacuum forming.

TABLE XII: ADDED FEATURES IN FINAL PLENUM DESIGN

#	Feature	Reason for Change
8	Remove Additional Hole in Plenum	No longer needed.
9	Remove Gap between Central Plenum and Dash Closeouts	Improve strength of bond between dash closeouts and central plenum.

The analysis of the new design details how the revised design performs with respect to the client's objectives. In the analysis, justification for each of the design modifications is presented.

4 Analysis of New Design

The revised design was analyzed to ensure that the client's objectives were met. The analysis is broken down into three sections:

1) Performance analysis
2) Analysis of manufacturing process
3) Analysis of installation process

The performance analysis was conducted using computational fluid dynamics software (CFD). The performance analysis involved analyzing airflow from the plenum, to ensure that objectives related to heat transfer and noise from the plenum were met. The performance analysis was also used to optimize the physical design of the plenum. Once the physical design was determined, the analysis of the manufacturing process was performed to determine exactly how the part will be produced. This manufacturing process analysis was performed through consultation with a vendor, and was conducted to ensure that the objectives related to the physical part (such as cost, sizing, number of components) were met. Following the analysis on the production of the plenum, the analysis of the installation process was conducted. It was conducted in consultation with the client, Ben Chao, as well as with one of the technicians that installs the plenum on the assembly line. The installation analysis involved determining the effects of the changes that were made to the plenum in terms of time saved, and ease of installation. The installation analysis ensured that all objectives related to the installation were met. TABLE XII describes how the three forms of analysis relate to specific target specifications.

TABLE XIII: FORM OF ANALYSIS AND RELATED TARGET SPECIFICATIONS

Form of Analysis	Related Target Specifications	
Performance Analysis	Reduce Defrost Time	Reduce Noise
Analysis of Manufacturing Process	Reduce Manufacturing Cost	Reduce Number of Parts
	Have a short payback time	Low weight assembly
Analysis of Installation Process	Reduce Installation Time	Installed by a Limited Number of Technicians
	Increase Number of Locations where Plenum can be Installed	

4.1 Performance Analysis

The performance analysis involved performing computational fluid dynamics (CFD) analysis to determine the air flow rate and noise produced by the plenum. The objective of the performance analysis was to ensure that the physical plenum design met the following client objectives:

1) Reduce defrost time
2) Reduce noise

The defrost time is dependent on numerous systems in the bus assembly including fan speed, heat exchanger efficiency, and air flow rate, among other factors. Since the team did not have access to models of all defrosting components, the defrost time could not be directly determined using CFD software. To estimate the reduction in defrost time, the effect of the plenum on the defrost time was isolated from the defrosting system.

The plenum acts as a duct to direct air from the heat exchanger to the windshield. The primary mechanism of heat transfer between the air and the windshield is assumed to be forced convection, such that the amount of heat transfer between the air and a particular point on the windshield depends on the following:

- Volume of air provided to particular location
- Temperature of the air
- Air velocity

The initial volume of air is determined by the fan speed, and the air distribution across the windshield is determined by the positioning of the louvers directly above the plenum. The louvers, which are placed above the plenum, are shown in Figure 12. The plenum is indicated by the blue portion of the assembly. The red sections of the assembly are the positions of the louvers.

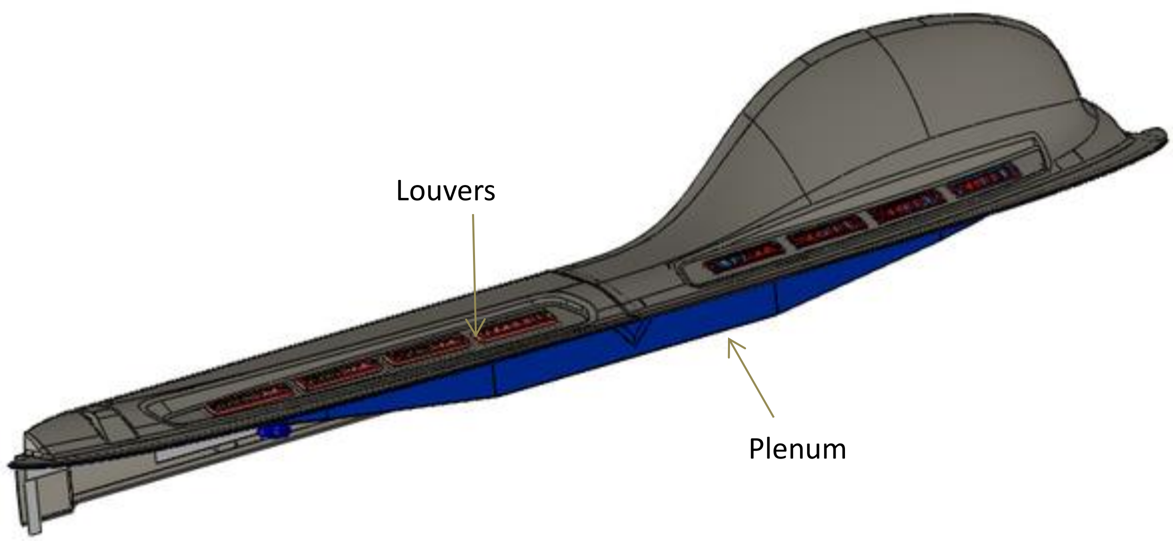


Figure 12: Louver positioning over the plenum

Figure 13 shows the detailed geometry of the louvers. The positioning of the louvers has a significant effect on the direction and quantity of airflow across the windshield.

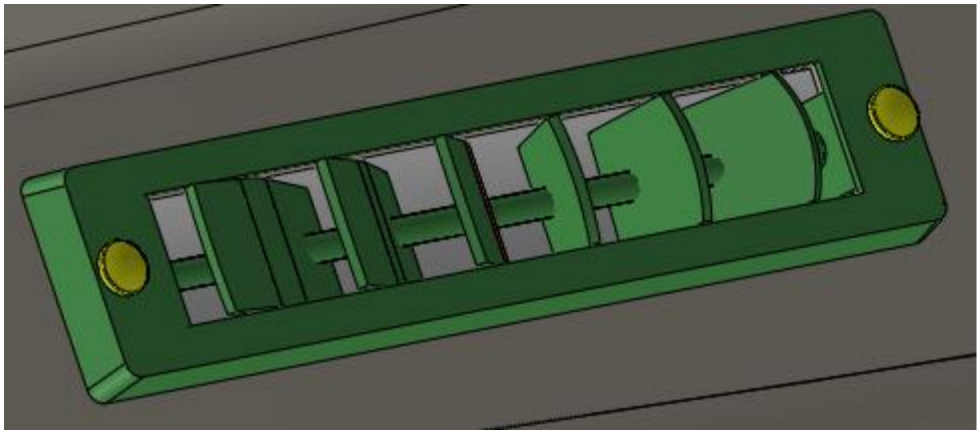


Figure 13: Close up of louver geometry

The plenum only has a small effect on the air distribution across the windshield, as the plenum shape can only affect the mass flow rate of air to each louver. The direction of airflow across the windshield is dominated by the louver geometry. The temperature of air is largely controlled by the heat exchanger performance, but the thermal conductivity of the plenum will prevent losses of heat as the air passes through the plenum. The air velocity is affected by the plenum significantly more so than the other factors. Since the air velocity through the plenum has the greatest impact on the defrost time, development of the new design focused on improving the air velocity; however, the thermal conductivity and airflow distribution to the louvers was still adjusted to improve heat transfer.

Given that an increase in air velocity will increase the amount of heat transfer between the air and the windshield, which in turn reduces the defrost time, the noise may have to increase slightly in order for the defrost time to improve (higher air velocity leads to higher noise levels when impacting the louvers). Since the reduction in defrost time was weighted more heavily than reducing the noise in the client's specifications, small increases in the noise (if defrost time is reduced) were acceptable. Noise levels produced by the plenum, due to interaction between the airflow and louvers, can be offset through reductions in the amount of turbulent flow in the plenum. Laminar flow within the plenum decreases the noise produced as air flows through the plenum. Taking these factors into consideration, the CFD analysis and optimization process was conducted. Important parameters for the analysis are contained in Section 4.1.1.

4.1.1 Parameters for CFD Analysis

The parameters for the CFD analysis are crucial to obtaining accurate airflow results, since the parameters define the boundaries conditions acting on the plenum in the CFD software. The CFD software used for the analysis was Star CCM+.

The first step in the analysis was to compartmentalize the analysis, such that the complex nature of the flow is broken into sections for which basic flow equations apply; the results from individual sections are combined to map airflow patterns in the plenum. To perform this type of analysis, a mesh was applied to plenum. The mesh on the plenum is shown in Figure 14.

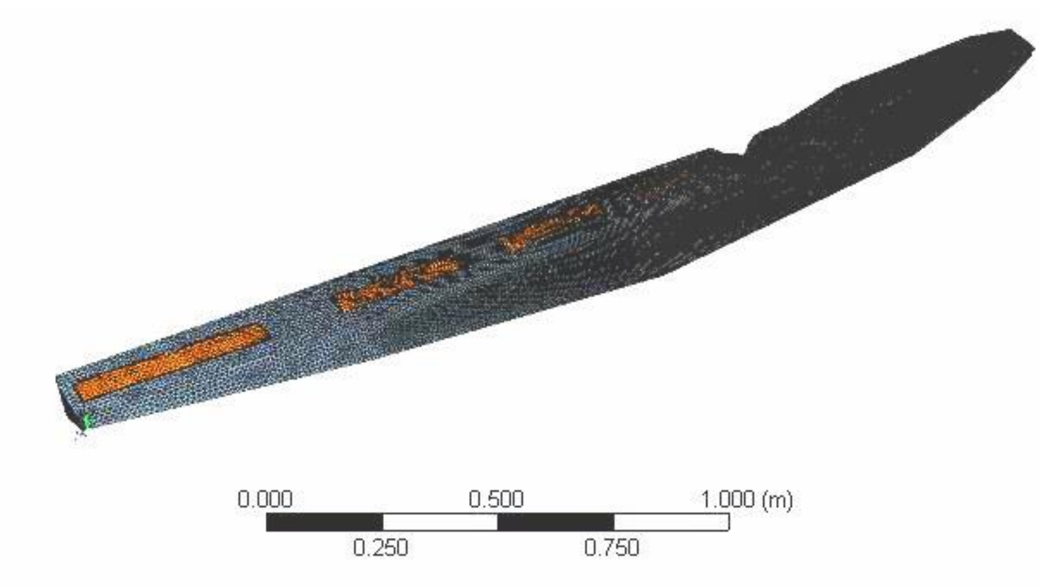


Figure 14: Mesh on defroster plenum

The mesh shape we used was tetrahedral, as it is applicable for complex geometries. Since the defroster geometry is complex and has lots of sharp edges, other meshing geometries would generate large errors. Furthermore, tetrahedral mesh produces fast results while minimizing the number of required memory cells [21]. Following the selection of a proper mesh, parameters for the fluid were determined.

Since the air is a compressible fluid (the density of air is changing in the defroster plenum), the fluid was modeled as a real gas with segregated fluid enthalpy. Using a segregated fluid enthalpy model not only considered the internal energy of the air, it also considered pressure-volume changes, which leads to more accurate results. The fluid is assumed to be in a turbulent state, as the Reynolds number of air into the defroster is much higher than the accepted transitional point (from a laminar to turbulent state), which is a Reynolds number of 2300.

The state of turbulence was modelled using the K-Epsilon turbulent model; this model accounts for kinetic energy transport as well as turbulence phenomena through the evaluation of turbulent kinetic energy and turbulent dissipation [25]. These are importance parameters for our design, since both the turbulence and kinetic energy have a significant impact when the flow is passing through the defroster plenum.

To perform the aero-acoustic analysis, we used the Curle noise source model. As air flows over a solid surface, a turbulent boundary layer is created. The Curle noise model calculates the noise caused by this turbulent boundary layer. The model represents the dipole sources of noise, which are caused by fluctuating surface pressure between the solid boundary and air flow. It is applicable for low-Mach number flows, specifically, the Curle noise model is valid at Mach numbers less than 0.3 [26]. In our case, the inlet velocity is approximate 2.8m/s, for which the corresponding Mach number is 0.0085; therefore, the Curle noise source model is applicable for our case.

Following the selection of fluid flow are aero-acoustic models, boundary conditions were applied. Table XIV describes all the boundary conditions that were used for the CFD analysis. Justification of the parameters is described below.

TABLE XIV: BOUNDARY CONDITIONS FOR CFD ANALYSIS

Parameters	Values
Inlet velocity	2.8 m/s
Inlet temperature	330 K
Outlet temperature	330 K
Outlet pressure	1 bar
Mesh size	4 mm
Environment pressure	1 bar
Environment temperature	300 K

The average inlet velocity was determined using equation 1.

$$\mathrm{v}_{\mathrm{inlet}} = \frac{\mathrm{Q}}{\mathrm{A}} \qquad \textit{(Eq. 1)}$$

A represents the inlet area to the plenum, which is 0.0508 m^2. The maximum flow rate leaving the heat exchanger is 462 cubic feet per minute; dampers divide this airflow among the driver's area and the windshield. When less flow is desired, the flow rate from the heat exchanger is reduced. Therefore, we assumed an airflow rate of 300 cubic feet per minute entering the defroster plenum. The magnitude of the airflow rate is not critical, as the study is to determine the relative performance of the new design in comparison to the old plenum design; as long as the inlet airflow rate is kept constant for studying both designs, the relative performance can be determined. The calculation of the inlet velocity is included in equation 2.

$$\mathrm{v}_{\mathrm{inlet}} = \frac{0.14\ \mathrm{m}^3/s}{0.0508\ \mathrm{m}^2} = 2.8\ \mathrm{m/s} \qquad \textit{(Eq. 2)}$$

The inlet and outlet temperature are assumed to the same. Since air remains in the plenum for a short period, this assumption is reasonable. The air temperature in the heat exchanger is 65 °C , therefore we assume the average air temperature in the defroster plenum is 57 °C. Similar to the airflow rate, the particular value for the temperature is not critical, as long as the temperature is kept constant for studying both the old and new designs. Since the outlet pressure is exposed to the atmosphere, outlet pressure is assumed to be atmospheric. We used a mesh size of 4 mm; this size is small in comparison to the size of the plenum, which is 2.2 m long, 0.12 m wide and 0.13 m wide. Therefore, using a 4 mm size provides accurate results, while also reducing the time taken to generate the CFD simulation.

Due to the condensed time frame in which the analysis was conducted, the CFD analysis was only a preliminary analysis. It is understood that an extensive CFD analysis, in combination with physical testing, will be performed to verify the results contained in this report.

4.1.2 Computational Fluid Dynamics Analysis and Optimization

To measure improvements in the defrost time, it was necessary to analyze the air velocity and airflow distribution at the location of the louvers. These quantities were compared from the new design in reference to the old design. Furthermore, the noise produced by the old design was compared to the new design, using an aero-acoustic analysis. The aero-acoustic analysis was used to measure the noise produced within the plenum (caused by turbulence), while the noise produced outside the plenum is considered to be positively related to the air velocity (as the higher the air velocity contacting the louvers, the more noise produced). The noise produced due to air contact with the louvers involves a much more complex CFD analysis, which could not be completed given the time constraints on the project. Instead, a nominal increase in noise with an increase in air velocity was added. Following the completion of the analysis, Section 4.1.2.4 summarizes the final design's air velocity distribution and noise level output. Prior to determining this data, the performance of the old design was studied.

4.1.2.1 Performance of Old Plenum Design

Using the parameters discussed in Section 4.1.1, the airflow analysis was conducted on the old design. To identify airflow distribution, a streamline analysis was conducted. Streamlines describe the flow pattern, and were used to identify areas of high mass flow rate (number of streamlines). The color scale indicates the magnitude of the streamline velocity, but since not all streamlines are pictured, the maximum velocity displayed in the streamline image does not correspond to the actual maximum velocity in the plenum. Figure 15 shows the airflow streamlines in the old design. The outlines of the louver locations are indicated as black lines on the figure, to show the airflow pattern in reference to the louvers.

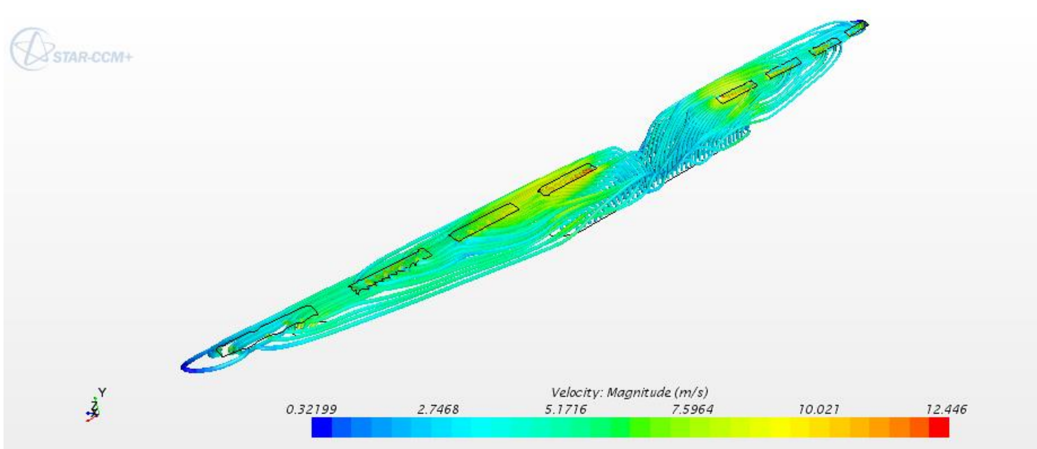


Figure 15: Streamlines of airflow within old defroster plenum design

Key features of the airflow in the old design are the low mass flow rates reaching the outer louvers, as well as the reversed airflow near the outer louvers. Since the louvers do not directly line up with the outer edge of the plenum, flow contacts the edge of the plenum and reverses. This reversed flow may contribute to the low mass flow rate reaching the outer louvers. Figure 16 details the velocity distribution entering the louvers. It is important to note that due to the mesh size, there are discontinuities in the calculation of parameters near sharp edges on the plenum structure. These discontinuities create inaccuracies in the analysis, which can lead to inaccurate predictions of extremely high velocity. Consequently, the velocities located near the edge of the plenum design should not be considered in the analysis.

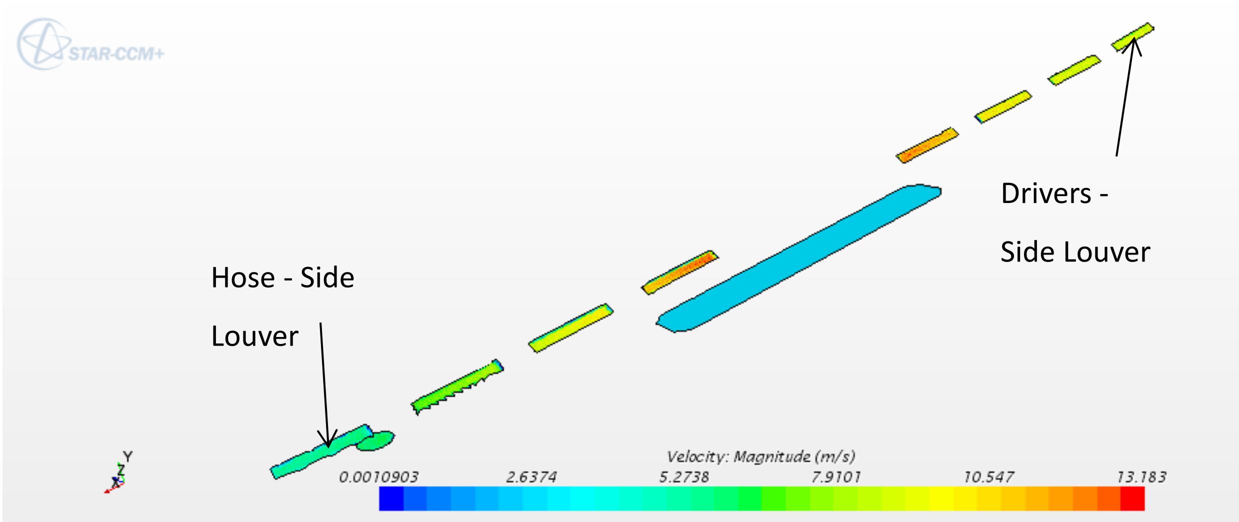


Figure 16: Velocity of airflow entering louvers and plenum for old design

The maximum velocity shown in Figure 16 is caused by discontinuities near the edges of the plenum. The actual bulk flow velocity exiting the louvers directly to the side of the centre ‘V’ is 12.5 m/s. The bulk flow velocity exiting the farthest louver on the hose side was approximately 6.5 m/s. The farthest louver on the driver’s side (without the hose) is approximately 8.5 m/s. During the analysis of the new design, these velocities were compared to those obtained for the new design to determine the relative airflow performance. Following the airflow analysis, an aero-acoustic analysis was performed, to determine the noise produced by the old design.

The aero-acoustic analysis determined the noise produced due to turbulence in the plenum; the noise produced due to air contact with the louvers was not considered in this section of the analysis. Figure 17 details the decibel levels produced by the old design.

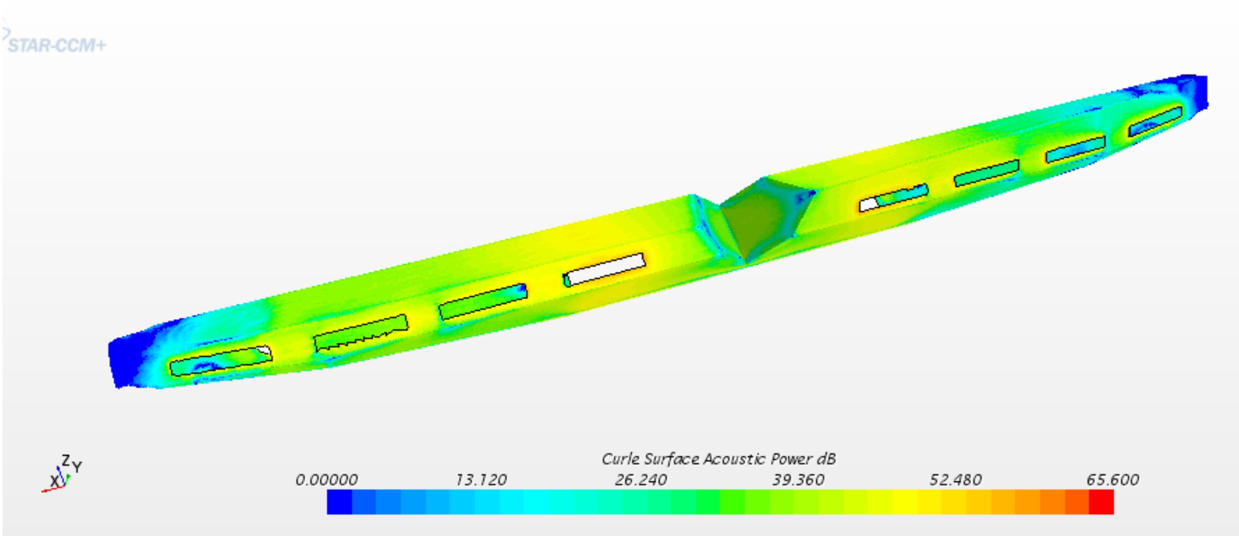


Figure 17: Aero-acoustic analysis for old design

Since the peak aero-acoustic values were near the plenum edges, the values at sharp corners could not be discounted. Therefore, the image was adjusted to remove extremely high outlying values. The peak noise level that remained following this adjustment was 65.6 dB. To better illustrate the acoustic distribution in the entire plenum, a bottom-view image of the acoustic distribution was created. Figure 18 shows the bottom views of the aero-acoustic analysis for the old design.

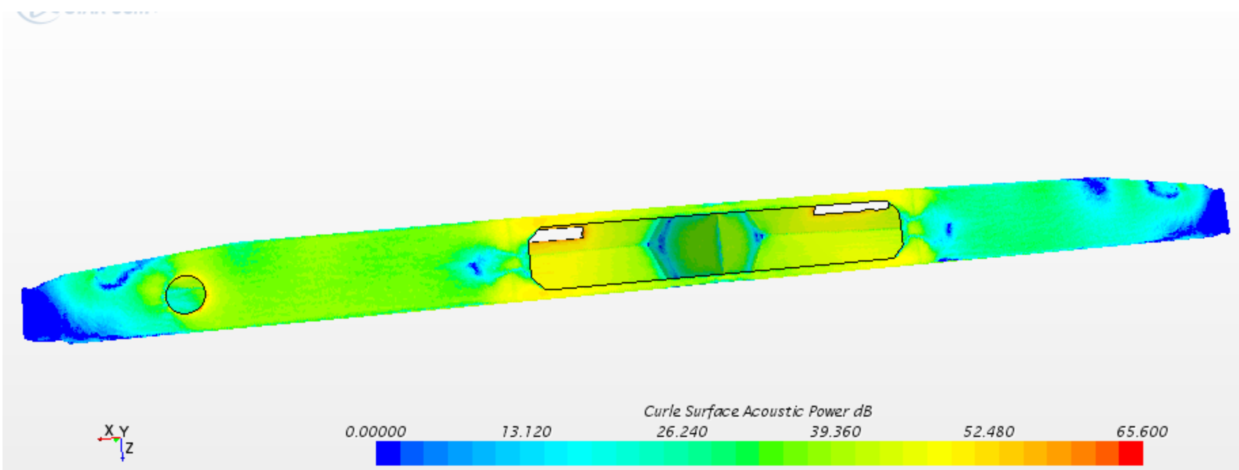


Figure 18: Bottom view of aero-acoustic analysis for old design

The noise levels in the plenum peak near the central louvers then reduced significantly toward the plenum edges. The distribution of noise produced due to turbulence in the old design is compared to the new design to determine the relative noise levels of the new design.

The noise produced due to air contact with the louvers is relative to both the exit velocity range and maximum exit velocity. The peak noise due to contact with the louvers is scaled by the peak velocity while the overall noise level is scaled by the nose distribution.

A summary of the performance parameters, detailing the velocity and noise characteristics, is contained in TABLE XV.

TABLE XV: SUMMARY OF PERFORMANCE OF OLD PLENUM DESIGN

Velocity Range	Velocity of Hose-Side Louver	Velocity of Driver's-Side Louver	Peak Velocity	Peak Noise Level (due to Turbulence)
6 m/s	6.5 m/s	8.5 m/s	12.5 m/s	65.6 dB

The noise distribution, shown in Figure 18, is also considered during the performance comparison of the old design and new design.

The features of the new design are summarized in Section 4.1.2.2.

4.1.2.2 Summary of Features in New Plenum Design

There were four changes that were recommended to improve the plenum performance, following the screening and scoring of physical design concepts in Section 2.2.3. Each of these changes was implemented in the new plenum design. These changes were:

- Flatten out the centre 'V' section

- Curve the centre 'V' section
- Curve the deflection panels
- Curve the bottom panels

Curving plenum sections should promote laminar flow in the plenum, which will reduce the noise produced by the plenum. Flattening out the centre 'V' section should increase the horizontal component of airflow, increasing the heat transfer between the air and the windshield at a distance from the heat exchanger.

Using these four changes, two designs were created to improve airflow in two different manners. Design 'A' was created with the goal of improving the maximum velocity; this change will decrease defrost time significantly in a localized area. Design 'B' was created with the objective of decreasing the range of exit velocities across the plenum, for a better distribution of air across the windshield; this change led to moderate reductions in total defrost time.

Design 'A' used curves in the centre 'V' section, bottom panels, and deflection panels to promote laminar flow. The centre 'V' section was flattened out and edges of the centre section were extended to the first set of louvers on either side of the centre 'V,' such that flow from the heat exchanger could flow directly out the first set of louvers.

Design 'B' also used curves in the centre 'V' section, bottom panels, and deflection panels to promote laminar flow. The centre 'V' section was also flattened out; however, the edges of the central section were placed far inwards from the first set of louvers. The centre 'V' was curved such that the air from the heat exchanger was directed horizontally along the length of the plenum, instead of towards the first set of louvers. The plenum area on the hose side was also decreased in order to reduce backflow; backflow was shown in Section 4.1.2.1 as a possible reason that the velocity at the farthest hose-side louver was reduced.

A performance analysis was conducted on both designs to see if the changes to the designs created the expected results.

4.1.2.3 Performance Analysis of Design 'A'

Figure 19 contains the streamlines for the revised design, in order to compare the flow distribution to the old design.

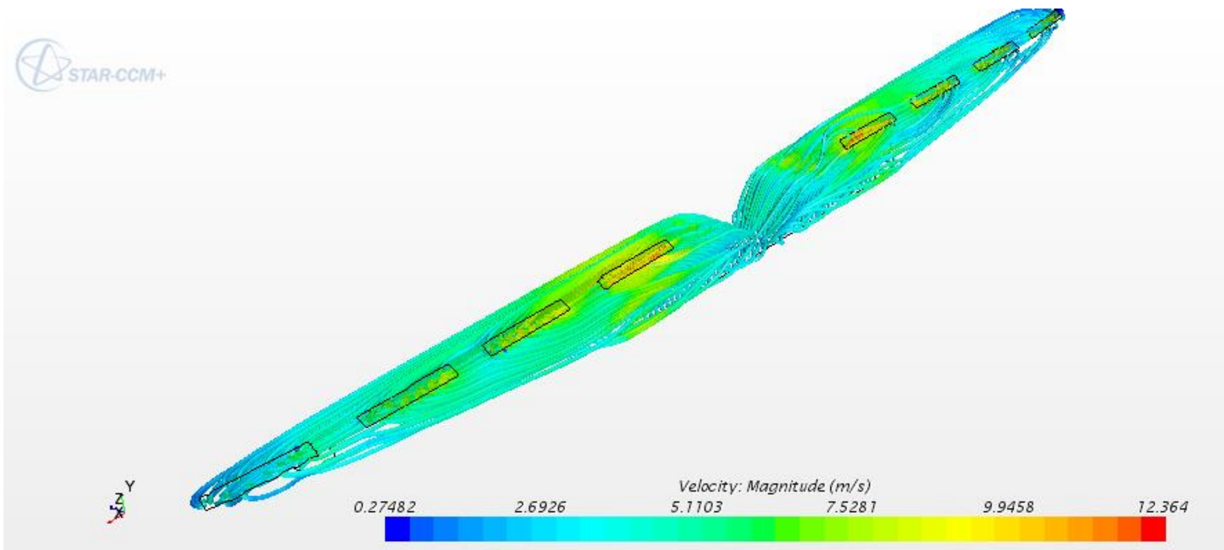


Figure 19: Streamlines of airflow within design 'A'

Design 'A' has a higher mass flow rate in the central region of the plenum, which is shown by the larger number of streamlines passing through the louvers directly to the side of the central 'V.' The low mass flow rate at the outer region and reversed flow still remain; however, the analysis of the velocity distribution allowed for a better understanding of the heat transfer effects caused by the revised airflow distribution (as heat transfer is related to velocity). The velocity distribution is shown in Figure 20.

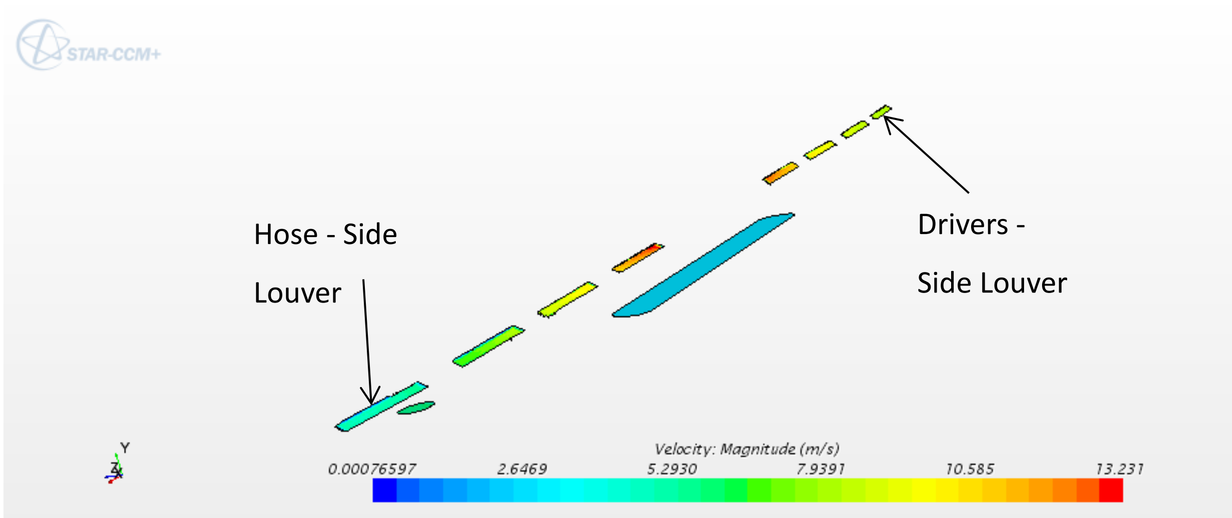


Figure 20: Velocity of airflow entering louvers and plenum for Design 'A'

The high concentration of red in the louvers directly to the side of the center 'V' indicates that the bulk exit velocity is close to the maximum velocity shown in Figure 20. The maximum velocity in the central louvers is taken to be approximately 13.1 m/s. The bulk velocity at the hose-side farthest louver is approximately 6 m/s. The bulk velocity at the louver on the opposite edge is approximately 8 m/s.

The peak velocity at the central louvers was increased 4.8%, while the velocity at the hose side was decreased 7.7%. The velocity at the opposite side was decreased 5.9%. Therefore, Design 'A' will increase the heat transfer to the central windshield region (which is critical to driver's visibility), but will sacrifice heat transfer at the outer edges. Due to the draw of air from the hose, the hose side of the plenum was impacted more severely.

To measure the performance of Design 'A' in terms of the noise produced; a preliminary aero-acoustic analysis was performed. The aero-acoustic analysis determines the noise produced due to turbulence in the plenum; the noise produced due to air contact with the louvers is not considered. Figure 21 details the aero-acoustic analysis for Design 'A.'

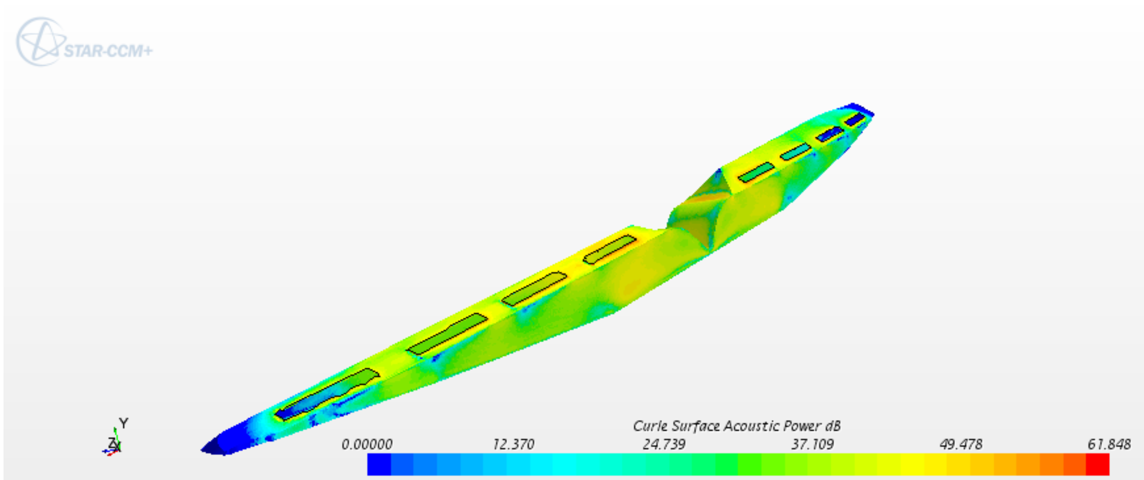


Figure 21: Aero-acoustic analysis of Design 'A'

Since the peak aero-acoustic values were near the plenum edges, the values at sharp corners could not be discounted. Therefore, Figure 21 was adjusted to remove extremely high outlying values. The peak noise level that remained following this adjustment, for Design 'A,' was 61.8 dB. However, not just the peak noise level is important in determining the total noise level produced by the plenum. The noise distribution due to turbulence across the plenum must be considered. To better illustrate the acoustic distribution in the entire plenum, a bottom-view image of the acoustic distribution were created. Figure 22 shows the bottom view of the aero-acoustic analysis for Design 'A.'

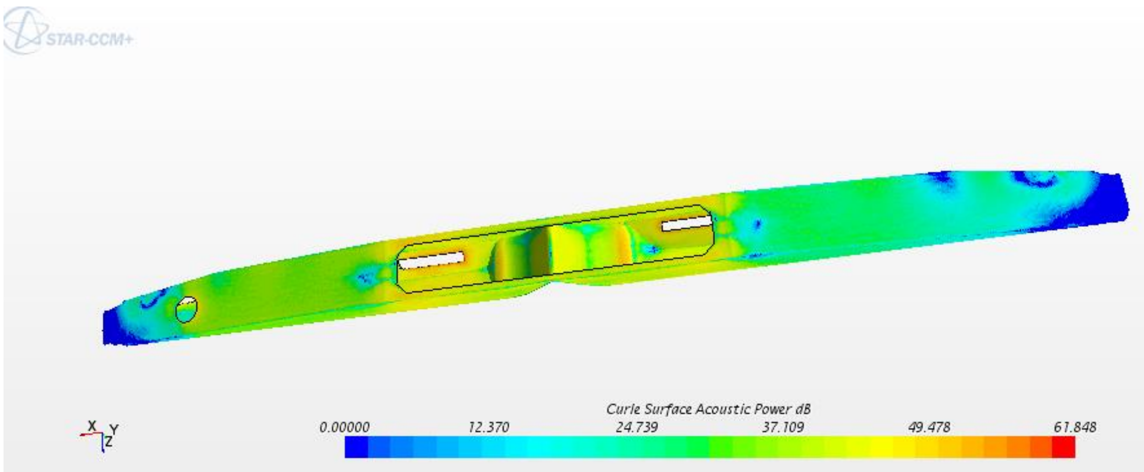


Figure 22: Bottom view of aero-acoustic analysis for Design 'A'

The colour distribution of the aero-acoustic distribution for both Design 'A' and the old design (pictured in Figure 18) is very similar. Since the colour distribution is scaled by the maximum value, the total noise level produced by the revised design is assumed to be the same ratio as the maximum decibel level. Consequently, since there is a 5.8% reduction in the maximum noise, there is assumed to be a 5.8% (3.8 dB) reduction in the overall noise produced by the revised design due to turbulence. The reduction is attributed to the increase in laminar flow within the plenum with the addition of a curved centre 'V.'

Due to the increase in velocity at the central section, the noise produced by contact of the air with the louvers plenum would increase; therefore, the peak noise levels produced by the plenum would increase beyond what is predicted in the aero-acoustic analysis (which only accounts for noise caused by turbulence).

A comparison of Design 'A' with the old design is presented in TABLE XVI.

TABLE XVI: PERFORMANCE OF DESIGN 'A' WITH RESPECT TO OLD DESIGN

Design	Velocity Range	Velocity of Hose-Side Louver	Velocity of Driver's-Side Louver	Peak Velocity	Peak Noise Level (due to Turbulence)	Noise Caused by Louvers
Old	6 m/s	6.5 m/s	8.5 m/s	12.5 m/s	65.6 dB	N/A
Design 'A'	7.1 m/s	6 m/s	8 m/s	13.1 m/s	61.8 dB	Increased

Design 'A' decreased the noise levels due to turbulence (due to the increase in laminar flow) while increasing the noise produced due to air contact with the louvers. Due to these conflicting values, additional analysis on the noise caused by the louvers is needed to determine if the design met the objective of noise reduction. The design increased the peak velocity; therefore, Design 'A' increased heat transfer between the air and the central windshield; however, the heat transfer at the edges of the windshield will decrease, due to lower velocities at the hose-side and drivers side louvers. The performance analysis of Design 'B' is presented in Section 4.1.2.4.

4.1.2.4 Performance Analysis of Design 'B'

Figure 23 contains the streamlines for the revised design, in order to compare the flow distribution to the old design.

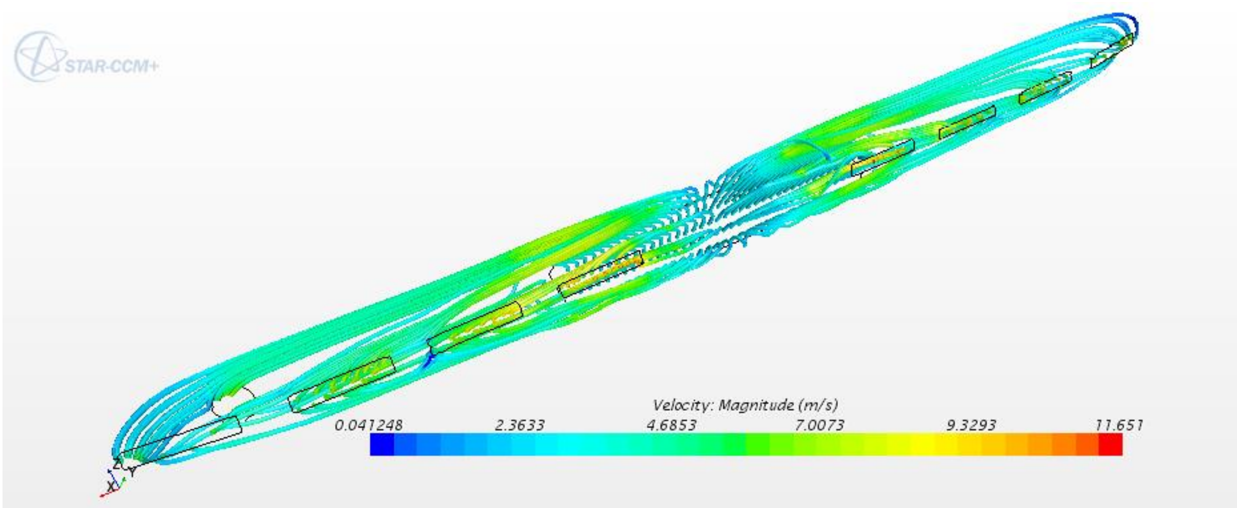


Figure 23: Streamlines of airflow within Design 'B'

The streamlines describing airflow within Design 'B' are shown in Figure 23.
The mass flow rate to the louvers is similar to both the old design and Design 'A;' the major change in airflow (as shown by the streamline analysis) of Design 'B' is the reduction in backflow at the hose-side louvers. The flow progresses directly into the louvers, with little decrease in velocity. The effect on the velocity of the air that reaches the louvers is shown in Figure 24, which describes the velocity distribution.

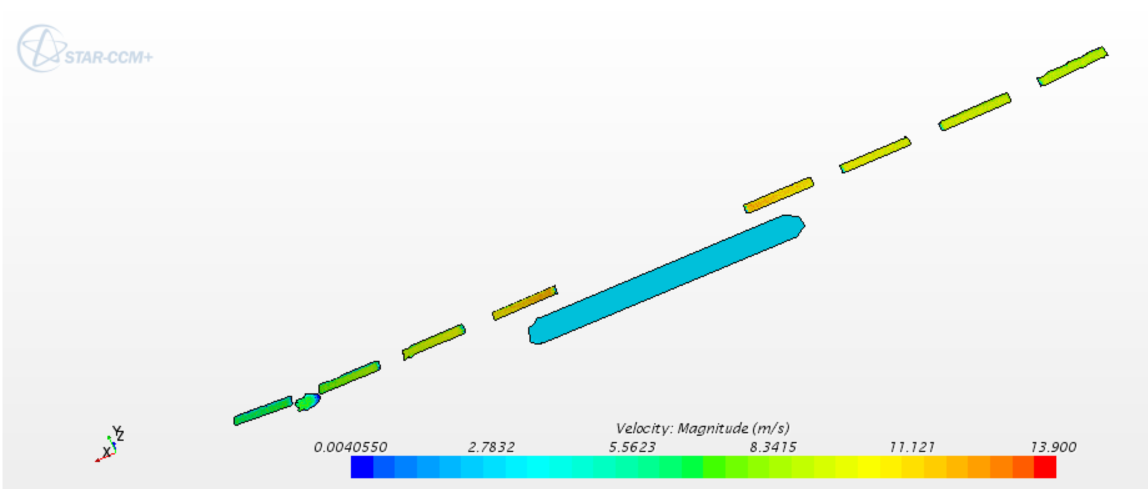


Figure 24: Velocity of airflow entering louvers and plenum for Design 'B'

As with the previous velocity distributions, the peak velocity shown in Figure 24 is caused by discontinuities in the meshing near the plenum edges. Taking this into consideration, the bulk velocity at the central louver is approximately 12 m/s, the bulk velocity at the outer hose-side louver is approximately 7.5 m/s, and the bulk velocity at the far louver on the opposite side is approximately 9 m/s.

In comparison to the old design, the velocity range decreased from 6 m/s to 4.5 m/s. In particular, the velocity at the hose-side louver increased 15.4% while the velocity at the opposite louver increased 5.9%. Since the total mass flow rate must be constant for all designs (as the same amount of air is entering the plenum), increases in air velocity at the far louvers corresponded to a 4% decrease in the air velocity at the central louver.

To assess the noise produced due to turbulence within Design 'B,' an aero-acoustic analysis was performed; the aero-acoustic analysis does not consider the noise produced due to air contact with the louvers. Figure 25 details the aero-acoustic analysis for Design 'B'.

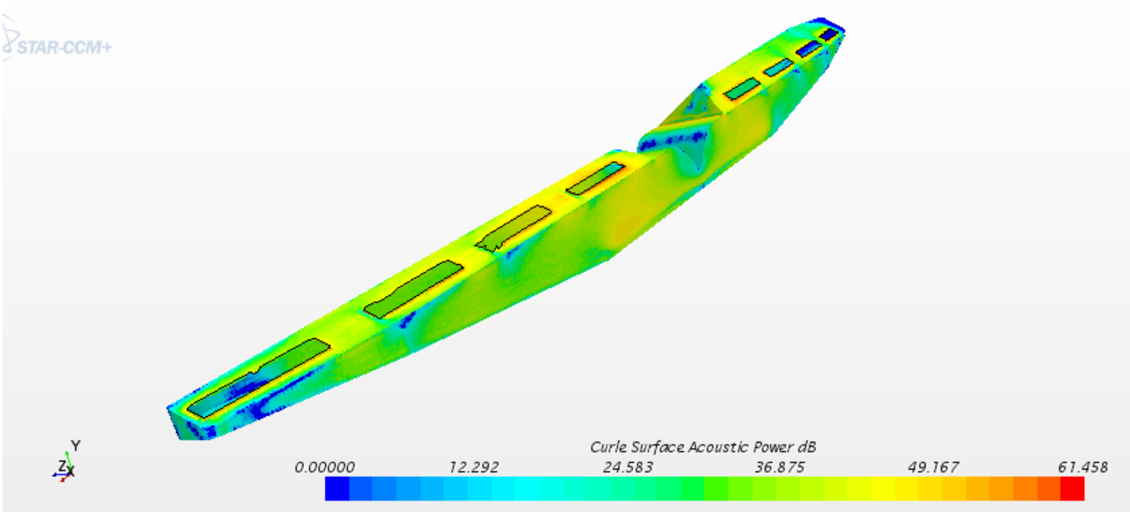


Figure 25: Aero-acoustic analysis for Design 'B'

The aero-acoustic analysis for Design 'B' was modified to characterize the actual noise level, instead of extremely high noise levels caused by errors in the CFD analysis near discontinuities in the plenum. The peak noise level for Design 'B' is 61.5 dB. This is 6.2%

lower than the decibel level produced by the old design. It is assumed that the decrease in peak noise was caused by an increase in laminar flow in the central plenum section.

To characterize the noise level distribution across the plenum, a bottom view of the aero-acoustic analysis is presented in Figure 26.

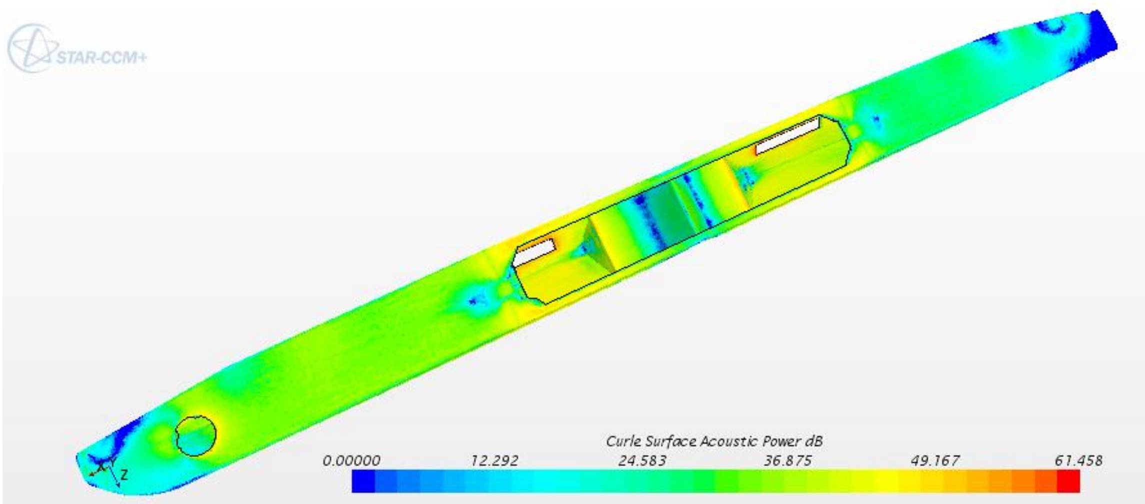


Figure 26: Bottom view of aero-acoustic analysis for Design ‘B’

Noise levels were distributed more evenly across the plenum in Design ‘B’ than the old design (pictured in Figure 18). Assuming that the reduction in the overall noise levels produced by the plenum is the same ratio as the peak decibel levels, the noise produced by the plenum decreased by 6.2% internally.

Since the peak velocity decreased, the peak noise levels produced due to air contact with the louvers decreased as well. Therefore, since both noise due to contact with the louvers and internal noise levels decreased, the total noise produced by the plenum decreased. A summary of the performance of Design ‘B,’ in comparison to the old design, is presented in TABLE XVII.

TABLE XVII: PERFORMANCE OF DESIGN 'B' WITH RESPECT TO OLD DESIGN AND DESIGN 'A'

Design	Velocity Range	Velocity of Hose-Side Louver	Velocity of Driver's-Side Louver	Peak Velocity	Peak Noise Level (due to Turbulence)	Noise Caused by Louvers
Old	6 m/s	6.5 m/s	8.5 m/s	12.5 m/s	65.6 dB	N/A
Design 'A'	7.1 m/s	6 m/s	8 m/s	13.1 m/s	61.8 dB	Increased
Design 'B'	4.5 m/s	7.5 m/s	9 m/s	12 m/s	61.5 dB	Decreased

Design 'B' lowered the range of air velocities exiting the plenum. Decreasing the velocity range across the louvers improves overall defrost time by evening out airflow across the windshield. Since the noise level produced by Design 'B' decreased from the old design, Design 'B' met both client objectives.

Design 'B' improved overall defrosting time instead of merely reducing defrost time in the central windshield (as provided by Design 'A'). Coupled with the fact that the noise produced by Design 'B' was lower than Design 'A' (as both the noise due to turbulence and noise caused air contact with louvers was lower), Design 'B' was selected for the final plenum design. The features of Design 'B' are included in Section 3 of the report (Details of Design).

Following the optimization of the physical design, the fabrication process was analyzed.

4.2 Analysis of Fabrication Process

The analysis of the fabrication process began with determining the exact manufacturing process used to produce the new plenum design, followed by a calculation of the costs incurred in producing the design. To ensure accuracy of the results, the analysis was conducted in conjunction with Plasticom Inc. (which is New Flyer's preferred vendor for performing vacuum forming operations). The objective of the analysis of the manufacturing process was to verify that the following client objectives were met:

1) Reduce manufacturing cost
2) Reduce the number of parts that the plenum consists of
3) Have a short payback time
4) Have a low weight assembly

Individual analysis of the production process and material selection describe how the revised plenum performs in relation to these objectives.

4.2.1 Production Process

Plasticom Inc. recommended forming the plenum in either three or four sections. The sections will be bonded together at Plasticom Inc. with Plexus adhesive and shipped to New Flyer in one complete part. When the sections are combined, the exact geometry of the plenum, discussed in Section 4, will be replicated. The three sections in which the plenum will be produced are pictured in Figure 27. Red surfaces are internal surfaces; they are the overlapping surfaces between the three parts that will be used to bond the parts together during post processing.

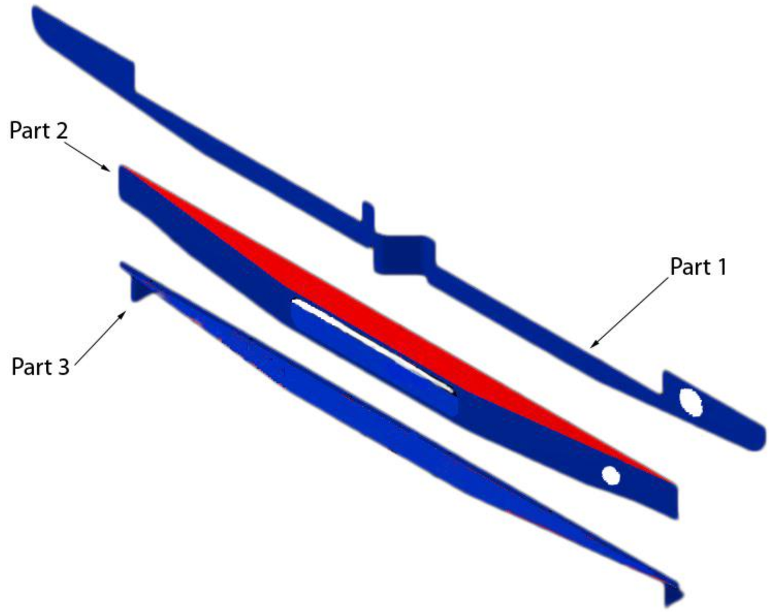


Figure 27: Depiction of pieces bonded together in manufacturing process

Part 1 consists of the centre ‘V’ and the dash closeouts. Part 2 consists of the bottom plenum structure, including the hole which attaches to the heat exchanger, the bottom curved panels, and the hose connection site. Part 3 consists of top plenum structure; namely, the two deflection panels, the top cover, the back lip which will be used to secure the plenum to the frame, and a redundant surface on the back side of the plenum which will be used to secure Part 3 to Part 2. The red surface on Part 2 indicates the area upon which the overlapping surface in Part 3 will be bonded. Part 2 can be secured to Part 1 using overlap on the underside of the deflection panels. To produce the plenum in four sections, Part 1 will be kept the same, but the back lip (used to secure the plenum to the frame) will be shifted to Part 2. This change would allow Part 3 to be divided in half; dividing Part 3 in half means the two deflection panels would be produced separately. Producing the plenum in four pieces allows for easier production, and would reduce the part cost and tooling costs by [redacted] [17].

The cost to produce the plenum in both three and four sections, assuming a [redacted] cost reduction for producing the plenum in four sections, is summarized in TABLE XVIII.

TABLE XVIII: COST OF PRODUCING PLENUM

Number of Sections	Cost per Part (USD)	Tooling Costs (USD)
Three Sections	[redacted]	[redacted]
Four Sections	[redacted]	[redacted]
Current Cost	$268	N/A

The costing assumes a production volume of 1500 – 2200 units; the current production volume is 2000 units/year. Therefore, the price should remain accurate even if there is a slight increase in production volume in coming years. The price incorporates the adjustments that were made to the centre 'V' section, as well as all predrilled holes. The final design, described in Section 4, includes four holes around the hose connection site and six holes on the back lip, which are the locations at which the plenum will be secured to the frame. If deemed necessary in future years, additional holes and contours that may be added to the part will have little increase in the cost per part [17].

The quoted cost does not include any gaskets or seals that are required. Therefore, the rubber section that is added to the deflection panels to take up tolerance will have to still be added at the New Flyer site. New Flyer Industries already adds rubber and foam to the current plenum, consequently performing this processing on site adds no additional cost to our new design.

To produce the individual sections at the lowest possible cost, the sections will need to be tailored to accommodate the forming and trimming operations that are necessary in the vacuum forming process. These changes will be minor, but must be discussed in detail with Plasticom Inc. if the plenum redesign is taken past the prototyping stage. Furthermore, the individual sections must have tabs added, to be used to bond the parts together during post processing. For Plexus to provide a sufficiently strong bond, a minimum of 0.25 inch wide tabs are needed.

Even though the plenum is produced in separate sections, the strength of the connected part should be sufficient, as the Plexus adhesive is rated for use in environments of -55^{o}C to 121^{o}C, if cured at room temperature [24]. Since the air entering the defroster plenum will be approximately 70^{o}C, the Plexus will still maintain a rigid hold on the plenum sections. Using Plexus, the rated shear stress for lap joints is 20 - 24 MPa [24]. The only stresses experienced by the defroster plenum are due to thermal expansion of the part in relation to the bus frame. There is a difference in the coefficient of thermal expansion between the steel bus frame and ABS plenum. Consequently, temperature change will cause the plenum and frame to expand and shrink at different rates, putting stress on the plenum. To account for thermal expansion stresses, the plenum is attached to the frame using pushpin rivets, which are placed in slotted holes. As the plenum and frame shift relative to one another, the rivets will move along the slotted holes. This movement will significantly reduce the stress that will be placed on the plenum. Therefore, the rated stress range for the Plexus adhesive should be acceptable for use in bonding the components of the defroster plenum.

The analysis of the production process demonstrated that the production volume can be met, and the part can be produced at a sufficiently low cost to meet the client's objectives. Furthermore, the tooling (overhead) costs are low enough that the payback period will be well below a year. The payback period was determined by dividing the tooling costs by the savings per coach. The calculation is shown in equation 3.

$$Payback\ Period = \frac{Tooling\ Costs}{Savings/Part} =$$ [redacted] *(Eq. 3)*

Lastly, the plenum will be produced in one section, which improves upon the current design (3 sections). To account for additional strength and weight considerations, the material selection is analyzed in the following section.

4.2.2 Material Selection

The price quoted in TABLE XVIII assumes that the material to produce the part is general purpose acrylonitrile butadiene styrene (ABS) (random colour), and that the plenum is produced using a starting gauge of 0.187 inches. To confirm whether ABS is suitable for the plenum application, an analysis of material properties was performed. Additional properties, which are not related to specific objectives, are listed to ensure that the full set of material characteristics for ABS is understood. TABLE XIX lists the mechanical properties of general purpose ABS, which describe the strength of ABS.

TABLE XIX: MECHANICAL PROPERTIES OF GENERAL PURPOSE ABS [20]

	Minimum	Maximum	Unit
Compressive Strength	60	86	MPa
Density	1060	1080	Kg/m^3
Elongation	5	25	%
Impact Strength	0.56	2.2	J/cm
Shear modulus	700	1050	MPa
Tensile strength	41	60	MPa
Young's modulus	2275	2900	MPa

As can be seen in TABLE XIX, ABS features high impact and flexural strength. Not listed is the fact that ABS has excellent molding characteristics and dimensional stability, which is ideal for the plenum application. Furthermore, since the density of ABS is between 1060 and 1080 kg/m^3, the revised plenum weight is 2.6 kg. This weight is below the old plenum weight of 4.15 kg. Therefore, the client's weight reduction objective was met. TABLE XX lists the thermal properties of general purpose ABS.

TABLE XX: THERMAL PROPERTIES OF GENERAL PURPOSE ABS [8]

	Minimum	Maximum	Units
Glass temperature	105	105	˚C
Service temperature	-20	80	˚C
Specific heat	1260	1675	J/Kg.K
Thermal conductivity	0.17	0.19	W/m.K
Thermal expansion	50	85	e-6/K

The air in the plenum is at approximately 70^{o}C, since the service temperature range of ABS encompasses the required temperature of 70^{o}C, the temperature requirements were met. Not listed is the fact that ABS satisfies material requirements regarding thermal stability and flame retardant characteristics. The required burn rate is under 4 inches/min, which is necessary for the plenum material selection. A detailed description of the burn rate test and requirements is included in Section 1.2.1.1.

The choice to produce the plenum using vacuum forming with general purpose ABS allows all manufacturing-related client objectives to be met. Following the fabrication and material process analysis, the actual installation of the plenum at New Flyer Industries was analyzed.

4.3 Analysis of Installation Process

The analysis of the manufacturing process began with determining the plenum installation process, and progressed to estimating the time taken to complete particular tasks in the total process. To ensure accuracy of the results, the technicians that are responsible for the plenum installation at New Flyer were consulted to determine the exact plenum installation process, and breakdown of time allocation in the process. The objective of the analysis of the manufacturing process was to verify that the following client objectives were met:

1) Reduce installation time
2) Installed by a limited number of technicians
3) Increase number of locations where plenum can be installed

Sections 4.3.1 and 4.3.2 describe how the revised plenum performs in comparison to these objectives, beginning with the pre installation process and followed by the installation.

4.3.1 Pre Installation

Before the plenum can be installed a set of preliminary steps must be followed to ready the part and the area for the installation. These steps detail the pre-installation process. The defroster plenum will be sent to New Flyer Industries in one piece and will contain pre-drilled holes in the outer flange. The part will be inspected by the technician for defects. After the inspection is complete, the area where the plenum is to be installed is prepared. This preparation includes cleaning the surfaces, and running any cables or wires that need to be installed prior to the defroster plenum installation. The next step is to glue foam strips to the bottom of the plenum, where the plenum comes into contact with other parts in the front end of the bus. The foam takes up tolerances between the plenum and bus parts, which dampen vibrations due to part movement when the bus is in operation; this damping effect will decrease noise. The next step in the pre installation process is to glue a rubber lip to the upper edge of the plenum outlet. The rubber lip will stop air from reversing directions and getting behind the plenum deflections panels (into the dash). By stopping this flow, the rubber lip enables all the air coming from the plenum to be forced and directed to the windshield, which will help to minimize unwanted pressure loss.

Once each of the steps described above have been completed, the defroster plenum is ready to be installed. There are virtually no differences in the pre installation process between the old and revised plenum design, and as such, the pre installation process will not have any significant effects on meeting the client's objectives. The installation process is described in Section 4.3.2.

4.3.2 Installation

The defroster plenum can be installed by one technician. The first step is for the technician to place the plenum into its location within the front bus frame. Once the plenum is in position, the technician should inspect to ensure fitment. Proper fitment includes a firm seat into the frame, no pinching of wires or cables, and no interference with adjacent parts. The next step is to drill holes in the frame, where the pre-drilled holes are located in the defroster plenum. There are six holes to be drilled in the frame. After ensuring that all drilled holes have proper alignment, double sided tape is to be placed on the bottom of the two front lips (on the former design they were referred to as the dash closeouts) of the plenum. Once all the holes have been drilled and the tape has been bonded to the bottom of the front lips, the plenum can be installed. First, the cover on the double sided tape is removed and the plenum is put in position. Then, pushpins are put in place over the drilled hole in the frame and pushed in using the technician's thumb. At this stage in the installation process, the defroster plenum is in position secured. The next step is to position the auxiliary heating hose on the bottom right hand side of the plenum. Using screws, the hose will be secured to the plenum. The screw locations are dictated by the predrilled holes in the plenum design. With these steps complete, the installation has been completed.

The revised plenum will still be installed by one technician, which meets the client's installation objective. Time will be saved during the installation process through the following four changes in the installation:

- The plenum is in one piece
- There are predrilled holes which dictate the locations at which holes need to be drilled into the bus frame; no measurement of these holes is needed
- Pushpin rivets are used to secure the plenum to the frame; these have faster installation than screws
- There are predrilled holes at the hose connection site, so no holes need to be drilled into the plenum

Multiple of the installation technicians were consulted at New Flyer to determine the time that was saved by each of these changes. The consensus was that our new design would save them approximately 10 to 15 minutes. It should be noted however, to determine the specific time saved, a prototype would need to be constructed.

The plenum can be installed at one location on the assembly line. As discussed in Section 2.3.4, the objectives of having the plenum in one piece, while being able to install the plenum at multiple locations have a strong negative correlation. Lowering the number of plenum components will severely limit the points in the assembly process at which the plenum can be installed. Therefore, the plenum will maintain a single installation site on the assembly line.

4.4 Meeting the objectives

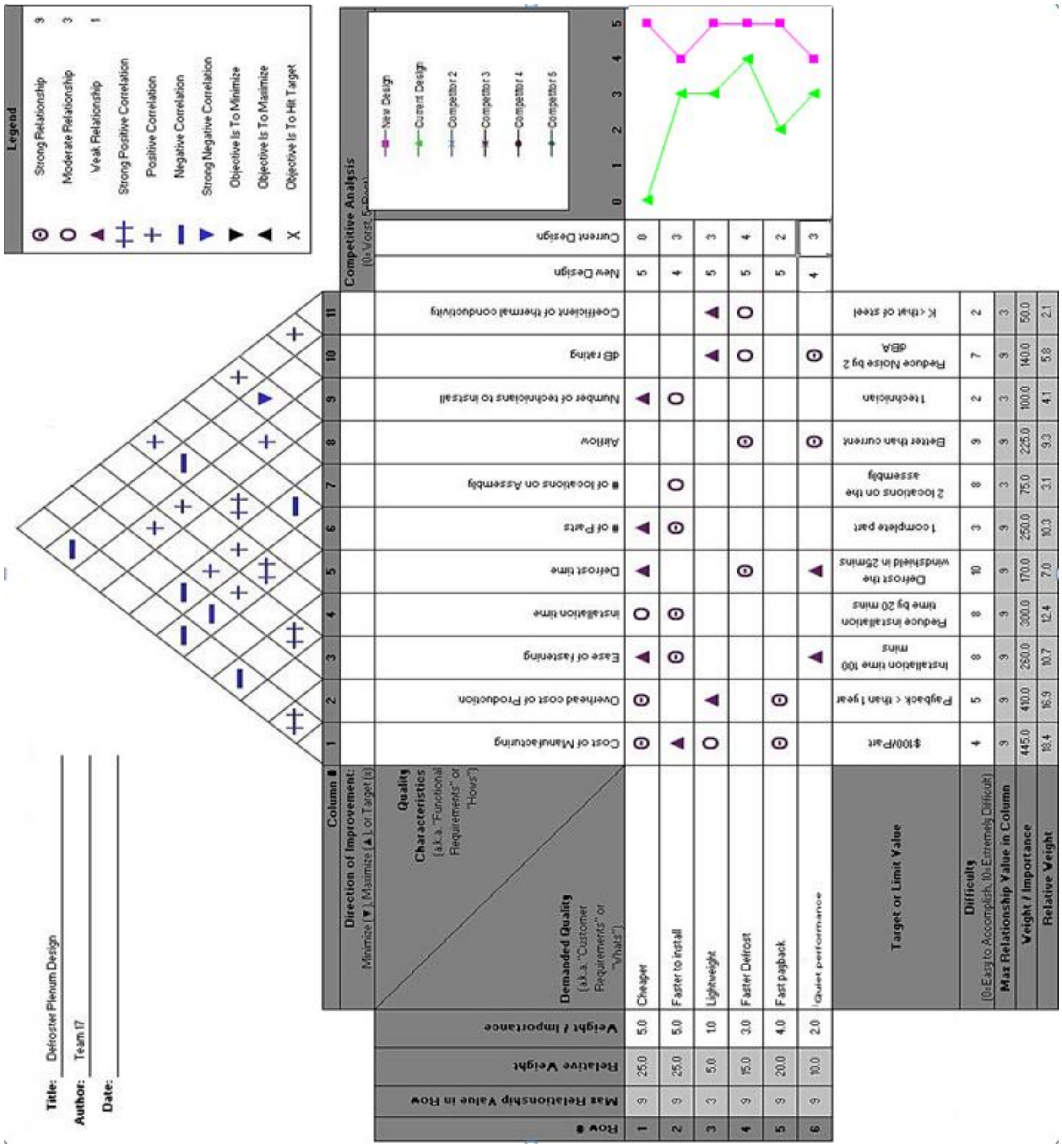
After conducting detailed analysis on our new design in Section 4 above, we can show that our design is a viable option for replacing the old defroster plenum that New Flyer Industries currently uses in their Xcelsior coach. To help demonstrate that our design can meet the objectives, Section 4.4.1 displays a house of quality which serves as a visual representation of how the client's needs are being met. Section 4.4.2 follows with explanation on how the key features of our new design actually served to meet the specifications.

4.4.1 House of Quality

We used a house of quality (HOQ) as a visual aid to help us graphically see that our design will outperform the current defroster plenum and meet the project objectives.

On the left hand side of the HOQ we have client needs along with the weighted importance of those needs. Each need is related to a series of quantifiable metrics; the strength of the relationship is shown symbolically. On the bottom are the target values for each metric, including a rating of how difficult the target specification was to achieve. The top triangle describes how the metrics are related to one another. There are negative relationships and positive relationships between the metrics. A positive relationship means that if one metric is improved, the other will be improved as well. If there is a negative relationship it means that if one metric is improved the other will worsen. On the right side of the HOQ, we ranked our new design compared to the current plenum. The house of quality is contained in TABLE XXI.

TABLE XXI: HOUSE OF QUALITY



As can be seen on the right side of the house of quality, there are no aspects in which the current plenum outperformed the new design. Our design meets all the objectives set out by New Flyer Industries. Section 4.4.2 describes how our design features enabled us to create a part that could meet or surpass all target specifications.

4.4.2 Summary of Final Design Specifications

The defroster plenum we designed will be one piece and made of ABS plastic. Our new design will decrease in weight by 1.55 kg under that of the current model. There will also be a significant cost savings in the manufacturing process as well as in material selection. Vacuum forming ABS plastic is very inexpensive in comparison to the current galvanized steel process of bending cutting and welding. As compared to the current defroster plenum, there will be savings of [redacted] per part. This corresponds to a payback on the manufacturing tooling cost after only [redacted] coaches built. This means that since New Flyer Industries on average is producing 2000 coaches per year, there will be net savings from that point forward on every bus produced after the [redacted] coach.

Our design will be faster to install then the current model by approximately 10 to 15 minutes. This reduced installation time will be accomplished due to some key features integrated into the design. The defroster plenum has pre drilled holes in the outer lip. These pre drilled holes remove the need for the technician to measure each hole and drill which is how the current plenum is installed. Once the holes are drilled into the frame, the technician needs only to quickly insert pushpin rivets into the holes. This will also save time as compared to screwing in each screw. Another feature is that that the defroster plenum will come in one piece. Having a bigger part means that it will only be installable at the one location along the process line. It does however, allow for faster installation since the technician only has one part to install instead of three.

The ABS plastic displays much lower thermal conductivity then the galvanized steel it is replacing. This will improve the windshield defrost as well since less heat is being lost through the walls of the air chamber. The increased velocity profile along the inside chamber of the part will cause the main improvement of defrost performance. This is due to the fact that when velocity is increased, the convective coefficient for the air passing over the window is increased as well. This leads to improved heat transfer from the air to the windshield, which will lead to faster melting of the ice and evaporation of the fog. From the velocity data and some basic knowledge of heat transfer, we believe that the windshield would be defrosted in less than 30 minutes if our new design was used in the defrost test. Through preliminary aero-acoustic modelling we can show that there is a localized decrease in noise near the outlet louvers on the dash in our design. This represents the sound due to airflow inside the air chamber of the defroster plenum. The aero-acoustic analysis does not take into considerations the noise produced by the airflow through the louvers. Our design does not increase the maximum velocity but rather increases locations of low velocity by 15.4%. This means that maximum noise levels should not increase, since maximum decibel levels are due to maximum velocity.

TABLE XXII below shows our new defroster plenum as compared to the current model, as well as compared to our target specifications. We can clearly see that our new defroster plenum will outperform the current model and our targets in almost all aspects. At minimum we have maintained the same quality as the current model such as number of locations where plenum can be installed and number of technicians required for installation. There are certain cases where we do not have sufficient data to confirm the specifications of the new design, but are confident that they will surpass the current model such as defrost time and noise levels. Our design has met the target for number of parts in the plenum, weight of the assembly, and installation time. The best improvement that we were able to accomplish with our design is related to the overall costing of the part. The cost of our part is well below the target. Also the payback is well below the allowable 2000 buses, which means that every bus manufactured after the [redacted] bus will be profit for New Flyer Industries in the way of savings. Overall our design has met all specifications and will be a suitable design to replace the current defroster plenum.

TABLE XXII: SUMMARY OF NEW DESIGN AS COMPARED TO OLD DESIGN AND TARGET SPECIFICATIONS

Imp	Metric	Units	Current	Target	New
5	Manufacturing cost	[Dollars/unit]	268	168	[redacted]
5	Installation time	[minutes]	120	100	<120
4	Number of parts in the plenum	[Parts]	3	1	1
4	Have a short payback time for new equipment purchased	[# of Coaches]	N/A	<2000	[redacted]
3	Defrost time	[minutes]	30	25	<30
2	Noise	[dBA]	65.6	63.6	61.5
5	Installed by a limited number of technicians	[technicians]	1	1	1
2	Number of locations where plenum can be installed in assembly line	[locations]	1	2	1
1	Low weight plenum assembly	[kg]	4.15	<4.15	2.6

5 Conclusion

At the beginning of the fall 2014 semester, our team was tasked with redesigning and optimizing the front windshield defroster plenum for New Flyer Industries' Xcelsior coach. The original design had some issues that needed to be addressed that we categorized broadly as manufacturing and material considerations, installation efficiency, and performance. The first phase of this design project was project definition. The project definition phase was when we first met with our client, toured the New Flyer facilities and researched our project. Time was taken to fully understand the project and make sure all team members understood what our design would have to encapsulate. The second phase of the project was the conceptual design phase. Through in depth research, meetings with our client and brainstorming, we were able to generate many concepts. Concept screening and scoring narrowed our focus to the most feasible of the concepts we had created. During the final phase of the project we finalized our design, and produced a design that we recommend to be moved forward for prototyping and testing at New Flyer Industries.

Team 17 recommends that our design of the front windshield defroster plenum should be moved forward for prototyping. The intention is for the part to be produced and integrated into the New Flyer assembly operation. There is potential in our design to save New Flyer Industries a significant amount of money, reduce the time required for installation as well as improve defrost time on the windshield.

Our defroster plenum design will be created from ABS plastic using vacuum forming. This Design yields significant savings in both the process and the material. The cost to produce one unit will be [redacted]. This unit cost correlates to savings of [redacted] per plenum, and a payback on tooling and molds within [redacted] coaches built. Considering that around 2000 coaches are produced per year, the low part cost will yield large savings for New Flyer industries.

Our new defroster plenum will be one complete part, combining the plenum itself and the dash closeouts. The plenum can only be installed in the one location on the assembly line. Our design will have a total weight of 2.6 kg. There are pre-drilled holes on the lip of the plenum that rests on the frame, as well as where the auxiliary heating hose connects. The defroster plenum will be fastened using pushpin rivets, and the heating hose will be fastened with screws. Having the plenum in one piece will make installation faster since only one part is installed instead of three. The pre-drilled holes removes all time spent measuring where to drill, and the pushpin rivets reduce the amount of time needed for securing all the screws. Overall, the installation time should be decreased by approximately 10 to 15 minutes.

Through smoothing of sharp surfaces and rounding and curving of the centre V, section we were able to improve the aerodynamic characteristics of the air moving through the plenum. The minimum velocity to the louvers was improved by 15.4% while the range of exit velocities was reduced from 6 m/s to 4.5 m/s. The improved velocity distribution was achieved by reducing the amount of areas within the plenum that were causing turbulence, allowing for smooth continuous streamlines. Another aspect that will improve heating performance will be that ABS plastic has a thermal conductivity of 0.18 $W/m \cdot K$, which is significantly lower than galvanized steel. This means that less heat will be lost through the walls of the plenum, allowing more heat will reach the windshield for defrosting. The improved aerodynamics as well as the improved thermal conductivity should enable the defrost system to defrost the windshield in less than 30 minutes. It should be noted as well, that the improved velocity uniformity reduced localized maximum noise levels which should lead to an overall reduction in noise levels. Figure 28 is a rendering of our final design, which stands as a general overview of the physical design to be moved forward for prototyping and testing.

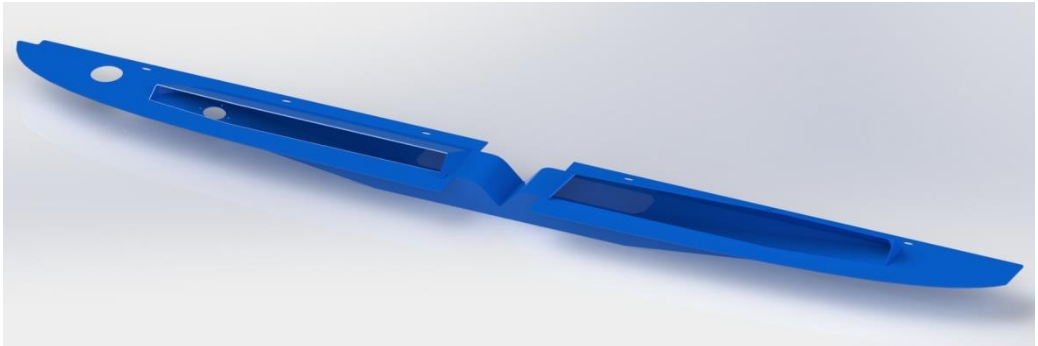


Figure 28: Final plenum design

With a working prototype, testing can be done to develop quantifiable data regarding exactly how much time can be saved during installation, and how much time can be reduced for defrosting. At this stage in terms of physical and dimensional data, preliminary CAD models have been produced as well as engineering drawings. For performance optimization, preliminary CFD and aero-acoustic analysis have been performed. From this point forward a prototype is recommended as it will allow for a comparison of the experimental data collected during the testing, with our computational results. A source for possible issues is our preliminary CFD analysis. Without verifying the defrost time in a physical test, it is uncertain whether our design will actually improve the defrost performance, based solely on CFD results displaying improved velocity. If after testing the prototype, it is found that the new design does not outperform the current model, it would be our recommendation to revert back to the current physical design to at least maintain the same level of performance. This would ensure that our engineering due diligence has been done to the best of our abilities.

It is also recommended that a detailed cost analysis be done at New Flyer Industries from the economics department. This should include taking time value of money into consideration. We have chosen the manufacturing process that is the most economically viable based on a simple payback from subsequent defroster plenum savings. We have limited resources for completing an economic analysis, such as required rate of return, NPV and typical interest rate used in calculations. This should be done to ensure that the best manufacturing process has been chosen from an economic standpoint.

The manufacturer has recommended the use of a Plexus adhesive for use in bonding the separate parts of the plenum during the manufacturing process. We discovered that this adhesive, in the past has been a source of problems for New Flyer Industries. In light of these concerns voiced by our client, we suggest the manufacturer should look into other means of bonding the plenum assembly together such as screws or rivets. From our research however, for the expected temperature range and stress on the part, the adhesive should be able to meet our design needs.

Our design has reached or surpassed the important target specifications and at the very least maintained similar quality to the current model. Our defroster plenum has met or surpassed the following specifications: cost, number of parts, payback period, installation time and weight. Our design will be able to improve defrost time and noise levels but we are unable to produce specific data on the degree to which they will be improved without further testing and verification with a prototype. We will maintain the same quality as the current model in terms of the number of locations at which the plenum can be installed as well as the number of technicians required for installation. Based on our analysis our defroster plenum should reduce unnecessary waste in part cost, improve assembly line efficiency with the reduction in installation time, as well as improve part performance with our physical design. Overall, our design is a viable option for New Flyer Industries to develop for prototyping and eventual implementation.

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Appendix

Appendix A: Engineering Drawings

Figure 36 through to Figure 40 shows the engineering drawings of our final design. Important to note is that unlike the original design, the part will be all one piece. Our design will fit snuggly into the space where the current plenum was positioned. The average thickness for the plenum is 0.1 inches.

From these dimensions we have ensured proper fitment within the bus frame and other bus components in the front of the bus.

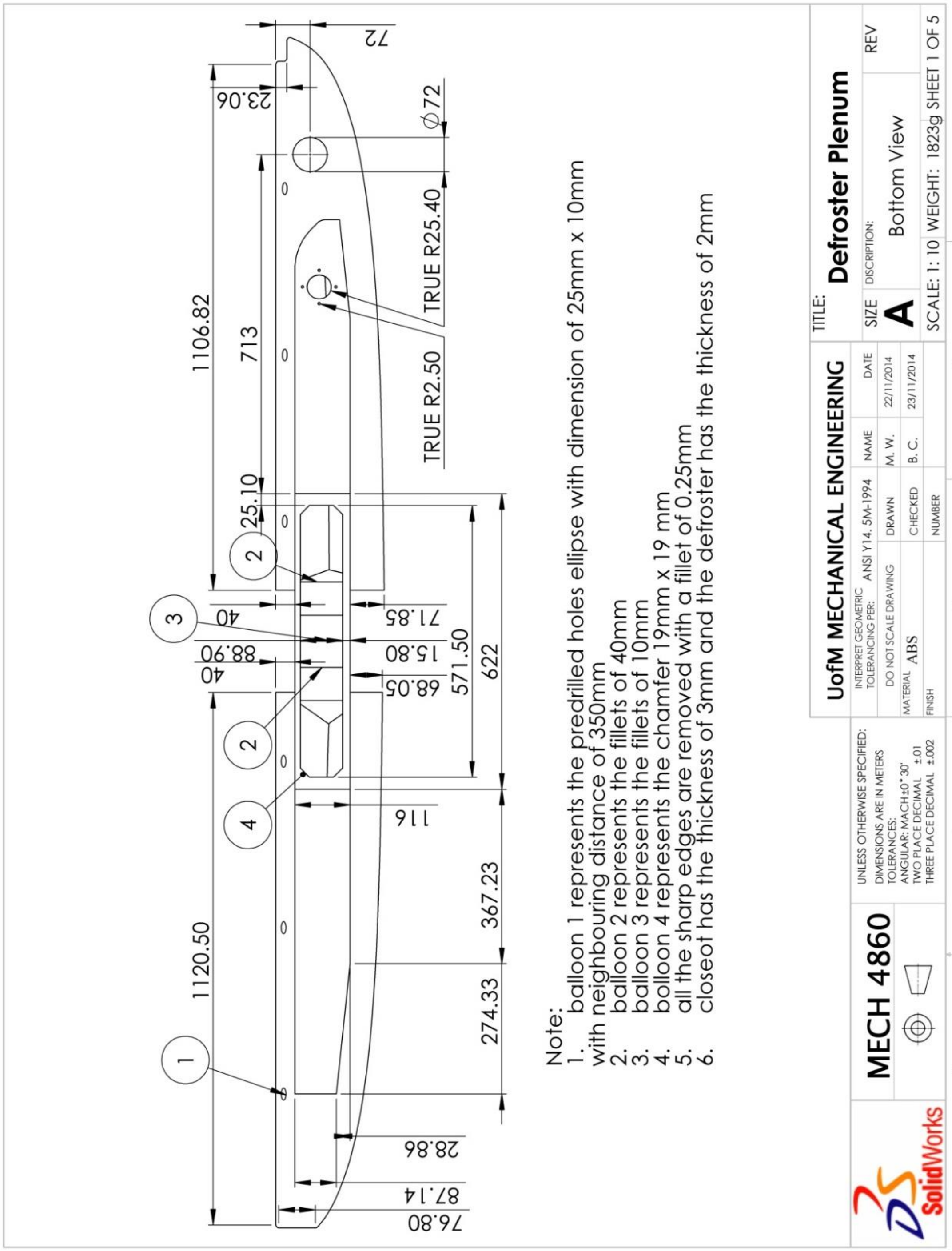

Figure 1: Engineering drawing of the final design from the bottom view

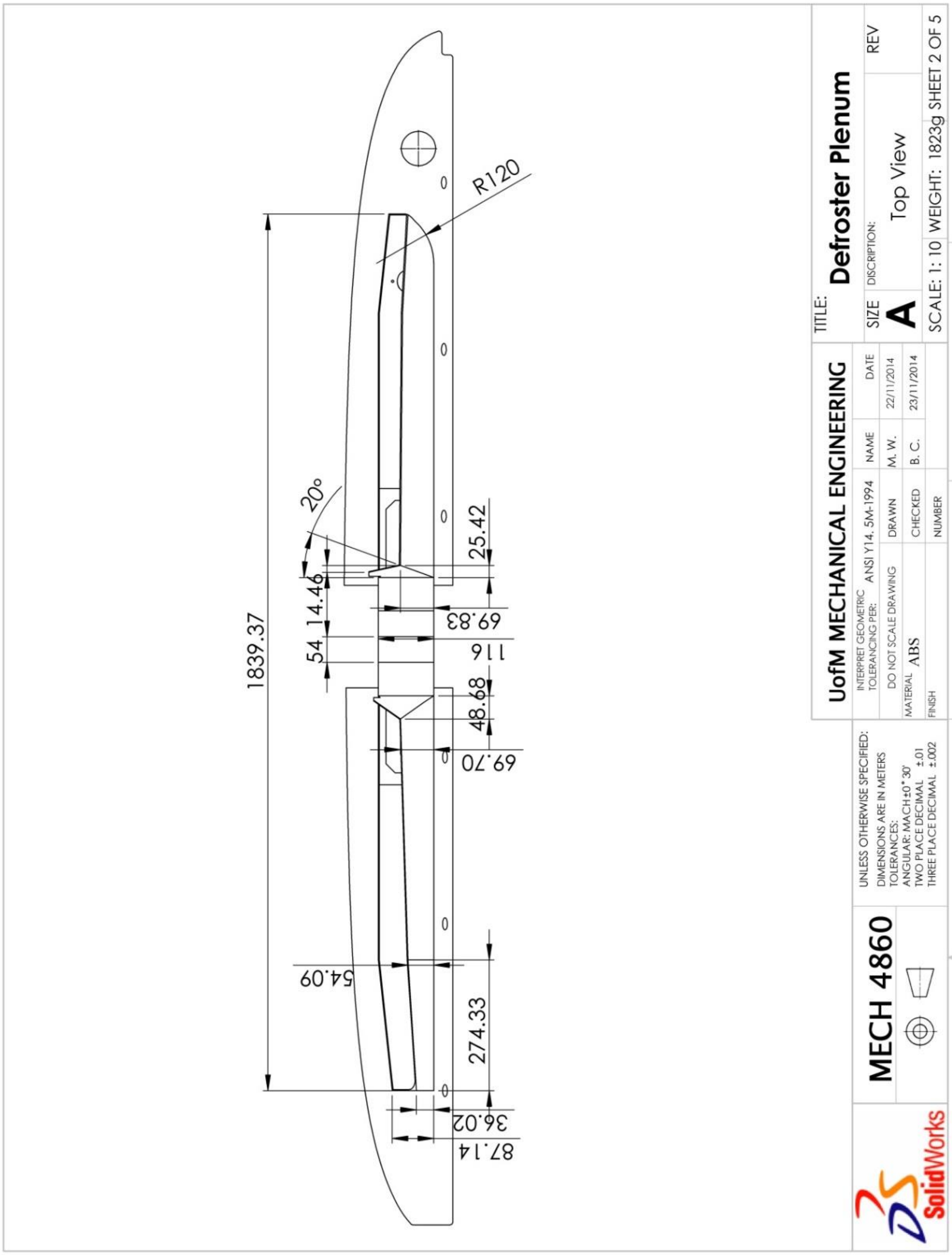

Figure 2: Engineering drawing of the final design from the top view

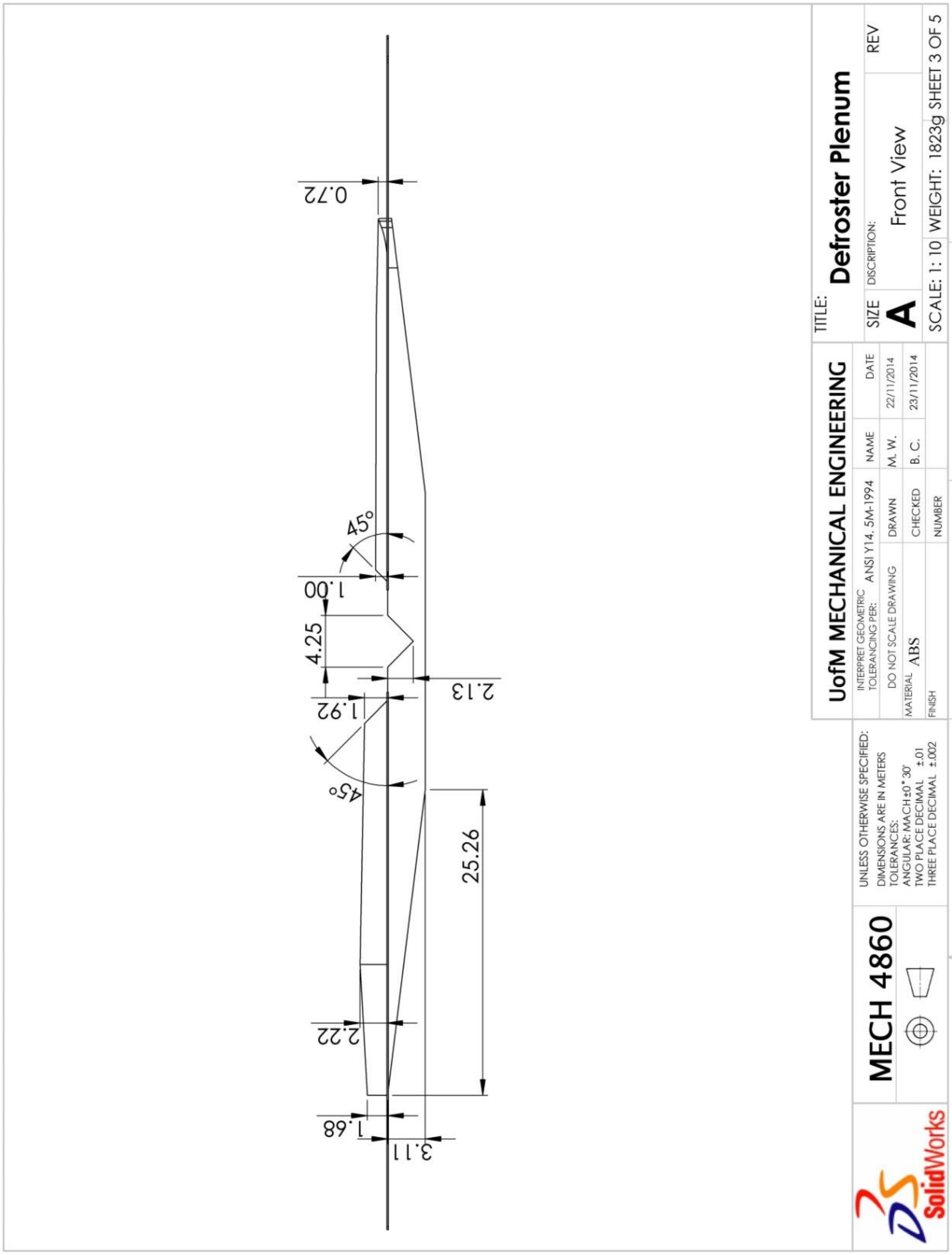

Figure 3: Engineering drawing of the final design from the front view

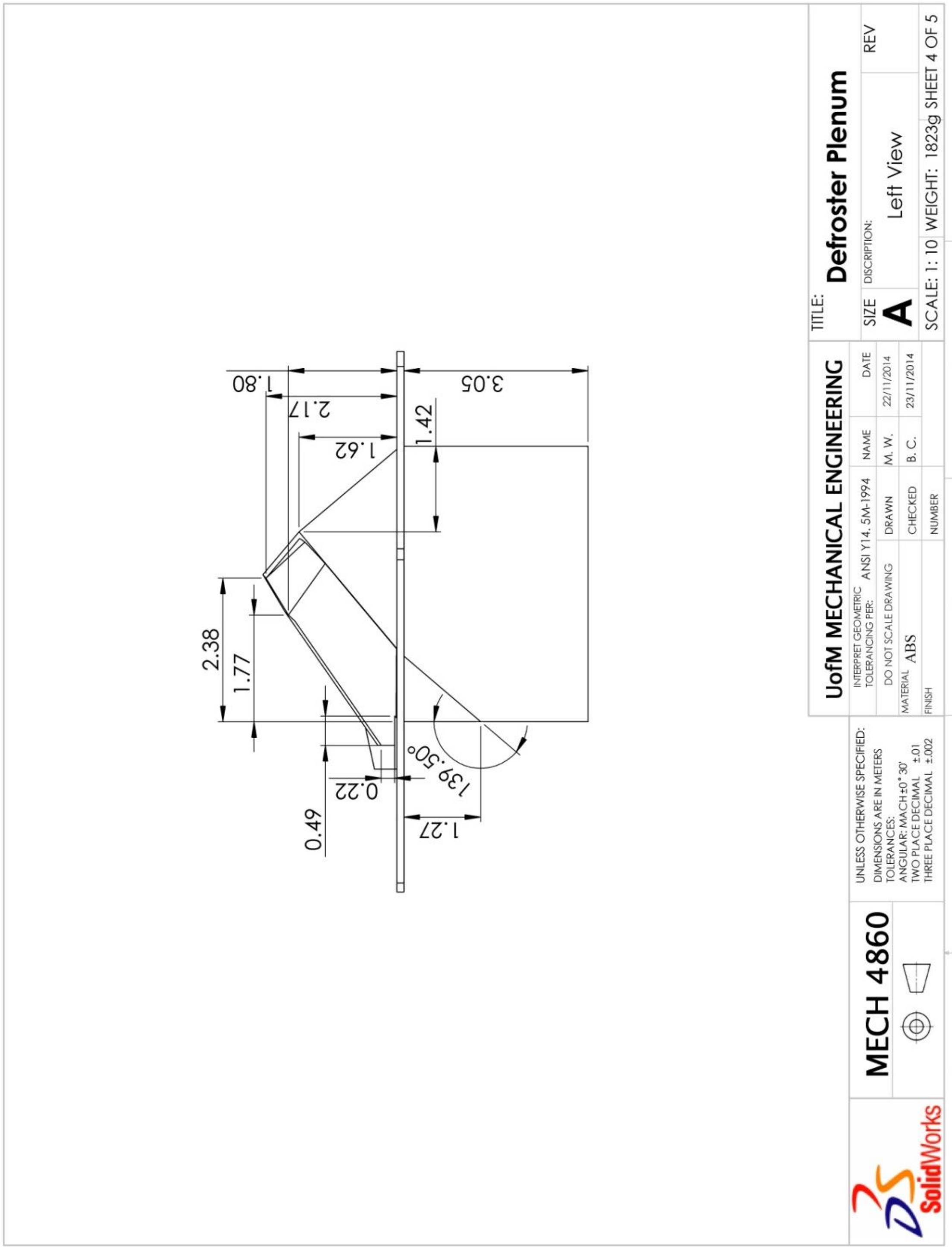

Figure 4: Engineering drawing of the final design from the left view

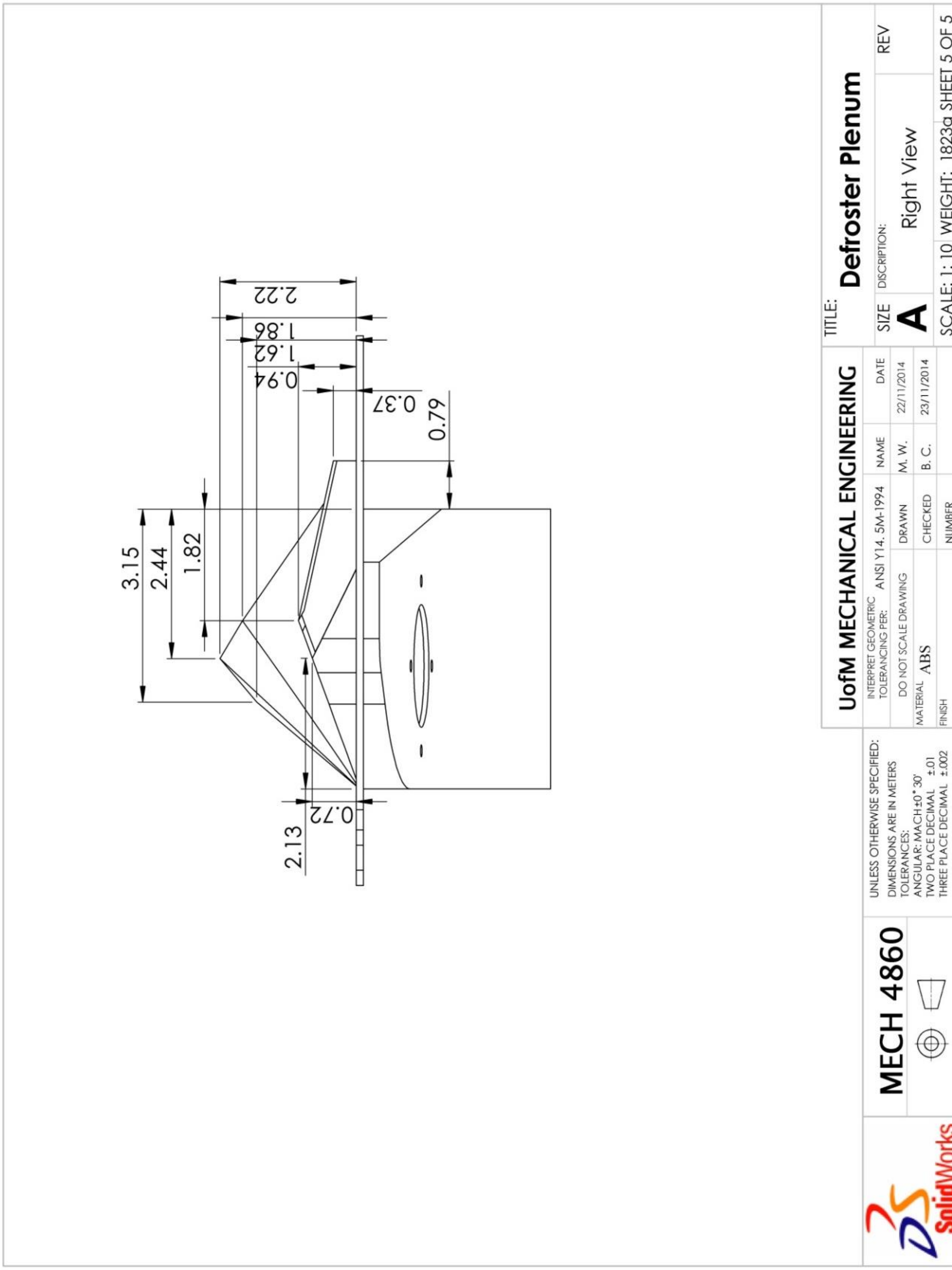

Figure 5: Engineering drawing of the final design from the right view

Appendix B: Concept Generation

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1 Competitor and Patent Review

The competitor and patent review was performed to identify the wide range of concepts that are currently available, as well as to ensure there was no patent infringement.

1.1 Patent Review

When researching existing patents, we found that there are not many patents related specifically to windshield defrosting systems for buses. Many of the patents that were found correspond to regular vehicle defrost systems. Two of the patents that our team read during the research phase are shown below. They are both quite dissimilar from the defroster plenum we will be designing; however, it was helpful for expanding our own ideas, while also seeing what else is being done in terms of defroster plenum designs in the automotive industry.

Figure 1 is a patent designed by the Mazda Motor Corporation. Mazda's ventilation system does not contain a physical plenum in the defrost system. The system for directing the hot air to the windshield uses duct tubes, connected to the center blower fan. The two parts labelled with the number 10 correspond to the windshield defrost system. As can be seen in Figure 1, this design is a complicated part with multiple pieces and various tubes.

[redacted]

Figure **Error! Bookmark not defined.**: Ventilation system for Mazda motor company [1]

The main problem with designing a similar system to the Mazda Motor Company is that there are much stricter space constraints in the Xcelsior coach; therefore, all the excess tubing would not fit. Figure 2 shows a patent for a ventilation system on a school bus. It can be seen that there are six locations where air is directed at the windshield and side windows for the purposes of defrosting. The school bus design is another case where the configuration of the vehicle is so different from the Xcelsior coach that it was difficult to use any of the information from the patent. For example, on a school bus the engine is in the front of the bus whereas the Xcelsior coach engine is in the back. Engine placement will affect the size constraints acting on the defroster plenum.

[redacted]

Figure 2: School bus dash, air distribution *[2]*

Following the review of defroster plenum designs, we concluded that since our design must fit into a very specific location under the dash of the Xcelsior coach, the design must be specific to New Flyer buses. In addition, most of the designs in the patents do not match the defrosting needs of the New Flyer bus, especially considering the transit bus specific codes and standards. Despite the dissimilarity to the requirements of our design, it was found that patent searches were useful for gaining better physical understanding of how other vehicles defrost their windshields. In particular, the patent review helped us see that there are many solutions to the same problem.

The next stage of the patent review examined the fastening method, to attach the plenum to the bus frame. For fastening the defroster plenum, we have looked into using something faster than the original design (which has six screws). The pushpin design can be seen in the following patent in Figure 3.

[redacted]

Figure 29: Pushpin fastener *[3]*

As the pin is pushed in, the ribbed edge of the rivet is expanded into the hole which secures it in position. Pushpin rivets are typically considered a one-time-use product; however, they are very cheap. They will allow for larger tolerances, which are crucial considering that the plenum and the metal frame of the bus have different coefficients of thermal expansion; thermal expansion would lead to cracking of the plenum if tolerances are too tight.

Prior to the patent review, our group was given access to the models of the current plenum that New Flyer has been manufacturing. Seeing the original design in some respects makes it difficult to come up with completely original designs. This is because when you see a particular design that works, a person sometimes gets "tunnel vision." The patents we researched served to broaden the range of designs our team looked at and analyzed.

1.2 Competitor Review

Motor Coach Industries (MCI) is another bus manufacturer located in Winnipeg. Being that MCI also produces large buses, we felt they may have relevant information pertaining to our redesign of the defroster plenum. Although MCI is not considered a direct competitor of New Flyer Industries, we were not granted access to these files and therefore were not able to conduct a competitor analysis.

2 TRIZ Methodology

TRIZ (Teoriya Resheniya Izobreatatelskikh Zadatch) is an acronym for the "Theory of Inventive Problem Solving". It is based on two basic principles. The first is that somebody, sometime, somewhere has already solved the problem or one similar to it. The second principle is to not accept contradictions; instead, we must resolve them. The team took the specific problems that we faced, and generalized them to the TRIZ general problems. Then, we applied the TRIZ specific solutions to the project problems, which helped our team to move forward into concept generation.

For our design, we wanted to create a plenum that is lightweight, easy to manufacture, and has a reduced installation time. The first step was to identify the contradictions. From TABLE I (containing the 39 TRIZ features) we determined the following contradictions:

32. Ease of manufacturing.
2. Weight of stationary object.
25. Loss of Time.

TABLE XXIII: LISTING OF TRIZ FEATURES

1: Weight of moving object	2: Weight of stationary object	3: Length of moving object
4: Length of stationary object	5: Area of moving object	6: Area of stationary object
7: Volume of moving object	8: Volume of stationary object	9: Speed of object
10: Force (Intensity)	11: Stress or pressure	12: Shape
13: Stability of the object	14: Strength	15: Durability of moving object
16: Durability of non-moving object	17: Temperature	18: Illumination intensity
19: Use of energy by moving object	20: Use of energy by stationary object	21: Power
22: Loss of Energy	23: Loss of substance	24: Loss of Information
25: Loss of Time	26: Quantity of substance	27: Reliability
28: Measurement accuracy	29: Manufacturing precision	30: Object-affected harmful
31: Object-generated harmful	32: Ease of manufacture	33: Ease of operation
34: Ease of repair	35: Adaptability or versatility	36: Device complexity
37: Difficulty of detecting	38: Extent of automation	39: Productivity

The second step, based on the TRIZ contradiction matrix (TABLE II) is to identify which are improving features and which are worsening features. Ease of manufacturing is an improving feature while weight and loss of time are worsening features. The third step is to refer to Altshuller's TRIZ principles to identify which may be useful for our design problem. The forty TRIZ principles are contained in TABLE II below.

TABLE XXIV: ALTSHULLER'S PRINCIPLES OF TRIZ

1. Segmentation	21. Skipping
2. Taking out	22. "Blessing in disguise"
3. Local Quality	23. Feedback
4. Asymmetry	24. 'Intermediary'
5. Merging	25. Self-service
6. Universality	26. Copying
7. "Nested doll"	27. Cheap short-living
8. Anti-weight	28. Mechanics substitution
9. Preliminary anti-action	29. Pneumatics and hydraulics
10. Preliminary action	30. Flexible shells and thin films
11. Beforehand cushioning	31. Porous materials
12. Equipotentiality	32. Color changes
13. The other way around	33. Homogeneity
14. Spheroidality	34. Discarding and recovering
15. Dynamics	35. Parameter changes
16. Partial or excessive actions	36. Phase transitions
17. Another dimension	37. Thermal expansion
18. Mechanical vibration	38. Strong oxidants
19. Periodic action	39. Inert atmosphere
20. Continuity of useful action	40. Composite material films

TABLE III lists the TRIZ specific solutions to the three contradictions that we identified for our design problem

TABLE XXV: TRIZ SPECIFIC SOLUTIONS

Worsen	Results	Action
Weight of stationary object	**1: Segmentation**	Divide an object into independent parts.
		Make an object easy to disassemble. • Like flexible manufacturing systems. • Different materials.
		Increase the degree of fragmentation or segmentation.
	27: Cheap short-living objects	Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities.
	36:Phase transitions	Redesign the edge.
	13: The other way round	Thinking different manufactory way.
Loss of Time	**35:parameter changes**	Change an object's physical state
		Change the concentration or consistency.
		Change the degree of flexibility.
		Change the temperature.
	Results	**Action**
	28: Mechanics substitution	Replace a mechanical means with a sensory
		Use electric, magnetic and electromagnetic fields to interact with the object.
		Change from static to movable fields, from unstructured

		fields to those having structure
Loss of Time		Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.
		Make portions of an object that have fulfilled their functions go away or modify these directly during operation.
	34: Discarding and recovering	Conversely, restore consumable parts of an object directly in operation.
	4: Asymmetry	Change the shape of an object from symmetrical to asymmetrical.
		If an object is asymmetrical, increase its degree of asymmetry.

After completing the TRIZ analysis, the team was ready to brainstorm. We used these eight principles to help develop concepts that will meet our target specifications.

3 Brainstorming

Following the use of TRIZ, review of competitors' products, and review of patented products, concepts were generated using brainstorming. For the brainstorming phase, ideas were split up into five categories:

5) Methods to fasten the plenum to the frame of the bus.
6) Material to produce the plenum.
7) Manufacturing process to produce the plenum.
8) New plenum designs.
9) Improvements to shape and features of the current plenum design.

By separating the ideas into categories, the team could focus on developing ideas that directly related to specific project needs, instead of trying to solve many issues at once. While some concepts, such as those within the categories of manufacturing process and material, may cause restrictions in the other concepts that may be used, the team did not want to restrict idea development by combining categories together. Instead, concepts from the different categories can be integrated into a total plenum design once the ideas had been screened and scored. Figure 4 below shows an exploded view of the defroster plenum as well as labels for the key features of the part. These labels will be important in identifying features of the plenum, when describing improvements to the design in TABLE IV.

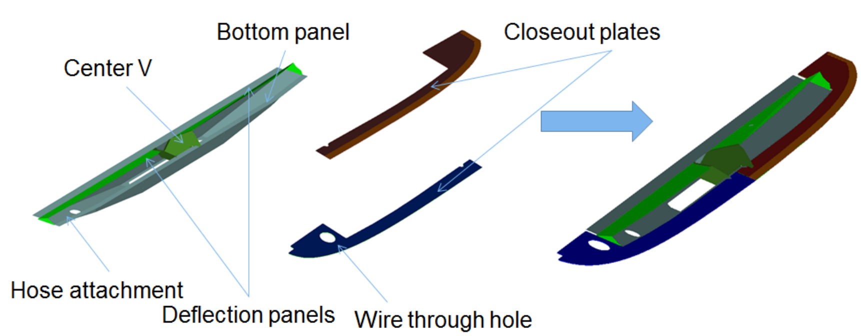
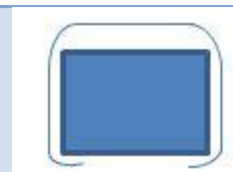


Figure 30: Exploded view of the defroster plenum

The list of initial concepts developed during the brainstorming session is contained in TABLE IV.

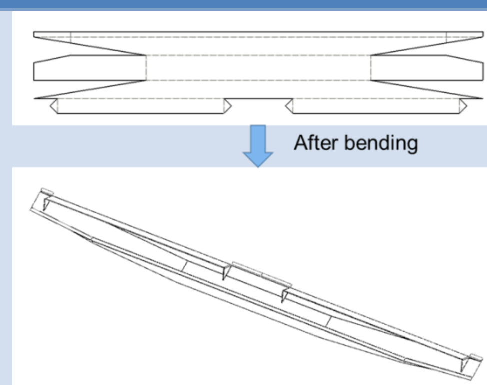
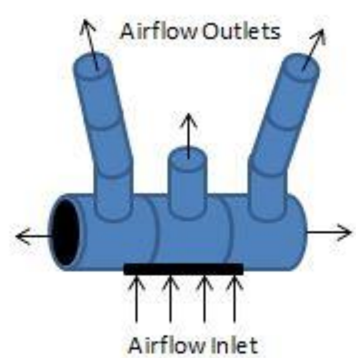
TABLE XXVI: BRAINSTORMED CONCEPTS

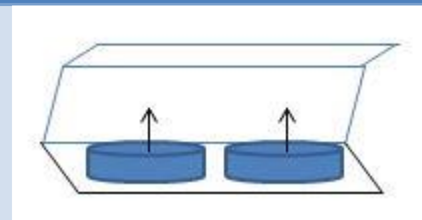
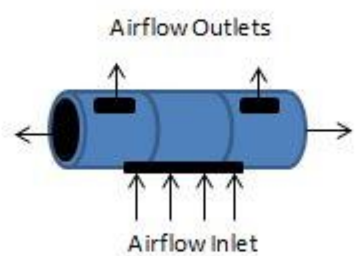
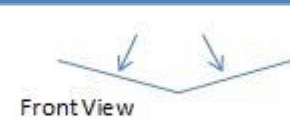
	Fastening Methods		
	Concept	**Improvement**	**Picture and/or Description**
1	Current Process	N/A	Screws are used to secure the plenum to the bus frame on one side, while double sided tape is used to attach the other side.
2	Plastic Rivet	Fast Installation, Low Profile	Plastic pin technician pushes in with thumb which secures it into place.
3	Square tube clip – attached by manufacturer	Fast installation	
4	Square tube clip – attached in house	Slightly faster installation	
5	Double Sided Tape	Fast installation	Tape that has adhesive on both sides.
6	Velcro	Removable	Velcro bonded to the plenum and the frame.
7	Screw with Template	Fast installation	Still use screws but use a template instead of measuring each hole to drill.
	Materials		

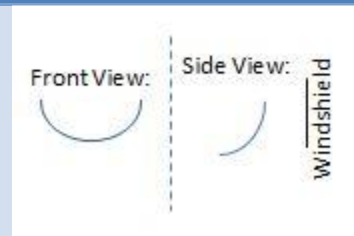
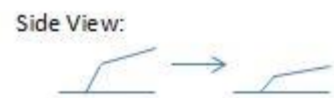
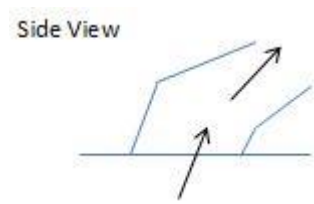
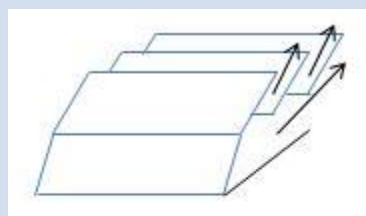
	Concept	Improvement	Picture and/or Description
8	Current Design	N/A	Galvanized Steel
9	Mild Steel	Slightly lighter, low cost	N/A
10	Stainless Steel	Improved durability.	N/A
11	Aluminum	Lighter, low cost	N/A
12	Copper	Possible improvements due to increased thermal conductivity.	N/A
13	Nickel	Lighter	N/A
14	Polycarbonate (PC)	Much lighter, improved heat transfer due to good thermal resistance.	N/A
15	Acrylonitrile Butadiene Styrene (ABS)	Much lighter, improved heat transfer due to good thermal resistance, low cost	N/A
16	Glass Fiber	Much lighter, improved heat transfer due to good thermal resistance, improved strength upon most plastics.	N/A
17	Acrylic/ polymethyl methacrylate (PMMA)	Much lighter, improved heat transfer due to good thermal resistance.	N/A

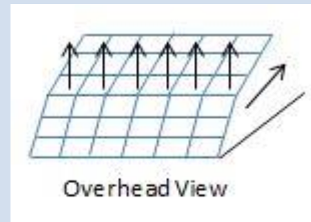
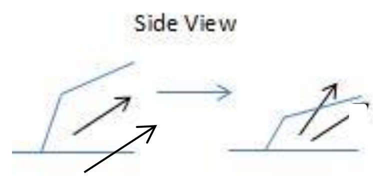
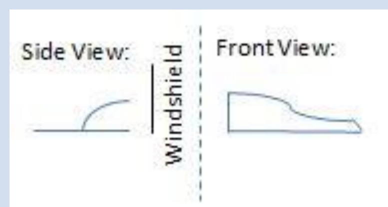
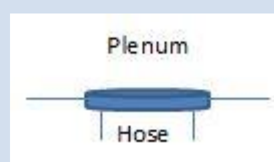
	Concept	Improvement	Picture and/or Description
18	High Density Polyethylene (HDPE)	Much lighter, improved heat transfer due to good thermal resistance. Good strength for plastic.	N/A
	Manufacturing Process		
19	Current Process	N/A	Part is cut in separate pieces from sheet metal, then part is welded
20	Purely Bending	Will eliminate need for welding, reducing costs	Part is formed from a single sheet of metal, using only bending operations such as a press brake.
21	Press Fitting	Will eliminate need for welding, reducing costs	Part is formed in separate pieces, and then is press fit together instead of welded.
22	Press Fitting and Bending	Eliminates welding, can selectively produce portions of part using two operations to reduce manufacture time	Certain portions of part are formed using bending, then separate pieces are press fit together
23	Compression Fitting	Allows for plastic forming, is quick, low cost	Moulds are constructed of part, and then plastic is poured into hot mould. Plastic is compressed to form part shape. Can be produced in 3 parts (deflection panels (2), then rest of part), then parts are bonded together.

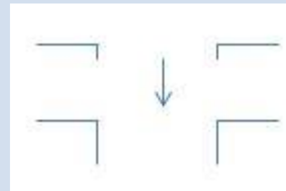
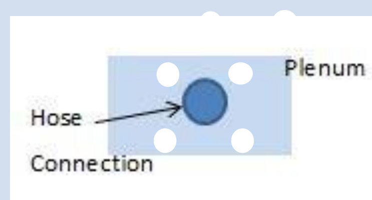
	Concept	Improvement	Picture and/or Description
24	Injection Moulding	Allows for plastic forming, low part cost, quick forming operations once mould is created, high dimensional accuracy, may be produced in one piece.	Moulds are constructed of part, and then plastic is poured into mould. Part can be produced in one piece, or separate moulds may be used, and pieces are bonded together.
25	Rotational Moulding	Allows for plastic forming, low part cost, moderate dimensional accuracy, relatively low mould cost, is produced in one piece.	Moulds are constructed of part, and then plastic is poured into hot mould. Part is rotated until plastic planes out on mould walls. Part is produced in one piece, and then holes are cut out from part.
26	Reaction Injection Moulding	Thermoset forming, relatively low part cost, relatively quick forming operations once mould is completed, high dimensional accuracy, may be produced in one piece	Moulds are constructed of part, and then thermoset is poured into mould. Lower pressures are needed than injection moulding as plastic sets inside mould. Part can be produced in one piece, or separate moulds may be used, and pieces are bonded together.
27	Fiberglass Forming	Allows for use of fiberglass, low cost, low mould cost, moderate dimensional accuracy	Individual pieces are produced using fiberglass moulding operations, and then are bonded together.

	Concept	Improvement	Picture and/or Description
28	Vacuum Forming	Allows for plastic forming, is quick, low cost, moderate dimensional accuracy.	Moulds are constructed of part, and then plastic is poured into hot mould. Plastic is compressed by suction to form part shape. Can be produced in 3 parts (deflection panels (2), then rest of part), then parts are bonded together.
	Total Design Ideas		
29	Purely Bent Design	Optimizes design for purely bending. This will reduce need for welding.	
30	Direct Tubes to Different Parts of Windshield	Allows for exact air distribution to those which currently have low airflow.	

	Concept	Improvement	Picture and/or Description
31	Fans Placed Underneath Deflection Panels	This will significantly improve air speed, by accelerating the air that is coming from the heat exchanger. Consequently, heat transfer characteristics will improve.	
32	Single Tube with Holes	Will improving airflow to sides, while allowing just enough air to flow mid windshield.	
	Improvements to shape and features of the current plenum design		
33	Flatten centre 'V'	Improve airflow to sides, by increasing horizontal component of air velocity.	
34	Raise centre 'V'	Improve airflow to middle, by increasing vertical component of air velocity.	
35	Curve centre 'V'	Reduce losses by optimizing airflow shape.	

	Concept	Improvement	Picture and/or Description
36	Contour 'V' in 2 Planes	Reduce losses by optimizing airflow shape.	
37	Lower Deflection Panels	Reduce area through which air can flow, increasing air velocity.	
38	Curve Deflection Panels	Reduce losses by optimizing airflow shape.	
39	Layer Deflection Panels	Lower deflection panels will deflect air upwards, increasing the vertical component of air velocity. Improve heat transfer to upper portions of windshield.	
40	Pieced Deflection Panels	Keep the majority of design features the same, but will allow air to flow through the deflection panels. This will improve airflow mid windshield.	

	Concept	Improvement	Picture and/or Description
41	Mesh Deflection Panels	Same design features, lower costs, but will allow air to flow through the deflection panels. This will improve airflow mid windshield.	
42	Holes in Deflection Panels	Keep the majority of design features the same, lowering costs, but holes will boost airflow in regions where it is needed.	
43	Add Planes of Curvature to Panels	Reduce losses by optimizing airflow shape. Shape panel such that regions with low airflow are reduced.	
44	Curve Bottom Panel	Reduce losses by optimizing airflow shape.	
45	Rubber/Foam Lip to Hose Connection	Take up tolerances between hose and hose connection site, allowing interference fit to reduce install time	

	Concept	Improvement	Picture and/or Description
46	Increase Area of Hose Connection	Allow for easier application of glue or double sided tape to connect hose with connection site on plenum.	
47	Clip on Fasteners for Hose Connection	Lower installation time as hose merely clips to plenum.	
48	Predrill Holes and use Plastic Rivets for Hose Connection	Significantly reduce install time by reducing the need to drill holes. In addition, plastic rivets have lower install time than screws.	
49	Manufacture All Parts Separately	Smaller parts will allow plenum to be installed at various assembly locations.	No drawing needed as no shape/feature changes.

After the brainstorming was completed, the 49 concepts developed were taken forward to the concept analysis stage.

Following the concept generation phase, concept analysis was performed to identify which concepts best met the customer needs. Section 3.1.1 describes the methodology of our concept analysis.

4 Concept Analysis

The following section is detailed screening and preliminary scoring method that our team used to narrow our preliminary concepts into a few feasible concepts. The screening and preliminary scoring led to sensitivity analysis and final scoring matrices that were used to give our team the final concepts to be integrated into our complete final design. The sensitivity analysis, scoring matrices and concept integration are contained in the body of the report. The methodology and process involved with the screening and preliminary scoring are contained in Appendix B as supplementary content.

4.1 Methodology

Screening and scoring of concepts for the fastening method, physical design, material, and manufacturing process was completed separately. Following concept scoring, a sensitivity analysis was completed if necessary. Using the data obtained during the sensitivity analysis the matrices were re-evaluated to make sure the best concepts were going to be pushed into the concept integration stage.

The procedures for concept screening, concept scoring, were developed in more detail in Sections 4.1.1 to 4.1.2 below.

4.1.1 Concept Screening Procedure

For each category, concepts were screened according to a plus/minus system. If given a plus, the design improved from the current design, if given a minus, the design performed worse than the current design, and if given a zero, the design was approximately the same as the current design in the given category. Since only three categories are used, sometimes there may be marginal improvements or decreases in the new designs (compared to the current design); small or large changes were ignored until the scoring matrix, if the concept proceeded. This would reduce the chance of near-negligible changes affecting the overall score of a design, in comparison to large changes in other categories.

4.1.2 Concept Scoring Procedure

An issue with concept screening is that all of the customer needs are treated as though they have the same importance, which is not the case. Furthermore, screening follows a better, worse or same format. This does not take into consideration how well the concepts achieve the customer's needs. The scoring matrix uses a weighted multiplier which takes into consideration the importance of each of the needs. The weighting schematic is accomplished using a weighting matrix. This weighting matrix compares all the customer needs to one another. Each need is compared to one another and whichever is more important gets a point. Once all the needs have been compared to one another, the procedure will return the weight of each of the criteria. Once the concepts have been scored, they are ranked according to how well they meet the scoring criteria. The scoring gives a precise answer as to which concepts meet the most important needs.

4.2 Material and Manufacturing Process Concept Selection

The material and manufacturing processes are critical in reducing the cost, installation time, number of parts, and payback time for the defroster plenum design. Since the cost and installation time are the primary objectives of the design, significant time was dedicated to selecting the optimal material and manufacturing process.

During the brainstorming stage, possible materials and manufacturing processes were identified separately. Since the criteria for the material and manufacturing process have significant variation, the concepts for materials and manufacturing processes were also screened and scored separately. Once the manufacturing process and material lists were narrowed down to the final three concepts, compatible materials were paired with the manufacturing processes, allowing a complete scoring of the material and manufacturing process together.

During the brainstorming stage, the following manufacturing processes were identified, and consequently were taken forward to the concept screening phase:

- Pure Bending
- Press Fitting
- Bending and Press Fitting
- Compression Moulding
- Injection Moulding
- Reaction Injection Moulding
- Vacuum Forming
- Rotational Moulding
- Fiberglass Forming

The following materials were identified during the brainstorming process:

- Mild Steel
- Stainless Steel
- Aluminum
- Copper
- Nickel
- PC
- ABS
- Acrylic/PMMA
- HDPE

Each of these materials was taken forward to the concept screening phase.

The concept screening of both material and manufacturing process identified which concepts meet the required objectives, and allowed for the creation of a shortlist of concepts that was taken forward to the concept scoring stage.

4.2.1 Concept Screening of Material and Manufacturing Process

The concept screening for manufacturing process compared the suggested manufacturing processes to the method of cutting the part from sheet metal, then welding the part. The concepts were compared using the criteria contained in TABLE V. The criteria are related directly to the client needs.

TABLE **Error! Bookmark not defined.**: CRITERIA AND RELATED CLIENT NEEDS FOR SCREENING MANUFACTURING CONCEPTS

Criteria	Related Client Needs
Overhead Costs	Reduce Cost, Short Payback Time
Part Costs	Reduce Cost
Dimensional Accuracy	Reduce Installation Time
Post Processing Needed	Lower Number of Parts
Adequate Production Volume	Reduce Cost

Each concept was scored using the criteria, and the top four concepts were chosen based on which had the most positive comparison to the current method. TABLE VI contains the letter used to identify the concept during the scoring process, and also makes reference to the row number for the concept in the brainstorming table (TABLE VI). TABLE IV provides a brief description of the concept, as well as a description on how the concept will improve on the current design.

TABLE XXVII: CONCEPT IDENTIFICATION FOR SCREENING OF MANUFACTURING

PROCESSES

Concept	Letter Identification	TABLE IV Reference
Current Process (Welding, Bending) **[4]**	A	19
Purely Bending **[5] [6]**	B	20
Press Fitting **[5] [7] [8] [9]**	C	21
Bending and Press Fitting	D	22
Compression Molding **[10]**	E	23
Injection Molding **[5]**	F	24
Reaction Injection Molding **[11] [12]**	G	26
Vacuum Forming **[5] [13]**	H	28
Rotational Molding **[14]**	I	25
Fiberglass Forming **[15]**	J	27

The concept screening matrix is contained in TABLE VII.

TABLE XXVIII: CONCEPT SCREENING FOR MANUFACTURING PROCESSES

Criteria	A	B	C	D	E	F	G	H	I	J
Overhead Costs	0	0	-	-	+	-	0	+	0	+
Part Cost	0	+	0	+	+	+	+	+	+	+
Tolerance	0	-	0	0	-	+	+	0	+	+
Post Processing Needed	0	-	-	-	-	0	0	0	-	-
Adequate Production Volume	0	0	0	+	+	+	+	+	+	-
Better	0	1	0	2	3	3	3	3	3	3
Worse	0	2	2	2	2	1	0	0	1	2
Same	0	2	3	1	0	1	2	2	1	1
Total	0	-1	-2	0	1	2	3	3	2	1
Rank	7	9	10	7	5	3	1	1	3	5
Proceed?	No	No	No	No	No	Yes	Yes	Yes	Yes	No

The four processes that were selected to proceed to the concept scoring phase were those that had a low part cost, while reducing the overhead costs. Metal manufacturing processes, namely the current process, pure bending, press fitting, and the combination of bending and press fitting, had relatively high costs and large processing requirements. Compression moulding did not proceed, due to the significant post processing requirements (removing flash, and bonding the separately molded parts together), as well as the low dimensional accuracy of the process. The last concept to not continue to the concept scoring stage was fiberglass forming. While the cost of fiberglass forming was low, the process is not suitable for high production volumes due to the intensive labour required to form the parts.

Once the screening of the fabrication processes had been completed, the materials were screened. Similar to the screening of the manufacturing concepts, the material concepts were compared to the current design, using a better, worse or the same scheme (denoted by + , -, 0). The concepts were compared using the criteria contained in TABLE VIII. The criteria are related directly to the client needs.

TABLE XXIX: CRITERIA AND RELATED CLIENT NEEDS FOR SCREENING MATERIAL CONCEPTS

Criteria	Related Client Needs
Density	Low Weight
Thermal Expansion	Reduce Noise
Strength	Reduce Cost
Thermal Conductivity	Lower Defrost Time
Cost	Reduce Cost

The cost and density directly relate to the client needs, but the other criteria have less obvious relationships. The thermal expansion coefficient should preferably be similar to that of the bus frame, which is constructed of steel. If similar thermal expansion coefficients are used, during temperature changes the plenum will not shift relative to the bus frame; relative shifting would increase the gap between the frame and plenum, which would increase noise due to vibration. The strength is important for reducing cost, as high strength materials can better withstand any applied stress and will last longer as a result. Furthermore, the thermal conductivity must be low, to reduce losses of heat as air passes through the plenum. Each concept was scored using the criteria, and the top five concepts were chosen based on which had the most positive comparison to the current method. TABLE IX contains the letter used to identify the concept during the scoring process, and also makes reference to the row number for the concept in the brainstorming table (TABLE IV).

TABLE XXX: CONCEPT IDENTIFICATION FOR SCREENING OF MATERIAL.

Concept	Letter Identification	TABLE IV Reference
Current Concepts	A	8
Mild Steel	B	9
Stainless Steel	C	10
Aluminum	D	11
Copper	E	12
Nickel	F	13
PC **[16]**	G	14
ABS **[17] [16]**	H	15
Glass Fiber	I	16
PMMA **[18] [16]**	J	17
HDPE **[16]**	K	18

The screening matrix is shown in TABLE X.

TABLE XXXI: CONCEPT SCREENING FOR MATERIALS

Criteria	A	B	C	D	E	F	G	H	I	J	K
Density	0	0	0	+	-	-	+	+	+	+	+
Thermal Expansion **[19] [20]**	0	0	0	-	-	0	-	-	0	-	-
Strength	0	-	+	-	-	-	-	-	+	-	-
Thermal Conductivity	0	0	+	-	-	-	+	+	+	+	+
Cost	0	+	-	-	-	-	+	+	+	+	+
Better	0	1	2	1	0	0	3	3	4	3	3
Worse	0	1	1	4	5	4	2	2	0	2	2
Same	0	3	2	0	1	1	0	0	1	0	0
Total	0	0	1	-3	-5	-4	1	1	4	1	1
Rank	7	7	2	9	11	10	2	2	1	2	2
Proceed?	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes

The materials shown in TABLE X that are selected to proceed to the concept scoring phase were primarily those that had a low to moderate part cost, low density, and low thermal conductivity. Four of the materials that met these criteria were plastics, namely PC, ABS, PMMA, and HDPE. Fiberglass also met every criterion, and consequently advanced as the primary concept. Stainless steel also advanced to the scoring stage, as stainless steel had a thermal expansion coefficient that was the same as the steel bus frame, and had a high strength. The concepts that were eliminated were primarily high cost options with few benefits. Only metals were eliminated during the concept screening phase, as metals are heavy, have high thermal conductivity, and are often expensive. Each of these characteristics is directly opposed to the ideal material characteristics for our design.

4.2.2 Concept Scoring of Material and Manufacturing Process

During concept scoring, the material and manufacturing processes were again scored separately. For the manufacturing process, during the concept scoring phase the processes of injection moulding, reaction injection moulding, vacuum forming, and rotational moulding were analyzed in more detail. In order to analyze the concepts with respect to the client objectives, the criteria weighting matrix was constructed. It is contained in Figure 5.

Criteria		A Cost	B Time	C # of Parts	D Noise	E Low Profile
A	Cost		A	A	A	E
B	Time			C	B	E
C	# of Parts				D	E
D	Noise					E
E	Low Profile					
	Total Hits	3	1	1	1	4
	Weightings	0.3	0.1	0.1	0.1	0.4

Figure 31: Weighting of criteria for manufacturing process scoring

The criteria are weighted heavily towards producing a low cost part. Using the weighted set of criteria, the rating of the four manufacturing processes was conducted. For the scoring matrix, a scale of 1 to 5 was used. A ‘5’ indicated that the criterion was met extremely well, while a ‘1’ indicated that the criterion was met poorly. To determine the concept score the sum of the criterion ratings, multiplied by the rating for each criterion, was determined. The scoring matrix is contained in TABLE XI.

TABLE XXXII: CONCEPT SCORING FOR MANUFACTURING METHOD SCORING

Concepts	Weighting	F	G	H	I
Overhead Costs	0.3	1	2	3	2
Part Cost	0.4	3	3	4	4
Tolerance	0.1	5	5	4	3
Post Processing Needed	0.1	5	5	2	3
Adequate Production Volume	0.1	4	5	3	4
Total		2.9	3.3	3.4	3.2
Rank		4	2	1	3
Proceed?		No	Yes	Yes	Yes

As demonstrated by the scoring matrix, the only concept with significant variation from the other concepts was injection moulding. Injection moulding has very high initial costs, which reduced the overall score. Since the remaining three processes had very close scores, a sensitivity analysis was conducted to verify the scoring obtained.

Once the manufacturing process had been determined, the material concepts were scored. For the material process, fiberglass, stainless steel, HDPE, ABS, PC, and PMMA were analyzed in more detail. In order to analyze the concepts with respect to the client objectives, the criteria weighting matrix was constructed. It is contained in Figure 6.

Criteria		A (Density)	B (Thermal Expansion)	C (Strength)	D (Thermal Conductivity)	E (Cost)
A	Density		A	C	D	E
B	Thermal Expansion			B	D	E
C	Strength				D	E
D	Thermal Conductivity					E
E	Cost					
	Total Hits	1	1	1	3	4
	Weightings	0.10	0.10	0.10	0.30	0.40

Figure 32: Weighting of criteria for material process scoring

Similar to the weighting of the criteria for determining the manufacturing method, the criteria are weighted towards producing a low cost part. The second most important criteria was that the thermal conductivity is low, which is directly related to the performance of the part. Using the weighted set of criteria, the rating of the four fabrication processes was conducted. The scoring matrix is contained in TABLE XII.

TABLE XXXIII: CONCEPT SCORING FOR MATERIALS

Criteria	Weight	C	G	H	I	J	K
Density	0.10	3	4	4	3	4	5
Thermal Expansion **[19] [20]**	0.10	5	3	2	4	1	2
Strength	0.10	4	3	4	5	3	3
Thermal Conductivity	0.30	2	3	4	4	4	4
Cost	0.40	1	3	4	2	2	2
Total		2.20	3.10	3.80	3.20	2.80	3.00
Rank		6	3	1	2	5	4
Proceed?		No	No	Yes	No	No	No

From the concept scoring matrix, ABS plastic emerged as the clear material choice. While the thermal expansion did not match closely with metal, this criterion was weighted very lightly. In all other categories, ABS exceeded the current material. There was a large change in many of the material rankings from the screening to the scoring matrix; this was due to the addition of both criterion weighting and increased analysis. The team found that fiberglass, although having a high strength, has inherently high costs in production. Furthermore, HDPE and PMMA were found to have high raw material costs. The heavy weighting of the criteria towards cost significantly reducing the scoring of fiberglass, PMMA, HDPE, and stainless steel. The increase in criteria weighting towards the thermal conductivity further reduced the score of stainless steel.

While the fabrication process selection was still unclear, the remaining three choices focus on plastic production. Since ABS was the highest recommended material, and is compatible with vacuum forming, reaction injection molding, and rotational molding, a sensitivity analysis was not undertaken for material selection. We proceeded directly to the final scoring.

4.3 Fastening Method Concept Analysis

The method for fastening the plenum to the frame of the bus is an important part of the process because it is the final piece of the puzzle for installation of the new design. During the brainstorming stage, the following 6 concepts for securing the plenum to the frame were developed:

- Plastic Rivet
- Square Tube Clip (attached to plenum by Manufacturer)
- Square Tube Clip (attached in house at New Flyer)
- Double Sided Tape
- Velcro
- Screw with measured template (Current)

TABLE XIII provides the letter used to identify each fastening concept in the screening and scoring process.

TABLE XXXIV: CONCEPT IDENTIFICATION FOR SCREENING OF FASTENING METHODS

Concept	Letter Identification	TABLE IV Reference
Plastic Rivet	A	2
Square tube clip attached by manufacturer	B	3
Square Tube clip attached in house	C	4
Double sided tape	D	5
Velcro	E	6
Screw with template	F	7

4.3.1 Concept Screening of Fastening Methods

The concepts listed in TABLE XIII were compared to the current defroster method (screws-no template) using a better, worse or the same scheme, denoted by +, -, 0. The concepts were compared using the following criteria:

- Cost of the fasteners
- Time required to install the plenum using that particular fastening method
- Number of parts required for technician at installation (e.g. Plenum, screws, clips, tape)
- Amount of noise the plenum produces while the bus is being driven, when plenum is fastened with a particular fastener
- Complexity of the installation (will the technicians require extra training?)

The way the rating criteria relate to the client needs is shown in TABLE XIV.

TABLE XXXV: CRITERIA AND RELATED CLIENT NEEDS FOR SCREENING FASTENING METHOD

Criteria	Related Client Needs
Cost	Reduce Cost
Installation Time	Reduce installation time
Number of Parts	Reduce number of required parts
Noise	Lower the noise produced
Complexity	Reduce Cost and Installation time
Low Profile	Fits within the frame of the bus

The screening was completed for all of the concepts; the top four concepts were chosen based on which had the most positive comparison to the current method. The results of concept screening are included in TABLE XV.

TABLE XXXVI: FASTENING METHOD SCREENING *[3]*

Criteria	A	B	C	D	E	F	Current
Cost	0	-	-	+	-	-	0
Time	+	+	+	+	+	+	0
# of parts	0	+	-	0	0	0	0
Noise	0	-	-	+	+	0	0
Complexity	+	-	-	+	+	+	0
Better	2	2	1	4	3	2	0
Worse	0	3	4	0	1	1	0
Same	3	0	0	1	1	2	0
Total	2	-1	-3	4	2	1	0
Rank	2	5	6	1	2	3	4
Proceed?	Yes	No	No	Yes	Yes	Yes	No

From the screening matrix, the square tube fasteners, as well as the current method (measuring and screwing), have been eliminated. The square tubing would have cost more than the other candidates and was a much more complicated idea. Since we are trying to simplify the design, this was not a practical solution. Lastly, using the current method is not acceptable since it would show no improvement to the current process.

4.3.2 Concept Scoring of Fastening Methods

Next the criteria weighting scheme was created so that the concept scoring could take place. The criteria were compared to one another to determine which is more important. From this we have a multiplier for a weighted scoring matrix. Criteria weighting enables us to take a closer look at the screened fastening methods to determine which concepts will be integrated into the final design. Figure 7 shows the criteria weighting matrix.

Criteria		A Cost	B Time	C # of Parts	D Noise	E Complexity
A	Cost		A	A	A	A
B	Time			B	B	B
C	# of Parts				C	E
D	Noise					D
E	Complexity					
	Total Hits	4	3	1	1	1
	Weightings	0.4	0.3	0.1	0.1	0.1

Figure 33: Weighting of criteria for fastening method

Once the weighting of the criteria had been completed, the concepts were scored using the weighted criteria. The scoring matrix is shown in TABLE XVI.

TABLE XXXVII: FASTENING METHOD SCORING

Criteria		**A [3]**		**D**		**E**		**F**	
	Weight	Rating	**Score**	Rating	**Score**	Rating	**Score**	Rating	**Score**
Cost	0.4	3	**1.2**	5	**2**	4	**1.6**	3	**1.2**
Time	0.3	4	**1.2**	4	**1.2**	3	**0.9**	3	**0.9**
# of parts	0.1	3	**0.3**	4	**0.4**	3	**0.3**	4	**0.4**
Noise	0.1	3	**0.3**	4	**0.4**	4	**0.4**	4	**0.4**
Complexity	0.1	4	**0.4**	5	**0.5**	3	**0.3**	5	**0.5**
Total			**3.4**		**4.5**		**3.5**		**3.4**
Rank			**3**		**1**		**2**		**4**
Proceed?			**No**		**Yes**		**Yes**		**No**

We determined that concept D and E would be the most suitable for the plenum application. Concept D was the double sided tape which did well since the cost of the tape is low and it would be fast to install. The Velcro scored second highest for similar reasons except it would be more time consuming; a strip of Velcro must be placed on the plenum and the frame, whereas the double sided tape can be installed on one of the two. These results were determined before any sensitivity analysis was completed. Due to the small differences in scoring between concepts, a sensitivity analysis was conducted. The sensitivity analysis will be conducted using revised criteria weightings, contained in Figure 8.

Criteria		A Cost	B Time	C # of Parts	D Noise	E Low Profile
A	Cost		A	A	A	E
B	Time			C	B	E
C	# of Parts				D	E
D	Noise					E
E	Low Profile					
	Total Hits	3	1	1	1	4
	Weightings	0.3	0.1	0.1	0.1	0.4

Figure 34: The criteria weighting for the revised fastening scoring

Large weighting was put on the low profile nature of the fastening method, which had not been considered in the earlier matrix. The revised set of criteria weightings were used in the finalized concept scoring.

4.4 Physical Design Concept Analysis

The design shape and structure affects virtually all of the client's objectives for the defroster plenum design. While the manufacturing process and material selection affect the cost and payback time quite severely, and the fastening method is the one of the primary methods for reducing installation time, the design shape and structure is still a significant factor in these two major objectives. Furthermore, the design shape and structure affects nearly all of the minor objectives. In particular, the design shape and structure is the sole area of improvement that affects the number of assembly locations at which the plenum can be installed. Due to the large number of objectives that are affected by the design shape and structure, significant time was dedicated to selecting the optimal design shape and structure.

During the brainstorming stage, improvements to the current design and new design structures were identified. While the new design aimed to meet a number of objectives at once, improvements to the current design often focused on meeting a single objective. The minor improvements could then be grouped together to meet all of the client's objectives.

The totally new physical designs and improvements to the current design that were identified in the brainstorming stage are taken to concept screening stage; concept screening was used to determine which concepts best met the client's objectives.

4.4.1 Concept Screening of Physical Designs

The concept screening is based on comparing the manufacturing concept to the current design, using a better, worse or the same scheme, denoted by + , -, 0. Both the totally new design structures and the improvements to the current design were scored using the same criteria. The list of criteria used to evaluate the concepts for the design shape and structure is contained in TABLE XVII. The criteria are related directly to the client needs.

TABLE XXXVIII: CRITERIA AND RELATED CLIENT NEEDS FOR CONCEPT SCREENING BASED ON MANUFACTURING

Criteria	Related Client Needs
Cost to Produce	Reduce Cost
Time to Manufacture	Reduce Cost
Time to Install	Time to Install, # of Technicians to Install
# of Parts	Lower # of Parts, Time to Install
Heat Transfer to Sides	Lower Defrost Time
Heat Transfer to Middle	Lower Defrost Time
Noise	Noise
Assembly Line Locations	Assembly Line Locations
Weight	Low Weight

Using the criteria, the concept screening of the design structures began with evaluating the new design structures that were developed. In case a new design structure was selected to be optimal, there would be severe restrictions on which of the improvements to the current design could be applied. Each new design structure was scored using the criteria, and the top concepts were chosen based on which had the most positive comparison to the current method. TABLE XVIII contains the letter used to identify the concept during the scoring process, and also makes reference to the row number for the concept in the brainstorming table (TABLE IV).

TABLE XXXIX: CONCEPT IDENTIFICATION FOR SCREENING OF TOTAL PHYSICAL DESIGNS

Concept	Letter Identification	TABLE IV Reference
Current	A	N/A
Fans	B	31
Single Tube with Holes	C	32
Direct Tubes	D	30
Purely Bent Design	E	29

The screening matrix is contained in TABLE XIX.

TABLE XL: CONCEPT SCREENING FOR PHYSICAL DESIGNS

Criteria	A	B	C	D	E
Cost to Produce	0	-	-	-	+
Time to Manufacture	0	-	0	-	0
Time to Install	0	-	-	-	0
# of Parts	0	-	0	-	+
Heat Transfer to Sides	0	+	+	+	-
Heat Transfer to Middle	0	+	-	+	-
Noise	0	-	+	0	0
Assembly Line Locations	0	-	-	-	0
Weight	0	-	0	-	-
Better	0	2	2	2	2
Worse	0	7	4	6	3
Same	0	0	3	1	4

Criteria	A	B	C	D	E
Total	0	-5	-2	-4	-1
Rank	1	8	4	7	2
Proceed?	Yes	No	No	No	No

From the screening process, the current design was selected as the optimal design structure. The simplicity of the current structure ensures that the structure is low cost, low weight, and can easily be combined into one part. The tubed designs, or addition of fans, increased the complexity of design in order to improve heat transfer characteristics, and consequently increased the cost, weight, and manufacturing time. The purely bent design greatly simplified the design shape in order to use only bending forming processes, which decreased the performance of the design, and hence was eliminated. Since the current design structure was selected as optimal, all of the design improvements could be applied to the structure.

Therefore, to determine which design improvements were carried forward to the concept scoring phase, the concepts were scored using the criteria listed in TABLE XVII. TABLE XX contains the letter used to identify the concept during the scoring process, and also makes reference to the row number for the concept in the brainstorming table (TABLE IV).

TABLE XLI: CONCEPT SCREENING FOR IMPROVEMENT TO SHAPE AND FEATURES OF THE CURRENT PLENUM DESIGN

Concept	Letter Identification	Table IV Reference
Flatten V	A	33
Raise V	B	34
Curve V	C	35
Contour V in 2 Planes	D	36
Lower Deflection Panels	E	37
Curve Deflection Panels	F	38
Layer Deflection Panels	G	39
Add Planes of Curvature to Panels	H	43
Pieced Deflection Panels	I	40
Mesh Deflection Panels	J	41
Holes In Deflection Panels	K	42
Curve Bottom Panel	L	44
Manufacture All Parts Separately	M	45
Rubber/Foam Lip to Hose Connection	N	46
Screw Holes to Hose Connection (Current)	O	N/A
Increase Area of Hose Connection	P	47
Clip on Fasteners for Hose Connection	Q	48
Predrill Holes and Use Plastic for Hose Connection	R	49

The design improvements focus on two separate categories: those which improve performance, and those that improve installation time. Since the design structure itself is quite simple, there were very few changes recommended to improve the manufacturability or product cost. Only one concept, concept 'M,' improves the manufacturability and number of assembly line locations at which the plenum can be installed. Concepts 'N' to 'R' improve the installation time by improving the hose connection site.

The concepts that focused on improving the hose connection site were ranked separately from the concepts that focused on other improvements, as the concepts can be integrated independently into the final design. The screening matrix, showing the analysis of both of these sets of concepts, is contained in TABLE XXI.

TABLE XLII: CONCEPT IDENTIFICATION FOR SCORING OF DESIGN

Criteria	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Cost to Produce	0	0	0	-	0	0	0	-	-	-	-	0	+	-	0	0	-	0
Time to Manufacture	0	0	-	-	0	-	-	-	-	-	-	-	-	0	0	0	0	0
Time to Install	0	0	0	0	0	0	0	0	0	0	0	0	-	+	0	+	+	+
# of Parts	0	0	0	0	0	0	-	0	0	0	0	0	-	0	0	0	-	0
Heat Transfer to Sides	+	-	+	+	+	+	+	+	-	0	-	+	0	0	0	0	0	0
Heat Transfer to Middle	0	+	+	+	-	+	+	+	+	+	+	+	0	0	0	0	0	0
Noise	+	-	+	+	+	+	+	+	-	-	-	+	0	0	0	0	0	0

Criteria	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Assembly Line Locations	0	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0	0	0
Weight	0	0	0	0	0	0	-	0	0	+	+	0	0	0	0	0	0	0
Better	2	1	3	3	2	3	3	3	1	2	2	3	2	1	0	1	1	1
Worse	1	2	1	2	1	1	3	2	4	3	4	1	3	1	0	0	2	0
Same	7	6	5	5	6	5	3	4	4	4	3	5	4	7	9	8	6	8
Total	2	-1	2	1	1	2	0	1	-3	-1	-2	2	-1	0	0	1	-1	1
Rank	1	10	1	6	6	1	9	6	6	2	4	1	10	3	3	1	6	1
Proceed?	Y	N	Y	N	N	Y	N	N	N	N	N	Y	N	N	N	Y	N	Y

While many concepts offered performance improvements, the vast majority of the concepts were eliminated due to an increase in the complexity of the design. The only concepts with increased complexity that moved forward to the concept scoring phase were those for which the increased complexity was offset by significant performance improvements. Namely, flattening out the centre 'V,' as well as the addition of curves to the bottom panel, deflection panels, and center 'V' will be carried forward to the concept scoring phase. Of the concepts that focused on improving the hose connection site, increased area of the hose connection site and predrilling holes for plastic rivets progressed to the concept scoring phase. The other two concepts, adding a rubber/foam lip to the hose connection site and using clip on fasteners, increased the cost of the design and were hence eliminated.

4.4.2 Concept Scoring of Physical Designs

The concept scoring was used to identify which improvements to the current design were carried forward to the concept integration phase. Since only one design structure progressed through concept screening, it did not need to be scored. To perform the concept scoring, a criteria weighting matrix was constructed. The criteria are compared to one another, to determine which is 'more important'. From this analysis, the multipliers for the weighted scoring matrix were generated. Figure 9 contains the criteria weighting matrix.

		Cost to Produce	Time to Manufacture	Time to Install	# of Parts	Heat Transfer to Sides	Heat Transfer to Middle	Noise	Assembly Line Locations	Weight
	Criteria	A	B	C	D	E	F	G	H	I
A	Cost to Produce		A	A	A	A	A	A	A	A
B	Time to Manufacture			C	B	B	B	B	B	B
C	Time to Install				C	C	C	C	C	C
D	# of Parts					D	D	D	D	D
E	Heat Transfer to Sides						E	E	E	E
F	Heat Transfer to Middle							F	F	F
G	Noise								H	I
H	Assembly Line Locations									G
I	Weight									
	Total Hits	8	6	7	5	4	3	1	1	1
	Weightings	0.22	0.17	0.19	0.14	0.11	0.08	0.03	0.03	0.03

Figure 35: The criteria weighting for the physical design scoring

Using the weighting determined in the criteria weighting matrix, the concept scoring was conducted for the five design shape improvement. The scoring matrix is contained in TABLE XXII.

TABLE XLIII: PHYSICAL DESIGN SCORING

Criteria	Weight	A	C	F	L	P	R
Cost to Produce	0.222	3	3	3	2	3	3
Time to Manufacture	0.167	2	2	2	2	3	3
Time to Install	0.194	4	4	4	4	4	5
# of Parts	0.139	4	4	4	4	3	3
Heat Transfer to Sides	0.111	3	3	4	4	3	3
Heat Transfer to Middle	0.083	3	4	4	4	3	3
Noise	0.028	4	4	4	4	3	3
Assembly Line Locations	0.028	2	2	2	2	3	3
Weight	0.028	4	4	4	4	3	4
Total		3.20	3.28	3.39	3.17	3.19	3.42
Proceed?		Yes	Yes	Yes	Yes	No	Yes

Since many of the improvements to the physical design can be integrated independently of one another, only one concept was eliminated during the concept scoring phase. Predrilling the holes to the plenum greatly improved the installation time, and required almost no increase in manufacturing cost. Since increasing the area available for hose attachment provided only moderate improvements to the installation time, it was eliminated. Following the preliminary scoring of the design shape and structure concepts, the centre ‘V’ will be flattened out and curves will be added to the centre ‘V,’ bottom panel, and deflection panels. In addition, holes around the site of hose attachment will be predrilled, with screws suggested as the form of attachment of the hose to the plenum. Since each of these changes can be integrated independently, no sensitivity analysis was needed. We proceeded directly to the final scoring.

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Appendix C: Project Schedule

List of Figures

At the outset of the project, a project schedule was created. The schedule detailed the start and end dates for each of the major project tasks, and was organized into three sections: project management, developing the design, and preparing the deliverables. The project management section details the Project Management Body of Knowledge (PMBOK) project management process groups. The design development section contains tasks related to producing design concepts, choosing a final design, and performing analysis on the final design. The section dedicated to the preparation of deliverables contains tasks that directly relate to producing the reports and presentations that must be submitted. There are also three major project phases, which are split up by major project deliverables. The first phase was the project definition. The second step was the conceptual design phase, in which research is used to generate possible solutions to the design problem. Once the possible designs were narrowed down to 2-3 concepts, the project entered the final design phase. In the third phase, detailed analysis was conducted and a final design was selected.

The final design phase involved performing analysis for the purpose of design selection and optimization. The concepts that progressed from the conceptual design phase were analyzed with additional information from vendors, allowing a final design to be selected. CFD analysis was performed concurrently to ensure that the physical design was optimized. As the analysis was performed, individual sections were written. Once the analysis was completed, the document was compiled and peer-edited. Information gained during the writing of the final written report was used to construct the final oral and poster presentations.

As the project progressed from the conceptual design phase to the final design phase, the project schedule changed. Finish-to-start relationships exist within the three major sections, and are also used to demonstrate task interdependencies across the three sections. Due to the task interdependencies, any tasks that got behind schedule caused delays in subsequent tasks. The delays were relatively minor, as the only major delays experienced during this phase of the report were in the CFD analysis; since the CFD analysis could be performed concurrently with many of the other project tasks the delays did not compound to other sections.

The delays in the CFD analysis were caused by unforeseen difficulties in performing the analysis, such as issues with creating a CAD model that worked with the CFD software, as well as defining the boundary conditions. Further delays were caused when the objectives in the performance analysis changed, following a meeting with the client. In total, even though the CFD analysis was started 2 days early, it was completed 9 days late, on November 22. Due to complications with the CFD analysis, the heat transfer analysis was removed. Both the sound and airflow analysis were performed concurrently. The other delays were relatively minor; the cost analysis was delayed 2 days due to delays in information transmittal from the vendors to the team while the report compilation was completed a day late to give everyone additional time to complete their sections properly. The one day delay in completing the individual subsections caused the peer edit of the report to start a day later. The only other change in the schedule was the simplification of the stress analysis, as stress is not a significant factor in the design development, allowing the stress analysis to be completed in one day. A summary of the changes to the schedule is contained in TABLE XXXIV.

TABLE XLIV: SUMMARY OF CHANGES TO PROJECT SCHEDULE

Task	Initial Deadlines		Revised Deadlines	
	Start Date	**End Date**	**Start Date**	**End Date**
Heat Transfer Analysis	Nov. 6/14	Nov. 8/14	Task Removed	
Air Flow Analysis	Nov. 8/14	Nov. 12/14	Nov. 6/14	Nov. 22/14
Sound/Noise Analysis	Nov. 11/14	Nov. 13/14	Nov. 6/14	Nov. 22/14
Cost Analysis	Nov. 1/14	Nov. 8/14	Nov. 1/14	Nov. 10/14
Stress Analysis	Nov. 16/14	Nov. 18/14	Nov. 16/14	Nov. 16/14
Complete First Draft	Oct. 25/14	Nov. 19/14	Oct. 25/14	Nov. 20/14
Peer Edit First Draft	Nov. 20/14	Nov. 24/14	Nov. 21/14	Nov. 24/14

The complete Gantt chart, showing the updated scheduling, is shown in Figure 41 and Figure 42. The current date is shown as a vertical orange line on the chart. The tasks to the left of the line have been completed.

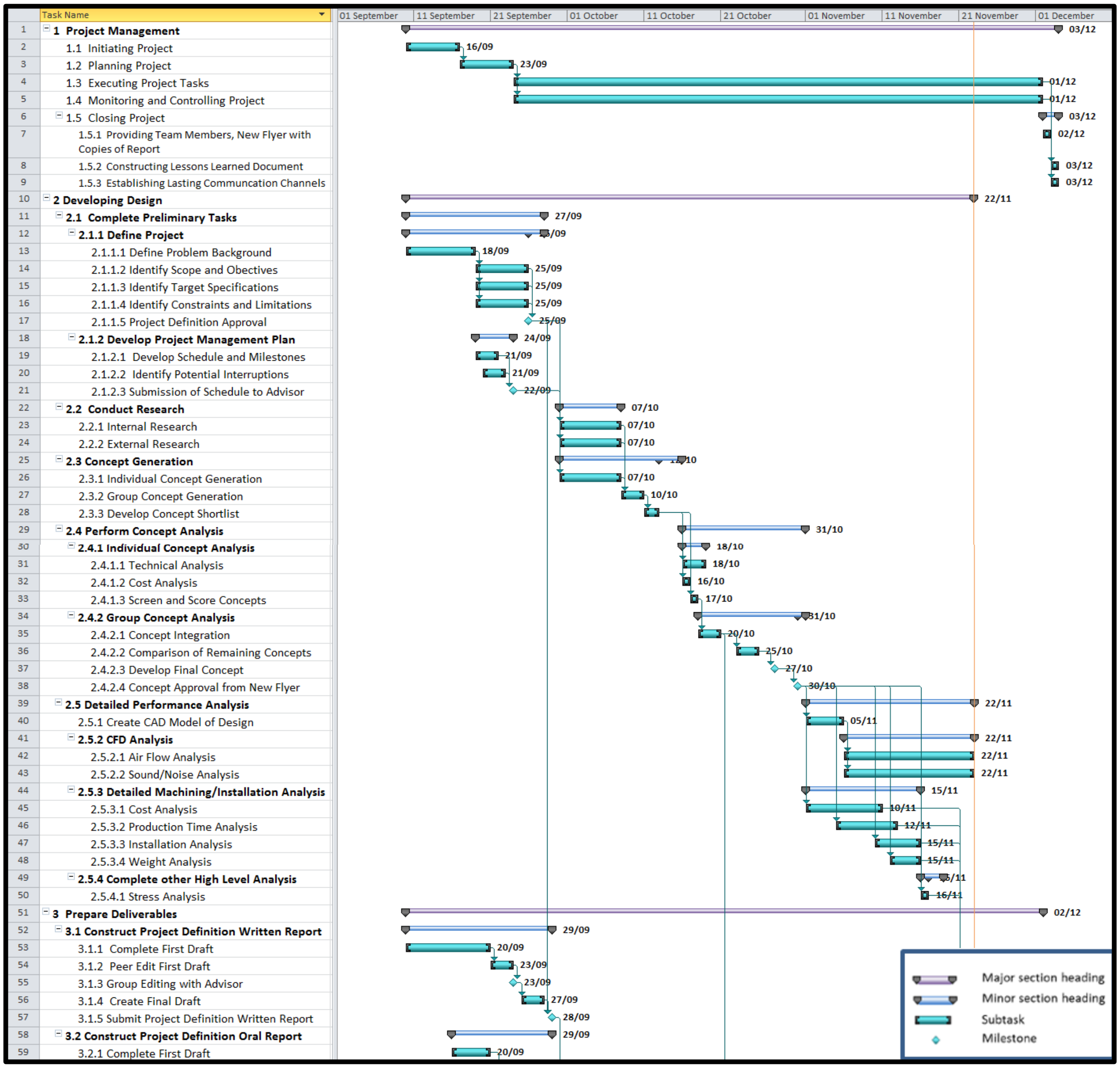

Figure 36: Gantt chart with updated project schedule, Tasks 1 to 3.2.1

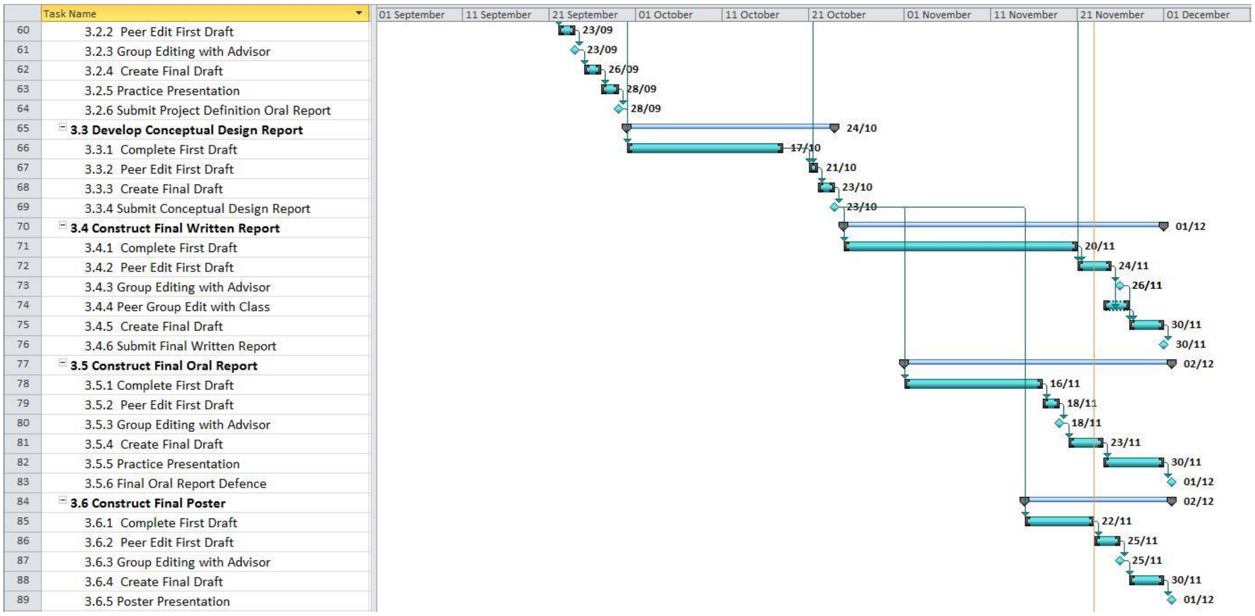

Figure 37: Gantt chart with updated project schedule, Tasks 3.2.2 to 3.7.3