Spring 2020

Senior Design Proposal for Brakes Subsystem 2019-2020

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FSAE Zips Electric Racing Brake System Design

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May 3, 2020, Akron, Ohio
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Abstract

This project is being done to assist the Zips Formula Electric Race Team in constructing a functional race car to FSAE specifications. Our group has the background knowledge in this field along with knowledge in supporting fields to make this project happen. We also have members of our design group that have had affiliations with students on the design team. These combined attributes make this senior design choice a logical, yet challenging one for our group.

The design for this project is based around optimizing the brakes subsystem for the 2019-2020 Formula Student Electric car. This subsystem is important for the car because a well optimized braking system will help the car keep its competitive edge. The purpose of this project was to create and implement a braking system that fulfilled performance specifications as determined by the team. Doing this required a number of different tasks to be completed, including a full redesign of the pedal box, new calculations for master cylinders, new layout for brake lines, design and manufacturing of new brake rotors, selection for new brake pads and calipers, and final manufacturing and assembly for all parts stated above.

This project was designed using SolidWorks to create 3D models and perform finite element analysis in order to identify the most efficient design for the pedal box, brake rotors, and brake line layout. This efficiency is based on material usage and weight, with a primary focus on weight reduction. New calculations for the master cylinders were performed using equations found in our cited sources. The design was to be evaluated on a variety of primary criteria such as the percent weight reduced from the previous year’s design, whether or not the car stops, and how well the car performs against the aforementioned team specified criteria, all while meeting the teams budget. Unfortunately, the physical testing of the car was not able to be done, hence why evaluation was not fully completed.

Having a poorly designed braking system could induce negative consequences such as poor performance attributes, like handling and balance of the car; increased costs due to frequently replacing worn parts; and increased weight of over designed components. In the design stage, finite element analysis programs were used to optimize the weight of the components while still meeting design requirements. Specific calculations were used to determine sizing of these various components. Throughout the year, this project required coordination with other subsystems to make sure our system worked within the overall design of the car.

Acknowledgement

Acknowledgement must be given to a couple of people, first and foremost, the project advisor Dr. Deckler. He has been a big help to both the Zips Electric Racing team as well as the brakes subsystem. From assisting in ordering calipers to providing helpful suggestions and feedback, he has been a pertinent part of this design project. In addition to Dr. Deckler, Dr. Shao Wang has also put in effort that must not go unnoticed. He took the time to coordinate with students in both Honors and non-honors, providing different opportunities for senior design, and keeping the class updated with requirements. His time is very much appreciated. Dr. Sawyer and Dr. Gopal have also assisted with senior design projects in any way they can. For this, we would like to acknowledge their time and dedication as well.

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Introduction

Background

The braking system on an automobile is designed to slow the car down. In a racing application such as this, the brake's main job is to stop the car as quickly and efficiently as possible while minimizing weight. For this project, the application is a student built race car designed to compete in the Formula SAE series (FSAE). This series is an International Collegiate Design Series that brings together universities from around the world to compete. The University of Akron has submitted a car for the 2020 competition model designated ZR20e, which is the car that this braking system was designed for.

This car is unique not because of the specs, but because of what it runs on: a battery. Electricity powers the entire vehicle, differentiating it from other FSAE competition cars. This difference affects various factors of the car, such as the materials needed for manufacturing, the overall weight, and many of the components. Looking at the braking system, not much is affected by the fact that the car runs on electricity. Since the purpose of brakes is to lose energy, the braking system does not rely on an energy source, allowing its components to be designed independent of the battery. However, the throttle pedal is a crucial part of the pedal box, which was a piece of this project. Accelerating the car does require energy, which affects the way it is designed. This throttle pedal was designed with two linear sensors that tell the engine control unit how much power is needed at the wheels.

Literature Search

Information on this topic involved usings both school and online resources. School resources involved speaking with our advisor and with the Science and Technology library on various texts and information that was on hand with relation to this topic. Online resources involved websites like OhioLink, Google Scholar, and Tilton Engineering's website that provided useful information on how braking systems are developed.

The first piece of literature found and the most used was a vehicle dynamics textbook written by Dr. Richard Gross here at the University of Akron. This book breaks down calculations from every aspect of a vehicle, from engine to frame to suspension. Chapter nine of this textbook details how to develop a braking system. The chapter mainly focuses on a vehicle with a disc braking system and a car without the effects of automotive aerodynamics. The chapter then goes into determining what kind of braking set up is optimal for the car and which equations will be used.

The second main piece of literature used for this project was the Formula SAE Rules and Regulations for competition year 2020. This guidebook specified what could and could not be used on this system per SAE specifications. Items like material choices, size restrictions, and various safety features required are all in this rulebook. To make a system that is eligible to compete, every rule, including those not listed specifically in the brakes section, has to be met. In that regard, this rulebook was invaluable.

Shigley's Mechanical Engineering Design: Tenth edition was also a text used for this project. Various calculations such as bolt strength, pin shear strength, and thread strengths were all derived from this textbook. This worked well alongside the 27th edition of The Machinery Handbook, which gave good starting points for material selection and bolt choices. As for the rest of these texts, such as the Formula SAE Tire Test Consortium, the Race Car Vehicle Dynamics Pacejka, Hans B. Tyre and Vehicle Dynamics: Tune to Win, these texts were used more for reference on both braking design and various data points needed to complete this project.

Principles of Operation

The main operation of a braking system like this is to stop a vehicle. Depending on its design and complexity, a vehicle's brakes generally take the motion energy of the car and turn it into heat and noise. The heat generated in a braking system is from the braking material coming in contact with the spinning piece attached to the axle. In a racing application such as this, a brake pad will come in contact with a spinning disk that is attached to the axle. This friction between the pad and the rotor can generate significant amounts of heat energy, in some cases to the point of brake fade and ignition of the brake pad material.

The brakes are actuated by the driver when the vehicle needs to come to a stop. Most modern day braking systems are actuated by a pedal on the floor. By depressing the pedal, the brakes are actuated and the vehicle is brought to a stop. In modern day vehicles this force is transferred from the pedal to the braking components by means of an incompressible fluid. Specially designed brake fluid is able to transfer the force of the brake pedal to the brake pads while maintaining head resistance needed to withstand the heat generated by friction. This fluid is pushed with a device known as a master cylinder that pushes the fluid throughout the system.

The throttle pedal is what connects the driver to the drivetrain and allows the driver to determine how much power is needed. The throttle pedal can use a direct connection such as a cable directly linked to the engine, or it can use a sensor to determine throttle position and relate that to how much power is needed by the drivetrain. This combined with the brake pedal creates what is known as a pedal box. This pedal box is an adjustable platform for the brake and throttle pedals to mount to and be easily accessible to the driver.

Product Definition

The system designed this year is an improvement over any system that came before it on the Zips Electric Car. The braking system was designed specifically for this car, with factors such as vehicle weight, center of gravity, wheelbase and tires making an impact on the design of the system specific to this car. There are also stringent rules set by FSAE that all aspects of this system must meet to be able to compete in any FSAE sanctioned competition. Based on various literature and source data, a braking system was designed and met all requirements set by both FSAE and the design team.

Conceptual Design

Expanded Design Brief

The brake system was required to be as light as possible, as cost-effective as possible, and packaged as small as possible when compared to previous years' designs, as well as meet all FSAE rules and guidelines as necessary. More specifically, to meet FSAE rules, the brake pedal and corresponding packaging were required to be able to withstand 2000 Newtons of compressive force; the braking systems for the front and rear wheels were to be independent; the throttle pedal was to have two independent return springs, with two independent throttle sensors; anything custom made from metal other than the brake rotors was to be made from aluminum, steel, or titanium; and the brake rotors were to be made from aluminum, steel, or cast iron. Additionally, the overall weight of custom components was to be less than 4.34 pounds, as well the total depth and height of the system were each not to exceed 10 inches. These measures were gathered from previous designs as well as from an ergonomics perspective.

Objective Tree

Before any designs were generated, an objective tree was created in order to clearly outline what the goals of the project were, as seen in Figure 1. From the design brief, three main goals arose: for this design to be cost effective, compact, and safe. In order to be cost effective, production and maintenance needed to be simple and effective. This led to the decisions to create as few custom parts as possible, to use 7075 aluminum due to its strong mechanical properties in conjunction with its low cost, and to maximize the usage of standard replaceable parts. In order for this project to be compact, the overall height and depth of the pedal box needed to be minimized. This was accomplished by maintaining low pedal heights and short pedal rails while achieving efficient usage of materials. Finally, in order to achieve a safe system, material strength and redundancies were included within the design process. The minimum acceptable factor of safety used was 1.4, and required redundancies such as duplicate throttle springs, duplicate throttle sensors, and independent brake fluid systems were implemented.

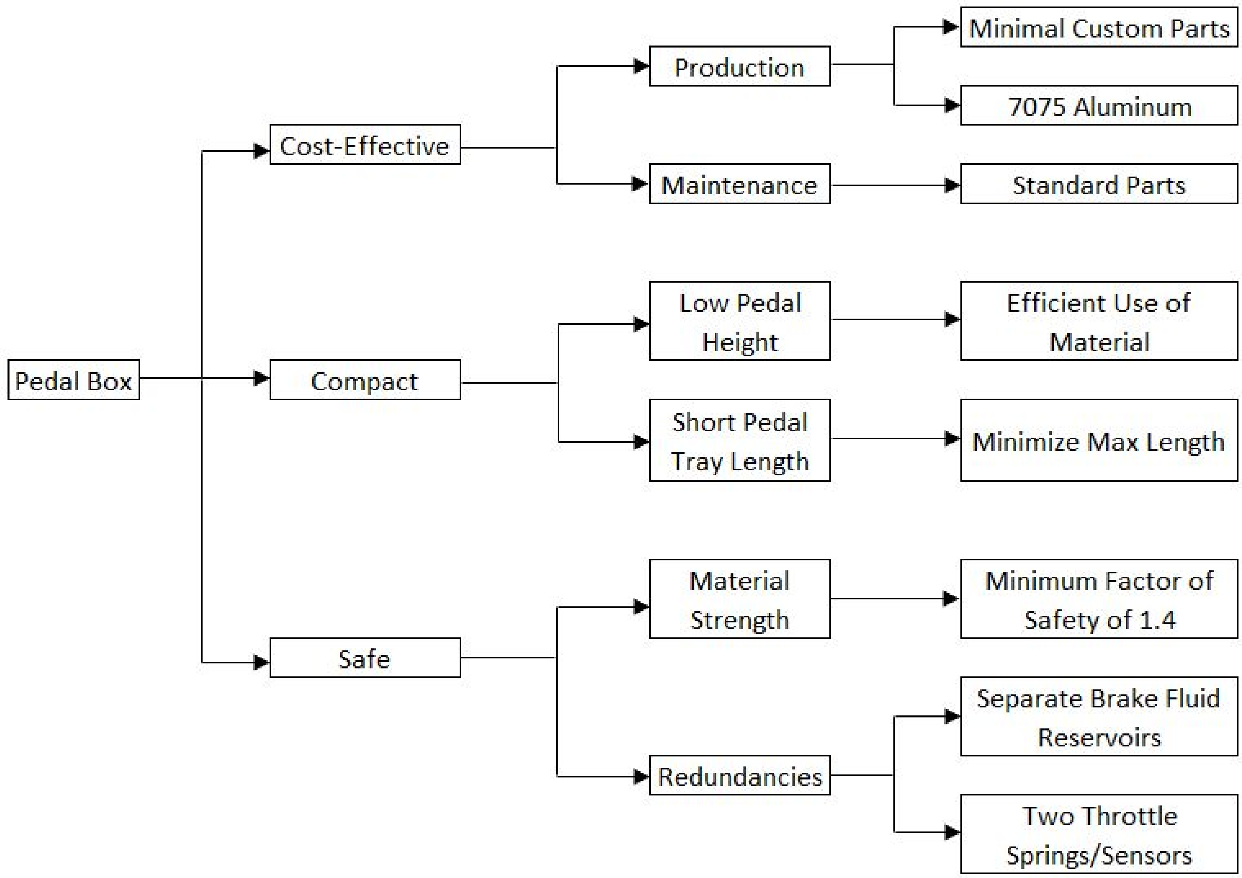

Figure 1: Objective Tree

Function-Structure Diagrams

In order to begin generating ideas for components of this project, an understanding of the overall function for the project must be achieved. To this end, function-structure diagrams were generated, as seen in both Figure 2 and Figure 3. The first function-structure diagram was completed to define the basic material, energy, and information inputs and determine the basic corresponding outputs. The basic material inputs were determined to be the brake and throttle pedal assemblies, with the basic material output being the stopped race car. For energy, the input was found to be the fluid pressure held in the brake lines, while the outputs were determined to be noise and heat generated during the braking process. The information input was entirely due to the driver determining when and how much force would be applied to the pedals, with no informational outputs.

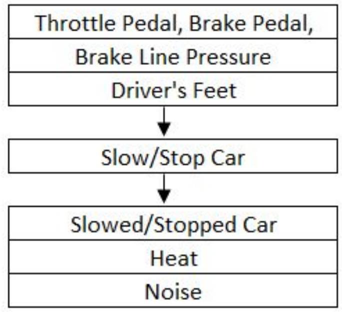

Figure 2: Overall Function-Structure Diagram

From this, a more detailed function-structure diagram was created, as seen in Figure 3. This diagram shows a more complete picture of what happens when the driver determines that applying force to the brake pedal is necessary. When that determination is made, the driver releases the throttle pedal, which in turn stops depressing the throttle sensors. This allows the sensors to return to their neutral position, which ceases the signal from the sensors to the electronic control unit (ECU). This loss of signal stops the flow of energy from the car battery to the drive train, allowing the car to naturally slow to a stop. As the driver releases the throttle pedal, he or she will also depress the brake pedal, which will in turn apply a compressive force to the master cylinders. As the master cylinders compress, they draw more brake fluid from the brake fluid reservoirs, which increases the fluid pressure in the brake lines. This increased pressure transmits the force of the driver on the brake pedal to the calipers, which then proportionally squeeze the brake pads against the brake rotors. The ensuing friction forces the brake rotors to stop rotating, effectively stopping the car's motion. During all of this, the brake lines must be able to store the brake fluid and withstand the pressure spikes due to sudden force applied to the brake pedal in order to effectively transfer the braking force from the driver to the rotors.

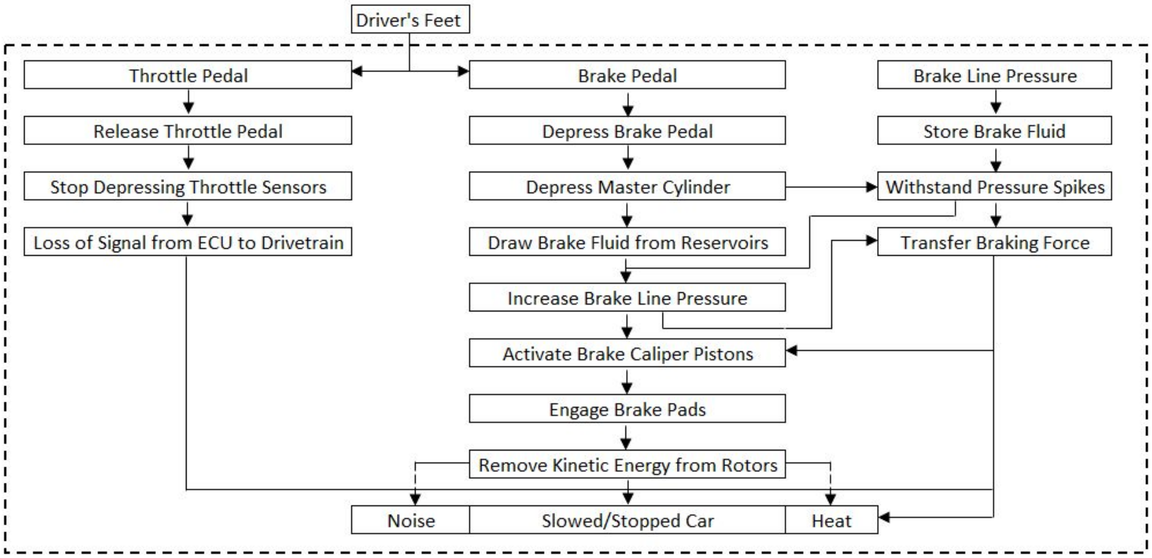

Figure 3: Detailed Function-Structure Diagram

Morphological Chart

Once the function-structure diagrams had been generated, concepts were able to be generated for individual components. Each component was required to fit within the function-structure diagram, meaning no aspect of the component was to go against any point laid out in the function-structure diagram. There are many common concepts across all pedal box designs when it comes to things like pedal shape, pedal tray design, master cylinder orientation, and throttle return springs. A morphological chart was constructed to lay out design options, new concepts, and major component choices, as seen in Figure 4. These included multiple options for components such as the brake pedal, throttle pedal, pedal tray, brake rotor, master cylinder orientation, throttle return springs, and throttle sensors. The brake and throttle pedals shared overall concepts such as whether the pedal spine should be straight or curved, as well as whether the spine should have cut-outs or be one solid piece. The brake rotors had concepts generated based on the size of the interior mounting hole as well as whether to include debris-clearing slots. Pedal tray concepts included one solid pedal tray for both pedals, one tray with cutouts to reduce weight, or two separate trays for independent pedal assemblies. Master cylinder orientation was considered, specifically on whether to have the master cylinder be vertical or horizontal, as well as on which side of the master cylinder should attach to the back of the pedal top. Additionally, the type of throttle return spring was included, with both linear and torsional springs having been considered. Finally, types of throttle sensors were considered, the options being either a short or long linear sensor, or a rotary sensor.

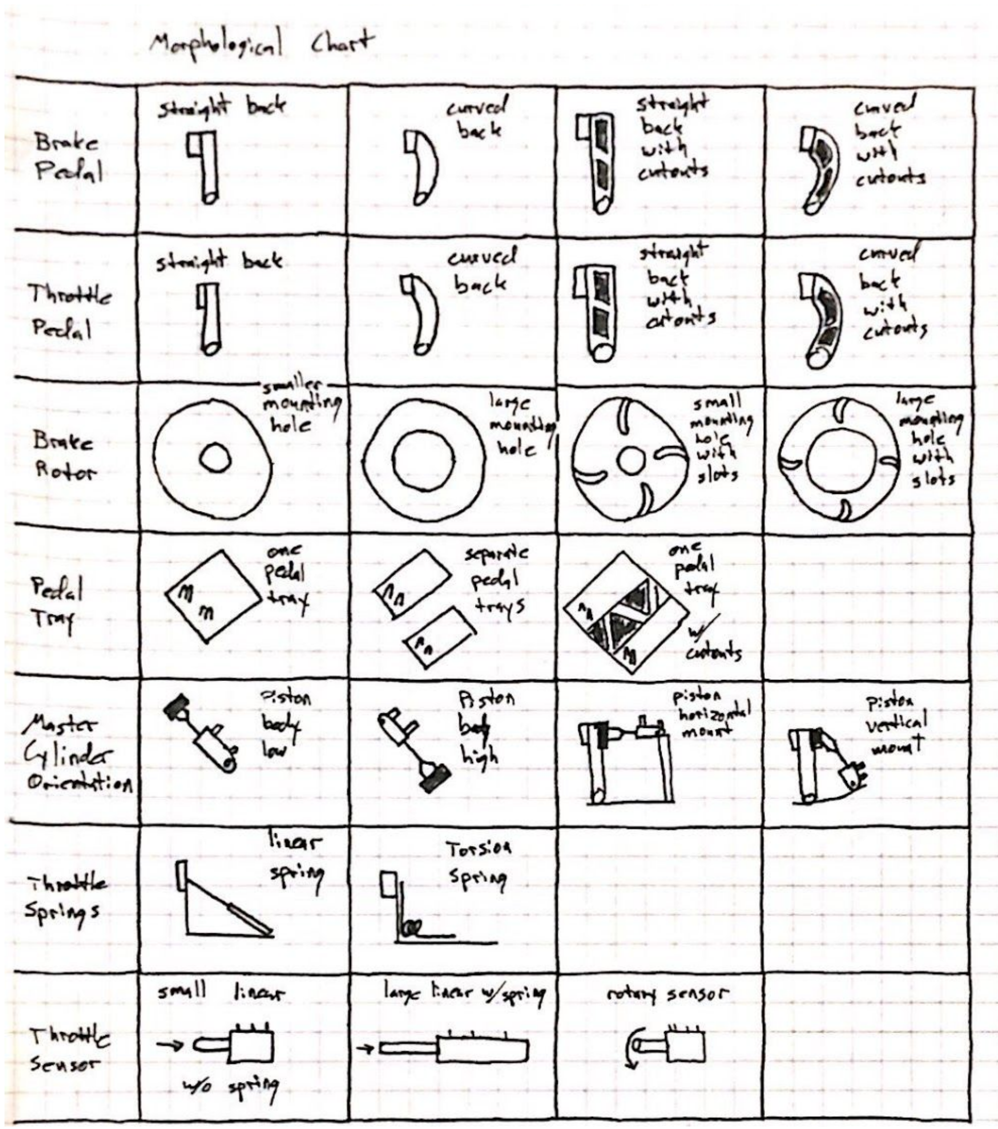

Figure 4: Morphological Chart

Concept Sketches

Once the morphological chart had been generated, sketches were drawn for some of the options. These sketches were not drawn to actual scale, but an attempt to keep components within the same sketch proportional was made. Additionally, sketches were only made for custom manufactured components. A throttle pedal was sketched to be straight-backed with cutouts, including torsional throttle springs and large linear sensors to visualize what that would look like after fabrication, as seen in Figure 5 and Figure 6. A straight-backed design was sketched due to simplicity of drawing, as well as the lack of primary functional difference between curved and straight-backed pedals. Cutouts were selected for this concept sketch due to the reduced weight resulting from less overall mass.

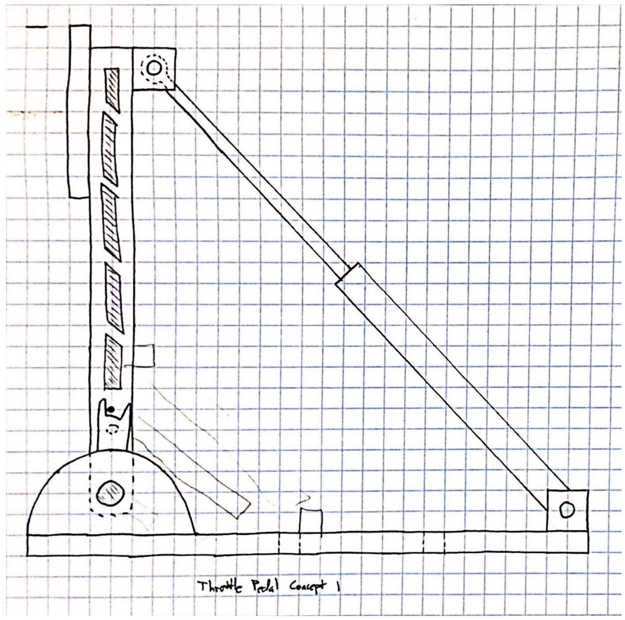

Figure 5: Throttle Pedal Assembly Concept 1 Profile View

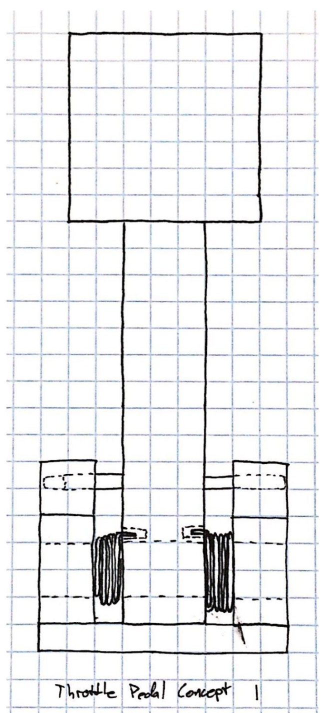

Figure 6: Throttle Pedal Assembly Concept 1 Front View

Two throttle pedal base plate concepts were generated, with Concept 1 designed for torsional springs and short linear sensors, as seen in Figure 7, and Concept 2 for torsional springs and long linear sensors, as seen in Figure 8. Figures 4 and 5 depict an application of Concept 2.

Each concept includes a pin for which to stop forward or backward movement when fixed to the pedal rails. Concept 1 would take up less space than Concept 2, and the central protrusion would be to accommodate the smaller sensors' need to be closer to the pedal. Concept 2 would provide more room for maintenance for the pedal and sensors, as well as be able to provide more mounting points on to the pedal rail.

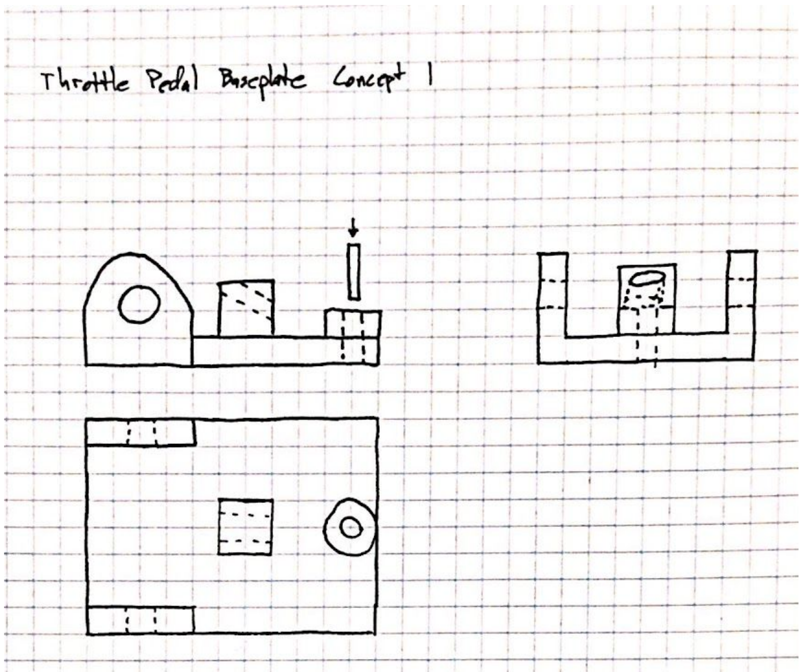

Figure 7: Throttle Pedal Base Plate Concept 1

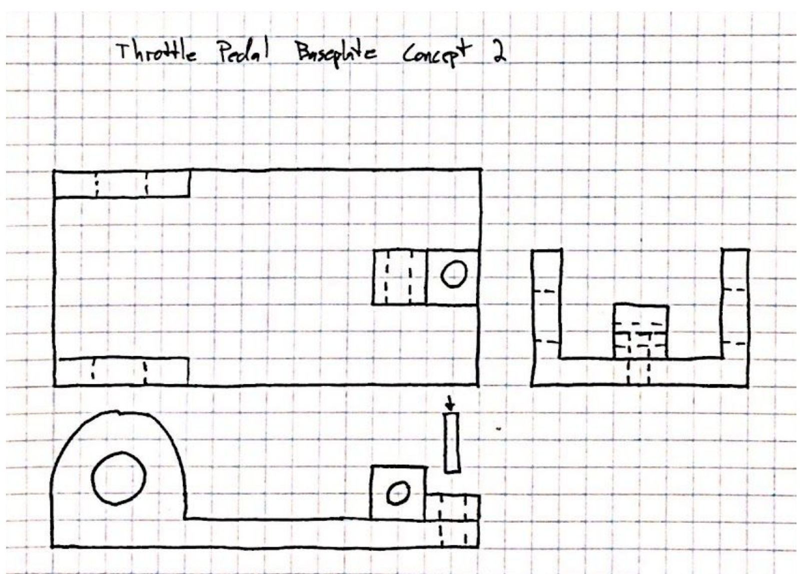

Figure 8: Throttle Pedal Base Plate Concept 2

Similar to the throttle pedal, a straight-backed, cut-out design for the brake pedal was generated, showing an orientation with a high piston body, as seen in Figure 9. This design would be required in conjunction with the brake pedal base plate Concept 2, as seen in Figure 10, due to how the master cylinder would need to be mounted. A straight-backed design was sketched due to the simplicity of drawing, as well as the lack of primary functional difference between curved and straight-backed pedals. Cutouts were selected for this concept sketch due to the reduced weight resulting from less overall mass.

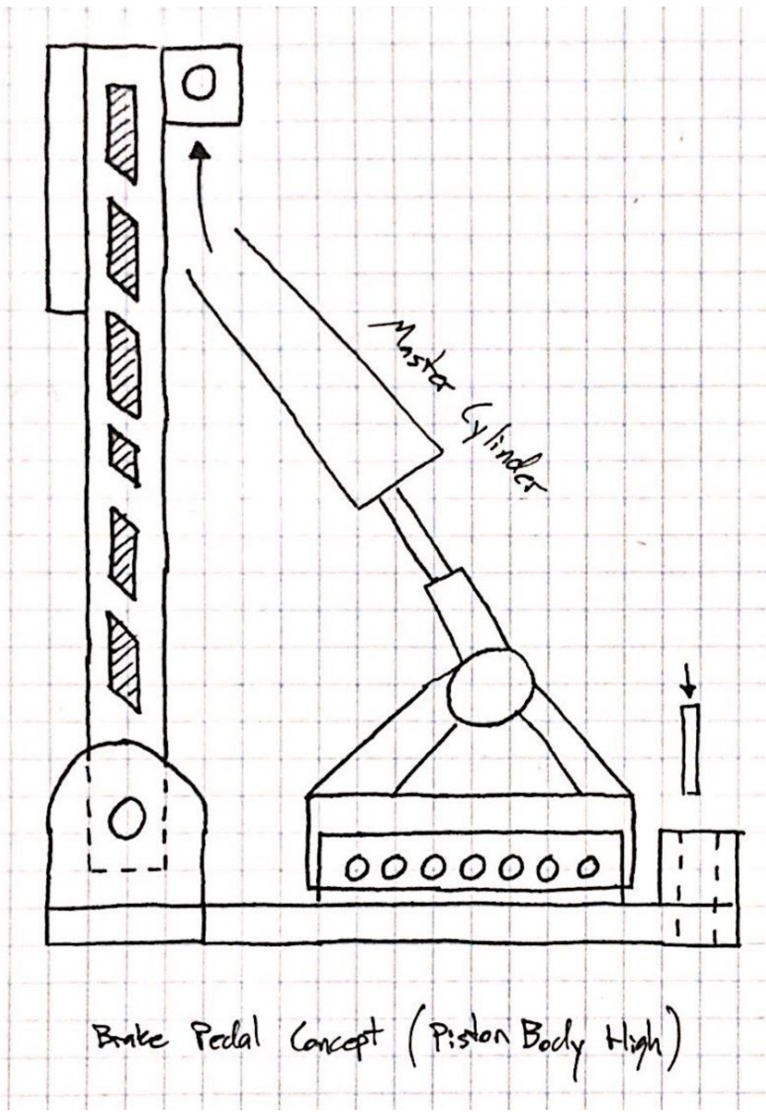

Figure 9: Brake Pedal Assembly Concept 1 Profile View

Two brake pedal base plate concepts are depicted as well, with Concept 1 suited for a master cylinder orientation with a low piston body as seen in Figure 10, as Concept 2 is for a master cylinder orientation with a high piston body as seen in Figure 11. The difference between the piston body orientation is the difference of mounting position and balance bar placement. The functional difference would only be seen during assembly and maintenance.

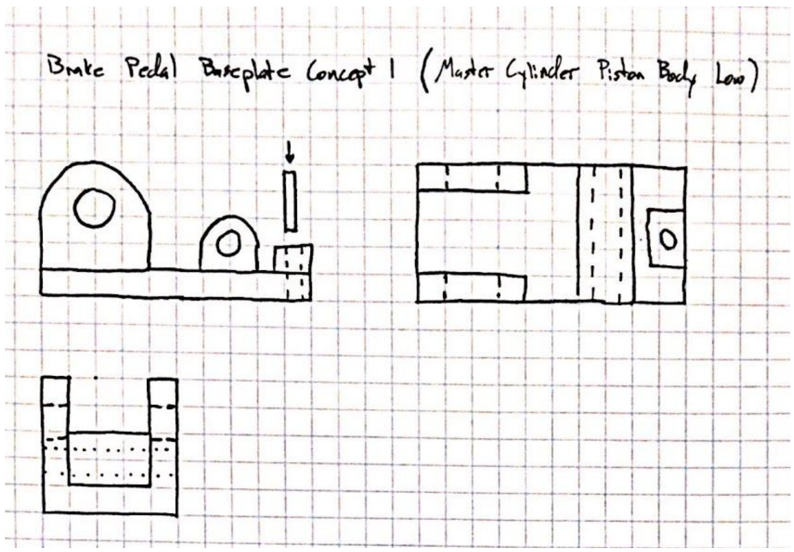

Figure 10: Brake Pedal Base Plate Concept 1

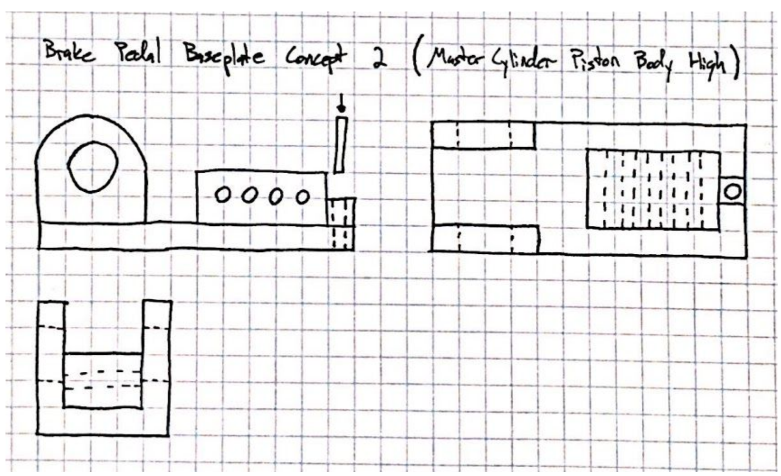

Figure 11: Brake Pedal Base Plate Concept 2

The pedal rails were relatively straightforward to depict in concept sketches, which are depicted as Concept 1 in Figure 12 and Concept 2 in Figure 13. Figure 12 shows a T-shaped profile to prevent vertical movement of the baseplate, while the base plate mount would be integrated into the bottom of each pedal base plate. Figure 13 shows a dovetailed design for the same purpose as the T-shaped profile in Figure 12. Both designs include positional holes to serve as locations for the baseplate pins to fit in order to lock the base plates in at a specific horizontal location.

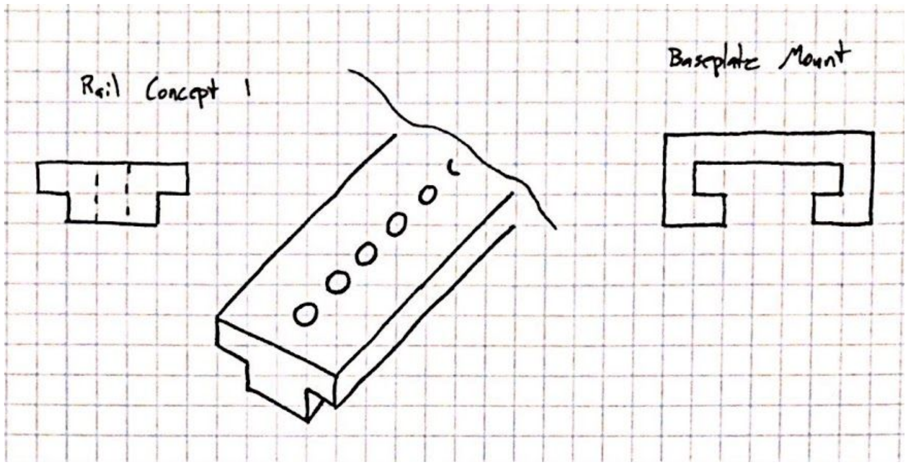

Figure 12: Pedal Rail Concept 1

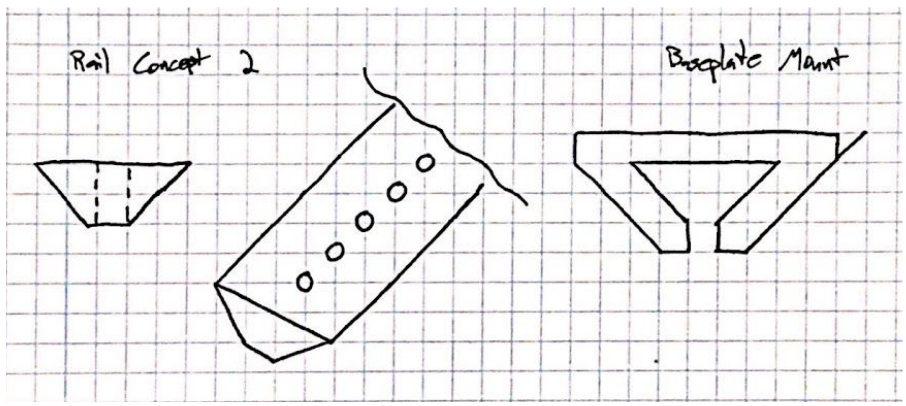

Figure 13: Pedal Rail Concept 2

Rough Screening Sheet

Once these concept sketches were generated and visualizations for individual components were possible, these ideas were subjected to screening. This rough screening process came down to a pro's and con's list, as seen in Table 1.

For the throttle pedal and brake pedal, the style of pedal backing was chosen between having a straight back and a curved back. Straight backing had the benefits of being simple to design, easy to manufacture, and require a minimal amount of material, however it had less compressive strength than a curved back pedal. The curved back pedal's benefits included being easy to manufacture, being stronger than the straight back pedal, and being just as cheap to manufacture. Thus, the curved back design was chosen.
Cut-outs were also considered for the pedal backs. Including the cut-outs would decrease the weight of the pedals as well as provide a very pleasing aesthetic for the design, while at the

same time they would reduce the overall strength of the pedal and be more complicated to manufacture. Excluding the cutouts would be simple and easy to manufacture, but would be much heavier. Since weight was a critical issue for this project, the decision to include cutouts was made.

When the brake rotor was considered, the size of the mounting hole was included in the decision-making process. A large mounting hole would reduce the weight of the brake rotors significantly as well as allow for simpler maintenance, but would require a redesign of the race car's wheel hubs. Smaller mounting holes would be heavier, but would not require a hub redesign. Since this project scope did not include hub design, redesigning the hubs to accomodate a larger mounting hole was not an available option, so the decision to use smaller mounting holes was made.

Whether or not to include slots on the brake rotor face was also factored into this project. Including thin slots on the disk face would increase the thermal efficiency of the disk, allow for debris buildup to be removed, and provide a pleasing aesthetic to the overall design. However, the slots would be more expensive and complex to manufacture. Not including these slots would be cheaper and simpler, but would ultimately be less safe for the driver to operate the vehicle. Since safety was paramount for this project, the decision to include slots on the brake disks was made.

The number and style of pedal trays was also considered. Using one solid pedal tray would have been simple to design, easy to manufacture, and cheap, but it would have made maintenance difficult, be heavy, and force the pedals to be dependent on one another for positioning. Using one pedal tray with cut-outs would be lightweight, cheap, and simple to manufacture, but would keep the pedals' positioning dependent on each other. Using two separate pedal trays would be lightweight,easy for maintenance, and would allow the pedals to be fully independent from one another, while being more difficult to manufacture. Ultimately, the separate pedal trays were chosen due to their reduced weight, ease of maintenance, and adjustability.

Master cylinder orientation was very important because it would determine the style of pedal tray used for the brake pedal. A low piston body would be strong and easy to accommodate for during manufacturing, but would be inconvenient for maintenance and difficult to package once assembled. A high piston body would be strong, easy to accommodate for during manufacturing, and would be convenient to package once assembled, but maintenance would be difficult. A horizontal piston would provide for easy maintenance, but would be much weaker, difficult to manufacture, and inconvenient to package once assembled. Thus, the decision was made to go with a non-horizontal, high piston body design.

The type of throttle return spring required consideration. Linear springs would be easy to maintain as well as be quite strong, while also being expensive and difficult to package.

Torsional springs would be convenient to package, strong, cheap, and lightweight, even though maintenance would be difficult. Torsional springs were chosen due primarily to weight and packaging concerns.

Three styles of throttle sensors were considered: short linear sensors, long linear sensors, and rotary sensors. Short linear sensors would be convenient to package, inexpensive, and extremely light weight, but would be fairly fragile with a small operational range. Large linear sensors would be stronger with a larger operational range, but would be expensive, heavy, and difficult to package. Rotary sensors would be small, light weight, and inexpensive, but would also be fragile, difficult to package, and much more complex to integrate into the overall design. Small linear sensors were chosen based on the overall size requirements for the pedal assembly as well as to minimize overall cost.

Two rail designs were considered, the T-shaped cross-section, and the dovetailed design. The T-shaped cross-section would be strong and inexpensive, but would bind up easily and be difficult to manufacture due to the required mount on the underside of the baseplates. The dovetailed design would be strong, cheap, and would not bind up as easily, but would also be difficult to manufacture due to the angled sides. Ultimately, the dovetailed design was chosen because manufacture would be easier than the T-shaped mount.

Table 1: Rough Screening Sheet

			Pro's	Cons	Yes/No
Brake Pedal	Back	Straight	Simple, Easy to manufacture, Cheap	Weaker than curved back	No
		Curved	Easy to manufacture, Strong, Cheap	Not simple to manufacture	Yes
	Cutouts	Yes	Light weight, Aesthetic	Lower Strength, More complex to manufacture	Yes
		No	Simple, Easy to manufacture	Heavy	No
Throttle Pedal	Back	Straight	Simple, Easy to manufacture, Cheap	Weaker than curved back	No
		Curved	Easy to manufacture, Strong, Cheap	Not simple to manufacture	Yes
	Cutouts	Yes	Light weight, Aesthetic	Lower Strength, More complex to manufacture	Yes
		No	Simple, Easy to manufacture	Heavy	No
Brake Rotor	Mounting Hole	Small	Hub stays the same as before	Heavy	Yes
		Large	Light, Easier maintenance	Hub needs redesigned	No
	Slots	Yes	Increased efficiency, Safer, Aesthetic, Less debris buildup	More expensive, More complex to manufacture	Yes
		No	Cheaper to manufacture	Lower efficiency, More likely to have debris build up	No
Pedal Tray	One Tray		Cheap, Easy to manufacture	Maintenance is difficult, Pedals not independent, Heavy	No
	One Tray w/ Cutouts		Cheap, Easy to manufacture, Lightweight	Maintenance is difficult, Pedals not independent	No
	Two Trays		Pedals independent, Lightweight, Easy maintenance	Difficult to manufacture	Yes
Master Cylinder Orientation	Piston Low		Easy to manufacture, Strong	Inconvenient packaging, Maintenance is difficult	No
	Piston High		Easy to manufacture, Strong, Convenient packaging	Maintenance is difficult	Yes
	Piston Horizontal		Easy maintenance	Inconvenient packaging, Weak, Difficult to manufacture	No
Throttle Springs	Linear		Easy maintenance, Strong	Expensive, Inconvenient packaging	No
	Torsion		Convenient packaging, Strong, Cheap, Light weight	Maintenance is difficult	Yes
Throttle Sensor	Small Linear		Convenient packaging, Cheap, Light weight	Weak material, Small operational range	Yes
	Large Linear		Strong, Large operational range	Expensive, Inconvenient packaging, Heavy	No
	Rotary		Small, Light Weight, Cheap	Inconvenient packaging, More complex to integrate	No
Rails	T-Shaped		Strong, Cheap	Bind easily, Difficult to manufacture	No
	Dovetailed		Strong, Cheap, Difficult to bind up	Difficult to manufacture	Yes

Weighted Decision Matrix

The rough screening sheet information was then reinforced with the outcome from a weighted decision matrix. Each concept was compared to its counterparts on the basis of overall cost to make, overall strength, how easy it would be to put into a small package, how it affected the overall safety of the system, how simple it would be to maintain, and how simple it would be to produce. A score of 5 represents the most effective result, while a score of 1 represents the least effective result. The rankings may be seen in Table 2. The concepts with the highest score were chosen to be used in this project.

Table 2: Weighted Decision Matrix

	Cost	Strength	Packaging	Safety	Maintenance	Production	Total
Rail Concept 1	5	5	3	5	2	2	22
Rail Concept 2	4	5	5	5	2	4	25
Throttle Baseplate Concept 1	5	4	5	4	3	3	24
Throttle Baseplate Concept 2	4	5	2	4	3	4	22
Brake Baseplate Concept 1	5	5	3	5	4	5	27
Brake Baseplate Concept 2	4	5	5	5	5	4	28
Master Cylinder Piston Body Low	5	5	4	5	3	4	26
Master Cylinder Piston Body High	5	5	5	5	5	5	30
Brake Pedal (Curved)	5	5	5	5	5	5	30
Brake Pedal (Straight)	5	4	4	4	5	5	27
Throttle Pedal (Curved)	5	5	5	5	5	5	30
Throttle Pedal (Striaght)	5	4	4	4	5	5	27
Brake Rotor (Slots, Small Mounting Hole)	5	5	4	5	5	5	29
Brake Rotor (Slots, Large Mounting Hole)	5	5	2	5	5	4	26
Rotary Throttle Sensor	1	3	2	4	5	4	19
Linear Throttle Sensor	5	3	5	5	5	5	28
Linear Throttle Spring	3	5	3	5	5	3	24
Torsional Throttle Spring	5	4	5	5	4	5	28

Embodiment Design

Product Architecture Design

A schematic diagram depicting the general layout of the pedal box, calipers, and brake rotors is shown below in Figure 14. At the front of the car, which is represented as the top of the picture, is the pedal box. Within the pedal box is both the throttle (right) and the brake (left) pedal with their representative components. There are two master cylinders that sit behind the brake pedal, one for the front calipers and one for the rear calipers. These cylinders each have a brake line that leads out to a series of brake lines that attach to their respective calipers. T-fittings are used to attach the brake lines together. The hard brake lines are represented by straight lines, while the flexible brake lines are represented by wavy lines.

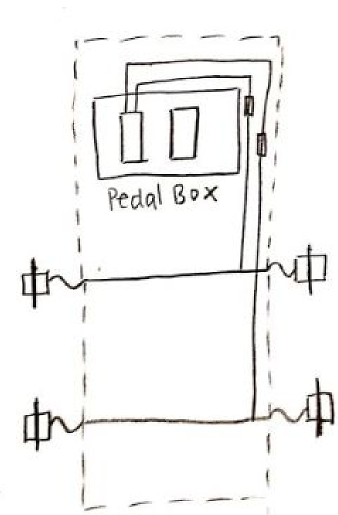

Figure 14: Product Architecture Design

Configuration Design

The two subsystems within the braking system consist of the pedal box and the rotor/caliper assembly. These are connected with brake lines that run from the master cylinders to the calipers. Purchasing brake lines required the distance they were to be laid out, which is where the following measurements come in. SolidWorks was used to measure these distances in order to purchase the correct brake lines. Figure 15 labels the distance on all axes from the brake pedal to the front caliper connected to the top left rotor. They are 20.176 inches apart in the z-direction (blue line), 19.35 inches apart in the x-direction (red line), and 4.84 inches apart in the y-direction (green line).

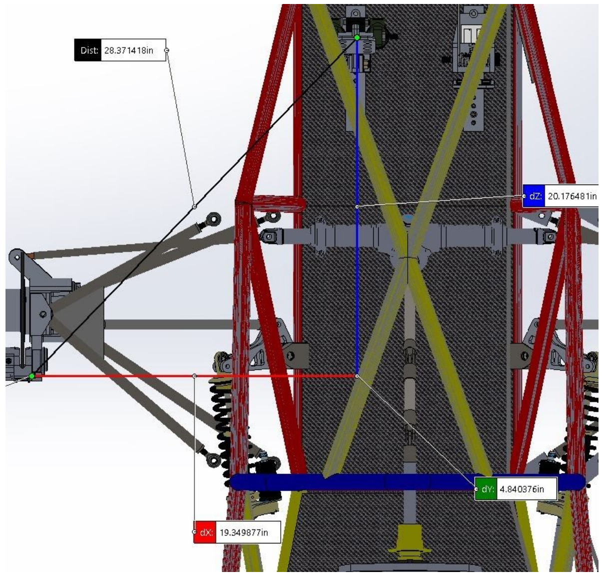

Figure 15: Distance from Brake Pedal to Front Caliper

Figure 16 below shows the measurements taken from the brake pedal to the rear caliper attached to the rear left rotor. They are 72.9 inches apart in the z-direction (blue line), 19.61 inches apart in the x-direction (red line), and 4.09 inches apart in the y-direction (green line).

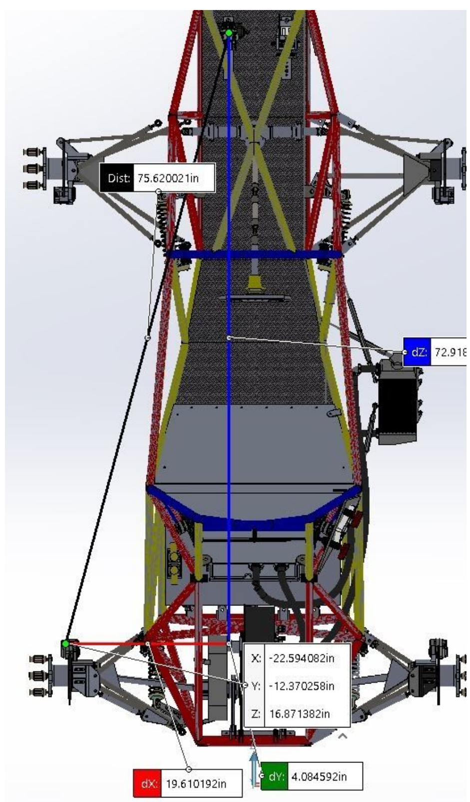

Figure 16: Distance from Brake Pedal to Rear Caliper

Figure 17 shows the measurement from one pedal to the other in one direction, which is simply 7 inches.

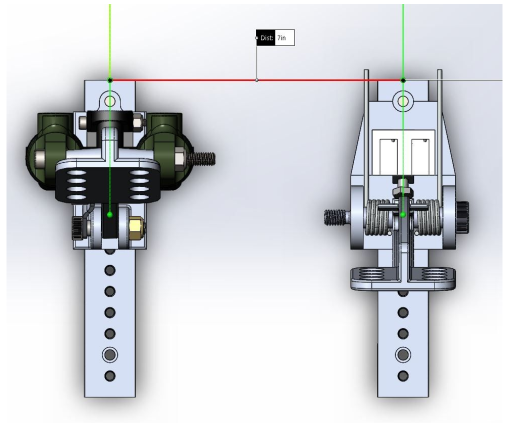

Figure 17: Centerline Distance between Pedal Assemblies

Application of Embodiment Rules

Clarity

The embodiment rules consist of clarity, simplicity, and safety. These rules allow for the design to be easy to use while maintaining the safety of the public. A design that incorporates clarity is one that clears all confusion about the product. In regards to the braking system of this electric car, the throttle pedal was kept on the right side while the brake pedal was kept on the left. These two assemblies were kept entirely independent of each other. This allows the driver to steer clear of any confusion while operating the vehicle. In addition, the front and rear braking systems were kept separate, each having their own master cylinder, fluid reservoir, and brake line connections. This was per FSAE regulation as well as to maintain clarity when testing the braking ability of the system.

Simplicity

Simplicity calls for functions to be created in a non-complex way. Instead of manufacturing the sensor housing for the throttle pedal, it was 3D printed using PLA. This simplified the total manufacturing process by saving time and material. In addition, both base plate rails were made to be identical, which played a part in simplifying the manufacturing process. The pin was also designed for simplicity, allowing ease of pedal adjustment. This pin simply needs to be lifted to allow the base plate to move along the rail, which gives a very quick adjustment while still securing the base plate in place. The same general structure was used for both the throttle pedal and the brake pedal to simplify the design process. Small linear throttle sensors were chosen over rotary sensors to avoid contrived geometrical issues when it came to sensor installation as well.

Safety

Safety has the designer incorporating various additions to the product to make sure that the user, or any other person, is not put in harm's way. A Brake Overtravel Switch (BOTS) mount was designed and installed within the brake pedal subsystem. If there is not enough pressure in the brake lines, or if the brake system fails for any other reason, this mount will travel with the pedal far back enough to flip a switch, shutting the car down. This provides safety to the driver in case of a braking system fail, as well as to any other drivers that could be put in harm's way. Reservoirs were also installed to hold extra brake fluid for the master cylinders. Any major fluid loss can be replaced by the fluid held in these backup reservoirs. In addition, extra brake pads were kept in stock in case the current ones wore out. Two throttle springs were included in the throttle assembly design, with each being capable of returning the pedal to the fully upright position. This was to ensure the throttle pedal would not remain in an active state if one spring were to fail. Additionally, the brake pedal was designed to withstand 2000 Newtons of force to ensure it would not fail under racing conditions. The front and rear braking systems were kept isolated from one another in case one system failed, maintaining the ability to slow the car in case of a malfunction.

Application of Embodiment Principles

Force Transmission

Within the design of the braking system, there were a couple of specific components that were designed and implemented for the purpose of dispersing applied force. The edges of both rails were rounded to reduce stress concentration while the base plate moves along the rail. Other mating surfaces, such as where the rails come in contact with the baseplates, were given small fillets for reduction of stress concentrations as well as ease of assembly. The bobbins that attach the rotors to their respective hubs assist with diminishing stress. With eight of them, they are able to split the applied load. They allow the rotors to float freely, giving them less rigidity and more movement. From this, the calipers are given a better grip on the rotors and braking torque is increased. The alignment of the base plates to the rails is another incorporated design that transmits force. The dovetail shape of the rail allows the base plate to glide along it, allowing for a smooth pedal adjustment. The spine of the brake pedal was also made thicker than that of the throttle pedal to account for the higher load it was required to bear, while the curved spine helps to mitigate the bending moment that occurs under load and translate it better into a compressive force applied to the master cylinders.

Division of Tasks

In order to create ease of function performance for each component, some tasks were divided between parts. The pedal adjustment is a task that has been split among two separate components: the rail and the pin. The dovetail shape of the rails allow the base plates to lock in on the vertical axis once they are slid onto the rail. Once this vertical position is set, the pin locks the pedal on the horizontal axis. This is so movement in both directions are independent of each other, making it easier for the driver to adjust the location of the pedal. In addition to this, the throttle and brake assemblies were isolated from one another, clearly creating a visual divide between them. This was to emphasize that there would be no mixing of tasks between the two assemblies. The inclusion of two master cylinders clearly divides the functions into a front and a rear system independent of one another.

Self-Help

Within this brake design, some of the components become more efficient when responding to forces from their surroundings. The rotors, for example, expand when they heat up in the system. Therefore, the breaking force is increased, increasing the efficiency of the braking system. Additionally, the springs that work with the pins to keep the pedals in place naturally work against a force of motion. The more the pin pulls up, the more the spring pulls it back down, keeping it in place which keeps the pedals from adjusting on their own.

FMEA

The Failure Mode and Effects Analysis below presents different failures that could occur within the car. The chart identifies the causes associated with these failures as well as what will occur if not taken care of. The risk priority number (RPN) is calculated by multiplying the severity, occurrence, and detection:

$$RPN = Severity \times Occurrence \times Detection$$

All three categories are based on a scale from 1-5. Severity is how critical the failure would be to the product or the amount of danger it could pose for any person. 5 is the most critical while 1 is the least. Occurrence tells how likely the failure is to occur, with 5 being the most likely and 1 being the least. Detection expresses how easy it is to detect the failure mode before it occurs, with 5 being the most difficult to detect and 1 being easiest.

The higher the RPN, the more of a risk that particular failure poses. Looking at the FMEA below, the highest risk is shown to have an RPN of 45. This failure mode consists of the wearing out of the brake pads, which could create insufficient friction, posing a risk to the driver and others around him/her. Because of these potential risks, this chart includes ways to decrease or completely cut out the possibility of these effects.

Table 3: FMEA Analysis

Process Step	Failure Mode	Potential Causes	Potential Failure Effects	Severity (1-5)	Occurrence (1-5)	Detection (1-5)	RPN	Mitigation
Driver pushes on brake pedal	Brake pedal base plate lifts off the rail	Plunger is not secured properly	Brake pedal becomes loose	4	1	5	20	Plunger is only able to removed by an upwards force
		Base plate is not properly attached to the rail	Brake pedal becomes loose	4	1	5	20	Dovetail design for base plate and rail
		Brake pedal does not support enough force	Car does not stop quick enough	5	1	3	15	Implement a factory of safety for the ability
	Brake pedal does not brake fast enough	Not enough brake fluid	Car does not stop quick enough	5	2	3	30	Careful calculation of master cylinder dimensions
	Brake pedal bottoms out	Not enough brake fluid	Car is not able to stop	5	2	3	30	BOTS mount
	Brake pedal slips out from driver's foot	Incorrect pedal face dimensions	Car does not stop quick enough	5	1	2	10	Careful design and additional factor of safety for dimension
Driver pushes on throttle pedal	Throttle pedal lifts off the rail	Plunger is not secured properly	Throttle pedal becomes loose	2	1	5	10	Plunger is only able to removed by an upwards force
		Base plate is not properly attached to the rail	Throttle pedal becomes loose	2	1	5	10	Dovetail design for base plate and rail
	Throttle pedal does not accelerate fast enough	Pedal travel is too short	Car is not fast enough	1	2	3	6	Coordinate with EE
	Throttle pedal bottoms out	Pedal travel is too short	Car is not fast enough	1	1	4	4	Add flanges to base of pedal
	Throttle pedal slips out from driver's foot	Incorrect pedal face dimensions	Car does not accelerate quick enough	2	1	2	4	Careful design and additional factor of safety for dimension
Calipers clamp on rotors	Calipers do not create enough friction	Not enough brake fluid	Car does not stop quick enough	5	2	3	30	Careful calculation of master cylinder dimensions
		Incorrect caliper dimensions	Car does not stop quick enough	5	1	2	10	Careful caliper calculation
		Brake pads are worn out	Car does not stop quick enough	5	3	3	45	Keep an extra set of brake pads
			Pedal vibration	3	3	4	36	Keep an extra set of brake pads
			Metal on metal noise	2	2	4	16	Keep an extra set of brake pads
			Rotors become damaged	4	2	3	24	Keep an extra set of brake pads

Preliminary Material and Manufacturing Process Selection

The majority of the components that were manufactured are made from 7075 aluminum. This metal was chosen because of its lightweight properties while still being sturdy enough to achieve the goals set for this project. 7075 aluminum was used for the brake pedal, throttle pedal, brake base plate, throttle base plate, both rails, both rail pins, and the bobbins. The bobbins and pins were machined using a lathe, while the rest of the aluminum components were made by CNC machines. The bobbins were simple enough to manufacture by hand, while the other components had more complexity to them.

The rotors, on the other hand, are made from grey cast iron. Since they must hold a lot more force and reach a much higher temperature, a sturdier material was needed, hence why grey cast iron was chosen. Along with the extra force, they are undergoing constant friction due to their interaction with the brake pads, which presents a need for harder material. The temperature requirement necessitated a material with a lower specific heat as well.

While almost all components were manufactured, the sensor housing for the throttle pedal was 3D printed. This was overall cheaper and faster for the system, seeing as no material needed to be bought. This allowed for quick part testing and for each rendition of the sensor housing to be custom-made to solve problems as they arose, such as potential issues with sensor fit or placement.

Numerical Calculations

The piston diameter for both the front and the rear master cylinders were calculated using a string of equations, starting with the percentage of weight on the rear axle, which is shown as:

$$R_{wr} = 1 - F_{wr}$$

$$= 1 - 0.45$$

$$= 0.55$$

While R_{wr} is the weight on the rear, F_{wr} is the weight ratio on the front, which was obtained from another car subsystem. From there, the rear weight ratio was multiplied by the wheelbase (*L*, also given by another subsystem*)* to obtain the center of gravity distance from the front axle.

$$CG_F = L * R_{wr}$$

$$= 60.5\ in * 0.55$$

$$= 33.275\ in$$

The same process was done to calculate the center of gravity distance from the rear axle, with the front weight ratio being used instead.
.

$$CG_R = L * F_{wr}$$

$$= 60.5\ in * 0.45$$

$$= 27.225\ in$$

Then, the weight of the car on the front and rear axles were calculated. The equations are respectively:

$$W_F = W * F_{wr}$$

$$= 630\ lbs * 0.45$$

$$= 283.5\ lbs$$

$$W_R = W * R_{wr}$$

$$= 630\ lbs * 0.55$$

$$= 346.5\ lbs$$

From there, the weight transfer was found. This calculation required maximum deceleration (A_{max}), the height of the center of gravity (*H)*, and the wheelbase (*L*), which were all obtained from a different subsystem.

$$W_{Tran} = \frac{(A_{max} * W * H)}{L}$$

$$= \frac{(1.5 * 630\ lbs * 11.05\ in)}{60.5\ in}$$

$$= 172.6\ lbs$$

The normal forces on the front and rear axles during maximum braking were calculated using different variables. These equations are, respectively, show below:

$$N_F = \left(\frac{W}{L}\right) * [CG_R + (A_{max} * H)]$$

$$= \left(\frac{630\ lbs}{60.5\ in}\right) * [27.225\ in + (1.5 * 11.05\ in)]$$

$$= 456.1\ lbs$$

$$N_R = W - N_F$$

$$= 630\ lbs - 456.1\ lbs$$

$$= 173.9\ lbs$$

The piston area was calculated using the radius of the caliper pistons (R_{CP}) which was obtained from ISR. Since both the front and the rear pistons have the same radius, this translates to equal piston area.

$$A_P = R_{CP}^2 * \pi$$

$$= (0.492\ in)^2 * \pi$$

$$= 0.761\ in^2$$

The total piston area, however, incorporates every piston into its calculation. The total area is different for the front and the rear.

$$A_{PTF} = A_p * \#of\ pistons$$

$$= 0.761\ in^2 * 8$$

$$= 6.087\ in^2$$

$$A_{PTR} = A_p * \#of\ pistons$$

$$= 0.761\ in^2 * 4$$

$$= 3.043\ in^2$$

The radius of force on the rotors was then calculated using the rotor radius (R_R) and the height of the brake pads (H_{Pad}), both data from the team.

$$R_{FR} = R_R - \left(\frac{H_{Pad}}{2}\right)$$

$$= 3.5\ in - \left(\frac{1.063\ in}{2}\right)$$

$$= 2.969\ in$$

The longitudinal forces from the front and rear tires were found using their respective normal forces and the coefficient of friction for the tire (μ_T), which was obtained from TTC.

$$F_{LF} = N_F * \mu_T$$

$$= 456.1\ lbs * 1.7$$

$$= 775.37\ lbs$$

$$F_{LR} = N_R * \mu_T$$

$$= 173.9\ lbs * 1.7$$

$$= 295.63\ lbs$$

This force, when multiplied by the radius of the tire from TTC (R_{Tire}), outputs breaking torque.

$$\tau_{BrakeF} = F_{LF} * R_{Tire}$$

$$= 775.37\ lbs * 10.05\ in$$

$$= 7792.47\ lbs \cdot in$$

$$\tau_{BrakeR} = F_{LR} * R_{Tire}$$

$$= 295.63\ lbs * 10.05\ in$$

$$= 2971.08\ lbs \cdot in$$

This torque allows the calculation of the friction force acting on the pad.

$$F_{padF} = \frac{\tau_{BrakeF}}{R_{FR}}$$

$$= \frac{7792.47\ lbs \cdot in}{2.969\ in}$$

$$= 2625.044\ lbs$$

$$F_{padR} = \frac{\tau_{BrakeR}}{R_{FR}}$$

$$= \frac{2971.08\ lbs \cdot in}{2.969\ in}$$

$$= 1000.873\ lbs$$

Used with the coefficient of friction of the brake pads (μ_{pad}), the friction force is inputted to find the normal force that the pads need to exert in order to stop the car. This coefficient was obtained from ISR.

$$N_{padF} = \frac{F_{padF}}{\mu_{pad}}$$

$$= \frac{2624.61\ lbs}{0.45}$$

$$= 5833.432\ lbs$$

$$N_{padR} = \frac{F_{padR}}{\mu_{pad}}$$

$$= \frac{1000.7\ lbs}{0.45}$$

$$= 2224.162\ lbs$$

The brake line pressure is then found using the following equation:

$$P_{LineF} = \frac{N_{padF}}{A_{PTF}}$$

$$= \frac{5833.432\ lbs}{6.087\ in^2}$$

$$= 958.367\ psi$$

$$P_{LineR} = \frac{N_{padR}}{A_{PTR}}$$

$$= \frac{2224.162\ lbs}{3.043\ in^2}$$

$$= 730.81\ psi$$

The motion ratio was calculated using simple geometry. This ratio is the difference in distance seen in Figures 18 and 19 divided by the amount the pedal moves backwards to compress the master cylinders. The higher this ratio, the higher the mechanical advantage on the master cylinders pushing fluid. The motion ratio was calculated to be 3.49.

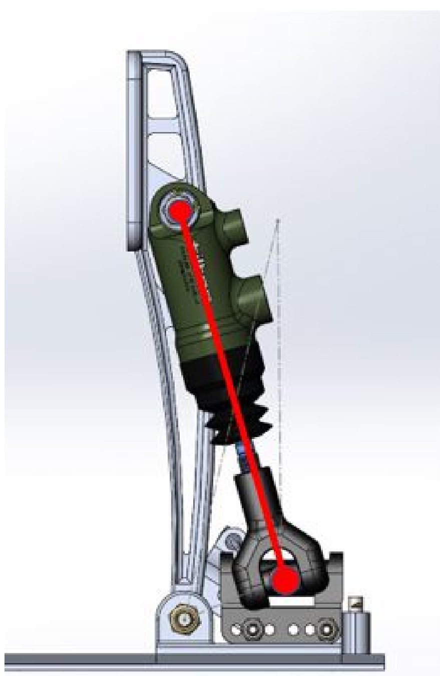

Figure 18: Brake Pedal at Rest

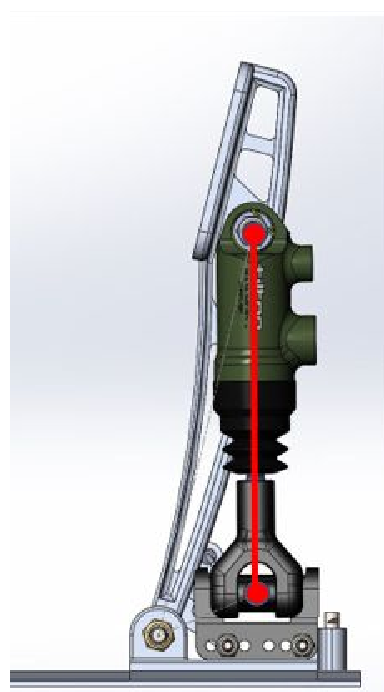

Figure 19: Depressed Brake Pedal

With the previously obtained pressure value and the motion ratio (*MR*), the piston area of the master cylinder is able to be found. F_{Driver} is the force of the driver, which is how much force the brake pedal should be able to withstand. This value is given by FSAE.

$$A_{MF} = (F_{Driver} * \frac{MR}{2})/P_{LineF}$$

$$= (150\ lbf * \frac{3.49}{2})/958.367\ psi$$

$$= 0.273\ in^2$$

$$A_{MR} = (F_{Driver} * \frac{MR}{2})/P_{LineR}$$

$$= (150\ lbf * \frac{3.49}{2})/730.81\ psi$$

$$= 0.358\ in^2$$

From the area, the diameter is able to be calculated. This diameter was used when purchasing both master cylinders for the braking system.

$$D_F = (\frac{A_{MF}}{\pi})^{0.5} * 2$$

$$= (\frac{0.273\ in^2}{\pi})^{0.5} * 2$$

$$= 0.59\ in$$

$$D_R = (\frac{A_{MR}}{\pi})^{0.5} * 2$$

$$= (\frac{0.358\ in^2}{\pi})^{0.5} * 2$$

$$= 0.675\ in$$

One can see that the diameter of the front and rear piston cylinders should be *0.59 in* and *0.675 in* respectively. These were the dimensions used when purchasing the master cylinders.

Detail Design

Load Path

The load path for this system is relatively simple. The driver applies a force up to 2000 Newtons onto the face of the brake pedal, which is then transferred to the master cylinders. The compression of the master cylinders forces brake fluid into the brake lines, rapidly increasing the fluid pressure within. This increased pressure then forces the caliper pistons to expand outward, putting them in contact with the brake rotors. As the caliper pistons expand outward, they press into the rotor with more and more force, increasing the amount of friction between the two until the rotor locks up and stops the tire from spinning any further, stopping the vehicle. A secondary load path exists that would transfer the load from the driver’s foot through the pedal, down to the pedal mounting point, and into the brake pedal base plate. The base plate would then transfer this load through the pedal rail, and into the vehicle chassis. The vast majority of this force is transferred through the master cylinders, as can be seen in the finite element analysis performed on the brake pedal in Figure 36 under Finite Element Analysis.

A separate load path exists for the throttle pedal. This path starts in a similar fashion, with the driver applying a variable force to the throttle pedal face. The pedal then transfers this force to the throttle sensors, until the pedal reaches the mechanical stop to prevent damage by bottoming the sensors out. The load is then distributed from the pedal to the baseplate, which transfers the load through the rails and into the chassis of the vehicle. This force transfer may be seen in the finite element analysis of the throttle pedal in Figure 37 under Finite Element Analysis.

Determining Hardware Needed

Once calculations were run to determine what components would be best, the next task in the project was ordering those components and getting ready for assembly. This began with determining all hardware required to manufacture and assemble this system. This includes all bolts, fasteners, washers and brake line hardware needed to assemble the system. To begin this process, a mockup of the brake system determined where fittings would be placed.

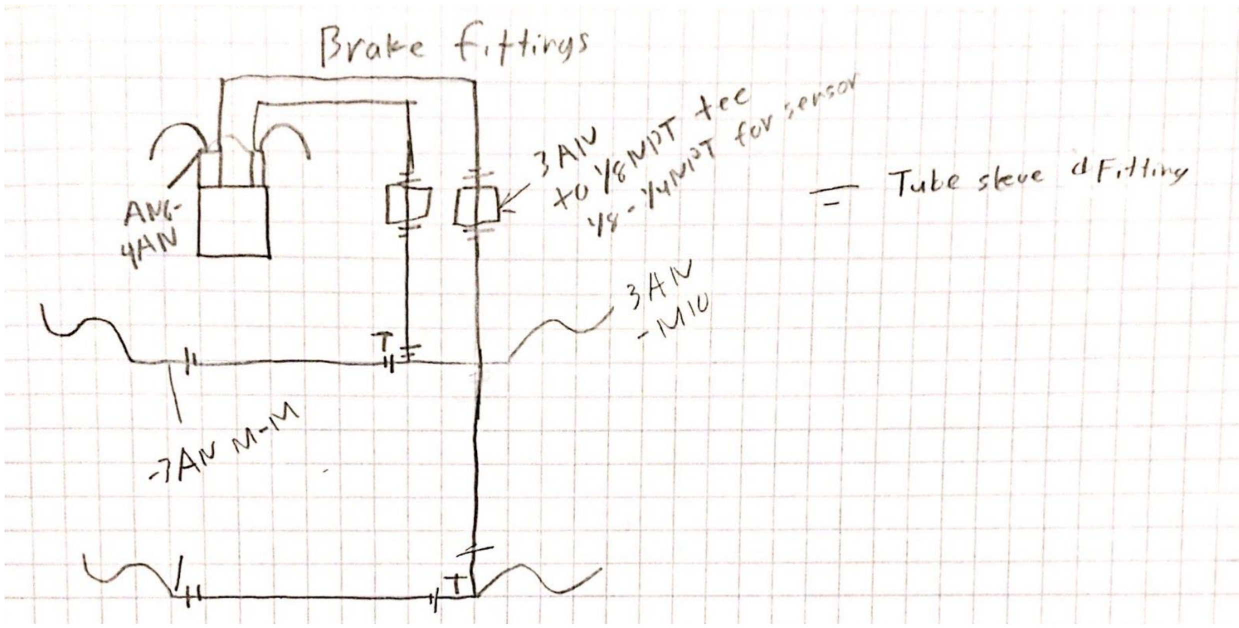

Figure 20: Brake Fittings Layout

As seen in Figure 20, a simple drawing is all that is needed to determine the amount of fittings needed for the system. In Figure 20, all straight lines represent stainless steel hard lines and all wavy lines represent braided steel flexible lines. Other points are the brake sensors which are represented by the two squares in-line with the hard lines, the brake pedal represented by the square off to the left, and the two master cylinders attached to the brake pedal. All brake lines in this system are 3/16 inch diameter brake lines.

The system begins with connecting the reservoirs to the master cylinders. To do this, a -AN6 to -AN4 adapter is needed. The master cylinders chosen have a -AN6 port where the fluid enters, and the tubing chosen for this application fits around a -AN4 fitting. Since there are two master cylinders, two fittings of this type were chosen. The outlet sizing for the master cylinders is a -AN4. Since the brake line diameter chosen was 3/16, there was an adapter needed to convert from -AN4 to -AN3, and again, two of these are needed, one for each master cylinder.

To get real time data on pressure readings while the brakes are in operation, two sensors were chosen that both met the pressure criteria needed and worked with the electrical system on board. These sensors had a 1/4NPT male fitting on them, so adapters were needed to mate this to an -AN3 system. To do this, a t-style adapter was chosen that converted from -AN3 to 1/8NPT. From there, a 1/8NPT to 1/4NPT fitting was chosen, allowing the sensors to be integrated into the system. Since there are two sensors, one for each line, each of these fitting required a quantity of two.

Finally there are the fittings that attach all the lines together. In this design there are two t-style fittings that connect both sides of the car to both the front and rear brake lines. As for the hard lines, everywhere there is a hardline connection to a t-style fitting or a male to male fitting, a tube nut and line fitting are required to make that junction. As seen in Figure 20, there are ten of these junctions, so ten tube nuts and line fittings are required. Flexible braided lines are purchased with line fittings attached, so there is no need for extra fittings at these junctions. Where the hard line and flex line meet, there is a need for a male to male fitting. In this case, there are two -AN3 male to male fittings needed on the left side of the car. Lastly, to connect all the flex lines to the calipers, a -AN3 to M10 fitting is needed. There are four of these connections, so four adapters were purchased.

Various fasteners were the last items to be purchased. All hardware for this project was purchased through a local supplier. Fasteners were chosen based on design application and availability, using common sizes and thread counts. All fasteners are broken down in the Bill of Materials shown later in this section.

Various parts were ordered from catalogue due to time and tool restrictions. Certain parts like the master cylinders and brake calipers are not able to be made with the tools in house and perform to the capabilities needed. Parts ordered for the brake pedal include the Tilton 78 series master cylinders and balance bar, the Brake overtravel switch, springs for the pins and a variety of nuts and bolts. Parts ordered for the throttle pedal include the linear sensors, pedal return springs, and mounting hardware. Other components that were purchased were various selections of brake lines, the MOTUL 600 brake fluid, ISR series 22-48 and -49 brake calipers and pads, and brake line sensors. These parts were ordered from their respective manufacturers and delivered to the design center.

Drawings and Assemblies of Designed Components

The next set of figures are all the components designed by the team. These designs are all done with calculations and knowledge supplied by the students of this team.

Figure 21 is of the final pedal slider used for both the throttle and brake pedal. This piece is used to mount the individual pedal trays to the frame of the vehicle. They are mounted using two ¼-20x2 inch bolts in the countersunk holes. Each of the holes, besides the countersunk holes, have a 5 degree draft angle to allow the pin to seat in the hole easily and allow for it to not move around while in the hole. The overhangs on either side are encompassed by the pedal trays to limit any vertical movement.

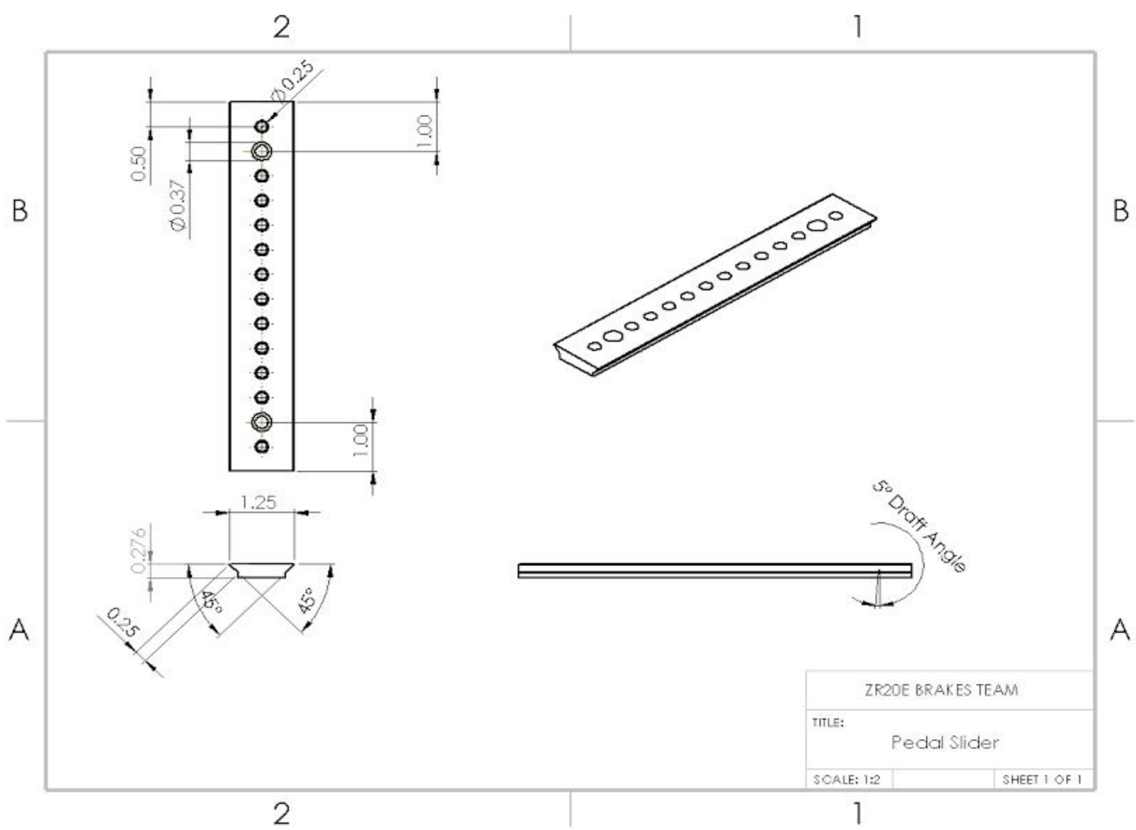

Figure 21: Pedal Rail Drawing

Figure 22 shows the drawing for the pins used in both pedal trays. This pin includes a 5 degree draft angle to seat in the holes drilled out in the pedal sliders. There is also a piece in the middle that allows for the spring to sit on the pin, and helps push the pin down into the holes. Cutouts are made on the top to allow the user to grab the pin and pull it upwards, allowing the pedals to be moved forward and backward. This pin was tested to withstand 2000 N of shearing force being applied on it.

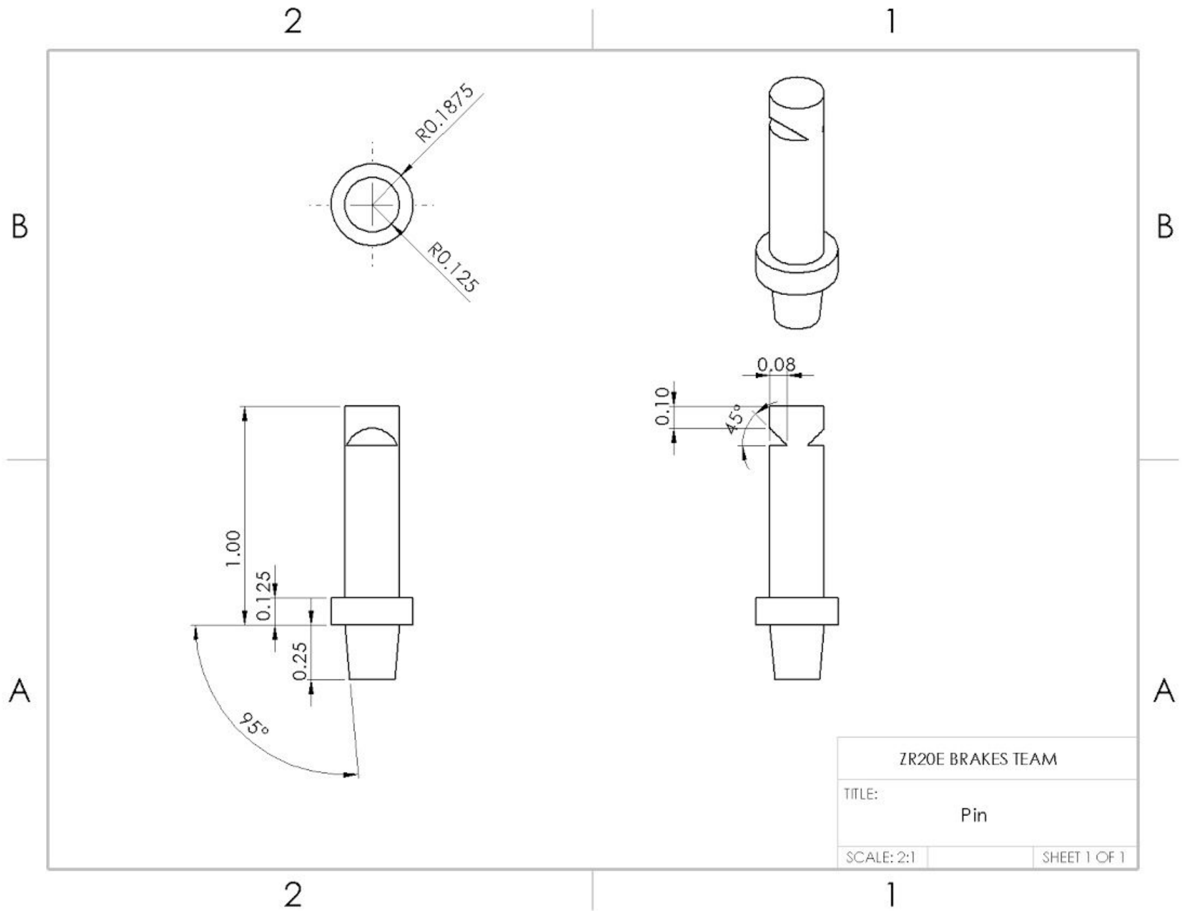

Figure 22: Pedal Tray Pin

Figure 23 shows the brake base plate and dimensions. The flanges on the bottom grab onto the rail and secure it vertically, while the hole in the rear houses the pin and spring, which prevent the plate from moving horizontally. The two uprights in the front house the bolt path used to guide the pedal and is where the pedal pivots from. Directly behind is where the balance bar mounts to the plate and is secured using two screws with locking nuts. There are multiple holes to allow the adjustment of the balance bar within the plate. This piece is made out of a single piece of 7075 aluminum and is tested to withstand 2000 Newtons in the vertical and horizontal directions. Overall the packaging is minimized and adapted to be easily machined on a CNC mill.

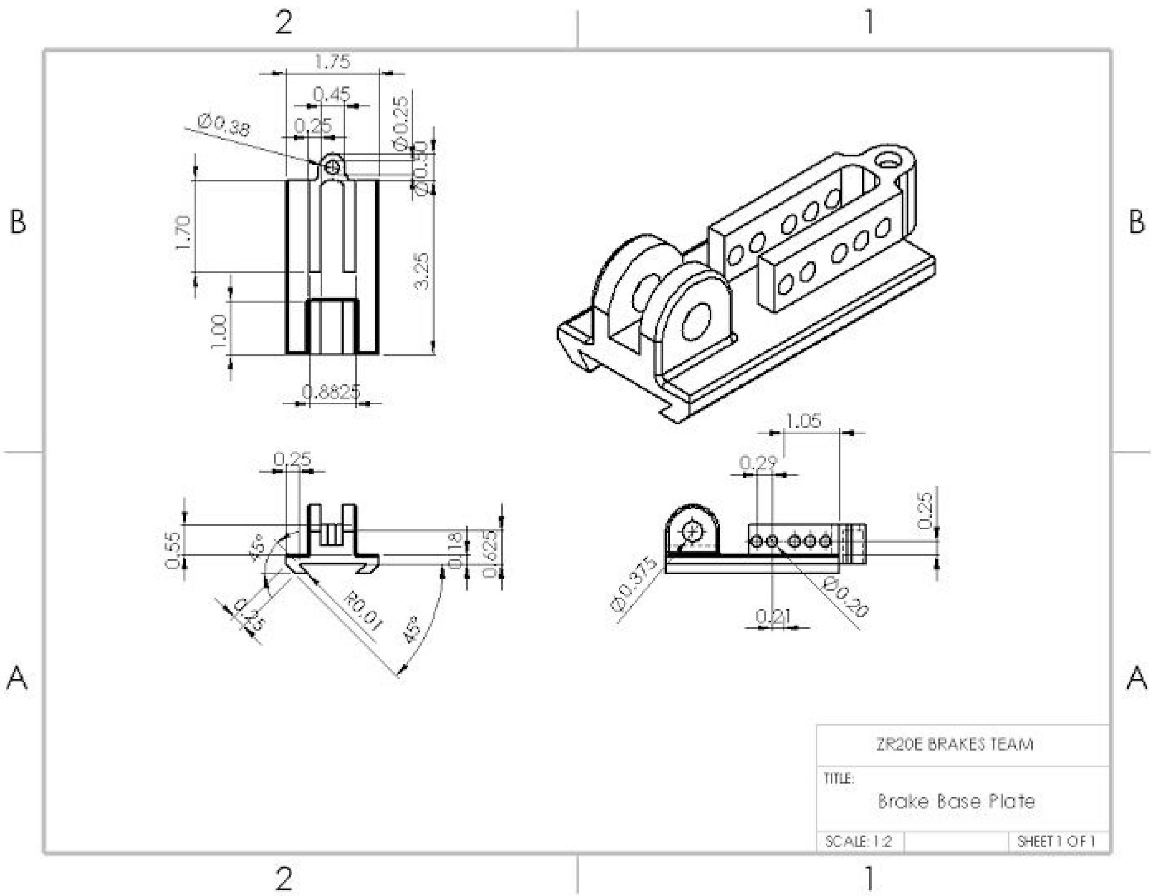

Figure 23: Brake Pedal Baseplate

Figure 24 shows the Brake Overtravel Switch Mount or BOTS mount. This mount is made from 0.1 inch thick aluminum plate and is jogged over to allow clearance within the pedal box. This mount attaches in two points to the pedal box to allow for stability and to make sure the switch does not move. The top hole houses the switch, allowing it to be placed behind the pedal should a brake failure occur.

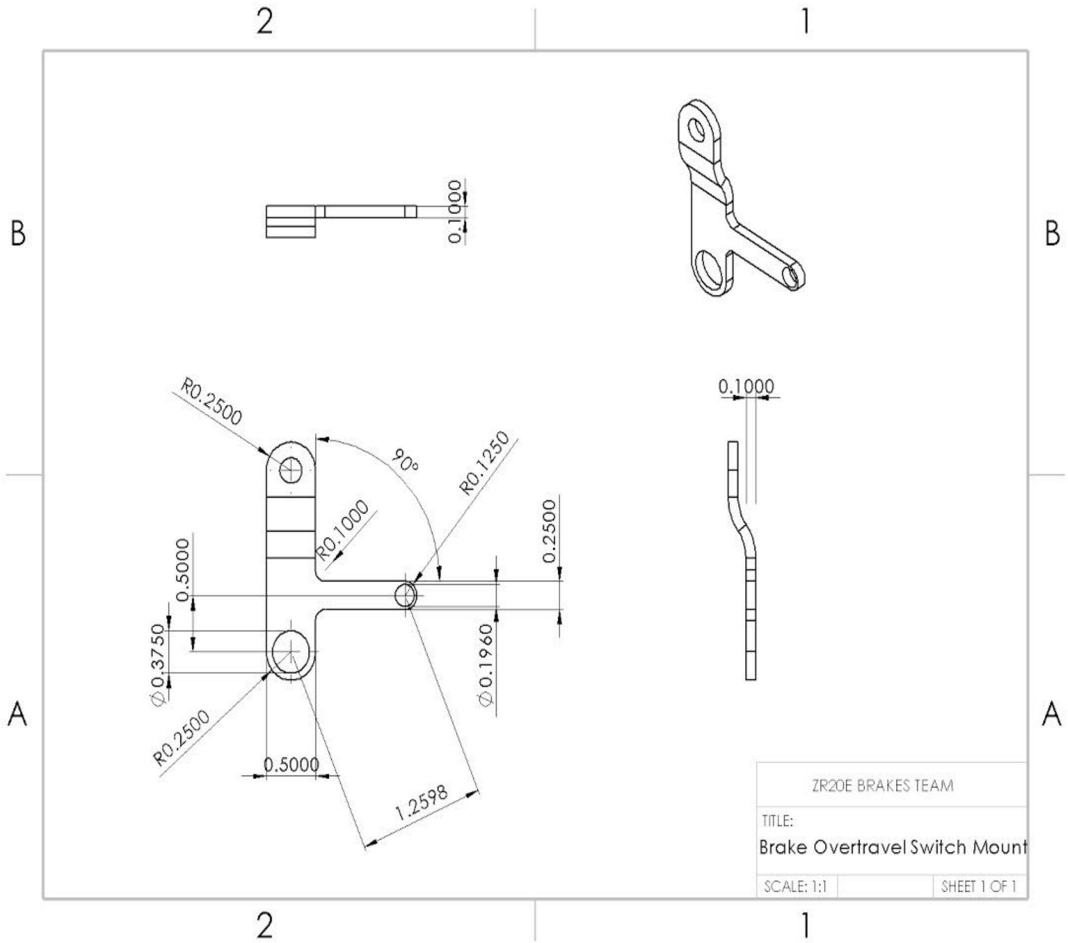

Figure 24: BOTS Mount

Figure 25 shows the final production version of the brake pedal. The pedal is symmetric, with eight holes cut out of the face to reduce weight. Along the back of the pedal is a curve to allow for better stress distribution and allow the pedal to sit forward on the base for better ergonomics. There are three main braces in the side of the pedal for added rigidity. Material was taken out of the sides and in between the braces for reduced weight, with fillets on all these mating surfaces to reduce concentrations of stress throughout the pedal. Finally, there are two arms that extend out to the distance needed to space out the master cylinders in assembly. These arms have a draft on them to further reduce weight over a solid, straight arm.

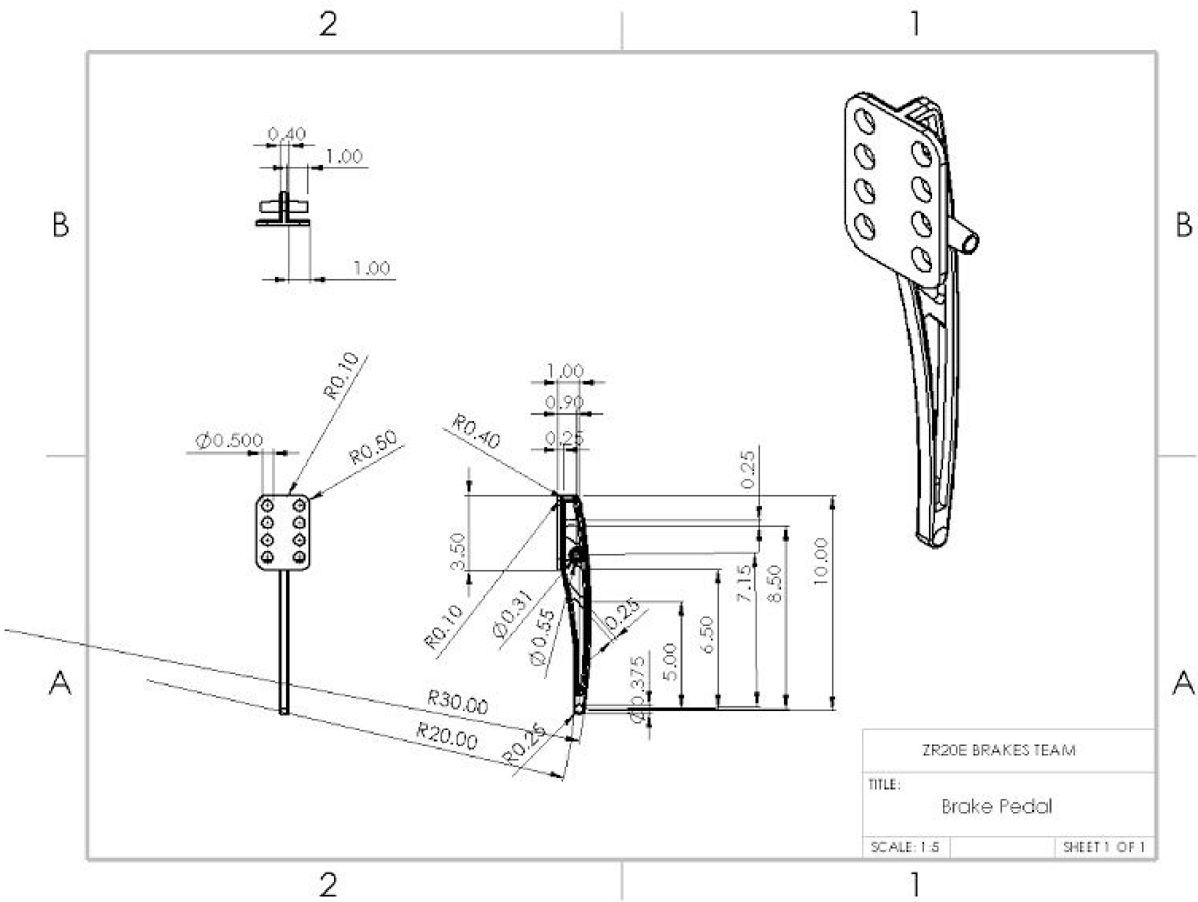

Figure 25: Brake Pedal

Figure 26 shows the final Brake Pedal Assembly with hardware. The design allows for a compact pedal tray, reducing the amount of space needed for a pedal of this size. This allows for the chassis to be shortened and for more adjustability with the added space. Figure 27 shows an exploded view of this assembly.

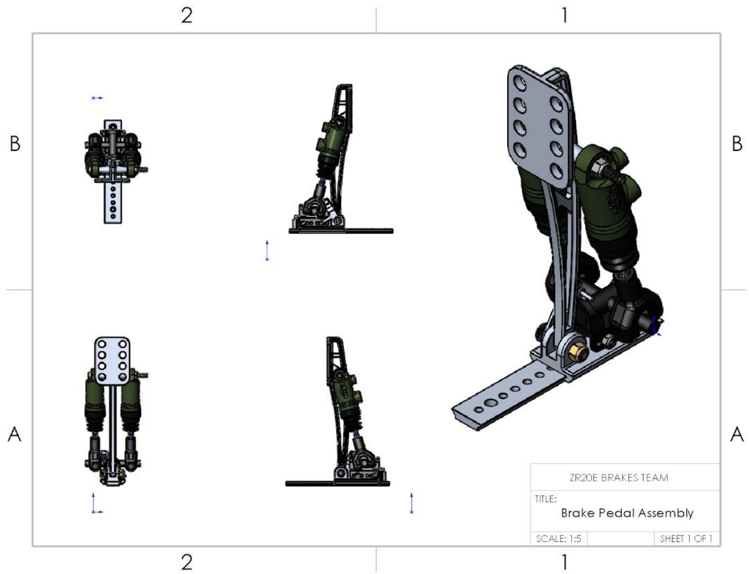

Figure 26: Brake Pedal Assembly

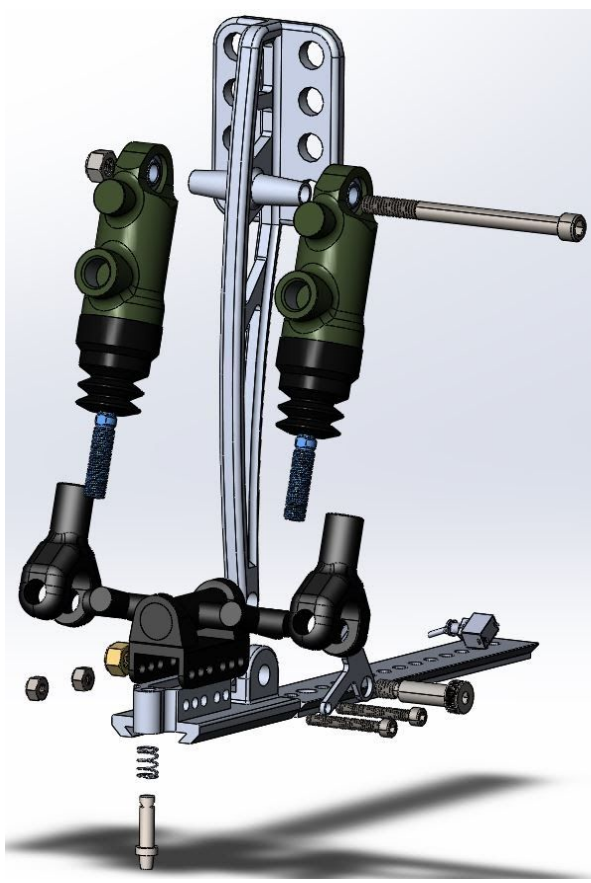

Figure 27: Brake Pedal Assembly Exploded View

Figure 28 shows the design for the throttle base plate. This base plate includes similar elements to the brake base plate for mounting and for the pin in the rear. The plate has space for the springs inline with the throttle pedal as seen in Figure 31. Lastly, there's a piece that comes up from the center and serves two purposes. The first and main purpose is to hold down the sensor mount for the pedal to act upon. This mount keeps the sensors in place during movement by the car. The second purpose of this is to act as a backstop for the pedal. Once the pedal is calibrated to the sensors on length of travel, a screw is inserted to the distance needed to act as a backstop. This prevents the pedal from traveling too far as to cause damage to the assembly.

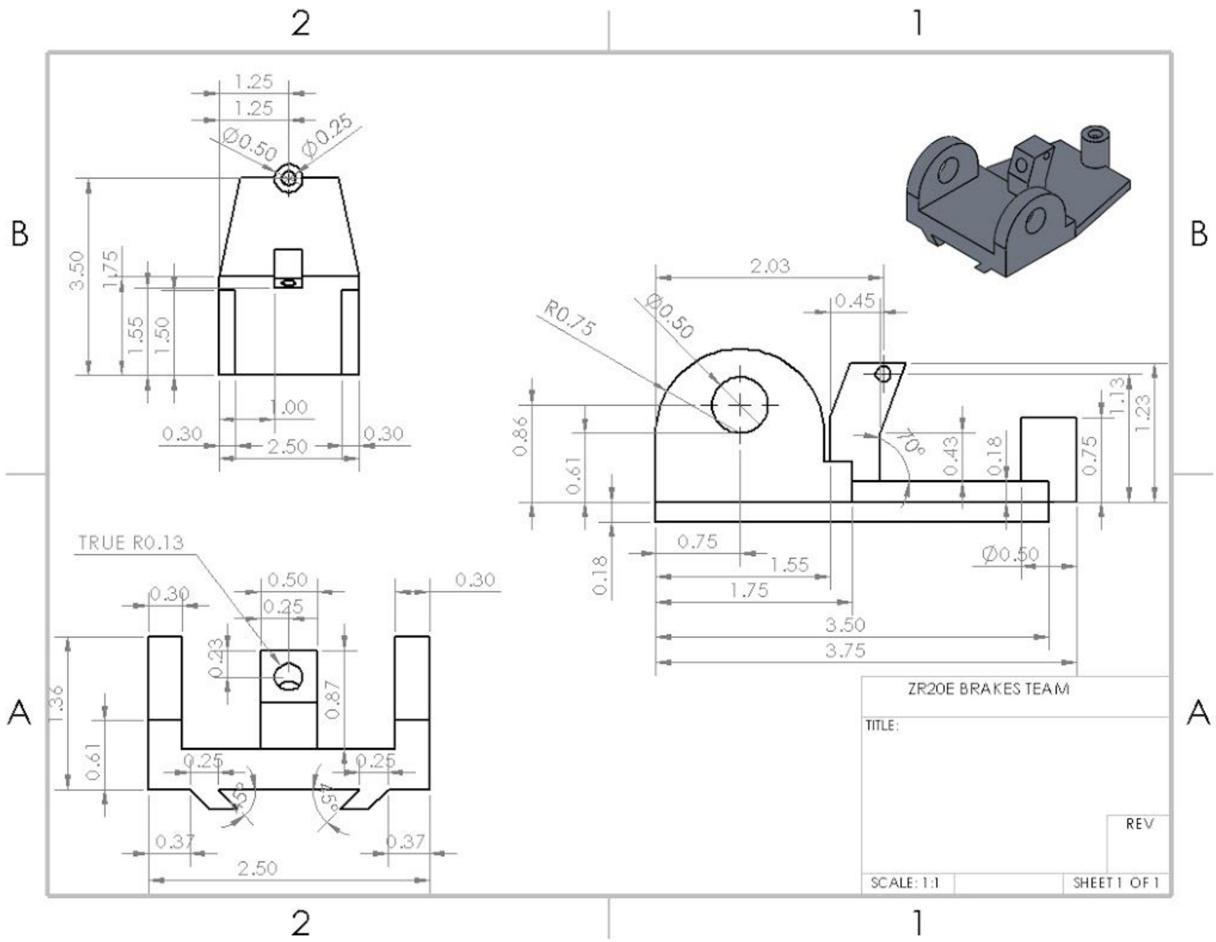

Figure 28: Throttle Pedal Baseplate

Figure 29 shows the linear sensor mount. This mount is printed with PLA plastic and attached to the throttle pedal base with a bolt that runs through the side of the housing. The sensors are attached using glue that adheres to plastic surfaces. This mount allows for the sensors and mount to be easily taken out for maintenance if needed due to component failure.

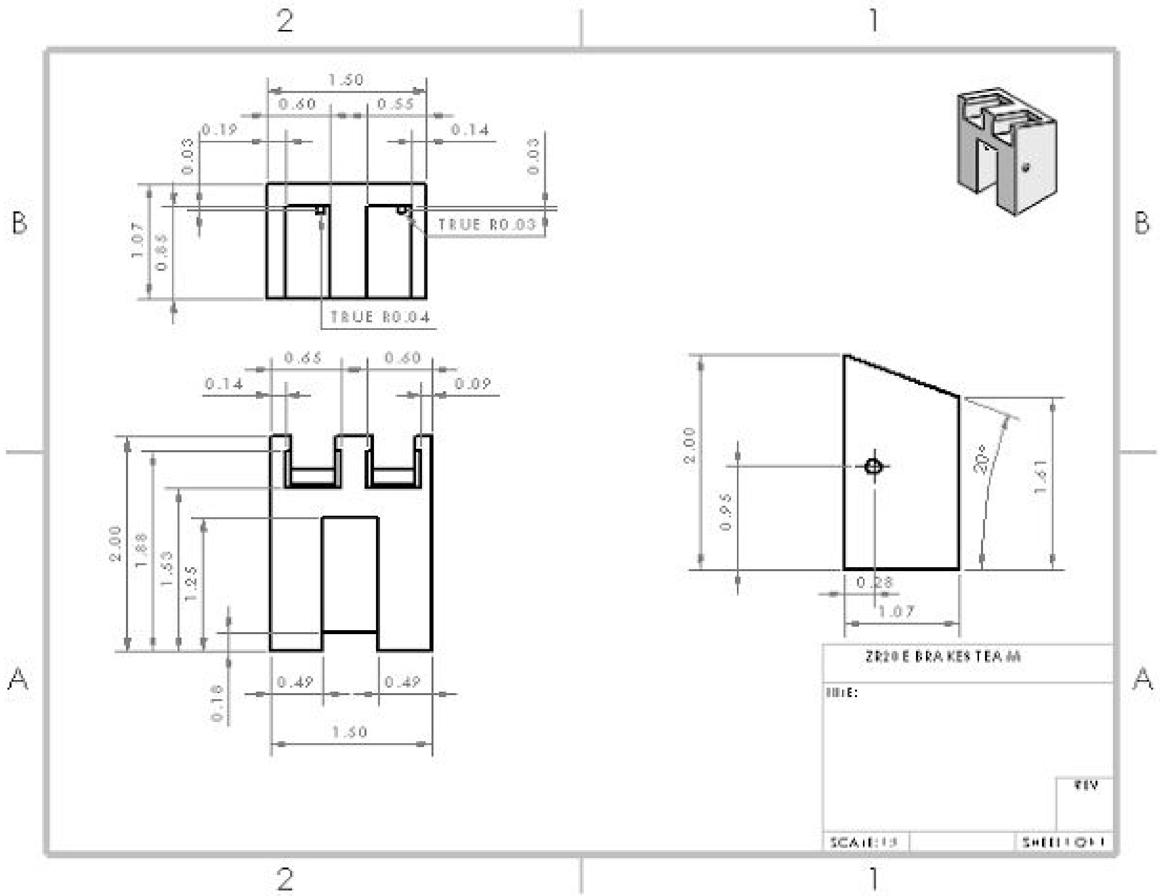

Figure 29: Throttle Sensor Mount

Figure 30 shows the final version of the throttle pedal. This pedal, like the brake pedal, has eight holes drilled into the face for reduced weight. Along the side profile, more material was taken out to reduce overall weight. There are two flanges that act on the linear sensors, pushing them when the pedal is depressed. In front of those flanges are two holes, one for each spring to be attached to the pedal. Along the front face of the pedal is a flange that runs perpendicular to add stiffness while minimizing material needed. Unlike the brake pedal, this one does not have added material that runs down the back due to lighter loads being applied. The curvature of this pedal was determined to be ideal for ergonomics, bringing the pedal forward off the base allowing for easier access by the driver.

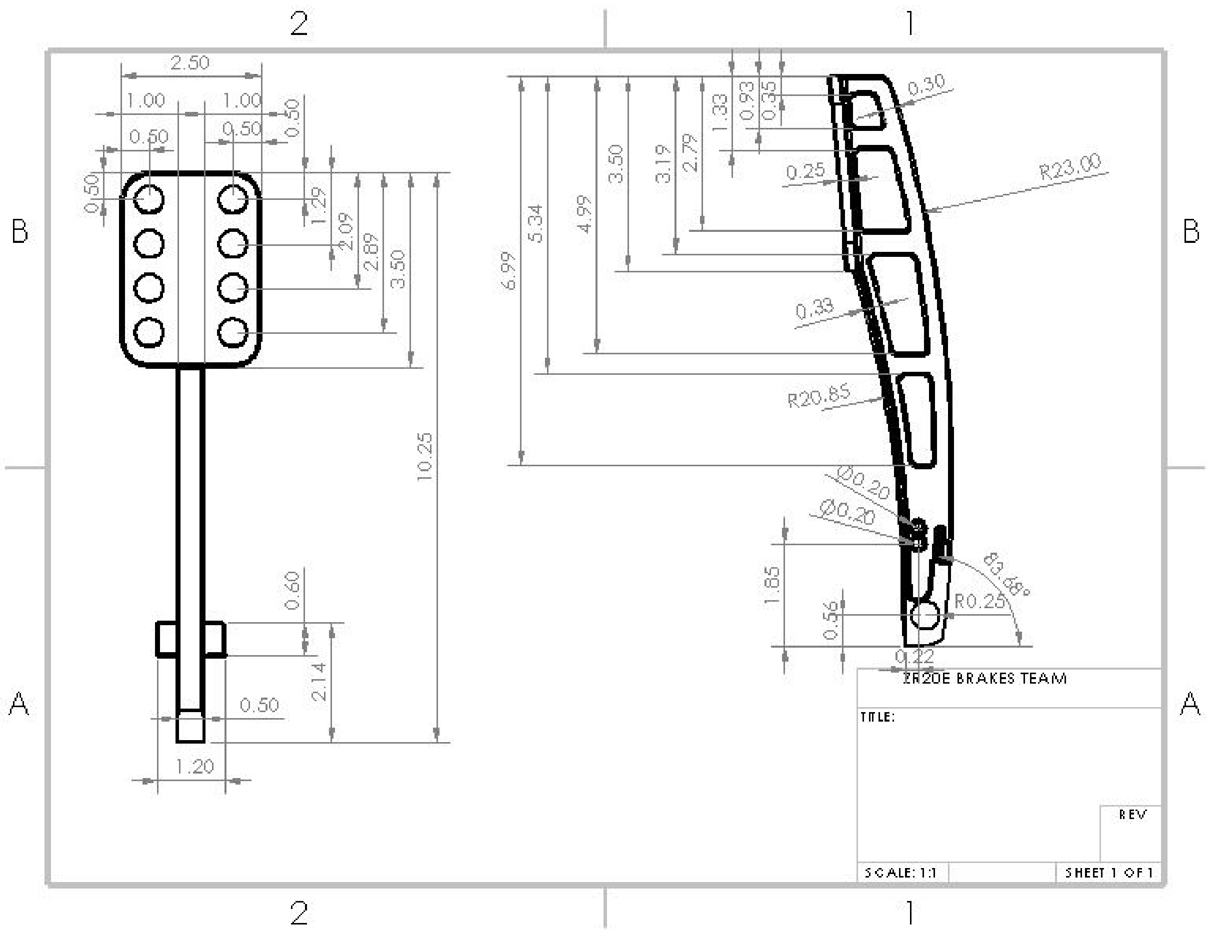

Figure 30: Throttle Pedal

Figure 31 shows the full assembly of the throttle pedal with all components and hardware installed. Similar to the brake pedal, the throttle pedal slides on the rail and allows for adjustment by the driver.

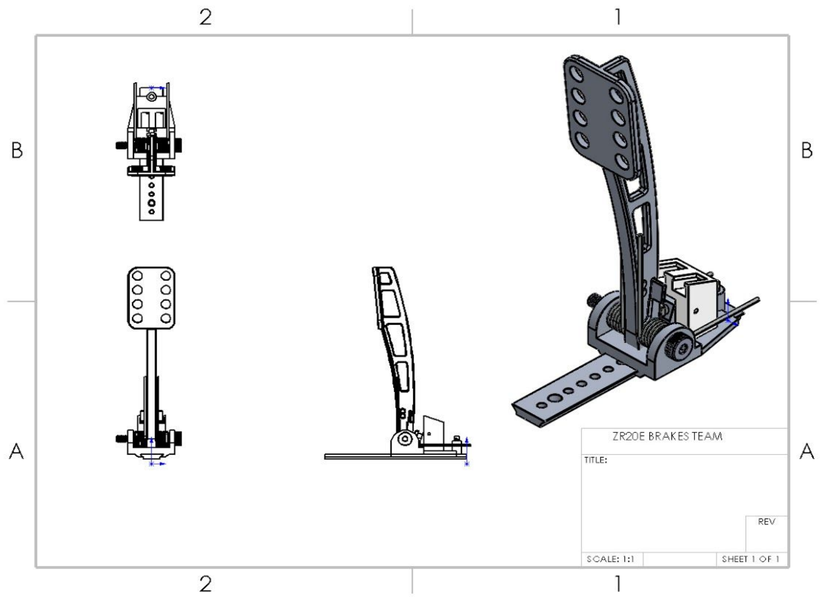

Figure 31: Throttle Pedal Assembly

Figure 32 shows the full assembly of the pedal box. A distance of seven inches between pedals was determined to be an ideal mix of small packaging and ergonomic ease for the driver. In a racing situation, the driver will use left foot braking, eliminating the need to have space to move the right foot over and brake. This setup complied with all FSAE rules and will be in the 2020 car.

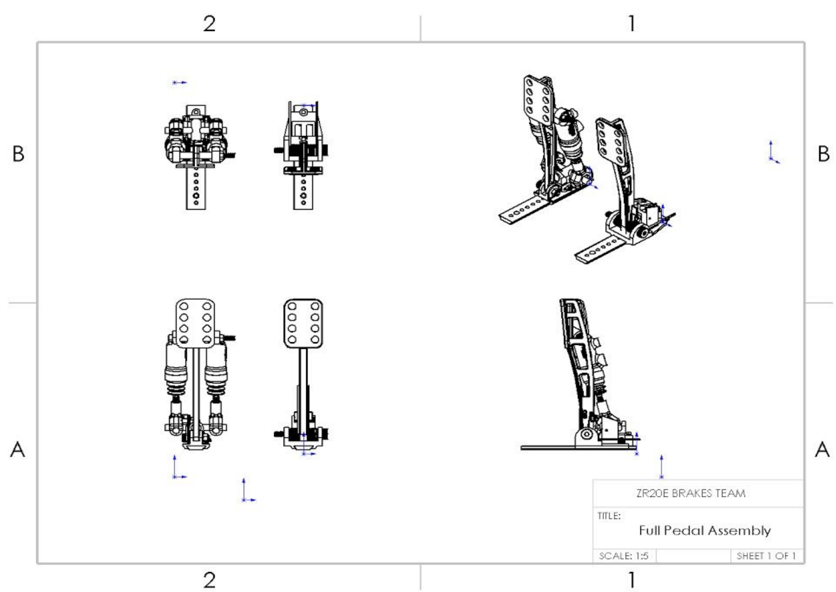

Figure 32: Full Pedal Assembly

Figure 33 shows the final bobbin design. This design allows for simple manufacturing on a lathe. A groove is cut in to allow a retaining ring to be attached, securing the bobbin in place. The face also has enough material to allow it to withstand the forces of braking. 45 degree chamfers were used instead of rounded fillets for ease of manufacture.

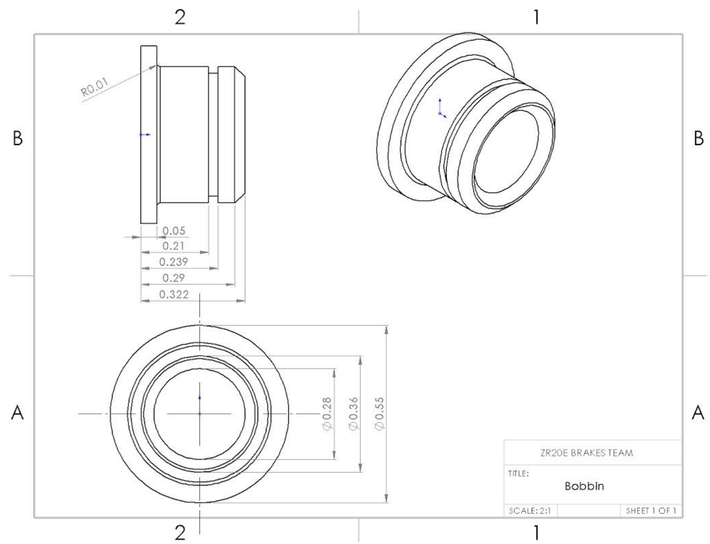

Figure 33: Brake Rotor Bobbin

Figure 34 shows the final rotor design. This design is used on all four hubs and allows for limited movement axially, known as a floating rotor. This allows for better braking performance and even brake wear. There are sixteen holes cut radially, eight for the bobbins and eight in between the bobbins to allow for minimal contact between the hub and the rotor. The face that comes in contact with the bobbins and hub has been cut into to reduce weight. There are four grooves cut on each side to allow for removal of debris during operation and for a small reduction of weight.

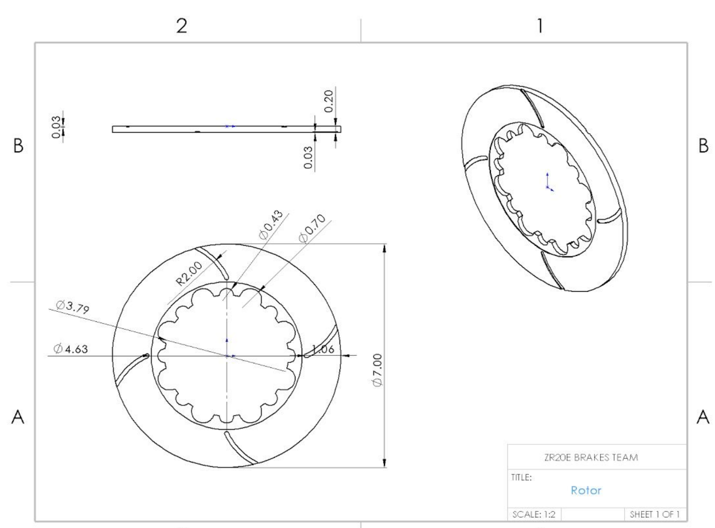

Figure 34: Brake Rotor

Figure 35 shows a completed construction of a front brake assembly. The eight bobbins hold the rotor to the axle, with retaining clips on the back side to hold the bobbins in place. The caliper is mounted as close as possible to the rotor - to allow for maximum rotor to brake pad contact while minimizing packaging - and facing towards the center of gravity to allow for better weight distribution. The rear brake assembly is similar to the front with the exception of a different caliper size.

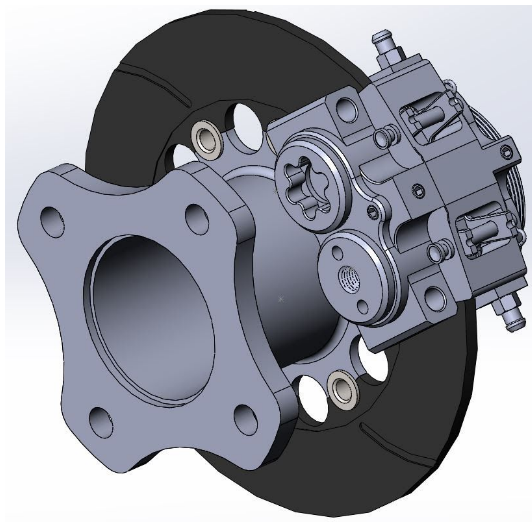

Figure 35: Front Brake Assembly

FEA Analysis

The pedals and the rotors are components that were designed to withstand a large amount of force. Figure 36 shows the finite element analysis (FEA) that was run for the throttle pedal, which was only required to withstand 1000 N of force. The resulting stress is shown throughout the pedal, confirming the success of the pedal design. Figure 37 shows the FEA for the brake pedal, which yielded similar results. This pedal, needing to withstand a greater force of 2000 N, was designed with a thicker structure in some areas in order to support the greater load. As shown, it also passed the FEA, maintaining an acceptable amount of stress throughout the pedal.

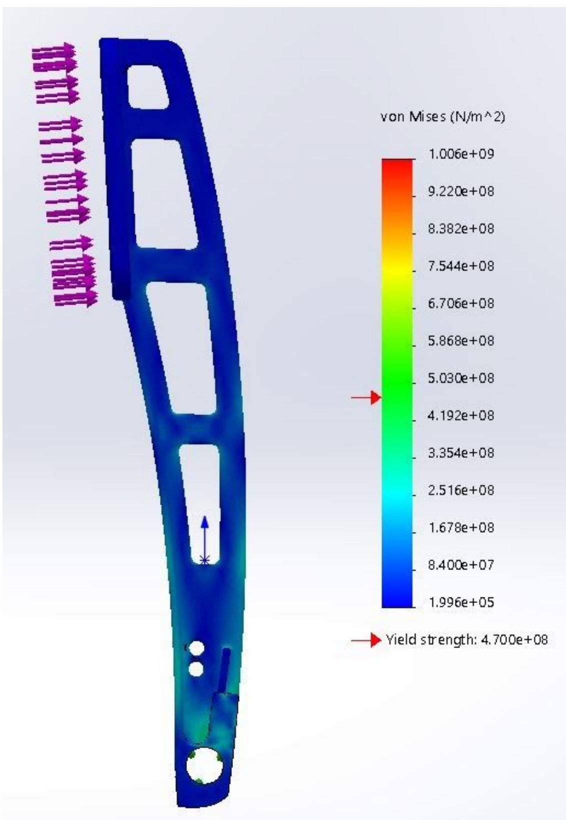

Figure 36: Throttle Pedal Stress at 1000N

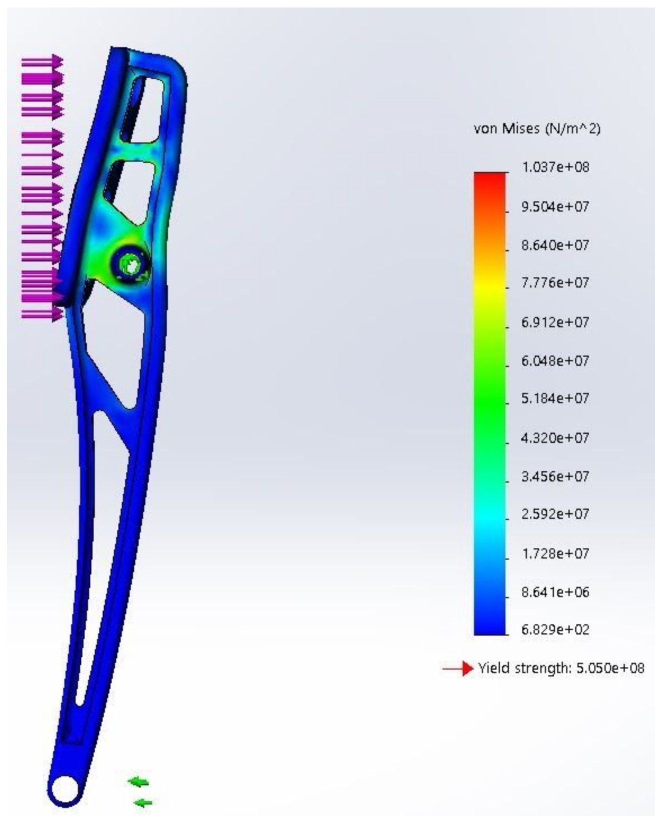

Figure 37: Brake Pedal Stress at 2000N

The stress on the rotor design was calculated similarly. The correct forces were applied to the rotor (as shown in figure 38) in order to output the resulting stress throughout the part. Like the pedals, the rotor design was deemed successful, as there was no sign of high stresses.

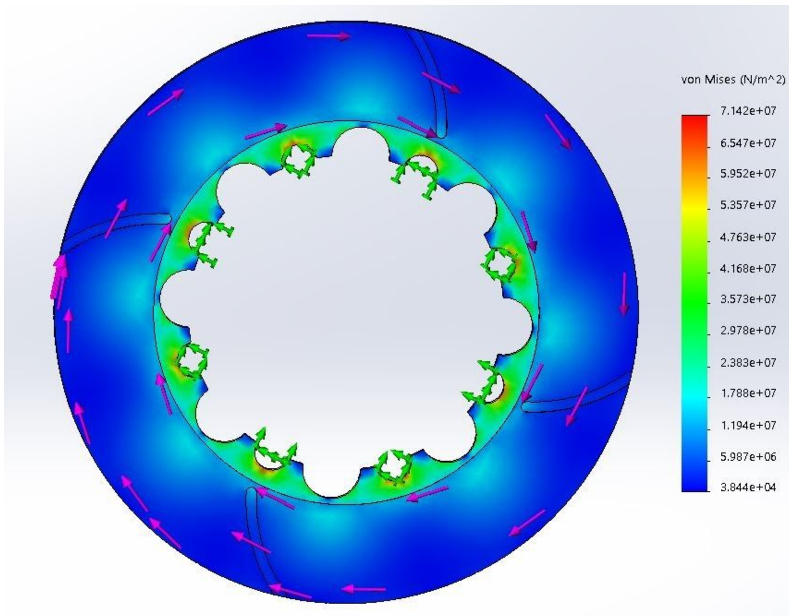

Figure 38: Brake Rotor Stress at 2000N

Table 4: Bill of Materials

Bill of Materials				
ITEM NO.	PART NUMBER	QTY	Cost	Total Cost
1	Brake Base Plate	1	$23.33	$23.33
2	P507-00 Balance Bar	1	$660.00	$660.00
3	TILTON 78-937	2	$180.00	$360.00
4	Pedal Slider	2	$10.00	$20.00
5	Brake Pedal	1	$90.00	$90.00
6	UNCOATED GRADE 8 STEEL NYLON-INSERT LOCKNUT	1	$0.35	$0.35
7	ALLOY STEEL SHOULDER SCREW	1	$3.14	$3.14
8	LOW-STRENGTH STEEL NYLON-INSERT LOCKNUT	2	$0.05	$0.10
9	STEEL SOCKET HEAD CAP SCREW	2	$0.34	$0.68
10	MC BOLT	1	$1.89	$1.89
11	GRADE 8 STEEL NYLON-INSERT LOCKNUT	1	$0.28	$0.28
12	Bots Mount Sheet Steel	1	$0.50	$0.50
13	Pin 0.5in Round Stock	1	$4.50	$4.50
14	MUSIC-WIRE STEEL COMPRESSION SPRINGS	2	$1.98	$3.96
15	BRAKE OVER-TRAVEL SWITCH	1	$7.99	$7.99
16	Throttle Pedal	1	$90.00	$90.00
17	Throttle Base Plate	1	$23.33	$23.33
18	0.5in Linear Sensor	2	$33.79	$67.58
19	Linear Sensor Plastic Mount	1	$1.79	$1.79
20	LH-Part- century_TO -5197LSCS	1	$13.99	$13.99
21	RLH-Part- century_TO -5197LSCS	1	$13.99	$13.99

22	T Fittings -AN3	2	$13.99	$27.98
23	AN 3 to M 10 Fittings	4	$6.47	$25.88
24	An3 to 1/8 NPT Fittings	2	$18.67	$37.34
25	1/8 NPT to 1/4 NPT Fitting	2	$3.99	$7.98
26	AN3 to AN4 Fitting	1	$10.29	$10.29
27	AN6 to AN4 Fitting	1	$12.75	$12.75
28	Tube Sleeves 6 Pack	2	$4.99	$9.98
29	AN3 Line Fittings 6 Pack	2	$4.99	$9.98
30	1/4 - 20 Bolts 2 in long	4	$0.42	$1.68
31	1/4 - 20 Nylon Locking Nuts	4	$0.05	$0.20
32	Steel Brake line 25 ft	1	$13.99	$13.99
33	Flexible Braided Brake Line 18in	4	$11.99	$47.96
34	Motul 600 Brake Fluid DOT 4 500ml	4	$15.26	$61.04
35	Plastic Tubing 2ft	1	$1.49	$1.49
36	External Retaining Clips 7/16	32	$0.13	$4.16
37	Bobbin Material - Aluminum 7075 1in Bar	1	$36.67	$36.67
38	Rotor Material - Cast Iron	4	$24.42	$97.68
39	ISR 22-048 Front Calipers	2	$223.23	$446.46
40	ISR 22-049 Rear Calipers	2	$131.90	$263.80
41	Brake Pads 12 Pack	1	$110.00	$110.00
42	Brake Cleaner Aerosol Can	1	$3.99	$3.99
43	3AN Male to Male	2	$4.98	$9.96
44	Brake Fluid Reservoir	2	$2.99	$5.98
Total Cost		**$2,634.64**		

Discussion

In order to validate the assumptions and calculations made during the design of this project, the overall product would have been rigorously tested. However, due to COVID-19, this testing was rendered impossible. The specific aspects of this project that would have undergone testing were the brake pedal assembly, the throttle pedal assembly, the throttle sensors, and the brake line pressure calculations. Without the ability to test these aspects, this project must rely on the previously reported calculations; however, the test procedures are outlined below.

In order to validate the brake pedal design, a force would have been applied to the pedal face up to and in excess of 2000 Newtons, and the results would be recorded. These results would include, but are not limited to, deformation of the pedal, shear of the pedal, bending or shifting of the pedal, anticipated pedal translation and rotation, or no visible effects on the pedal. The design would have been validated with no visible or otherwise measureable unexpected pedal bending, shifting, moving, cracking, or other deformation. This would prove the pedal has the capacity to function normally while under a 2000 Newton load as per FSAE regulation.

The throttle pedal would undergo a similar test set up, with a lesser force applied to it. With no specific force threshold to meet, the only criteria for the throttle pedal is that it would not break or deform under racing conditions. This can be translated to the maximum force a driver would normally exert on the throttle pedal, which was reasonably assumed to be 1000 Newtons. In order to validate the throttle pedal design, it would need to meet the same criteria the brake pedal must meet, under a load of 1000 Newtons. This would prove the throttle pedal has the capacity to function properly under racing conditions.

The throttle sensors would need regular testing and calibration in order to maintain the accuracy of the signal sent to the ECU. The frequency of the testing and calibration would have been a measure of how well the throttle assembly was designed, because the better and more accurate the design, the less frequently calibration would be necessary. The benchmark for this project was to ensure sensor calibration once per drive, and this was chosen because the calibration would be able to be completed quickly and efficiently while preparing the vehicle for testing, but could not be easily done once testing began. Meeting this goal would validate the accuracy of the throttle assembly design.

Brake line pressure would have been the most important aspect of this project to validate. The inclusion of brake line pressure sensors into the system would allow for a simple way to measure the actual brake line pressure in order to validate the calculations used to determine brake rotor size, master cylinder size, and brake caliper selection. Readings from these sensors would be recorded under maximum braking scenarios, with the vehicle reaching predetermined speeds and subsequently locking the wheels and coming to a stop. These readings would then be compared to pressures calculated for identical scenarios, which would be found by measuring initial speed, stopping distance, time taken, and friction coefficients for the tires on the road. For the brake line pressure design calculations to be verified, the calculated pressure and the measured pressure would both need to be under the maximum pressure calculated during the design phase, as well as for the two pressures to be within ten percent of each other. This would prove the validity of the brake rotor, master cylinder, brake caliper, and brake line designs.

Conclusion

The goal of this project was to create a functional braking system for the Zips Electric Race Team that was lightweight, cost-effective, compact, and would meet all FSAE rules and regulations. The end result was a system where the total weight of custom manufactured parts came out to 1.73 pounds with a total pedal box dry weight of 3.5 pounds, surpassing the goal of a sub-4.34 pound system. The total project cost without sponsorships was $2634.64. This project also met its goal of being as compact as possible by utilizing short components and designs, such as the torsional throttle springs, the master cylinder orientation chosen, and short throttle sensors, giving a total length required for the pedal box of 7 inches while accounting for positional adjustability. This project created a system that, on paper, would have met all of the FSAE rules and requirements and would have passed the FSAE technical inspection, which was a Zips Electric Racing team goal. This project successfully met all of the goals as outlined in the design brief. Future projects may be performed using this project as a springboard by finding additional ways to reduce weight of the braking system without compromising strength or function or by finding more convenient ways to package this system in order to have less overall length.

References

[1] Baumeister, Theodore Jr., et al. Standard Handbook for Mechanical Engineers. Tenth ed., McGraw-Hill Book, 1978.
[2] Budynas, Richard G., et al. Shigley's Mechanical Engineering Design. Tenth ed., McGraw-Hill Education, 2020.
[3] “Formula SAE Rules 2020.” 25 July 2019.
[4] Formula SAE Tire Test Consortium , PhpBB Limited, 19 Aug. 2019, www.fsaettc.org/.
[5] Milliken, Douglas L., and William F Milliken. Race Car Vehicle Dynamics: Problems, Answers, and Experiments. SAE International, 2003.
[6] Oberg, Erik, et al. Machinery's Handbook: a Reference Book for the Mechanical Engineer, Designer, Manufacturing Engineer, Draftsman, Toolmaker, and Machinist. Edited by Christopher J. McCauley et al., Twenty-Seventh ed., Industrial Press, 2004.
[7] Pacejka, Hans B. Tyre and Vehicle Dynamics. Elsevier Butterworth-Heinemann, 2009.
[8] Smith, Carroll. Tune to Win. Motorbooks International, 1999.

Appendices

Appendix A: Additional Images

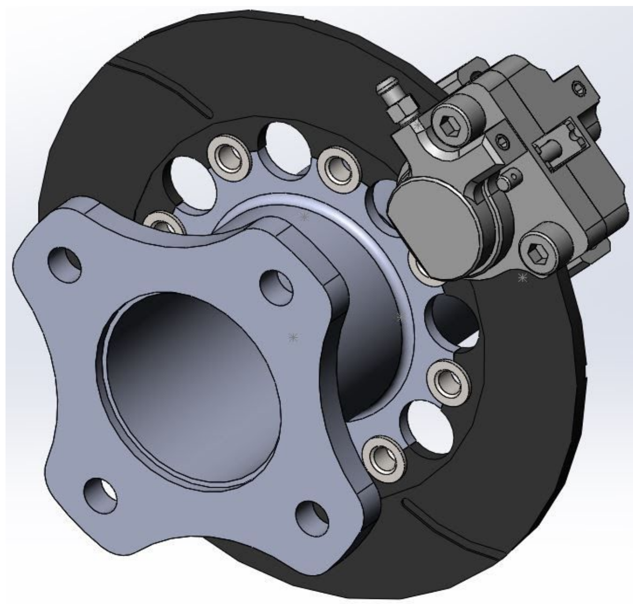

Figure 39: Rear Brake Assembly

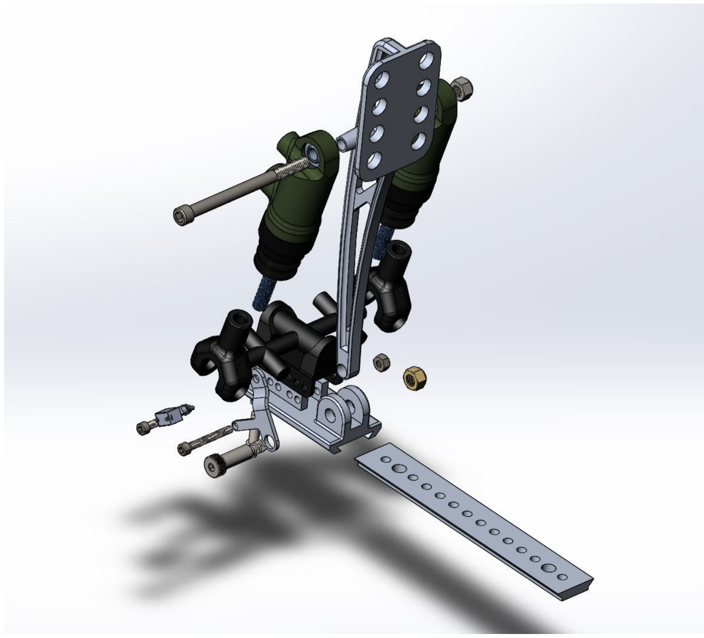

Figure 40: Brake Pedal Assembly Exploded View 1

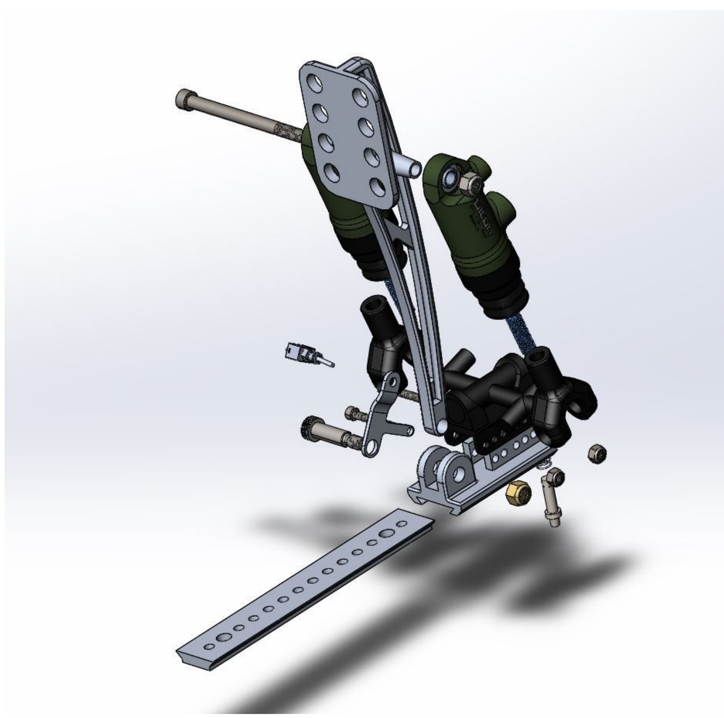

Figure 41: Brake Pedal Assembly Exploded View 2

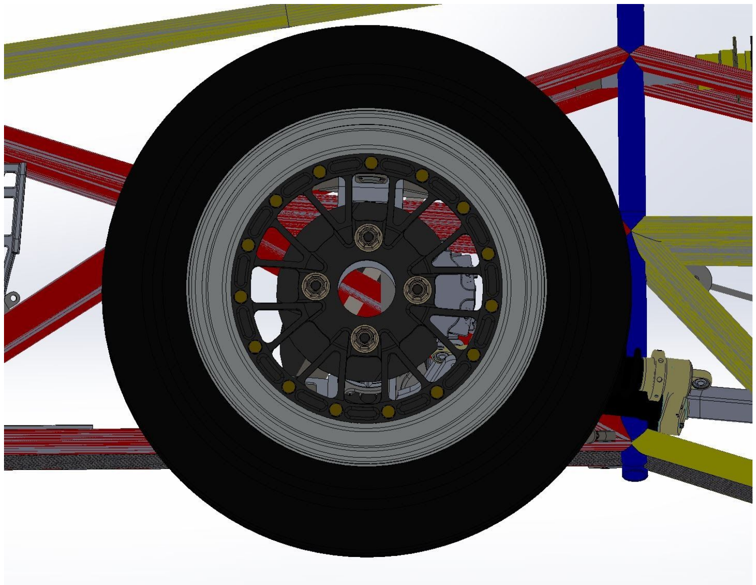

Figure 42: Front Brake Assembly with Wheel

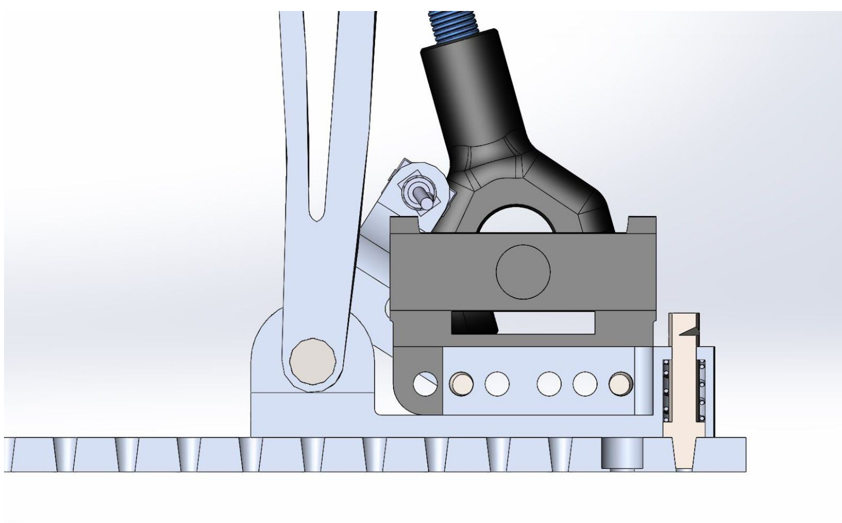

Figure 43: Brake Base Plate Cross-Section

Appendix B: Purchasing Catalog

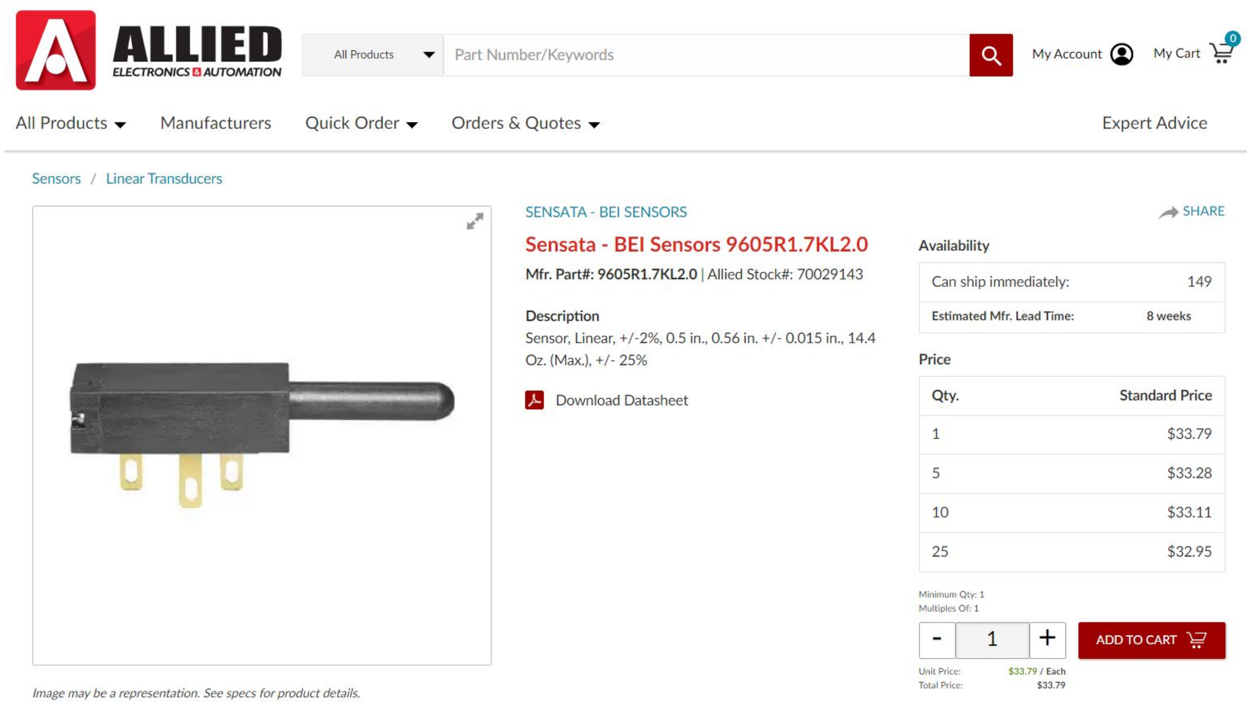

Figure 44: Linear Sensor

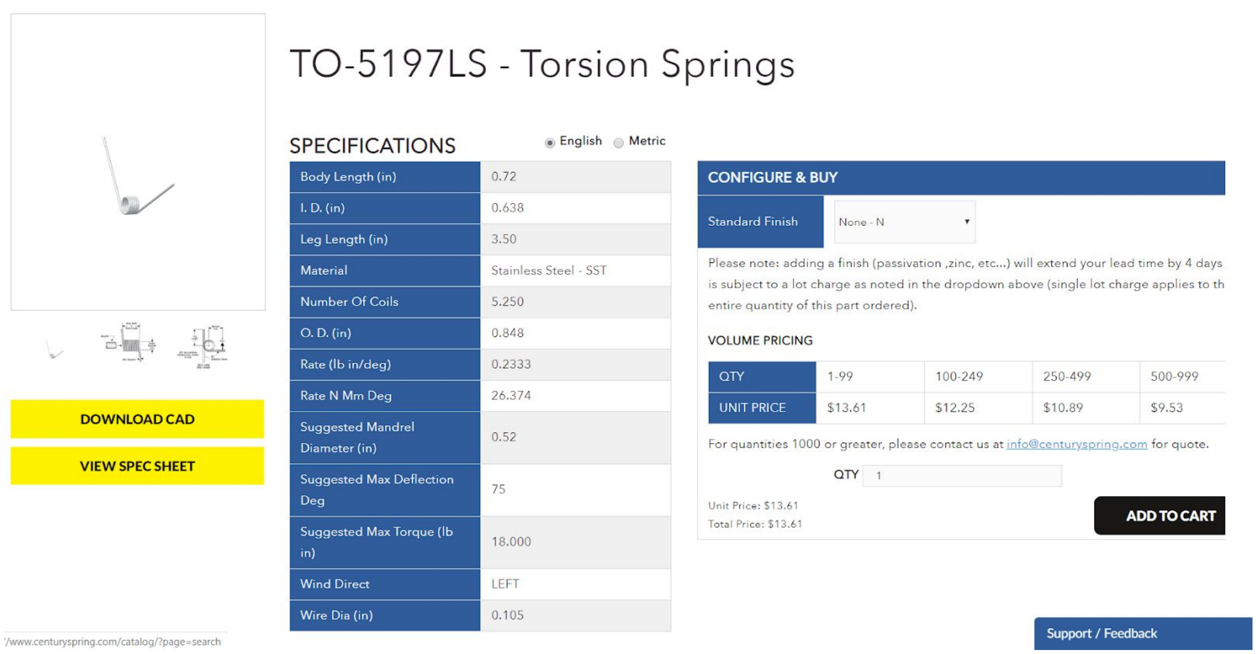

Figure 45: Left Hand Throttle Spring

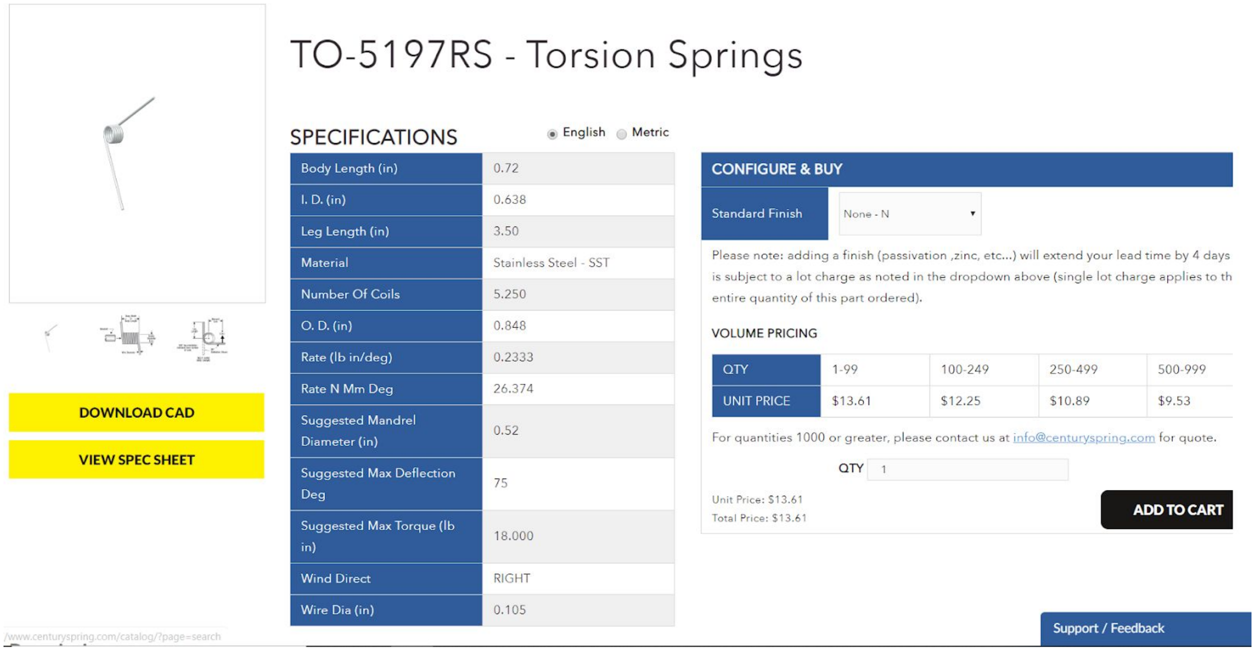

Figure 46: Right Hand Throttle Spring

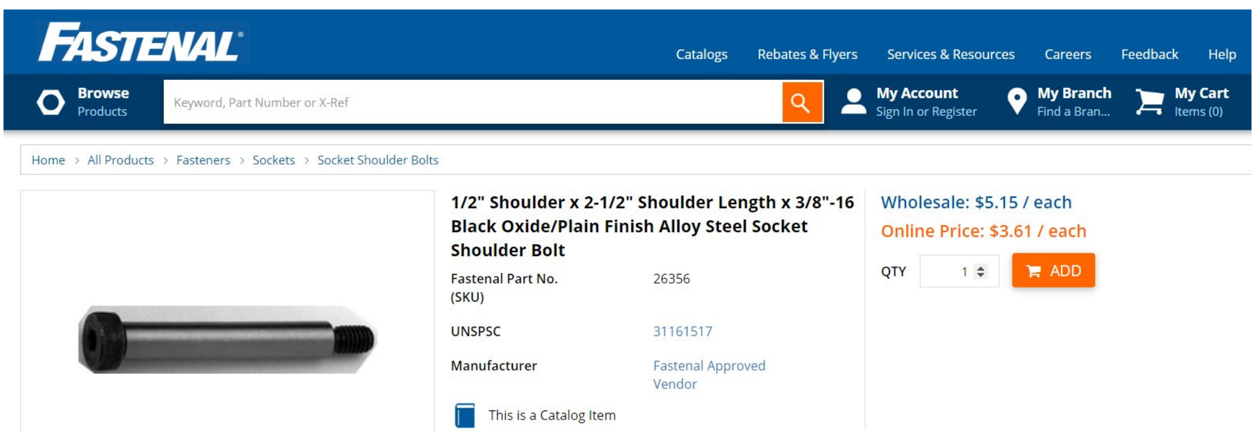

Figure 47: Throttle Assembly Shoulder Bolt

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22-048 4-piston caliper

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The 22-048 caliper was originally designed to be used in a two caliper brake system for 125cc bikes. But it was also intended as a brake caliper for light weight cars, as Formula SAE cars. The car version of the caliper has the brake fluid inlet in one of the caps.

This caliper got only 27 mm height of the swept disc area. This means the disc can be made light.

Technical data

Part number (Click on Part# to view image)	22-48
Piston diameter	25 mm (x4)
Piston material	Tufram coated aluminium alloy
Pad type	ISR 29-002 (x4)
Pad area	14 cm2
Swept height of disc	27 mm
Disc size	150 - 250 mm
Disc thickness	4.6 - 5.0 mm
Hydrualic thread	M10 x 1.25
Weight incl. pads	0.46 kg
Surface finish	Clear anodised

Figure 48: Front Calipers

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22-049 2-piston caliper

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The 22-049 caliper was originally designed to be used for Motocross bikes but the caliper is also suitable for all kinds of lighter bikes and cars . It can be used in a one or two caliper brake system.

This caliper has only got a 27 mm height of the swept disc area. This means the disc can be made light. It also means that the brake disc gets a clean "low profile" design.

Technical data

Part number (Click on Part# to view image)	22-049-OA (RH) 22-049-OB (LH) 22-049-OC (RH car) 22-049-OD (LH car)
Piston diameter	25 mm (x2)
Piston material	Tufram coated aluminium alloy
Pad type	ISR 29-002 (x2)
Pad area	7 cm2
Swept height of disc	27 mm
Disc size	150 - 250 mm
Disc thickness	4.6 - 5.0 mm
Hydrualic threads	M10 x 1.25
Weight incl. pads	0.29kg
Surface finish	Clear anodised

Figure 49: Rear Calipers

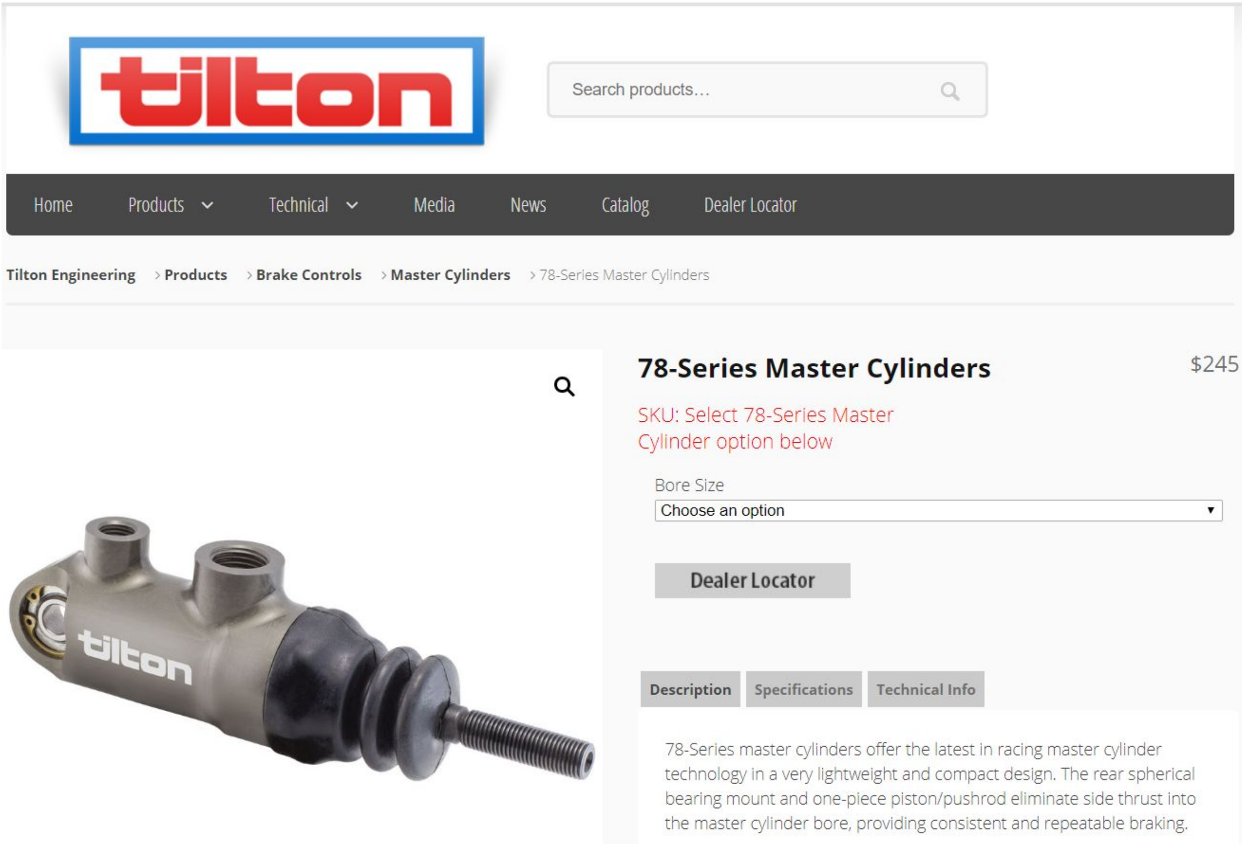

Figure 50: Master Cylinders

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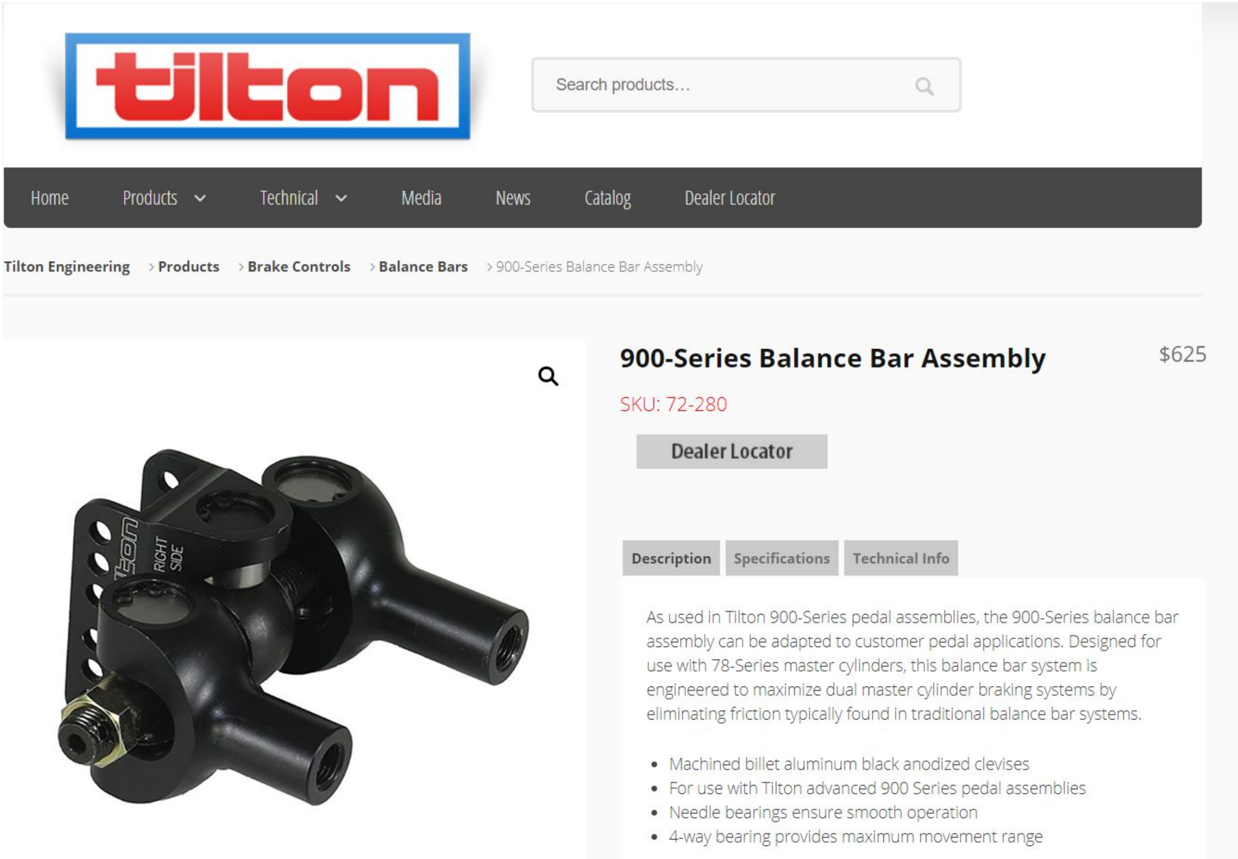

Figure 51: Balance Bar

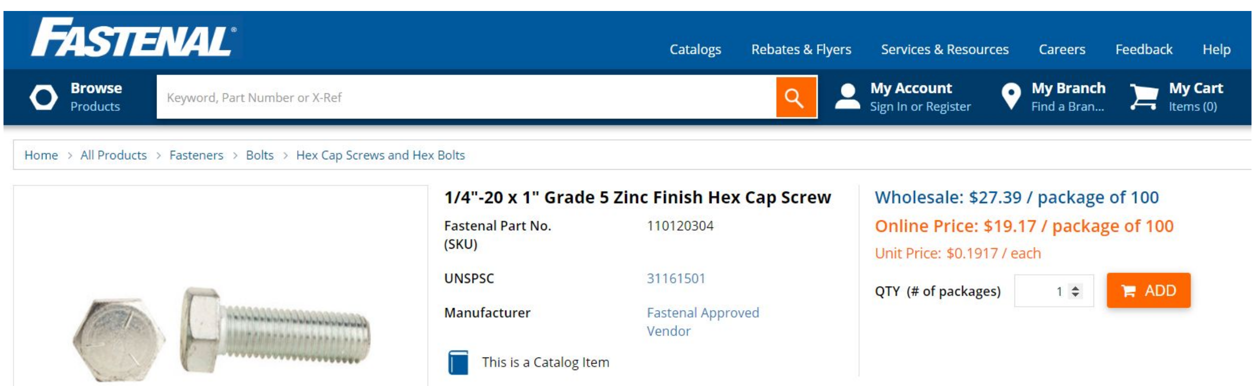

Figure 52: ¼-20 Hex Bolt - 1”

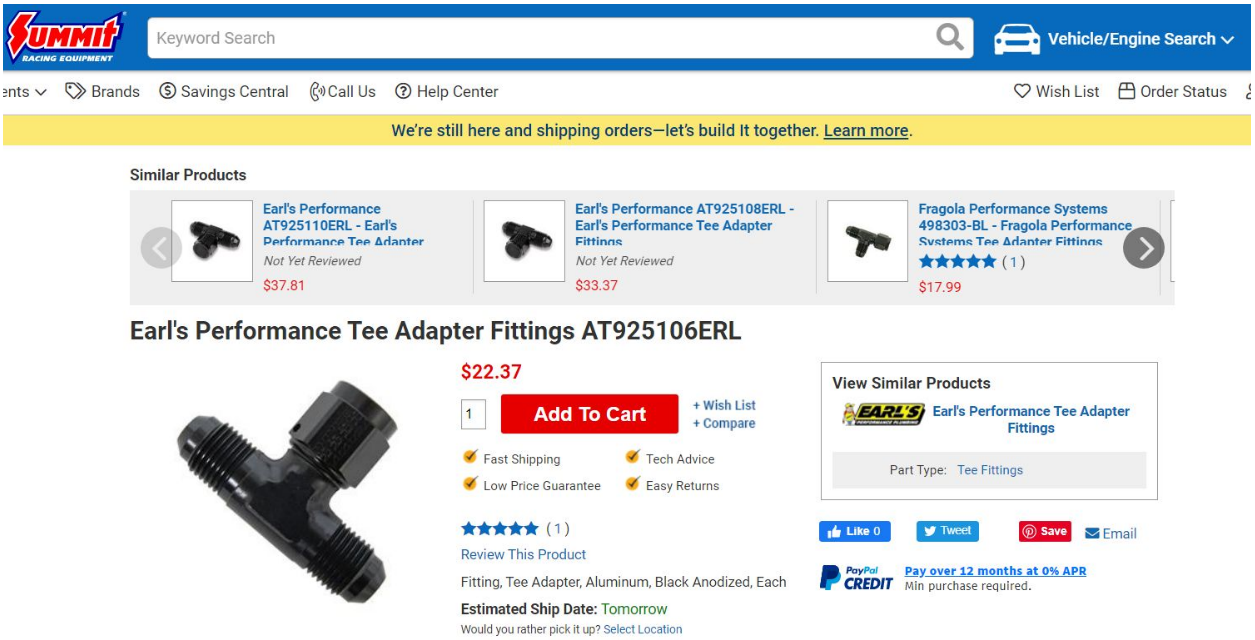

Figure 53: Tee Adapter Fitting

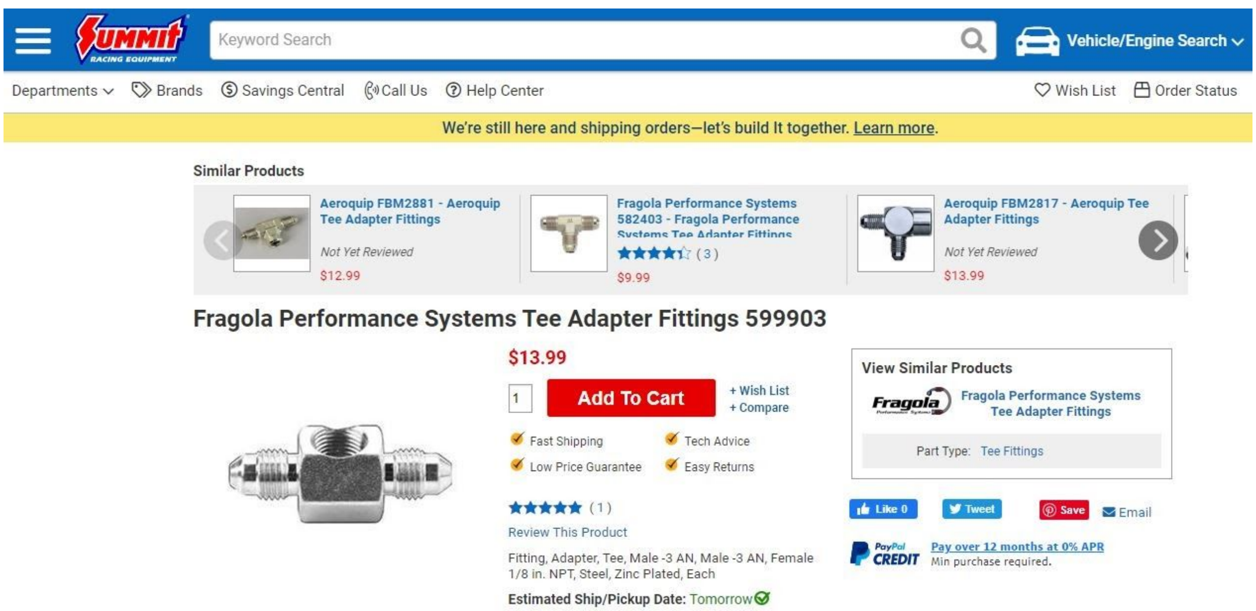

Figure 54: AN to NPT Tee Adapter Fitting

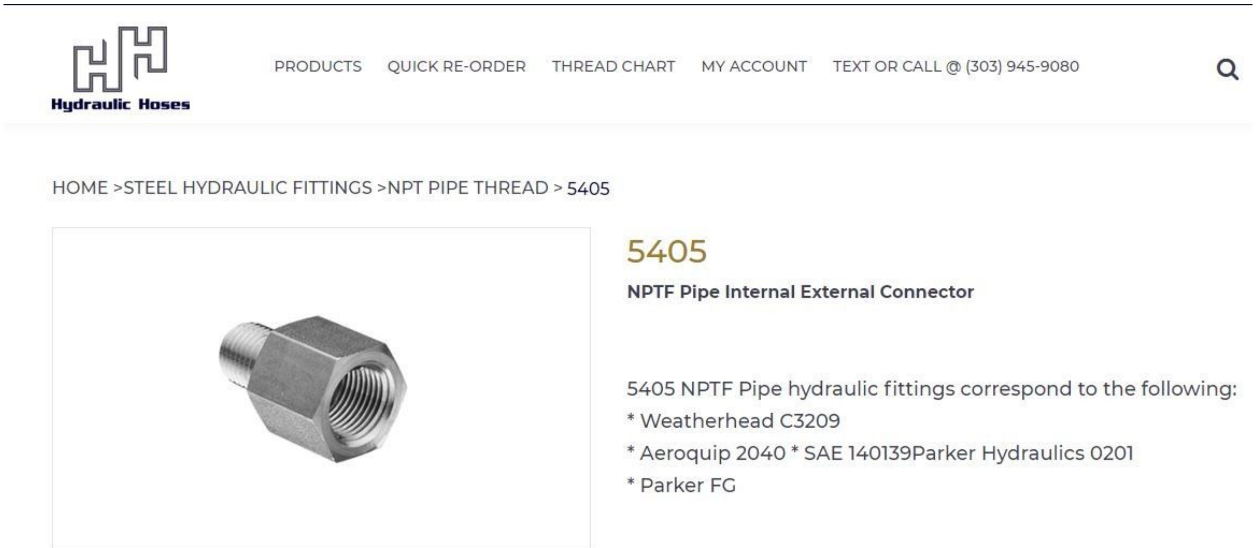

Figure 55: ⅛ to ¼ NPT adapter

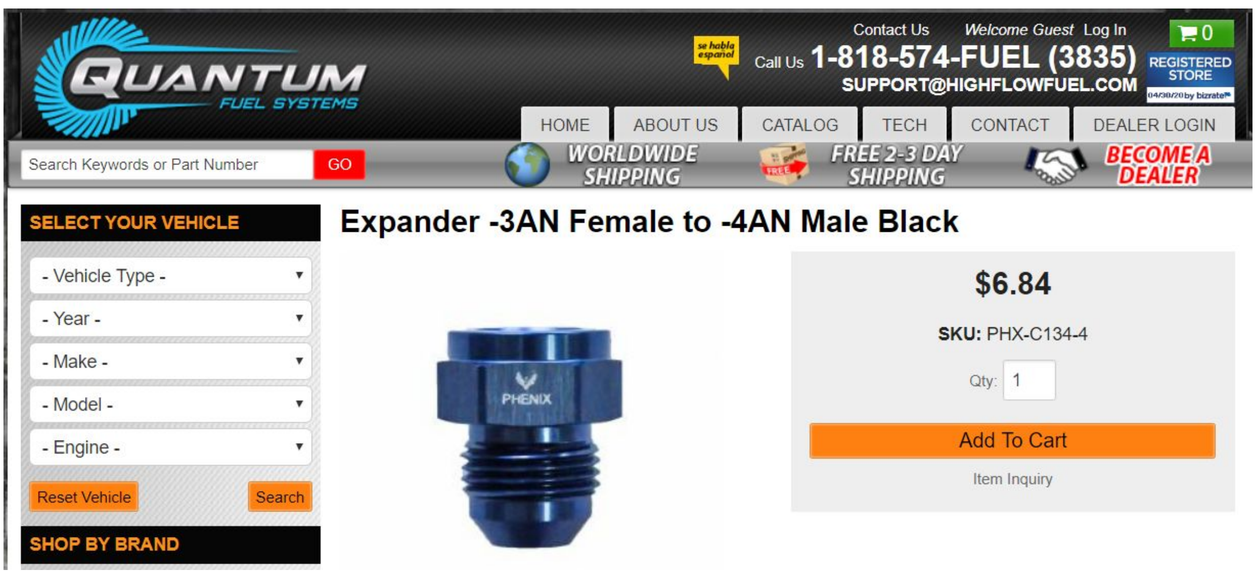

Figure 56: -3AN to -4AN Fitting

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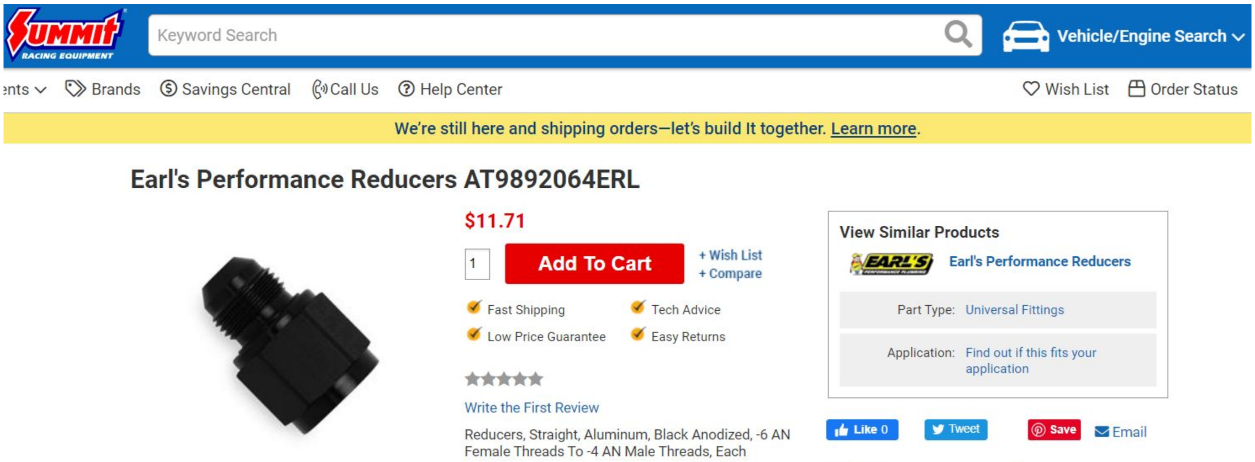

Figure 57: -6AN to -4AN

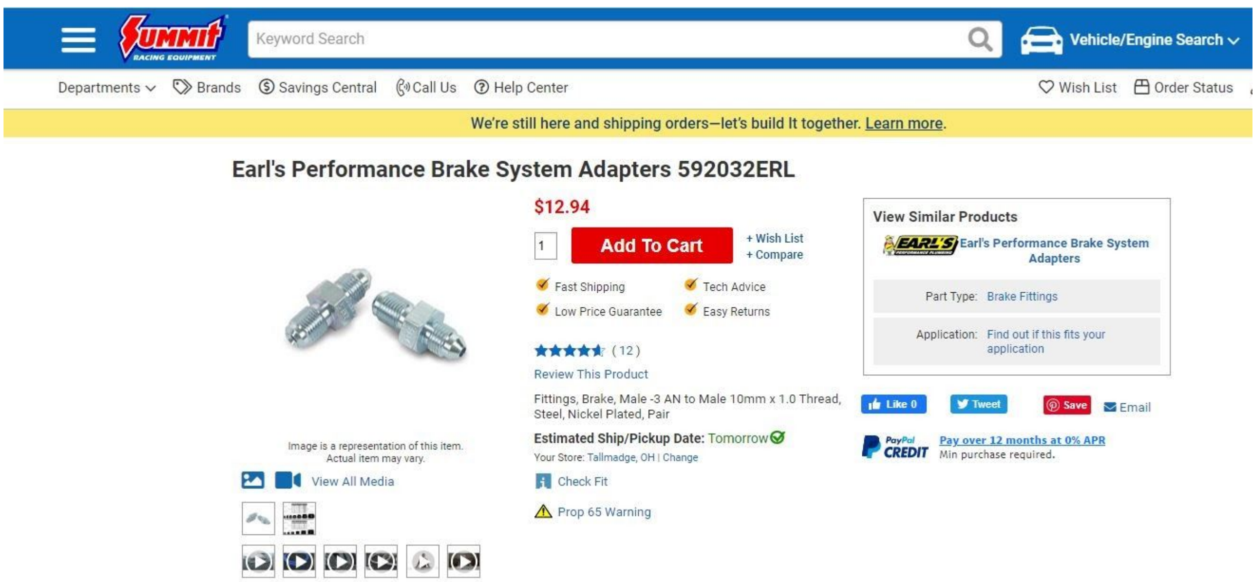

Figure 58: -3AN to M10

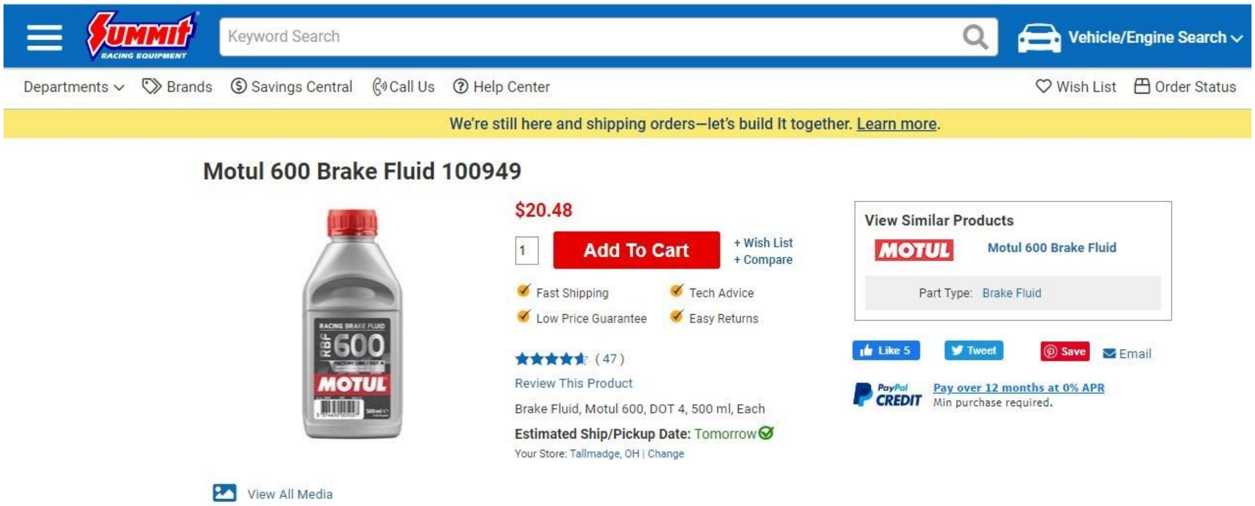

Figure 59: Brake Fluid

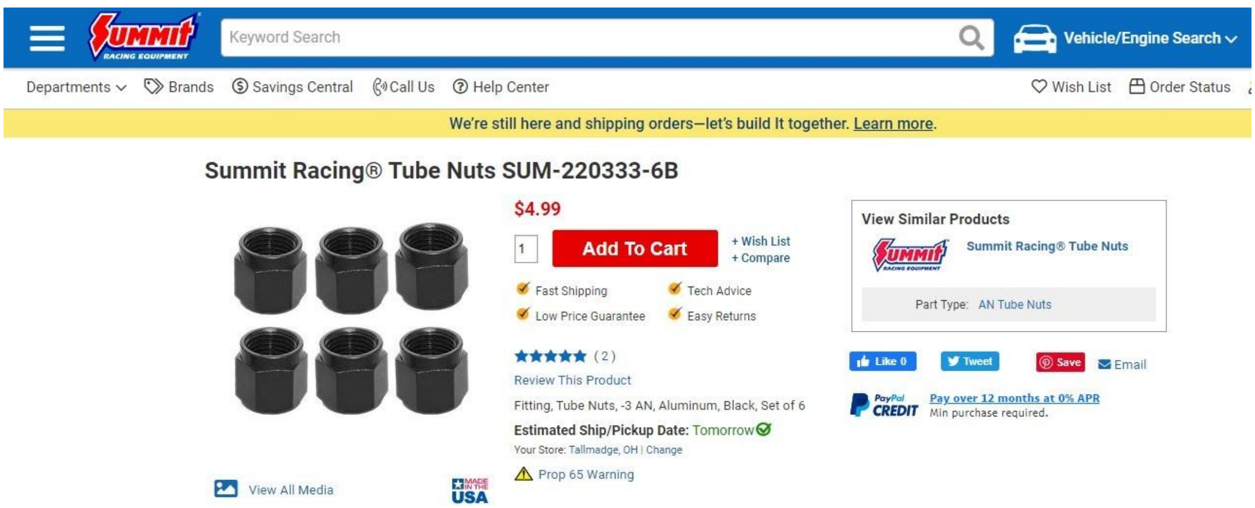

Figure 60: Tube Nuts

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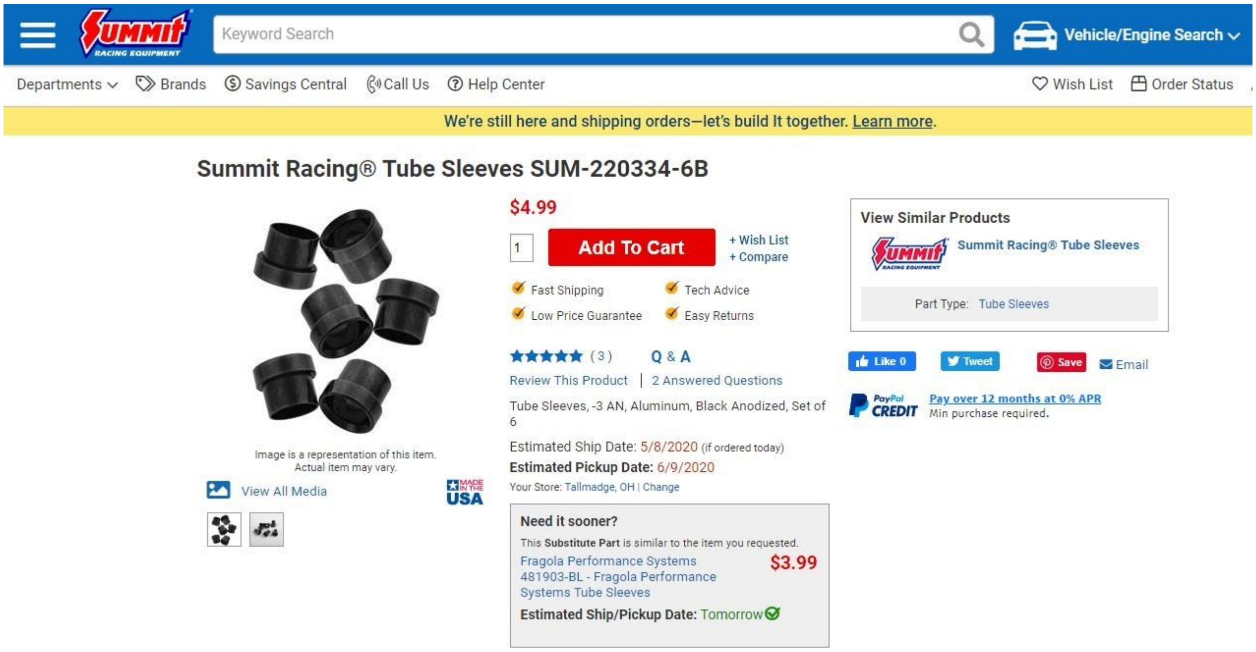


Figure 61: Tube Sleeves

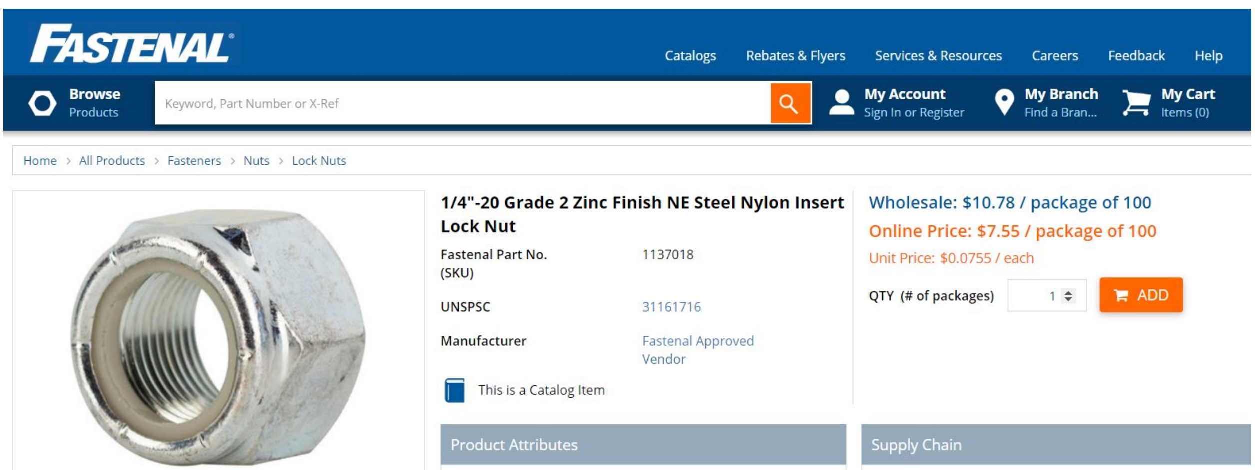


Figure 62: ¼ - 20 Locknuts

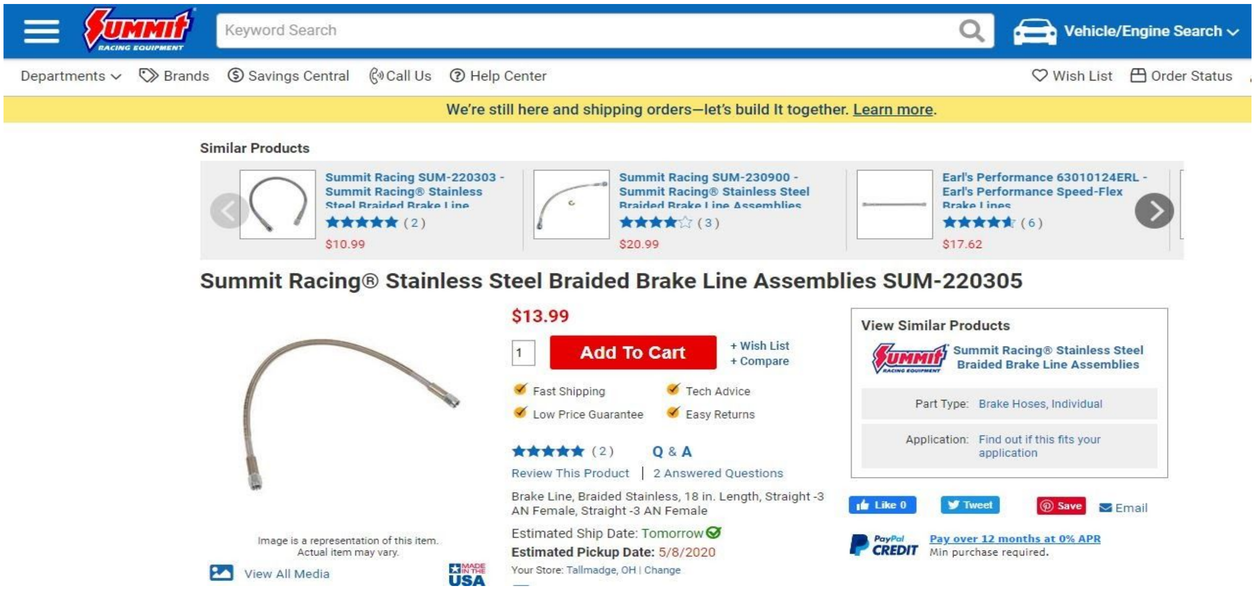


Figure 63: Braided Steel Line

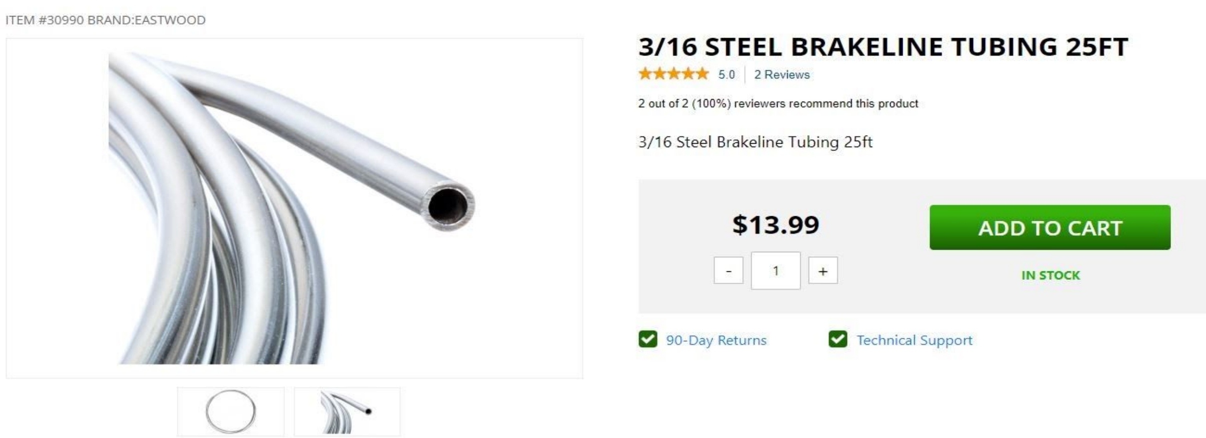


Figure 64: Steel Brake Line

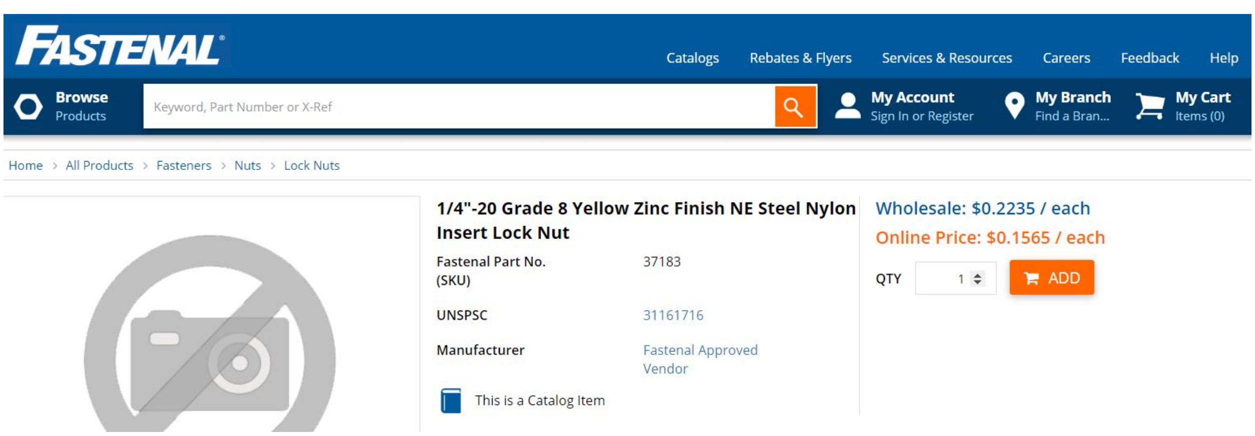


Figure 65: ¼ - 20 Locknuts

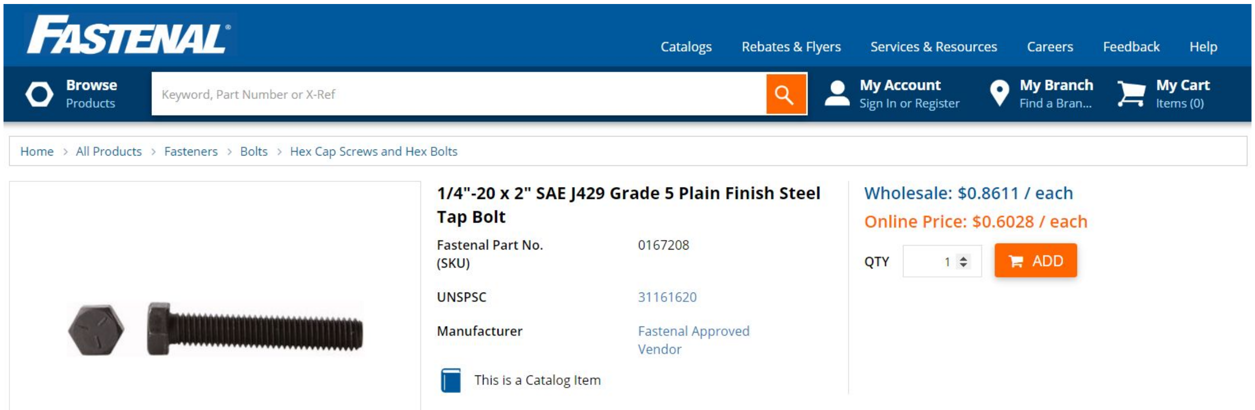


Figure 66:¼ - 20 Locknuts

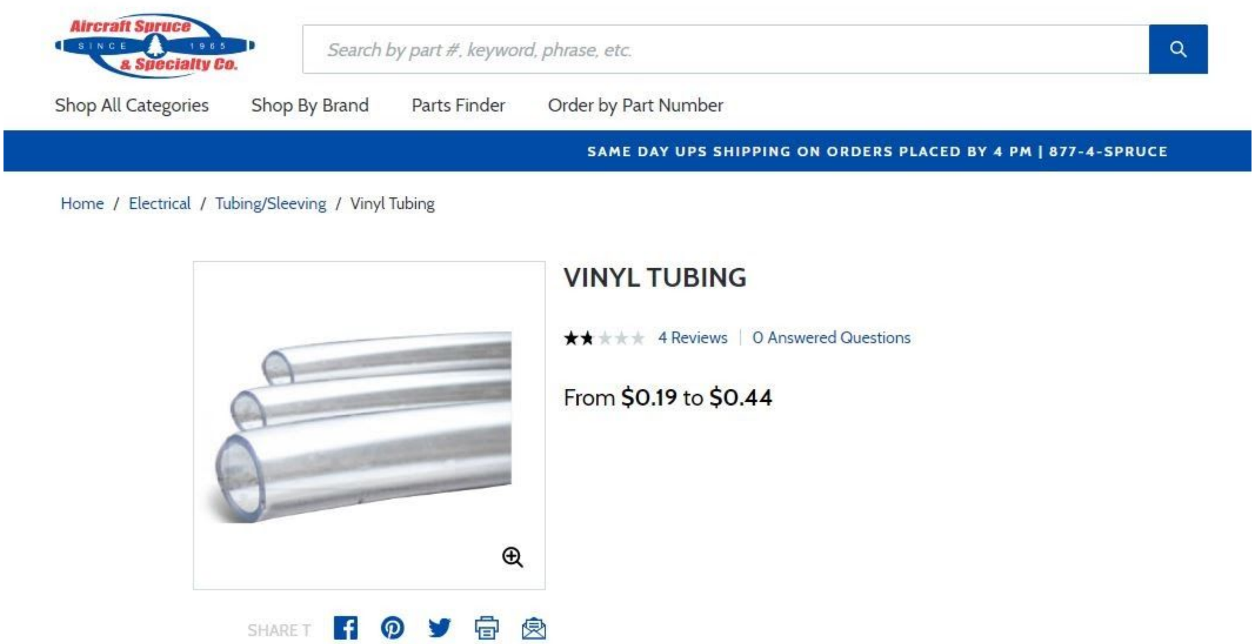
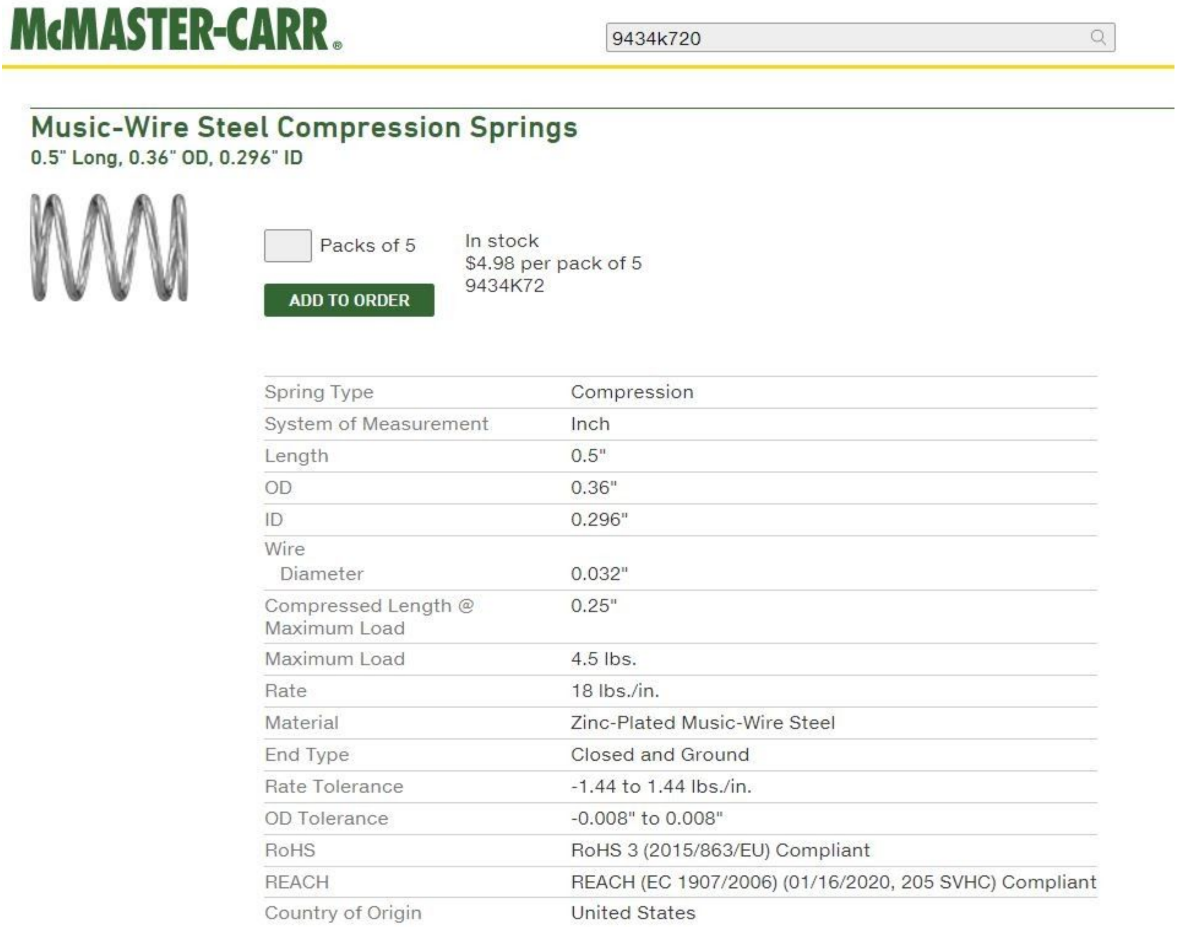


Figure 67: Vinyl Tubing



Spring Type	Compression
System of Measurement	Inch
Length	0.5"
OD	0.36"
ID	0.296"
Wire Diameter	0.032"
Compressed Length @ Maximum Load	0.25"
Maximum Load	4.5 lbs.
Rate	18 lbs./in.
Material	Zinc-Plated Music-Wire Steel
End Type	Closed and Ground
Rate Tolerance	-1.44 to 1.44 lbs./in.
OD Tolerance	-0.008" to 0.008"
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
Country of Origin	United States

Figure 68: Pin Springs

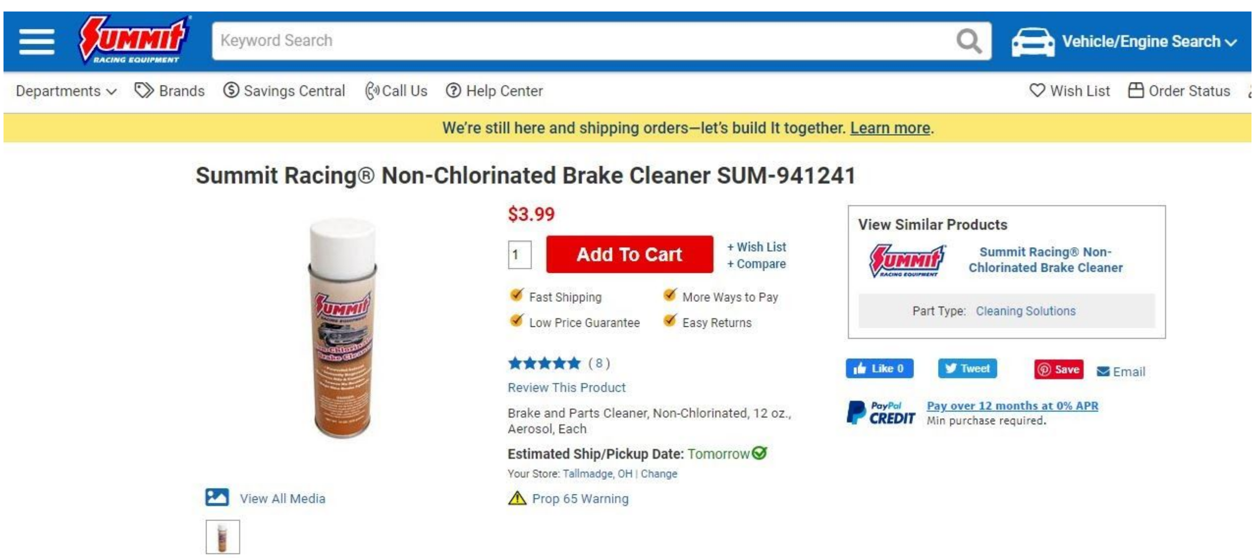


Figure 69: Brake Cleaner

May 3, 2020, Akron, Ohio
United States

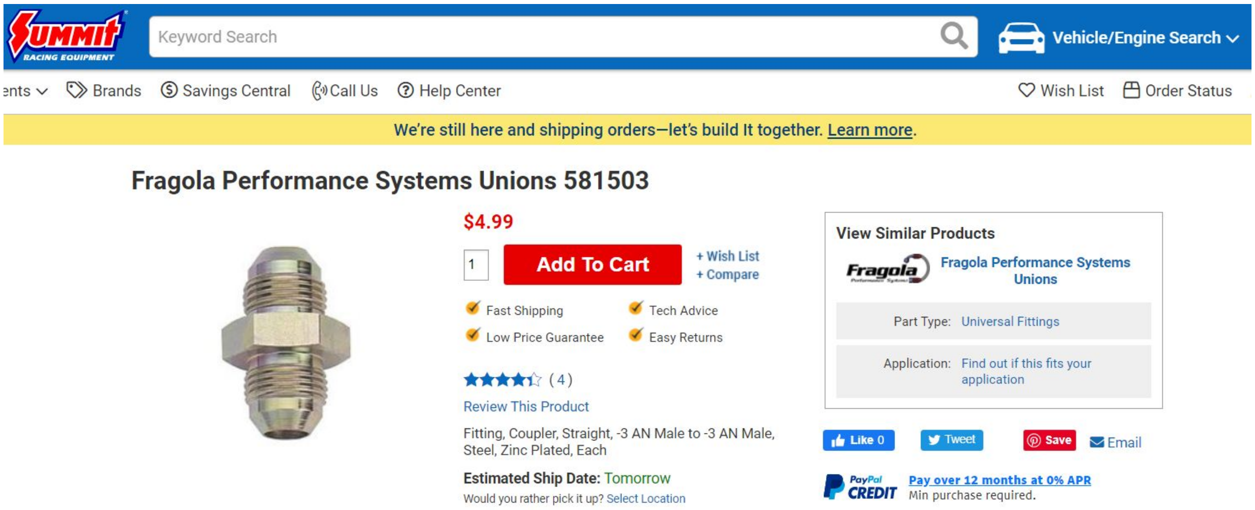


Figure 70: -3AN male to male fitting

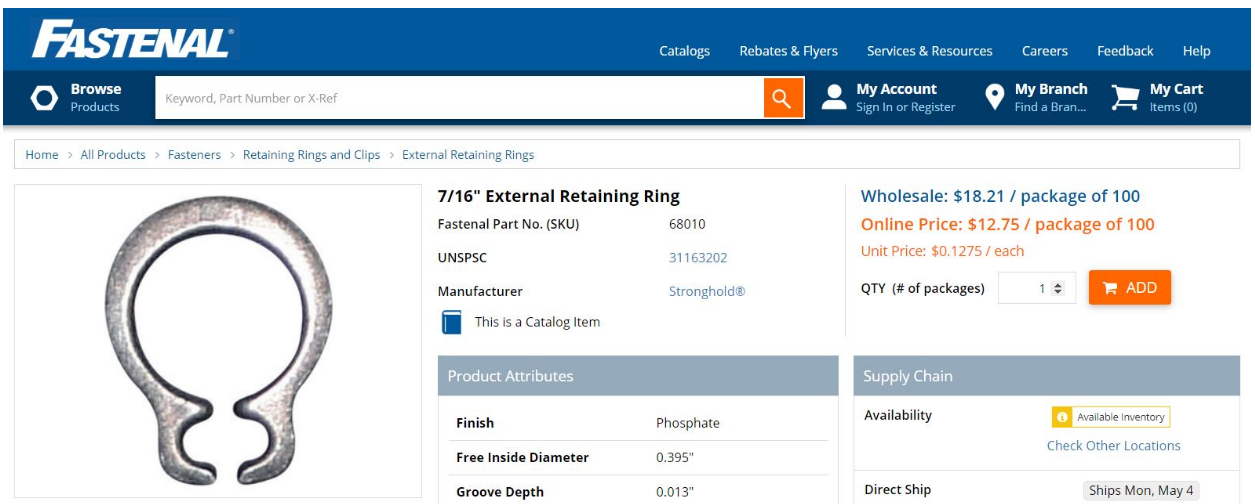


Figure 71: 7/16 Retaining Rings