Mini Cooper Ram-Air Brake Duct System

by

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Executive Summary

Due to extensive track use, Mini Cooper GP's (Figure A) are notorious for having brake overheating problems. In the conceptual design stages of the car, BMW engineers intended to install brake ducts to prevent overheating, but due to time constraints, the cars were shipped without the ducts they were intended to have. The goal of this project was to design and manufacture a brake duct kit for the Mini Cooper GP. After a conceptual design of the system, make-buy decisions were made for each component. The components to be made were designed using computer-aided drafting, engineering, and manufacturing software. The components manufactured for this project included left and right wheel hub brackets and a pulley bracket. The system was installed and tested to determine the effectiveness of the newly designed and manufactured brake duct kit. Installation instructions were created for a car owner to expedite the installation process.

If the decision to enter production is made, the potential revenue is $18,000. This would, however, require an investment of roughly $10,000, leaving a **net profit of approximately $8,000**. This assumes that all engineering work is already done and not factored into the expenses.

Figure A: Mini Cooper GP

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1. Introduction

Problem Statement

The Mini Coopers, and especially the "GP" model, are used for track racing extensively around the country and the world. BMW engineered and shipped 2,000 of these special limited-edition models for use in sport and racing applications, and almost all of them have seen hours of track time. The model was originally advertised as having brake ducts for cooling installed. Due to budget and time constraints, the feature was abandoned. The car is equipped with two faux air ducts on the front bumper, but these are not connected to any brake cooling system. During racing or hard driving, the brakes are used extensively, which leads to overheating in the braking system. Excessive heat in the calipers can lead to boiled brake fluid, rendering it useless. Extreme temperatures in the rotors can lead to cracking and warping. The details of the heat generated when braking are discussed in detail in the **Background** section.

According to an article on MotoringFile.com, an online Mini Cooper news and community website,

> *"One of the most sought after features by many of us who take our MINIs to the track are working brake cooling ducts. As most track day junkies know, one of the first things that starts to fail on a MINI on the track are the brakes. And one of the biggest reasons for that is a lack of cooling the pads and rotors." <http://www.motoringfile.com/2009/02/20/diy-friday-official-jcw-brake-duct-retrofit>*

Many GP model owners have attempted to create their own brake ducts, and a few companies have created duct kits as well. There are several problems with all the products currently available. There are three basic options available to customers: creating your own, buying cheap small ducts that do not properly funnel air, and buying very expensive ducts that funnel the air properly. The first option, creating your own, is completely void of air flow analysis, and the installation process is muddled because the owner ad-libbed the process. The second option, which is a small brake duct kit that does not correctly funnel or distribute air, includes a single-piece carbon fiber duct. It does not effectively cool the brake rotors because the air is pointed at the inside of the wheel, but not directed directly into the brake hub. The kits are single-piece carbon fiber ducts, and retail for $225. The third option, which correctly funnels and distributes the air, and is very similar to the design that will be built for this project, retails for over $350. This allows for a market niche for a similar product to be sold for a greatly reduced price. Creating this niche product will be the goal of this project. Detailed critiques of each competitor kit are located in the **Background** section.

Scope

This project will pick up where the BMW engineers left off by completing a brake duct system for the Mini Cooper GP, which will be designed for installation by the owner in one afternoon. The kit will include the necessary hosing, bracketry, hardware, installation instructions, and stencils for the necessary cuts. It will be packaged and shipped in custom designed packaging. At the outset of the project, the scope of the project was to include not only the hosing system and associated bracketry, but a redesigned carbon fiber molded duct as well. Unfortunately, as the project developed, it became clear that a new duct would not be possible due to the design of the front bumper of the vehicle. Installing a new duct would require cutting of critical joints in the bumper. Therefore, the scope of this project was altered to exclude the manufacturing of a new duct, so the kit will now be attached to the existing duct that came installed on the car.

Expected Deliverables

- Design

  A design for a brake duct kit to help cool Mini Cooper GP front brake rotors will be completed. The design will be created by comparing the current kits on the market and brainstorming for new ideas. Final solid modeling will be completed using Computer Aided Design (CAD) programs. The models will also be tested using these same programs to analyze fluid flow through the ducts and associated hosing. Computational Fluid Dynamics (CFD) in FlowWorks will be used to test the flow rate and ensure laminar flow in the system.

- Prototype

  After the designs are completed, manufacturing will begin on a prototype. This prototype will allow for a test fit to the car, and bring to light any necessary design changes that will need to take place to finalize the kit design. The solid model prototypes will be imported to a Computer Aided Manufacturing program to aid in their production. The components of the prototype will either be manufactured on campus or purchased from suppliers.

- Testing

  The brakes were tested in real-world application with straight-line braking cycles. Thermal paint was applied to the rotors to determine their maximum temperature. The details and results of this test are included in this report (in **Methods** and **Results**).

- Installation instructions and stencils

  A complete set of installation instructions are included in the package. These expedite the installation process for the owner, so that it can be completed in one afternoon. Stencils were created to guide the owner while making the small cuts during the installation.

- Economic Analysis

  An economic analysis was performed to evaluate the cost and profitability of the kit (see **Results**).

Market research was also conducted to compare these costs to competitive kits (see **Background**).

- Technical Report

The next section, **Background**, includes information on market research, disc braking systems, brake cooling, composite manufacturing processes, and hardware specifications. Section 3, **Design**, will discuss the methods used for reverse engineering the factory duct, bracket design, CFD analysis, and make-buy decisions. Section 4, **Methods**, will cover the bracketry fabrication and the testing methodology. Section 5, **Results**, includes the installation of the kit and the results of the on-road testing. A brief **Conclusion** (Section 6) summarizes the contents of this report.

2. Background

Market Research and Existing Products

Preliminary online research of existing brake duct products demonstrated the need for a product like the one that will be designed and manufactured for this project. For these products, the best way to study customer attitudes and opinions are forums and discussion boards on websites that specialize in either after-market car parts or the Mini Cooper itself. On these boards, members post links to products, ask questions, and discuss solutions for their vehicles.

Websites that specialize in after-market parts are useful in showing brake duct products for any make and model vehicle. Websites that feature the Mini Cooper (such as NorthAmericanMotoring.com) are useful in seeing all the various products that customers have tried installing on their vehicle. Many customers will start fresh threads, showing the product they selected, pictures of the installation steps, and the final product. They will also post their opinion about the product, and other customers can add their comments and questions, which sparks useful discussions. There are also boards which revolve around certain types of parts. There are many discussion boards available discussing brake ducts specifically. Customers post links to or pictures of the products they used. Prices and effectiveness are discussed in length. Put simply, it is a glimpse into the minds of the customers and is the most effective market research tool available for this project.

Current Mini Cooper Brake Duct Market Analysis

Performance Brake Cooling System Upgrade, $360 <MiniMania.com>

Although this system is easily installed, it has several major drawbacks, first being the price. At $360, it is $85 more expensive than the closest competitor. Secondly, the ducts for this kit pick up “dirty” air from the bottom of the car (**Figure 1.1**). “Dirty” air is very turbulent and would negatively affect the flow into the duct and to the rotor. Lastly, the routing of the hose is a major issue. Looking at **Figure 1.2**, you can see that the hose comes very close to contacting the wheel. With the wheels turned, the duct could likely contact the wheel, running the possibility of catastrophic failure of the system. The components of this kit are pictured in **Figure 1.3.**

Figure 1.1: Under-car view

Figure 1.2: Installed kit

Figure 1.3: Kit components

By keeping the kit developed for this project simple, as compared to the above kit, yet still effective, costs are kept down, allowing the final selling price to be much lower. With regards to duct location, the kit developed for this project uses ducts located on the front bumper. By using ducts in the front of the car, the system is supplied with non turbulent air that easily flows into the duct, through the hose, and to the rotor. By routing the hose through the bumper and through the front suspension, rather than from the bottom up, the kit for this project easily clears the wheels lock to lock.

Brake Cooling Kit, $225 <MiniMania.com>

This system is very similar to the one manufactured in this project, but it has one major drawback. The hose used has a maximum operating temperature of 300˚F. During testing, temperatures on the brackets that hold the hoses to the rotor reached slightly over 400°F. Although this hose would most likely work for the short term, during a long race there is a possibility of the hose failing due to heat.

Figure 1.4: Kit components

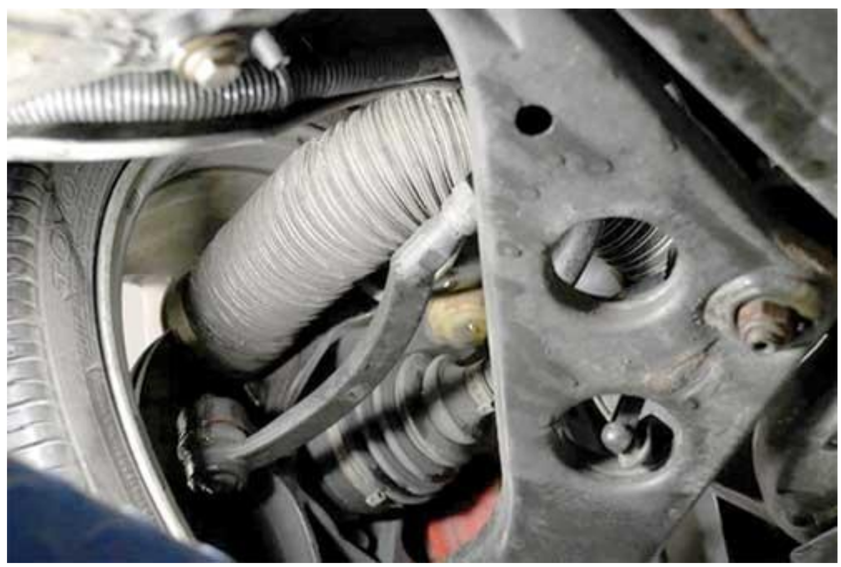

Figure 1.5: Installed kit

The kit designed in this project uses a higher grade of hose that is safe for use up to 550°F environments (PegasusAutoRacing.com). The hose never reached this temperature during testing, so there should be no issue with the hose failing due to heat.

Way Motor Works Mini Brake Duct Kit, $275 <WayMotorWorks.com>

Initial inspection of the Way Motor Works kit (Figure 1.6) would lead one to believe that this should be an amazing kit. There is no denying its beauty: the combined ducts and hoses mount into the front bumper for good flow, it has no interference issues with the wheels, and the transitions are quite smooth. The issue is its length (Figure 1.2). These ducts stop nearly a foot away from the brake rotors (**Figure 1.7**).The air flow is not effectively directed to the center of the rotor, where the air is being pulled through the ventilation slots. There is already air flow through the wheel well. The point of a brake duct kit is to direct extra air straight into the brake hub, so the ventilation slots are utilized.

Figure 1.6: Kit ducts

Figure 1.7: Kit installed

The kit for this project funnels the air directly into the vanes of the rotor by having a mounting bracket at the rotor. Where the hose attaches to this bracket, the hose is held at a 15˚ angle to further position the hose at an ideal angle so the air is directed straight into the vanes of the rotor so maximum cooling can occur.

Literature Review

Brake Cooling

The speed a vehicle is travelling is directly correlated to the rotational velocity of the wheels. In disc braking systems, when the brakes are applied by the driver, a series of mechanical and hydraulic mechanisms translate the force to move a piston in the brake system, which pushes the brake pads against the rotor (Ellinger 76). The brake caliper, which holds the piston and brake pads in place, is mounted to the chassis, and remains stationary, while the brake rotor is mounted to the wheel hub on the end of the rotating axle. When the pads are pushed against the spinning rotor, the friction force between the two causes the rotational velocity of the wheels, which slows the car down. The coefficient of friction between the brake pads and the rotor that were installed on the Mini Cooper GP as tested is 0.33 at operating temperature (Wilwood Brake Pad Catalogue). The braking action is a direct conversion of kinetic energy to thermal energy through friction. (Ellinger 76).

The average temperature rise in the braking system can be calculated, and it is linearly related to the amount of change in the kinetic energy of the car. Rehkopf gives an example of a 30 mph to 0 stop in an average passenger car, and the temperature increase seen in the brakes is 58˚F. Because the velocity term in the kinetic energy equation is squared ($KE=mv^2/2$), braking at high speeds will produce much more heat. For example, braking from 90mph to 60mph in the same average vehicle will produce an approximately 291˚F temperature rise (Rehkopf 51). In the case of a performance car on a track, most of the braking will be done at very high speeds, so the temperature increases in the brakes can be quite substantial.

The braking system, and especially the rotor, is subjected to very high heat loads due to this transfer of energy. This heat is the transferred to the surrounding air as it passes over the rotor (Ellinger 77). Disc brake rotors are commonly vented, with radial fins in the center that help with cooling. In general, open wheeled race cars don't have major issues getting air to the brakes to cool them (Storer 118). Modern road cars have large bodies which block much of the airflow to the rotors, hindering cooling. Brake ducts will help direct the air to the rotors, which will in turn help to cool them.

Braking systems that get too hot can inhibit performance. According to Carroll Smith, brake fad can be associated to three things: green fade, pad fade, and fluid fade (Smith, Engineer 189). Green fade simply refers to pads that have not been bedded in before use and is not an issue as long as bedding is accomplished before heavy use. Pad fade refers to the pad and rotor getting to hot and decreasing the coefficient of friction between the two. Fluid fade refers to boiling the brake fluid in the brake lines and causing gas bubbles to form in it decreasing the hydraulic pressure to the caliper piston (Smith, Engineer 190). In this case, the driver can only slow down if he brakes harder, which in turn makes the problem worse. Brake ducts primarily help with pad fade by forcing more air into the vanes of the rotor and cooling it faster. A byproduct of cooling the rotor is you also cool the contacting pads and help reduce the risk of boiling the brake fluid.

Why not cool the rear brakes? It is a simple matter of weight transfer. As a car decelerates, a moment is created, increasing the force on the front tires. The weight transfer can be calculated using $(mah)/l$. Where m is the mass of the car, a is acceleration do to gravity, h is the center of gravity height, and l is the wheelbase of the car (Baker 6). As much as 80% of the braking that a car does is done by the front brakes. Knowing this, it will only be necessary to put ducts on the front of the car to have the greatest affect on braking performance.

While the main goal of brake ducts is to maintain the proper operating temperature of the braking system, there is another benefit besides just making the car stop better. It gives the driver confidence, consistency, and controllability (Smith, Tune 107). Mini Coopers often see track time with beginner to intermediate drivers behind the wheel. Confidence in their machine is necessary for them to progress as racers, and brake ducts will greatly increase this confidence on the track.

Carbon Fiber

Composite materials have become very popular in the automotive racing industry because of their lightweight yet rigid properties. The typical modern composite used in racing is one consisting of a fibrous material with a bonding resin. The combination of the fibers and resin give the materials an incredible strength-to-weight ratio. The most popular composites today are fiberglass and carbon fiber. According to Simon McBeath, carbon fiber's popularity arose in the aircraft design business, and wasn't used with any regularity in auto racing until the 1970's. Once very expensive, almost any modern race team can afford to purchase or make carbon fiber components for their cars (McBeath 14). Carbon fiber components are extremely popular in the racing industry today, because they have the highest ratio of stiffness to density of any commercially available composite (McBeath 15). Before the scope changed for the project, the brake ducts for the Mini Cooper were to be designed and manufactured out of carbon fiber.

The most common way to create carbon fiber components is a process called open mold wet hand layup. An open mold means that the mold is one-sided; that is, the critical features of the part are created by a single positive or negative mold surface (Groover 324). A hand lay-up consists of laying multiple layers of the composite material over each other onto the mold. A wet lay-up signifies that the resin material is separate from the fiber material, and the two are layered on one after the other to create the composite matrix (Groover 324). The alternative method is using a "prepreg", where the fibers are prepared with the resin material prior to the lay-up process. Prepreg carbon fiber material is readily available, and is the industry standard, but it must be stored in a freezer and cured in an oven. Before the scope changed for this project, the brake duct was going to be created with the open mold wet layup process, which can be completed at room temperature.

Hardware

In the design of the brake duct, the back of the duct itself will attach to a high-temperature hose. To attach these two parts, a standard worm gear hose clamp will be employed. According to Carroll Smith, many failures of these parts occur due to over tightening. The bolts should be tightened to only 15 in-lb to avoid this problem (Smith, Nuts 179). The hose clamps on the brake duct will be installed following this guideline.

According to the Bentley Mini Cooper Repair Manual, the lug nuts that attach the wheels are specified to be tightened to 84 ft.-lbs, and the caliper bolts should be torqued to 80 ft.-lbs. These specifications will be listed in the installation instructions to ensure safety.

3. Design

The first step of the project was to brainstorm and attempt to visualize the product in the car. The design needed to be effective at improving air flow to the brake rotors, without being more expensive than other kits currently available on the market (a summary of the other kits can be found in the **Background** section). After removing the wheel, the faux duct, and the splash guard assemblies, various ideas were visualized and discussed. The basic design of the product was completed at this stage.

A prototype was visualized and sketched, and the steps taken to realize this are included in this section. It was determined to reverse engineer the faux duct that was originally installed on the car, for modeling and testing purposes. The other components of the prototype were either to be purchased or manufactured on campus.

Reverse Engineering

The original scope of the project included creating a new duct for the front bumper of the car. The motivation for a new duct was to improve the airflow over the original ducts. With a model of the original duct, its airflow capability could also be analyzed. The biggest step in the design process was the reverse engineering of the faux duct. The duct to be designed needed to fit in the area left by removing the faux duct from the bumper, while improving the airflow to the rotors. Basic measurements were taken with traditional measuring tools such as calipers and angle fingers (**Figure 3.1**). A flatbed scanner was used to create an image of the profile of the part (**Figure 3.2**).

Figure 3.1: Measuring factory-installed faux duct

Figure 3.2: Scanned image of faux duct

This image file was then imported to SolidWorks to create spline curves of the feature. Critical measurements were taken with the “Measuremind 3D” program in the IME Metrology Lab (**Figures 3.3 and 3.4**).

Figure 3.3: Optical measurement machine

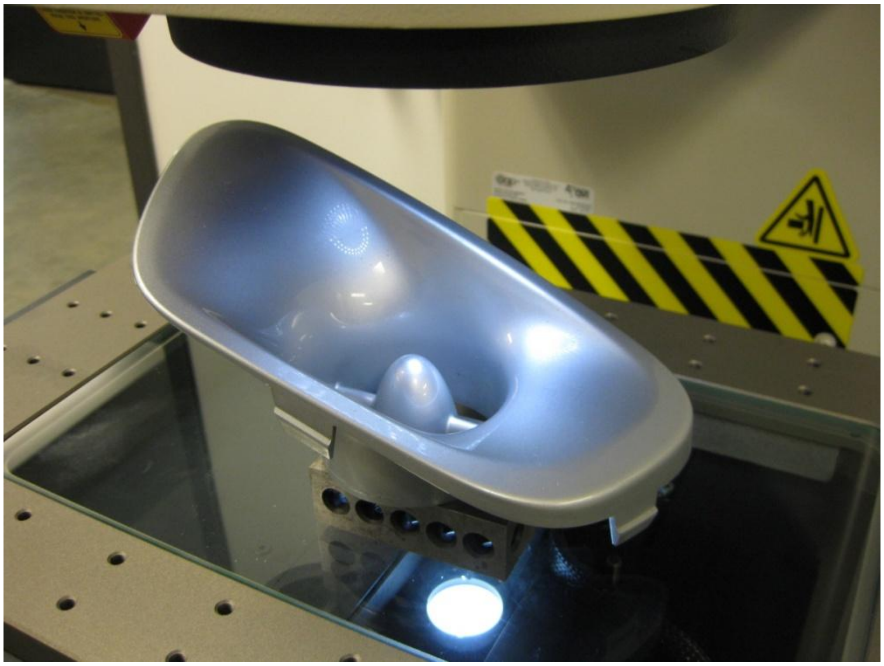

Figure 3.4: Measuring the profile

The most difficult feature to measure was the radius on the front of the part, which matches the radius of the front of the car. This was accomplished in Measuremind by taking three points along the radius in question (**Figures 3.5 and 3.6**).

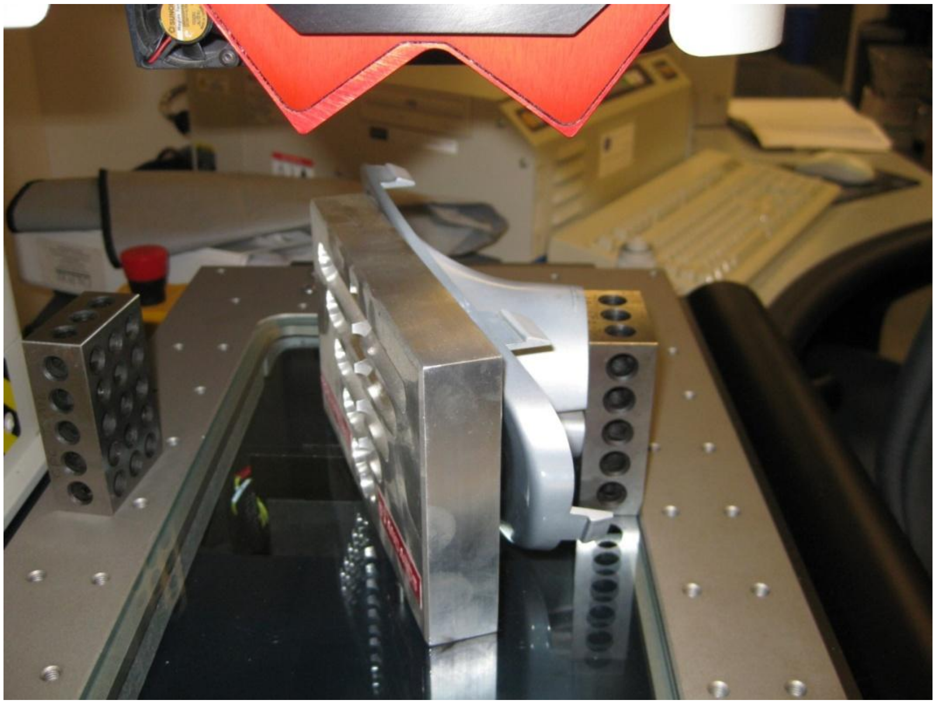

Figure 3.5: Measuring the radius of the front of the part

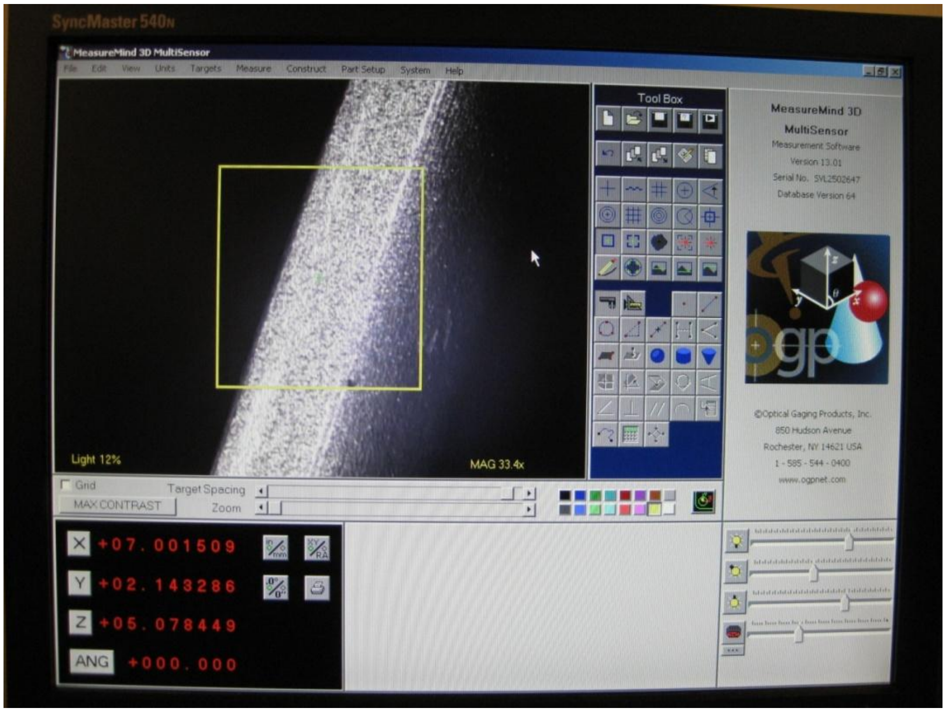

Figure 3.6: Measuremind 3D software interface

These three points were then plotted in SolidWorks, and a curve was fitted to the points. The calculated curve's radius was equal to the radius of the front of the part.

From the scanned-in surface, the calculated radius, and the other key measurements that were obtained from the Measuremind program, the first iteration of the duct was created. Two planes were constrained to be at a set angle to each other. One of these planes contained the spline image, and the other contained a 3" diameter circle, which represented the back of the duct. A loft was generated, with four guide curves between the two planes, to generate the correct geometry (**Figure 3.7**).

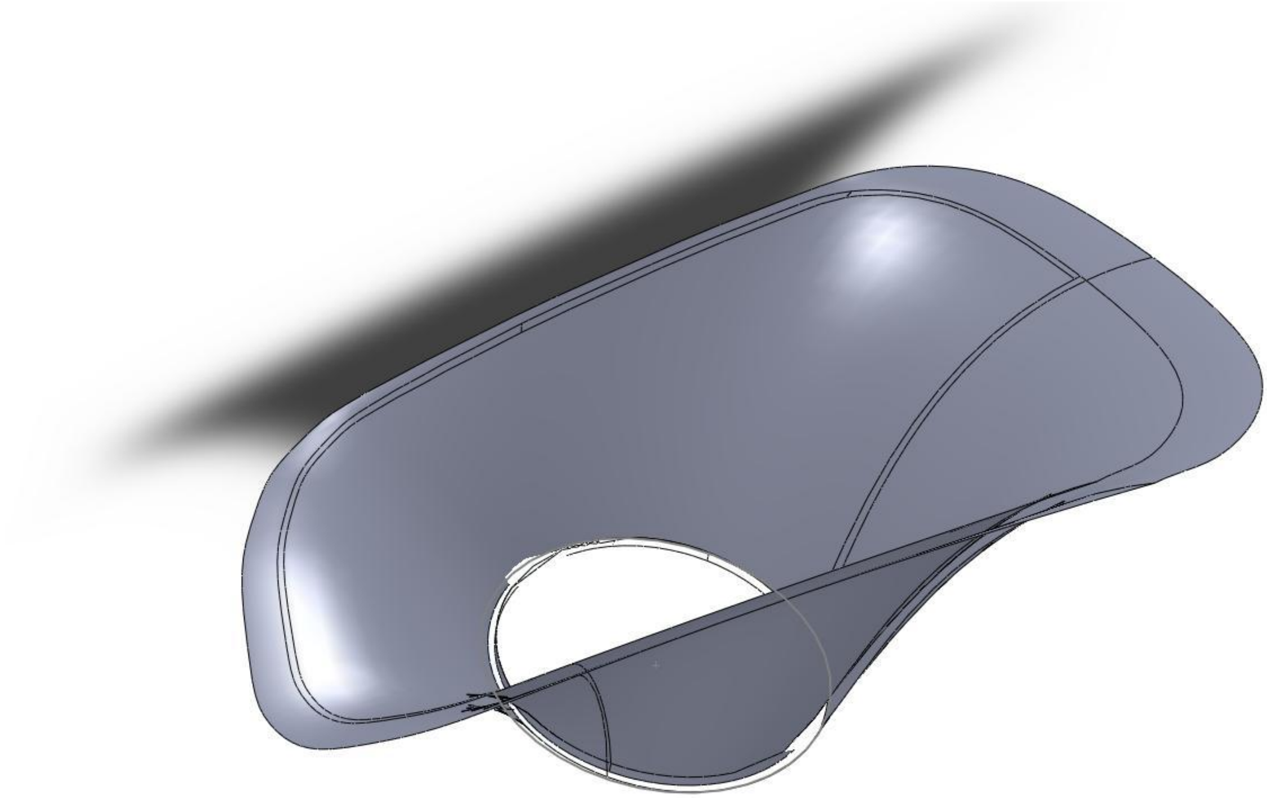

Figure 3.7: SolidWorks model, first iteration

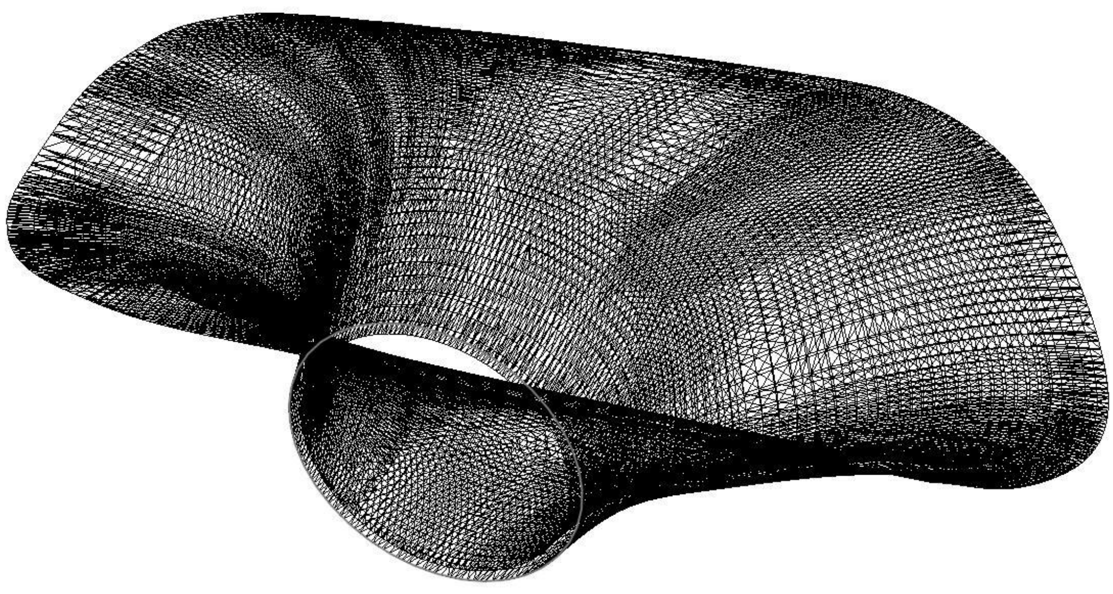

Figure 3.8: .STL model, first iteration

A rapid prototype was created using this first iteration of the duct. The SolidWorks model was saved as a .stl file, with an angular tolerance of +/-2˚ and a deviation tolerance of +/-.001” (**Figure 3.8, above**). This file was loaded onto the Stratasys rapid prototyping machine, and left to run over night (13 hour run time). The majority of the support material could be physically removed, but the remainder was chemically removed in a solvent leaving the finished part (**Figure 3.9**).

Figure 3.9: Rapid Prototyped model, first iteration

This first iteration rapid prototype was taken to the Mini Cooper for a test fitting. The fit was marginal at best. The back circle needed to be shrunk to 2.5" diameter, and the guide curves the controlled the lofts were too aggressive, and needed to be adjusted. These changes were made to the SolidWorks model (**Figures 3.10 and 3.11**), and the second iteration rapid prototype was created on the Stratasys.

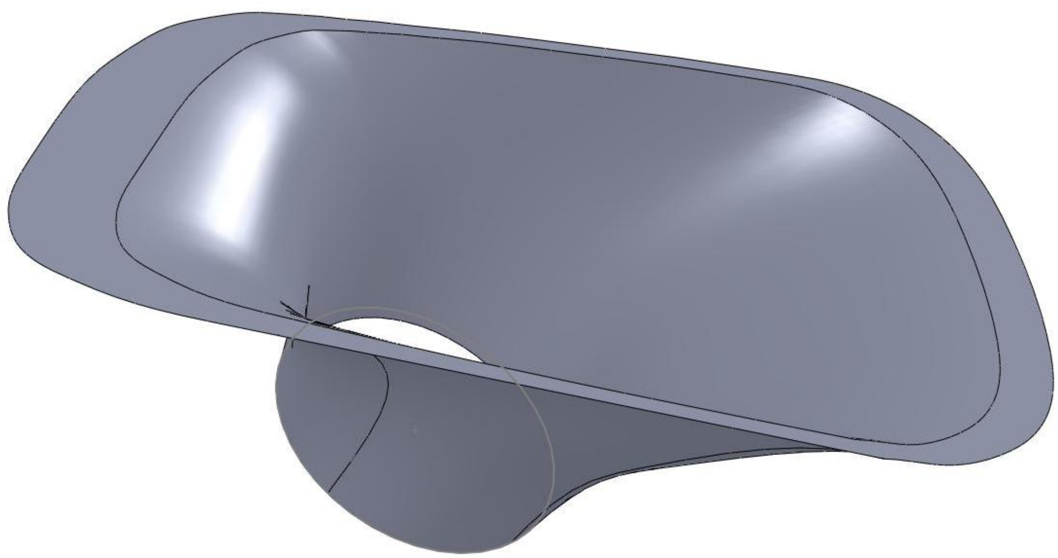

Figure 3.10: SolidWorks model, second iteration

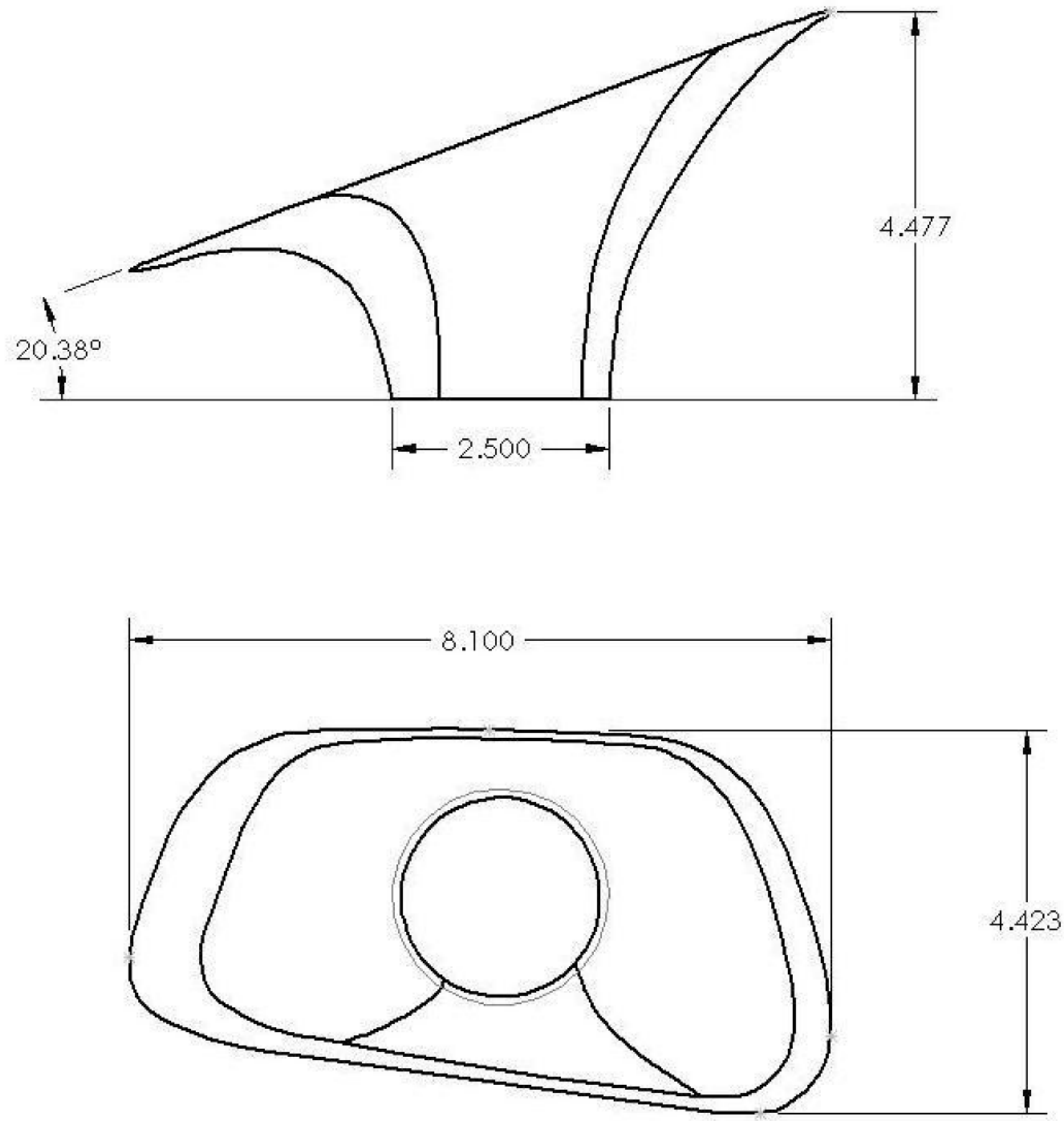

Figure 3.11: 2D drawing of second iteration duct

The second iteration model fit much better, but when trimming the plastic on the front bumper, aluminum weldments were exposed (**Figure 3.12**), which were critical to the structural integrity of the bumper. Because these weldments could not be cut, the scope of the project was altered to exclude the carbon fiber duct. While the rapid prototyping turned out to be superfluous work, the effort to reverse engineer the duct was required to analyze the flow using Computational Fluid Dynamics (CFD) (**Figure 3.13)**.

Figure 3.12: Aluminum weldments exposed after bumper trimming

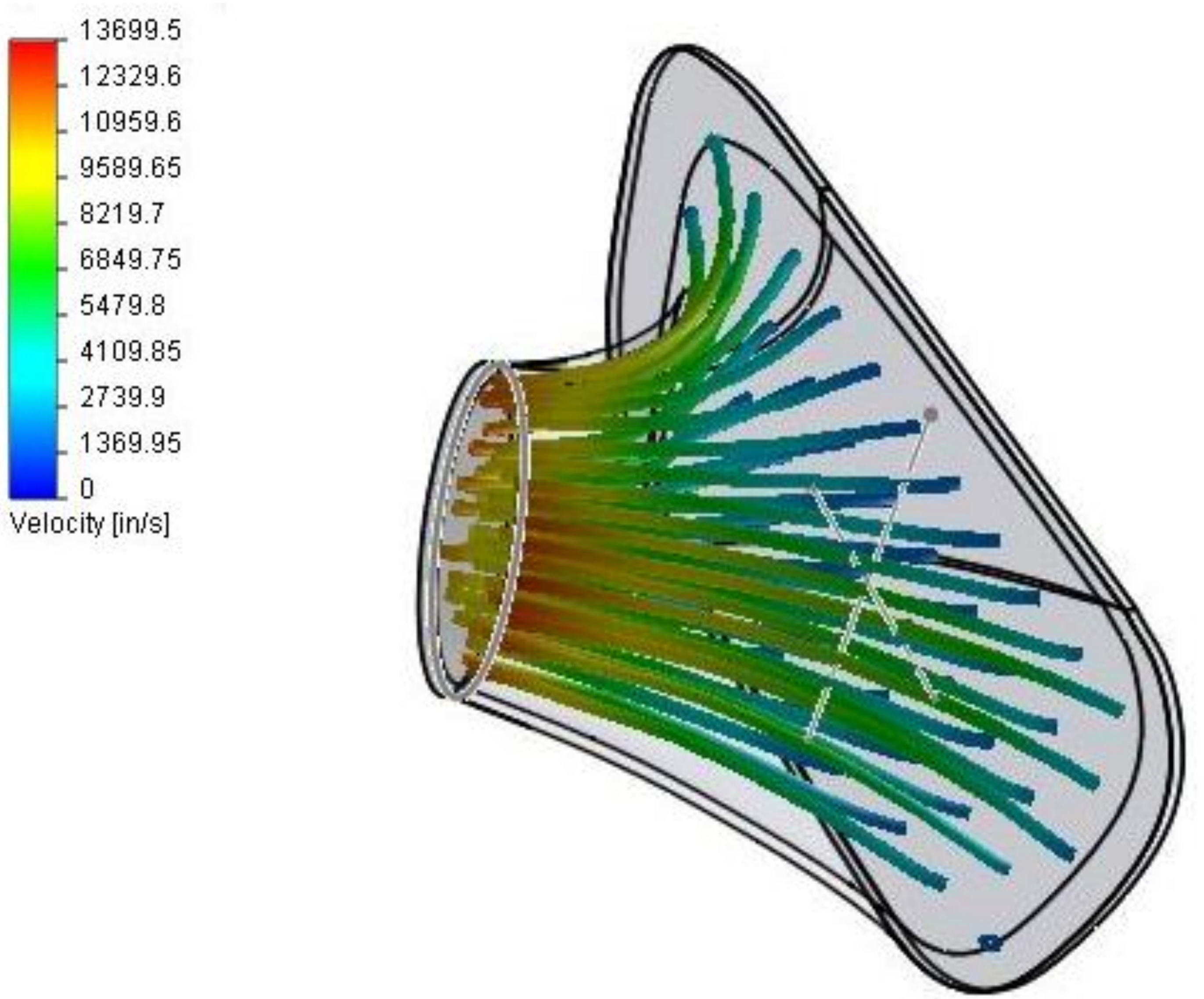

Figure 3.13: CFD Analysis of the factory-installed duct

Before the actual prototype duct kit was manufactured and on car testing was done, extensive computer simulations where run to analyze the air flow through the duct and associated hose. Computational Fluid Dynamics (CFD) was used to complete this analysis. The CFD program used was FlowWorks, a program built into SolidWorks.

Although rudimentary, FlowWorks is an easy to use program for basic CFD analysis. To analyze a system, all that is required are start and end conditions. FlowWorks then creates a mesh though the part and analyses the flow cell by cell. It then generates a video showing lines traveling through the duct and hose so the user can have a visual representation of the air flow through the system. These lines change color to indicate the air velocity, and direction to indicate turbulence. If the lines are not jagged, the user can assume that the flow is laminar and turbulence is low through the system.

For the new duct and hose, several assumptions were made.

1) The air entering the duct would be traveling 80 mi/hr or 117.3 ft/sec

2) At the rotor or outlet there would be standard atmospheric pressure of 14.7 psi.

3) The hose would be modeled as having a perfectly smooth inner diameter

With these conditions, FlowWorks started calculating the theoretical air flow through the brake duct system (**Figure 3.14**).

After the simulation was run, it was determined that 41 ft^3/s of air would travel through each side of the kit to the rotor.

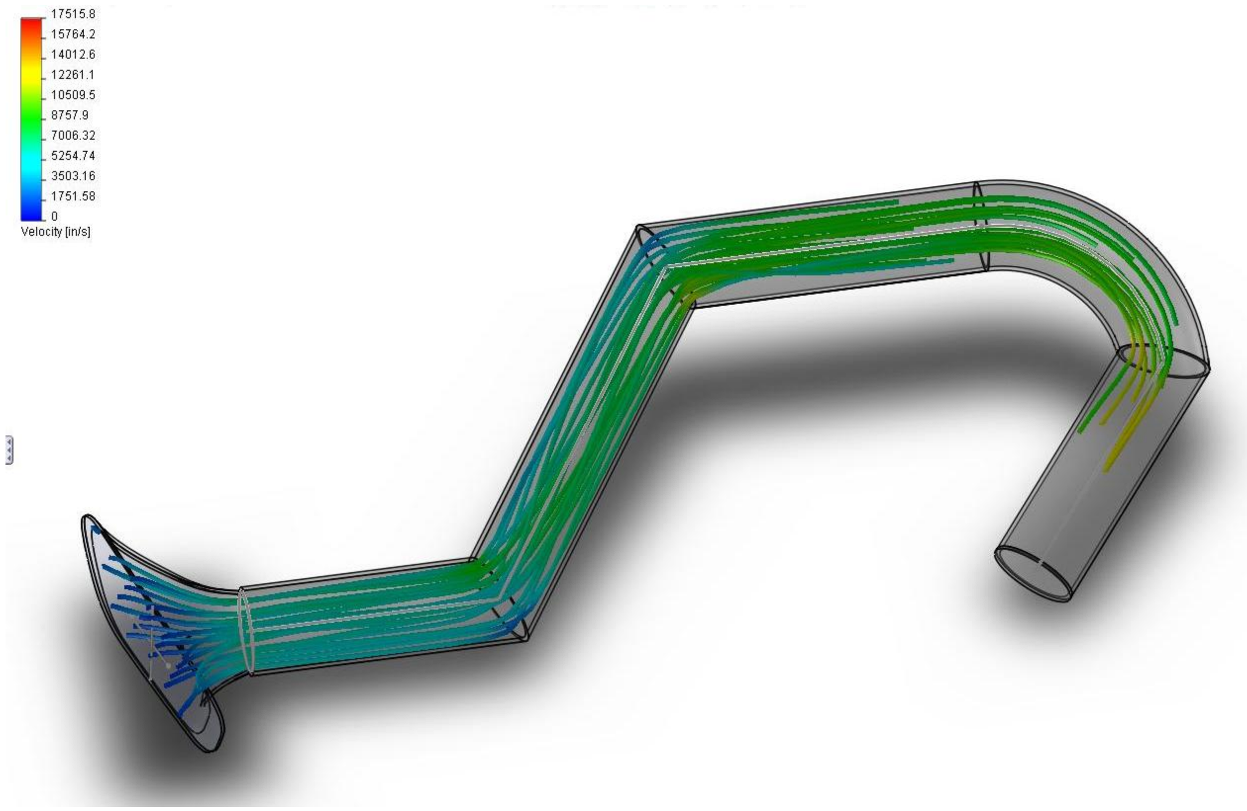

Figure 3.14: CFD Analysis of Entire System

Bracketry

Once the basic design of the product had been visualized, a major step in the design process was to design brackets to hold the hose in the right place on the car. The first two brackets are mirrored parts, one for each side of the car. After considering the equipment available on campus, it was decided to create the brackets out of sheet metal by using the HAAS CNC laser. This would be the easiest process available for creating the desired shapes with dimensional reliability.

The car comes from the factory with a backing plate near the brake rotors. There are 4 mounting screws that attach this to the wheel hub. The bracket for this project uses three of these screws, which go through the smallest three holes in the drawing (**Figure 3.15**). The bracket's general shape was designed to give it enough rigidity against bending while the car was being steered. The compression and tension on the hose could result in the bracket being bent into the brake rotor, so rigidity was of upmost concern. Because of this, the brackets were designed to be 0.050" 4130 steel.

The three tabs in a circular pattern (**Figure 3.15**) are designed to be bent 90˚ away from the drawing view (into the page). These tabs were to be welded to a small section of stainless steel tubing, which the hose slips over, and is then connected by a hose clamp. The tubing was designed to be cut at a 15˚ angle, so that the air is directed into the center of the brake hub correctly. The critical dimensions on these brackets are the location of the three mounting holes relative to the location of the center of the tab pattern to hold the hose, as well as to the large radius that wraps around the wheel hub. The outer profile of the bracket is not critically dimensioned, but thick sections were used to increase rigidity.

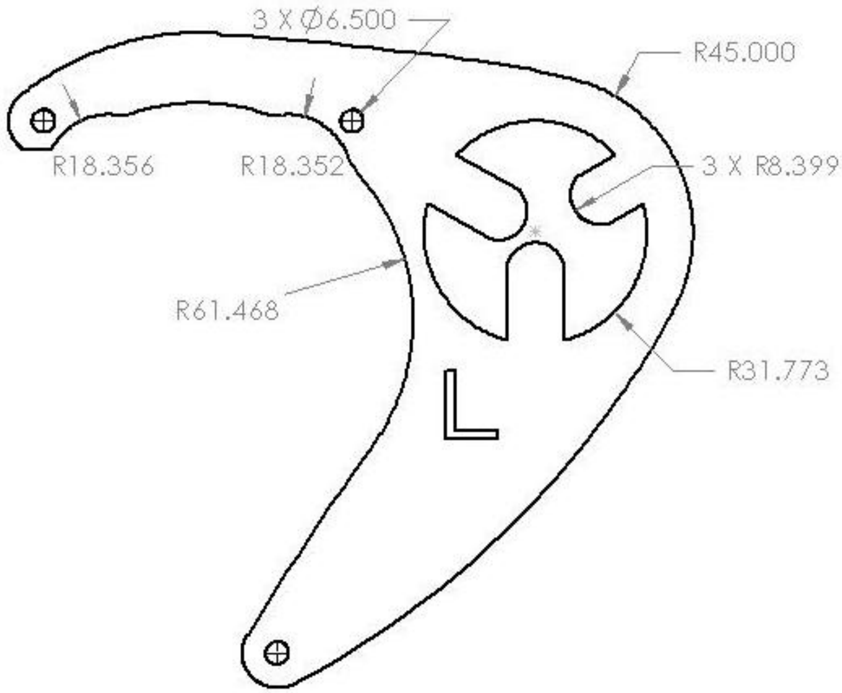

Figure 3.15: CAD Sketch of wheel hub bracket

The third bracket required for the kit is installed only on the right side of the car. Its purpose is to guard the hose from a crank pulley. The only critical dimensions on the part are the size of the bolt clearance holes and the distance between them (**Figure 3.16**). The other dimensions were determined by using a cardboard mock-up. Again, the bracket was designed to be a laser cut sheet metal piece, and all bend angles to be 90˚. Because the part is under low forces, a mild 1018 steel was used, at .035" thickness.

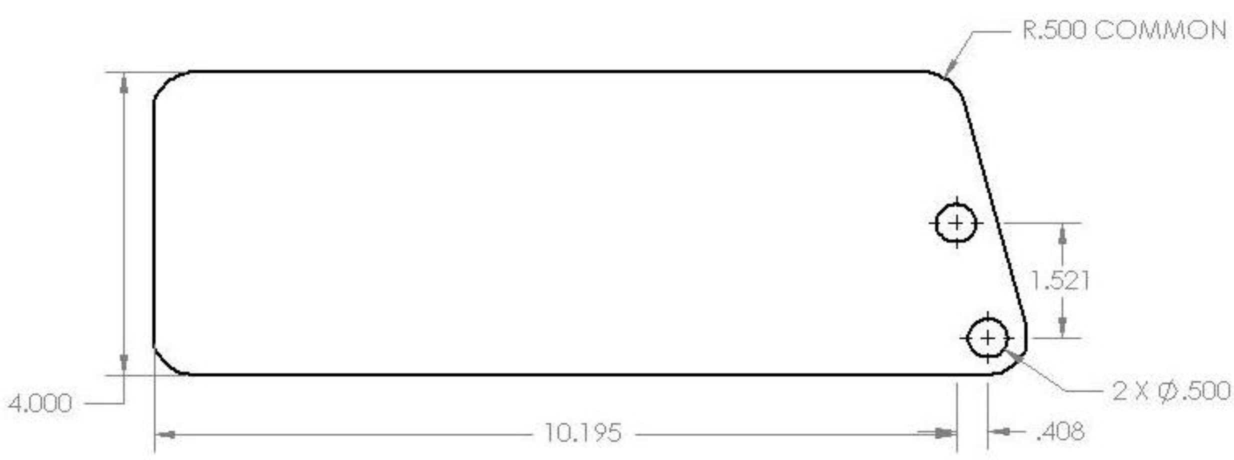

Figure 3.16: CAD Sketch of pulley bracket

4. Methods

Bracketry Fabrication

Once CAD models of all three brackets were created in Pro/Engineer, the models were imported into Pro/Manufacture. Trajectory paths were created for the outlines of all the features that were to be cut. CNC code was output from these tool paths, and the code was verified before being run. **Table 4.1** shows the cutting parameters used in the laser. **Figures 4.1 and 4.2** show the brackets after fabrication, but before painting.

Table 4.1: HAAS CNC Laser cutting parameters

Material	Thickness	Power	Frequency	Feed Rate	Assist Gas	Burn Through Time
1018 Steel	0.035"	90 W	1000 Hz	40 ipm	40 psi Oxygen	1 s
4130 Steel	0.050"	100 W	1000 Hz	15 ipm	80 psi Oxygen	2 s

Figure 4.1: Left wheel hub bracket

Figure 4.2: Pulley bracket

On-Road Testing Methodology

Spinning objects inside spinning wheels inside moving cars are tricky to measure the temperature of. A solution to this was thermal paint, which was used to measure the temperature of the rotors during testing. Thermal paint is applied to the rotors, and as the rotors increase in temperature the paint changes color. The paint can change to six distinct colors, corresponding to different temperature ranges (**Table 4.1**).

Color	Temp (°F)
Red:	0-678
Red/Brown:	679-804
Brown:	805-1074
Ylw/Grn:	1075-1326
Green:	1327-1470
Beige:	1471+

Table 4.1: Thermal paint color codes

Ideally, a full data acquisition system would have been used to gather real time temperature data as the care was driven. Unfortunately, there was not a system available at the time of the testing that could be installed on the car. Instead thermal paint was applied directly to the rotors to record the maximum temperature they reached during the testing sessions.

The testing sessions were designed to quickly and consistently heat up the brakes. The driver started out from a stop and as quickly as possible accelerated in a straight line to 80 mph then braked till 20 mph three times followed by a 100 mph to 0 mph cycle. These cycles were then immediately followed by a 4 mile road course where the driver pushed the car to approximately 80% of its performance level. At the end of each testing session, another section of thermal paint was applied to each rotor and the test repeated. Due to concerns about warping or cracking the rotors, only two sessions were run.

During the testing, to compare ducted and non-ducted brakes, the kit was only installed on one side of the car. At the end of the testing, the rotors from each side of the car were compared to see if there were differences in the color of the thermal paint.

5. Results

Installation

The kit designed and manufactured for this project was installed on a Mini Cooper GP. Careful notes of each step were carefully taken in order to generate a set of installation instructions, which can be seen in **Appendix A**. The kit was also installed for testing, the details of which are in the following section.

Test Results

For this project, two distinct testing methods were used: 1) computer simulation, and 2) on road testing. The results of the computer simulation tests using Computational Fluid Dynamics can be seen in the **Design** section of this report. Due to budget constraints, the on road testing was somewhat limited.

Figure 5.1: Thermal paint after testing

In **Figure 5.1**, the top rotor is from the side of the car without the duct. The bottom rotor is from the side with the duct. While both rotors reached temperatures upwards of 1500˚F, the temperature data gathered was inconclusive. There was not a discernable difference in the color of the thermal paint. Although the thermal paint did not lead to any conclusive results, the black paint used to keep the rotors from rusting that was vaporized off during testing did. Note the white powder left in the vanes of the rotors. This powder could be blown or easily scratched of the cast iron rotors. The side that had the duct had a significantly less of this white powder than the side without the duct. It is believed that because there was extra air moving through the rotor with the duct, it helped to blow out this powder. Over a long race, this extra air would surely help to cool the rotor.

Economic Analysis

2000 Mini Cooper GP's were manufactured and shipped internationally in 2006. Because the entire kit designed this project was done so in metric units, the kits can be sold to any country. A fair assumption of a 5% market share yields a production run of 100 kits, which is the assumed lot number for the following calculations.

An economic analysis was performed on the kit designed for this project. The materials are listed along with their prices (**Table 5.2**). All prices are per kit. The calculated materials cost of the kit is $80.67. The most expensive component is the high-temperature hosing. Other sources for hosing were researched, but this hosing is an industry standard, and has been proven reliable over years of use around the world.

Table 5.2: Material Costs

Item	Quantity	Price	Total
2.5" Dia. Hose (per foot)	7	$ 7.22	**$ 50.54**
LR Brackets (4130 .050")	2	$ 5.25	**$ 10.50**
Stainless Steel Pipe 2.5"Dia. x 3"	2	$ 1.44	**$ 2.88**
Pulley Bracket (1018 .035")	1	$ 2.75	**$ 2.75**
12 x 1.5 mm Nuts	2	$ 0.25	**$ 0.50**
3" Hose Clamps	4	$ 1.25	**$ 5.00**
Fenderwell Clips	3	$ 1.50	**$ 4.50**
Packaging Materials	1	$ 4.00	**$ 4.00**
		Total Direct Material	**$ 80.67**

The labor costs were estimated for the kit as well. Each task is named along with an estimation of time in a production environment (**Table 5.3**). The most important assumption is that the sheet metal fabrication will be outsourced, at a standard machine shop quote rate of $150/hour. This rate accounts for the setup costs of the shop, and will include the bracket laser cutting, pipe cutting, bracket bending, and spot welding. The estimated price for powder coating is $200 per lot, regardless of size (there would be 300 brackets in a lot of 100 kits).

Table 5.3: Labor Costs

Labor	Time (Hr)	Price/Hr	Total
LR Brackets Laser Cut	0.0167	$ 150.00	**$ 2.50**
Stainless Pipe Cut	0.0167	$ 150.00	**$ 2.50**
Pulley Bracket Laser Cut	0.0125	$ 150.00	**$ 1.88**
90 Bends (both brackets)	0.0333	$ 150.00	**$ 5.00**
Spot Welding	0.0333	$ 150.00	**$ 5.00**
Cut Hose	0.0083	$ 25.00	**$ 0.21**
Powdercoat Painting		$200/lot	**$ 2.00**
		Total Direct Labor	**$ 19.09**

The total cost to create the kit is $99.76. As discussed in the **Background** section, the least expensive kit on the market retails for $225. At a selling point of $179 (an 80% profit margin), this product will be the least expensive and most effective kit on the market.

It should also be noted that there will be no overhead costs. Because this is such a small production run, it would be possible to assemble the kit in ones garage. A contract could then be established with a large performance parts dealer like minimania.com and the kits drop shipped to the consumer. For these reasons, indirect costs are assumed to be negligible.

This analysis has shown the possibility of creating a niche product with high profitability. However, due to the limited market size, there is a low ceiling on the number of kits that could be sold. With a profit margin of 80%, and assuming the parts to make 100 kits are ordered from a machine shop, 56 kits would have to be sold to break even on the investment. Under this scenario, the initial investment would be approximately $10,000, and the potential income from selling all 100 kits would net about $18,000 in income, an $8,000 profit.

6. Conclusion

Due to extensive track use, Mini Cooper GP's are notorious for having brake overheating problems. In the conceptual design stages, BMW engineers intended to install brake ducts on the car to prevent overheating, but due to time constraints, the cars were shipped without the ducts they were intended to have. The goal of this project was to design and manufacture a brake duct kit for the Mini Cooper GP. After a conceptual design of the system, make-buy decisions were made for each component. The components to be made were designed using computer-aided drafting, engineering, and manufacturing software. The components manufactured for this project included left and right wheel hub brackets and a pulley bracket. The system was installed and tested to determine the effectiveness of the newly designed and manufactured brake duct kit. Installation instructions were created for a car owner to expedite the installation process.

Some significant conclusions:

- Results of thermal paint tests inconclusive
- HAAS laser produced high-quality parts quickly and cheaply
- FlowWorks effective and easy to use
- Economic Analysis shows high profitability but small market

The results from the thermal paint test showed almost no difference in the maximum temperature reached by the rotors during the testing. Because the ranges represented by the colors of the paint are so large, the results of the test were inconclusive. A temperature difference of 200˚F would not necessarily be detected because they would be in the same color range.

The bracketry produced on the HAAS laser was of very high quality. In mass production, these parts would likely have been stamped, but the cost of a stamping die is prohibitively expensive for the low production numbers planned for this kit. Laser cutting is a cost-effective method for creating these parts at this production level.

FlowWorks easily allowed for validation of laminar flow of air through the hose and duct, confirming the intuition of the design engineers. However, the analysis done by FlowWorks is simple. Optimization of the duct design and hose routing would require a much more intricate and expensive CFD program.

The economic analysis was thorough and showed the possibility of creating a niche product with high profitability. However, due to the limited market size, there is a low ceiling on the number of kits that could be sold. With a profit margin of 80%, and assuming the parts to make 100 kits are ordered from a machine shop, 56 kits would have to be sold to break even on the investment.

Although a product was created, the success of the project is questionable. Huge amounts of time and money would have needed to be invested in an industry setting to produce this product. Because of the niche market, only a relatively small amount of money could be made by producing this product. In all reality, a company would be better off spending its time and resources on a product that could be sold to a much wider consumer base. All the components designed for this project are universal to every Mini Cooper S from 2002 to 2006. The Mini Cooper S model is the base trim for the John Cooper Works and GP models. A small duct would have to be developed to fit these models, but this would allow for a much larger market base in the hundreds of thousands.

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Appendix A

Mini Cooper GP Brake Duct Kit Installation Instructions

Figure A.1: Wheel removed from car with jack underneath

Step 1: Carefully jack the car up getting both of the front wheels of the ground following the instructions included in the owner's manual

Step 2: Remove the wheel, caliper backing plate, and rotor. The backing plate will not be re-installed

Figure A.2: Removal of wheel wells from car

Step 3: Remove the 16 fasteners from each wheel well and remove both of the wheel wells from the car

Figure A.3: Duct hole cut

Step 4: Using the supplied bumper template as a guide use a 2.5 in hole saw and cut a hole in the bumper directly behind the duct outlet. File the hole until the supplied orange hose slides easily through the hole.

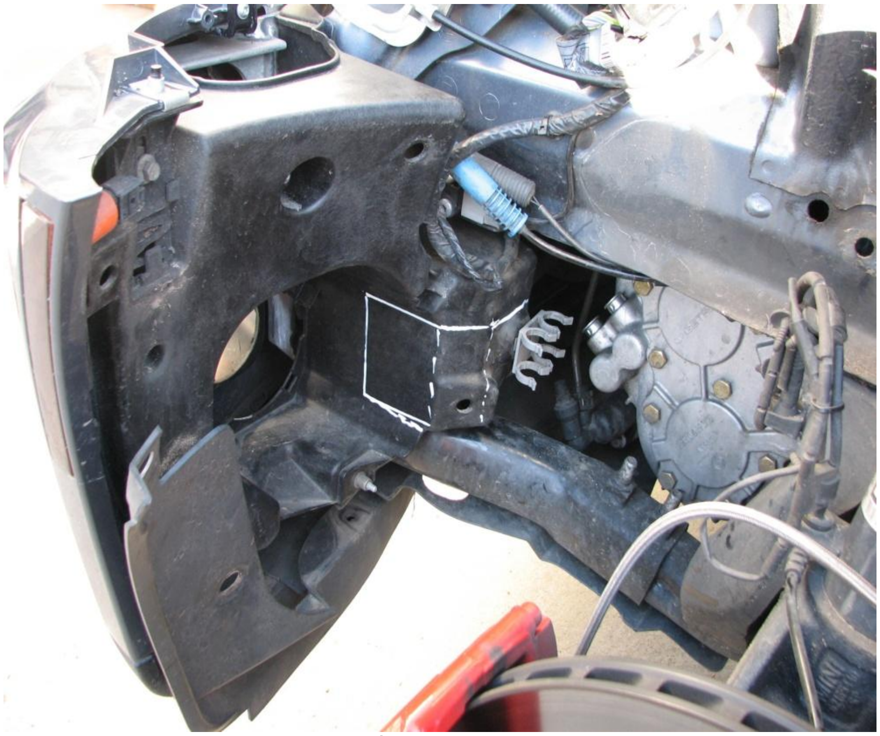

Figure A.4: Bumper marked for cutting

Step 5: Using the supplied templates cut a hole in the rear part of the front bumper using a body saw. Do this on both sides of the car.

Figure A.5: Holes cut in bumper

Step 6: After the hole is cut remove any rough edges with a file

Figure A.6: Installed pulley guard

Step 7: On the passenger side of the car install the pulley guard bracket using the supplied nuts

Figure A.7: Installed wheel hub bracket with attached hose

Step 8: Install the wheel hub brackets to both sides using the screws from the factory installed backing plate. Connect the supplied hoses hose to the wheel hub brackets.

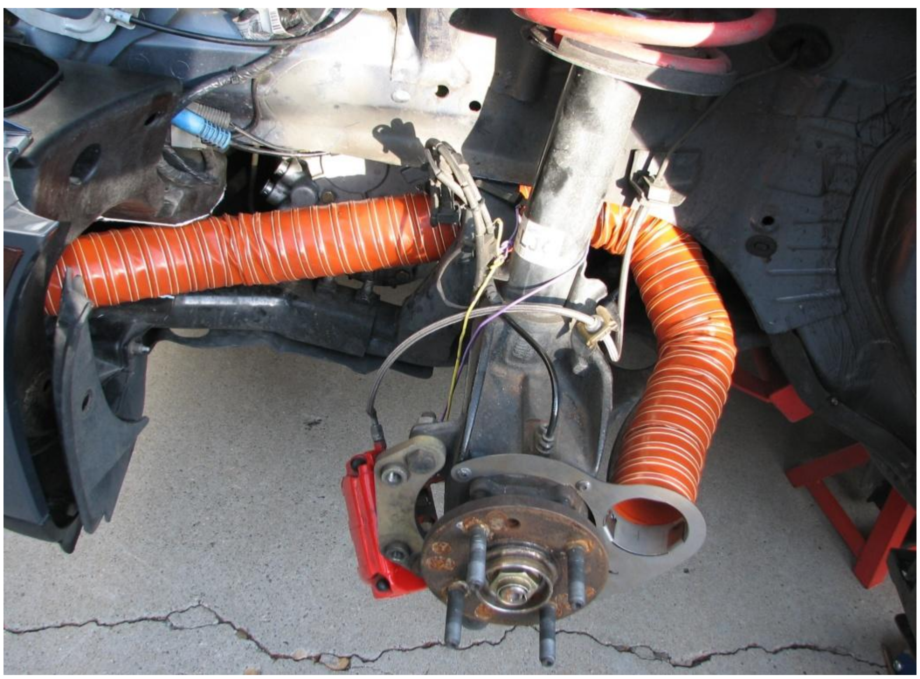

Figure A.8: Completely installed system

Step 9: For both sides, route the orange hose behind the shock and underneath the motor mounts to the hole cut in the front bumper, taking care to push the hose into the recessed slot cut into the rear of the front bumper. Connect the hose to the front duct and clip the duct back into place. Reverse steps to reinstall brakes and wheel well.