

Vehicle Air Extractor Redesign

ME 450: Team 18

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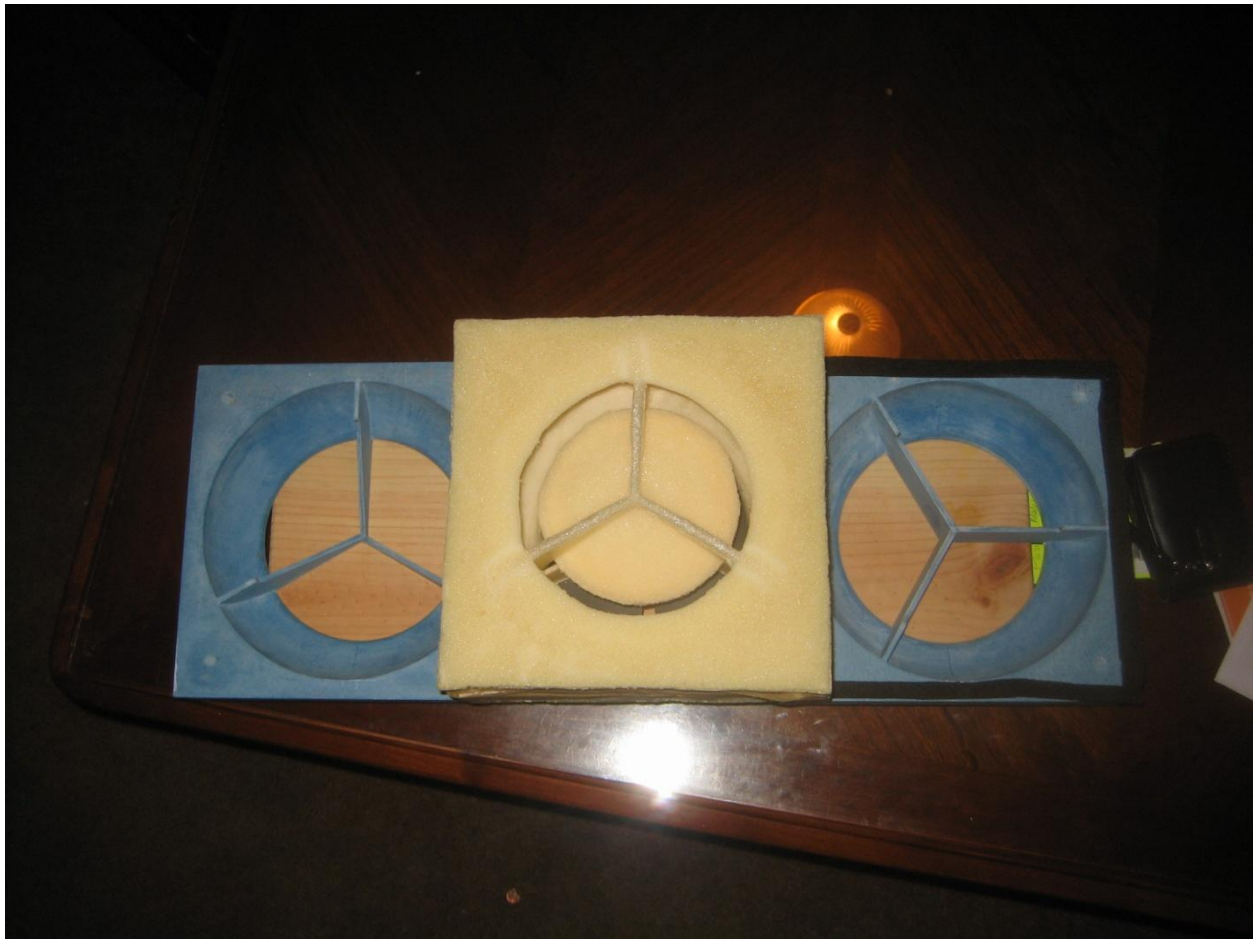


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1 ABSTRACT

In the automobile industry, the customers are very sensitive to the feel of their vehicle's doors. The first signal of vehicle quality is during the customers' opening and closing of the doors. One method for controlling closing effort is to design extractors that exhaust cabin pressure during closing events. Currently, the vehicle cabin is susceptible to noise from the exterior coming through the air extractor. We are asked to re-design the current air extractors to maintain cabin pressure and ventilation, while preventing noise from entering the vehicle.

2 INTRODUCTION

Our project sponsor is Ford Motor Company and our direct contacts are Professor Darrell Kleinke and Ken Reo. In the initial project description, we were asked to develop an analytical method to design a venting system on a typical vehicle. Based on our skill set, we felt that developing this model would be outside of our abilities. Currently, this venting function is performed by air extractors located near the rear of the vehicle. These air extractors are necessary because vehicle cabins today are practically sealed air tight to prevent exterior noises from entering the passenger cabin and lowering the perceived quality of the vehicle. Since the cabins are sealed, any air source can build up pressure in the vehicle cabin when the windows are closed. This can either be caused by the heating, ventilation and air conditioning (HVAC) system or by the door closure event. Any perceptible increase in cabin pressure also lowers the perceived quality of a vehicle. Thus, the air extractors are installed in the vehicle to relieve the steady state airflow from HVAC or the pressure pulse wave from the door closure event. The air extractors also serve the purpose of allowing airflow so that the HVAC can defrost the windows properly.

However, we found that the main issue with the current air extractors was that they let too much noise from the outside of the cabin to the inside of the cabin. After discussing with our sponsors, we felt that redesigning the air extractor to reduce noise transmission was within our scope. Thus, we narrowed our project scope to redesigning the air extractor to maintain or improve on the current air extraction performance while reducing noise transmission significantly. We are treating our role in the project as that of a tier one supplier to Ford.

Strong emphasis was put on the QFD diagram to generate concrete numbers to define the important factors that will affect our product. Our team discussed the engineering requirements we needed, and compared the requirements with Ford's air extractor and cabin pressure specification books to generate requirements. These requirements helped us develop a Functional Analysis System Technique (FAST) diagram and Morphological Chart. From these two processes, concepts were generated to satisfy the primary objectives of the air extractor.

Once the important design criteria were generated, we then brainstormed concept ideas. We evaluated six design concepts for our re-designed air extractor using a Pugh Chart. This allowed us to benchmark the concepts against the current air extractor using the customer

requirements. By setting airflow performance and sound reduction as our highest priority, the circular air extractor with a sound deadening cone in the middle was decided as the best design.

Once we drew our selected design concept on CAD, we then utilized FLUENT to perform computational fluid dynamics (CFD) analysis to prove the validity of airflow capabilities. We went through an iteration process to determine the final design concept. After going through this process, we found that a single sided cone with a lower inlet wall profile proved to have the best airflow capability.

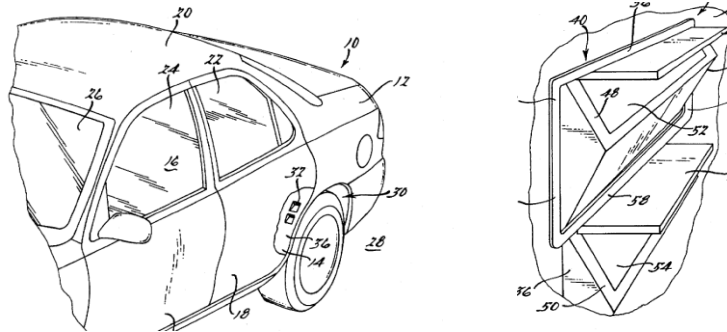
Manufacturing the prototype required us to create a reverse volume of the inlet and outlet pieces to cast pieces out of a set of molds. In order to create the molds, we constructed them using a mill, lathe, and ban saw out of mahogany, balsa, and pine wood. Once the molds were created, we then poured the REPRO plastic and liquid foam in to produce our prototypes. Finally, the flaps were added onto the outlet pieces.

Testing was performed at the Ford PDC using the flow meter. Airflow performance was tested with and without the air flaps on the outlet piece, and then benchmarked against the Taurus and F-150 air extractor models. The airflow performance proved to be sufficient to meet Ford's standard requirements.

3 INFORMATION SEARCH

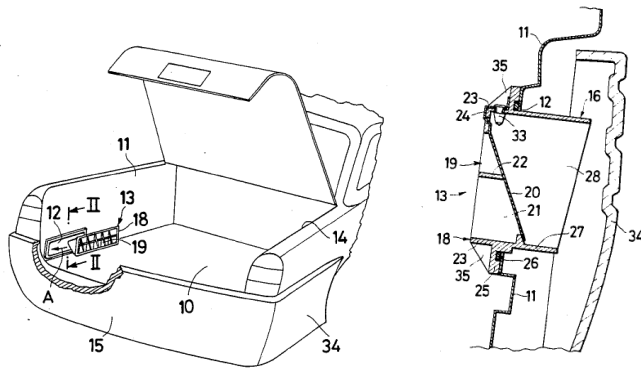
In order to get a better idea of where improvement could be found, current Ford patents related to air extractors were found in a literature search conducted by our team. It was found that Ford currently has a method and model for designing a vehicle door system without needing to first build a prototype [1]. This is done by selecting a door design and from this design, a set of system data properties are then generated (door structure, panels, mating surfaces, vehicle attributes, and seals) (Appendix A, p.9). The door system is then subjected to predetermined conditions and compared to the design criteria. If performance does not meet criteria, the system is modified and model generation is repeated until performance meets criteria. This is important because body cavity information, which includes volume, leakage, and air extractor areas, is used as a part of the generation of door system data in this model. Ford has also provided additional literature on the model with regards to modeling of the cabin pressure's contribution to door closing and velocity [2]. Equations and experiments are displayed in this report which can be later used in redesign and comparison. Ford air extractors are located on depressions of body panels (over the rear wheel well in the diagram and on rear bumpers). It includes an aperture formed from the depression and an air extractor valve surrounds the depression [3]. The air extractor's base rests on a grid and the valve controls fluid travel through the aperture in response to pressure build up in the cabin (Figure 1). The grid's pattern appears on the base to support the flap when it is not extracting cabin air and to stop outside air flow and debris in.

Figure 1: Current Ford air extractor location and design.



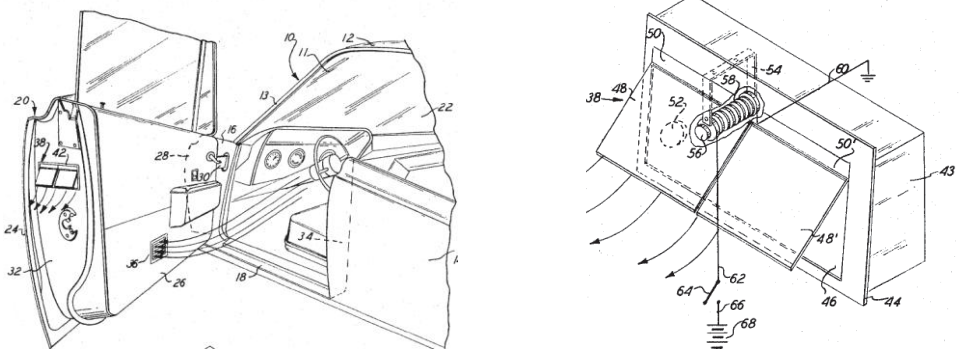
Benchmarking with competitors is also considered and a patent for an alternate air extractor is found for Alfa Lancia (Figure 2, p.3). The function and many other parts are found to be similar to the Ford air extractor. The Alfa air extractor consists of a non-return valve and a casing which serves the same function as the base in the Ford design [4]. A difference found is in implementation as the extractor is located on the wall of the trunk near the rear bumper which is not always the case for Ford. The Alfa also uses the same grid pattern and diaphragm which is supported in the casing and adheres to the grid when not extracting air.

Figure 2: Alfa Lancia air extractor design and location.



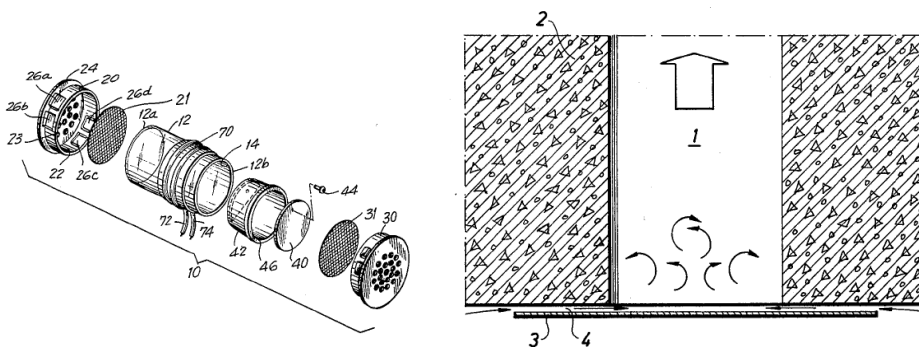
An even older Ford air extractor is found from 1967 [5] (Figure 3). The location of this air extractor is on the inner door panel as opposed to the rear of the vehicle and the valve is magnetically controlled. These changes were probably made due to a combination of reasons which may include noise inlet, cost, ease of implantation, and location.

Figure 3: 1967 Ford air extractor location and design.



Other air extractor designs were also found, such as the pressure relief port [6] (Figure 4, p.4). This device consists of two end caps which rest on two sides (front and back side of wall). A tube extends from the two end caps and is the size of the opening of the wall. This relief port uses a flexible diaphragm within the tube which has a closed position to cut off air flow and an open position to equalize pressure between the two sides of the wall. The idea of a tube between two housings may help with noise reduction. A noiseless air extractor designs is also found based on the principle of trying to increase flow speed with increasing acceleration in the direction of flow [7] (Figure 4, p.4). A plane or disc larger than the size of the opening is placed on the restricted side. This disc can be rectangular or circular and the gap between should be about a tenth of the disc diameter. Due to the nature of this design, all the air flow should meet at a centralized location and noise should be cancelled.

Figure 4: Air extractor designs which could be used to suppress noise. The left shows the tube with two end caps and the right shows the gap in front of the air channel.



Other noise cancellation research included a look into materials and methods currently used in vehicles. Viscoelastic plastics are typically used to manufacture wheel housing, instrument panels, and door panels to reduce cabin noise [8]. The base, grid housing, and flap materials should be examined and maybe altered to a material with better sound deadening properties such as viscoelastic plastic. Carpet construction is typically used to suppress noise. Nissan uses a group of small blocks between layers of carpet in order to better suppress noise [9]. When

feet typically rest on carpeting, the area compressed is much larger than the size of the feet which worsens sound deadening. A group of blocks is implemented near the top so the area the feet rest is the only area compressed. A concept similar to this could be used with the area around the air extractor or with the flap itself.

After the first Design Review, we continued to gather information for our project. Our search led us to Dearborn, MI again to the Ford Product Development Center (PDC). At the PDC, we met with Ford's acoustics experts who have been working on a different air extractor acoustics problem for over two years. We found that the air extractors not only allowed sound to travel through them from outside, but also created a flap reverberation noise during the pressure release from the door closure event.

The acoustics experts have been trying to alleviate this flap reverberation issue by varying the flap material, angle, and profile. They have also varied the valve type, experimenting with variants of the current valve as well as butterfly type valves. They asked that we take this problem into account when creating our design.

They have also created a method for testing the flap reverberation noise as shown in the Acoustics Box in Appendix D. This box works by sending a pressure pulse wave, modeled after the pulse wave of a door slam event, through the air extractor. A microphone is set one half meter away from the air extractor to record the flap reverberation noise. The way they find the data for the pressure pulse wave profile is by placing a pressure transducer on a vehicle dashboard and recording the pressure wave during a door slam event. They then attempt to replicate this wave using a woofer in the acoustics box. We hope to test our prototype on this box to benchmark against the current products.

The acoustics group also informed us of a metric that Ford uses for the air extractor volumetric flow rate. They said that Ford requires a vehicle to have a total of 500 cubic feet per minute (CFM) of air flow at one inch gauge pressure of water. In this metric it is assumed that approximately 150 CFM leaks through the vehicle body, so the air extractors need to exhaust a total of 350 CFM. This means that if there were 5 air extractors, each of them would need at least 70 CFM.

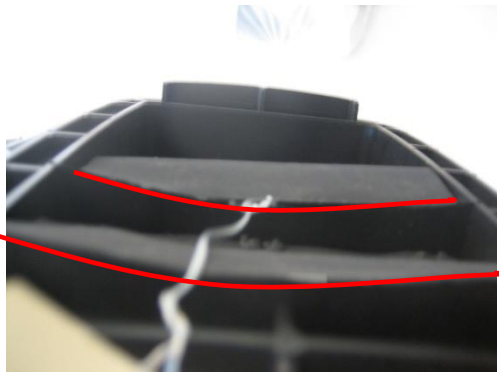
While in Dearborn, we also visited the Ford Benchmarking Center to see the various air extractors in Ford's vehicles along with its competitors' vehicles. We found that for common vehicle types, air extractors are typically placed in the same locations. As shown in Figure 5 below, the air extractors in trucks were placed at the back of the cab. These vented between the cab and the trunk bed. In cars and SUV's, the air extractors were placed behind the C pillar, in the trunk or in the rear bumper fascia.

Figure 5: Ford F-150 air extractor location



We also found that most air extractor designs were essentially the same. All of them were one way valves using fabric or rubber material as flaps. After speaking to Professor Kleinke about the similarity of designs, he told us that the extractors could be made by the same suppliers. Thus, it is not out of the ordinary that many of the air extractors essentially have the same design. While most exhibited the same designs, the flap materials, angles, and profiles varied from model to model. On Figure 6, p.6 you can see the parabolic flap profile in the Toyota Rav4 We believe this might aid in pressure release at lower gauge pressures. It may also reduce flap reverberation noise.

Figure 6: Curved flap profile on Toyota Rav4 air extractor highlighted in red



Some air extractors also had sound proofing qualities by way of using soundproofing materials or a sound shield. In Figure 7, you can see the Toyota Rav4 air extractor used a sound deadening foam behind the air flaps to absorb some of the sound. Also in Figure 7, you can see the Toyota Tundra air extractor. This design uses a 'silencer' or 'sound shield' to create bends in the air pathway as a means of sound reduction.

Figure 7: Sound deadening foam in Toyota Rav4 air extractor (left). Sound shield on Toyota Tundra air extractor (right)



4 QUALITY FUNCTION DEPLOYMENT (QFD)

In order to account for every design detail, an extensive quality function deployment process was undertaken. The resulting QFD diagram is shown in Appendix B on page 21. Each section of the QFD is described below.

4.1 Customer Requirements

As a tier one supplier, our customer is the Ford Motor Company. To get the major customer requirements for our QFD model of the air extractor prototype, we interviewed Professor Darrell Kleinke, Mr. Ken Reo, Mr. Todd Dishman, and Mr. Dick Newton of the Closure Group to find out what the functional and physical requirements were. The customer requirements can be grouped into three major categories: road noise, air flow/pressure, and manufacturability/cost.

Current air extractors allow exterior road noise to the cabin, so it is required that the new prototype reduces or prevents the transmission of sound through the extractor. By preventing noise transmission, this will enhance the overall perception of vehicle quality.

The air extractors are important to cabin air flow and pressure. While a car is stationary, the air extractor should reduce pulse pressure created by the door closure event so that it is not uncomfortable to the human ear. Also, the air extractor helps to prevent pressure from building up inside the cabin while a car is stationary or in motion. The air extractors also help ventilate the cabin for the HVAC system while all the windows are closed. They also play an important role for window defrosting by maintaining air flow in the vehicle. Along with these requirements, the air extractor should not let water, dust or fumes flow back into the cabin.

The manufacturability/cost category has to do with the air extractors' size and cost. The air extractors should be less than \$2.00 and be as small and lightweight as possible. The part should be easy to manufacture. Also, these air extractors should not add any additional steps during vehicle assembly.

Each of the customer requirements were directly compared to each other customer requirement and either given a '1' for more important or a '0' for less important. The total amount of points for each customer requirement was summed and normalized as a percentage of the total points given for the section. The results were the relative weights in terms of percent for each of the requirements.

The four most heavily weighted customer requirements were “doesn't let water, dust, fumes and fumes back into the cabin,” “ventilates cabin,” “maintains comfortable cabin pressure while driving” and “endures vehicle exterior conditions.” “Reducing cabin noise level” was seventh in importance. Although the criterion to reduce cabin noise level was ranked seventh, we still believe that this is one of the important criterions for our project. The reason behind this is due to the fact that there was only one customer requirement and engineering specification to reduce noise. We could not find a direct correlation that was important for customer and engineering requirements other than these two, thus lowering this ranking. However, one of our main foci of this project is still to reduce cabin noise level.

Requirements such as manufacturability and durability rivaled noise dampening in weight. This tells us that if the basic functions: “ventilates cabin,” “does not let water, dust and fumes back into the cabin” and “endures vehicle exterior conditions” are not met, then the product design will not be a success. Even though the noise level reduction is one of the reasons for the project, other factors cannot be sacrificed to achieve this goal.

4.2 Engineering Specifications

Our contacts at Ford provided us with the engineering specifications that will satisfy the customer requirements. These are grouped below much like the customer requirements in the last section.

To satisfy the customers' level of noise transmission reduction, our goal is to have the air extractor transmit only 50% of the road noise level.

The maximum pressure increase during driving due to HVAC pressure increase is 149 Pa. Along with this, the maximum pressure increase due to shutting of the car door is 150 Pa. Correlated with these two requirements, the air extractor needs to allow 2000 cfm air flow through it during these two actions.

The maximum cost of the air extractor is \$2.00 dollars. This component needs to withstand temperatures ranging from -40F to 180F. The mass of our design should be 100 grams, slightly heavier than the current air extractors. However, we took into account the fact that we will likely be adding complexity to the current design.

Current air extractors are placed in the back of the car because that is where the minimal coefficient of external pressure is, and it reduces sound travel to the cabin. The maximum dimensions of the air extractor are: 95mm tall * 180 mm wide *50mm deep. There needs to be at least 10 mm clearance between the air extractor and any other component and the housing clearance zone must be at least as large as the open area to and from the air extractor. There

must be two air extractors to compensate for the closing of doors on opposite sides. The number of materials and steps in the assembly must be minimized.

Each of the engineering requirements were compared to each of the other specifications and given a “1” for more important or a “0” for less important. The total amount of points for each engineering specification was summed and then normalized as a percentage of the total points given for the section. The results were the relative weights in terms of percent for each of the specifications. These relative weights can be seen in the QFD diagram (Appendix B, page 21) and in Table 1 on page 9.

Table 1: Engineering Specifications

Engineering Specification	Importance Rating(%)	Target Value
Height (-)	0	95 mm
Width (-)	0	180 mm
Depth (-)	0	50 mm
Weight (-)	1	100 grams
Pulse pressure (-)	6	150 Pa
Noise transmission (-)	13	50%
Cost (-)	7	\$2.00
Should endure max temperature (-)	4	180 °F
Should endure min temperature (+)	3	-40 °F
Min gauge pressure (+)	7	0 Pa
Max gauge pressure (-)	8	150 Pa
Bends in air pathway (+)	11	4
Steps in assembly (-)	3	1
Extract air (+)	12	2000 cfm
Expansion past housing clearance zone (-)	7	0 mm
Flap opening clearance (-)	7	10 mm
Parts around vent blocked (-)	7	0
Materials (-)	7	3

4.3 Benchmarks

As seen in the benchmarks section of the QFD diagram, air extractors from an F-150 and a Lincoln sedan were graded on a scale from 1 to 5 on the level that the air extractor satisfies each customer requirement. A score of 5 is desirable and a score of 1 is undesirable. This benchmark reveals that the components satisfy most of the components but do not satisfy the sound transmission requirement. It is clear that the technology exists to satisfy most of our requirements except for that of sound reduction.

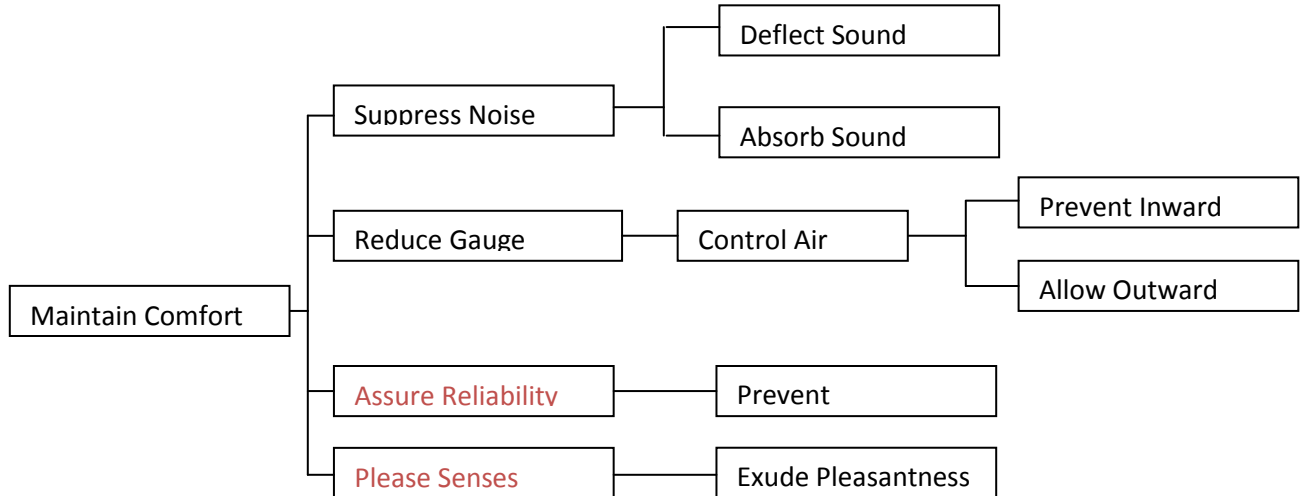
4.4 House of Quality

Once we defined the engineering specifications in our QFD diagram, we correlated each engineering specification to one another. By figuring out the correlation between two specifications, we can improve on one criterion and have an effect on another. By comparing each side by side, we can see what effect will improve both specifications, and which ones will not. For example, if we increase the number of bends through the air pathway, we can ultimately reduce the sound transmission through an extractor, but also reduce the air flow through the extractor. Thus, these are negatively correlated. A positive correlation example would be reducing the number of materials and reducing cost. These go hand in hand so these have a positive correlation.

5 CONCEPT GENERATION

To avoid overlooking any design necessities, a FAST diagram was developed to determine the primary objectives that the concept needs to satisfy. As seen in the FAST diagram in Figure 8, it was determined the purpose of the air extractor is to maintain a certain degree of comfort for the driver and passengers. To achieve this, the two primary functions of suppressing noise transmission and reducing gauge pressure between the inside and outside of the car were isolated. Along with these two, the air extractor also had to satisfy the secondary functions of assuring reliability and pleasing the senses.

Figure 8: Concept FAST diagram



To suppress the noise transmission between the inside and the outside of the car, it was determined that air extractor will have to have either deflect or absorb the incoming sound. To reduce the gauge pressure, the air flow will have to be controlled. This will have to be done by preventing inward air flow while allowing for air to flow out of the car.

After the primary functions of the air extractor were determined, a Morphological Chart was developed to decide what design factors or solutions will address each primary function. As seen in Table 2, factors involved in suppressing noise transmission include: mounting location, bends in air pathway and sound deadening material. A high-tech possibility could involve noise cancellation equipment such as the equipment seen in headphones for music. Because our constraint on cost is so low however, noise cancellation is not an option in this project. Factors and ideas involved in controlling air flow include: flaps, porous material, valves and size of openings.

Table 2: Concept Morphological Chart

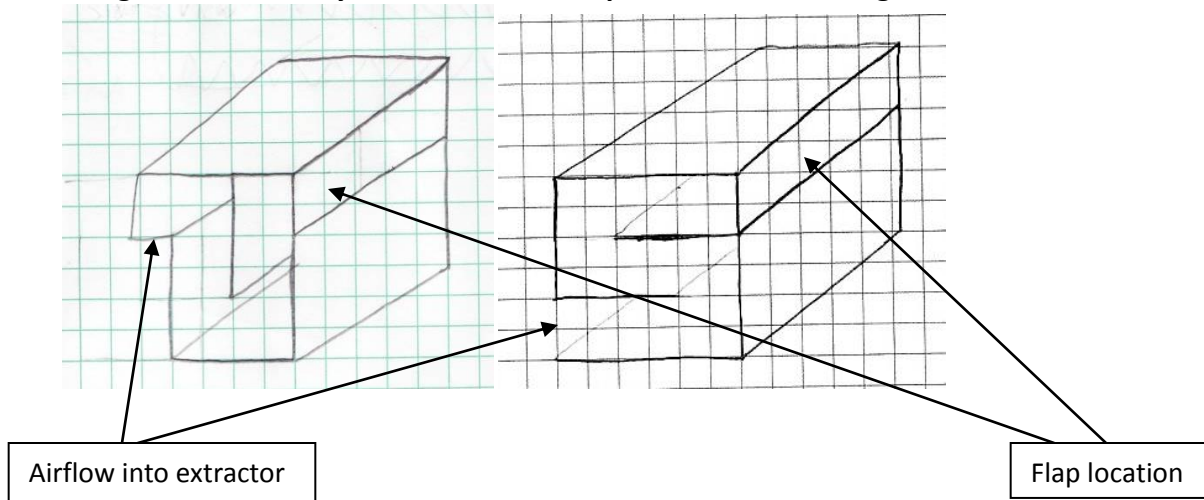
Function	Options				
Suppress Noise	mounting location	bends in pathway	sound deadening material (i.e. foam)	noise cancellation equipment	muffler system (tubing)
Control Air Flow	Flap	porous material	valve	size of opening	

After discussing the factors that affect each of the primary functions, it was decided that the concepts developed were to fall under one of four categories of air extractors: geometry based, silencer add on, foam based, and tube based. Each of these concept classes are discussed in the following sections. All concepts shown are assumed to have flaps to prevent inward air flow.

5.1 Geometry Air Extractors

The initial ideas generated from the Morphological chart pertain to altering the geometry of the air path. If the area of air inlet and outlet is the same as the current extractor, we assume this should maintain the similar air flow characteristics and also deaden the sound transmission due to the torturous path noise would have to travel to reach the passenger. The sample concepts shown below consist of a plastic housing with bends in the air pathway. Variation within these concepts consists of varying the air pathways themselves, the manner in which we add bends, and the location of the valve. Example concepts are shown below in Figure 9. The concept on the left shows a shield to redirect air through a bend while the concept on the right shows a path with two bends. Further research needs to be done to find the flow characteristics of these purposed air paths.

Figure 9: Geometry air extractor concepts in different configurations

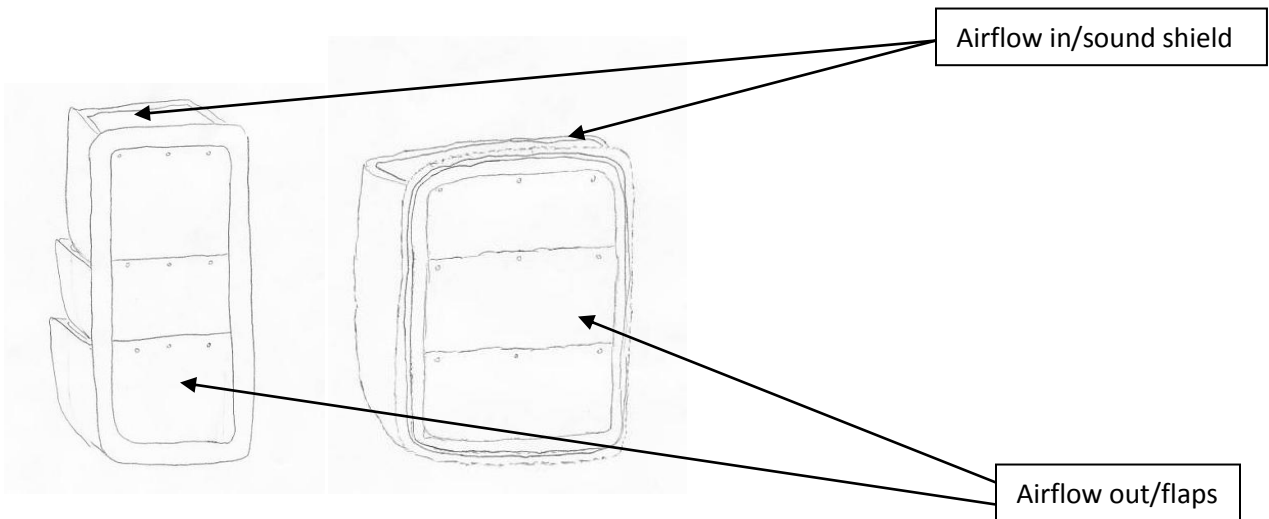


Some advantages to this category of air extractors are its low cost to manufacture (injection mold) and sound deadening from the bends when compared to the current air extractor. Some disadvantages include requiring much more space in mounting, a bigger sized extractor, to achieve the same flow characteristics, and its increase in degree of difficulty to manufacture compared to the current air extractor. A grid pattern and flaps will be used to ensure one way air flow.

5.2 Silencer Add On Air Extractors

Upon benchmarking competitive air extractors from Toyota, add on silencer piece concepts were also considered and generated. These concepts consist of an existing air extractor with a plastic scoop piece attached to the back that blocks the direct path for noise to travel through. Variation within these silencer concepts included single piece or pieces broken down into sections. Sound deadening material could also be added to the inside of the silencer piece to further deaden sound. Advantages of these types of air extractors would be ease to manufacture and use of an existing platform by designing so it snaps onto the current air extractor. A disadvantage would be requiring a lot more space to mount and possibly needing to find a new mounting location due to the extra volume from the silencer. Example concepts from this category are shown below in Figure 10 on page 14.

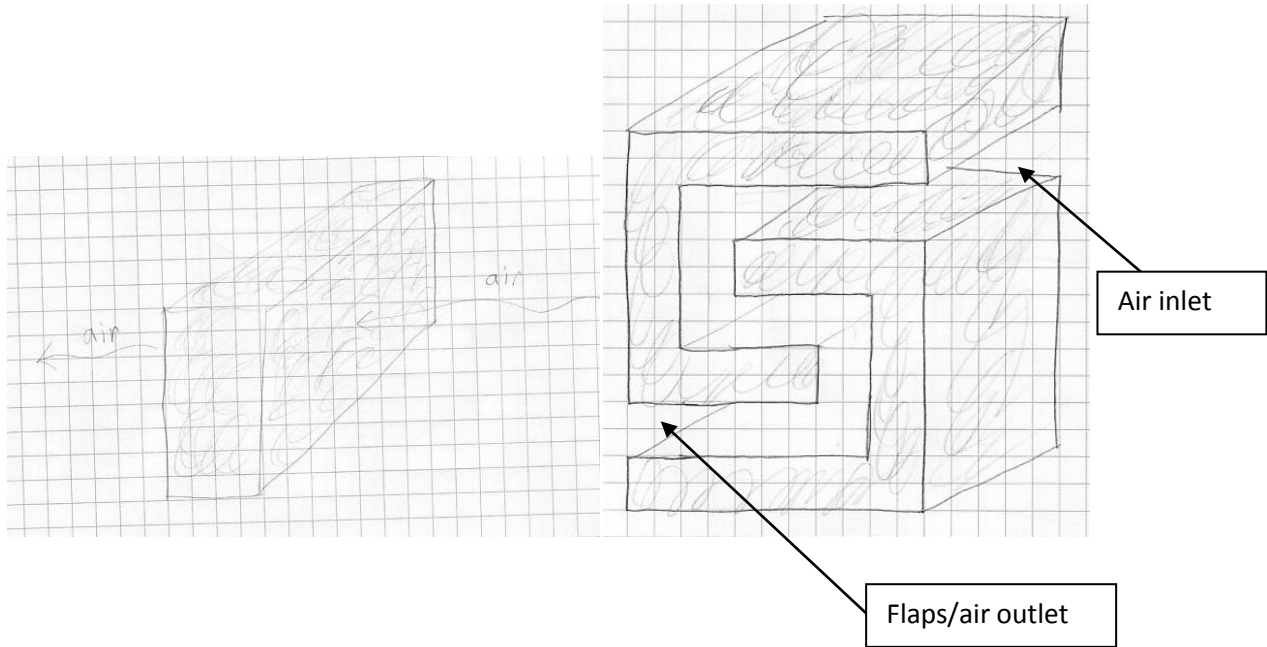
Figure 10: Silencer based air extractor concepts. The left shows a sectional silencer while the right has a one piece silencer design.



5.3 Foam Air Extractors

From the morphological chart, concepts involving sound deadening material were generated. On the recommendation of our sponsor, we were told to look into developing concepts using sound deadening foam material. As stated in the silencer design, foam can be used to insulate and line the extractor. The concepts in this section differ because they are actually made mostly out of sound deadening material. Our foam concepts ranged from a block of foam that would have to be highly porous to allow air flow and concepts involving bends similar to the ones seen in the geometry concepts section. Advantages to these concepts are high levels of sound deadening. Along with this, they are also lightweight. A disadvantage is the higher cost in material but further research will show to what degree the cost difference would be between foam and plastic air extractors. Air flow characteristics are also unknown for this material which is something we must factor. Some example foam extractors are shown below in Figure 11 on page 15. A grid pattern and flaps will be used to ensure one way air flow.

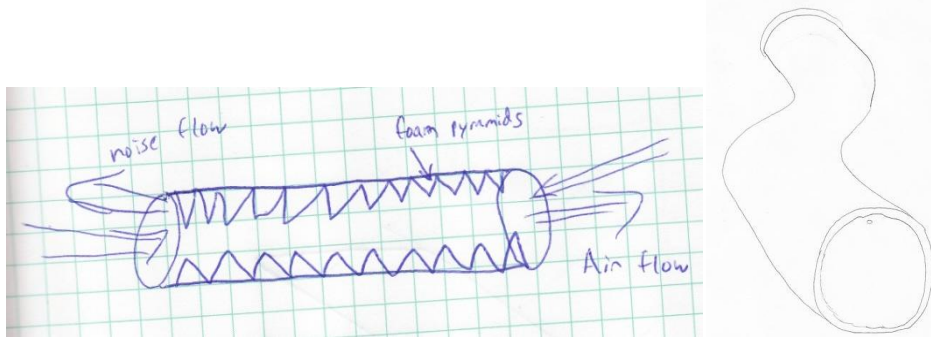
Figure 11: Foam based air extractor concepts



5.4 Tube Air Extractors

Another concept derived from the morphological chart is the tube based air extraction system similar in concept to the vehicle's exhaust system. In this concept, noise has a much longer path to travel in order to reach the passenger. Concepts generated use similar features to earlier concepts such as sound deadening material in the tube or bending the tube as seen below. Advantages to these concepts include more versatility in mounting locations for the ends of the tubes and the air outlet could be mounted closer to the driver. This would allow for an easier door closure event. A disadvantage to these designs is the higher degree of difficulty in mounting during vehicle assembly and finding space to put all the tubing. Example tube concepts are shown in Figure 12 on page 16. The concept on the left utilizes sound deadening foam to line the interior and the concept on the right utilizes a bend in an attempt to suppress sound. A grid pattern and flaps will be used to ensure one way air flow.

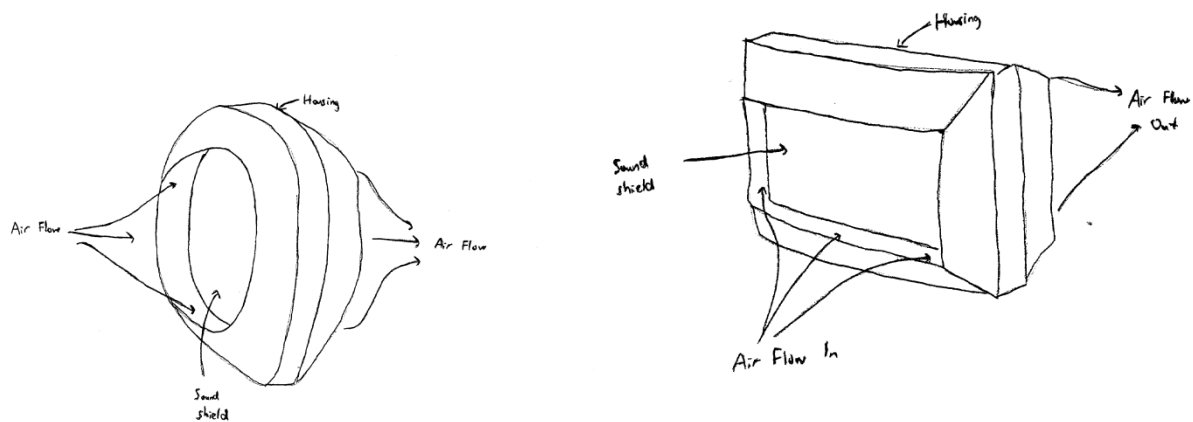
Figure 12: Tube based air extractor concepts. Foam lining is used on the left.



5.5 Sound Shield Concepts

Similar in theory to a lot of the previously mentioned concepts is the housing air extractor with a sound shield. The sound shield (a sound deadening material) is sized and shaped to the inlet and outlet of the housing and placed in parallel with the two holes. Air flow is achieved by shaping the housing so that its cross sectional area is larger around the placement of the sound shield. This creates an indirect path for sound to travel through while allowing a not as torturous path to constrict air flow as seen in the geometry based concepts. A patent in the information search section states that air flow around a disc should cause quenching of sound when the air path remerges. The housing with sound shield concepts generated will allow the opening area around the sound shield to be equal to the area of the sound shield/inlet and outlet. This is done to maximize possible air flow while keeping the design as compact as possible. A grid pattern and flaps will be used to ensure one way air flow. As seen below in figure 13, the concept on the left utilizes a circular shape while the concept on the right utilizes a rectangular shape.

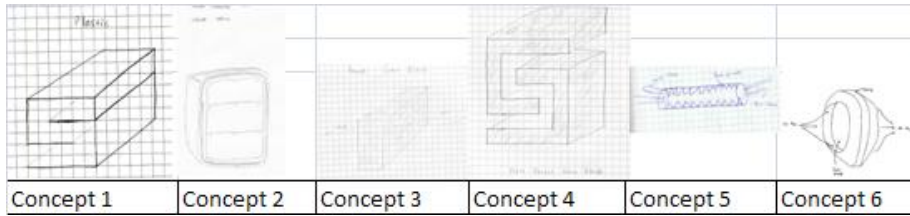
Figure 13: Housing with sound shield concepts. Circular shaped concept on the left and rectangular shaped concept on the right.



6 CONCEPT SELECTION

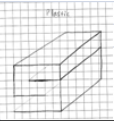
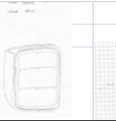

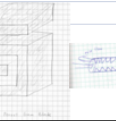
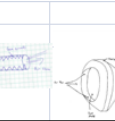

The top five designs were chosen using a 'go-no go' method. Concepts that are similar in nature and have similar features are eliminated automatically on the logic that they would score roughly the same on the Pugh Chart. This is also to ensure that each category is represented at least once to allow as diverse of a mix as possible. We kept in mind these concepts represented a category in general as well as the concept itself when scoring. The top six designs chosen are shown below in Figure 14.

Figure 14: Top six concepts selected using 'go- no go' method



The top six designs were then quantitatively compared to one another. This was accomplished using a Pugh Chart. The Pugh Chart benchmarked our concepts against the current air extractor. Using the customer requirements and customer requirement weights from our QFD, we compared the hypothetical performance of the top five concepts directly to the current extractor. This is done by giving a “+” if it outperforms the current, “0” if there is no perceived change, or “-” if it performs worse. A raw total using only the + and – can be seen in the second to last row of the table where “+” is 1 and “-” is -1. A weighted score is also derived using the customer requirement weights which is perceived to be more useful as it emphasis importance of the factors unlike the raw total. This is achieved by adding the weight to its score if a “+” is found for the requirement and subtracting the weight if a “-” is found for the requirement. In both cases of raw and weighted totals, a 0 does not affect the score. The Pugh Chart is shown below in Figure 15.

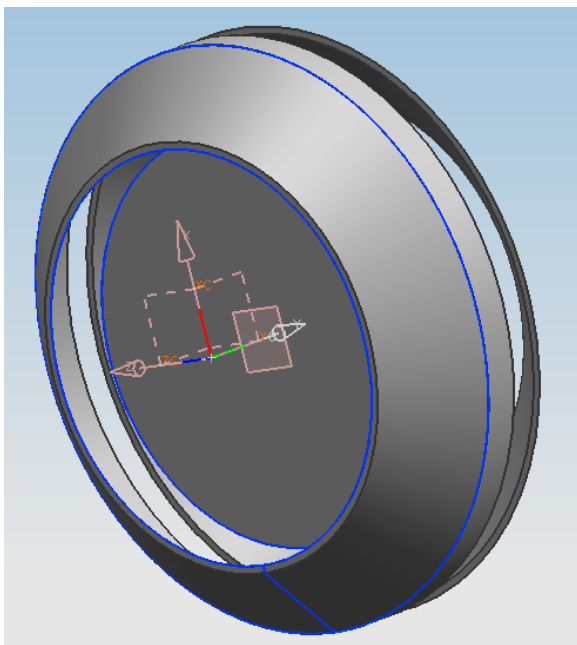
Figure 15: Pugh Chart used to benchmark concepts against current extractor

								
	Weight	Original	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Reduce cabin noise level	8	0	+	+	+	+	+	+
Ventilates cabin	13	0	0	0	-	0	0	0
Maintain comfortable cabin pressure while driving	12	0	0	0	-	0	0	0
Maintain comfortable cabin pressure during closing event	8	0	-	0	-	-	0	0
Doesn't let water, dust, fumes back into the cabin	15	0	+	+	+	+	+	+
Manufacturable according to vehicle production volume	9	0	0	0	+	0	0	0
Should be inexpensive	4	0	0	-	-	-	-	-
Parts last ten years	9	0	0	0	0	0	0	0
Endures vehicle exterior conditions	13	0	0	0	0	0	0	0
Should be small	5	0	-	-	0	-	-	-
Should be easy to manufacture	1	0	-	-	+	-	-	-
Easy to assemble during vehicle assembly	1	0	0	0	0	0	-	0
Should be lightweight	3	0	0	0	0	0	0	0
	100							
Total +		0	2	2	4	2	2	2
Total -		0	3	3	4	4	4	3
Total		0	-1	-1	0	-2	-2	-1
Weighted Total		0	4	13	-4	5	12	13

7 SELECTED CONCEPTS

Based on the raw score total, concept 3 is rated the best. Taking into account our QFD weights however, concept 2 and 6 are ranked the highest and concept 3 becomes the worst. This is due to the fact that concept 3 performs certain customer requirements well that were rated low in terms of customer importance while performing poorly in highly weighted requirements. After generating our Pugh Chart and showing our top two concepts to an engineer from Ford with expertise in the field, he suggested we continue with concept 6 due to difficulties in getting air flow to specifications in a concept such as concept 1 and 4, the costs associated with concept 5, and the lack of innovation allowable in concept 2. Based on concept 6, we will further focus on generating an air extractor concept based on a foam sound shield. We will investigate housing material and dimensioning is currently set where the area of the inlet, outlet, and sound shield are equal to the F-150 air extractor and the open area around the sound shield is equal to these as well. Shown below in Figure 16 is a CAD drawing of our initial prototype.

Figure 16: CAD drawing and dimensioned drawing of our selected concept



8 ENGINEERING ANALYSIS

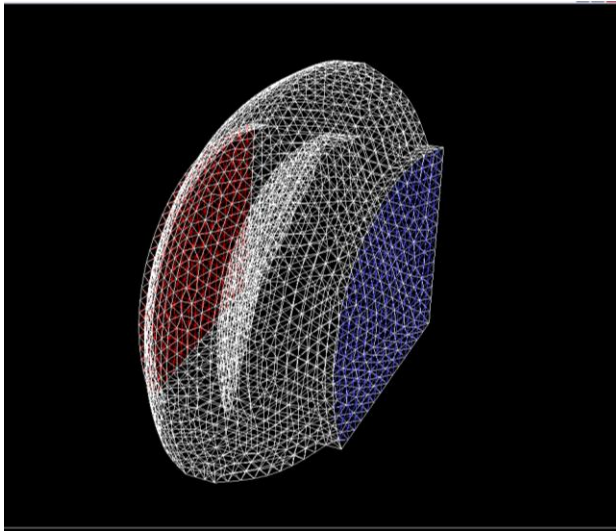
8.1 Quantitative Analysis

As shown in the final design section, our model involves three ribs that hold the sound shield in its place. Because of this, the air flow of our model is split into three different air flow paths. To assess our model, we analyzed one of these air flow paths under the assumption that the air flow will behave the same in each path. Ford's specifications for vehicle air extraction require that they pass 500 CFM for a 249 Pa gauge pressure between the inside and the outside of the

car. Because there are typically two air extractors per vehicle, each air extractor should pass 250 CFM for the given pressure differential. So, we analyzed one third of one air extractor to extrapolate the value of the total volume flow for two whole air extractors.

We used the computational fluid dynamics software, FLUENT, to model the volume flow through our air extractor. As shown below in Fig. 17, we created an input file with the specified boundary conditions to create the 249 Pascal pressure differential.

Figure 17: One third air extractor FLUENT input model



The first model we considered involved a shell that was perfectly symmetrical at the mid plane. The air path lines and steady state volume flow for this model is shown below in Fig. 18 and Fig. 19.

Figure 18: Air path lines for first modeling attempt (Air inlet on the left)

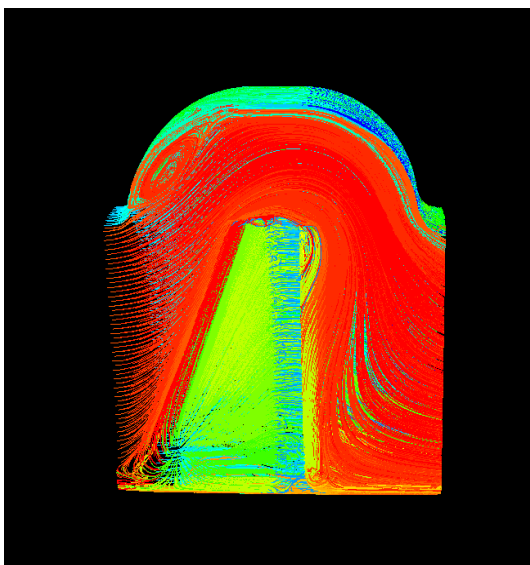
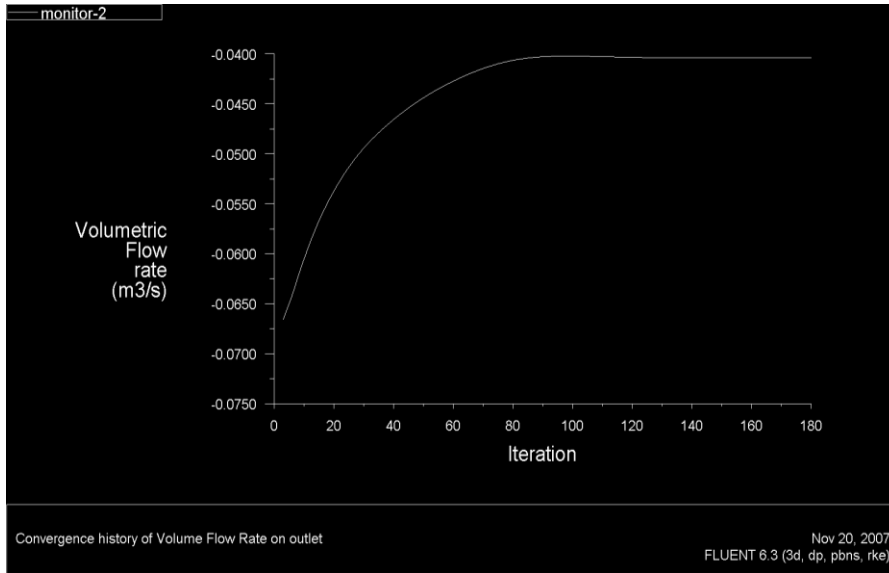


Figure 19: Steady state volume flow for first modeling attempt



This model achieves a 254.2 CFM flow rate which corresponds to a flow rate prediction of 508 CFM for two whole air extractors. According to this model however, we noticed that there was an area of recirculation at the top left corner of the air flow model on the inlet side. In order to try to correct this, we made a model that had a slimmer profile at that spot along the air path. The air flow path lines and steady state volume flow for this next trial are shown in Fig. 20 and Fig. 21.

Figure 20: Air flow path lines for the final trial (Air inlet on the right)

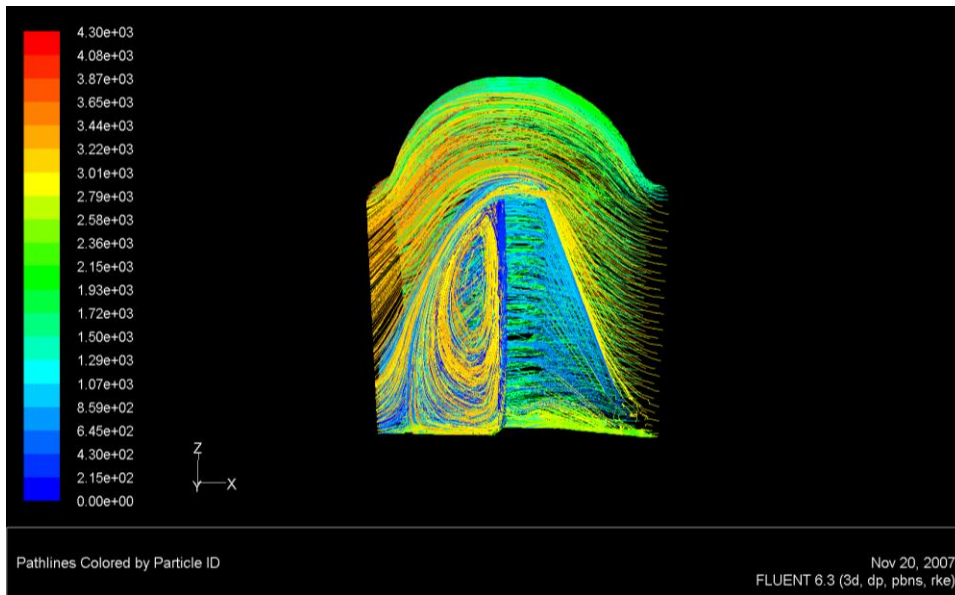
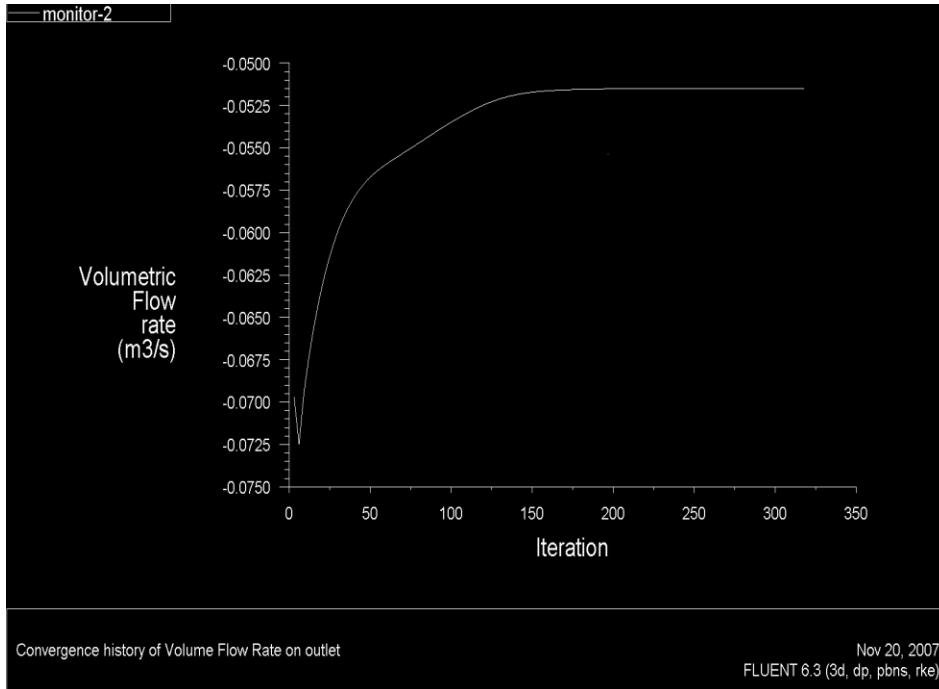


Figure 21: Steady state volume flow for first modeling attempt



As shown in Fig. 20 and 21 above, the targeted recirculation problem was corrected. Instead, a much larger recirculation pattern appeared near the outlet. However, the volumetric flow rate prediction of was 333.7 CFM per air extractor (667.4 CFM for two air extractors). This value is significantly larger than the CFM prediction for the first modeling attempt. Because of time constraints, we settled with this design at the time. This high value of flow rate is desirable because it leaves room for the CFM decrease for the analysis with flaps attached. The next step in this process is to run a FLUENT model that mimics the use of flaps by analyzing the pressure distribution across static “flaps” and comparing the weight required to hold the flap at that angle for the given pressure distribution. The goal is to design flaps that will not decrease the total volume flow value of 667.4 CFM below 500 CFM.

In dimensioning the concept, area of the inlet and outlet are set equal to the maximum allowable cross sectional area from specifications in the current air extractor which are 180 mm by 95 mm. This gives us an inlet/outlet diameter of 141.86 mm. The cross sectional area around the sound shield is equal to the area of the inlet and outlet. The maximum diameter is therefore 200.63mm. The dimensions of the housing are 226 mm by 84 mm by 84 mm due to the choice to shape the housing as a box. Dimension of the sound shield are shown in section 9.1.

To assist in material selection, CES Edupack version 4.7 software by Granta Design Limited is utilized to help determine which materials best fit the application. Desirable attributes for the housing include low price, low density (lightweight), a higher Young’s Modulus (housing should be rigid), and a high temperature range to ensure the housing will not melt. Upon searching the material index, a list of possible candidates in the thermoplastics category with their criteria

is listed below in table 3 (a sample graph from the CES software used in material selection can be seen in Appendix E).

Table 3: Thermoplastic candidates for housing with material properties

Acronym	Material	Density lb/ft ³	Price USD/lb	Young's Modulus 10 ⁶ psi	Maximum Service Temperature (F)
ABS	Acrylonitrile-butadiene-styrene	63.05-75.54	1.139-1.339	0.1594-0.4206	143.3-170.3
Nylons, PA	Polyamide	69.92-71.17	1.449-1.619	0.38-0.3641	230-284
PE	Polyethylene	58.62-59.93	0.7794-0.8574	0.09007-0.13	194-230
PET	Polyethylene terephthalate	80.53-87.4	0.7295-0.8024	0.4003-0.6005	152.3-188.3
Acrylic, PMMA	Polymethyl methacrylate	72.42-76.16	1.059-1.165	0.3249-0.5511	107.3-134.3
Acetal, POM	Polyoxmethylene	86.77-89.27	0.9993-1.239	0.3626-0.7252	170.3-206.3
PP	Polopropylene	55.56-56.81	0.6395-0.7348	0.13-0.2248	212-239
PS	Polystyrene	64.93-65.55	0.6695-0.7141	0.174-0.3771	170.3-217.1
tpPVC	Polyvinylchloride	81.16-98.64	0.7257-0.9979	0.3104-0.6005	140-158

Acrylonitrile-butadiene-styrene is ideal for the housing material due to its low density and Young's Modulus while remaining relatively affordable and appropriate for temperatures it will encounter. The CES software also lists some of its typical applications which include safety helmets, automobile instrumentation/components, and small appliance housing which are very similar to the material properties that are desired but will not be used and kept in consideration only as an alternate material. Polystyrene is chosen due its lower cost, a higher temperature range, similar density and Young's Modulus, and its recyclability which will be further explained in the "Design For Environment" section. Typical applications are also similar such as household appliances and video/cassette casing. Material selection for the sound shield will consist of a sound deadening foam and the flaps will consist of rubber. CES software has properties for a limited number of foams so we will assume sound deadening foam will fall under the category of or have similar characteristics to flexible polymer foam as seen in table 4 below. A low cost rubber is listed below as well that fits in the temperature range.

Table 4: Material characteristics of generic foams and chosen rubber

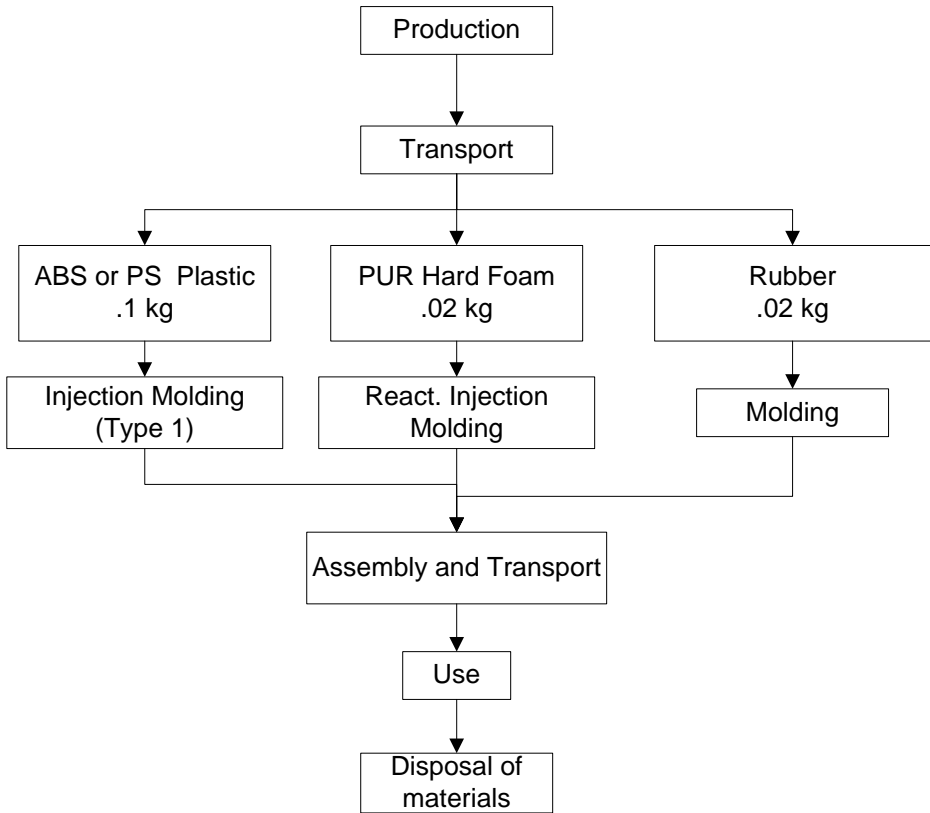
Material	Density lb/ft ³	Price USD/lb	Young's Modulus 10 ⁶ psi	Maximum Service Temperature (F)
Flexible Polymer Foam	4.37- 7.179	1.411- 1.505	5.802e-4-1.74e-3	181.1-233.3
Rigid Polymer Foam	10.61- 29.34	5.643- 11.29	0.02901-0.06962	152.3-332.3
Butyl Rubber	56.19- 57.43	0.5601- 0.6161	1.45e-4-2.901e-4	206.3-242.3

Tolerances for the injection molded housing are based on material choice. For a given dimension X, the tolerance is $X \text{ mm} \pm X*(.15/50 \text{ mm})$ is allowable. For the inlet and outlet openings, a tolerance of $X \text{ mm} \pm X*(0.1/10 \text{ mm})$ is allowable.

8.2 Design for Environment

In an effort to make our product more environmentally friendly we have decided to follow an Ecodesign model which optimizes a product design to minimize its environmental impact over its lifetime. The first step in this process is creating a process map to visually see how the materials are turned into our air extractor. This process map is displayed in Fig. 22.

Figure 22: Process map to visualize lifecycle of product



In this map we take into account the lifecycle three different materials used in the air extractor: plastic used to create the casing, foam used to reduce sound transmission, and rubber used for the flaps. Using this process map and process weights from the Eco Indicator 99 Manual for Designs we then created a chart which shows the environmental impact of each important stage of the process. We chose to focus our chart on production, processing and disposal of the materials. We ignored use because there is no environmental impact from the use of our air extractor. In our design we will use fabric flaps but rubber was used in the process map because numbers were available for rubber in the Ecodesign manual; also rubber was used for some Ford air extractor flaps.

In our environmental impact chart (Fig. 23) we initially performed calculations using ABS as the casing material. We found that the production of ABS was the highest impact step so we chose to reduce the impact by using PS. This material had similar physical properties, but a reduced production impact, and a negative recycling impact. These two factors combined reduced the impact of our outer casing from 42.3 mPt to 14.1 mPt.

Figure 23: Comparison of material choice with respect to recycling impact

WITH ABS				WITH PS			
Production				Production			
Material or Process	amount	indicator	result	Material or Process	amount	indicator	result
ABS	.1 kg	400	40	PS (HIPS)	.1 kg	360	36
PUR Hardfoam	.02 kg	420	8.4	PUR Hardfoam	.02 kg	420	8.4
EPDM Rubber (with molding)	.02 kg	360	7.2	EPDM Rubber (with molding)	.02 kg	360	7.2
		total	55.6			total	51.6
Processing				Processing			
Material or Process	amount	indicator	result	Material or Process	amount	indicator	result
Injection Molding- ABS	.1 kg	21	2.1	Injection Molding- PS	.1 kg	21	2.1
React. Injection Molding	.02 kg	12	0.24	React. Injection Molding	.02 kg	12	0.24
		total	2.34			total	2.34
Disposal				Disposal			
Material or Process	amount	indicator	result	Material or Process	amount	indicator	result
Municipal Waste ABS	.1 kg	2	0.2	Recycling PS	.1 kg	-240	-24
Landfill PUR	.02 kg	4.3	0.086	Landfill PUR	.02 kg	4.3	0.086
		total	0.286			total	-23.914
Total Impact	58.226			Total Impact	30.026		
ABS Impact	42.3			PS Impact	14.1		

The second stage of Ecodesign is using design for environment (DFE) guidelines to help minimize the impact of our product. The guidelines are shown in Fig. 24. We were able to implement the bolded guidelines into our design.

Figure 24: Guidelines for Ecodesign

DFE-1	New concept development
DFE-2	Physical optimization
DFE-3	Optimize material use
DFE-4	Optimize production techniques
DFE-5	Optimize distribution
DFE-6	Reduce impact during use
DFE-7	Optimize end of life systems

In designing our new concept we were able to physically optimize it in several ways. First of all, we are adding functions to the air extractor to serve more than one purpose. The added function of noise transmission reduction to the air extractor itself will reduce the additional insulation and bends in the air pathway that were previously necessary. We also physically optimized it by minimizing the amount of material necessary by using a hollow casing. We were able to optimize material use by using Polystyrene that had a lower environmental impact than ABS. We would hope to optimize end of life by having the air extractor either be reused as a spare part for another vehicle, or recycled through melting. Our product minimizes its impact during use by extracting air without the use of any motor or pump. This keeps our impact during use close to zero.

In full scale production, we will the design tweak it so that both sides of the casing can be snapped together in one step. Originally we thought about attaching the casing together with screws, which we may still do in our prototype. For our production model though, we can optimize the production technique by easily reducing the amount of steps necessary to attach the casing with snaps. These snaps should be fairly easy to detach with a generic tool. This will also help in detaching the casing in case of recycling, also optimizing the end of life system.

8.3 Design for Manufacturing

We tried to optimize our design for manufacturing, specifically injection molding, using some of the guidelines provided in Table 5.

Table 5: Design for injection molding manufacturing principles*

DFIM-1	Minimize wall thickness
DFIM-2	Keep uniform wall thickness
DFIM-3	Add draft angle
DFIM-4	Avoid sharp corners
DFIM-5	Keep rib thickness as 60% of wall thickness
DFIM-6	Avoid side pins in molds
DFIM-7	Avoid internal depression
DFIM-8	Do not over tolerance

*Bolded principles are used in design

With respect to injection molding manufacturing specifically, certain design principles should be taken into account for robust manufacturing as listed in the table above. Such principles include minimizing wall thickness and using ribs if necessary to help create the sense of a thicker wall. The design will incorporate a wall thickness of 3 mm (0.118”) and will not require ribs. This feature will allow faster production time due to lower pressure requirements and less material. Uniform wall thickness should also be used and the thickness of the plastic housing will be 3 mm (0.118”) throughout. This is to ensure even pressure throughout the product when being manufactured. Tolerances are kept in proportion to 0.2 mm for every 50 mm for walls and 0.08 for every 10 mm for holes. This is to ensure precise products with excellent build quality.

8.4 Design for Assembly

We tried to optimize our design for assembly using some of the guidelines provided in Table 6.

Table 6: Design for assembly, part handling, part insertion and joining principles*

DFAS-1	Minimize part counts
DFAS-2	Modularize multiple parts into single subassemblies
DFAS-3	Permit assembly in open spaces
DFAS-4	Standardize to reduce part variety
DFPH-1	Maximize part symmetry
DFPH-2	Add features to facilitate orientation
DFPH-3	Avoid parts that are easy to tangle or nest
DFPH-4	Color code different parts that are shaped similarly
DFPI-1	Add features for easy insertion
DFPI-2	Add alignment features
DFPI-3	Prefer z-assembly. Never require turning over
DFJ-1	Eliminate fasteners
DFJ-2	Allow access of tools
DFJ-3	Prefer snap fits
DFJ-4	Avoid over constraining

*Bolded principles are used in design

In order to reduce time and cost in assembly, design for assembly principles have to be taken into account when producing our design. Design for assembly states minimization of parts should be taken into account hence we only have the following parts for the air extractor: front piece of housing with grid for flaps, 3 flaps, circular sound shield in middle, and the back piece. This is the minimum number of parts at the moment without costing too much in integrating parts together while allowing easy assembly as well. The housing could be produced as one piece but would not permit assembly in open space (due to the sound shield) which is another design for assembly principle we will adhere to and why the housing is broken into two pieces. Though this is contradictory to minimizing part count, the reasoning is justified by the advantages in assembly. In terms of part handling principles, the ribs on both housing pieces have notches to help orient the sound shield when it is inserted in assembly. This will allow alignment with ease and also help keep in shield in place after production. In terms of design for part insertion, the parts can be assembled on the z axis and do not require turning over and the front piece with the flaps should be added second to last so that the flaps are added last without turning over. This is to ensure an efficient assembly that is easy to repeat. In terms of design for joining, fasteners are eliminated in mass production (we will use fasteners for the prototype) for the housing and will instead incorporate snap fits to join the housing. This is to reduce parts, costs, and assembly time.

8.5 Failure Mode and Effect Analysis

In order to identify potential failures, the effects of these failures, and preventive actions, a Failure Mode and Effect Analysis chart is generated. This is done by listing components, component functions, and potential failures of these components with causes and effects of failure. Ratings for severity, occurrence, and failure detection are given and multiplied together to get a risk priority number (RPN). Current design and testing are asked to be evaluated for a recommended action to lower the RPN. We are then asked to estimate severity, occurrence, and detection for the new recommended action. This is done using a scale of 1-10 where ten is the highest (product is inoperable, very likely, and undetectable for respective categories in order of severity, occurrence, and detection). A small sample of the FMEA chart is seen in Figure 25 below. For example if the flap were to remain open at all times it may cause higher road noise to be let back into the cabin due to the flap becoming stuck on the housing. There are currently no designs or tests to prevent this. This failure would happen occasionally (occurrence rating 4), is noticed by the average consumer (severity level 3), and likelihood of detection is moderate (detection rating 3). The rest of the FMEA chart can be found in Appendix F.

Figure 25: Sample FMEA chart for flap component of redesigned air extractor

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanism(s) of Failure	Occurrence (O)	Current Design/ Control Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
Flaps - Reduce gauge pressure by controlling air flow	Flaps remain open at all times	Higher road noise levels let into cabin	3	Flap becomes stuck on housing	4	None	3	Design block to prevent flaps from opening too wide	36	3	2	3	18
		Allow flow back into cabin (fumes, debris)	5	Flap becomes stuck on housing	4	None	5	Design block to prevent flaps from opening too wide	100	5	2	5	50
	Flaps become stuck closed	Discomfort for passengers from pressure buildup	3	Too much flow trying to go in wrong direction	4	None	5	Add more lines to grid to better spread out area of flap	60	3	3	5	45
		Difficulty closing doors	2	Too much flow trying to go in wrong direction	4	None	4	Add more lines to grid to better spread out area of flap	32	2	3	4	24
	Flaps fall off	Higher road noise levels let into cabin	3	Adhesive not adequate deteriorates	2	None	3	Design clips are use stronger adhesive	18	3	1	3	9
		Allow flow back into cabin (fumes, debris)	5	Adhesive not adequate deteriorates	2	None	5	Design clips are use stronger adhesive	50	5	1	5	25
		Requires complete replacement of unit	7	Adhesive not adequate deteriorates	2	None	3	Design clips are use stronger adhesive	42	7	1	3	21

The chart states we should focus on flap and sound shield failures judging from the RPN numbers. This is due to the likelihood and severity of these two problems compared to housing failure. A recommendation to help with detection of this problem would be to implement a testing apparatus to allow visibility of the air extractor unit with a simulated pressure pulse as opposed to testing an assembled vehicle with door closing.

9 FINAL DESIGN

The final design of the air extractor is assembled with two parts for the housing, a sound deadening piece and flaps. The housing has an “outlet flow” piece and an “inlet flow” piece.

These two pieces attach together to suspend the sound deadening material between them. The flaps are attached to the outlet flow piece. Each piece is described in their respective sections below.

9.1 Sound Deadening Piece

The sound deadening piece shown below in Fig. 26 has two functions. The main function is to block sound transmission through the air extractor. This is why one side is completely flat. This flat is pointed towards the outlet of the air extractor so that a maximum area normal to the sound coming in is created. The second function of the air extractor is to direct air as it flows past the extractor. This is achieved by the conical side of the sound deadening piece. This side is pointed towards the inlet of the air extractor so minimal recirculation is created. Dimensions of the sound deadening piece are shown in Fig. 27.

Figure 26: Two views of sound deadening material insert piece

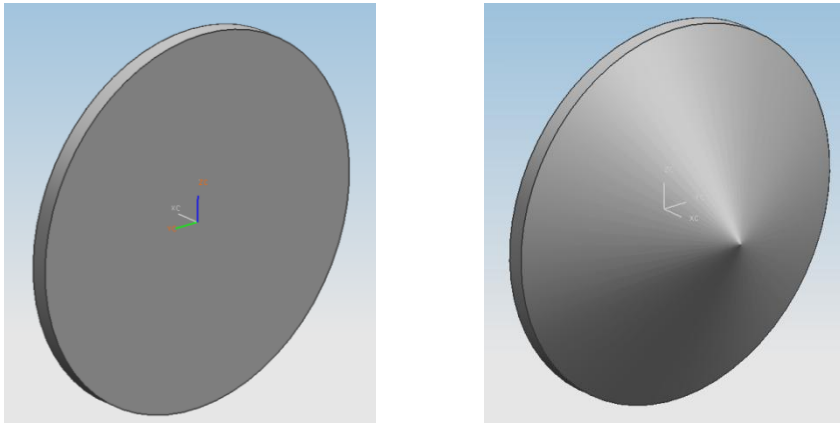
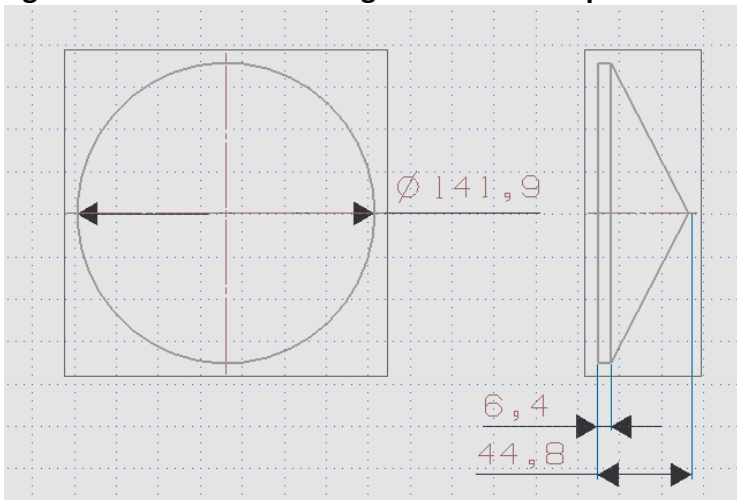


Figure 27: Sound deadening material insert piece dimensions



All Dimensions are in millimeters.

9.2 Inlet Piece

The inlet piece has multiple functions. This piece accepts the air flow from the inside of the car through the smaller diameter hole. The cross sectional area then increases so the air can flow

around the sound deadening material. The air “exits” this piece through the side with the larger diameter hole. The support ribs have a cutout to receive the conical side of the sound deadening material. The inlet piece has screw holes so that the prototype can be screwed together. The inlet piece is shown in Fig. 28 and Fig. 29.

Figure 28: Two views of the inlet piece

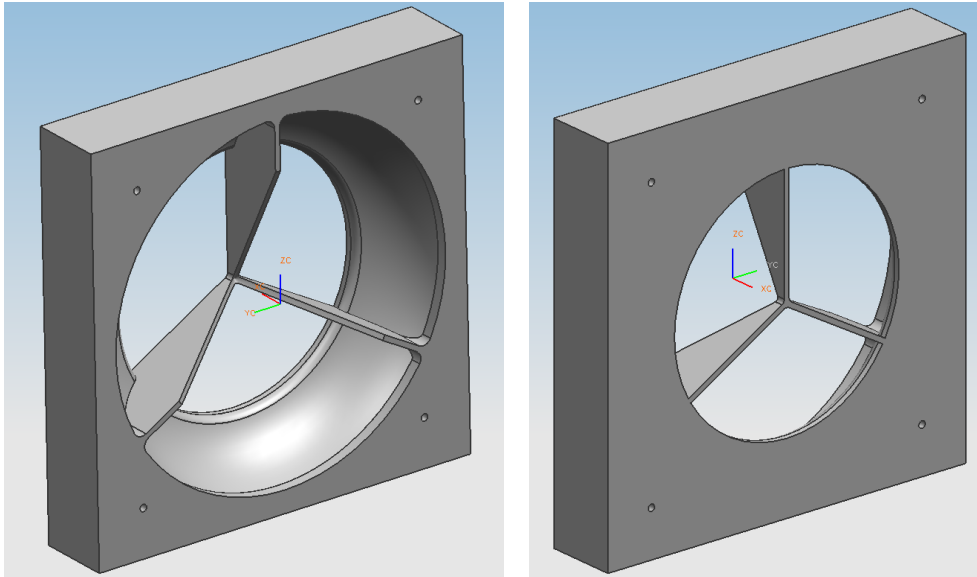
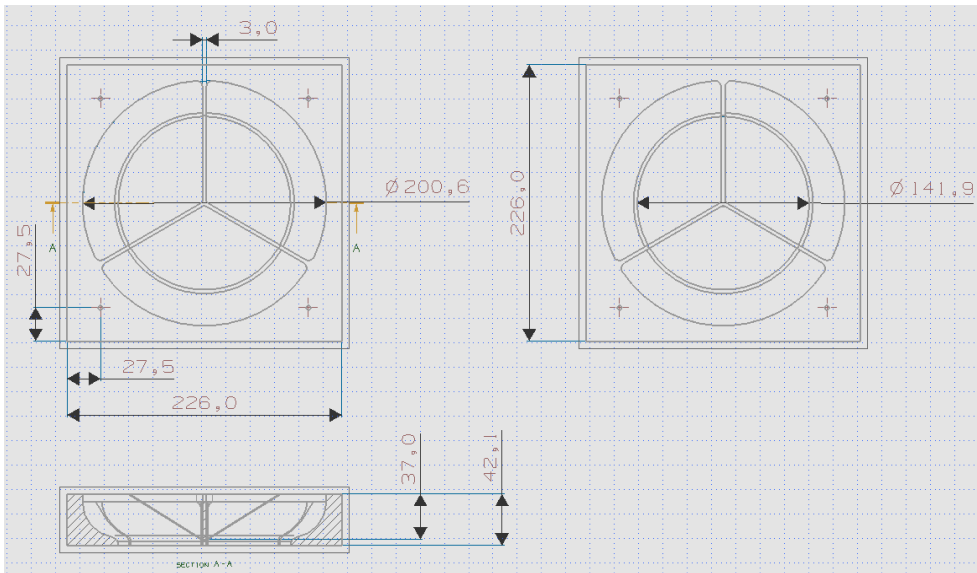


Figure 29: Inlet piece dimensions



All Dimensions are in millimeters. Prototype is symmetrical at the 90,210 and 330 degree planes about the center. All fillets and rounds have radius of 5mm.

9.3 Outlet Flow Piece

The outlet piece has most of the same functions as the inlet piece. This piece accepts the air flow from the inlet piece through the larger diameter hole and releases it through the smaller diameter hole. The ribs are formed to support the flat side of the sound deadening material. The piece has screw holes so that the prototype can be screwed together. The outlet piece is shown in Fig. 30 and Fig. 31.

Figure 30: Two views of the outlet piece

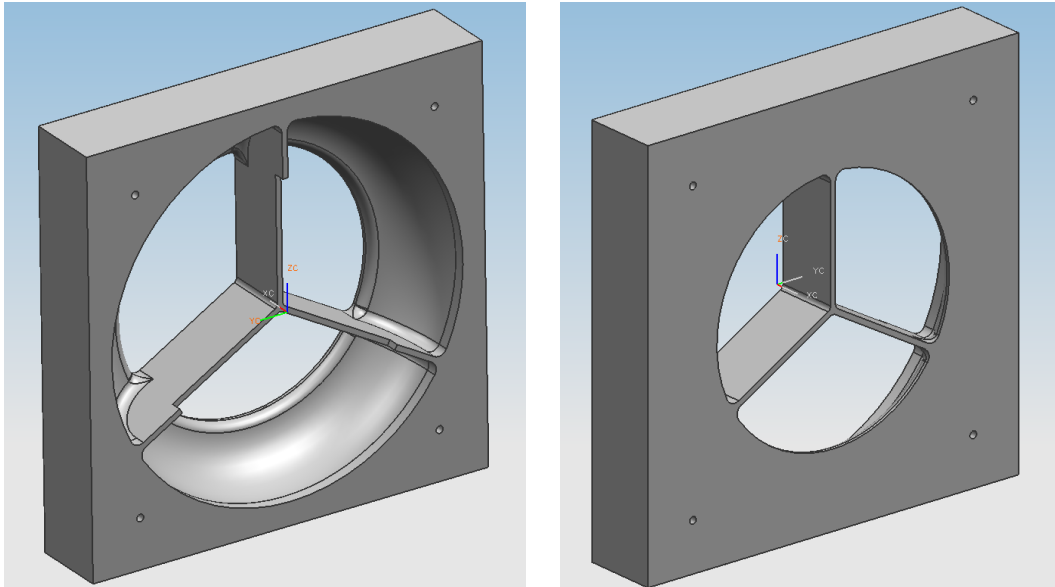
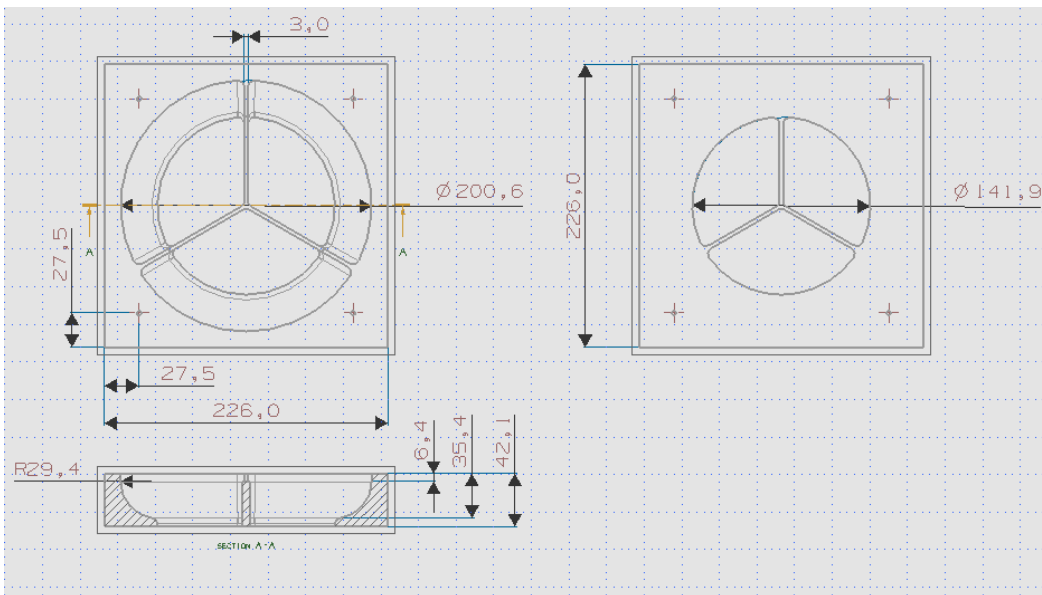


Figure 31: Exit flow dimensions

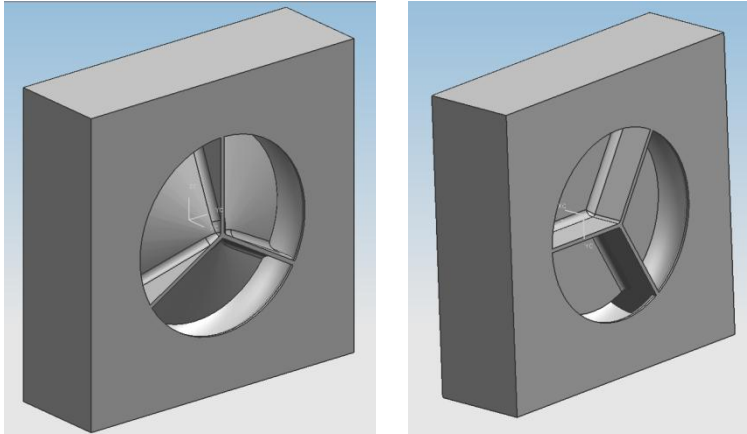


All Dimensions are in millimeters. Prototype is symmetrical at the 90,210 and 330 degree planes about the center. All fillets and rounds have radius of 5mm.

9.4 Full Assembly

The inlet and outlet pieces attach together to support the sound deadening material between them as shown in Fig. 32 below.

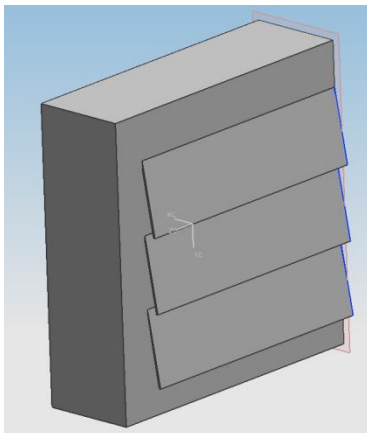
Figure 32: Two views of the inlet piece



9.5 Flaps

The exact dimensions and methods of attaching the flaps still need to be decided upon. The final decision will aim towards having more, smaller flaps than one large one. The flaps will be attached to the external side of the outlet piece as in the example shown below in Fig. 33.

Figure 33: Example of flaps on outlet piece



9.6 Bill of Materials

The total cost of the production of the prototype is \$205.67. This price involves the materials and labor for the housing, sound deadening material and flaps. Prototypes are going to be made on molds we produce so that we can test various combinations of the housing material and B-Quiet Extreme sound deadening material. The breakdown of the cost for the prototype is shown below in Table 7.

Table 7: Bill of materials

Quantity	Part Description	Purchased From	Part Number	Cost
1	Foam-Liquid 2-Part	West Marine	314080	\$100.69
1	B-Quiet Extreme 12 ft^2	B-Quiet	-	\$39.99
1	B-Quiet V-Comp 13.5 ft^2	B-Quiet	-	\$64.99
1	Current Flap Material	Ford Motor Company	-	\$0.00
			Total	\$205.67

10 MANUFACTURING

10.1 Cost Model for Mass Manufacturing

Cost analysis for materials, tooling, and labor must be calculated to validate the production of the concept. Cost modeling is broken down into three categories: material cost, tooling cost, and production cost. The “material cost per unit” equation listed below is the logical first step in calculating the cost so raw materials cost can be found. We assume 5% waste on injection molding which is about average for injection molding. Material for the housing is calculated to be about \$0.12/unit.

$$([\text{Material Weight} + \text{Scrap}] * \text{Material Cost/Lb})_{\text{Housing}} \quad (\text{Eq. 1})$$

Tooling cost per unit will be calculated for two conceivable manufacturing methods. Injection molding cost is calculated depending on the complexity of the product. The design is split in half and will require two molds to produce. Based on the irregular contour and cam/lifters needed for undercut, the injection molds is rated at medium complexity with one cavity for each mold. Taking the average of the cost range, estimated cost for each mold is \$15,000 or \$30,000 for both molds. Tooling cost per unit can then be found by dividing tooling cost by our estimated production volume (100,000 units) which comes out to \$0.30/unit.

Production cost is calculated by first finding the tonnage of the machine being used. Capacity of the machine needed can be calculated by the formula below where σ is a material rating in terms of ton/cm², N is the number of cavities, and A is the projected area of the part across the mold. Tonnage rating is approximately 255 tons.

$$T = \sigma NA \quad (\text{Eq. 2})$$

Direct labor costs, dependent on T, are calculated based on the manufacturing method of injection molding used in equation 3 below. Direct labor cost is calculated to be \$45.30/hr. Processing time for the two molds or a whole unit is calculated with equation 4 listed below and found to be 18.5 seconds each mold or 37 seconds/unit (.0103 hours/unit). Multiplying this figure by \$45.30/hr gives us a production cost of \$0.47/unit.

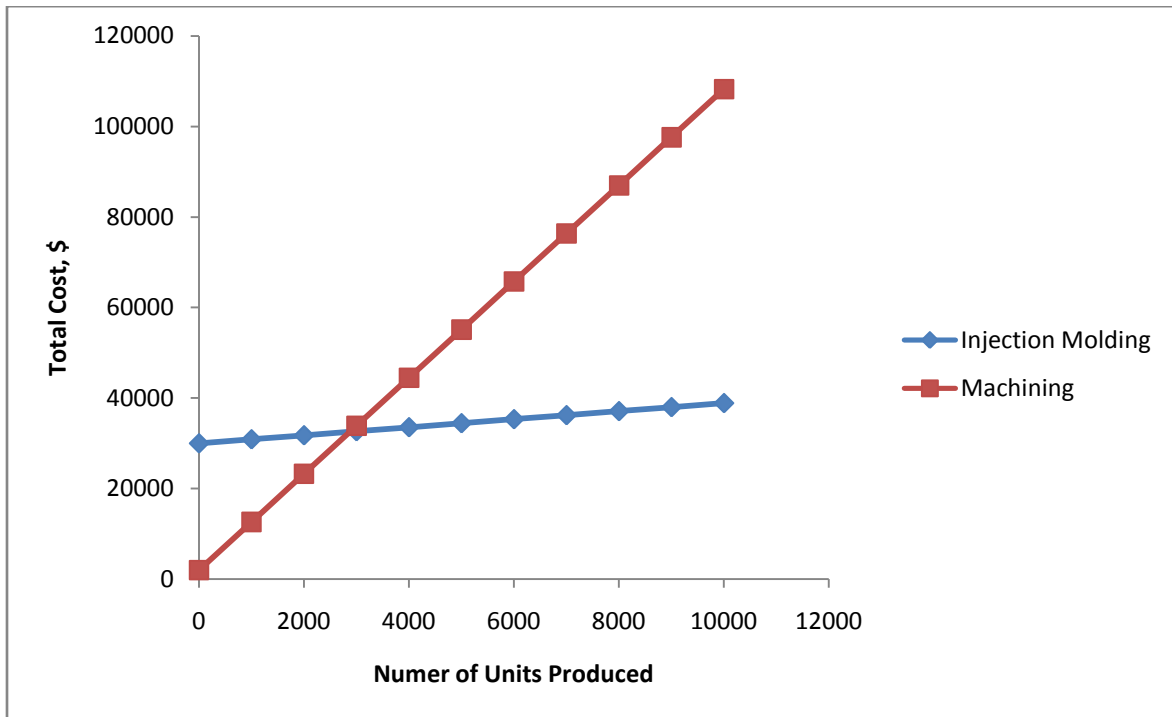
$$\text{Direct Labor/hr} = 30 + 0.06T \quad (\text{Eq.3})$$

$$\text{Processing Time} = (5 + th^2/\alpha)/N \quad (\text{Eq. 4})$$

Total cost by summing material, tooling, and production cost per is \$0.89/unit.

Validating which manufacturing method should be employed when mass producing the air extractor is accomplished through comparison of cost analysis. Two possible manufacturing methods include machining and injection molding for the plastic housing. Initial cost for a mold used for injection molding is \$30,000 as stated earlier while initial cost for a fixture used in machining is estimated at \$2000 for typical applications. Injection molding is rated at \$0.59/unit including only materials and processing while machining is rated at \$10.62/unit including materials and processing (\$0.12 for materials and \$50/hr for CNC machining * .21 hr/unit which is \$10.50/unit). Fig. 34 below compares injection molding to machining costs in terms of number of units produced.

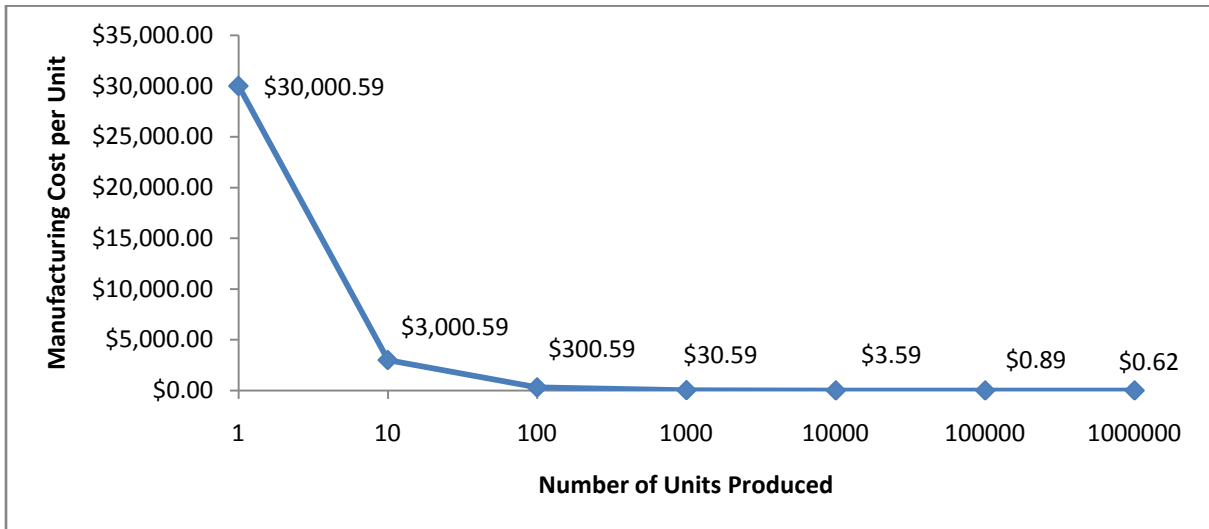
Figure 34: Economies of scale graph comparing injection molding to machine costs



As seen in the graph, machining is cost effective compared to injection molding when the number of units produced is less than 3000. Injection molding is the cost effective method when number of units produced is greater than 3000. Our application will entail much more than 3000 units seeing as automobile production is a much higher figure than 1500 vehicles (two extractors per vehicle). In the long run, injection molding is the much more cost effective manufacturing method. Cost per unit with respect to production unit volume is calculated as well to determine what cost per unit is at different intervals. In terms of product cost per unit calculation, we calculate cost by adding material cost (\$0.12/unit) equipment cost (\$30,000

mold cost) divided by the number of units, and production cost (\$0.47/unit). Fig. 35 below shows how number of units produced alters cost per unit.

Figure 35: Economies of scale graph showing cost per unit with respect to units produced in log scale



Labor cost and materials costs are functions of manufactured volume and will increase at a constant rate with respect to manufactured volume. Equipment cost is a fixed cost and will therefore decrease manufacturing cost per unit substantially when more units are produced. We estimate the manufacturing cost to be less than \$2.00 per unit when taking into account the number of vehicles produced per year.

10.2 Prototype Manufacturing

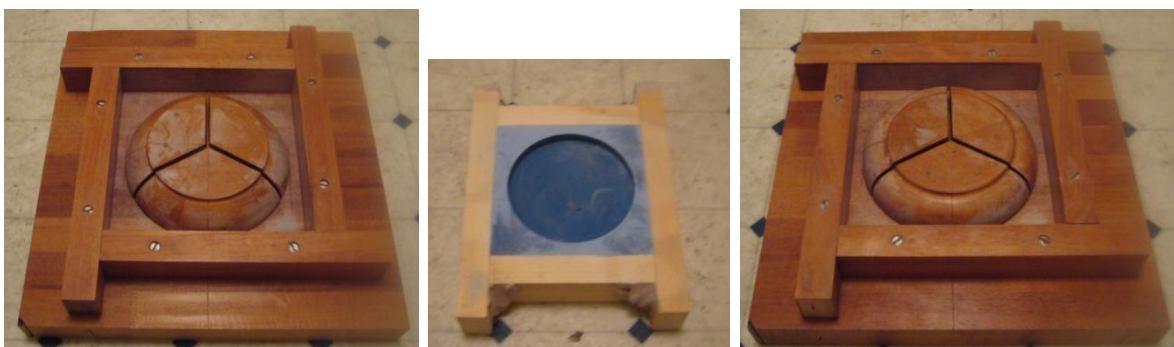
The plan to construct the prototype involved making a mold of the reverse volume so material could be poured into it to make the correct shape. We chose to produce molds because prototypes of different materials could be easily made. The mold for the prototype was constructed on 11-24-07 along with a REPRO plastic prototype. The liquid foam was purchased on 11-30-07. The foam prototype was then constructed 12-01-07.

The reverse volume of the prototype was built into two halves that were to be attached together to encompass the sound deadening piece as shown before in the final design section (Figure 37, pg. 37). The processes for constructing the two reverse volumes were very similar to each other so it can be assumed the same for both halves unless otherwise noted. The first step was to cut a solid piece of mahogany down to the height of 42.1 mm. The piece was then taken to the lathe to be turned down to the outer diameter of 200.6 mm. Once this was done, the smaller diameter of 141.9 mm for the inlet/outlet sections was cut to a depth of 5.1mm. A cutting bit with a radius of 6.35 mm was used to cut this section so that a filleted corner was left on the mahogany piece.

From here, the two pieces' processes differ. For the outlet piece, a radius of 29.4 mm was cut into a piece of plastic to be used as a guide to make the radius for the curved wall on the lathe. For the inlet piece, more material was cut off to get the "slimmer" profile of its curved wall. After these two pieces were turned on the lathe, they were each cut into three pieces on the ban saw. The cuts were a width of 3 mm. These were to be used as the ribs later on. For the outlet piece, 3 pieces of balsa wood were attached to the insides of each cut to make the outline for the sound deadening piece. For the inlet piece, 3 balsa wood pieces were cut and attached to the insides of each cut to make the outline for the sound deadening piece. At this point, the shapes of the inside part of the molds were completed. After this, four pieces of mahogany wood were cut to the height of 50 mm. Then, a mahogany board was planed and sanded flat so that the walls and inside pieces could be attached to it. The shapes for all the necessary mold pieces were finished. Sanding sealer and wax was applied to each piece so that the plastic or foam would not stick to it when poured. Along with this, slight draft angles were applied to the pieces so that the plastic or foam could be lifted out with ease. Once the wax was applied, the mold pieces and walls were secured down to the flat board. Then the foam/plastic was poured up to a height of 50 mm. It was then lifted out of the mold and sanded down to the right height to make a smooth and flat surface. For the plastic prototype, four holes were drilled into the prototype so that the two pieces could be bolted together.

To make the sound deadening piece, a piece of pine was turned on the lathe to the dimensions shown in the sound deadening piece section (section 9.1). This was then secured to a board with a wall around it to make a mold. The mold was poured with the REPRO plastic and the end result is in Figure 36. Foam was then poured into this mold to make the sound deadening piece.

Figure 36: In order from left to right: Inlet, sound deadening piece and outlet mold



Because this product is intended for mass production, the manufacturing and assembly processes needs to be altered to account for various requirements as stated earlier in sections 8.2, 8.3, 8.4 and 8.5. First, the actual product most likely will not be attached together by bolts, so there will be changes made to the mold so that each piece can incorporate some type of snap fits so that pieces can be pressed together and locked. Along with this, the actual product

mold will need to account for flap attachment as well. The prototype has a bulky, square frame design that will waste material if used in production. So, the mold for the product will be sleeker so that only the necessary amount of material will be used for the product. The material for the mold will have to be a low cost, sound deadening, sturdy material and satisfy cost, longevity and performance standards. Because this is a simple product, there should be no ethical issues involved if it performs its desired function properly.

The final prototypes are shown in Fig. 37 below in foam and REPRO plastic forms.

Figure 37: Final Prototype: Disassembled plastic prototype in blue with assembled foam prototype in yellow



11 TESTING

After visiting the Ford PDC several times, we found that Ford currently has a robust flow meter which we were able to use to test airflow. It works by attaching the air extractor to one side of a sealed box as shown in Fig. 38. The box is then pressurized to 1 atm and the flow meter records the volume of air being pumped into the box to maintain this pressure. Of course, at steady state pressure, the airflow into the box equals the airflow out and thus we have our airflow number. The air extractor is attached with duct tape. To minimize leakages we passed over the seals with a stethoscope to listen for air leaks. These spots were then resealed with more duct tape until the whole perimeter of the air extractor was sealed.

Figure 38: Sealed box with foam prototype attached (left), Flow Systems flow meter (right)



We tested the airflow on several different air extractors with different variations on our prototype. A summary of our results are reported in Table 8. We first attached our foam prototype to the flow meter with flaps on. Under these conditions we achieved a flow rate of about 185 CFM. We then decided to remove the flaps to see how our prototype would compare with our FLUENT analysis with no flaps. Our FLUENT analysis predicted that we would achieve about 233 CFM at 1 atm Pressure. After running the flow meter, we achieved a flow rate of about 215 CFM which is over 90% of our predicted value.

Table 8: Air extractor flow rates

Air Extractor	Experimental flow rate (CFM)	% of predicted flow rate
Foam with flaps	185	NA
Foam without flaps	215	92%
Plastic with flaps	165	NA
Plastic without flaps	185	79%
Ford F-150	475	NA
Ford Taurus	120	NA

Next, we tried to run the test on our plastic prototype with the wooden cone in the center rather than the foam. However, on this particular day we had trouble fitting the wooden piece into the plastic prototype and it left a gap between the two sides of our air extractor. We still wanted to try running tests on this prototype as well, so we placed a foam lining in the gap to

prevent air leaks and ran the test. We achieved airflows significantly lower than with the foam prototype (160 CFM with flaps, 185 CFM without flaps), but we believe that much of this can be contributed to the gap in the prototype which could create turbulent flows as shown below in Figure 39.

Figure 39: Foam between pieces



We then ran the airflow test on Ford F-150 and Taurus air extractors shown mounted on the sealed box in Fig. 40. The Ford F-150 air extractor had the same inlet opening area as our prototype, and it achieved 475 CFM. However, this is near the best case scenario for this size opening because the F-150 air extractor is simply an opening with flaps. Any complexity added to reduce sound transmission will inevitably reduce air flow.

Figure 40: Mounted Ford Taurus air extractor (left), Ford F-150 air extractor (right)



There are two more criteria which should be tested for in the future: sound transmission and flap noise. Since the ME sound lab was unavailable for testing after we built our prototype, we were unable to test for sound transmission.

To test for sound transmission, we recommend using the ME department sound lab, or an equivalent acoustic lab. First, our air extractor should be attached to the top of the sound proof box in the sound proof room. Then several different sound frequencies should be played from a speaker inside the box. A microphone connected to a data acquisition unit should be placed directly above the air extractor to measure sound transmission. The test should be performed

with flaps open since that's when most noise pollution enters the car. This experiment should then be repeated with other air extractors and the noise levels can be directly compared.

The final test involves using the acoustics box displayed in Appendix D to test flap noise. Theoretically, this test works by sealing the air extractor on the right side of the box, and sending a simulated door slam pressure pulse through the air extractor. While the flaps open, close, and reverberate, a microphone placed 0.5 m away records the flap noise. Currently, this test box is out of commission and requires debugging. We would recommend that this test be conducted on our prototype in the future once the system is debugged. We would also recommend that these tests be conducted on other air extractors to benchmark against.

12 FUTURE IMPROVEMENTS

The design of our prototype air extractor proved to have an air flow performance sufficient enough to meet the design requirements set by Ford. Although we were not able to test for the sound transmissibility of our prototype, the basic design should reduce outside noise from coming into the vehicle cabin. However, room for improvement of our prototype is still existent, including problems with installation, material selection, and sound flap attachment.

The brittle REPRO plastic material used for manufacturing our prototype cannot be implemented in real life. The foam material for housing is not realistic either due to cost and durability issues. We decided in a mass production situation, using polystyrene would be best for manufacturing and environmental reasons. The selection of our material will be important since this affects our sound and airflow performance. Currently, as discussed in the testing section of this document, the foam prototype proved to have a higher air flow performance. We believe that this is due to the porous material of the foam, allowing for flow through the material itself as well. Also, sound testing through the plastic prototype will allow sound to flow through much easier compared to other materials. Therefore, it would have been ideal to have selected a material closer to that of polystyrene in order to prove both airflow and sound deadening capabilities. In addition to the material selection, the width dimension of the prototype will need to be reviewed. The outer shell of the prototype will be trimmed to fit with the inner wall shape (trimming off the corners), which will reduce the overall dimension. However, our prototype is 84.2 mm wide, which is still much wider than the current extractor dimension. This width may cause problems when installing into the actual vehicle since space is a crucial issue. One solution to this may be to introduce a thinner sound-deadening cone in the middle of the air extractor to make the overall dimension much thinner. Since we have proven that a single conical shape for the sound shield is good for air flow performance, making this piece thinner will not require a significant design change. This would require scaling down and regenerating our model using computational fluid dynamics.

To verify a better sound shield performance, our prototype will also need to have a better flap attachment. Currently, the flaps are pinned or glued to the prototype outlet. This may cause the flaps to fly off when there is a constant airflow over a long period of time. We could not machine any additional holes due to a risk of damaging the brittle material of the outlet. In mass production situations, an included frame may be designed to be manufactured on the outlet piece and flaps can be easily attached. This will allow for high manufacturability and the flaps will sustain high airflow situations and be robust.

13 CONCLUSION

In our first few weeks we were able to accomplish several important steps. We met with our sponsors and created our new problem definition: redesign the air extractor to maintain or improve on the current air extraction performance while reducing noise transmission significantly. In our information search we found several new ideas that aren't used in the auto industry for relieving pressure that we may be able to apply to our design. We also did research and found some methods and materials for reducing noise transmission. We have created customer requirements and engineering specifications for our QFD through our discussion with our sponsors which will guide our design. We found that while noise transmission reduction is not the most important engineering specification in terms of the function of the air extractor, it will still be our focus in our redesign.

After Design Review 1, our group went to the PDC again to clarify more engineering problems that we must take into account. This included the reverberation noise the flaps create during door closing. We were also able to investigate competitors' air extractor models to compare against Ford's and our prototype designs.

With the engineering problem defined, our group brainstormed ideas to come up with the best design that will fulfill both air extraction and sound proofing capabilities. We used a 'go, no-go' process to narrow down to five concepts. We then used a Pugh Chart to select our final concept.

Since DR2 we have been able to perform a computational fluid dynamics analysis on our selected design to tweak its profile for better airflow. We also performed DFE, DFMA, and FMEA analyses on our design to further optimize it for those applications. We were able to predict the cost of our prototype to be around \$200 which is within the range of our budget. We also performed a full scale manufacturing process and cost estimate for our air extractors. Our results showed that at a volume of 100,000 pieces, our cost would be less than \$1. Based on these results, our model would be feasible given the cost constraint of \$2.

After testing the airflow performance on the airflow meter, we have proven that the CFD analysis was valid since the test result numbers were close to that on the computer. We were

also able to achieve Ford's airflow capability requirement of 175 CFM per air extractor. However, we were not able to test the sound transmissibility of our manufactured prototype to benchmark this criterion against the current air extractors. Only through physical judgment were we able to conclude that the sound reduction performance was higher. Further sound testing will prove the validity of our prototype design in more detail.

14 ACKNOWLEDGEMENTS

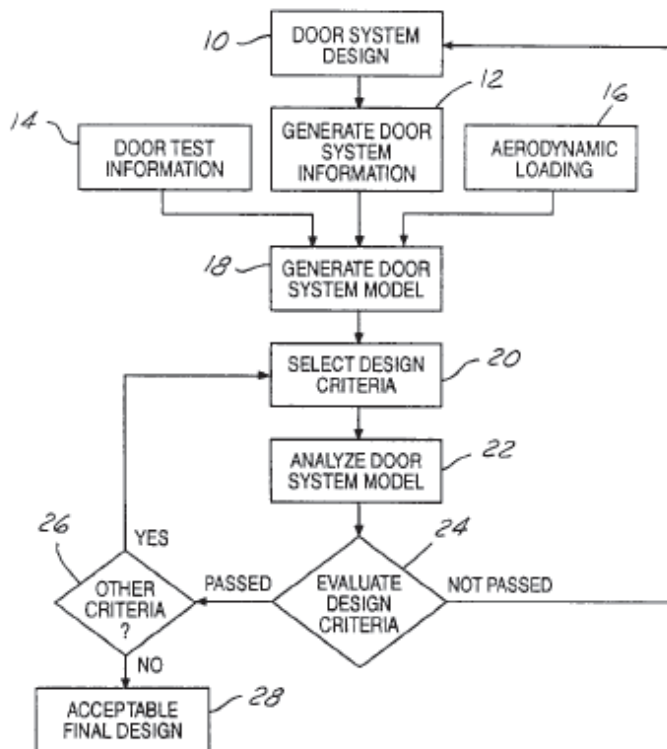
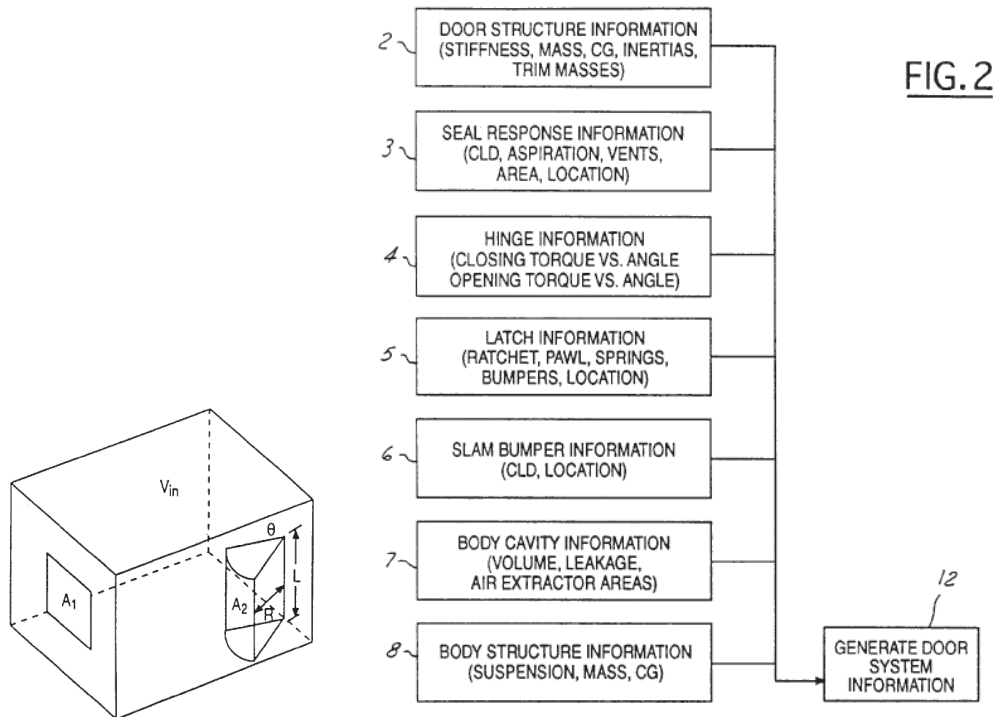
Our team would like to first thank Professor Bogdan Epureanu for his guidance and enthusiasm throughout the project. Special thanks to Dr. Darrel Kleinke for all his hard work and time spent working with our team to help achieve our goals. We would also like to thank Roger Michna, Ken Reo, Alexander Petniunas, Todd Dishman, and Dick Newton at Ford Motor Company for their help with using equipment and taking the time to answer our questions. Lastly, we would like to thank Ford Motor Company for sponsoring this project.

15 REFERENCES

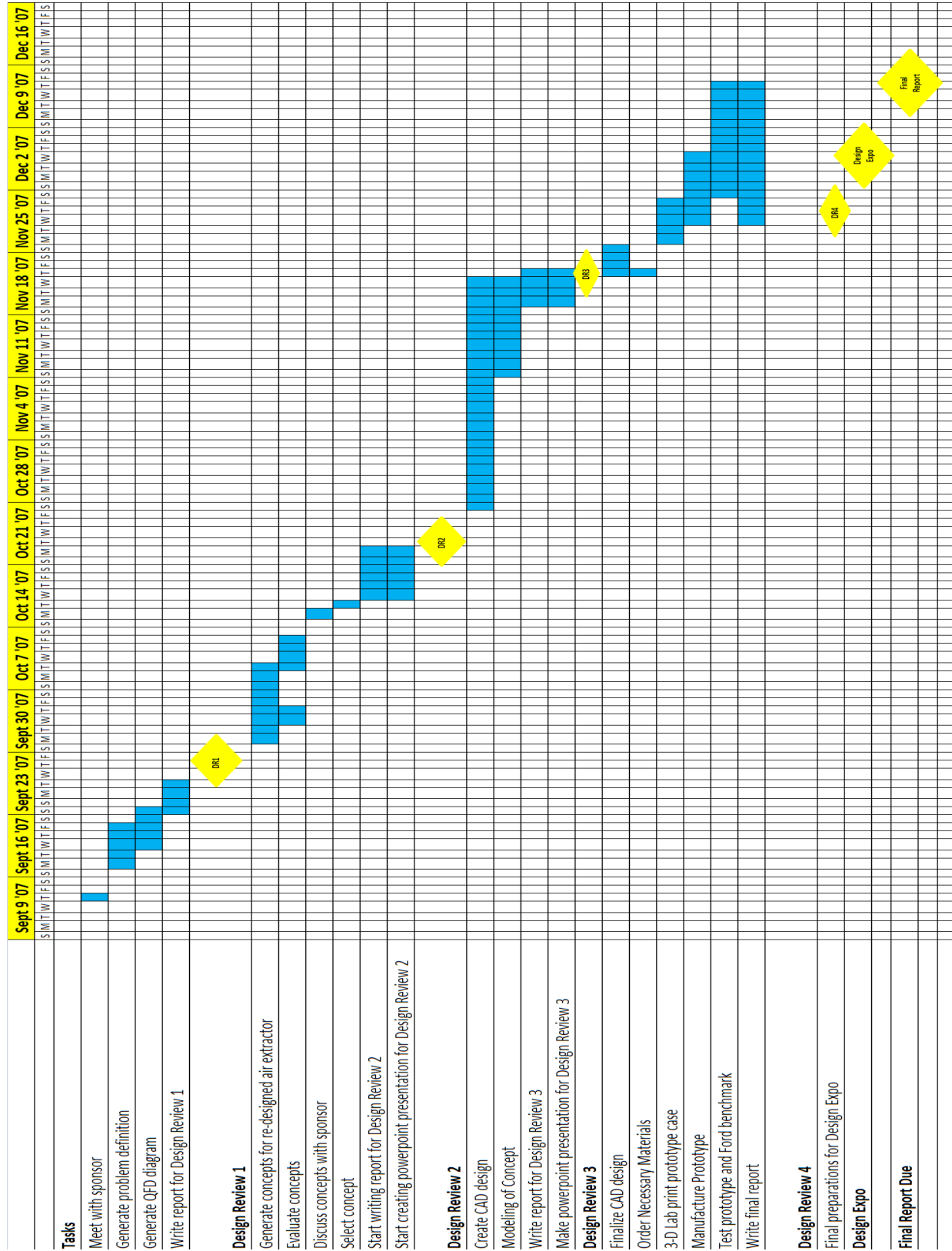
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16.0 APPENDICES

16.1 Appendix A – Vehicle Door Design Model

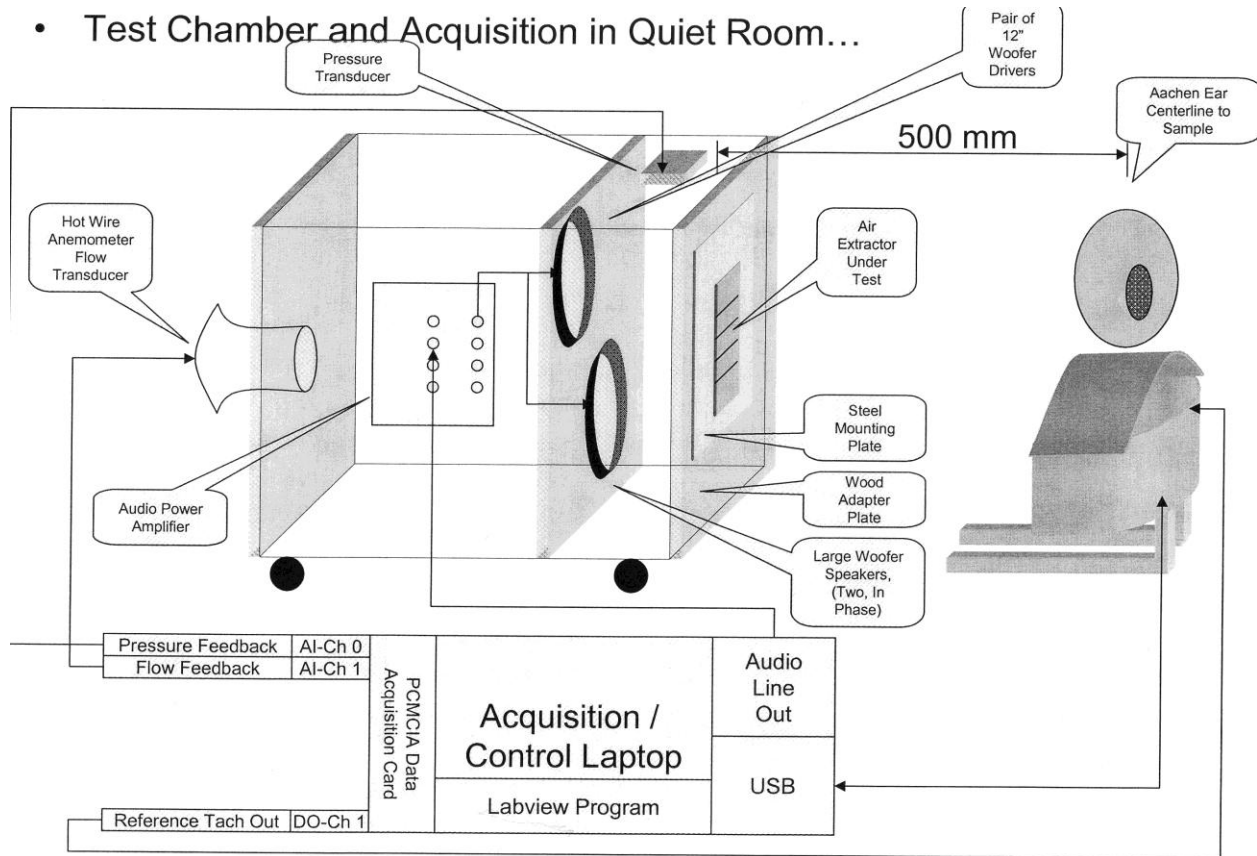


16.3 Appendix C – Gantt Chart

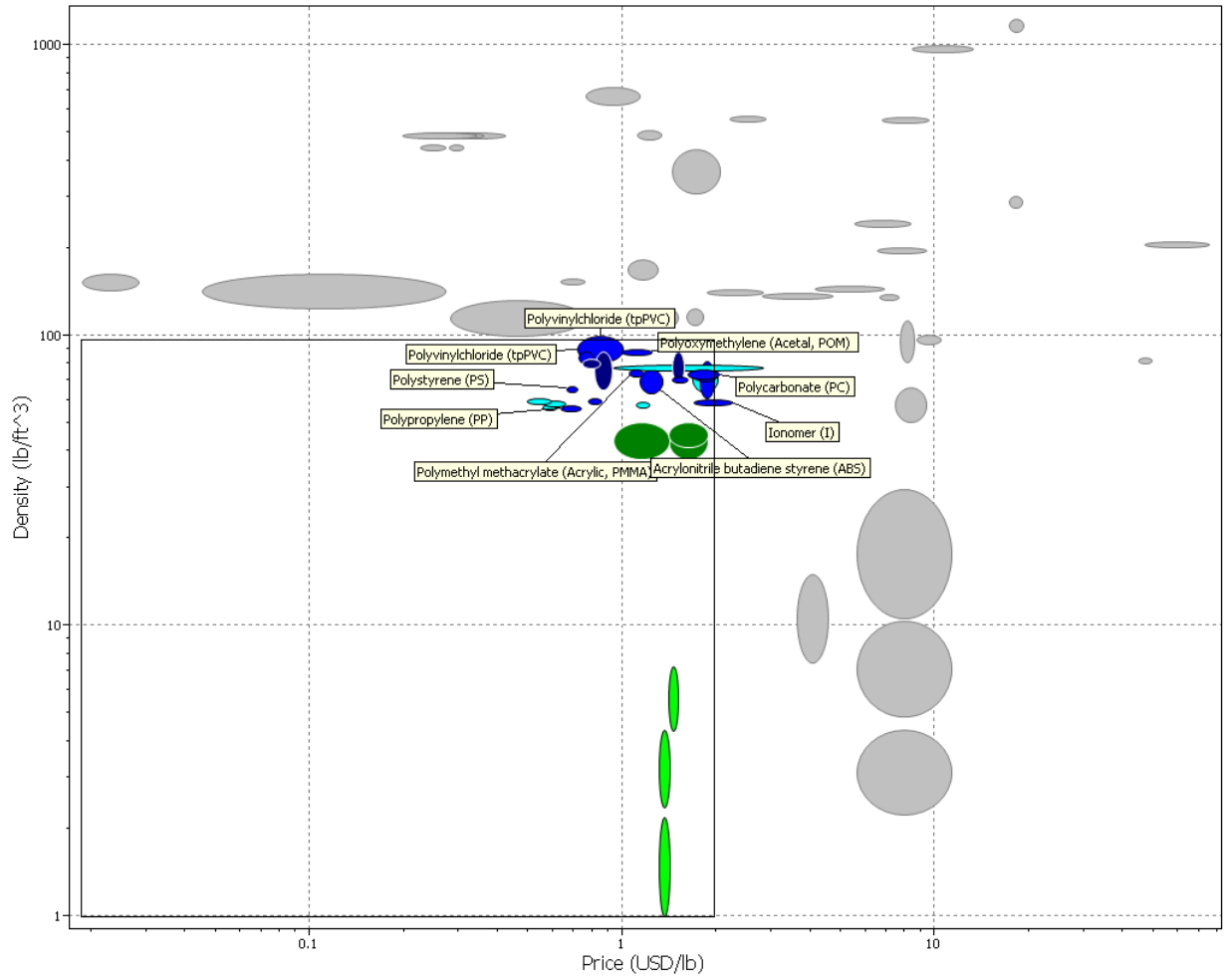


16.4 Appendix D – Ford Acoustical Testing Apparatus

- Test Chamber and Acquisition in Quiet Room...



16.5 Appendix E – Material Selection Graph



16.6 Appendix F – FMEA Chart

FMEA Chart														
Product Name: Air Extractor														
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Team 18	Occurrence	Current Design/Control Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN	
				Potential Causes/Mechanism(s) of Failure										
Flaps - Reduce gauge pressure by controlling air flow	Flaps remain open at all times	Higher road noise levels let into cabin	3	Flap becomes stuck on housing	4	None	3	Design block to prevent flaps from opening too wide	36	3	2	3	18	
		Allow flow back into cabin (fumes, debris)	5	Flap becomes stuck on housing	4	None	5	Design block to prevent flaps from opening too wide	100	5	2	5	50	
	Flaps become stuck closed	Discomfort for passengers from pressure buildup	3	Too much flow trying to go in wrong direction	4	None	5	Add more lines to grid to better spread out area of flap	60	3	3	5	45	
		Difficulty closing doors	2	Too much flow trying to go in wrong direction	4	None	4	Add more lines to grid to better spread out area of flap	32	2	3	4	24	
	Flaps fall off	Higher road noise levels let into cabin	3	Adhesive not adequate deteriorates	2	None	3	Design clips are use stronger adhesive	18	3	1	3	9	
		Allow flow back into cabin (fumes, debris)	5	Adhesive not adequate deteriorates	2	None	5	Design clips are use stronger adhesive	50	5	1	5	25	
		Requires complete replacement of unit	7	Adhesive not adequate deteriorates	2	None	3	Design clips are use stronger adhesive	42	7	1	3	21	
	Sound shield - Suppress noise transmission of exterior conditions and flaps	Sound shield location shifts	Impede air flow	3	Shield shape distorts	3	None	5	Selected Material Testing	45	3	2	5	30
			Higher road noise levels let into cabin	3	Shield shape distorts	3	None	3	Selected Material Testing	27	3	2	3	18
Sound shield material deteriorates		Higher road noise levels let into cabin	Affected by exterior conditions	3	Affected by exterior conditions	3	None	5	Selected Material Testing	45	3	2	5	30
			Current material selection not adequate	3	Current material selection not adequate	3	Computer Aided Material Selection Program	5	Selected Material Testing	45	3	2	5	30
		Require complete replacement of unit	Affected by exterior conditions	7	Affected by exterior conditions	3	None	3	Selected Material Testing	63	7	2	3	42
			Current material selection not adequate	7	Current material selection not adequate	3	Computer Aided Material Selection Program	3	Selected Material Testing	63	7	2	3	42
		Allow flow back into cabin (fumes, debris)	5	Current material selection not adequate	3	None	5	Selected Material Testing	75	5	1	5	25	
Housing - Remain reliable in operation through life of vehicle	Housing material deteriorates	Higher road noise levels let into cabin	3	Current material selection not adequate	1	None	3	Selected Material Testing	9	3	1	3	9	
		Require complete replacement of unit	7	Current material selection not adequate	1	None	3	Selected Material Testing	21	7	1	3	21	
		Allow flow back into cabin (fumes, debris)	5	Current material selection not adequate	1	None	5	Selected Material Testing	25	5	1	5	25	
	Housing falls off	Higher road noise levels let into cabin	3	Clips or snap fit to between unit and vehicle fails	2	None	3	Fatigue testing	18	3	1	3	9	
		Require complete replacement of unit	7	Clips or snap fit to between unit and vehicle fails	2	None	3	Fatigue testing	42	7	1	3	21	
		Allow flow back into cabin (fumes, debris)	5	Clips or snap fit to between unit and vehicle fails	2	None	5	Fatigue testing	50	5	1	3	15	

16.7 Appendix G – B-Quiet Properties and Characteristics

	<u>B-Quiet® Vcomp</u>		<u>B-Quiet® Extreme</u>
<u>Transmission Loss</u> in dB:		<u>Acoustic Loss Factor</u> ASTM E756 @ 200 Hz:	
125Hz	15	0C (32F)	0.16
250Hz	17	10C (50F)	0.19
500Hz	21	20C (68F)	0.29
1KHz	28	30C (86F)	0.20
2KHz	34	40C (104F)	0.14
4KHz	37	Temperature Range	-55C to +110C -67F to +230F
STC	27	Thickness	1.15mm (45mil)
Temperature Range	-40C to +121C -40F to +250F	Weight (per sq. ft.)	0.33 lb
Thickness	3/8"	Price (per sq. ft.)	\$1.40 (price based on 100+ sq. ft.)
Weight (per sq. ft.)	1 lb		
Price (per sq. ft.)	\$4.07 (based on 40.5+ sq. ft.)		