AN ABSTRACT OF THE THESIS OF

Colton Swearingen for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on May 30, 2014. Title: Design, Manufacture, and Validation of the Formula Student Pedal Assembly.

Abstract approved: ____

Robert Paasch

Formula Student challenges collegiate teams around the world to compete against one another in global racing competitions. Global Formula Racing (GFR) is a collaboration between Oregon State University and German at Duale Hochshule Baden-Wurttemberg Ravensburg students to build a racecar. The task assigned was to create a pedal assembly for the 2014 car that would better perform than the pervious years design. The primary goal was weight reduction, because the pedals are located at the front of the car, reducing weight there has a greater affect on the center of gravity and weight transfer. Every component started from scratch and was designed from the ground up. By utilizing data from previous years, a better, lighter concept for each part was designed. Each component was also designed for simplicity of adjustment, using as few different tool sizes as possible. Catia was used as the CAD modeling software. Using the built in finite element analysis (FEA), each part designed to withstand loadings according to driver input forces. Using this method for design allowed for fewer components to be bought, with only bearings being purchased. The brake pedal alone was 214 grams lighter than last years pedal. The assembly has been tested and drove the team to victory at Formula Student Michigan.

Key words: Pedal Assembly, Formula SAE, CATiA
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Design, Manufacture, and Validation of the Formula Student Pedal Assembly

By

Colton Swearingen

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Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Colton Swearingen, Author

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Design, Manufacture, and Validation of the Formula Student Pedal Assembly

1. Project Description

1.1 Introduction

The Society of Automotive Engineers (SAE) is an organization of engineers representing the fields of automotive, aerospace, and other mobility based engineering disciplines. Each year they sponsor a Formula SAE (FSAE) competition. FSAE is collegiate level design competition sponsored by SAE. Schools from all around the world compete to design, build and race a formula style racecar. Strict guidelines are enforced to ensure safety and even competition. The idea is for students to get hands on experience on an actual collaborative work project, which involves real world scenarios of dealing with vendors, sponsors, bosses, and deadlines. The cars were originally to be designed for the purpose of showing off a new weekend racing car to be used by the non-professional autocross racer. A fictitious manufacturer then would evaluate the design and award teams for profitability, performance, and customer appeal to name a few. These considerations are the reason that FSAE host competitions around the world; they allow the teams to compete with each other directly, showing off the driving ability of the cars, and to be judged.

Global Formula Racing (GFR) is the first—that we know of—collaborative effort between two universities to compete in Formula SAE. The two schools are, Oregon State University (OSU), and the Duale Hochshule Baden-Wurttemberg Ravensburg (DHBW-

R). The two schools began collaboration efforts in 2005 and have worked together since 2010 to create identical cars in both Europe and the U.S. Since 2011, rather than make two identical combustion cars, DHBW-R has built an identical chassis with an electric drivetrain, while OSU has continued in the combustion car effort (GFR12 team).

While there is only one car being built at OSU, over fifty OSU students work on it each year, hundreds of sponsors provide reduced cost or free parts, thousands of hours of machining and manufacturing time, and many thousands of dollars. The car is divided up into a half dozen sub-teams (chassis, suspension, etc.). The pedal assembly is just one small component, which provides a critical piece of the car. It allows the driver to tell the car to go. The pedals are grouped under the suspension sub-team, composed of five OSU students and three more in Germany (working directly with the eCar). The pedal assembly is under redesign this year for the explicit purpose of reducing weight, cutting cost, making it easier to adjust, stronger and less susceptible to stresses.

The pedal assembly and brakes comprise quite a number of parts. The area, which comprised the bulk of the analysis for the GFR14 car was in the pedal assembly. There are a few goals that were accomplished throughout the design process for the GFR14 car pedal assembly. The first was to raise the heel bar block up to 1.5 inches (38 mm) off the monocoque floor. This is based on driver input and preference. Second, the throttle pedal was redesigned. Its appearance will be similar to that of the GFR11/12 cars. The GFR11 car utilized a two-piece throttle, a vertical arm machined from aluminum, and a horizontal bar connected at a right angle. This throttle yielded approximately 10 degrees during the season. The GFR12 car had a similar design yet was made of two pieces of hollow aluminum tubes welded together. This throttle was not heat treated after welding and also bent during the season. The reason that the GFR14 car will consider using this style of throttle is due to its lightweight and ease of manufacturing. It will be one of several considerations, and if it is determined that there is a better solution, then it will be implemented. The pedal was mounted directly adjacent to the brake mount, using the same base. This reduced the weight from the base and simplified the overall design. Third, a sliding base mount will be considered, which allows the entire pedal assembly to be moved quickly between positions. This has the potential to add weight back onto the lightened assembly, however, there will still be a net loss of weight--over the GFR13 car--and this will make adjustments for leg length far more convenient. Lastly, the throttle stop (?) position needs to have better placement. Drivers who are using the full throttle have a tendency to want to go faster still. To do this the driver applies more force to the pedal; known as the "Mario Kart Factor" the result can be a deflection in the throttle causing the throttle valve to open past full and therefore lose power from the engine. It is important to address this factor, because if it is not accounted for the car could lose power and speed on the track, losing points for the team.

The brakes and hydraulics were not looked at for the GFR14 car due to major emphasis on the pedal assembly. There were underclassmen interested in doing an analysis on the brakes, but none committed to the project. Given that little will change, an analysis of the current brake calipers and rotors was done to determine if they will work within the specified bounds of the GFR14 car. This was accomplished through FEA and hand calculations for braking forces and given that they meet the expectations for the GFR14 car, will be bought and put on the car. The only other major consideration on brakes is finding sponsors for the components. This was difficult because the brakes are relatively commonplace for teams and the companies that produce the calipers and hoses only make those components. They therefore have no desire to sponsor teams like GFR.

1.2 Brakes and Pedal Assembly Project Description

This project is to design and manufacture the complete brake system for both the combustion and electric Formula cars. While all components must be manufactured, engineering development will focus on the pedal assembly including the throttle pedal, brake pedal, and pedal base which interfaces with the monocoque. The 2013 system works sufficiently well, but there is room for improvement in weight, manufacturability and, driver comfort. The brake pedal and base are heavier than necessary while the throttle pedal was not strong enough, yielding in service. Special care must be taken to fully understand the forces the driver applies on the pedals during use and the parts designed to not fatigue in 1 year of service. At present, adjustability of the pedal assembly is sufficient, but could be easier and quicker - particularly in the areas of throttle cable integration. Pedal adjustments are currently made from underneath the front of the monocoque but options should be explored to move the adjustment inside to allow for a larger front splitter. During the fall, testing should be done to determine if we want to include a remote brake bias adjuster on the new car.

Project Specific Requirements

4 complete sets of all parts should be made- 2 for each combustion and electric car.

Part list includes but is not limited to:

Pedals

- Pedal base
- Throttle pedal
- Brake pedal
- Master cylinders
- Balance bar
- Brake fluid reservoirs and mounting
- Brake fluid reservoir lines
- Throttle cable
- Pedal side plates

Brake system

- Rotors
- Rotor mounting circlip
- Calipers
- Brake lines
- Brake fittings

Mechanical Design:

- Follow GFR design philosophy and meet factor of safety requirements
- Be of minimum weight which meets other requirements such as strength, stiffness, manufacturability, etc
- Use metric hardware wherever possible
- Pedals should be adjustable 100 mm for-aft
- No tools should be necessary to adjust pedals
- Pedal position must be positively locked
- Pedals should be adjustable by one person in 30 seconds
- Pedal adjustment shall not interfere with front splitter
- All brake lines should be covered with heat shrink or other lightweight clear tubing to prevent abrasion of nearby parts

Manufacturing:

- If welded assemblies are utilized, fixtures need to be manufactured before the end of fall term
- Manufacturing should begin week 1 of winter term

Post processing of components:

- Steel components need to be plated (Electroless nickel or otherwise)
- Any welded aluminum parts must be heat treated back to full strength

1.3 Rules and Constraints

Brake and Throttle System Rules

*Rules taken from 2014 Formula SAE Rules designated in [XN.N.NN] format

- The brake pedal shall be designed to withstand a force of 2000 N without any failure of the brake system or pedal box. This may be tested by pressing the pedal with the maximum force that can be exerted by any official when seated normally. [T7.1.8]
- The brake pedal must be fabricated from steel or aluminum or machined from steel, aluminum or titanium. [T7.1.9]
- There needs to be a brake over travel switch, which will cut power from the engine in the case of excessive braking. This switch can be either a toggle or a push button and can have no return from the drivers controls. It must be activated efficiently without being triggered early or not at all.
- The brake system will be dynamically tested and must demonstrate the capability of locking all four (4) wheels and stopping the vehicle in a straight line at the end of an acceleration run specified by the brake inspectors. [T7.2.1]
- A brake pedal over-travel switch must be installed on the car as part of the shutdown system and wired in series with the shutdown buttons. This switch must be installed so that in the event of brake system failure such that the brake pedal over travels it will result in the shutdown system being activated and controlling the systems as defined in Part IC Article 4 (IC vehicles) or [EV5.4] (electric vehicles). [T7.3.1]
- Repeated actuation of the switch must not restore power to these components, and it must be designed so that the driver cannot reset it. [T7.3.2]
- The switch must be implemented with analog components, and not through recourse to programmable logic controllers, engine control units, or similar functioning digital controllers. [T7.3.3]
- The Brake Over-Travel switch must be a mechanical single pole, single throw (commonly known as a two-position) switch (push-pull or flip type). [T7.3.4]

eCar Specialty Rules

- EV ONLY: The first 90% of the brake pedal travel may be used to regenerate brake energy without actuating the hydraulic brake system. The remaining brake pedal travel must directly actuate the hydraulic brake system, but brake energy regeneration may remain active. Any strategy to regenerate energy whilst coasting or whilst braking must be covered by the FMEA. [T7.1.10]
- The throttle pedal must have two independent springs for throttle return. [EV 2.3.3.]

Cockpit Rules (wiring and pedal placement)

- A free vertical cross section, which allows the template shown in Figure 9 to be passed horizontally through the cockpit to a point 100 mm (4 inches) rearwards of the face of the rearmost pedal when in the inoperative position, must be maintained over its entire length. If the pedals are adjustable, they will be put in their most forward position (Figure 1). [T4.2.1]

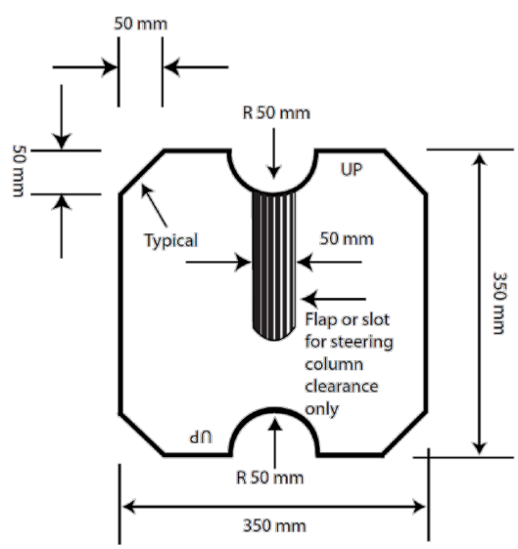


Figure 1. Internal cross section template for cockpit

Note: Cables, wires, hoses, tubes, etc. must not impede the passage of the templates required by [T4.1.1] and [T4.2] *(2014 Formula SAE Rules)

- The pedals will be placed in the most forward position. The bottom 200 mm circle will be placed on the seat bottom such that the distance between the center of this circle and the rearmost face of the pedals is no less than 915 mm (36 inches).[T3.10.4]

- There must be a throttle position sensor (TPS) on the eCar as no throttle cable exists for an electric motor. This requires an additional mounting point be designed into the pedal base that can easily and feasibly work for both the eCar and cCar.
- The throttle needs to have a limiting adjustment for far end travel.
- There can be three or four brakes. If three are used then the rear differential has a disc brake, which acts directly on the rear axle.

Fastener Rules

- All threaded fasteners utilized in the driver's cell structure, and the steering, braking, driver's harness and suspension systems must meet or exceed, SAE Grade 5, Metric Grade 8.8 and/or AN/MS specifications. [T11.1.1]
- [T11.2.1] All critical bolt, nuts, and other fasteners on the steering, braking, driver's harness, and suspension must be secured from unintentional loosening by the use of positive locking mechanisms. Positive locking mechanisms include:
    - Correctly installed safety wiring
    - Cotter pins
    - Nylon lock nuts
    - Prevailing torque lock nuts
- [T11.2.2] There must be a minimum of two (2) full threads projecting from any lock nut

Fluid Rules (Hydraulics)

- [S2.7.2] Part 2 – Tilt Table Tests
    - Each vehicle will be tested to insure it satisfies both the forty-five degree (45°) fuel and fluid tilt requirement (Rule T8.5).
        - Test relevant to brakes

1.4 Points and Considerations

The pedal assembly directly affects the reliability, performance, and design of the car impacting points in both the static and dynamic events.

In the static events the design aspects of the car are evaluated in the following areas: Technical inspection (no points, but must be completed to compete, otherwise no points), cost analysis, presentation, and design. All of these areas are affected by the pedal assembly and brakes. If the pedals are extremely heavy, then the team will lose points due to weight. If the design is flawed, or lacks the engineering fundamentals to back up the design, points could be lost. If the assembly is made of rare, expensive materials the cost analysis could lose points. However, if the design is light, well documented, and made as cheaply as possible, points will be gained for the team.

The brake fluid reservoirs, of which there are two, both located within the monocoque, are not pressurized like the rest of the hydraulic system. Because they are unpressurized and each hold about 15 ml of brake fluid, there is a risk of leaking. To pass inspection during the tilt test there can be no fluid leakage. This requires that there be a tight seal on the lid of the reservoirs and that they be secured within the monocoque.

For the dynamic events, which include: acceleration, autocross, endurance, fuel economy, and skidpad, it is important the design be functional and reliable as well as easily adjustable for different drivers. Should the throttle yield under the "Mario Kart Factor" then the max throttle will be less than the actual max, slowing the car. [D8.7.3] A driver change must be made during a three (3) minute period at the midpoint of the heat. Because of this the ability to quickly adjust the pedals is key.

During the acceleration event it is imperative that the throttle response be consistent and controllable. A near linear response between driver input and engine output is desired. Throttle travel and throttle body opening work together to develop this linearity. Neither throttle travel nor throttle body opening are linear but together they can be. The more accurate the throttle control is, the better the driver can correct for tire slip, and other factors, maintaining the highest possible acceleration through the finish.

For the autocross, the cornering nature of the car is tested. This pushes the suspension and aero teams to the test. Yet, the more control the driver has over the throttle response the more accurately he can control the car, maintaining high speeds, quick accelerations and keeping the lap times as quick as possible, pushing the car as close as he can to the limits of its design.

The endurance event last 22km and the pedals must maintain functionality and comfort for the driver throughout the duration. Given the three-minute pit stop for driver changes, the pedals must be changeable in less time. Again, it is important that the driver has accurate and consistent control over the throttle and brake response in order to ensure the quickest time possible. These considerations are even more important because the fuel economy test takes the endurance run into account.

During the skidpad test the driver experiences high lateral acceleration and must be capable of maintaining control of both the throttle and brake pedals during this process. Lateral stiffness and stability for the driver’s foot become increasingly important for this event. It is also very important for the throttle to respond as linearly as possible, with the greatest smoothness attainable. The subtle changes in engine response that the driver requires to make the car perform at peak efficiency are directly related to the throttle pedal response. This action in the past has not been up to the standard of the GFR team. According to Trevor Takaro, this has mostly been a result of engine tuning rather than throttle pedal design. However, the more precise the throttle response is the less error that will result from that end. The design of the pedal should reflect these considerations, with smooth action, high precision movements, and no slop in travel.

As is now evident, the pedal assembly must function reliably and efficiently across several events in order to achieve peak performance. The score the team receives is directly affected by the performance of the pedals, whether it is in the throttle response, the endurance event reliability, fuel economy of the car, skidpad testing or acceleration testing, or the static events.

Some additional considerations for the functionality of the pedals is how easily they can be adjusted. Four separate adjustments are possible on the pedal assembly: Pedal position, throttle stop, throttle cable tension, and brake balance. Pedal Position is the preference of the driver and goes in accordance with leg length and height. The pedals are designed with four pedal placements. The throttle stop allows for the adjustment of the end travel on the throttle pedal. The throttle cable tension is as important to the car as the pedal or the wheels, without proper tension the car will not perform as was designed. The last of the adjustments is that of brake balance. Brake balance allows for more or less pressure to be applied to either the front or rear brakes. Doing this gives optimal control of braking letting more power come from the front, where the weight shifts under braking, and less at the back, preventing tire skid and slip from over-braking. All of these are important and the balance between points, cost, functionality, reliability, comfort, ease of use, and simplicity of manufacturing must be taken into account for the final product.

1.5 Requirements

The overall goal that the team has determined for the pedal assembly is to cut the assembly weight by half (1 kilogram). This is a very aggressive goal but is just within reach. This can be accomplished not only through the pedal assembly but also through the interaction with other subteams. The other subteam that can reduce weight due to pedal redesigning is that of the monocoque hard points. By adding a sliding mount, three mounting holes from each hard point on both sides of the car can be removed. The weight loss there can be considered a net gain for the car, and the pedals.

The overall cost to the team is also determined as a significant goal for the pedals and brakes. The current system has many parts that are both expensive and not heavily sponsored. It is the task for this year to both find new sponsors as well as eliminate outside costs by making more of the pedal assembly in-house and using standard sizing for bolts that are readily available.

For the greatest success, Colton Swearingen will be working on a redesign of the pedal assembly (throttle, brake, base, all included bolts, and sensors), reducing weight, making the system easier for manufacturing, assembly, driver interaction, and cost the team less. The brakes (calipers, rotors, hydraulic lines, and master cylinders) will be mostly reused from last year, unless analysis indicates a needed change.

From driver interview it has been determined that the heel rest needs to be raised up to 1.5" off the monocoque floor. The heel rest should be made of a single bar, not carbon cups as has been done in the past. A go-kart style throttle works well and is desired, although not required. The throttle and brake both should have the same travel kinematics providing the current throttle and brake response in accordance with driver input to the throttle and brake respectively.

1.6 References and Background

Brake System

The brake system will not be changed this year, however, it is important to both understand the workings, and to double-check all calculations with a parallel analysis. The brake system consists of brake pedal, master cylinders, brake lines, brake calipers, brake pads, brake rotors, and wheels/tires.

The above list is in order of reaction from driver to stopping power. The basics of braking are all based on energy transfer. In order to stop, or slow, a vehicle, kinetic energy must be absorbed and transferred. For cars this transfer is released mostly as heat. This heat comes from the frictional interaction between the tire and the ground, as well as between the brake rotors and the brake pads.

The force transfer from driver input to stopping power is all a result of mechanical leverages. Starting with the driver, the input force upon the brake pedal is amplified five times, due to the moment arm ratio for travel. This was simply calculated based upon the pivot points for the master cylinders and brake pedal. Every incremental movement of the brake pedal face moves the master cylinder push rods five increments.

The pushrods transfer the amplified force into a hydraulic pressure, which can be sent to the calipers. Hydraulic pressure is a result of pushrod force divided by the bore area for that master cylinder. It is then in the calipers that hydraulic pressure is changed back into a linear pushing force in the opposite reaction as in the master cylinders. This force is double that which is calculated for a single brake pad because there are two pistons and two pads upon which the force is applied.

With the drivers braking energy now outside the monocoque, it is able to create stopping power. The force applied to the rotors is used to create a torque upon the wheel assembly. Torque at the rotor is equal to the force upon the rotor multiplied by the coefficient for kinetic friction between the rotor and pads, multiplied by the effective radius of the calipers. Because the tire, wheel, caliper, and hub are all mechanically coupled, the torque in the wheel is the same throughout the system. From this braking power can finally be determined. Dividing the torque of the wheel by the wheel radius results in a force imparted upon the ground by the tire. However, because most cars have four wheels and tires, the total stopping power is the sum of all four tires stopping force. So long as this force is lower than the static friction force of the vehicle, the car will slow and not skid. If the braking force is greater than that for the cars static weight, then the tires will stop rotation and the car will skid.

The static weight force for braking is based upon weight transfer during braking and the frictional interaction between the tire and the ground. During deceleration the weight of the vehicle and driver is not consistent with that of a non-moving car. More weight is transferred to the front of the car, and therefore the front tires and calipers. The front of the car imparts far greater stopping power than that of the rear. Calculating the weight transfer is a simple matter of knowing the deceleration rate, the center of gravity for the vehicle and driver, and the wheelbase length. A vertical force due to weight can then be calculated for the front and rear of the car. Finally, from this, the highest braking force for the car can then be calculated based upon the coefficient for static friction between the tire and the ground (Walker).

FEA

It is necessary to denote how much of the analysis will be conducted. Through the CAD (computer aided design) program CATiA, all the components that go into the pedal assembly will be modeled. From these models it is possible to run FEA (finite element analysis) on each part. FEA works by taking the known dimensions, geometry, and material properties of a given part. The software of CATiA then takes the given geometry and creates a 3D mesh. Then using numerical methods it takes the input force and calculates the stress created upon each grid using the material properties and geometry as boundary conditions. This then becomes an estimation of the actual stress. Because the grid size is selected by hand, it is possible to create a grid too large, yielding false results (Qi).

FEA has been around since the early 1940s, however it only became a real viable solution since the advent of computers in the 1950s. The early computations created stiffness matrices which could be used in equations for beams and other element. Shigley's *Mechanical Engineering Design* offers a very detailed explanation to the history and usage of different FEA methods (Budynas & Nisbett).

FEA is the primary method behind which the parts were evaluated in the model. At the same time, each part had a similar calculation done by hand in an attempt to confirm different analysis methods. CATiA is a good FEA software which not only allows single parts to be evaluated, but also for an entire assembly of parts to be analyzed at once. Assembly FEA, however, is far more complicated, takes a lot more time to set up and run. What it does do is allow for a complete visual of the system in a realistic loading situation.

Design/Ergonomics

This project is largely design, and because it is directly in contact with the human body, it is also an ergonomic design that should be considered. While there are many books, which discuss ergonomics, much of what should be considered already has been done in the automotive and racing industries. Therefore some of the best resources for design will come from images of consumer cars and Formula 1 racecars.

The other input of great importance is that of the existing drivers. They have used the system in past years and have an idea as to what it should feel like and what needs to change or remain the same. For this reason, past and current drivers take precedence over innovation. If a system is designed that is too different from what a driver is used to, it may not be worth the advancement, even if it is theoretically better. Innovation where human interaction is crucial is often done in stages to allow for adaptation to the new technology.

The pedals, like the steering wheel, are a point of leverage, and if not properly supported will tire the driver. The brake and throttle each need a point upon which the heel can rest and provide a pivot point from which leverage is achieved. Should the pedals be designed with this heel support too close to the driver it can be beyond comfortable reach for foot flexion. Also if the heel support is too far away from the driver, the foot will not be able to flex enough and will subsequently apply braking force before the heel even touches the support. For this reason, and from driver input, a vertical alignment is preferred when the pedals are not in use between the contact surface of the throttle and brake pedals and the heel support.

It is also important to understand that the human body is not standardized. Some people have large feet, some small. Some have long legs, some short. Some have feet that naturally twist out, while others are straight, and other still are twisted inward. These all will have an impact upon how and were each pedal is designed and placed.

2. Current State Analysis and Benchmarking

2.1 Current State Analysis

The current pedal performed inadequately in competition having a slight deflection of the throttle pedal due to a series of circumstances including: a strong-footed driver and improperly aligned throttle stop. Neither of these situations should have affected the pedal had it been designed properly. The inability of the throttle pedal to maintain its shape resulted from a lack in load considerations during design. The back throttle stop should be located at a point higher up on the throttle arm to lower the loading.

The current pedal assembly (Figure 2) employs a dual-arm throttle, the same brake pedal, bias bar and master cylinders as were used on the GFR11/12 cars, and involves a number of welding points (Figure 3). The entire throttle side fixture required welding. The entire assembly weighs just over 1.7 kg (without master cylinders but with balance bar)

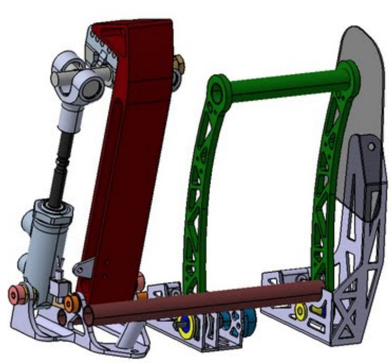


Figure 2. Pedal assembly for GFR13 car (image credit Jesus Meraz)

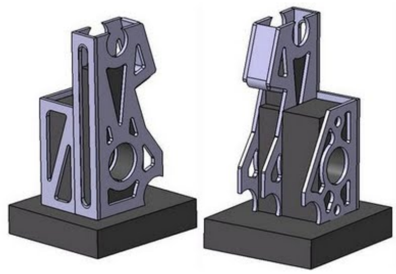


Figure 3. Welding fixture for right side mount (image credit Jesus Meraz)

The current throttle heel rest sits too low to the floor, causing the drivers foot to be in an uncomfortable position and risks slipping up beyond the rest. The throttle pedal alone weights 98 g, which is 15 g lighter than the throttle on the GFR11 car, yet nearly twice as heavy as that of the GFR12 car at 56 g.

The current brake pedal has an adequate feel, weighs 340 g (without bias bar), and has a minimal deflection of 3.4 mm at 400 lbs (1779 N) of force (as reported from FEA in the 2013 pedal report). The 2013 report also indicated that the average input force upon the pedal ranged from 355 N to 445 N. This is well below the 1779 N finite element analysis for the brake pedal. This result is as expected, because during FEA it is customary to test under the worst-case scenario loadings. The object in question should be able to withstand worst-case scenario loadings, and a little more for factor of safety. There is 9 mm of slop in the current brake pedal, which must be traveled before hydraulic engagement. Beyond this the pedal is firm and responsive. The long travel before brake engagement is more than would be expected. This could result from several minor failures or a single larger one. Some of the areas, which could have affected the travel to this point, are:

- Brake pad / brake rotor wear
- Low hydraulic fluid levels / air bubble in the hydraulic line

- Slop in the brake pedal connection
- Human error in measurement (off by a couple mm is possible)

The brake pedal base is made of 4130 steel and has been designed to take the worst-case scenario loading, 2000 N (450 lbf) for the FSAE 2014 season. The reasoning behind the use of such high grade steel is due to a 5:1 ratio of pedal travel to master cylinder pushrod movement. This causes the forces at the pedal base to be five times that which the driver inputs. The entire pedal base (brake base (red), heel rest (far red bar), carbon stabilizers (gray left), and throttle base (silver)) weighs 430 g (Figure 4).

The same master cylinders and bias bar have been used since 2011. They are Tilton 77 series with ⅝" and 7/10" bore sizes for front and rear cylinders respectively. Each master cylinder weighs 143 g. The bore sizes are different allowing for more braking power at the front of the car for better traction during weight transfer. The bias bar allows for accurate adjustment of the braking for front and rear. The current bias bar costs the team $450 each and weights 188 g (bar, mount, balance bar clevises x2).

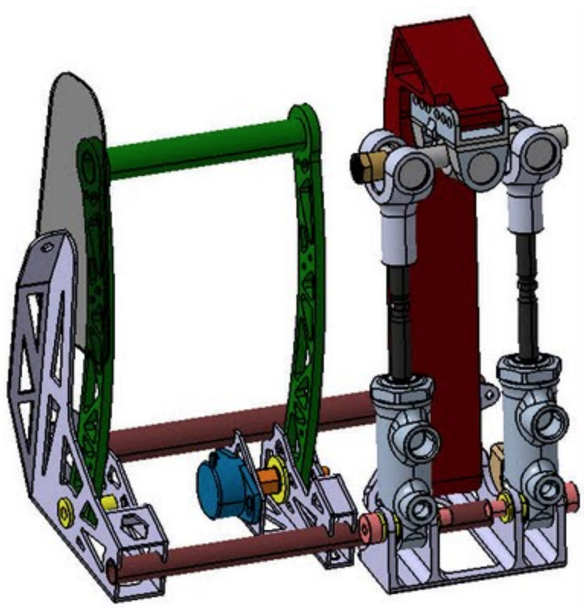


Figure 4. GFR13 pedal assembly (rear view)

The throttle pedal base was welded together from numerous laser cut sections and shows no sign of wear. It needs some design consideration that needs taken into account for putting it back together (there is a specific order of operations that needs to be done or the throttle won't work properly). In order for everything to go back the throttle must first be put into place, then the spring needs installed, then the shoulder bolt goes through, and finally the whole thing is secured with a shoulder sleeve and a nut from the inside of the pedal. The left side throttle base, and subsequent mounting of the throttle position sensor (Blue in picture above) (TPS for the eCar) has a single shoulder bolt (orange leading off of blue TPS) that passes through (Figure 5). However, since it was bent during the last year it is extremely difficult to put said bolt back in place. There is no leverage point and it gets stuck inside the TPS mount where neither hand nor tool adequately fits.

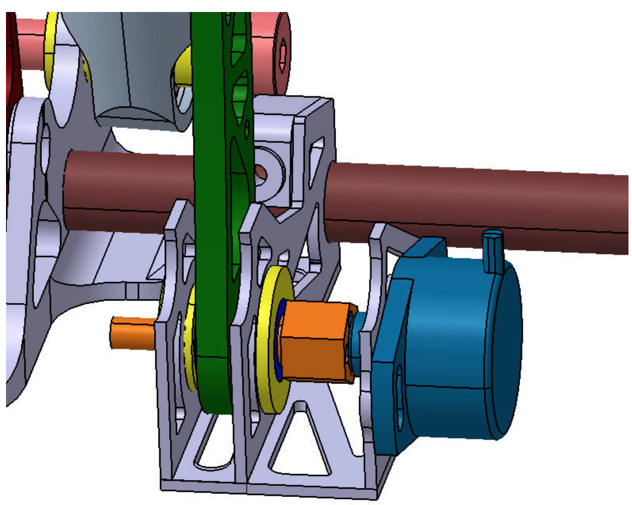


Figure 5. GFR13 TPS sensor (blue), TPS bolt (orange), and mount. (image credit Jesus Meraz)

Below is a SWOT Analysis for the pedal assembly.

Strengths

- Throttle was far better designed over the GFR11/12 cars
    - The pedal was supported on both ends giving better stability towards torsion
    - Throttle pedal yielded less than previous years
- The kinematic motion for both the throttle and brake worked well
- The brake is made very sturdy
- Heel bar is superior to heel cups (GFR11/12)

Weaknesses

- Pedal adjustability is cumbersome (see section 2.2 Benchmarking for more details)
    - Takes average of 1 min 50 sec to adjust to new location
- Full pedal assembly is heavy (1.7 kg)
- Adjustability for tall drivers is not adequate (6'+)
- Throttle pedal yielded
- Throttle arm bent
    - Throttle stop caused the bend

Opportunities

- Pedal base could be lightened considerably
- Moveable base could make the adjustability easier
- Strain gauge/load cell could be implemented to aid eCar regenerative braking
- Better throttle stop could be designed

Threats

- CATiA is a new and unfamiliar software
    - Building parts, assemblies, and FEA, will take time
- Throttle is still susceptible to bending under the "Mario Kart Factor"
- For some of the parts to be made in-house, CNC coding is required
    - Have not done CNC before
        - CNC training done in November
        - Still unfamiliar with CNC
    - Need to get certified during fall term
- Time
    - Short term (10 weeks) in which to accomplish all design and analysis
- Attachment of the heel rest is complicated with a single left side base

2.2 Benchmarking

The current state of the pedal assembly includes all the cars currently on hand in the formula SAE workshop, plus any report that is on hand. The GFR11, GFR12, and GFR13 cars are all currently in the workshop. It is from these cars that a baseline of comparison can be made and they offer three stair steps of improvements on which the GFR14 car can build upon.

One of the most important measurables for the GFR team is weight savings, especially in the front of the car--the front rear weight distribution greatly affects the handling of the car. Since the pedal assembly is at the very front of the monocoque, it is important that the weight be considered at the forefront of design. The pedal assembly has evolved over the past three years by a marginal amount. Since 2011 the pedal assembly has gained 0.6 kg in weight. This was in the wrong direction for weight, but was accepted due to other advantages made in the design.

For example, the mounting process for the GFR13 car is far superior to that of the GFR11 car. The average time for adjusting the pedals on GFR11 from one position to another (for different height drivers) is 2 min and 17 seconds (taking as long as 2 min 55 seconds). The reason is that the mounting is done via a quick release skewer pushed up through the monocoque floor into the pedal base. This makes adjustment far more difficult due to alignment issues with the skewer and the base. The GFR13 car improved this design by incorporating a threaded bolt onto the pedal base. This then slid down through monocoque floor and utilized a nylock wing nut to secure the pedals in place. This reduced the average pedal movement time down to an average of 1 min 51 seconds.

The GFR12 car used a combination of these two scenarios where a threaded sleeve was incorporated into the pedal base and fell into the monocoque floor and then quick release skewers were used to hold it in place. The average adjustment time for the GFR12 car is 2 min. Adjustment times can be found here and in Table 1.

Table 1. Pedal assembly adjustment times

Car year	GFR11	GFR12	GFR13
Adjustment times	02:43	02:27	02:43
	02:55	02:42	01:53
	02:20	02:25	02:04
	02:00	01:41	02:01
	01:55	01:55	02:00
	01:50	01:31	01:20
	02:16	01:53	01:28
	02:20	01:29	01:26
Average Time change	**02:17**	**02:00**	**01:51**
11 to 13			**00:25**
11 to 12		**00:17**	
12 to 13			**00:08**

In the 2013 report a calculation was shown to determine, based on material properties, the force required to yield the throttle pedal. This force amounted to 407 N or about 92 lbf. Given that the throttle pedal in question (GFR12) yielded, a force of at least

400 N (92 lbf) can be expected for as input from the driver. Given that the average driver weighs between 140 and 180 lbs (60 to 80 kg) it is reasonable that the force applied to the pedals could equal that weight.

The GFR13 car pedal succumbed to the same throttle pedal fault as the previous two years, it bent due to material yielding. The failure mode for the GFR13 pedal however was slightly different from that of the previous two years. It failed as a result of improper load placement upon the throttle upright arm. As was shown in the initial design consideration FEA by Jesus Meraz on the throttle upright (Figure 6) a max stress of 600 MPa was seen in a single point on the throttle arm. This design, which was eventually selected, was given the go ahead because the loading was deemed a result of CATiA restraints rather than design issues. That exact point is where the throttle yielded and was because the back arm at that point is placed into bending from the throttle stop, which is placed between nodes of the truss structure of the pedal. Had the throttle stop been placed at a node the pedal may very well have performed perfectly. There was also the issue that the drivers left side throttle stop had stripped threads and was no longer adjustable to the correct length. Because of this, the stop on the right side took all of the load. The result of the failure is shown in Figure 7 and resulted in a twisted horizontal throttle.

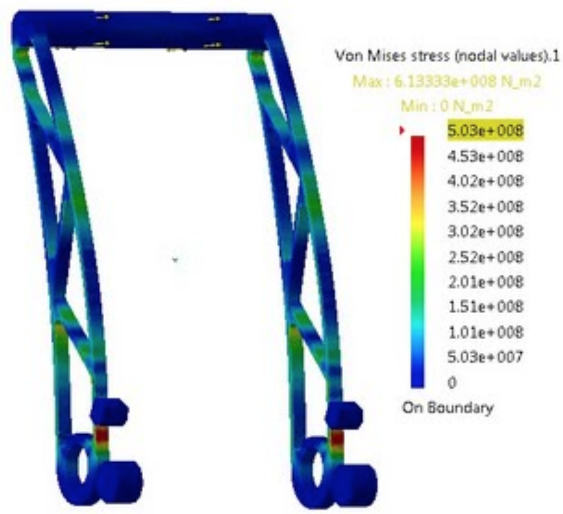


Figure 6. FEA of GFR13 throttle pedal (Image by Jesus Meraz)

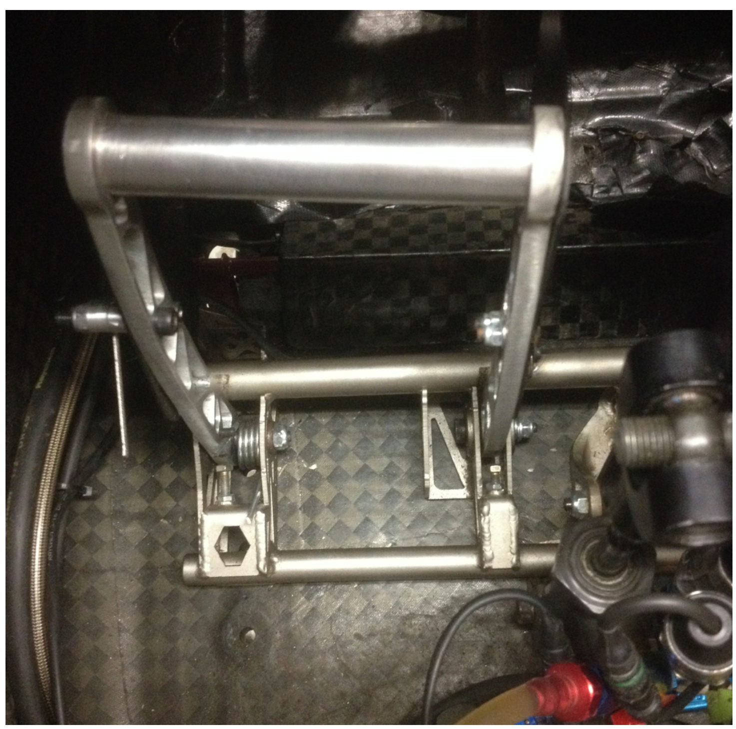


Figure 7. GFR13 double upright pedal bending

This was an improvement in design over the previous two designs which both yielded from torsional instability under heavy loading. This pedal did not twist so much as bend on one side and now leans more to the left.

This area of design has shown an underestimate in the magnitude of the force imposed by the driver. Aluminum tubing, while light, has not been used successfully in the last three years. The throttle pedal therefore has the opportunity to be made from a stronger material. This does not necessarily mean a heavier pedal, just one made from something of higher yield strength. Making the throttle out of stronger material would also benefit the throttle for potential “Mario Kart” effect. This effect is demonstrated when the throttle is at the end of its travel, yet the driver wants to go faster, so then more force is applied to the throttle regardless to the fact that no added speed benefit will ensue.

The overall weight of the pedal assembly is of great importance to the team. For the GFR14 car the goal is for the entire assembly to be under 1.0 kg (2.2 lbs) For this to happen the assembly, without nuts and bolts, needs to weigh less than 800 g (1.76 lbs). The extra 200 g (0.44 lbs) is left as an estimate for nuts, bolts, washers, fasteners, and welds. A detailed list of part weights can be seen for the GFR13 car in Table 2.

While weight is indeed important, it goes hand-in-hand with the cost of materials and manufacturing. To lessen the cost for the team, the brake bias bar is to be manufactured in house. As of last year they cost the team $450 with our team discount. Using a spherical bearing, two spherical rod ends with press-fit threading as adjustment clevises, and a main shaft threaded from hardened steel (1100 + MPa yield strength).

Table 2. GFR13 car pedal assembly detail weights

Item	Weight (g)	
Brake Pedal, Bias Bar, Push rod clevises	697	
Push rod adjustment clevis	74	each
Locknut	8	
Brake pedal alone	340	
Bias bar/needle bearing attachment	188	
Throttle pedal	98	
Side foot stop wings	30	each
Brake cable clamp	3	
Brake cable mounting bolts	8	
Pedal base	410	
Throttle pedal + base	1017	
Total Weight	**1714**	

An area, which is always under considered and very much underappreciated, is that of maintenance and user access. For the GFR13 car pedal assembly, seven different wrench sizes and four different Allen keys were needed to adjust the entire assembly. Several of these areas were also extremely difficult to access with a wrench. For the GFR14 car the goal is to need only two Allen key sizes and two wrench sizes.

3. Design Analysis

From a design perspective there were only a few main contenders in terms of functionality and feasibility for the GFR14 car pedal assembly: the current system (with minor adjustments); two designs with a unified base and slanted throttle: one with a rails system for adjustment, the other having four positions, and a two part base with a single upright throttle.

These designs have been weighted using empirical and explicit means. The use of a "Design Matrix," each variable is weighted in accordance with team values which leads to two of these being front-runners: the unified base without slides, and the unified base with slides. Through hand calculations, CATiA drawings, FEA (Finite Element Analysis) and availability of materials considerations each part was assigned a material, which would work best.

Table 3. Design matrix

		Design Iterations			
		1	2	3	4
	out of 10-->	Current State	Sliding Base	Unified Base no slides	Single upright throttle two part base
Requiremtents	**weight**				
low weight	20%	5	7	10	6
High reliability	25%	7	6	6	6
packaging	5%	3	10	10	5
ease of adjustment	15%	3	7	5	3
low cost	20%	5	8	9	7
ease of manufacturing	10%	4	5	6	4
maintainance	5%	4	6	8	5
	100%	4.95	6.85	7.55	5.45

The design matrix, shown in Table 3, is a way in which several designs can be compared at the same level in order to determine which has the better overall use for the team under given priority of performances. Reliability, cost, and weight are very important to the team, therefore they weigh more heavily on the design selection; while maintenance, which is still quite important, is less a major factor on the teams driving performance to win competitions. From this design matrix it is shown that the unified base design with no slides is the highest rating. The sliding base comes in second, 0.7 points behind GFR13.

These designs were narrowed from the priorities that will give the team the most points at competition and allow the car to operate most effectively all while maintaining a conscious diligence on the material usage, availability and cost.

3.1 Design Considerations

Current "GFR13" System (Figure 2)

As was discussed above in the SWOT analysis there were some good things about this design and a few considerations, which would make the system better. This style of design was obviously considered in determining what to use for the upcoming pedal assembly design of the GFR14 car.

The Brake Pedal

As has been the case since 2009, when it was designed, the brake pedal itself has not changed. It is rather bulky and heavy and could be slimmed down considerably to make it light and just as functional. Currently the pedal weights 340 g (0.75 lbs). This weight and others can be seen in Table 2 detailing items on the pedal assembly.

Pedal Base

This design implemented a single base for the brake, and master cylinders, and a second base, which was welded from sheet metal for the throttle. This system allowed the structure of the throttle side assembly to be far lighter than that of the brake base, yet it was more complicated and required welding time and fixturing to complete.

Throttle

The throttle in this design is great for having no torsion about the “Z” axis (supported on both ends). This is more ideal than a single unified upside down “L” arm because it is less likely to twist. There is an opportunity in this design, by simply fixing the location of the throttle stops, so that they do not contact the pedal arm at a weak point, this design could be viable. However, this design also has added weight and manufacturing time included in laser cutting, welding, and extra material.

Unified Base, New Brake Pedal with and without Sliding Adjustment Rail

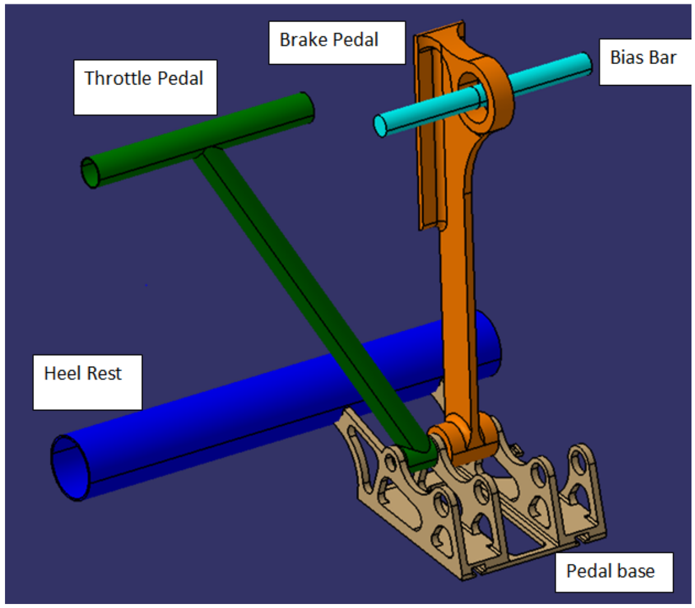


Figure 8. Unified base without slides

A New Brake Pedal

Designing a new brake pedal while utilizing all the same points of interest (in terms of kinematic response for braking action) is mostly a consideration of where extra material could be removed from the current pedal. Given an aluminum composition CATiA generates a weight of (126 grams) for this design of pedal (shown in Figure 9), which is 214 grams lighter than last years brake pedal. This pedal also is designed to utilize an in house built bias bar for front/rear brake bias adjustment. This has the added benefit of saving $450 (minus cost of spherical bearings for in house built bar) on each car. The brake pedal went through several design iterations; Figure 8 above shows an earlier design, which was later modified for greater strength.

The initial FEA on that brake pedal was inaccurate and due to constraints, did not show high stress in the areas of highest stress. In the FEA there are several constraints, which are important to understand, because the boundary conditions completely dictate how the system reacts. Figure 9 shows the brake pedal with a small portion of the driver contact area constrained from rotating, and then equalizing forces are placed in accordance with hand calculations. These forces are placed where the aurora bearing will go, at the point of foot contact, and within the lower axis of the pedal.

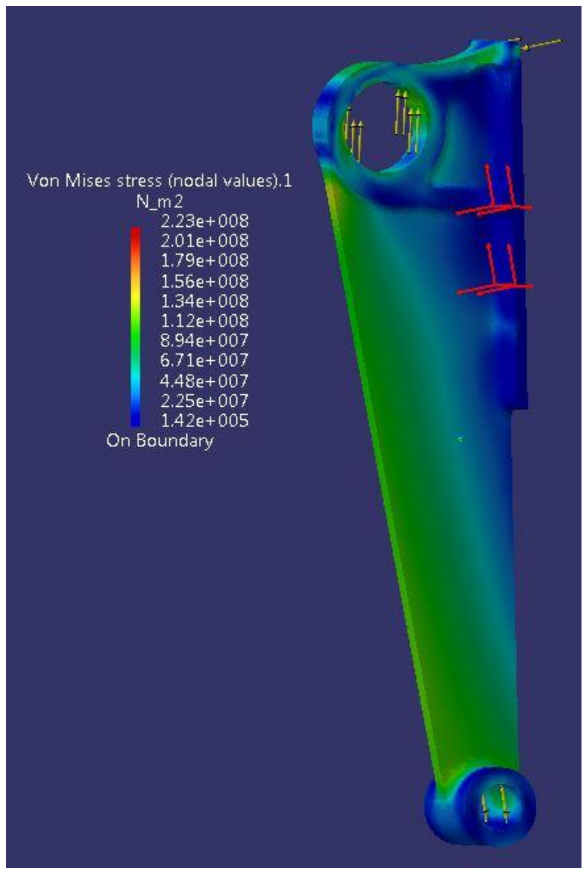


Figure 9. Brake pedal FEA with loading and constraints shown

Unified Pedal Base (Figure 8 tan part)

A single unified pedal base for the brake pedal, master cylinders, and throttle pedal has the advantage of far less material, manufacturing time, and bolts. Because of these savings, the overall weight of the pedal base can be lightened. Also by combining the heel rest support into the design of the pedal base, this becomes one less item that needs manufacturing. All of this gives the opportunity to make a base in a single machining process, which after the heel rest is welded into place, can be heat-treated to the desired strength (700 to 900 MPa yield). Figure 10 shows the FEA on the unified non-sliding base.

A single unified base has the advantage of lower weight, more room for your hands to reach in and adjust the pedals, and overall simplicity. The design is born around having near vertical master cylinders. The purpose of which is to get a greater leverage ratio of 5 to 1. The ratio was designed a few years back by a past student, for this design it was simply incorporated. What the brake pedal ratio does is dictate four points: the brake pivot axis, the master cylinder axis, the balance bar axis, and the contact point for the driver's foot. From those points, mounting holes were sketched, the size of which was determined based upon the minimum steel pin required for the brake axis. Because of the reactionary force of the brake pedal, and the strength of 8.8 steel, it was determined that a ¼" pin would be needed. Then, accounting for the size of a bushing to be placed between the ¼" pin and the base spline, a ⅜" hole was to be used. Building off of this a side profile was determined which most efficiently utilized available space. Weight reduction cutout were drawn in and extruded. Finally it was decided that the heel support should also be combinable with the rest of the base. To do so, two arms were extended from the base splines. The diameter of the heel support was determined through EES iteration of: weight, wall thickness, and outer diameter. A 1" x 0.035" (outer diameter x wall thickness) tube was decided upon. Thus the sizing of the heel rest extrusion points was completed.

By moving both pedals and both master cylinders to the same base, a single pin can be used to hold each of the two respectively. In the past a shoulder bolt has been used to constrain the master cylinders and pedals. A pin has the added advantage of lighter weight. And because it does not tighten down, it will not bend the splines as a bolt would when it is over tightened. Both the brake and throttle pedals are designed to fit snuggly in place with the help of plastic thrust washers from IGUS. Any additional tightening on the axis will result in the bending of the splines, which will pinch both pedals, adding friction, and reducing operational efficiency.

Once the overall design shape had been determined, it was then possible to start cutting weight in low stress areas. The low stress areas were determined through FEA, as well as through load path considerations. The FEA on the final part can be seen below in Figure 10. It is from this analysis that the weight reducing cutouts can be sized. Because it was the intent to have this part machined, the radii for the corners of the cutouts were sized just slightly larger than the intended tool which would be available for machining. It was later determined, through talks with the manufacturer, that the part would be plasma cut and welded together. This was considered during preliminary design, however for cleanliness of the final part, machining was favorable. Both manufacturing processes will work, and because Silver Eagle offered to make the parts for free using plasma cutting and welding this is the process that will be utilized.

For the FEA in Figure 10, it is important to understand how it was loaded. Three separate loadings were applied to the base, each via a virtual rigid part. The virtual part acts like a pin placed inside the axis holes. The far left has forces shown in the image, the middle loading is 10,000 N upward force and 2,000 N towards the driver, and the farthest to the right is 2,000 N imparted by the heel rest. The base is then clamped as it will be sitting on the floor of the monocoque.

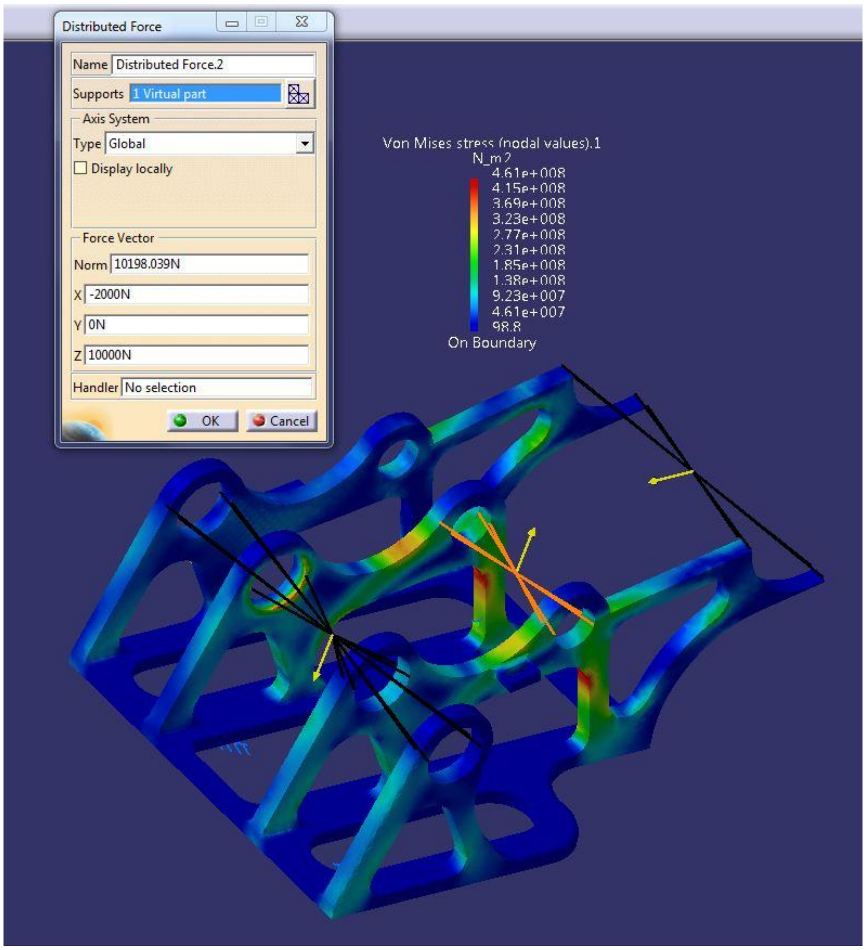


Figure 10. Pedal base FEA

Heel Rest

The heel rest is the point where the driver's feet contact the assembly. This gives the driver a point to pivot upon while operating the pedals. From driver input it was determined that the heel stop should be increased in height from last year, specifically it was to be 1.5” off the monocoque floor.

Throttle Pedal

The throttle pedal in this design is a round hollow tube, which leaves the pedal base at an angle and joins with a horizontal bar at that point. This requires a longer moment arm for the throttle, and due to constraints placed by the base, the tubing for this design will need to be made out of steel to accommodate the larger torque applied. Using a thin-walled steel tubing, while unlikely to be lighter than an aluminum tube will provide greater strength and more opposition to yielding.

Material Sizing has been set up with an EES (Engineering Equation Solver) code which allows the tube sizing to be determined via outer diameter of tube, inner diameter, wall thickness, or total weight desired given a particular yield strength (Figure 11 and full code in 9.1.1). This code is written under the assumption that the entire arm is in bending about a clamped base. This is an overestimate than what is actually happening which adds a second factor of safety to the product design.

```
"Heel Rest Calc"
"Material Properties"
sigma_yield = 700*10^6                              [Pa]

"Set Variables (pick one)"
"Weight = 0.3"
r_o = 0.02                                          [m]
"r_i = 0.018                                        [m]"
"t_inch = 0.03"
"t = 0.0027                                         [m]"

r_o^4 - r_i^4 = 4*F_ap*d*r_o/sigma_allow
F_ap = 900                                          [N]
d = 0.13                                            [m]
sigma_allow = sigma_yield/FS
FS = 2
t = r_o - r_i
t_inch = t*25.4                                     [in]
```

Figure 11. Partial code from EES for throttle upright and heel rest size calculation

Sliding Base option (Figure 12)

This option will utilize the same base but adds an operation for machining, cutting a “T” shaped groove into the base to allow rectangular slides to move along the rails. Along with added machining time, this also adds material and therefore weight to the pedal assembly. While it would be nice and easy to move the pedals if they are on rails (no reaching under the car, removing wing nuts, and moving the pedals) it has a drawback of implementing a positive locking mechanism for securing the base to the slides. This is difficult because, if the slides are locked inside the monocoque (example, nylon wing nut) it is a tighter space in for maneuvering and access by hand. This does have the potential to reduce the adjustment time from nearly two minutes to down around 10 to 30 seconds (if done properly).

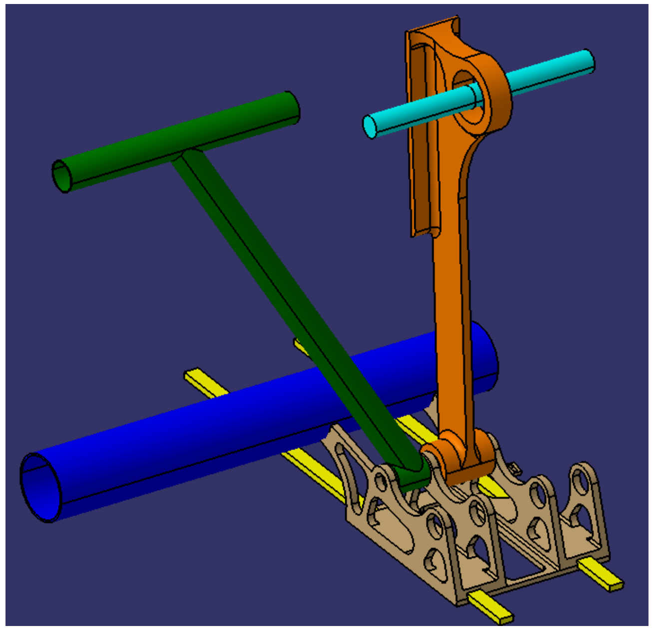


Figure 12. Unified base with Slides (yellow)

Two Piece Base with Single Upright Throttle Pedal

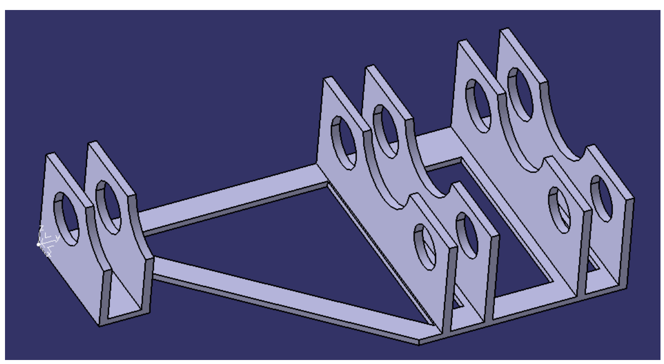


Figure 13. Two piece pedal base mock-up

Brake Pedal

The same new brake pedal as discussed for the unified base section can be used here.

Pedal Base (Figure 13)

The throttle base would be best represented by a standalone base mounted to the monocoque floor and attached to the brake pedal base with a triangular three point attachment. The brake side base would be similar to the current state, a single piece of machined steel to hold both the brake pedal and master cylinders.

Throttle Pedal

A single upright throttle pedal would be lighter, and would require no welding. However, it would be more difficult to incorporate the top of throttle foot stops (the carbon sheets that keep the drivers foot from sliding off the pedal). An additional considerations for this design is the need for a throttle cable attachment which, with a single upright throttle will be more difficult to route.

3.2 Ergonomic Considerations

First off, what is ergonomics? The Merriam-Webster dictionary defines ergonomics as, “an applied science concerned with designing and arranging things people use so that the people and things interact most efficiently and safely.” This project deals predominantly with the feet, and some with the lower leg. Because the pedals directly interface with the driver, it is important that they perform in accordance with the human body. Throughout the design phase the size, position, and range of motion for the drivers feet were taken into consideration. This was combined with input from current and previous drivers as to what they individually felt and wanted to feel.

Heel Rest

The first instance affected the heel rest. From driver input it was asked that the heel rest be raised to 1” to 1.5” off the monocoque floor. Because they had driven the car, they had a good idea of where it should be, but to determine if this was actually the height that would best work for the drivers feet research was required. In the book “The Measure of Man and Woman” by Alvin Tilley, there are several images which show the 1st , 50th, and 99th percentile man/woman body geometry (Figures 14 and 15). The location of the ankle joint center of rotation was of particular interest for the heel stop. The 1st percentile man shows the most ease of rotation about the heel rest as a result of his radius of ankle rotation being closest to the bottom of the foot. Therefore when the 1st percentile man is in the car, the pivot of the heel rest will lie only 1” above the actual rotation of the ankle. For the 99th percentile man this distance increases to 1.7”.

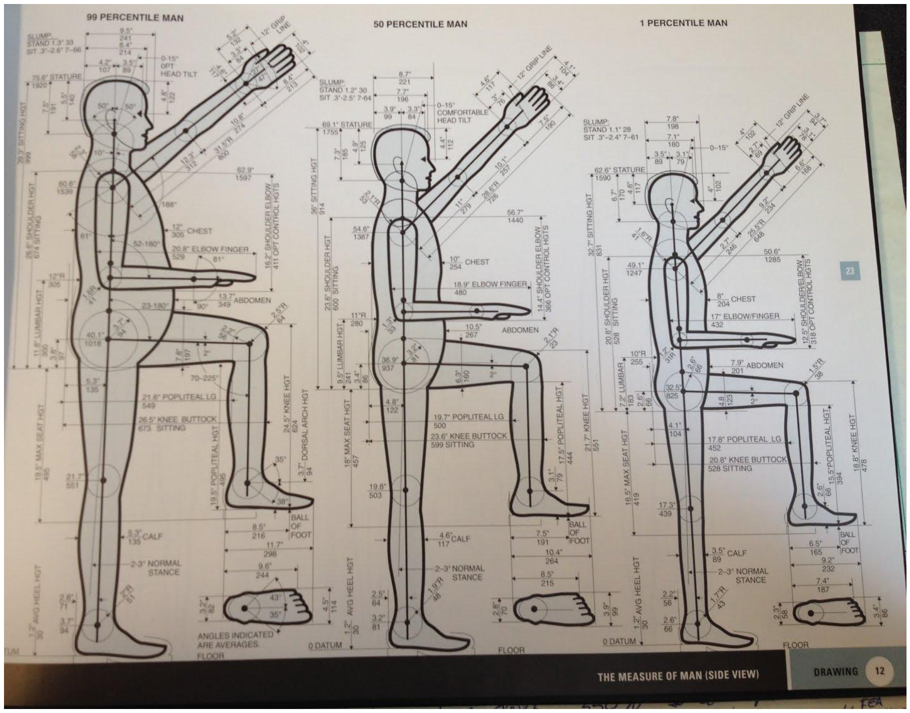


Figure 14. Percentile measurements of men (Tilley)

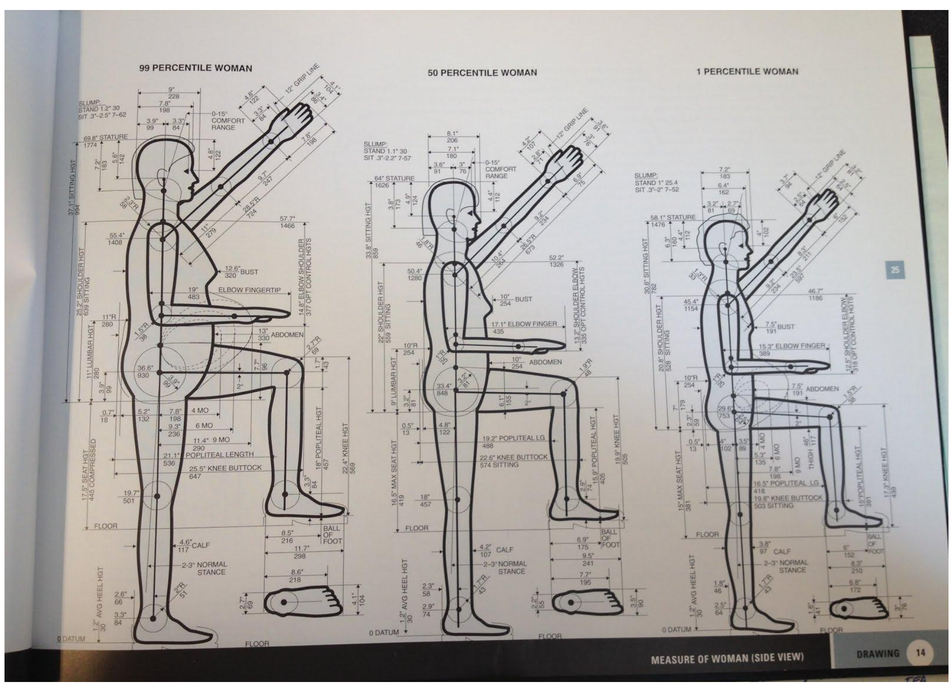


Figure 15. Percentile measurements of women (Tilley)

Recall that the driver recommended the height to be between 1 and 1.5 inches. The 1st to 99th percentile man/woman largest range is 1.8 to 2.8 inches, with the low range being the 1st percentile woman and the high range resulting from the 99th percentile man. Then, when looking at how the throttle and brake pedals operate, it is seen that the pedals utilize the heel rest as a fixed point for creating a moment between the ankle center of rotation and the heel rest. If the heel rest is above the height of the ankle center, then the foot will be unable to create the moment in the proper direction without considerable effort. However, as long as the ankle center is above the heel stop then a moment will be easily reproduced, creating a lever arm to impart a force upon the brake or throttle pedal. With this information known, it is decided that the heel rest be located 1.5” off the monocoque floor. This passes driver input and design for the 1st percentile human.

Brake Pedal and Throttle Pedal

The foot is able has a maximum range of motion (ROM), and a comfortable ROM. These can sometimes be greatly different. For comfortable ROM Tilley recommends staying within the 5th percentile for ROM. As with lengths, there are also percentile ranges for body flexibility. These are further broken down for men and women. Because this car is to be designed with both male and female drivers considered, it is prudent to use whichever has the lower comfortable ROM. In most cases it is the man who has less flexibility. Extension of the foot from a neutral 90 degree angle with the lower leg, has a comfortable range of -13 degrees (foot pulled up towards shin) to 25 degrees away. Women have approximately 5 degrees more range of motion. This can be seen in Figure 16, along with most all other ranges of motion of the body.

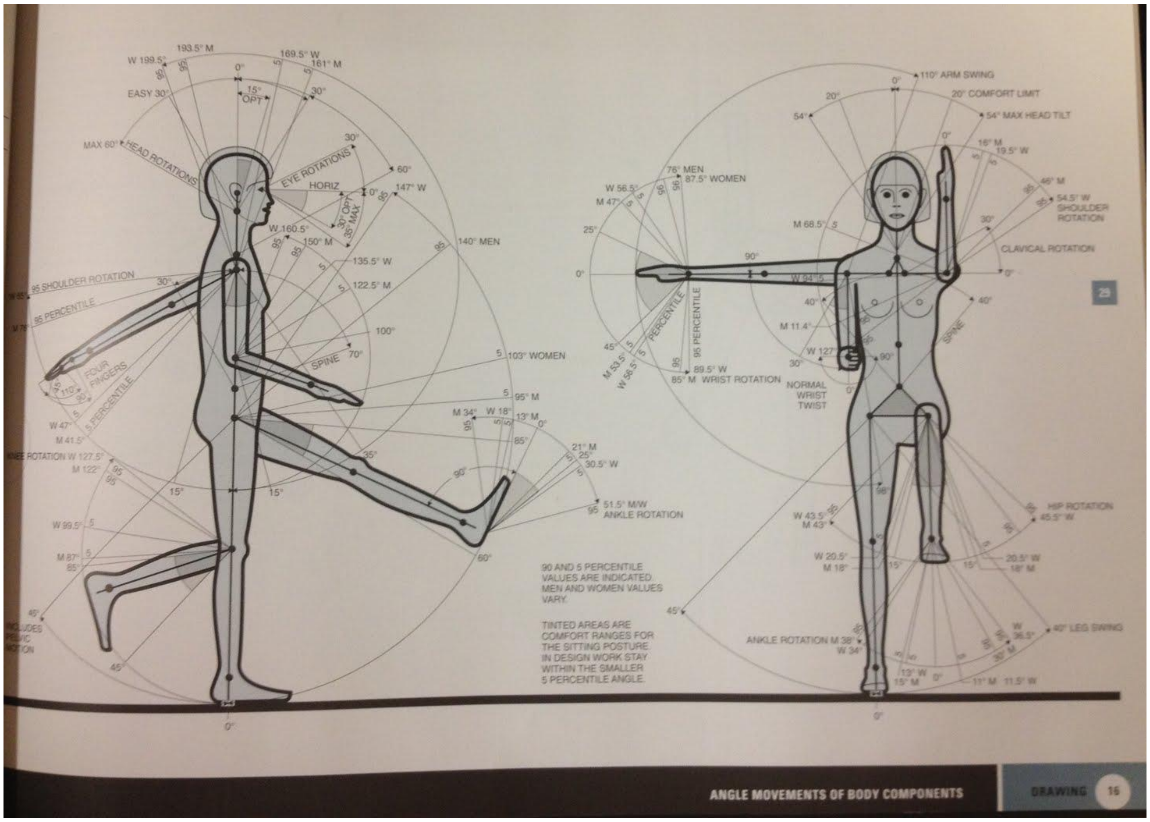


Figure 16. Range of motion for most body joints (Tilley)

This directly relates to the design placement of the brake and throttle pedals. The first consideration however will be the angle of the lower leg with respect to the monocoque floor. The range for this is between 0 and 20 degrees, depending upon pedal placement, driver leg length, and seating position. The comfortable range for ankle flexion at the 5th percentile range can be designed to compensate for the lower leg angle while seated in the car. Therefore should the driver's leg be 20 degrees off the floor, then the angle from the heel rest to the contact point of either pedal should be 7 degrees away from the driver. The lowest maximum (man or woman) range of motion is 34 degrees. This means that the throttle could be placed as far as 14 degrees angled towards the driver with respect to the heel rest. Driver input on the subject was to have the throttle and brake contact points vertically aligned with the heel rest contact point. This is the location which was chosen for the pedal assembly. What this means for design is this: any man seated in the cockpit with a lower leg angle greater than 13 degrees to the monocoque floor, 18 degrees for a woman, will exceed the comfortable ROM when the pedal is not activated. Should they exceed the comfortable ROM it is not going to cause any harm because the foot still has 20 degrees of motion, it will simply require a little effort to keep it there without activating the pedal.

There is only one last consideration, which should be made: the length of time a driver is in the car. A traditional car on the road should be designed to allow for comfortable driving for up to 12 hours, while our car has drivers in the cockpit only 12 minutes for the longest race (endurance). It is therefore slightly less important for this car than it is for commercial vehicle. With this final bit considered, it was chosen that the pedals would be vertically aligned so pedal contact point was vertical to heel rest contact point.

Since both pedals deal with the length of the foot and are a direct result of human interaction, they can be grouped together. Ideally the ball of the driver's foot will be the point of contact upon the pedal. The 1st to 99th percentile range for men and women is 152 mm to 216 mm for the distance from heel to ball of foot (Table 4).

Table 4. 1st, 50th, and 99th percentile measurements for the feet of men and women (Tilley).

	Heel to Ball (mm)		Heel to Tip of Toe (mm)		Width of Foot (mm)	
Percentile	Man	Woman	Man	Woman	Man	Woman
1st	165	152	232	210	86	76
50th	191	175	264	241	99	90
99th	216	216	298	298	114	104

The data in Table 4 was used to create a standard sizing for the throttle and brake pedals. The throttle was designed to have a point of contact of 198 mm above the monocoque floor. This is just 1 cm less than the maximum length reachable for the 1st percentile woman; this also lands just longer than the 50th percentile man for length from heel to ball of foot (Table 4). This same distance was utilized for the brake pedal contact point.

Because the brake pedal is designed to not have side constraints, there is no particular width requirement. The throttle pedal, however, is designed for longer use and therefore has side supports, which keep the drivers foot in place. Because this will create a fixed width for which a foot must be able to fit within, it is important that it be wider than the foot. Using the data from Table 4, the last two columns, it can be seen that the width must be at least 114 mm if it is to accommodate the 99th percentile man. This is beyond the design requirements of 95th percentile, but should be considered. For this reason the throttle pedal was designed to have a width of 115 mm, which when finalized was closer to 117 mm due to end caps, which were welded onto the ends, creating a mounting point for the side restraints. Only the largest width was required, because if the longest, widest foot will fit, so too will the narrowest.

Now the first thing most people ask when they see the throttle pedal is this: "I have driven in a lot of cars, and none of those pedals look anything at all like the one designed." This is true, car throttles and brakes are designed quite differently. The accelerator on a car typically will have a large 2" x 4" contact pad, which is able to pivot about its center as the accelerator is pressed. This is due to the length of travel of the pedal, upwards of seven inches. The throttle pedal for the GFR14 car is designed to have little more than two inches of travel. Also, because this is a racecar, the pedal is either fully depressed or off, at all times, there is little time when the pedal is in a medium position. Combining the usual position of the throttle, and the overall travel length of the pedal, it makes far more sense as to why the pedal looks quite different. It must also be considered how the driver sits in this car, which is nearly laying down. The legs are in a near horizontal position from hip to pedals. A typical car will have the driver sitting higher than the pedals, which will also require different positions to keep the driver comfortable.

3.3 Material Considerations

Materials That could reasonably be used are: Aluminum, Carbon Fiber, Steel, Titanium.

- Titanium would be a great choice due to its strength being equal to that of most steels at half the material density (4.5g/cc). Titanium can be welded however, it requires a chamber be built and special welding skills.
- Aluminum is nice because of its lightweight with a density of 2.7g/cc.
    - 6061 Aluminum is a good easy to procure material that has the advantage of being weldable.
        - Welded Aluminum however requires heat treatment in order to regain strength lost during welding.
    - 7075 Aluminum is better for machined parts, as it cannot be welded, and has strength similar to most steels.
- Steel is a must for some parts, which require higher loadings and greater strength and durability. However its density is far greater at 7.8g/cc. Steel can be heat treated to reach strengths beyond that of any of the other considered materials. It also is an easily and commonly welded material.

- Carbon Fiber is a very versatile material which strength depends greatly upon the design of the fiber layup.
    - Layup is also quite time intensive as well as the following heat treatment for curing the resin-bonding agent.

Brake Pedal

Due to rule restrictions mentioned above, the brake pedal must be forged or machined from Aluminum, Steel or Titanium.

For weight purposes and loadings, Aluminum and Titanium are the two most likely candidates with aluminum leading due to its slight weight savings over Titanium. Steel, if designed in accordance with its strength, could also be as light a design as an aluminum pedal.

Bias Bar

Due to the loadings applied and the size restriction this will need to be made from a very high strength steel (at or greater than 1000 MPa yield).

Pedal Base

This is likely to be machined from either 4130 or 4340 steel. The loads applied require high yield strength, which can be obtained from heat-treated steel. Deciding between the two steel alloys is more a determination of what is more readily available from sponsors. Either material would work nicely, with 4340 being preferred because it has higher strength with the same weight.

Throttle Pedal

For the unified base designs the throttle cannot be made out of aluminum due to size restrictions at the base (Figure 17) which lead to a required strength that beyond that of aluminum. A carbon fiber pedal is under consideration as it has the potential to work. However carbon would requires time and knowledge for layup. Steel is a likely second choice due to readily available access to steel tubing and its high strength. Titanium again would likely work but is more difficult to obtain and requires a chamber to weld in.

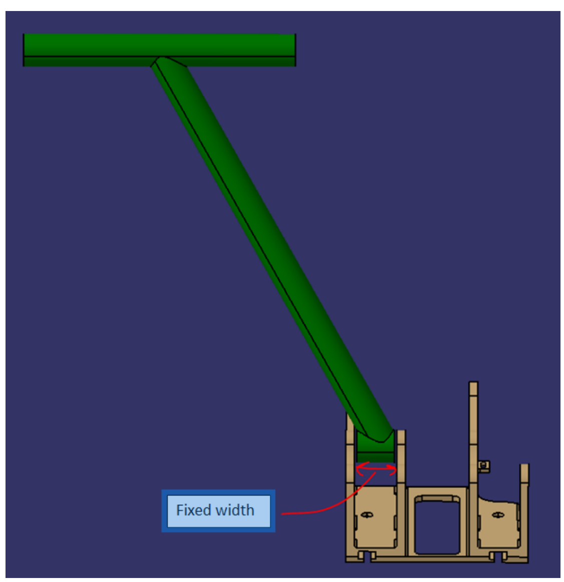


Figure 17. Fixed width view of pedal base (other parts hidden for clarity)

3.4 Brake System

The brake system starts at the pedal assembly and ends at the wheels. As in all cars the brake system is responsible for providing stopping power. What is not always considered is how those brakes operate. After all the brakes are simple, push on the pedal and the car is slowed via the brake pads at each wheel. That seems simple enough. Yet it does not have any specifics. What exactly is needed, in terms of actual braking force, to slow the car at a specified rate? What size should the master cylinders, and brake calipers be, and how large a diameter is needed for the brake rotor.

These are some of the considerations, which are involved in determining the stopping forces. It is because of the multiple variables that could be changed within the brake system that it should be considered a second project aside from the pedals. They need to be related and designed together, but both have enough work that to do them well, they should be done separately.

The brakes are hydraulic and use a combination system from cars/motorcycles. The calipers themselves are designed for motorcycles, while the master cylinders and pedals are that of a car. Fluid within the system is compressed within the master cylinders upon input force to the brake pedal. This increased pressure is transferred to the brake calipers through the hydraulic lines. At the master cylinder, the pressure is transferred back into linear force to activate the brake pads. Friction between the pads and the rotors causes a braking moment at the wheel. Then stopping is a result of that moment creating a braking force due to friction between the road surface and the tires.

Such is the simple workings of the brakes. Getting specific, it is desired that under braking conditions that all four tires provide equal braking power with no skidding of the tires. This is accomplished by correctly sizing the front/rear master cylinders, front/rear brake calipers, front/rear rotors, and determining weight shift bias during braking. Together is there are too many variable to work out by hand. Therefore some constraints are necessary. Since high braking force is desired, this is easily achieved by having the largest brake rotor possible, creating the most stopping power. The size of the rotor is limited by the diameter of the wheel and the size of the largest brake caliper. Since the wheel size is known, it is possible to iterate between different master cylinder sizes and rotor diameters. However, because weight is also a high consideration, it is desired that the brake caliper be as light as possible, yet still be able to accomplish its goal.

The GFR13 car used Brembo P34 front calipers and AP Racing CP4226 rear calipers. These were selected through the last brake redesign given all the above stated considerations and much thought. To better understand how the braking forces work a Matlab code was written which would indicate stopping power due to input braking force. This can be viewed in Appendix 9.1. These calculations have all been made before, but it completes the project being able to see the full scope of the system. Under braking conditions weight is shifted forward. This means that more stopping power is required of the front brakes. For this reason they use a smaller master cylinder bore, and larger brake calipers.

3.4.1 Brake System Calculation Force Overview and Detailed Overview (Walker)

The brake system is a simple matter of physics. Energy is taken from the driver and converted into stopping force through hydraulic leverage. In a perfect system there will be no energy lost and all the drivers force will be used to stop the car. In reality there are losses from heat and noise. All the equations for braking can be derived from the base equations of kinematics and fluids.

Braking starts with driver force input upon the brake pedal. This in turn creates a pressure increase in the brake lines with respect to the bore size of the master cylinder. The brake line pressure is the same pressure at the brake caliper. The pressure at the caliper is then turned back into a force with respect to the caliper bore size. Friction between the pads and the rotors then causes a force upon the rotor. With a given effective radius of the caliper, this force becomes a torque upon the wheel. With the tire torque equivalent to the rotor torque, the force of the tire on the ground can be found.

The brake system starts at the driver. The driver applies force upon the brake pedal. This force is then amplified by a factor of five through the motion ratio of the master cylinder with respect to the brake pedal. Equation 1 show this where MCB_{ratio} is the master cylinder to brake ratio. This motion ratio is easily calculated via the geometry relation of the brake pedal lower axis, the balance bar axis, and the master cylinder lower axis. The placement of the master cylinders yields a 5:1 ratio of force of master cylinder to input force.

$$F_{MC} = F_{Brake\ Pedal} * MCB_{ratio}$$

Equation 1. Force amplification of driver force to master cylinders

From this the brake line pressures can then be calculated for the front and rear. Pressure is unique because it will be constant within a closed system. It is then from pressures that mechanical leverage is achieved. Equation 2 shows the calculation for brake line pressures where A_{MC} is the bore size area of the master cylinder. This is derived from the definition of pressure, which is force divided by the area. To enumerate Equation 2, the master cylinder bore is 7/10".

$$P_{line} = F_{MC} \div A_{MC}$$

Equation 2. Brake line pressure calculation

Because the pressure is constant from the master cylinders to the brake calipers, a new force can be calculated which is the force of the brake pad upon the brake rotor (Equation 3). $A_{Caliper}$ is the bore size area of the caliper, not the pad area.

$$F_{Caliper\ Pad} = P_{line} * A_{Caliper}$$

Equation 3. Force calculation of a single pad upon the brake rotor

Because there are two brake pads for each caliper, the clamping force created is twice that of that in Equation 3. It is then from the clamping force that a frictional force can be determined for an individual brake rotor. Equation 5 calculates this frictional force given a pad/rotor friction coefficient ($mu_{pad/rotor}$), the area of the pad, and the calculated clamping force from Equation 4.

$$F_{Clamp} = F_{Caliper\ Pad} * 2$$

Equation 4. Clamping force of a single brake caliper

$$F_{rotor\ friction} = F_{Clamp} * A_{pad} * mu_{pad/rotor}$$

Equation 5. Frictional force on rotor due to clamping force of caliper

Friction at the rotor gets one step closer to actually stopping this car. The friction force on the rotor creates a torque about wheel axis. This torque is consistent throughout the all points of the wheel. Because the torque at the tire radius is the same as that of the rotor it is just via the radius ratio of the rotor to that of the tire. Equation 6 and 7 calculate the torque and the force exerted by the tire onto the ground respectively. $R_{effective}$ is the effective radius of the brake pads upon the rotor.

$$T_{wheel} = F_{rotor\ friction} * R_{effective}$$

Equation 6. Wheel torque calculation

$$F_{Wheel\ on\ Ground} = T_{Wheel} / R_{wheel}$$

Equation 7. Tire force upon the ground

The assumption of Equation 7 is that there is sufficient traction to handle this stopping force. These equations assume that there is no downforce on the car except that of gravity, which is in fact incomplete. During race conditions the car has both a front and rear wing, which create considerable downforce. At 40 mph the car theoretically creates 1.5 times the car weight in downforce. These equations are therefore most valid when the wings are not on the car; it also represents a worst case scenario for driving.

The second half of the equations deal with the weight of car and driver, and the resulting weight distribution when braking. Because the center of gravity is above the ground there will be a moment caused by braking which will result in weight being transferred to the front wheels. This will create a larger normal force upon the front wheels, allowing for harder braking on the front wheels. Equation 8 will determine the static weight on the wheels when the distance between the front or rear axle is known (CG_x) as well as the wheelbase length (WB). For consistency of units the mass is in kilograms (kg), all distances are in millimeters (mm), forces are in Newtons (N), torque is in N*mm, and all areas are in $mm^{2.}$

$$W_{static} = CG_x * M\,car + driver\ / WB$$

Equation 8. Static weight on the wheels

While Equation 8 deals with the static weight, Equations 9, 10, and 11 deal with the weight transfer, dynamic front weight, and dynamic rear weight respectively. The dynamic weight is calculated based upon the deceleration, and the weight transfer. Weight transfer (WT) is determined based upon the location of the center of gravity, the mass of the car, the deceleration, and the wheelbase length (Equation 9).

$$WT = a * h_{CG} / WB * M_{Car + Driver}$$

Equation 9. Weight transfer to the front wheels

$$W_{fd} = W_{static} + WT$$

Equation 10. Dynamic weight on front wheels while braking

$$W_{rd} = W_{static} - WT$$

Equation 11. Dynamic weight on rear wheels while braking

From equations 10 and 11 the weight is now known for the car. Using this to the force that is achievable from friction to actually stop the car can be calculated (Equations 12 and 13), where g is the gravitational constant, mu_{tire} is the friction coefficient between the tires and the ground, and W_{fd} is as calculated in equation 10.

$$F_{front} = W_{fd} * g * mu_{tire}$$

Equation 12. Friction available from the front tires based upon weight transfer

$$F_{rear} = W_{rd} * g * mu_{tire}$$

Equation 13. Friction available from the rear tires based upon weight transfer

$$F_{available} = F_{front} + F_{rear}$$

Equation 14. Total friction available for stopping

By the numbers: From the calculations above, as calculated from the Matlab code in 9.1.3, it is determined that the maximum braking force that could be applied (without wings) is 180 N of driver input force, which translates to 0.8 g of deceleration. If a higher deceleration is used, the car will lose static friction between the tires and the ground, causing the car to skid. This is determined by comparing the friction force caused by braking (Equation 7) to the total friction available (Equation 14). The braking force used to calculate the braking force from Equation 7 is then iterated until it matches forces with Equation 14. This then determines the maximum deceleration.

These numbers are for the worst-case scenario where the team is racing the car with no wings. This would be a very unfortunate situation given the above-mentioned data. From the data collected by the on-board data acquisition unit (DAQ) it was determined that the average input of force by the driver was between 350 N and 450 N. This of course was back calculated from brake line pressure. Since the master cylinder bore size is known it is a simple matter to convert back to driver force. 350 N and 450 N are both clearly larger than 180 N which was calculated for a no wing car, the difference then is a result of the downforce created via the wings, giving the car an artificially heavier weight.

The brake system acts as a control loop, with the driver acting as the regulator. The desire at any point is to travel at the highest speed possible without sliding. To do this, the driver must slow the car through the corners. The desired speed at each corner is a combination of driver familiarity and smoothness, and tactile response to the traction available from the car at given speeds and angles of corner. Through a corner the driver is performing feedback analysis to determine whether more force can be applied to the brake, or if less brake and more throttle would be possible.

3.4.2 The Actual Brake System

Each component that makes up the brake lines is documented in the flowchart 9.2.3. Several of these component, including the brake line hoses, fluid reservoirs, and several fittings, which connect the master cylinders to the hoses and the pressure sensors can be seen in Figure 18. Then in Figure 19 are the brake calipers. Shown are the Brembo

P34 calipers on the Left and the AP CP4226 on the right. These are the front and rear calipers respectively. These calipers act upon the rotors shown in Figure 20.

Figure 18. GFR13 pedal assembly showing brake lines, fittings, and hoses

Figure 19. Brembo P34 front (left) and AP CP4226 rear calipers (right)

Figure 20. Ground rotors in stock in the SAE workshop

The only change that is being implemented is a new type of brake line. These are made of Kevlar and are being tested on the combustion car. The electric car will still be using the same steel braided cables as last year.

4. Design Selected

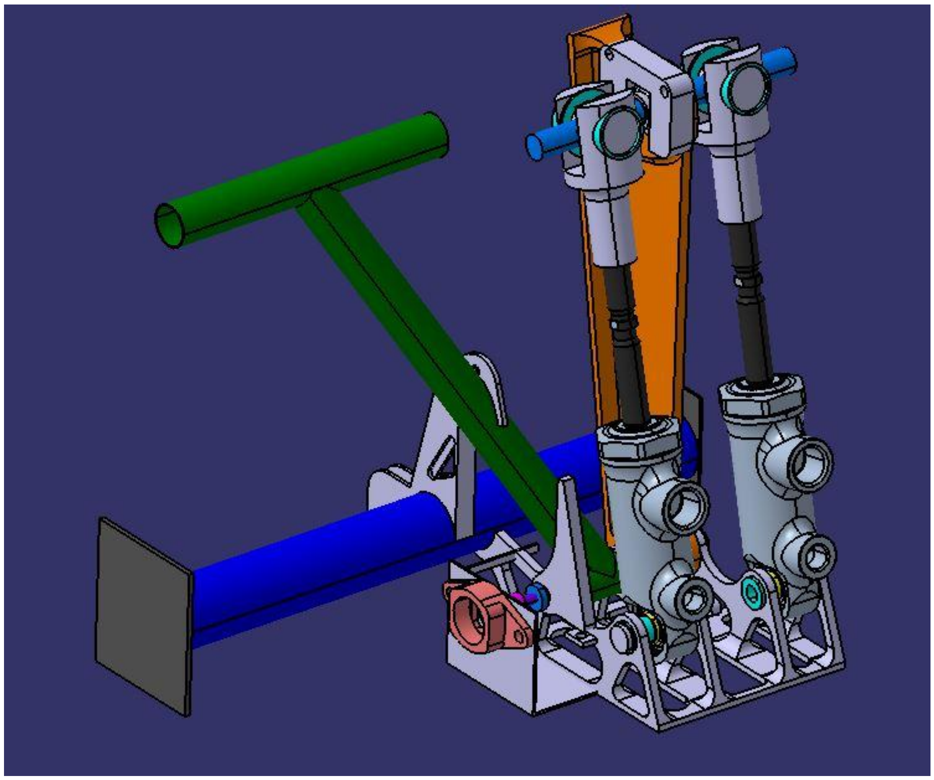


Figure 21. Final design selected for GFR14 car

The design selected (Figure 21) incorporates the following features: a fixed pedal base with four positions for leg length adjustment; a two piece angled throttle which shares a base with that of the brake and master cylinders; the brake pedal utilized a redesigned load path which added depth of material and reduced stresses; the balance bar clevises were designed around a round stock, rather than a square stock for simplicity of machining; the balance bar itself is being made as was designed; and finally a round heel bar for foot placement while driving.

Pedal Base

The unified pedal base was chosen for many reasons. It first allows for more free space within the foot cockpit, more free space means more weight savings. The space is saved by not having a right side throttle-mounting tower nor the arms connecting this tower to the pedal base. The final design is shown below in Figure 22.

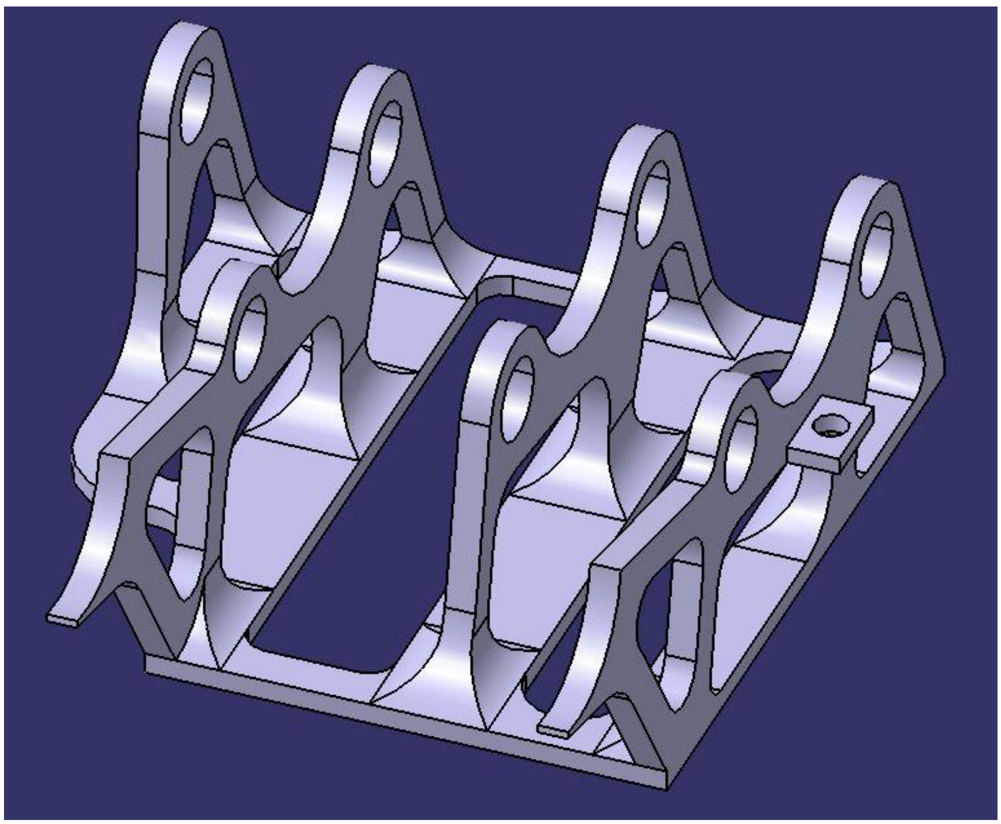


Figure 22. Pedal base

By combining the throttle and brake into the same base it also reduces the number of pins and fasteners that will be required to hold the pedals in place. To further simplify matters, and make the system have less frictional resistance to movement, a clevis pin will be used rather than a bolt. A bolt works by tightening down to the point that it cannot rotate itself free. However once a bolt is tightened properly it has pulled tension on the two external walls. In this case the outer two walls of the pedal base, which can create extra resistance for pedal movement. A pin however does not need to be held tight to the wall by a nut, rather it uses a cotter pin placed and bent through a hole in the pin shaft. This system does not have any added tension to the pedal base walls, keeping resistance low. Time was also a serious consideration. To keep manufacturing time to a minimum a single base reduced welding, fixturing and complexity, all of which will make the building of the pedals quicker.

The design of the pedal base utilizes the same brake/master cylinder movement ratio that was used on the last three cars. From those constraints the design was built around it. Analysis of the pedal base through FEA (Figure 10) showed that the critical loadings were within the limits of the steel base.

Dimensions of pedal base: used to determine stock block needed:

Length: 4.364”
Width: 3.425”
Height: 1.445”
Cost for two blocks: $75
Supplier: Coyote Steel

Brake Pedal

The Brake pedal has the most dramatic change over the last few years’ designs. It has been completely redesigned and no longer utilizes the Tilton Balance Bar. Instead a fully OSU designed balance bar will be integrated into the pedal design. By designing a balance bar in house, it reduces reliance on outside vendors, gives experience in solving problems, and allows for a more streamlined design of the brake pedal (Figure 23).

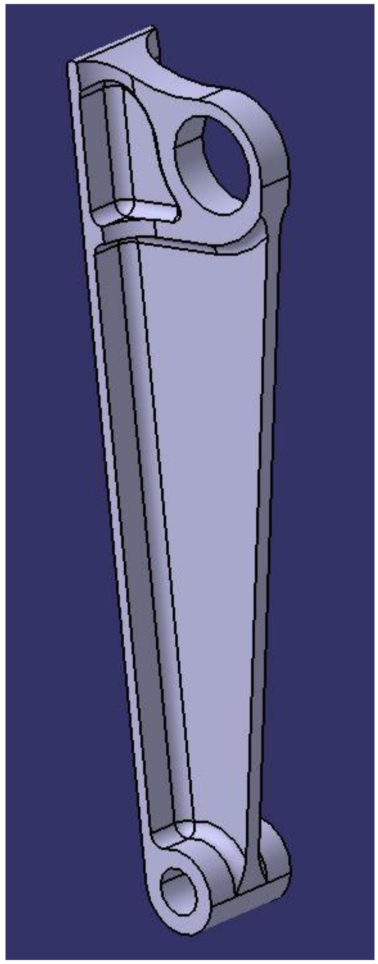


Figure 23. Brake pedal

The brake pedal was especially difficult to run FEA (Figure 9) due to issues with constraints. CATiA FEA software will data display based on the constraints set, which may not represent the system properly. This was a prevalent problem and made FEA initially very difficult. A full set of rotational constraints upon the base pivot point holds the entire base forcing bending where rotation should be allowed. Similarly the upper balance bar pivot needs constrained to the master cylinder line of motion.

Throttle Pedal

The throttle pedal (Figure 24) was chosen as an angled upright throttle and connects midway to a horizontal arm. The throttle arms were designed to used ⅝” x 0.035 (outer diameter x wall thickness). The wall thickness and outer diameter of the throttle arm were calculated using a factor of safety of 2 and an input force of 200 lbs of force. Hand calculations were made and from those a EES code was written which allowed the variability of any input force (Figure 25 and full code in 9.1.2).

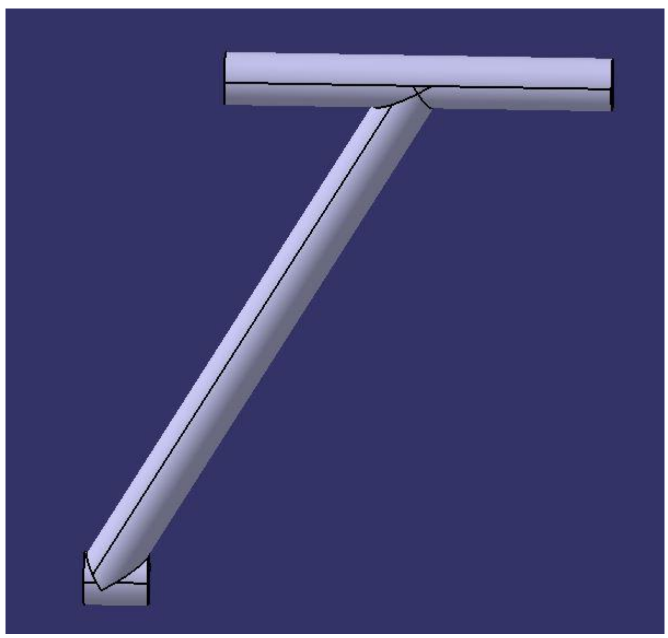


Figure 24. Throttle pedal

```
"Steel Throttle Upright"
"Material Properties"
FS = 2
"sigma_yield = 700*10^6                    [Pa]"
E = 205*10^9                               [Pa]

"Set Variables (pick one)"
"Weight = 0.3"
"r_o = 0.02                                [m]"
"r_i = 0.018                               [m]"
t_inch = 0.086
"t = 0.0027                                [m]"
D_in = .625
r_o_inch = D_in/2
r_o_inch*25.4/1000 = r_o

M = F_ap*d
c = r_o
sigma_allow = M*c/I
I = (pi/4)*(r_o^4 - r_i^4)
F_ap = 600                                 [N]
d = 0.192                                  [m]
sigma_allow = sigma_yield/FS
t = r_o - r_i
t_inch*25.4/1000 = t

deflection_mm = F_ap*d^3/(3*E*I)*1000

A/pi = r_o^2 - r_i^2

tau = 4*V/(3*A)
V = F_ap

Vol = A*W
W = 192*10^(-3)                            [m]
Weight = rho*Vol
Weight_lbs = Weight*2.20462                [lbs]
rho = 7850                                 [kg/m^3]
```

```
Main
Unit Settings: SI C kPa kJ mass deg
A = 0.00009395              c = 0.007938
d = 0.192 [m]               deflection_mm = 3.059
D_in = 0.625                E = 2.050E+11
FS = 2                      F_ap = 600 [N]
I = 2.257E-09               M = 115.2
ρ = 7850 [kg/m^3]           r_i = 0.005753
r_o = 0.007938 [m]          r_o,inch = 0.3125
σ_allow = 4.051E+08         σ_yield = 8.102E+08
t = 0.002184                τ = 8.515E+06
t_inch = 0.086              V = 600
Vol = 0.00001804            W = 0.192
Weight = 0.1416             Weight_lbs = 0.3122
```

Figure 25. Throttle upright EES code for sizing

Throttle Stop

Designed to fit atop a special ledge on the pedal base, this part is incorporated into a major part of the assembly. In past years this part has been a simple bolt that was adjustable and contacted the pedal directly. This piece, while larger than a bolt allows for a larger contact area with the pedal, at a higher leverage point. This reduces the overall stresses experienced by the throttle stop, but increases weight. This was the most streamlined solution to a throttle stop requiring no additional base support.

Through hand calculations and FEA testing (Figure 26), the thickness was determined to need a minimum thickness of 3.5 mm. This was increased to 3/16”

(0.1875” 4.76 mm) due to material availability from GK Machining. The throttle stop experiences five times more force than that which is exerted by the driver. This is why the throttle stop is solid; it is required in order to not fail. The load tested is 4000 N, the equivalent of a factor of safety of 2. It is then constrained for rotation about a pin, and clamped at the lower right face, which will be in contact with the stop bar. The highest stress then occurs in the middle where the bend radius is farthest from the to points of loading.

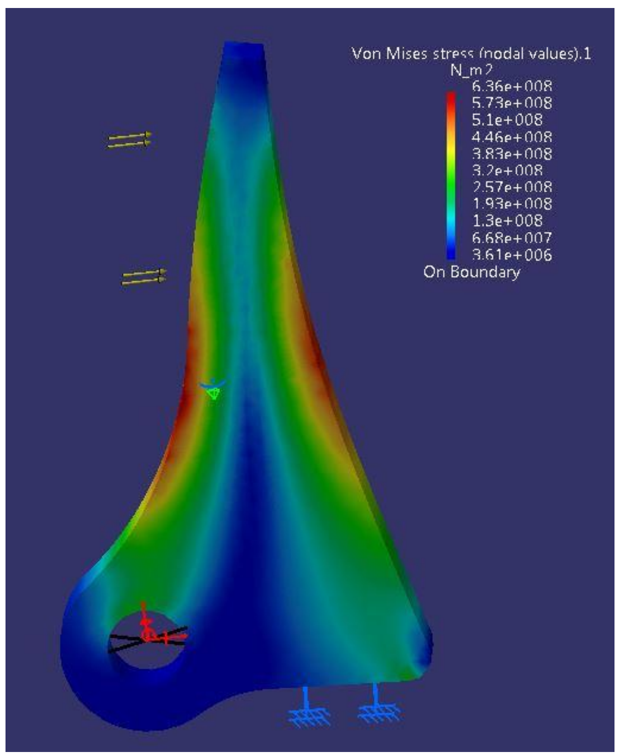


Figure 26. FEA throttle stop with 4000 N load

eCar Specialty

eCar Throttle Pin / TPS Lock Washer

The eCar requires a few interesting pieces due to the nature of an electric motor. With a combustion motor there is a throttle cable, in an electric motor there is no such cable. A sensor is used to determine how far the throttle has rotated, which is then extrapolated into power for the motor to output. In order to turn the sensor the throttle pin must rotate at the same rate as the throttle pedal. To accomplish this a unique pin was designed which has a round shaft for the brake side of the pin, then becomes a square drive, which is used to force rotation, before returning to a round threaded shaft. Shown below in Figure 27. The square drive interfaces with a special washer with corresponding square drive. This washer is welded to the throttle base and acts as the gear driving the TPS (throttle position sensor). The TPS lock washer is shown below in Figure 28.

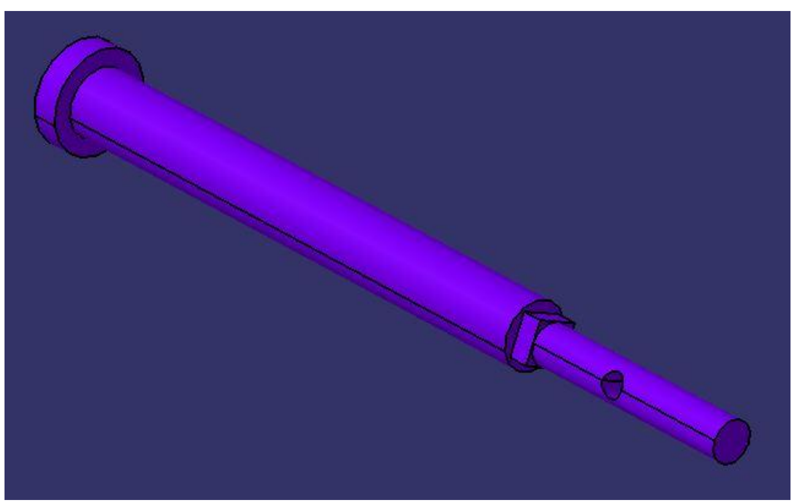


Figure 27. eCar throttle pin (GFR_14_10_54_201)

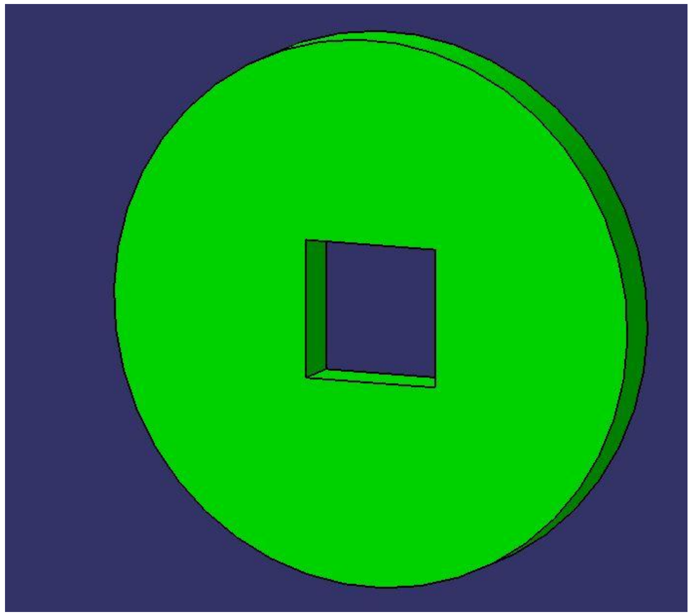


Figure 28. TPS lock washer (GFR_14_10_54_292)

There were several designs that went into consideration on how to make the TPS work most effectively. An early design that showed promise what that of a three-bar-linkage system. This linkage would be welded at one end to the throttle pedal, and at the other would be fixed to another pin. This pin would be responsible for turning the magnet holder--in the same way as the selected design. As is shown in Figure 29 the linkage seems rather simple. The downfall was how to provide a smoother tight-fitting pin to hold the three linkage bars together. This proved to be a fatal flaw for the linkage and as a result was passed upon. However, the design, if perfected does show promise because it would allow the TPS to be mounted directly to the pedal base towards the outer edge of the car. This would make wiring cleaner and reduce the number of large parts needed for other variations of design.

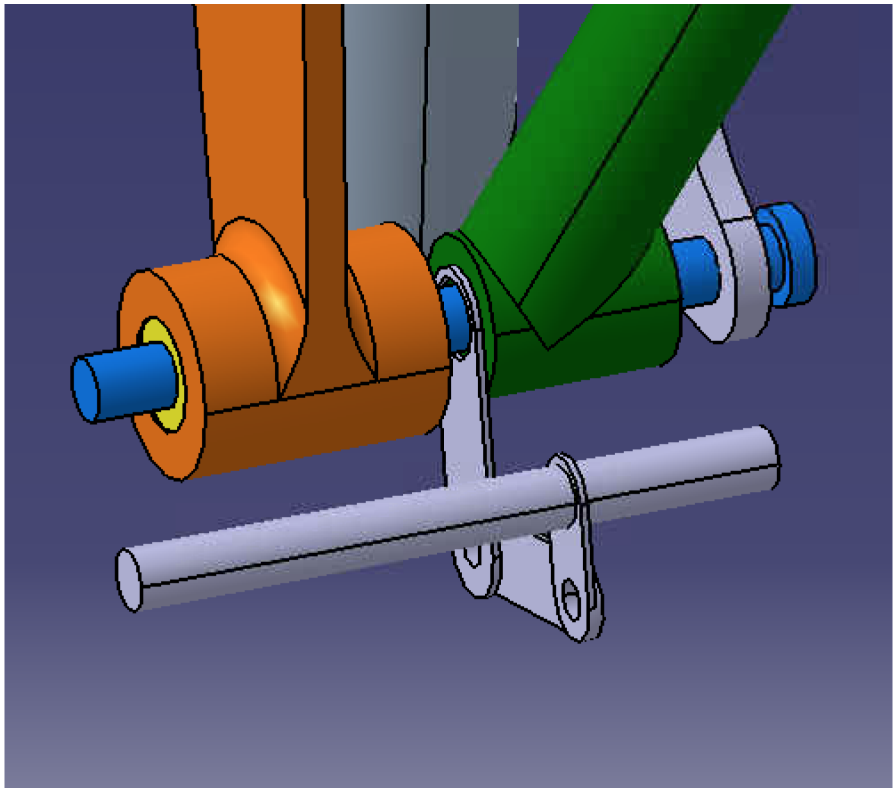


Figure 29. TPS linkage (heel rest and base hidden for better view)

TPS mount

While those two components allow the throttle pin to rotate at the same instance as the throttle, it will do no good if there is not TPS to read. The TPS must be mounted a specified distance away from the pedal base. This mounting plate is to manufactured and welded into place with concentric holes to that of the throttle pin. The positioning of the TPS mount was determined predominantly by packaging constraints and ease of access. The most sensible position was therefore in the center of the pedal assembly to right of the base behind the heel rest.

The design is a simple L bracket, which will be manufactured in the OSU shop. To mitigate vibrational disturbances and help rigidity, the mount has an side which extends off the bracket and welds higher up on the pedal base. The TPS mount is shown in Figure 30 TPS Mount Image. Many last minute adjustments were made to lighten weight and make room for the mounting holes. The reason for some of these late changes was due to communication with the German students doing the eCar throttle sensors. It was determined in the first week of January that a sensor we were counting on was no longer available and a smaller sensor was to replace it. This smaller sensor EAN22K has narrower mounting holes (30 mm instead of 38 mm) and the mounting holes size was different (4.2 mm instead of 4.5 mm). Due to the spacing issue two of the holes were angled 22 degrees off level. The angled sensor mounting holes correspond to the newer magnetic sensor. By offsetting the level it will change the clocking of the magnet. To correct for this the magnet will need to also be rotated by 22 degrees. The angled alignment fixed the spacing issues and allows the system from last year to be used (Variohm 2841 sensor). This also required that the mounting plate be moved 10 mm farther away from the pedal base. All of this was orchestrated through email with two German Students, Alex and Vinzent.

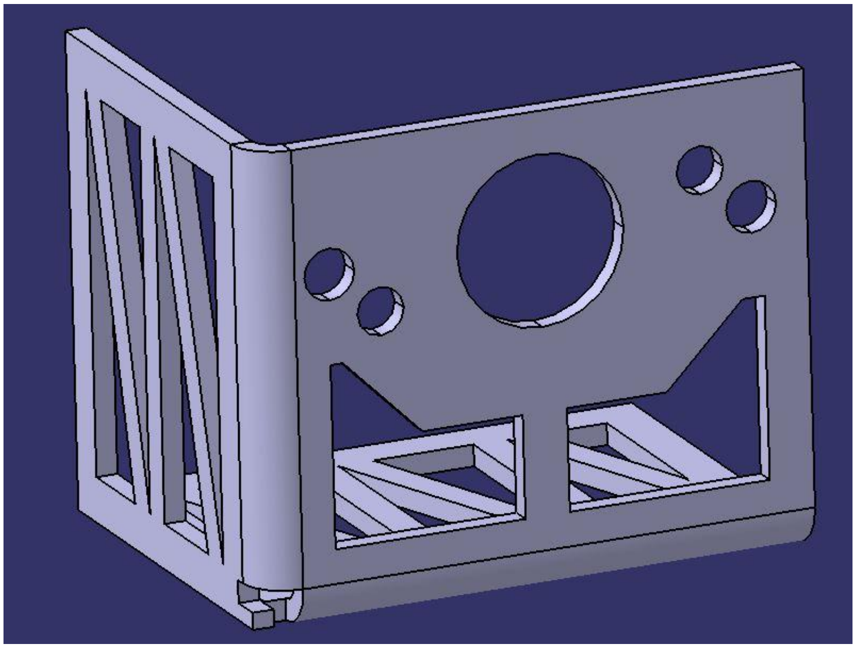


Figure 30. TPS mounting plate

TPS Magnet Holder

Being made by German Students at DHBW, this was designed to thread onto the throttle pin. It is then locked in place by a nut, and is adjustable 5mm. The drawing can be found here.

This is a straightforward part. It is a simple cylinder with a threaded hole on one end (Figure 31 left) and a shallow hole to hold a magnet on the other (Figure 31 right). It will require at most three operations: Turning on a lathe; drilling a hole; tapping a hole for threads. The magnet will then be glued into place on the shallow hole side, and the entire thing will be threaded onto the throttle pin and locked in place with a 4 mm nut.

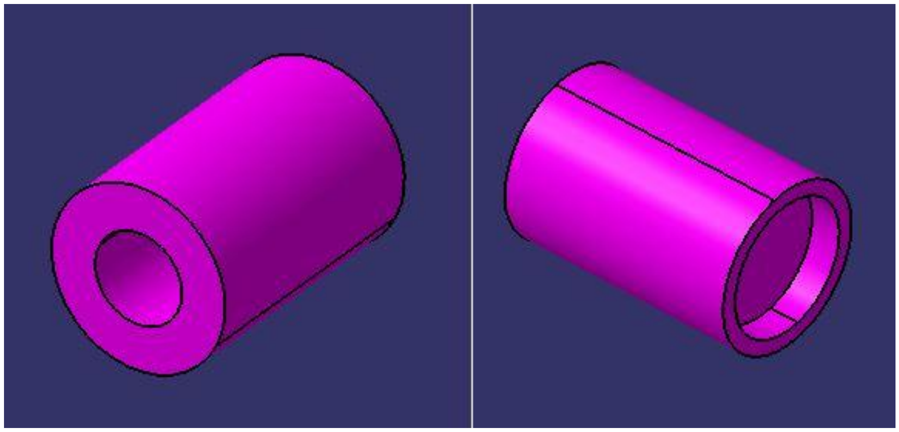


Figure 31. TPS magnet holder front (right) and back (left) views

Balance Bar System

Never before has OSU made its own balance bar system. This is the first attempt. The balance bar itself (Figure 34 blue shaft) is being made by Kelko Products out of Ohio. They are fully sponsoring this part. The size was designed to mimic that of the Tilton Engineering balance bar that has been used for the last several years. It using a ⅜" coarse thread, however it would be more useful to have a fine thread. From Tilton Engineering's head engineer the hardness range (35-38 Rockwell B) they use during heat treatment was acquired. This information was passed on to Kelko and will be matched. The threaded area of the balance bar is comprised of rolled threads (rather than cut or turned threads) because this retains the strength of the material.

The Clevis, which attaches the balance bar to the master cylinders, is also being designed this year (Figure 32). The entire system for reference is shown with half the parts missing on the left and right to show the stages of how this works. The blue is the Kelko made balance bar; the yellow are barrel nuts threaded to interface with the balance bar; green is an IGUS plastic bushing to reduce friction between the balance bar and the

Clevis; silver are the Clevis' themselves; pink is the Aurora Spherical Bearing which allows for bias to be adjusted to the front and rear brakes.

Igus makes plastic components such as washers and bushings. Both of these are used in the pedal assembly. While plastic is not the typical material thought of for its strength, these parts are quite tough. The strength of some parts are equal to that of steel, yet lighter, and some parts are even stronger. The bushings and washers are both used to create a tight fit yet have a low friction surface to allow easy movement of interfacing parts. The parts are not only preferable because of the low weight, but also because Igus is offering full sponsorship on any parts needed. The part that would be interesting to try for next year is the spherical bearing they make from plastic. It shows higher than required strength and would be lighter and cheaper than the Aurora bearing.

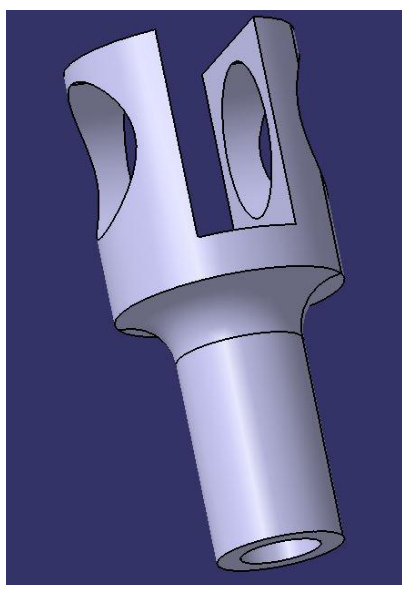


Figure 32. Balance bar clevis

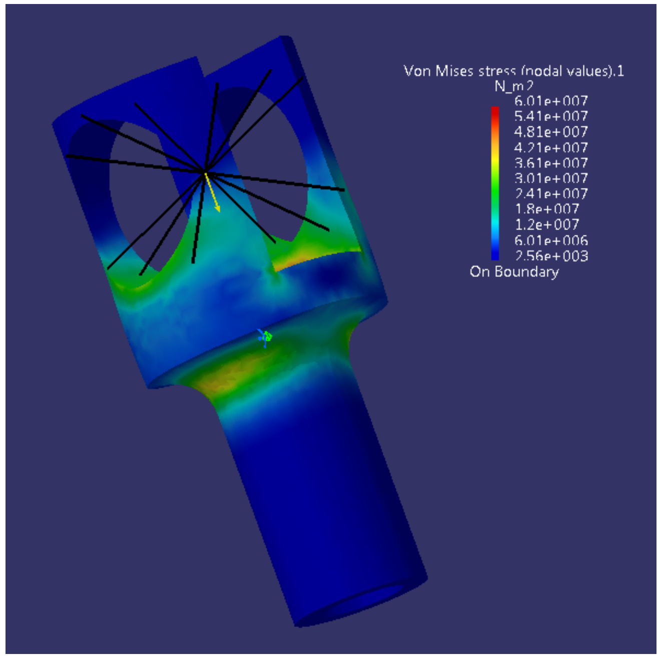


Figure 33. FEA on balance bar clevis

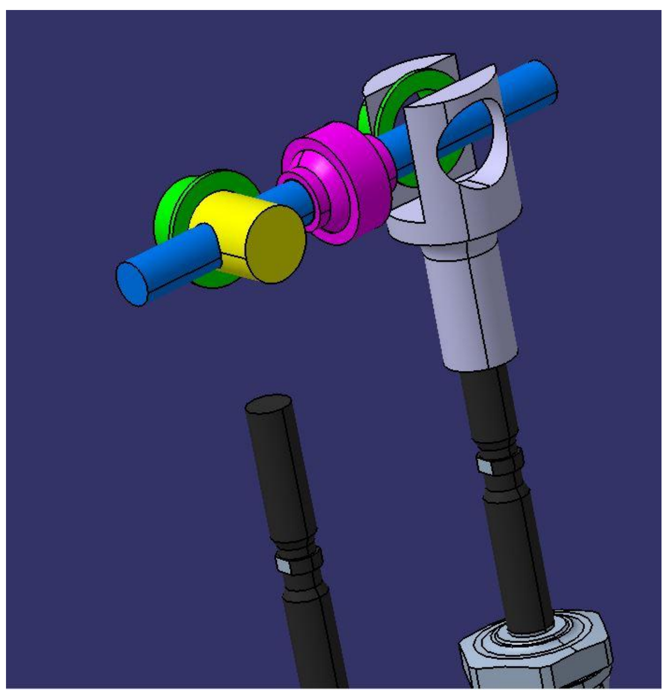


Figure 34. Balance bar system

Above Figure 34 shows the Balance Bar System. This consists of:

Blue Shaft:	Balance Bar
Yellow cylinder:	Barrel Nut
Pink:	Aurora Spherical Bearing
Green:	Igus Bushing
Gray:	Balance Bar Clevis
at bottom:	Partially shown master cylinders

FEA was run on the Clevis' to determine strength and wall thickness needs (Figure 33). A Load of 5000N was applied along the vertical axis upon the two holes using a rigid virtual part connection. The thread connection of the master cylinders was clamped to simulate the fixed position when fixed in place. The holes were designed to be large enough that an IGUS bearing could fit, and have perfect contact between themselves and the balance bar.

Small Components for Pedal Assembly

This is a list of the smaller, yet still very important, components, which have a tendency to be overlooked in both design and implementation.

- Brake/Throttle axis pin 2.75" x ¼" (Fastenal) (Figure 35)
    - Had to be remade by hand on OSU lathe due to loose fitting Fastenal part

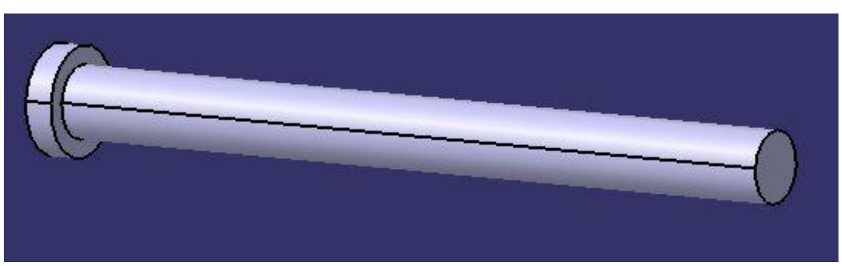


Figure 35. cCar throttle pin

- Master cylinder axis pins
    - OSU lathe Manufacturing
    - 6 mm OD
- Cotter pins for brake axis and master cylinder pins
- Thrust washers for brake axis (IGUS supply)
- Bushings for master cylinder axis
    - Damper bearing inserts reduce master spherical bearing to 6mm
- ¼” shaft ⅜” OD bearing for eCar throttle pin (Misumi USA)
    - Product number BR74
- Sleeve bushing for eCar bearing
    - OSU lathe manufacturing
- cCar/eCar bearings for brake axis
    - 7/16” roller bearings placed inside of the lower axis of the brake and throttle pedals
- Brake pedal bearings (on brake/throttle axis)
- Throttle pedal bearings (on brake/throttle axis)
- Master cylinder clevis bushings (IGUS supply)
- Threaded barrel nut for interface between master cylinder clevis’ and balance bar
    - Manufactured from 4130 steel at OSU
        - Turned on lathe
        - Center drilled on end mill
        - Threads tapped by hand
- Throttle cable
    - Bought at Peak Sports in Corvallis, OR
    - Tandem brake cable 2300mm long

Nuts:

- TPS nut (4 mm thread)
- Throttle Adjustment nuts (2x)

Several of these components are seen in Figure 36, an exploded view of the master cylinder axis with the left master cylinder hidden for clarity. The teal bushings were all made in Germany, half of which were sent to the USA for the combustion car. Counting from the left, the 2nd, 3rd, 4th bushings are identical, while the 1st is slightly longer to compensate for the additional width needed for the throttle pedal. The yellow bushings are a damper insert bushing which are shared with the suspension system, GFR_14_20_ 46_011.

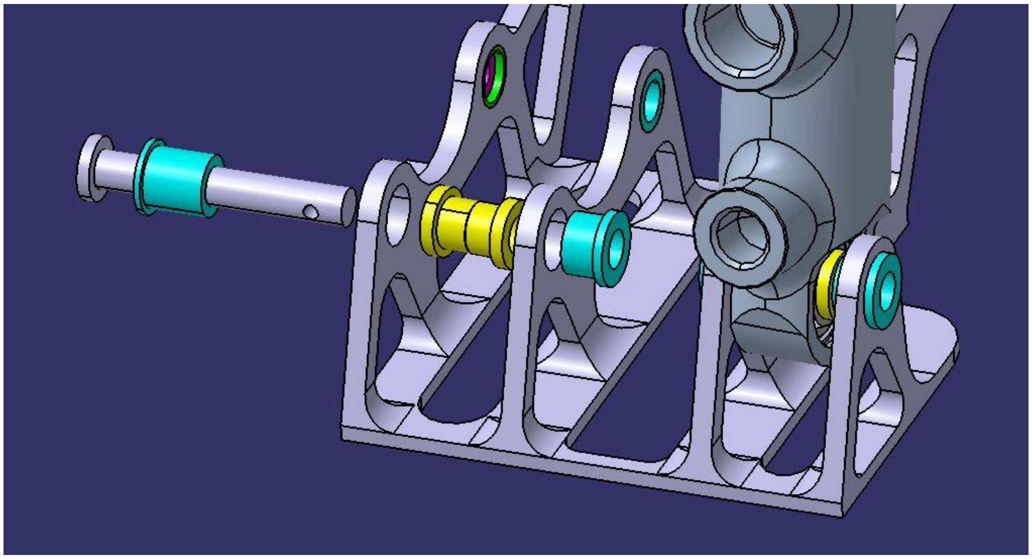


Figure 36. Exploded view of master cylinder axis

Brake System

The brake system is also part of this design report, however it is not being changed this year due to the pedals being redesigned and time constraints. Last years brake assembly will be remanufactured and the materials will be procured once again.

A huge effort has been made by Nathan Cheung to get the brake assembly parts and components organized, ordered and put together. He has been instrumental in getting the brake assembly on its way and on time.

During Fall term of 2013 an order was placed out to Tilton Engineering; they offer a standard FSAE team discount on all components. The price sheet can be found here. Ordered were two sets of each front and rear master cylinders (⅝" and 7/10" bore) along with a rebuild kit for a master cylinder, which went out during testing.

Last years team did an awesome job at detailing the brake lines. This flowchart in

9.2.3 was created to show where each part goes along with links to each part buying location. Purchase Request Orders were placed by Nathan Cheung to both Pegasus and Summit Racing for these parts. Bother orders were done at the end of Fall term 2013. They will be arriving within the by January 24th.

While the system remains unchanged this year, it was still examined. Because stopping is a key component to any car, it is important that it work reliably. 9.1.3 is a Matlab code designed to show weight transfer and stopping forces for the car. The equations, while correct, should have all the input variables checked for accuracy. Then it would also be beneficial to confirm that the resulting value has proper units. To sum up how the equations work, by inputting the weights and measures of the car, the stopping forces can be calculated from any given starting velocity. An interesting graph would then be possible by changing input velocity and comparing this to other variables such as stopping distance, maximum force available for braking, and weight transfer.

4.1 Manufacturing Plan

Pedal Base

Silver Eagle Manufacturing, a local Oregon company, did manufacturing of the pedal base. The design is very different from last year and will also be plasma cut and welded together rather than machined.

Stages of Production

1. CAD Model Completion
2. Engineering Drawings
    a. Create a drawing from the CAD model
    b. Use a common datum for the entire part
    c. At least one drawing for each view
        i. Keep each drawing view clean and clear
        ii. Use a second view, or third, for drawings with a lot of detail
3. Convert CAD model into STP format and send to Silver Eagle for machining
4. Convert each upright spline into a dxf file
    a. Send both dxf and stp files
5. Welding
    a. Heel rest support bar to pedal base
    b. eCar only
        i. Weld on the TPS (throttle Position Sensor) mount to base
6. Final welded parts will be heat treated at OSU
    a. Heat treat to Rockwell B 95
        i. Equivalent yield strength of 700 MPa
7. Finalized Part for OSU cCar complete and put into brake/pedal bin.
8. Finalized Base for eCar packaged and sent to DHBW

Throttle Components

Pedal

The throttle pedal is made of three individual components. Two Tubes and a round stock steel.

Procedure of Manufacture:

1. Material Procurement
    a. Material has been procured through EMJ metals at no cost
        i. Being the contact for all GFR/Baja for material needs with EMJ has taken a lot of time. This time is mostly spent in email with EMJ and other team members.
    b. First material need quote sent in January 7th. Waiting on arrival
2. Stock is cut to length from the specified drawings
    a. link to drawings
3. The upright arm will be cut twice on the end mill to get the welding points correct
4. The base piece is milled from round stock steel
    a. Cut to Length (horizontal bandsaw)
    b. Hole is bored slightly small (end mill)
    c. Reamed to exact size (end mill)
5. Clean parts
    a. Scotch-brite pad
    b. Acetone
6. * Create a welding fixture
    a. Details below
7. * Pieces are welded together
    a. Weld the horizontal arm to the vertical arm
    b. Weld the Vertical arm to the lower pivot cylinder
    c. ** Weld the throttle attachment into place on the vertical arm
8. Heat Treat
    a. Thread safety wire through pedal
        i. This provides a loop which can be used to pull the throttle pedal out of the oven when hot
        ii. Use iron tongs to remove pedals
    b. Heat to 855 degrees C
        i. Hold for 1 hour
    c. Water quench
    d. Heat 480 degrees C
        i. Hold for 1 hour
    e. Air cool

Throttle Pedal Welding Fixture *

The welding fixture used for the throttle pedal was created from a single block of 6061 aluminum. This was found on the scrap metal shelf in the SAE shop. To hold the parts in the correct orientation, a ⅝" ball nosed end mill was used to create slots which the throttle arms could sit in. Using the drawings created for the throttle, the fixture was created with the same dimensions. Two considerations were made. The first was the location for the throttle spring attachment. This piece, laser cut from GK, needed to be placed a specified distance from the base. To simplify the fixture, it was determined that this piece would rest between the throttle upright arm and the fixture. This can be seen in Figure 37. The placement of this part was from which the rest were aligned. Using a rotary XY table the desired angle for the upright arm was created.

The second consideration was how to do both the lower and upper weld areas on the same block of aluminum. Because the piece was too small to fit the three weld locations, two separate slots would be needed. The first slot created the top weld between the vertical and horizontal arms. The second slot allowed for the lower cylinder to be welded into place on the vertical arm, and the weld for the throttle cable attachment.

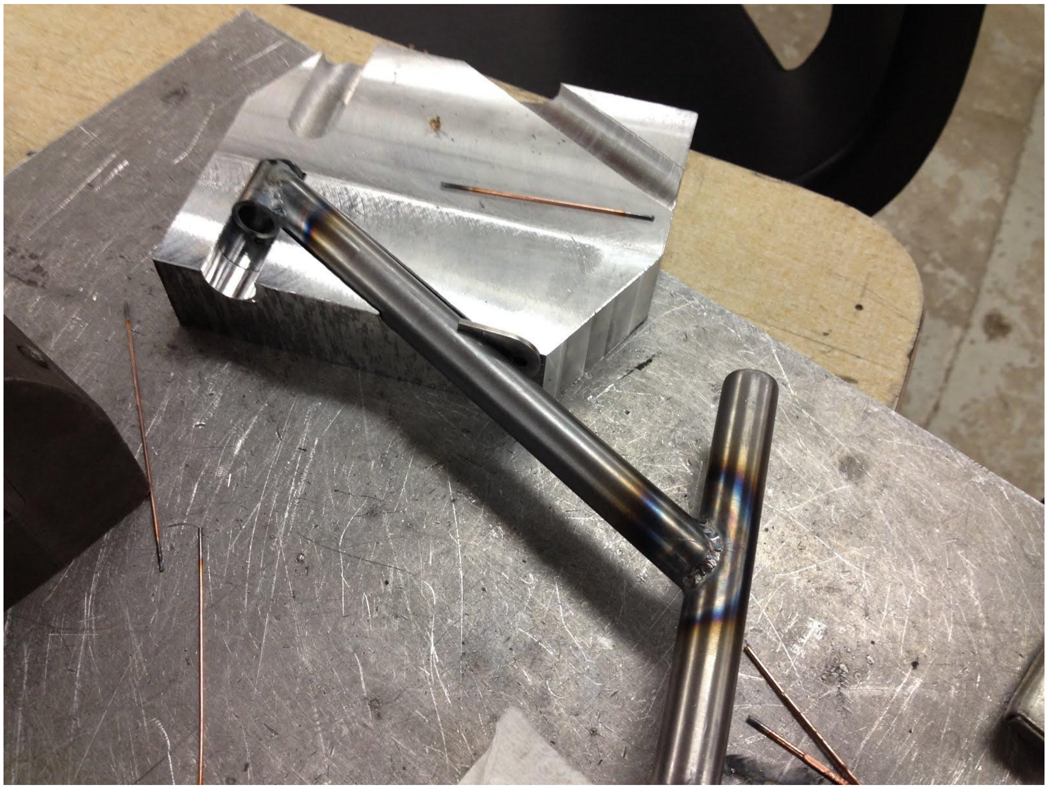


**Figure 37. Throttle pedal welding fixture. Second slot in use in image

Throttle Stop (Figure 38)

GK Machining is making the throttle stop. It will be laser cut from 3/16” stock they will be supplying.

1. Finalize design (December 12th)
2. Verify design with available stock at GK (January 6th)
    a. Change part thickness slightly to match the available 3/16” stock
    b. Repeat step 1
3. Create part Drawing
4. Create .dxf formatted file for laser cut path (January 8th)
5. Get back finalized parts
6. Clean parts
    a. Use sandblaster to get hard dirt off
    b. Then use scotch-brite air tool head
7. Send out for nickel plating

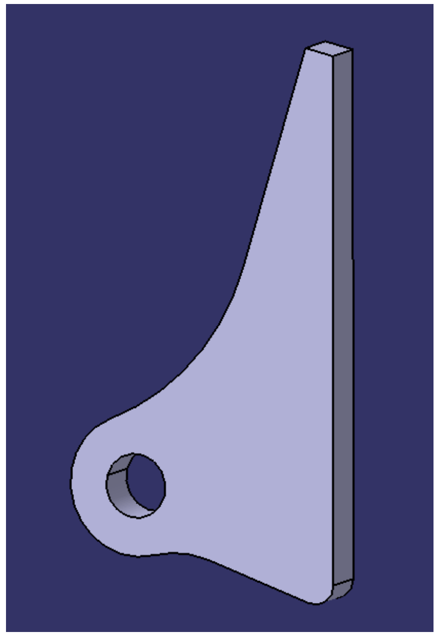


Figure 38. Adjustable throttle stop

Cable tower (cCar) / Pedal/cable attachment (cCar) / TPS Mounting Plate

These sheet metal steel pieces will be laser cut by GK Machining. They will be made from 1.803 mm thick (14 gauge) mild steel. These will then be welded at OSU by an experienced TIG welder. A sample engineering drawing of three of the laser cut base pieces can be seen here. The TPS mounting plate has the least clearance for welding and as such a test piece was made from scrap metal at OSU to generate a full size model to determine if there is enough room for the TIG welding cup to fit into the area in question of welding. The test piece can be seen in Figure 39 (scale: this entire part easily sits on the face of an iPhone).

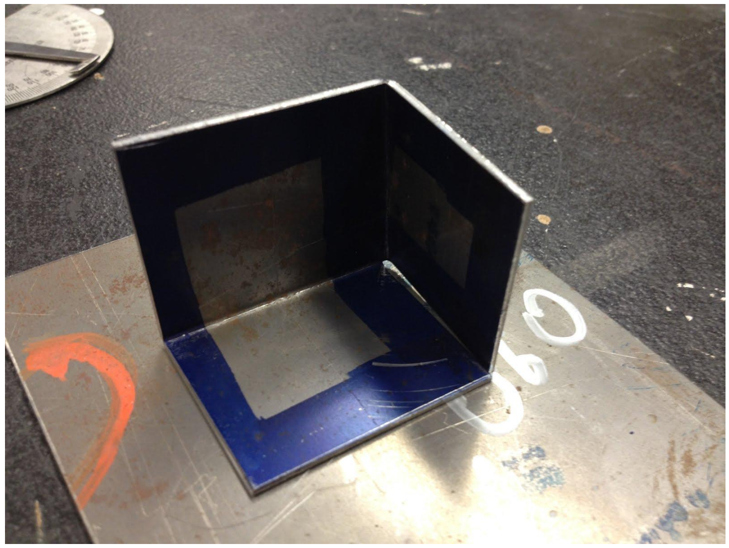


Figure 39. TPS mount test piece made at OSU

The throttle cable tower was redesigned to the same specifications as was finalized but done in the Generative Sheet Metal workbench. The result, with some weight saving cutouts from GK Machining is shown in Figure 40. The advantage of the sheet metal workbench is the ability to unfold the bend lines and easily generate a dxf file for laser cutting. The unfolded view is shown in Figure 41.

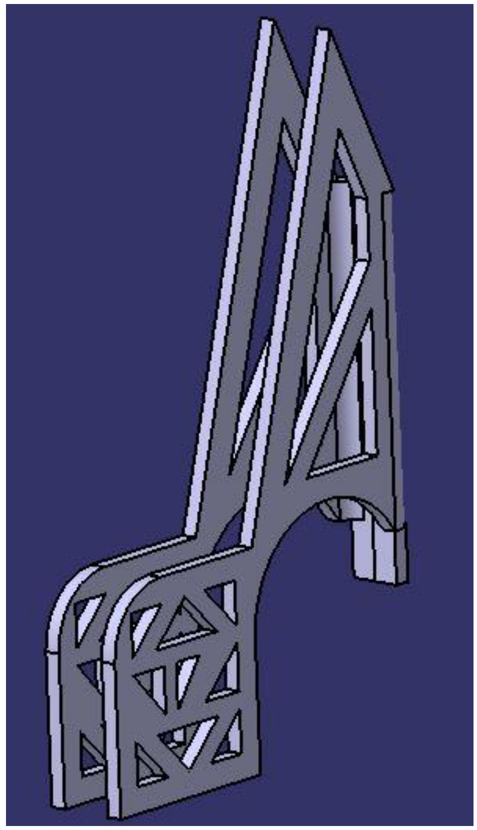


Figure 40. Cable tower

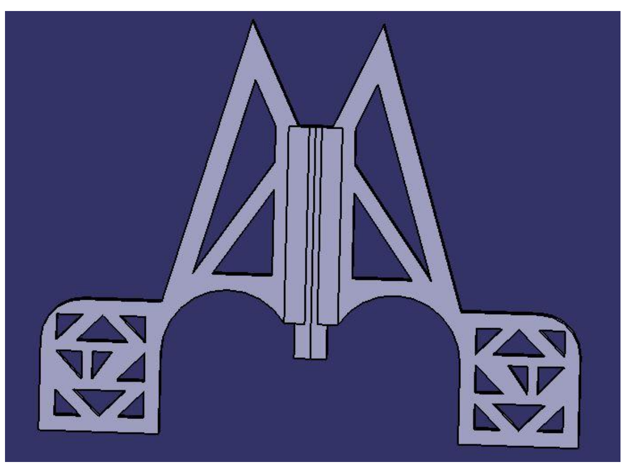


Figure 41. Unfolded cable tower

Brake Pedal

The brake pedal has two manufacturing plans. The first is to have a company to sponsor CNC time to manufacturer the part. The second is to make the part here at OSU on the CNC machines. CNC certification is no longer an issue, however, CNC efficiency and effectiveness are. Using Edgecam is still a component, which has yet to be used and explored.

Stages of Production

Made by Silver Eagle Manufacturing

- Stock provided at no cost from EMJ is a round piece of 7075 Aluminum
  - 2.75" round
- CAD model in .stp format given
- Using the horizontal bandsaw the stock will be cut to a length 1" longer than is needed.
- Material will be squared off for ease of fixturing
- Fixturing was determined by the machinist at Silver Eagle.
  - He used the CNC end mill to make the round stock into a square
  - Table clamps held the square in place for machining.

Outsourced Manufacturing

- Send CAD file in form of stp along with drawings for review
- Upon approval of drawings send in material
- Wait for lead time on part

Once the brake pedal is finished at the manufacturer it must then be finalized. Axis bearings from McMaster Carr and Aurora will then be pressed into the brake pedal.

Heel Rest Bar

Possibly the most simple part in the entirety of the pedal assembly, the heel rest bar is a single piece of 1”x0.028 (OD x wall thickness) which will be cut to a specified length. It is going to be manufactured at OSU and will use material procured from EMJ.

This part will then be welded here at OSU to the pedal base. Following welding both parts will be sent for heat treatment where the needed yield strength will be 700 MPa. Heat treatment will be done by Stack Metallurgical in Portland, OR.

Smaller Components for eCar specifics

All of the smaller eCar specific components are being made in Germany for both logistical reasons and because the DHBW team has a manufacturer procurement student (Julia Sonntag) who has amazing skills at finding companies to make components. These components include all bushings required on the pedal base, the eCar brake/throttle pin, and the magnet holder.

Brake rotors

The rotors are not changing from last year. The rotor blanks are being purchased through Braketech. The rotors then need to be water-jetted which is being coordinated with Daniel Fusion. The second run on water jetting can be done within a weeks notice, the rotor blanks were taken up to Albany in the First week of February for water-jetting.

The process will take less than 3 hours using the following dxf images (Figure 42) as a cutting pattern.

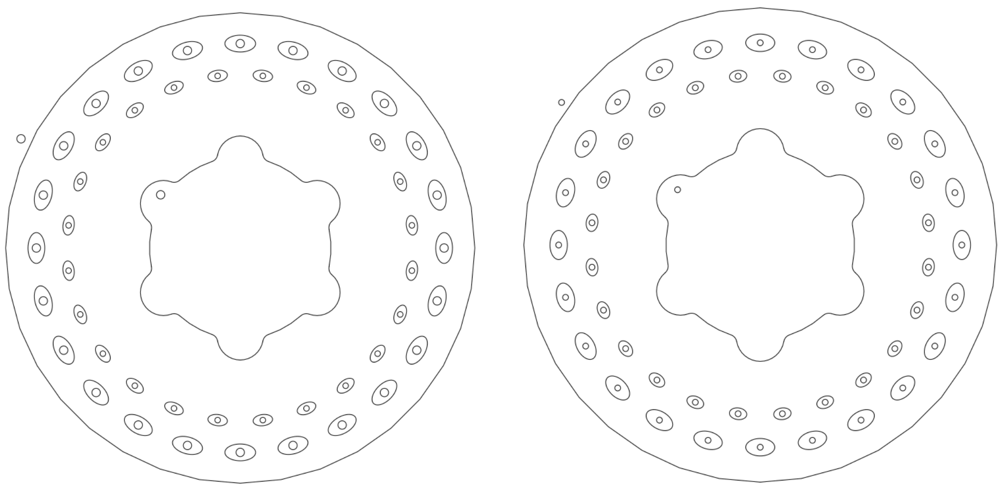


Figure 42. Front rotor .dxf (left) and rear rotor .dxf (right)

After water jetting the rotors will need to be ground to the correct thickness (4 mm for front, 2 mm for rear). F&F Grinding out of Portland, OR did this. The rotors were dropped off and picked up by Nathan Cheung.

4.2 Supplier Contacts

While designing the pedal assembly there was also time spent being the contact for a couple suppliers. The first supplier contacted was Tilton Engineering. They supply the master cylinders and in the past have also supplied the balance bar. This year however, an in house designed balance bar was designed. This was done for two reasons: first, by buying a part it takes away from the design freedom, and design challenge of creating one specific for the GFR14 car and brake pedal; second, is that the balance bar costs $275. The in house designed balance bar cost only as much as the Aurora spherical bearing, which is $16.62. All other components were either donated or the material was donated and the rest was done at the MIME shop at OSU.

Tilton gives a standard SAE pricelist for all components. However, I was able to talk with their head engineer about the strength of their balance bar. It was from him that I learned that the balance bar of ⅝” should be hardened to between 35-38 on a Rockwell B scale. First contact was made through email, but follow-up questions were made via phone.

I was also the contact for F&F Grinding. The owner, Roy Friend, has been our contact in the past. He can be difficult to get a hold of, but persistence will get him to answer. He is nice but short in phone calls. He donates all the grinding at no cost to the team. Just let him know a week before you drop them off, and give him a week to get them done.

The largest and most complex contact was that with EMJ metals. They were first contact via email. The contact was Jon Nelson. He was a corporate level contact who was able to get a number of the materials we needed. For the first order I was able to procure over $2000 worth of materials. However, as more projects were finishing up, some materials that were not first known, were now needed. Mr. Nelson at this point was no longer responding to email. After two weeks of this, and simultaneously sending emails through the team to see about material needs, a new contact was needed. Evan Taylor had previously worked with a David Goodrich at EMJ Portland. Mr. Goodrich was then able to help me with some of the last needed materials. One order was just for BAJA who was also in need of some materials not found elsewhere. Not all materials, which we requested, could be found, and some were not quite what we ended up needing, the reason is because EMJ donated materials, which were presently in sock in the Portland warehouse. Materials that they have but located elsewhere could be obtained but only for retail pricing.

In the end I ended up being the contact for Silver Eagle Manufacturing. They, along with a couple other companies, were contacted after a manufacturing sponsor failed to respond. (This will be covered in Manufacture Changes). The Ali Saalabian was the main contact. He was most helpful and very willing to help, even at the 11th hour. Later I would have more direct contact with Vern Thompson, the head machinist. Contact was at first just through email, but phone calls were able to answer and expedite some of the easy questions, then followed up by an email to ensure a seamless line of communication.

5. Implementation

The following section is divided up by how parts were created starting with carbon fiber. This covers the parts made on the end mill and lathe, as well as those made by hand. At the end of this section are design and manufacture changes that came about for specified reasons.

5.1 Carbon Fiber Manufacturing

Several of the components are going to be made at OSU by various individuals.

There is a single type of part on the pedal assembly, which will be manufactured using carbon fiber composites. These parts are the side supports which keep the drivers feet on the correct pedals. The particular composite being used for this part is T-700 from Toray composites. It is a pre impregnated carbon fiber, which means that the resin is already inside the lattice structure of the carbon weave. The advantage of this type of carbon fiber is that it can easily be layered and baked in the oven.

The part was designed to cover the heel rest bar and then extend out towards the driver in order to keep the heels from slipping off. A 1:1 scale drawing was made and from that the exact scale print was cut out and used as a template for making the repetitive parts (Figure 43). It is important that once work begins with the blue material and especially the carbon fiber sheets, that latex gloves be worn. This keeps oils from your hand off the carbon fiber sheets. The paper template was used to create identical template out of a blue material used for backing of the carbon fiber sheets. The blue material is used to keep the carbon fiber from attracting bits of debris and to keep the sheets from sticking to each other during the layup process.

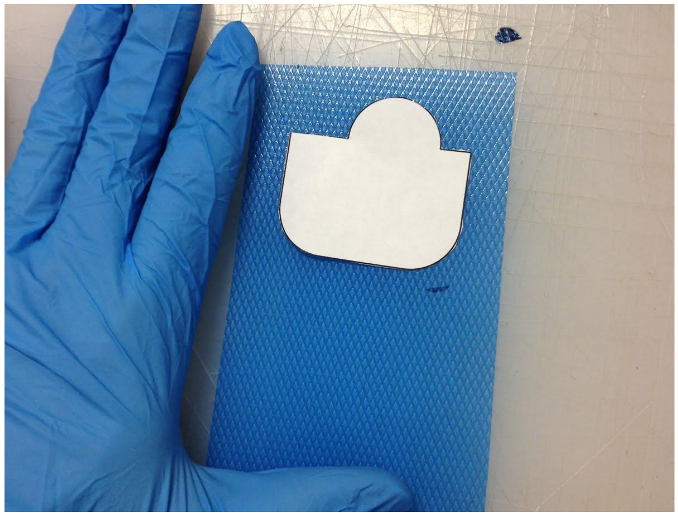


Figure 43. Paper template for carbon fiber molds on blue backing material

The next step is to place the blue template onto the carbon fiber. Lining up the edge of the template with the edge of the carbon fiber allows for quicker manufacturing time (Figure 44). Using a sharp razor blade the carbon was then cut to the exact size of the blue template. The carbon is very easy to cut and requires little pressure.

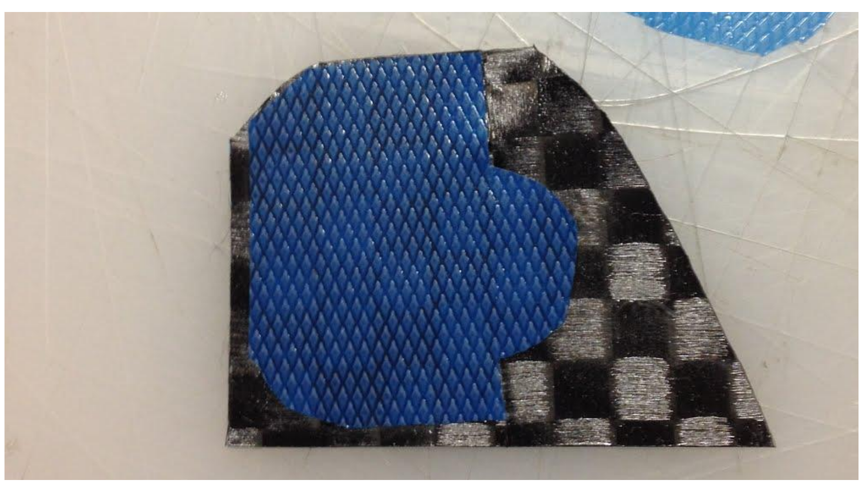


Figure 44. Blue material template stuck onto carbon fiber T-700 at 0 degree layup

The strength of carbon fiber comes from the layup, the weave, and the curing cycle, which hardens the resin within the fibers and creates a solid part. To add strength to the heel stops the layup type is 0,45,0,45,0 degrees and consists of five layers. Layup was done this way to ensure symmetric layering. By having the layers symmetric, it keeps the parts from warping during the curing process. Figure 39 shows the 45-degree layup of the even layers.

To ensure that each layer-completed part has the proper layup order of alternating angled it is easiest to place them on top of each other until all five layers are complete. Then start on the next part. Cutting of carbon layers took between an hour and a half and two hours. It was expedited by the chassis team being in the composites lab at the same time. The scrap pieces they had left over were more than large enough for these small parts. Also all the scrap pieces already had a blue backing. Therefore rather than creating a blue template for each pieces, a single completed blue backed carbon sheet was used directly on the next sheet to cut out the next piece. This reduced cutting time by 30%. Once all 40 layers were cut and stacked appropriately it was time to begin layup.

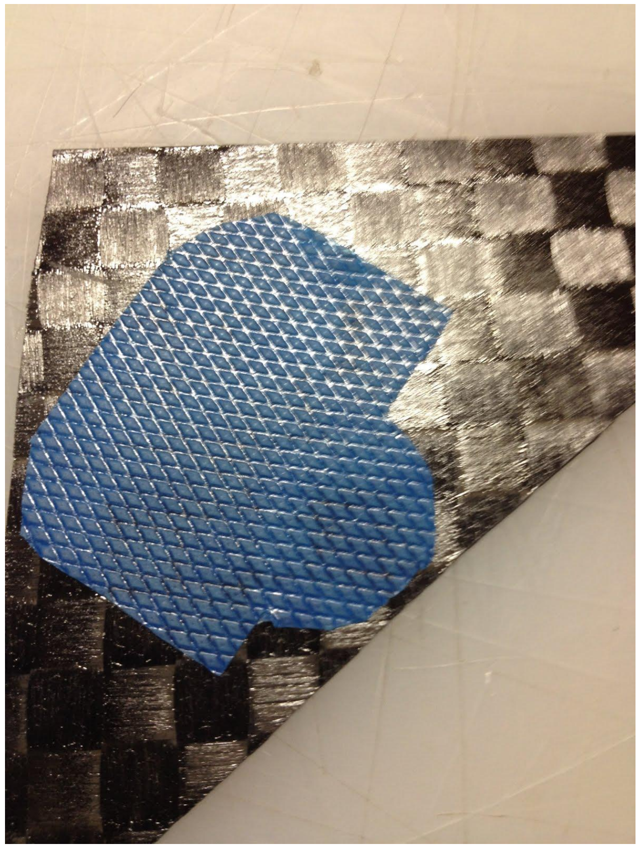


Figure 45. 45-degree layup of the even layers

Layup of the parts starts with finding a sheet of metal thick enough to not bend and large enough that all your parts can fit with room in between and some space on the edge. It is also important to leave room for the vacuum seal connector which will be place on the metal sheet.

To prepare the metal plate for layup it is first cleaned using Acetone and a paper cloth (Figure 46). The plate needs to be cleaned until no more black comes off, which will require two or more coats of acetone and rubbing clean. Once clean a mold removal, which allows the carbon fiber sheets to be easily removed from the metal plate after curing, is placed on the plate. The mold removal is not mark as such and can easily be identified by another student who is familiar with carbon fiber or if it is already out, using proper technique, an unusual smell that greatly resembles that of an ocean aquarium. This removes the acetone should be left to sit for about five minutes in order for it to fully dry.

Figure 46. Acetone, cloth, and metal plate being cleaned

Now that the plate is cleaned and prepped it is time to lay up the carbon fiber sheets. Start by placing each stack of five sheets in the appropriate place on the plate to get a sense of where they will fit best (Figure 47). Using the razor blade each sheet must then be separated from the blue backing. It is easiest to do this by looking for the light blue areas and easing the blade tip betwixt the carbon and blue material (Figure 48). At times the fibers will try and separate with the blue material and this should be mitigated but is not going to destroy the part.

Figure 47. Approximate placement of each part on plate

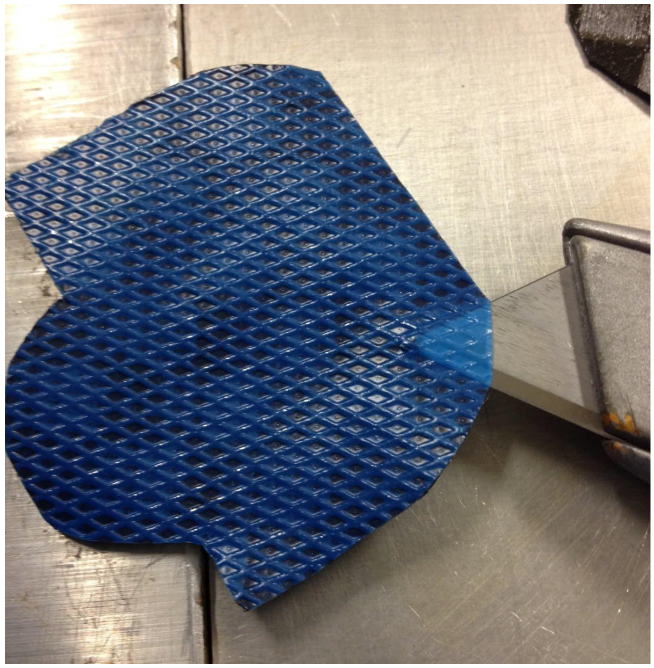


Figure 48. Easiest way to remove blue material from carbon sheet

Using a roller to flatten each layer, place the first piece, then lay the second on top of the first and roller flat again (Figure 49). Repeat this with all five layers. Repeat this with each of the 8 parts. When finished the final plate will look something like Figure 50.

Figure 49. Roller technique to flatten the layers and remove bubbles and wrinkles

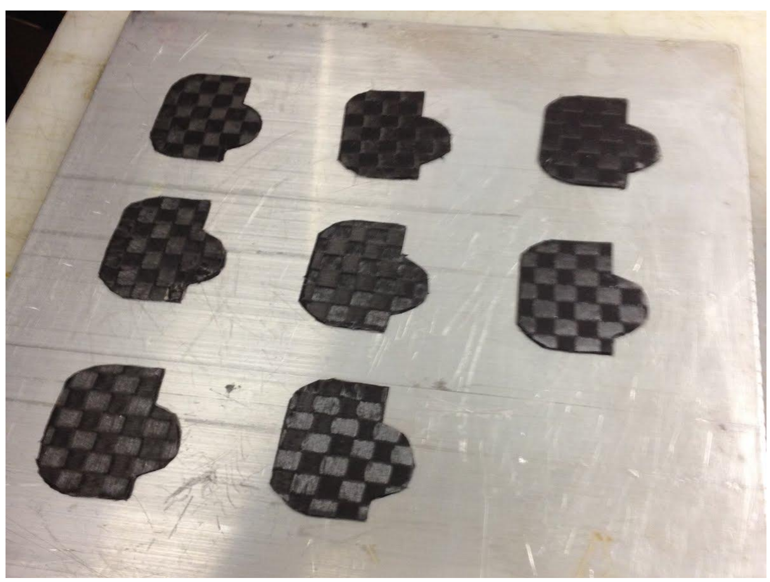


Figure 50. Completed layup of all 8 parts

After all the parts are fully laid up it is time to create a vacuum bag. There are four pieces, which will be added on top of the parts. First is a white sheet with red stripes. This layer will absorb the resin that escapes the parts during curing (Figure 51). The next layer is a blue sheet, which is placed over all the parts (Figure 52). The third layer is a vacuum distribution layer, which is a thicker material that feels like felt (Figure 53). The last layer is not done next. Before the last layer is placed on each of the previous layers should be cut to size so there is at least half an inch of free plate all around the parts. Using a yellow sealing strip, completely surround all parts (Figure 54). Then collect a vacuum nozzle. Separate the two parts of the vacuum nozzle. Place the bottom half on top of the third layer and within the boundary of the yellow sealing strip (Figure 55). Finally a pink sheet of plastic is cut to a slightly oversized piece and place on top of the first three layers and the bottom of the vacuum nozzle (Figure 56). Firmly press down all around the edge on the yellow sealant to create a tight seal between the pink sheet and the yellow. Cut a small slice in the pink sheet directly in the center of the nozzle connection (Figure 57). Then connect the top half of the vacuum nozzle. Connect the vacuum hose and wait for curing.

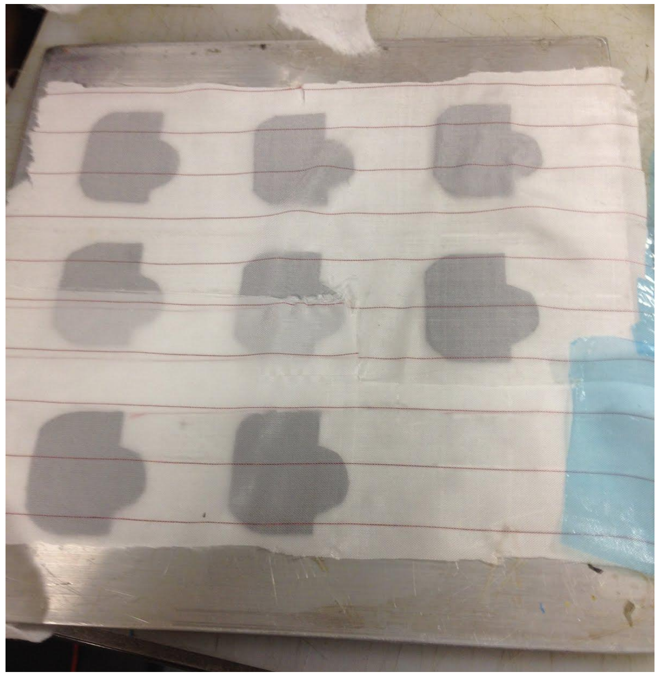


Figure 51. First layer on top of parts

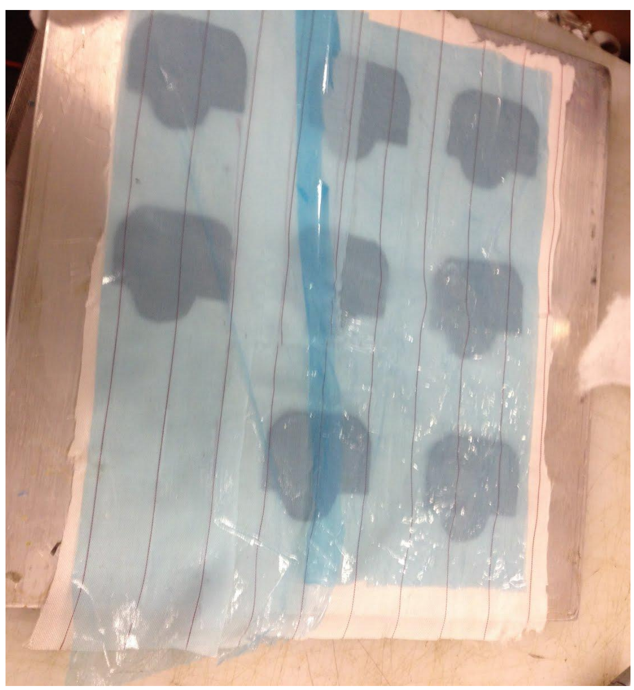


Figure 52. Blue second layer

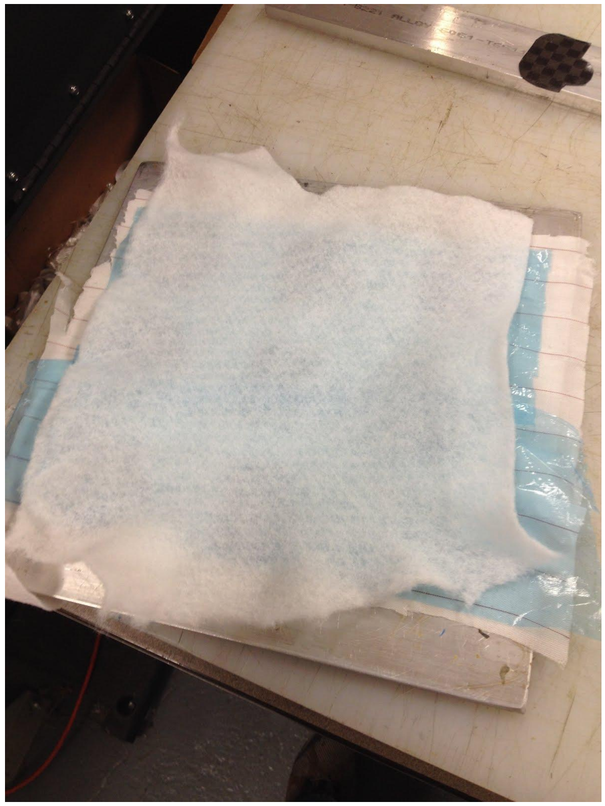


Figure 53. White “felt feeling” third layer

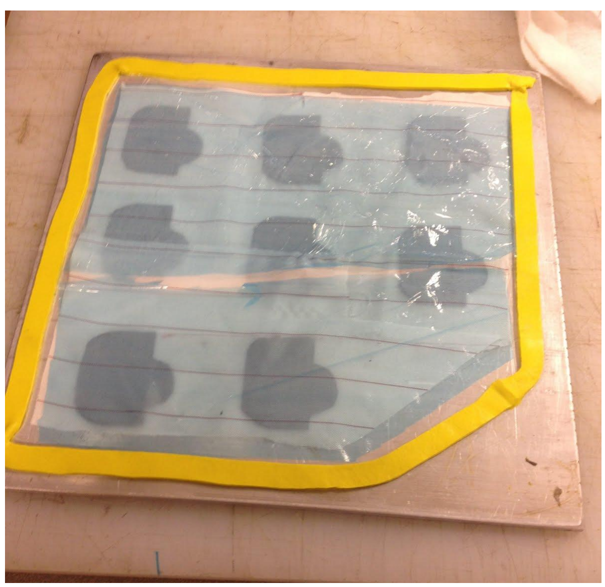


Figure 54. Yellow sealing strip in place

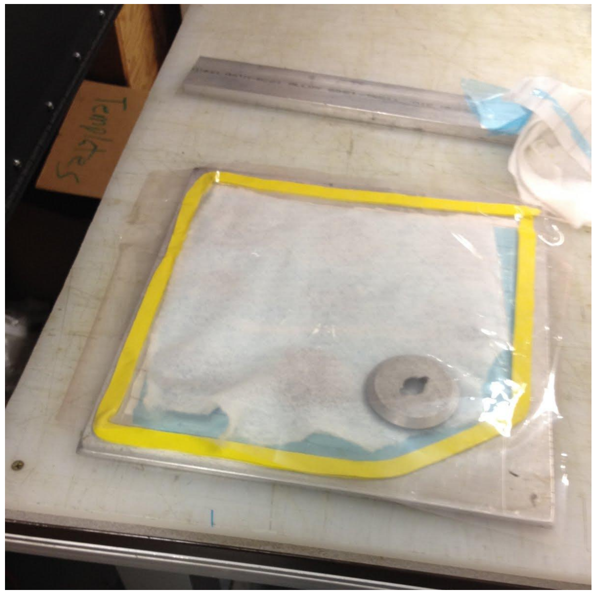


Figure 55. Placement of the vacuum bottom and pink final sheet in place

Figure 56. Small slit cut in the top pink layer to allow for the top half of the vacuum nozzle access

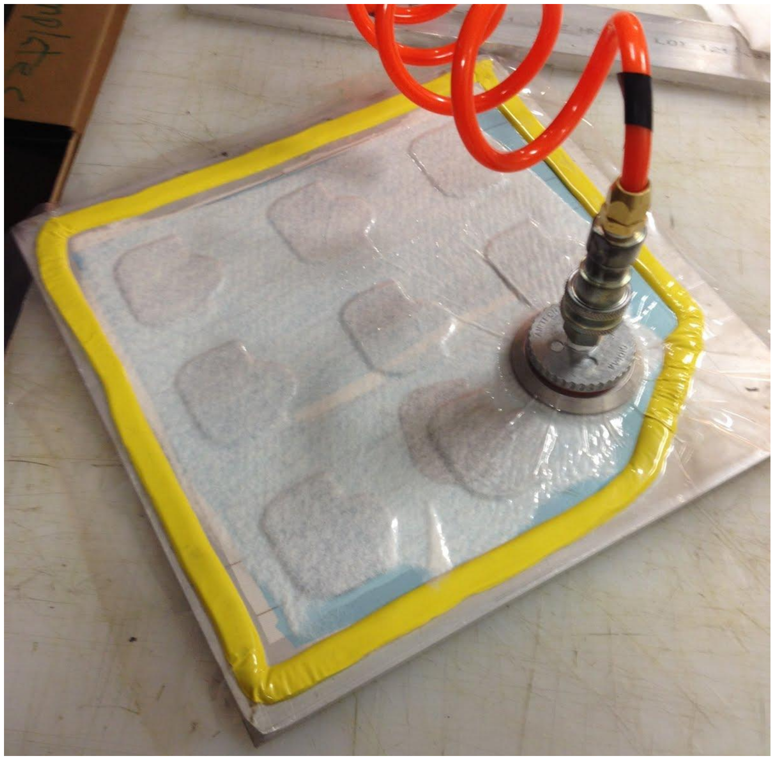


Figure 57. Vacuum hose connected and seal holding

The curing cycle information can be determined through the help of the composites teaching assistant Paul Weitzman. Using the information provided on the GFR body page on cure cycles a 4-hour cure at 250 degrees is to be used to bake the parts. The link to cure cycles information sheet can be found here.

A second set of carbon plates were made by underclassman Trystan, using the same process as described above. Below in Figure 58 is the image of the final parts ready for cure. These parts are designed as side stops for the throttle pedal.

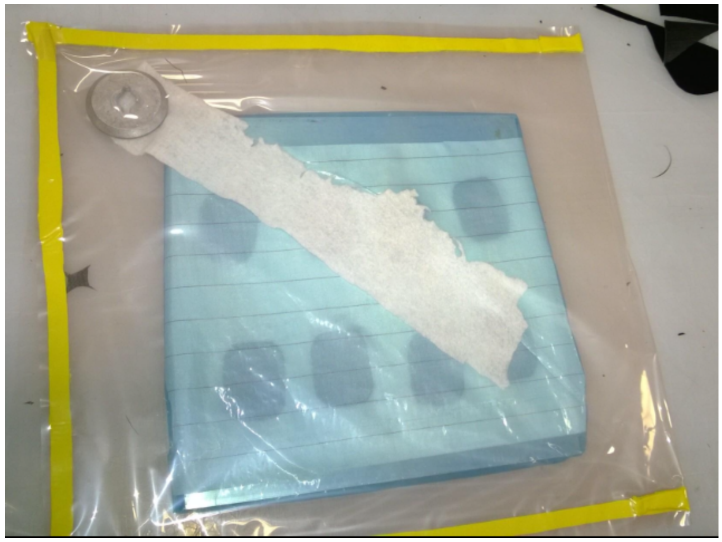


Figure 58. Vacuum-sealed parts

All the carbon parts were left with rough edges after exiting the oven. To clean the parts up required sanding. Carbon dust is a huge health risk factor and every precaution should be taken. You must:

- Wear a dust mask
- Wear safety goggles
- Gloves will help protect against carbon fiber slivers however will not stop them

Use sandpaper and go over all edges until they are clean and smooth. Final parts will be ready for positioning.

This process was used in the manufacture of all carbon parts for the pedal assembly. After the carbon plates in Figure 52 were placed onto the finalized pedal assembly, it was determined that the driver preference was to make these pieces larger. They act as foot restraints, keeping the drivers foot from leaving the throttle and interfering with the brake. The larger parts measure 5”x3.5”.

5.2 OSU Machining

Using both steel and aluminum as base material, there are several parts which are being manufactured at OSU.

5.2.1 Lathe Machining

Three parts that are to be manufactured at OSU will require lathe work. The first are clevis pins that will be used to connect the master cylinders to the pedal base. Second, the balance bar clevis will also include end mill machining. Third, barrel nut will also require end mill machining.

The first part to be manufactured was the master cylinder clevis pins. These pins were turned on the lathe using ½” round stock provided by EMJ. Figure 59 shows the final turned product. The lathe process was to turn the pin until the shaft was of the correct diameter, then the head of the pin was created through the use of a parting tool. Once parted the pin would fall to the table. After cooling the pins were taken to a belt sander and the tip was given a 45-degree chamfer. This chamfer allows the pin to more easily slide into its required place in the master cylinders.

Figure 59. Master cylinder clevis pins

At the same time as the master cylinder clevis pins were being made, a sleeve bushing was also made from the same stock. These sleeve bushings were turned to 3.75mm in diameter from the ½” stock of 4130. Then the center was drilled out on the lathe by increasing the bit size. The final pass for the inner hole was cut to size using a five thousandths of an inch oversized reamer. Figures 60 and 61 show the parting and hole reaming process respectively.

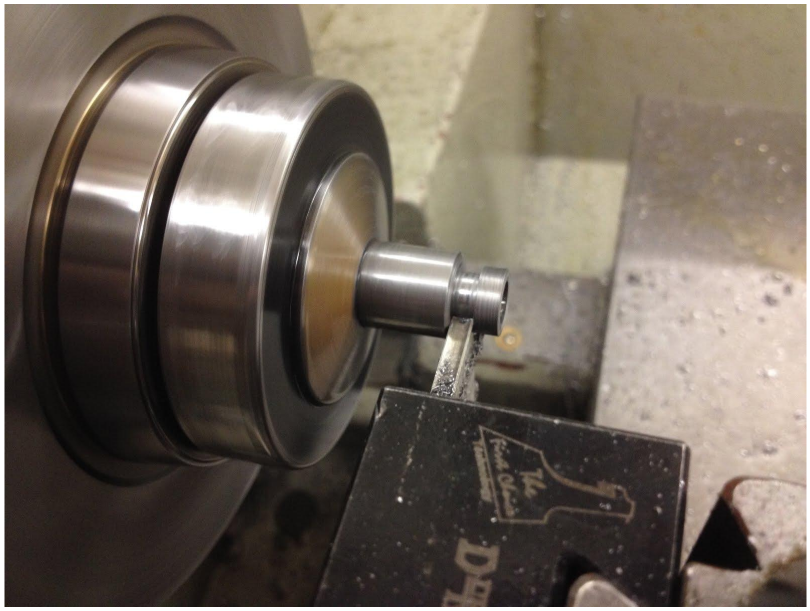


Figure 60. Parting of the sleeve bushing

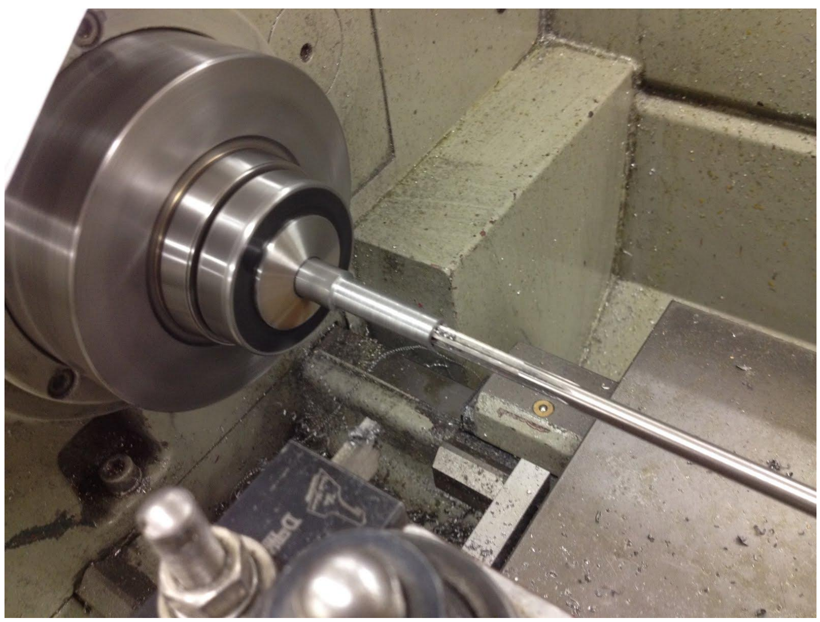


Figure 61. Reaming of sleeve bushing

Once out of the lathe, each of the bushings are rough and in need of cleaning. Each bushing had a very thin-wall left over from the parting process. To remove this, take pliers and pinch the thin remnant, this will easily remove this excess material. Then take the pliers and hold the bushing. With the bushing held in the pliers, take a scraper and clean the inner and outer edges of each bushing (Figure 62).

Figure 62. Deburring tool shown with sleeve bushing held with pliers

Master Cylinder Clevis'

Taking 1" 6061 aluminum stock and cutting it to approximately 2.7" will ready the pieces for production. Eight of these pieces will be cut. Next place each pieces on the end mill, cut each of the pieces to the exact length of 2.36"; this creates a standardized stock length from which each part can be created in the exact same manner. Each part was individually placed into a 1" collet on the lathe. Because there is no way to easily repeat the exact placement of each stock piece, the end must be zeroed each time. Figure 63 shows the turning process that made the created the narrower end of the part. To create a nice rounded fillet between the narrow and full sized part, it was initially done by hand. After finding a rounding tool, the fillet was redone. This created a nice clean finish which is visible in Figure 64. With the narrow end and fillet finished, the center was drilled out using increasing drill sizes starting with a ¼" up to the correct tap size for a ⅜-24 tap.

The master cylinder clevis must thread over the master cylinders, in order for this to be accomplished, each part must be tapped for a ⅜" - 24. The air-compressor powered auto-tap does is regulated too low to work on more than 2 threads before it has too much resistance and stops. From there, each part was hand tapped. In order to create nice threads, about ⅛ of a turn or less of cutting followed by several turns off will free all chips from the cutting blades. After every couple turns remove the tap altogether and use the compressor to blow out the aluminum chips. This is continued until the threads are done.

Figure 63. Turning process for master cylinder clevis'

Figure 64. Parts after turning and thread tapping

In order to make a bias adjustment bar in house, there were several parts that required manual machining. Above in Figure 64 are the clevises, which will hold the master cylinders to the bias bar. To connect the clevis' to the bias bar there are two interfacing parts. The first is an IGUS plastic bushing, which will provide a hard smooth surface for the second part to rotate about. The second part is a barrel nut. Shown in Figure 65 are the blank cylinders that will later be drilled and tapped. The tapping process is done by hand in the same manner as was done with the master cylinder clevis'.

5.2.2 End Mill Machining

Lathe work is now finished and some parts will need to be finished on the end mil.

Pictured below in Figure 65 is the next step for creating the master cylinder clevises. Holding the part using an "X" block in the vice the hole was placed in the same location for each part using five tools (center drill, ¼", ⅝", 23/32", boring bar). Although the dimensions of the plastic bushing were known, in order to create a tight fit, the hole size was tested incrementally to get the proper fit.

The final step was quite tricky. To create a slot perpendicular to the hole just created there are two options. The first is the one chosen. The second is the one that should have been utilized had it been known at the time. Choice one: Place each rod into the appropriate sized collet fitted within a square block for use on an end mill vice. Take a very straight rod about six inches long and small enough to fit through the hole. Using a level, zero the bar with respect to the holes. This will create the slot at a 90 degree angle to the holes. Using a ½" end mill, create the slot by moving down 0.1" each pass. Proceed .4" then move the end mill in the "y-axis" to repeat this same step on the other side this is because the slot width is wider than the end mill. For the final 0.3" a different approach was used. Move the end mill all the way out, cut the entire depth moving in slowly. Again, because the slot is 0.61" wide, wider than a ½" end mill, only proceed 0.25" into the slot depth. Move back out, shift the end mill to the far side and go in ½". This will ensure that strength is maintained in the now thinning arms of the master cylinder clevis. This reduces chatter, and surface area upon which the end mill has contact, preserving the tool and ensuring a cleaner finished part. Clean the part holes and edges with a scraping tool. The parts can then be cleaned using a cleaning pad or sand paper.

The completed parts can now be assembled with the other respective parts. First however, the plastic bushings from IGUS need the flanged end flattened into a "D" shape. This is because the fillet takes up more room than was expected. Also the flanges are thicker than described in the part drawings. The flange thickness will also need to be reduced. Both these are done using the belt sander. With the modifications completed, place the bushings into the holes from inside the slot. Press into place gently as the arms are not designed for strong side loadings.

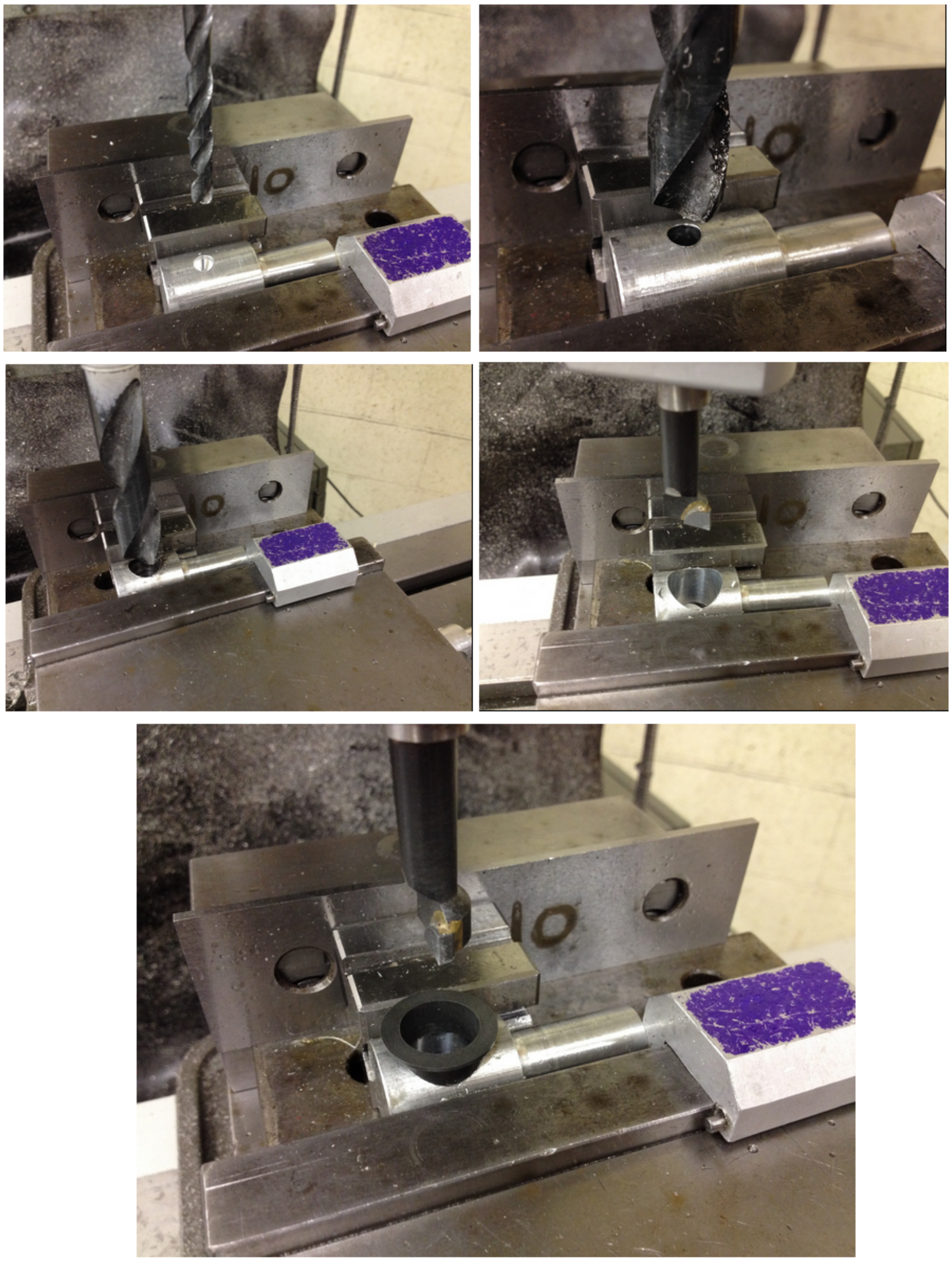


Figure 65. Stages of hole production for master cylinder clevis’

5.2.3 Cutting Tubes

All the tubing required for the throttle pedal and heel stop came in 20 foot long sections from EMJ metals. These then needed to be cut to length, cleaned, and prepared for welding.

The heel rest bar was cut from 1”x0.028 steel on a miter saw by an underclassman. Only two pieces were required, but six pieces were cut to length. This was a smart decision, because three were required due to improper weld placement.

5.2.4 Welding / Weld preparation

Some parts used the lathe, not for manufacture, but for ease of cleaning. In order for welding to be done right, the surface of the all parts must be cleaned with a scotch-brite pad, followed by a cleaning with acetone until both the outside and inside of all parts is free of all dirt and grime. All tubes come from the supplier with a thick coat of grime on the outside. Use gloves to expedite the hand cleaning process afterwards. Figure 66 shows the throttle pedal upright arm in the lathe being cleaned with a scotch-brite pad.

Lathe Details for cleaning tubes

Speed: 800-1200 rpm

Collet: ⅝” (Throttle arms); 1” (heel rest tube)

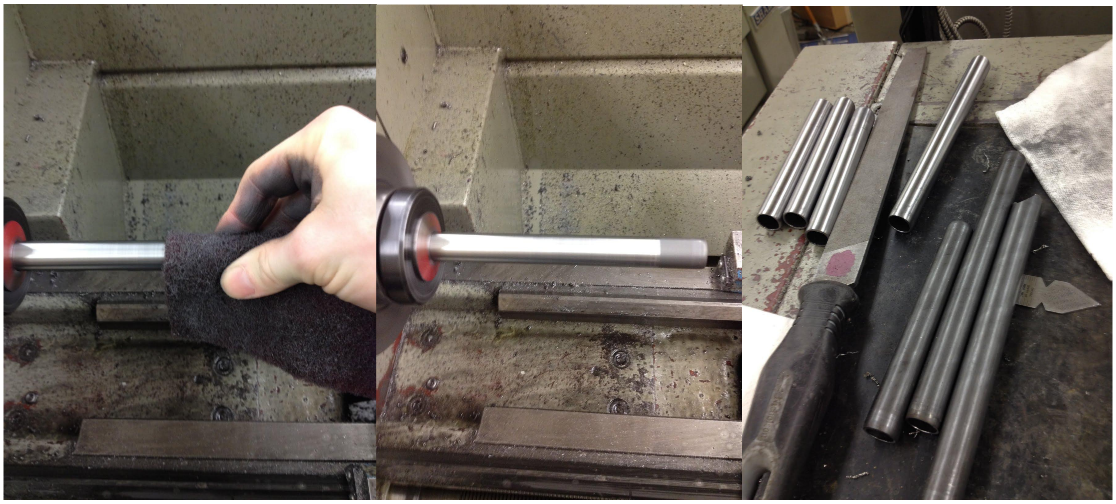


Figure 66**.** Cleaning tubes with lathe during and after images. Note the grime that ended up on the hand in the first image. Use gloves.

Final cleaning of many parts is done with a single scotch-brite pad, however, to expedite the process, use of the air tool with scotch-brite rotary head is far quicker and leaves a very nice finish.

5.2.5 Welding / Fixturing

Several parts required welding. The welding done is all for steel parts and was done by Trevor Takaro using the SAE shop TIG welder. The list of parts which need welding are listed below:

1. Pedal base
    a. Floor mounting pegs - pedal base
    b. Heel Rest - Pedal base
        i. Place 28mm left of drivers left welding spline
    c. Throttle tower - heel rest bar
        i. Place 102mm from left end of heel rest to center of tower
    d. Brake over travel switch - pedal base
        i. Place in concentricity with both pedals axis and master cylinders axis
        ii. Place to the left of the drivers left spline upon which the heel rest is welded

2. Heel Rest
    a. End Caps - Heel Rest
    b. 1.25” squares
        i. Replaced with 1” circles
        ii. Cut from 1” die
3. Throttle Pedal
    a. Horizontal arm - Vertical arm
    b. Vertical arm - Lower cylinder
    c. Throttle cable attachment - vertical arm

Pedal Base

The pedal base required several pieces to be welded to it. But before any pieces could be welded to it it must first be completed. Using a fixture made from an aluminum block, the mounting pins were located and put in place. Once in place they were welded from above. Figure 67 shows the fixture for locating the mounting pegs of the base, as well as what would act as a holding platform for all further welding.

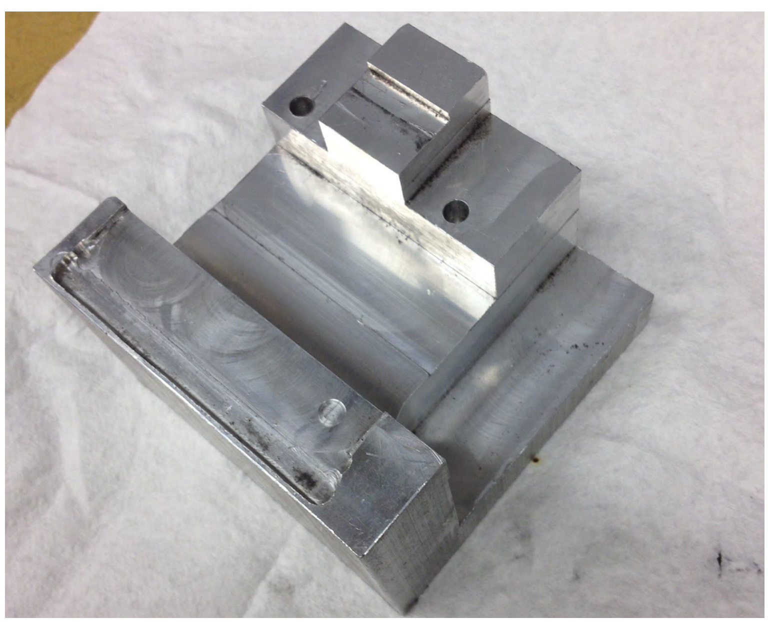


Figure 67. Welding fixture for pedal base

The first to be put in place was the heel rest bar. This was measured and held in place by hand. Once tacked on, the rest of the weld was done. Second was the throttle tower, measured with calipers and confirmed location with the throttle pedal in place, this was held using several block. Two stacked blocks behind held the tower kept it in a vertical position.

Heel Rest

Before the heel rest can be welded to the base it needs to have metal end caps welded into place. The first way these were made was to create a 1.25” square from thin sheet metal. This was then tacked into place with 8 tack welds. A better way, which was used for the eCar, is to create a 1” circle, just smaller than the outer diameter of the tube, which will just sit on the ledge. This piece can then easily be welded into place, creating a seamless end. To make this 1” circle, use lever punch in the MIME machine shop with a 1” die.

Throttle Pedal

The welding process for the throttle required a fixture to hold the arms in the correct orientation. The weld fixture, shown in Figure 68, used was a simple three slots cut with a ⅝” ball nosed end mill. Cut to a depth just over ⅝” for each slot. The first was cut along the mill “X” axis and is to locate the horizontal arm. Farther down an angled slot was cut to locate the vertical to the horizontal arm. A third slot was created, also angled, which intersected with a small slot for the lower cylinder. In Figure 68 it can be seen that the throttle cable attachment is also located using this fixture (seen in the very center of the image).

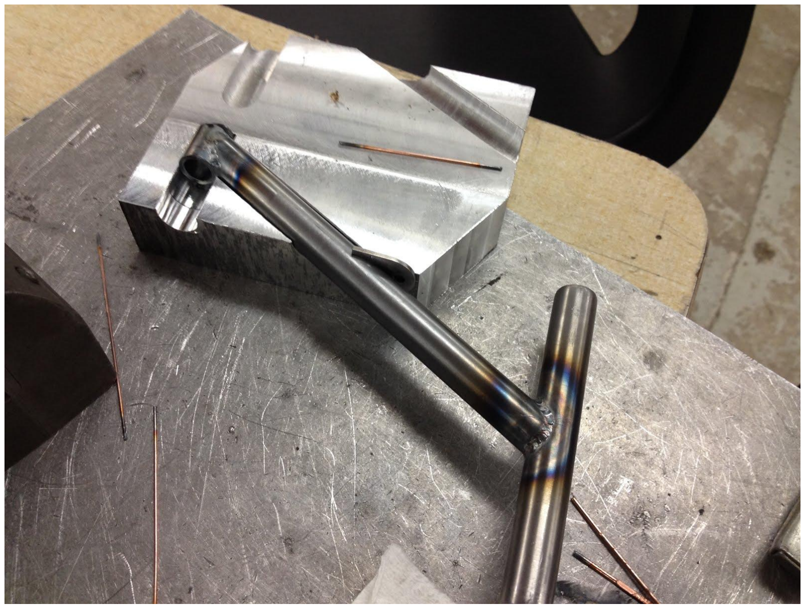


Figure 68. Throttle pedal welding fixture with throttle pedal in place

5.2.6 Heat Treatment

Time constraints lead to heat treatment of the throttle pedal and pedal base here at OSU. Doctor Warnes is the professor in charge of the oven, and he was contacted by Nico Varela. GFR was given use of the oven and the key can be loaned out, for a few minutes, to open the door, by Brian Jensen.

During the design process the required strength was calculated for both the throttle pedal and the pedal base. Using the material 4130 steel, and the calculated strength required (in MPa), it is possible to search the Matweb database to find a heat treatment that matched the required strength. Each heat treatment in Matweb shows the details of temperature and cooling. Looking for the strength each treatment yields, pick the one that best fits.

The following heat treatment details worked for both the throttle pedal and pedal base. They required very similar strengths, which simplified heat treatment.

Heat Treatment details

- Tempering
  - Oven Temperature: 850 degrees Celsius
  - Hold for 1 hour once at temperature
- Water Quench
  - Immediately after Tempering
  - Water cools very quickly and is cool to touch within a few seconds of immersion
- Annealing
  - Oven Temperature: 480 degrees Celsius
  - Hold for 1 hour
- Air Cool
  - Let cool for 1 hour

To use the oven first contact doctor Warnes, or the GFR contact who has been in contact with Dr. Warnes. Once you have approval get the key from Bryan Jenson. Go to the heat treatment oven and open it to ensure that nothing is in there or in the way. Then test placement of all parts while the oven is cool. This will give an idea of what the parts will look like while in the oven and ensure a good fit. Close the oven, press and hold the up arrow until the desired temperature is reached. Then press the bottom button once to set the temperature. I usually would press, wait, and then press once more to ensure that it actually set. Make sure the oven is fully closed. A red light will come on in the front when the oven is heating.

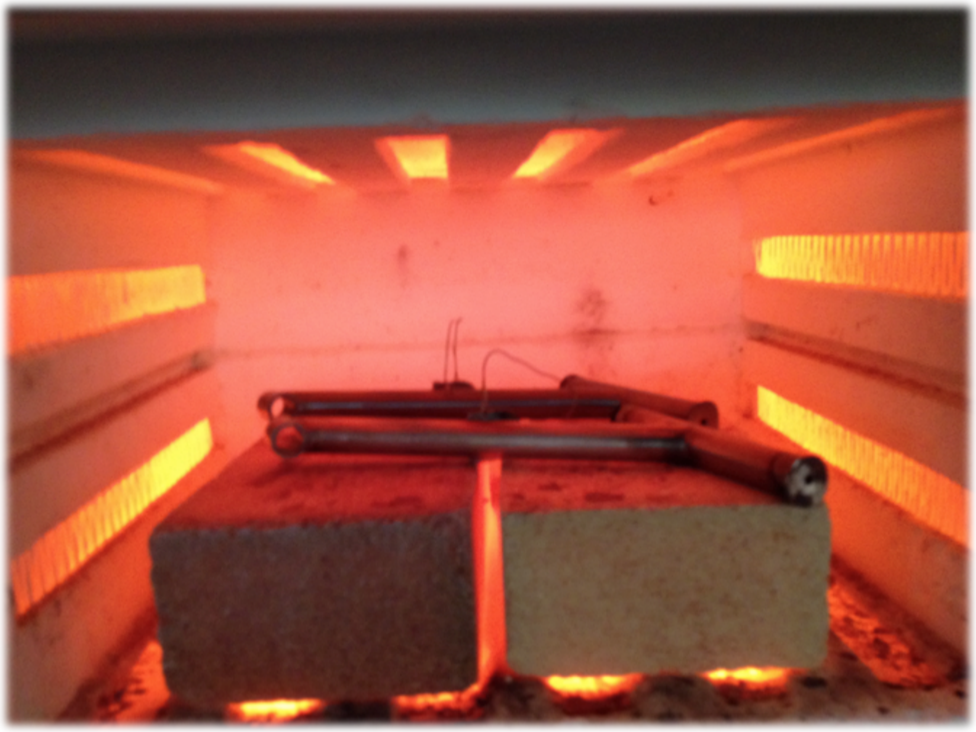


Figure 69. Oven at 850 degrees Celsius with throttle pedals placed inside

Figure 70. Colton Swearingen displaying proper attire for heat treatment, holding steel retrieval pliers, splash apron, and shield (Gloves not pictured)

Prepare the parts by threading safety wire into a handle. This can be seen in Figure 69 as thin wisps of wire just above the throttle pedals. This is done so that the parts can be retrieved from the oven using the long steel pliers (Figure 70). Using the long pliers to remove the parts without this wire would result in a local conductive cooling of that part. When removing parts wear the apron, shield, and gloves provided in the lab. The gloves protect you from the heat, the rest protect you when quenching parts. Water quenches the metals very quickly, and as a result the parts can be removed after only a few seconds of being in the water (Figure 71).

This first heat cycles is called tempering. Tempering toughens the metal giving it higher yield strength, but make the material more brittle.

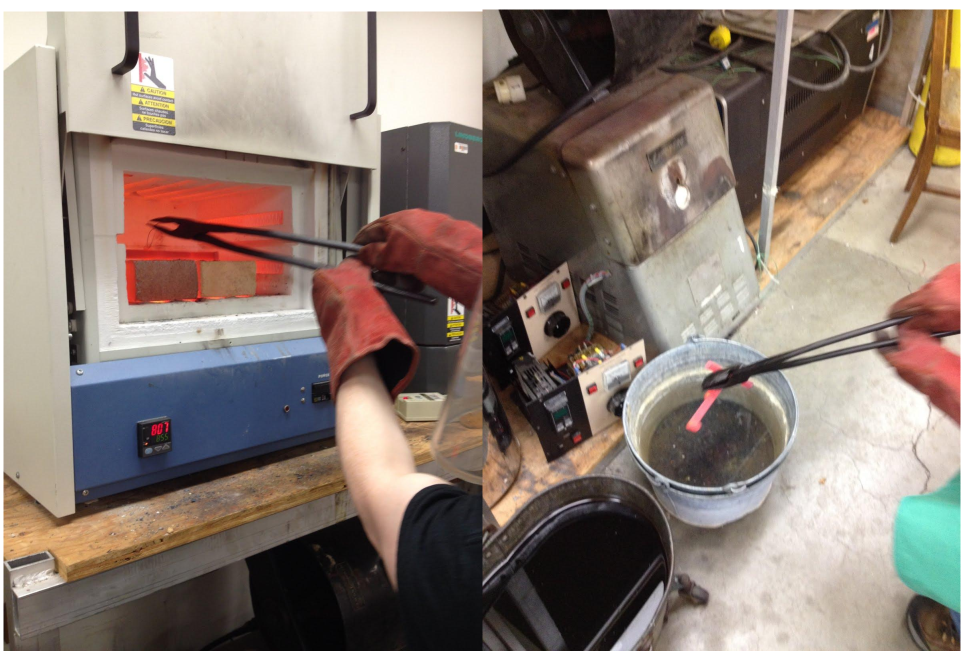


Figure 71. Oven removal of parts and quenching in water

Annealing takes place following the tempering cycle. This takes place at a much lower temperature and allows the material to become more homogeneous while reducing brittleness at the cost of a small amount of toughness. From this state an air cool yields the final product.

There is a downside to heat treatment. Specifically to the ovens at OSU, they leave a lot of baked on residue on the parts. This comes from an uncontrolled environment and is very difficult to remove. Figure 72 shows the pedal base just out of the oven, covered in baked on grime.

Each piece then gets cleaned roughly by wire brush, followed by sandblasting. This leads to a finish as seen on the right side of Figure 73. A final cleaning step involves using an air tool with a Scotch-Brite head to get a very shiny clean look. This final look can be seen in the full model of Figure 74.

Figure 72. Pedal base after leaving the heat treatment oven

Figure 73. Throttle pedal just out of the oven (left), after sandblasting (right)

5.3 Design Changes

All design changes came with good reason. The Balance Bar Clevis' had two changes. The first was a result of tool availability. The radius that transitions between the ½" and the 1" part was rounded using the available tool. The ½" radius tool differed slightly from the design, however the radius is there for weight savings and stress relieving. There is no specific radius that would work best without running computer optimization; instead any radius within a reasonable range would work.

The second change primarily reduced the weight of the balance bar clevises. It also made the part look better and cleaner. The change was to round the top corners of the part as shown in Figure 66. As shown above in Figure 33, the FEA gives little to no stress applied to the corners, proving that rounding will have no impact upon performance.

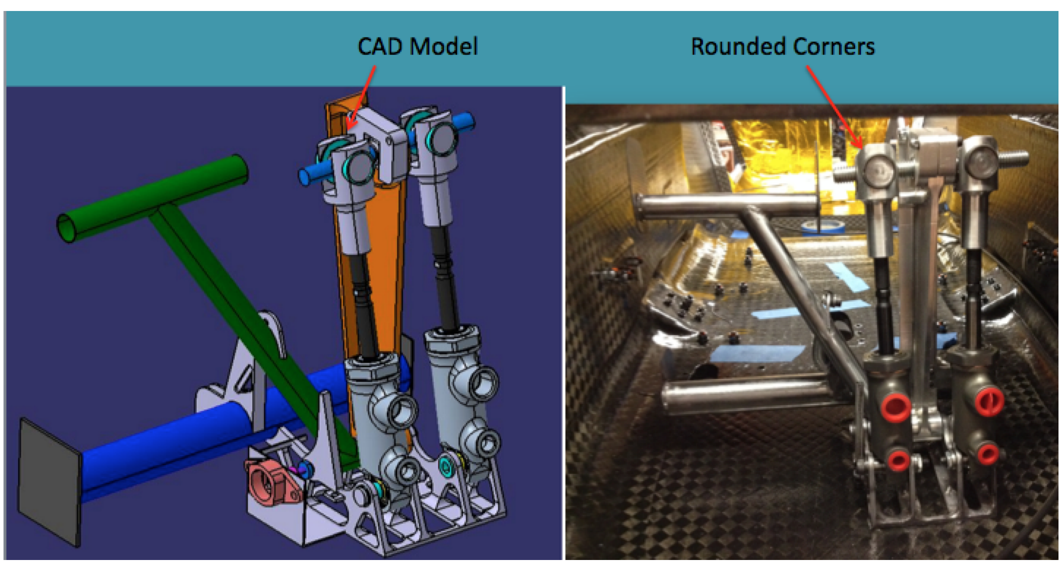


Figure 74. CAD model vs. physical model showing rounded clevis corners

The barrel nut was originally going to be bought, however, due to the supplier selling the business and a minimum order of $50, the parts were then going to be manufactured here at OSU. The trickiest part of the barrel nut was to tap the threads for the barrel nut. The OSU Machine Shop has an auto-tap, however, the pressure regulator is set too low to allow for taping of a ⅜” x 16 thread. The combination of steel and a large thread size required too much torque. As a result the threads were tapped by hand. This caused problems because starting the threads straight is difficult. Each barrel nut took about 10 minutes to do properly. Using 1/16th - 1/8th of a turn before backing off the tap allows for the chips to fall out and create clean threads. The final part was cleaned by using the tap by hand alone to get the smoothest finish. To make threading the balance bar into the barrel nut easier, each thread opening was bored out creating a cupped surface. The part was then sent to get electroless nickel plating.

There is a bushing, which interfaces with the barrel nut and the balance bar clevis. In the CAD model, the parts fit perfectly. In reality, the head of the bushing was too thick and too large a diameter to fit properly with the given radius inside the clevis. Both issues were easily resolved. To reduce the thickness of the head they were placed against the belt sander until they were sufficiently thin. This is a reasonable fix because the bushing head is there to keep a tight fit and will maintain its hardness even if the material is thinner.

To allow the bushings to fit due to the head being too large, one edge was flattened, creating a “D” shaped flange. This allowed a better fit and also keeps the bushing from rotating. Because the now flattened portion of the bushing does not have direct contact with the balance bar, it is within reason to make this modification.

Should this design be used again it would be advisable to more accurately model the bushing and slot. Also if a tool with a smaller radius were used it would have better allowed for the fit. With that said it is better to error on the side of too tight and modify, than it is for the fit to be loose.

The throttle pedal, once put into place next to the brake pedal, was too wide. The reason for this inconsistency was due to improper placement of the horizontal arm for welding. When it was designed, the vertical arm was supposed to bisect the horizontal arm. However, in the CAD model as in the physical, there was a 1 cm offset to the driver’s right. Because of this, the carbon fiber endplate for the throttle ran into the balance bar of the brake pedal. This can be seen in Figure 75. This was resolved by cutting 1 cm off the left side of the throttle pedal. The reason this can be done opposed to creating a new pedal, is because the horizontal arm was cut 5 mm longer than the model, and because in the design 1 cm was added to the width over last years throttle. By cutting the throttle down a little, it is still within the range for a good operational throttle pedal. In Figure 68 on the right image the finished product can be seen, and note there is no interference issue.

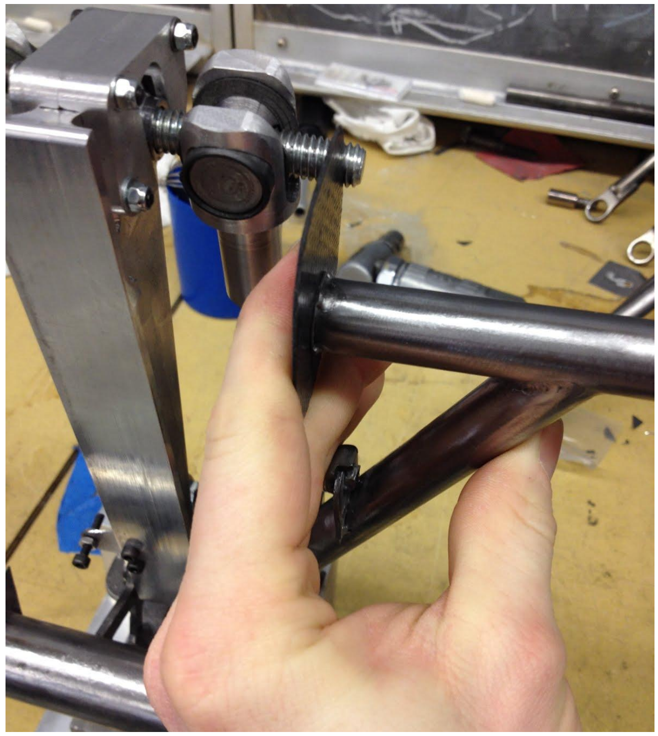


Figure 75. Interference of throttle pedal with balance bar

5.4 Manufacturer Changes

Due to a series of unfortunate events including but not limited to: communication, response time, sponsorship, and time management; two outsourced manufactured parts were no longer sponsored and being manufactured by an outsourced manufacturer.

The pedal base was built last year at A-Dec, a dental products company with large machining capabilities using CNC mills. However, given the combined efforts of our Formula team with that of the OSU Baja team, the sponsorship, which was assured here, was taken away for higher priority components for the Baja car. With this sponsorship gone, Hanard Machining was the backup for part manufacturing needs. The brake pedal was to be made here, and the pedal base was to be added on to the list along with other components of the Formula team. As of week 6 of a 10-week term, there was still no response from Hanard assuring and detailing the sponsorship ability for manufacturer. With this being the case, now both the brake pedal, and the pedal base would need to be either made at OSU on the CNC mills or, another manufacturer not yet being utilized could be found and convinced to make parts at the eleventh hour.

Silver Eagle Manufacturing is the eleventh hour hero. Found in the sponsor vendor sheet, with two ex OSU Formula student employees, the company was contacted on Monday of week 6. After several phone transfer attempts, the COO (chief operating officer) was reached and he (Ali Saalabian) was open to sponsorship. Through email .stp files and drawings were sent of the brake pedal and pedal base.

I was informed that there were some clarifying questions from the machinist (Vern Thompson) doing the Mastercam and CNC work on the parts. Contact with Mr. Thompson was made via phone. Given the design was done in metric and the company uses English tools, some of the radius callouts would be difficult to machine. Most of these were non-structural stress relieving radii and he suggested that an English size tool close to the design be used. Therefore some of the radii used as fillets are different from the CAD model.

The pedal base had a more difficult solution. Silver Eagle does a lot of machining, but does not have every tool that exists. They lacked a near 2 ½ inch end mill that would be required to machine this part. The head machinist said it would not be possible for him to manufacture, and even if he could it would take far too long, which would exceed the time allotted for donation. He also suggested the solution to the problem: Weld the upright spline arms to the base plate. The material would be changed to A572 steel, (hardness upon heat treat was confirmed through two metallurgists at heat treat companies around the country via telephone) because this is the material they have on hand that would work. It was asked that .dxf files of each of the three unique splines uprights be sent to expedite manufacturing and reduce workload on Mr. Thompson (Figure 76). This was done the weekend after Week 6 of winter term. The four splines would then be welded to the base plate and returned to OSU. The issue of manufacturer was solved and new and old contacts were made.

Another company, King Machining, out of Corvallis, OR was contacted about making some parts, however, given the late notice and the workload that they had promised to other paying customers they were unable to offer sponsorship. The cost to make the eight small head cap pieces would total around $800, far more than could be afforded. These will be made by hand at OSU using the Bridgeport CNC end mill.

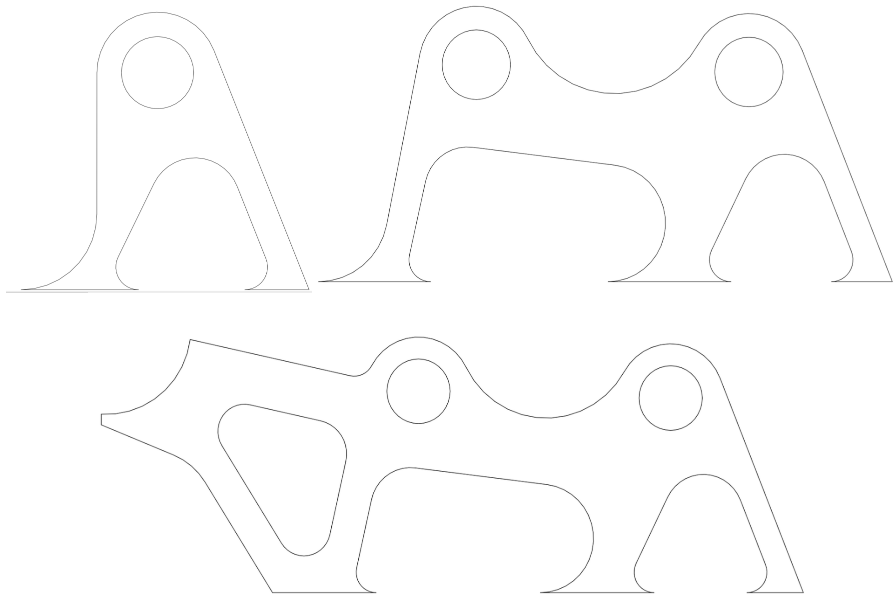
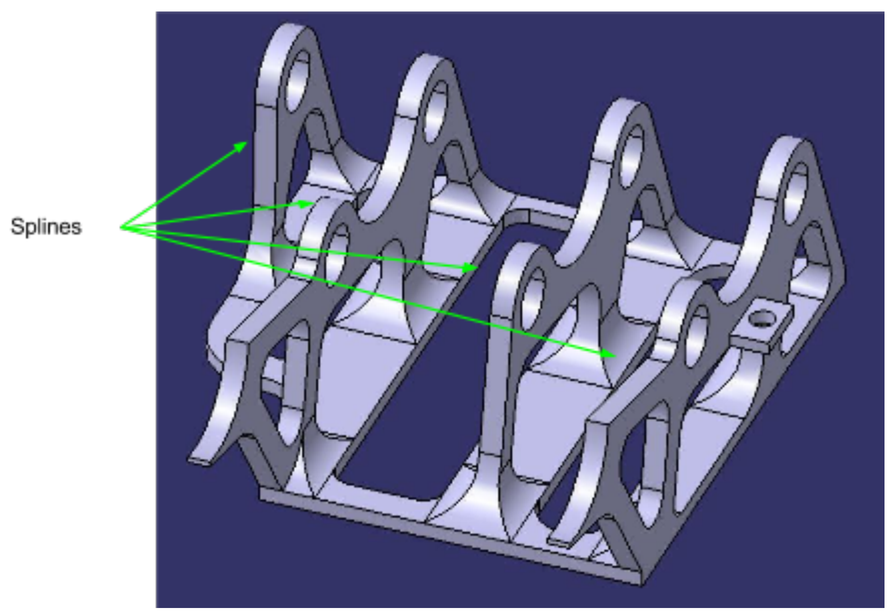


Figure 76. .dxf images of pedal base splines shown in 3D below (not to scale)



Copy of Figure 22. Pedal base with spline annotation

6. Testing

6.1 Tests Complete to Date

The first tests completed were fit and compliance based. The first tests were part to part fit. The master cylinders have to be able to thread into the master cylinders themselves. Once the clevises were tapped and the treads fully cleaned, the master cylinders were threaded into place. The fit was perfect.

Some other parts were not so simple. The pins, which hold the master cylinders in place, and the throttle and brake pedals, were oversized by a .001”-.008”. This made a fit impossible as was. To correct this, sad paper was used to file the oversized areas down to size. The oversize was the result of the pins being 3.5” long combined with the natural inaccuracy of the lathes. With a little work the pieces fit perfectly.

The same issue of fit was found in the barrel nuts. These need to slide into the bushings of the master cylinder clevises, yet due to the bushings being approximately 0.004” undersized and the barrel nuts being 0.01” oversized. They were placed back into the lathe and the .01” were removed. The fit was then retested.

6.2 Tests to Complete

The following are outlined tests, which would be performed if time and money were more available.

1. Throttle pedal
    a. Will measure the angle of horizontal to vertical arms to confirm design
    b. Confirm that weld did not affect the straightness of arms
    c. Place throttle pedal in a fixture which simulates the foot force, throttle stop, and axis of rotation
        i. Test yield strength on Instron machine
        ii. Determine where failure will occur first
2. Pedal Clevis
    a. Compressive test to determine actual strength
        i. Place in Instron machine
        ii. Apply load until failure
        iii. Compare to FEA
    b. Fit test
        i. Thread master cylinders into clevis to confirm threading
        ii. Place bushings into holes
        iii. Place barrel nut into bushings
        iv. Thread bias bar into barrel nut to confirm spacing
3. Brake pedal
    a. Place brake pedal in a fixture which accurately places the loads from driver and master cylinders
    b. Place strain gauges on the thin portions of the pedal
4. Heel rest bar
    a. Test actual bending stress
    b. Clamp bar in a collet and apply loads where the foot does.
5. Carbon foot restraints
    a. Test carbon for applicable loads
        i. Clamp one end and apply an increasing load until failure
        ii. Same test but with a single rivet holding the plate in place
            1. Where does failure occur: rivet or elsewhere.
            2. Load upon failure
        iii. Repeat with two rivets
            1. How much large loading can be taken with two rivets
6. Brake line pressures
    a. How does brake pressure relate to input force on brake pedal
    b. Pressure gauges are in place
        i. Read the data acquisition for brake line pressure

The test, which is most desired, is that of the brake pedal. Because the brake pedal is so much lighter and thinner this year over the past, it deserves the greatest attention in testing. It is important to not only compare to the FEA, but to prove that it is strong enough to hold up during real life use.

The testing that should be done is rather simple. Start by placing two linear strain gauges onto the brake pedal and points where the highest stress is likely to occur. For this pedal that is at the midsection farthest from the driver. The center section of the brake pedal is too thin to place the strain gauge on the narrow end, however right up against the edge on either side will do just fine given the deflection mode and magnitude likely to be seen. The second strain gauge should be place just behind the front contact plate at approximately half way up the pedal.

With these two strain gauges in place it is important to take readings. Because these are not critical readings, and will have little impact beyond the scope of this report, the two strain gauges on the brake pedal will only be plugged into the Motec data acquisition unit (DAQ) during this static testing. The other sensors, which should be included in the DAQ for this test, are the brake line pressure sensors. Between the two sensors a graph of brake line pressure can be compared with stress in the brake pedal at each point. The pressure sensors can then be back calculated to input force if it is so desired.

To run the test, place a driver in the car, and turn on the DAQ. With the car sitting statically in the garage, have the driver apply force to the brake pedal. Have them start as lightly as possible and very slowly add force. Continue to increase the force upon the brake pedal until a near maximum applicable force is attained. The system is design to take 2000 N of force, and a typical application is between 250-450 N. Therefore, apply considerable force. Then slowly release the pressure. Repeat this three times to get a series of data points which can be compared and averaged. Graph the brake line pressures versus stress at each point. Compare this data to that of the FEA performed for the brake pedal. It is not important that the data be exactly the same. It is more important to see what the difference is, and to judge how they differ and explain why they are different.

Without doing the strain gauge test it is still possible to discuss how it is likely to be different between FEA and reality. The biggest reason there is going to be a slight difference is because of how the model was constrained for the FEA. In the model constraints must be main upon each part. These constraints are simulated and do not always ideally replicate real life. During one analysis run the lower pivot was clamped and the point for the spherical bearing was held from rotating. An input force was applied at the top of the brake pedal and the results showed far greater stress at the base of the pedal due to how the lower pivot was constrained. A better analysis took hand-calculated values and applied forces and directions at the base, foot contact point, and spherical bearing. These yielded consistent values, which made sense.

7. Conclusion & Recommendations

7.1 Conclusion

One of the best learning opportunities about Global Formula Racing (GFR) is that it is an international collaboration. GFR is set up like a business, run by managers, with a boss, and clients. GFR is also like a research firm, with donations from companies who want to see the product do well, financial backers and investors. Through this students are able to get work experience that is very similar to what is expected in the workforce.

Collaborative work across the world is something that very few people have the opportunity to do while in college. GFR is partnered with a school in Germany and together two cars are built, one with a combustion power train and one with an electric drive. Due to the eight-hour time difference, many issues take a few days to resolve through email. Video calls through Skype can expedite this, however, there is still difficulty scheduling meetings, as well as communicating in person. The German students speak very good English, but it can sometimes take a little longer.

The brake and pedal assemblies offered a large variety of design challenges with numerous variability for each component. For anyone interested in ergonomics and human interaction, this is a fantastic project. The first challenge of this project was simply choosing which project to tackle, because the brake and pedal assemblies are each a project unto themselves. The choice of the pedal assembly was made because it offered more design work and had the opportunity to lose more weight off the car.

Weight reduction one of the way in which we can make the car faster. As a team, we are trying to win competitions. We do this by having the fastest car with the best handling, and the best team to bring together a great presentation for both design and business. When all the team members know a lot about every system of the car, it shows well. And when we top this off with winning performances in competition it proves that as a team we did well.

While some things could be done better and could benefit from a longer project period, the following image (Figure 77) very nicely sums up the effort put into this year's Formula Student racecar.

Season 2014

Events	cCar
FSAE Michigan	**1st overall** 1st Autocross 1st Skidpad 1st Endurance 17th Acceleration 4th Engineering Design

Figure 77. Results from FSAE Michigan for GFR

7.2 Recommendations

To start I will discuss the items that I would change and why. First, the idea of making the balance bar in-house is fantastic, however, using a spherical bearing as the main pivot is not the optimal choice. A spherical offers rotation in all three axes while the balance bar should only operate in line with the vertical master cylinders. There are several ways to correct this; a needle bearing could be used for example.

Also for the brake pedal, a rounded pad for foot contact was added after design. This pad was made from plastic and covered in grip tape. This part should be modeled properly next year, as well as considered for 3D printing.

For the throttle, I would change the springs from extension springs to torsion springs. It will make the base slightly wider, but operationally they are more secure, and would be integrated more seamlessly.

The pedal base has a few little idiosyncrasies; first, it was originally designed to be machined from a single block of 4130. Instead the base plate, and each spline were plasma cut and welded into place. Welding the pieces together makes a lot of sense given the volume of empty space between splines, which must be removed via hours of machining. The disadvantage to welding is the quality of the part. When the two pedal bases came back from Silver Eagle, they were warped and not perfectly square. It took several hours of carefully beating the metal straight again. Also, the base plate was undersized by 2 mm. This should not have been an issue, but the mounting pegs require a hole be drilled into the base at the two front corners exactly 55 mm apart, and the clearance between the part edges and the holes was then less than 1 mm. While this was able to work, I would advise a different method for placing the mounting pegs. My first option would be to use an entire hex-head bolt and place it through the base top to bottom and weld the head in place. To do this the base would need to be extended in a couple places.

One last design change that occurred from last year to this year is the spacing of the master cylinders. I made the brake pedal narrower than last year, as a result, the pedal base narrowed, moving the master cylinders close together. This does not affect performance, but does limit adjustability. Therefore I would design the brake pedal/pedal base in such a way that the spacing is widened, allowing better adjustability for the master cylinders.

Overall I was pleased with how the single integrated base simplified the pedal assembly. I think improvements could yet be achieved and innovative new ideas implemented.

The brake pedal should also be taller and designed with a rounded contact point for the foot. Since the part is already being made on the CNC end mill, it would not be difficult to include this rounded face. It should be taller by about 1.5 inches. This is because this pedal was designed to have a plastic rounded contact point added onto the pedal, which extends 1 inch above the top of the existing aluminum pedal. The part would look cleaner and would be stronger with an all aluminum contact point created with the same rounded contact area. This should then be covered with grip tape, like that used on skateboards.

For the eCar base, I think it would be worthwhile to create a second base design, one that integrates the TPS (throttle position sensor) mount into the base as a whole, rather than weld one into place later. The advantages I see would yield better aligned holes for TPS rotation, less welding time, and simplicity. To do this will require a little more modeling time, and more drawing and dxf files, but this seems worth the gain.

Something that I did calculate and model yet would redo is the movement of the throttle cable. As the throttle pedal moves it pulls more cable, and as it does this the angle of incidence between the cable mounting point to pedal changes. To compensate for this, I placed the cable attachment point so it was at approximately mid-angle. This causes the least cable rub and will last the longest.

As far as senior projects go, SAE is by far the most beneficial toward workplace learning experience. The dynamic work environment and team structure parallel real-world work environments. This gives students with little or no engineering work experience a feel for how work after college will be done. At the very start of this project each student is given a project description with a few ideas of what should be designed, the rest is left up to the engineer. In the workforce this is how a new product will be designed; the process will be similar to: design requirements to sketches to decision matrix to CAD models to final design to design revisions to completed physical product. In some cases a prototype will be created, followed by testing and then a final product.

7.3 Future Student Advice

Future Student advice

Aside from those ideas stated above, I would advise that you take the time to learn CATiA quickly and early (if you have never used it before). It is similar to any other CAD program, yet because all the drawing and extrusion buttons are in different locations and look different; it takes quite a long time to get used to using the system. Long hours early on learning CAD and planning exactly what design is in mind will greatly assist how quickly and easily modeling will go.

During the design consideration phase, make sure to think about how this will be manufactured. It is very easy to design something that will be extremely difficult to make. Sometimes the difficulty will not be in the machine passes but in fixturing the stock. All machined parts will have to be fixtures. It is not required that the design be based upon available fixtures, but some form of simplicity in fixture and simplicity in design should be reached.

Something that I did, and suggest you do is to create a single point in the model, which is offset directly from the car origin. Then use this point as an origin upon which all of your other points is based. This will allow you to move that single point, update the model, and have the entire assembly move as one.

The pedal assembly and brake assembly are given as one project; these are really two separate projects of which you will have only enough time to redesign one. So chose the one you wish to work on and then find someone to help you with the other. Nathan Cheung was instrumental in helping me coordinate all the components for the brakes. It is still the your project so delegate and then make sure it is getting done.

Manufacturing is where all your hard work in design becomes real. Towards week 9-10 of fall term start looking for and finding manufacturing sponsors. Look through the sponsor vendor document in the team Google drive and find one that no one is using, or see if one of the already confirmed sponsors has room for your parts. Remember, the more you have outsourced, the less that you will have to make yourself. If you start early and know by finals week where each of your parts will be made, it will make the manufacturing term far smoother.

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9. Appendix

All equations are valid, however numbers should be double checked before using. Check for consistency in units and correctness in values.

9.1 Matlab and EES Codes

9.1.1 Heel Rest Calculation EES code

```
"Heel Rest Calc"
"Material Properties"
"sigma_yield = 700*10^6          [Pa]"
E = 180*10^9

"Set Variables (pick one)"
"Weight = 0.3"
"r_o = 0.02       [m]"
"r_i = 0.018      [m]"
t_inch = 0.028
"t = 0.0027       [m]"
D_in = 8/8
r_o_inch = D_in/2

M = F_ap*d
c = r_o
sigma_allow = M*c/I
F_ap = 900        [N]
d = 0.13          [m]
sigma_allow = sigma_yield/FS
FS = 2
t = r_o - r_i
t_inch*25.4/1000 = t
r_o_inch*25.4/1000 = r_o

A/pi = r_o^2 - r_i^2
tau = 4*V/(3*A)
V = F_ap
Vol = A*W
W = 220*10^(-3)          [m]
Weight = rho*Vol
Weight_lbs = Weight*2.20462    [lbs]
rho = 7850        [kg/m^3]

I = (pi/4)*(r_o^4 - r_i^4)
deflection_mm = F_ap*d^3/(E*I)*1000
```

9.1.2 Throttle Upright arm EES sizing code

```
"Steel Throttle Upright"
"Material Properties"
FS = 2
"sigma_yield = 700*10^6      [Pa]"
E = 205*10^9 [Pa]

"Set Variables (pick one)"
"Weight = 0.3"
"r_o = 0.02      [m]"
"r_i = 0.018     [m]"
t_inch = 0.086
"t = 0.0027      [m]"
D_in = .625
r_o_inch = D_in/2
r_o_inch*25.4/1000 = r_o

M = F_ap*d
c = r_o
sigma_allow = M*c/I
I = (pi/4)*(r_o^4 - r_i^4)
F_ap = 600       [N]
d = 0.192        [m]
sigma_allow = sigma_yield/FS
t = r_o - r_i
t_inch*25.4/1000 = t

deflection_mm = F_ap*d^3/(3*E*I)*1000

A/pi = r_o^2 - r_i^2

tau = 4*V/(3*A)
V = F_ap

Vol = A*W
W = 192*10^(-3)       [m]
Weight = rho*Vol
Weight_lbs = Weight*2.20462          [lbs]
rho = 7850      [kg/m^3]
```

9.1.3 Brake Calculation Matlab

```
clc; close all;
% Brake Calculations
%% Knowns (input values here)
M_v = 241.8182;             % Mass of Vehicle and Driver (kg)
WB = 1575;                  % Wheelbase length (mm)
h_cg = 280;                 % Height of center of gravity (mm)
A_mc = [197.83, 248.16];    % Bore area front master cylinder [front, rear] (mm^2)
A_cal = [907.46, 1010];     % Bore area of caliper piston [front, rear]
mu_pad = [.45, .40];        % coefficient of friction caliper/rotor [front, rear]
R_eff = [64.87, 64.87];     % Effective radius for caliper [front, rear]
R_tire = 457;               % Tire radius
V = 60;                     % Vehicle Velocity upon braking (kph)
V_mph = V*0.621371;         % Vehicle Velocity upon braking (mph)
CG_x = [670, 905];          % Distance from axle to CG [front, rear] (mm)
mu_tire = .8;               % coefficient of friction between tire and road
x = 10;
%F_bp = 50:x:2000;          % Force input on Brake Pedal (N)
F_bp = 180;
F_bp_lbf = F_bp*.224808943;
n = length(F_bp);
g = 9.81;
MCR = 5;                    % Master Cylinder Brake Force Ratio

%% Brake force

P_mc = F_bp.*MCR./A_mc;           % Front Master Cylinder Pressure
P_cal = P_mc;                     % Pressure at Caliper same as at MC
F_cal = P_cal.*A_cal;             % Force at the caliper
F_clamp = F_cal*2;                % Clamping force on rotor for 2 piston Caliper
F_friction = F_clamp.*mu_pad;     % Friction force on rotor
T_rotor = F_friction.*R_eff;      % Torque at front rotor
T_tire = T_rotor;                 % Torque of tire same as torque of rotor
F_tire = T_tire./R_tire;          % Force on ground from tire

F_deceleration = F_tire(1)*2+F_tire(2)*2;   %Sum of tire forces (*2 for two front and
two rear tires)

%% Stopping Distance
a_v = F_deceleration/M_v;       % Deceleration m/s
a_g = a_v / g;                  % Deceleration in terms of G
SD = (V/3.6)^2 / (2*a_v);       % Stopping Distance

%% Weight Transfer
WT = (a_g)*(h_cg/WB)*M_v;  % Weight Transfer to front
W = CG_x*M_v/WB;           % Weight on wheels (static) [front, rear]
```

```
W_f_d = W(1) + WT;              % Dynamic Weight due to weight transfer front
W_r_d = W(2) - WT;              % Dynamic Weight due to weight transfer rear

%% Tire effects from weight transfer
F_Ftires = mu_tire*W_f_d*g;    % Force on Front tires to ground
F_Rtires = mu_tire*W_r_d*g;    % Force on Front tires to ground

F_deceleration2 = F_Ftires+F_Rtires;
a_v2 = F_deceleration2/M_v;       % Deceleration m/s
a_g2 = a_v2 / g;                % Deceleration in terms of G
SD2 = (V/3.6)^2 / (2*a_v2);       % Stopping Distance

fprintf('Velocity upon Brake initiation (kph) %.2f\n',V)
fprintf('Velocity upon Brake initiation (mph) %.2f\n',V_mph)
fprintf('Driver input braking force (N) %.2f\n',F_bp)
fprintf('Driver input braking force (lbf) %.2f\n',F_bp_lbf)
fprintf('Deceleration (m/s^2) %.2f\n',a_v)
fprintf('Deceleration (g) %.2f\n',a_g)
fprintf('Force of Deceleration (N) %.2f\n',F_deceleration)
fprintf('Stopping Distance (m) %.2f\n',SD)
fprintf('Weight Transfer to Front Wheels (kg) %.2f\n',WT)
fprintf('Dynamic Weight on Front Wheels (kg) %.2f\n',W_f_d)
fprintf('Dynamic Weight on Rear Wheels (kg) %.2f\n',W_r_d)
fprintf('Force Between Front tires and the Ground (N) %.2f\n',F_Ftires)
fprintf('Force Between Rear tires and the Ground (N) %.2f\n',F_Rtires)

fprintf('Deceleration (m/s^2) %.2f\n',a_v2)
fprintf('Deceleration (g) %.2f\n',a_g2)
fprintf('Force of Deceleration (N) %.2f\n',F_deceleration2)
fprintf('Stopping Distance (m) %.2f\n',SD2)
```

9.2 Other Documents

9.2.1 Tilton Price Sheet

TILTON ENGINEERING FSAE PRICE LISTEFFECTIVE: NOVEMBER 7, 2011

PART NUMBER	DESCRIPTION	RETAIL	FSAE
72-XXX	**Balance Bars and Adjusters**		
72-250	Balance Bar Assembly, 3/8" - 24, 2.5" center-to-center	60.00	43.50
72-260	Balance Bar Assembly, 7/16" - 20, 2.625" center-to-center	60.00	43.50
72-280	Balance Bar Assembly, for 72-901 and 72-902	625.00	453.13
72-408	Remote brake bias adjuster, billet, for 3/8", 7/16" & 1/2" shafts	195.00	141.38
72-504	Remote brake bias adjuster, standard model, for 1/2" - 20 shaft	70.00	50.75
72-507	Remote brake bias adjuster, standard model, for 3/8" - 24 and 7/16" - 20 shaft	70.00	50.75
72-560	90 degree balance bar remote cable coupling, 3/8"	95.00	68.88
72-561	90 degree balance bar remote cable coupling, 7/16"	95.00	68.88
73-XXX	**73-Series Integral Reservoir Master Cylinders**		
73-750	3/4" master cylinder	55.00	39.88
73-875	7/8" master cylinder	55.00	39.88
73-1000	1" master cylinder	55.00	39.88
74-XXXX	**74-Series Universal Master Cylinders**		
74-625U	5/8" master cylinder kit (remote kit, small and large reservoirs)	85.00	61.63
74-700U	7/10" master cylinder kit (remote kit, small and large reservoirs)	95.00	68.88
74-750U	3/4" master cylinder kit (remote kit, small and large reservoirs)	85.00	61.63
74-812U	13/16" master cylinder kit (remote kit, small and large reservoirs)	95.00	68.88
74-875U	7/8" master cylinder kit (remote kit, small and large reservoirs)	85.00	61.63
74-1000U	1" master cylinder kit (remote kit, small and large reservoirs)	85.00	61.63
74-1125U	1-1/8" master cylinder kit (remote kit, small and large reservoirs)	85.00	61.63
75-XXXX	**75-Series Compact Universal Master Cylinders**		
75-625U	5/8" master cylinder kit (remote kit, small and large reservoirs)	105.00	76.13
75-700U	7/10" master cylinder kit (remote kit, small and large reservoirs)	115.00	83.38
75-750U	3/4" master cylinder kit (remote kit, small and large reservoirs)	105.00	76.13
75-812U	13/16" master cylinder kit (remote kit, small and large reservoirs)	115.00	83.38
75-875U	7/8" master cylinder kit (remote kit, small and large reservoirs)	105.00	76.13
75-937U	15/16" master cylinder kit (remote kit, small and large reservoirs)	115.00	83.38
75-1000U	1" master cylinder kit (remote kit, small and large reservoirs)	105.00	76.13
76-XXX	**76-Series Compact Master Cylinders**		
76-625	5/8" master cylinder	125.00	90.63
76-700	7/10" master cylinder	135.00	97.88
76-750	3/4" master cylinder	125.00	90.63
76-812	13/16" master cylinder	135.00	97.88
76-875	7/8" master cylinder	125.00	90.63
76-937	15/16" master cylinder	135.00	97.88
76-1000	1" master cylinder	125.00	90.63
77-XXX	**77-Series Pivot Mount Master Cylinders**		
77-625	5/8" master cylinder	395.00	286.38
77-700	7/10" master cylinder	395.00	286.38
77-750	3/4" master cylinder	395.00	286.38
77-812	13/16" master cylinder	395.00	286.38
77-875	7/8" master cylinder	395.00	286.38
77-937	15/16" master cylinder	395.00	286.38
77-1000	1" master cylinder	395.00	286.38
74,75,76,77-XXX	**Master Cylinder Parts & Accessories**		
74-200	Fitting, remote inlet, plastic	4.00	2.90
74-202	Master Cylinder Reservoir, small (4 oz)	8.00	5.80
74-203	Master Cylinder Reservoir, medium (6.8 oz)	8.00	5.80
74-204	Master Cylinder Reservoir, large (10.7 oz)	8.00	5.80

TILTON ENGINEERING FSAE PRICE LISTEFFECTIVE: NOVEMBER 7, 2011

74-206	Master Cylinder Reservoir Cap	5.00	3.63
74-207	Master Cylinder Reservoir Cap with baffle and seal	6.00	4.35
74-208	Master Cylinder Clamp, for reservoir and remote	2.00	1.45
74-210	Master Cylinder Reservoir Filter, for small reservoir	4.50	3.26
74-211	Master Cylinder Reservoir Filter, for large reservoir	4.50	3.26
74-212	Remote Reservoir Adapter	9.00	6.53
74-212-A	O-ring, master cylinder to reservoir, 75 series	1.50	1.09
74-212-B	O-ring, master cylinder to reservoir, 74 series	1.50	1.09
74-214	Master Cylinder Remote Hose, 30" long	5.00	3.63
74-216	Remote reservoir adapter with AN4 fitting	34.00	24.65
74-400	Master Cylinder Pushrod	8.00	5.80
74-XXXRK	Rebuild Kit, for 74 series master cylinder, specify size	25.00	18.13
75-XXXRK	Rebuild Kit, for 75 series master cylinder, specify size	25.00	18.13
75-010	Return Spring, for 75, 76 or 77 series master cylinder	4.00	2.90
75-020	Spring Guide Pin, for 75, 76 or 77 series master cylinder	5.00	3.63
75-030	Push Rod, for 75 or 76 series master cylinder	8.00	5.80
75-060	Pressure Seal Shim, for 77-625	1.50	1.09
75-061	Pressure Seal Shim, for 77-700	1.50	1.09
75-062	Pressure Seal Shim, for 77-750	1.50	1.09
75-063	Pressure Seal Shim, for 77-812	1.50	1.09
75-064	Pressure Seal Shim, for 77-875	1.50	1.09
75-065	Pressure Seal Shim, for 77-937	1.50	1.09
75-066	Pressure Seal Shim, for 77-1000	1.50	1.09
75-310	Pressure Seal, for 77-625	6.00	4.35
75-311	Pressure Seal, for 77-700	6.00	4.35
75-312	Pressure Seal, for 77-750	6.00	4.35
75-313	Pressure Seal, for 77-812	6.00	4.35
75-314	Pressure Seal, for 77-875	6.00	4.35
75-315	Pressure Seal, for 77-937	6.00	4.35
75-316	Pressure Seal, for 77-1000	6.00	4.35
76-XXXRK	Rebuild Kit, for 76 series master cylinder, specify size	25.00	18.13
77-412-20-5	Shim Kit, for 5/8", 7/10" or 3/4" bore 77 series cylinder, .020" thk	20.00	14.50
77-412-30-5	Shim Kit, for 5/8", 7/10" or 3/4" bore 77 series cylinder, .030" thk	20.00	14.50
77-412-40-5	Shim Kit, for 5/8", 7/10" or 3/4" bore 77 series cylinder, .040" thk	20.00	14.50
77-412-50-5	Shim Kit, for 5/8", 7/10" or 3/4" bore 77 series cylinder, .050" thk	20.00	14.50
77-412-60-5	Shim Kit, for 5/8", 7/10" or 3/4" bore 77 series cylinder, .060" thk	20.00	14.50
77-414-20-5	Shim Kit, for 13/16" or 7/8" bore 77 series cylinder, .020" thick	20.00	14.50
77-414-30-5	Shim Kit, for 13/16" or 7/8" bore 77 series cylinder, .030" thick	20.00	14.50
77-414-40-5	Shim Kit, for 13/16" or 7/8" bore 77 series cylinder, .040" thick	20.00	14.50
77-414-50-5	Shim Kit, for 13/16" or 7/8" bore 77 series cylinder, .050" thick	20.00	14.50
77-414-60-5	Shim Kit, for 13/16" or 7/8" bore 77 series cylinder, .060" thick	20.00	14.50
77-416-20-5	Shim Kit, for 15/16" or 1" bore 77 series cylinder, .020" thick	20.00	14.50
77-416-30-5	Shim Kit, for 15/16" or 1" bore 77 series cylinder, .030" thick	20.00	14.50
77-416-40-5	Shim Kit, for 15/16" or 1" bore 77 series cylinder, .040" thick	20.00	14.50
77-416-50-5	Shim Kit, for 15/16" or 1" bore 77 series cylinder, .050" thick	20.00	14.50
77-416-60-5	Shim Kit, for 15/16" or 1" bore 77 series cylinder, .060" thick	20.00	14.50
77-015	Inlet fitting, AN4, for 77 series master cylinder	15.00	10.88
COM-5	Spherical pivot bearing, for 77 series master cylinder	17.00	12.33
90-1000	Lever-type prop valve, 7 Setting, AN3 & 3/16 inverted flare	109.00	79.03
90-1003	Lever-type prop valve, 7 Setting, 10mm X 1mm port threads	109.00	79.03
90-1100	Prop Valve Repair Kit For 90-1000, 90-1003, 90-2001 & 90-2003	20.00	14.50
90-2000	Screw-type prop valve, AN3 & 3/16 inverted flare	109.00	79.03
90-2003	Screw-type prop valve, 10mm X 1mm port threads	109.00	79.03

9.2.2 EMJ Price Quote

16440 NE MASON ST
ATTN:
PORTLAND OR 97230

DATE: 12/6/2013
CUSTOMER NUMBER: 280303
QUOTE NUMBER: 379476
FOB: Delivered
CUSTOMER PO#: OSU Beaver Racing

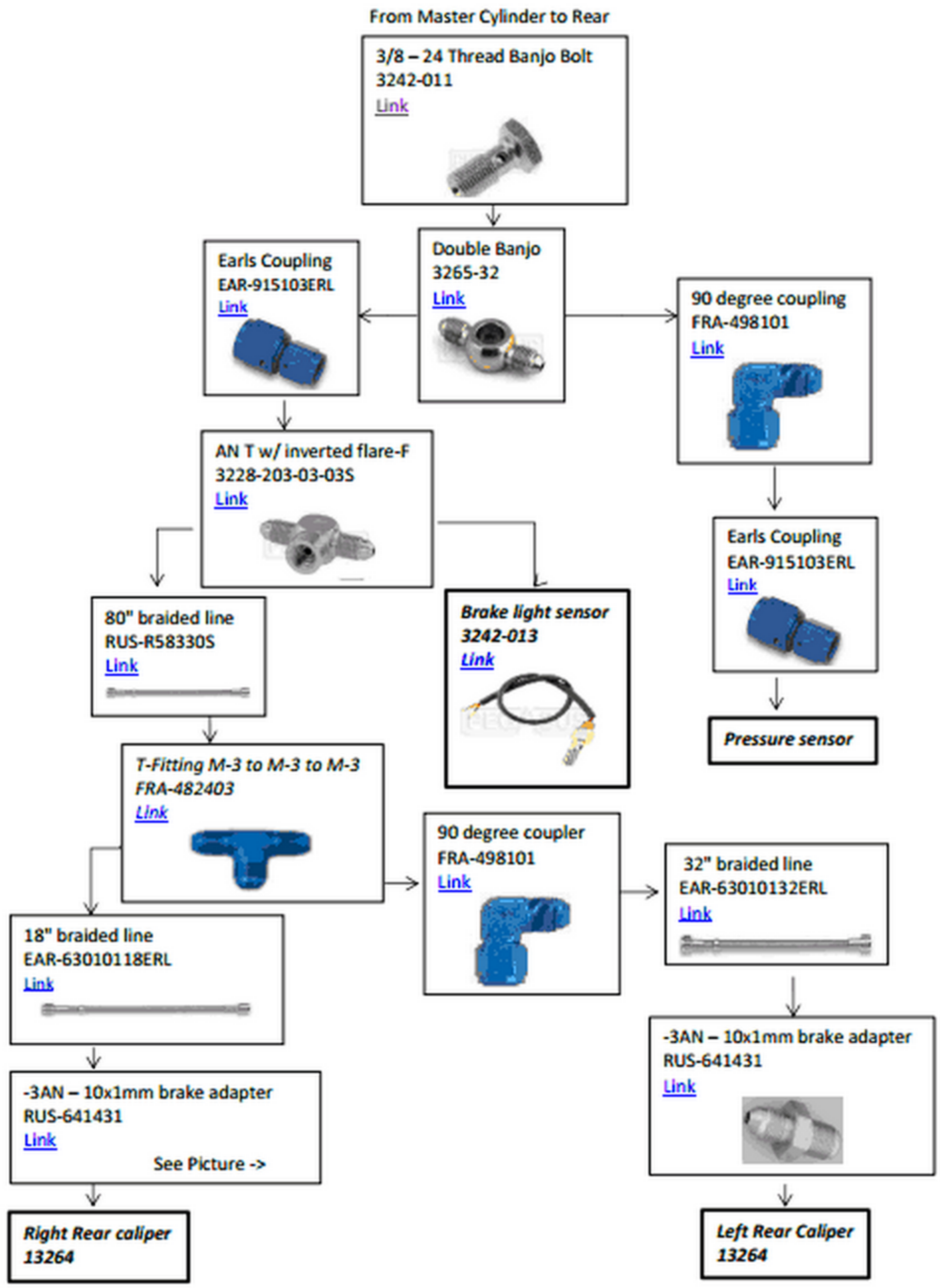
CUSTOMER:
OREGON STATE UNIVERSITY
204 ROGERS HALL
COVALLIS OR 97331
ATTENTION: Colton Swearington
PHONE NO: 503-2069187

SHIP TO:
OREGON STATE UNIVERSITY
SOCIETY OF AUTOMOTIVE ENGINEER
204 ROGERS HALL
COVALLIS OR 97331

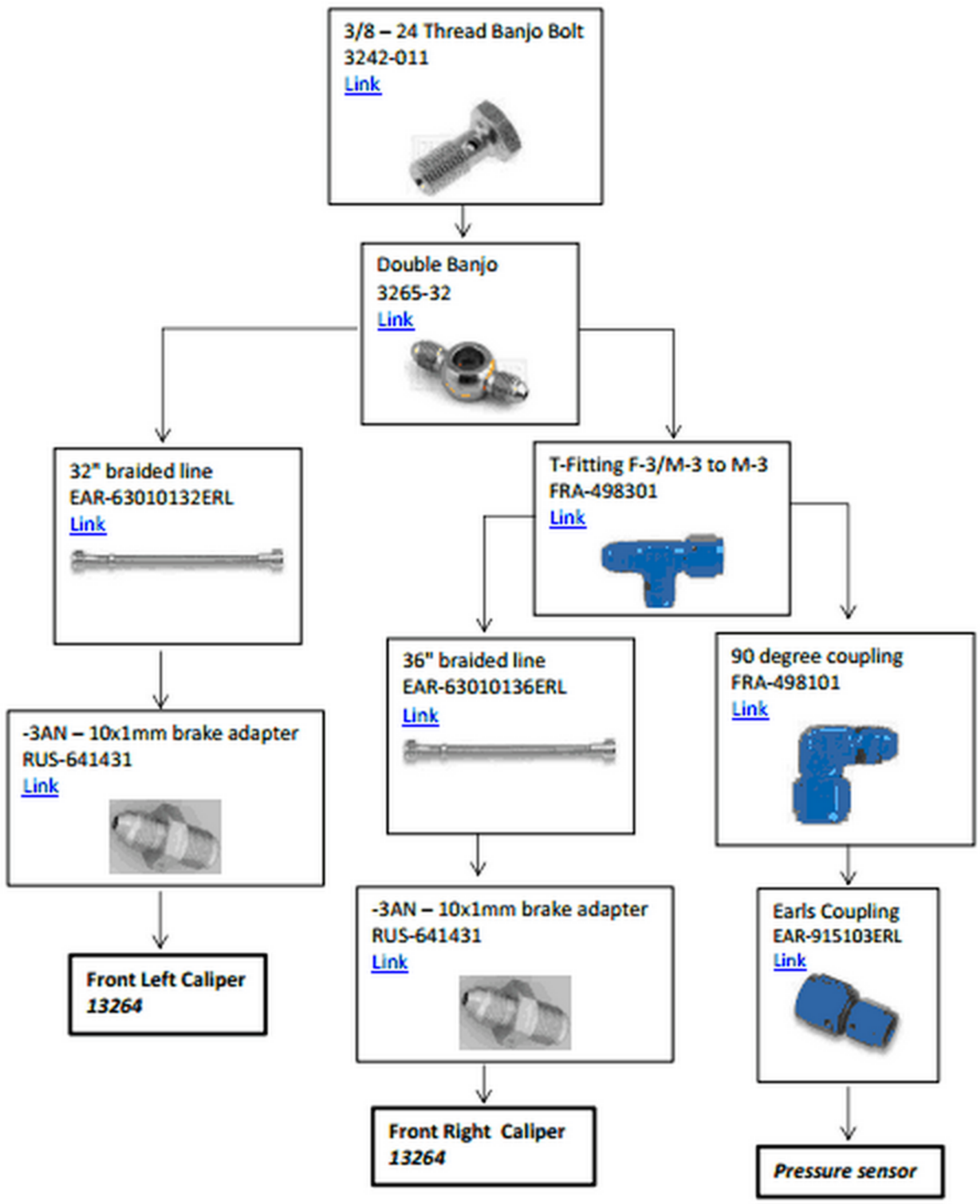
ITEM #	DESCRIPTION	ORDER QTY.	UOM	UNIT PRICE	EXT. PRICE
100074	10 Tubes-200 FT 4130 CDS TUBING AMS T 6736 COND N; .500 OD X .035 W (.430 ID) X 17/24' R/L **SHIP VIA:** OUR TRUCK	200	FT	$0.00	$0.00
	LINE WEIGHT:	35	LB		
100161	5 Tubes-100 FT 4130 CDS TUBING AMS T 6736 COND N; .625 OD X .035 W (.555 ID) X 17/24' R/L **SHIP VIA:** OUR TRUCK	100	FT	$0.00	$0.00
	LINE WEIGHT:	22	LB		
100934	1 Tube-20 FT 4130 CDS TUBING AMS T 6736 COND N; 1.000 OD X .035 W (.930 ID) X 17/24' R/L **SHIP VIA:** OUR TRUCK	20	FT	$0.00	$0.00
	LINE WEIGHT:	7	LB		
501060	10 Bars-134 LB 1018 CF BAR ASTM A108 1/2 RD X 20' R/L **SHIP VIA:** OUR TRUCK	134	LB	$0.00	$0.00
	LINE WEIGHT:	134	LB		
513252	2 Bars-173 LB 7075-T651 CF BAR AMS QQ A 225/9, QQ A 225/9 2-3/4 RD X 12' **SHIP VIA:** OUR TRUCK	173	LB	$0.00	$0.00
	LINE WEIGHT:	173	LB		
101564	4 Tubes-80 FT 1008-1010 CREW TUBING FC .010 ASTM A513/2 1.000 OD X .065 W (.870 ID) X 20' **SHIP VIA:** OUR TRUCK	80	FT	$0.00	$0.00
	LINE WEIGHT:	52	LB		
102858	2 Tubes-40 FT 1008-1010 HREW TUBING FC .010 P&O ASTM A513/1 1.000 OD X .095 W (.810 ID) X 20' **SHIP VIA:** OUR TRUCK	40	FT	$0.00	$0.00
	LINE WEIGHT:	37	LB		

TOTAL WEIGHT: 460 LB
TOTAL: $0.00

9.2.3 Brake Line Flow Chart



From Master Cylinder to Front



Pre- Master Cylinder

Reservoir
3755
Link

↓

Transparent Tubing for Brake Reservoir
7568
Link

↓

4AN Barb to F-4AN
SUM- 220700
Link

↓

Single Banjo
3265-46
Link

↓

9/16- 18 Thread Banjo Bolt
3242-026
Link

↓

Master Cylinder