Cal Poly BSAE Brake Caliper

Final Design Review (FDR) Report

Ben Leistiko

Carter Foye

Colin Williams

Nathan Berger

Mechanical Engineering Department California Polytechnic State University San Luis Obispo

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Abstract

In the past, the Cal Poly Racing Baja SAE team has used off-the-shelf brake calipers for their vehicle. Off-the-shelf calipers have been either oversized, resulting in a heavy and hard to package system, or undersized, resulting in an unreliable system that does not provide adequate braking power. The goal of this project was to provide a caliper that meets the requirements of Cal Poly's Baja SAE team. Our final design consisted of a two piece CNC machined caliper that uses the complex piston seal geometry from an existing mountain bike brake caliper. Using an existing caliper as a reference allowed us to focus more on creating an improved caliper design and improved our chances of our first machined prototype functioning as intended. Ultimately we were able to get our first prototype to function on the Baja SAE car and the design was able to stop the car effectively both in testing and at competition.

Contents

1. Introduction

We are a team of mechanical engineering students who all have multiple years of experience on Cal Poly Racing's Baja team. We are all currently in lead positions, and one of our teammates was previously brakes lead. Our team's 12 years of combined experience with the Baja team has allowed us to identify problems that hinder our competition performance.

One such problem is the lack of off-the-shelf brake calipers that satisfy the team's needs. Historically the braking system on the Baja car has been plagued with issues related to the calipers used on the car. Rapid pad wear, failure to reliably lock the wheels, caliper seal failure, and challenges with caliper packaging have all been issues with the calipers used. Numerous off-the-shelf options exist and have been used in the past, but all have issues that lead to them not being an acceptable solution for the team. The general trend we have seen is that the calipers are either too small and have issues with performance and reliability or too large and challenging to package.

The entire Baja team has a stake in this issue because braking performance affects our placement at competition. While the team is affected by caliper choice and performance, the brakes lead, suspension leads, and service leads are most concerned with the specifics of caliper performance. The brakes lead is concerned with all aspects of the caliper because they are responsible for delivering a functional brakes system. The suspension leads are most concerned with size and means of mounting, as they are involved in integrating the calipers with front suspension. The service leads care most about maintenance requirements and serviceability, because once the system is on the car, they will be responsible for maintaining the calipers.

2. Background

2.1. Competition Background

The Cal Poly Racing Baja team participates in an international collegiate design competition put on by the Society of Automotive Engineers called Baja SAE. In this competition, students are tasked with the technical challenge of building a one-person all-terrain vehicle to compete in static and dynamics events with around 100 other teams. All teams must use the same 14HP (air restricted to 10HP) Kohler engine, and the vehicles are regulated by a booklet of rules that specify things like chassis design, safety features, and bounding boxes for the vehicle which are all verified at a Technical Inspection at competition. After a team passes technical inspection, they can participate in the rest of the competition.

To pass final tech inspection, a vehicle must demonstrate the ability to lock all four wheels while driving at speed. This demonstration is done on either dirt or pavement. This event is called "brake check" and is one of the highest dynamic load cases we see in the braking system, so it must be considered when designing calipers for the Baja team.

In addition to these "static" events, there are a collection of dynamic events, such as Acceleration, Maneuverability, Suspension, and Sled Pull. Acceleration and Sled Pull are self-explanatory and are tests of the vehicle's max acceleration and ability to pull a weighted sled. Maneuverability tests a vehicle's ability to precisely navigate tight turns at speed, whereas Suspension tests a vehicle's capability to surmount more technical obstacles like rock piles and logs. The vehicle is given a score based on the relative performance compared to the rest of the vehicles in each individual event. Lastly, at the end of the competition, there is a 4-hour long Endurance race. The objective of this race is to record as many laps as possible in the 4-hour long time span. Each track differs based on the competition site, but most are around a mile long and often are based on an existing motocross track. In general, teams who see the least failures in endurance perform the best, as they stay on track the longest and complete the most laps.

2.2. Research

We identified four main sources of information: online documentation about caliper design, manufacturer information about existing products, people with knowledge about brakes systems (past and current Baja brakes leads), and testing of the car this project is based on.

2.2.1. Online Resources

A brake caliper uses hydraulically actuated pistons to press friction pads against a brake disk (brake rotor) to generate braking torque. Braking torque is transmitted through a vehicle's wheels to decelerate it or slow its speed. Figure 1 shows a cross section of a typical brake caliper.

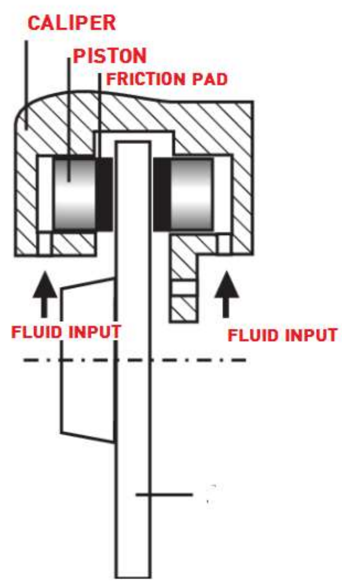


Figure 1: Brake Caliper Cross Section.

There are research papers and reports online that cover the process of designing custom brake calipers. One such report was produced by an SAE India Baja team. That paper is very applicable to this project because it covers the design of a caliper for the same type of vehicle our project is focused on. The report provides a somewhat surface level overview of the entire caliper design process, including the preliminary calculations required to size a braking system. A key takeaway from this design guide is that the piston seal will likely be the most challenging part of the design process. Fortunately, the paper references another research paper that covers analysis of piston seal geometry. The reason brake caliper piston seals are such a significant design challenge is because they serve as both a seal and a retraction spring. When the brakes are applied, the piston moves forward, and when the brakes are released, the elasticity of the seal pulls the piston back. This means that there must be no slipping between the piston and the seal throughout piston travel.

A research paper titled "Analysis of Brake Caliper Seal-Groove Design" covers methods of modelling the piston-seal system to design functional seal-groove geometry. The researchers used Abaqus CAE to create a finite element model of the seal, with friction and cylinder pressure modeled. Abaqus CAE was used because it is ideal for solving complex models with nonlinear geometry, contacts, and materials, which made it ideal for modelling highly nonlinear seal rubber. An important takeaway from the paper is that analysis of the seal will always yield approximate results. Physical testing will be needed to determine if the seal geometry will work over prolonged use and at a range of temperatures. This will usually involve trial and error, but ideally analysis will help get the design close enough to minimize the number of iterations needed.

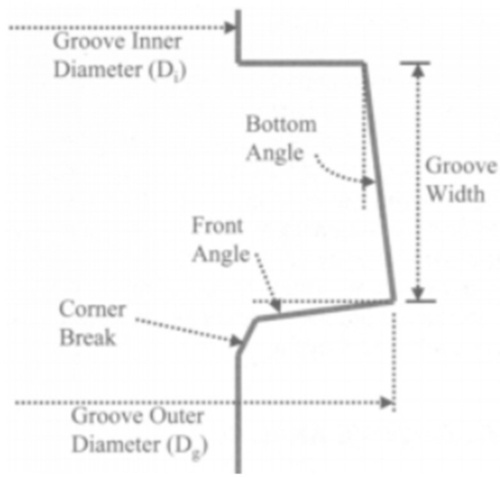


Figure 2: Seal-Groove Design Parameters.

Figure 2 shows the parameters that the designer can change when designing seal-groove geometry. The specific values will depend on the application, but the research paper did give some ballpark values which will aid in our design. These values are summarized below in Figure 3 with data from the research paper. This paper only gave ballpark values for Front Angle, Corner Break, and Groove Diameter.

Front Angle (degrees)			Corner Break (mm)	Groove Diameter (mm)
6.5	10.0	14.0	0.3	59.53
			0.7	59.53
			0.3	59.69
			0.7	59.69

Figure 3: Ballpark values of seal design parameters.

Another report, titled “Design and Analysis of Modular Caliper Assembly,” goes into detail about mechanical and thermal analysis of a braking system. The braking system analyzed in the report is not a Baja system, but the principles are not specific to the type of vehicle. The thermal analysis content of the report is very useful, as our team members have significant experience with structural analysis, but less with thermal analysis. An important aspect of brake system thermal management is controlling how much heat is transferred into the caliper. Rotors have a lot of surface area and are usually made of heat resistant materials including cast iron, steel, and ceramic, while calipers have components that are more heat sensitive. For this reason, it is desirable for most of the generated heat to be dissipated into the rotor. A clever idea presented in the report is the use of a titanium insert between the friction pad and the piston. Titanium has low thermal conductivity, which helps limit the amount of heat transfer into the caliper body.

The design guide by the SAE India team also covers structural analysis of a brake caliper body. The paper describes calculation of the forces that must be considered, which are the internal forces due to pressure in the caliper and the reaction force between the caliper and the rotor. This reaction force depends on wheel diameter, weight on the axle, and max vehicle deceleration. If max deceleration is not known, a braking torque requirement could be used instead. In the research paper, Ansys Mechanical was used to perform FEA simulations. An image of their FEA results is shown below.

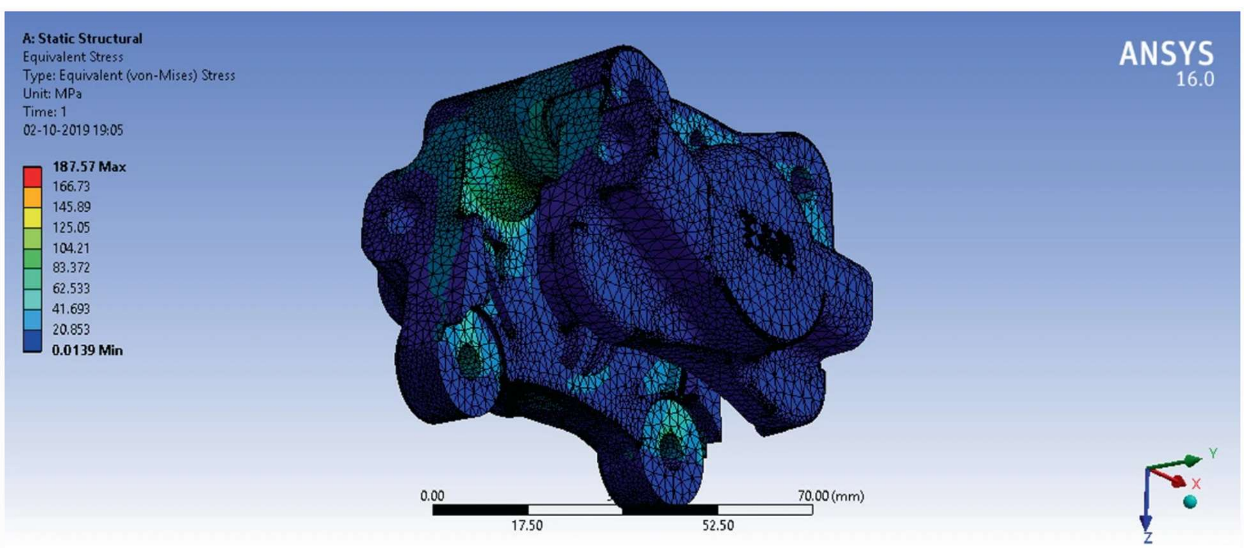


Figure 4: Finite element analysis of a two-piece brake caliper.

In the research paper, max deformation was found to be 0.198 mm. This value will not be the same for our calipers. However, the calipers in the research paper were designed for a vehicle very similar to ours, so the FEA results do provide a general magnitude that will let us know if our requirements are reasonable.

2.2.2. Existing Caliper Information

Many different caliper options exist for mountain bikes, dirt bikes, ATVs, and similarly sized vehicles. However, the team has consistently struggled to find a caliper that works well for the car without drawbacks.

The current caliper of choice is the Wilwood PS1 caliper. It is large in every aspect--pads, pistons, body, and fittings--but it is easily able to provide enough braking torque to reliably lock the wheels of the car during brake check. Its drawbacks are that its size makes it challenging to package at the front wheels and that it adds un-sprung mass to the car compared to a smaller caliper option.

Figure 5. Wilwood PS1 caliper.

The calipers used from 2019-2022 are formula mini moto calipers. It is considerably smaller and lighter than the Wilwood PS1 calipers with large pistons and pads for its size. However, it is a two-piece design that is bolted together and lacks stiffness. This resulted in the caliper splitting along the center seam and the O-ring in between failing from lack of compression, and the lack of stiffness resulted in the caliper not being able to consistently provide enough braking force to lock the wheels.

Figure 6. Formula mini moto caliper.

In 2018 Sram Guide calipers were used. They were lightweight and compact mountain bike calipers with a 4 piston design. The guide calipers had thin pads that wore out quickly and required thin rotors that had issues with warping.

Figure 7. Sram Guide caliper.

2.2.3. Alumni Interviews

Alumni interviews were conducted to help with problem statement development and learning more about past Baja brakes systems. The interviews gave us new perspective about the problem and helped broaden the potential scope of the problem from a specific focus on caliper function and choice to a more general focus on brakes knowledge and lack of data.

Our initial problem statement development was primarily based on direct observation of and interaction with brake issue, and previous CDR presentations that outlined issues from past years. Based on these limited viewpoints, our problem statement was focused on specific issues like packaging and serviceability, and the lack of off-the-shelf options for our car. While these are valid issues we have encountered, the interviews brought to light that many of the issues we have encountered in the past seem to stem from a lack of understanding of the system, lack of testing and benchmarking different caliper models, and lack of data to use while designing.

Almost all brakes design is done with theoretical models that require specifications of the caliper that are hard to get without buying and testing them. All the interviewees brought up this issue and suggested focusing on developing well-though-out requirements for our project by testing a variety of calipers on a braking dyno to compare them to our current system performance and see if we can find options currently available that meet our needs. Doing this would allow us to get valuable data on existing options that could aid in future caliper choices as well as help us understand what aspects of caliper design would be most helpful to incorporate in our own project.

2.2.4. Testing

As of the beginning of this project, we did not know anything about the performance of the Baja SAE tires. This is crucial for driving the requirements of the brake caliper design because tire performance is one factor that determines how much tangential force a caliper must be able to produce. In general tire longitudinal performance is characterized based on a plot of longitudinal load generated by the tires versus normal load on the tire and slip ratio (a metric comparing expected velocity based on tire rotational speed and actual forward velocity). This curve depends on the surface that the tire is operating on. Brake check generally takes place on pavement, but vehicle performance is desired on dirt, so testing will occur on multiple surfaces.

Tire performance will be characterized as follows:

- The car is equipped with pressure transducers that measure front and rear brake line pressure. The vehicle is also equipped with front and rear wheel speed sensors.
- The rear caliper will be removed so that the only force applied to the vehicle during stopping is applied via the front calipers.
- Then, the rear wheels can be used to measure vehicle speed/acceleration and the front wheel speed can be used to measure tire slip.
- Finally, data from multiple braking events will be recorded and used to determine the longitudinal force versus slip of the tires.

3. Objectives

Commercially available solutions for brake calipers on the Cal Poly Baja SAE vehicle are either undersized and cannot reliably lock up the wheels or they are too large and are both heavy and difficult to package onto the vehicle. As an engineering team, Baja SAE needs a low-cost solution that is easier to package into the car and saves weight. As a race team, Baja SAE needs a solution that allows brake check to be easily passed and not waste any time at competition.

Our first step in determining this project's objectives was defining the components our team will deliver on. We defined the scope of our project to only include calipers as shown below.

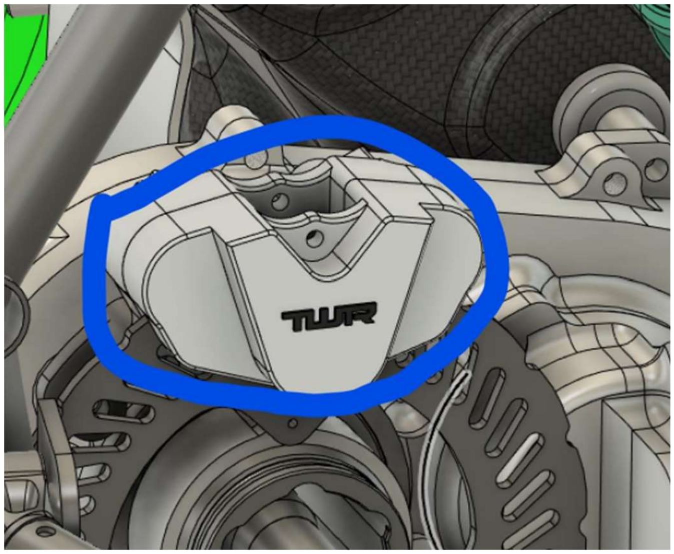


Figure 8: Rear Caliper Boundary Sketch.

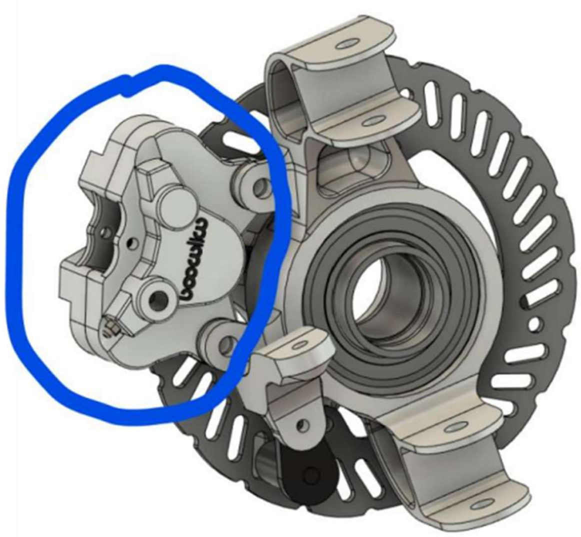


Figure 9: Front Caliper Boundary Sketch.

This means that we will not be doing the detailed design of any other components of the braking system and the car. However, we will do some high-level design for these components to drive the brake caliper's requirements. This includes things such as selecting a range of rotor diameters and an operating pressure based on components likely to be used in the braking system.

The customer requirements can be summarized into two categories: needs and wants. The needs of the Baja team are to pass the brake check event, to not overheat calipers, and to have a reasonable operating pressure. The wants of the customer are easy maintenance, long service intervals, and inexpensive production.

These requirements were used in the Quality Function Deployment method that ensured customer requirements were analyzed and understood by our team. For this process, we used a QFD House of Quality. The process we completed for this was as follows:

1. We identified our customers to be the 2023-2024 Brakes Lead, Suspension Lead, and Service Leads, and the machinists on the team who would be responsible for making our components.

2. We determined the customers wants and needs as listed in the table below.

3. We weighted the customer requirements based on the impacts they have on the customers' experience with our product.

4. We got a baseline of what calipers are currently on the market that could perform similarly to our caliper and how they perform in each specification category we have.

5. We determined what validation could be done to ensure that the specifications were met.

6. We characterized relationships between what the customer needs/wants to how specific things can be physically changed on the caliper to achieve those requirements. The relationships were characterized as a strong relation, a medium relation, a weak relation, or no relation.

7. Lastly, we set engineering targets for the specifications we listed out.

Spec #	Specification Description	Requirement or Target	Tolerance	Risk	Compliance
1	Max Allowable Pressure	3000 psi	Minimum	L	A, T
2	Lockup Pressure (Tarmac)	1280 psi	Maximum	M	A, T
3	Lockup Pressure (Dirt)	700 psi	Target	M	A, T
4	Max Allowable Rotor Temp	375 C	Minimum	M	A, T
5	Mass	0.65 lbm	Maximum	L	I
6	Pad Life	8 hours, 99.5%	Minimum	H	A, T
7	Caliper Life	91 hours, 99.5%	Minimum	L	A, T
8	Footprint	Formula Caliper Size	Maximum	L	I
9	Pad Acquisition Method	Outsourced	--	L	I
10	Piston Manufacturing Method	Outsourced	--	L	I
11	Bleed Port Location	Top of Caliper	--	L	I
12	Cost	$ 105	Maximum	M	I
13	Time to manufacture	30 CNC hours/season	Maximum	M	I
14	Mounting Style	Axial	--	L	I
15	Caliper Stiffness	30000 N/mm	Minimum	L	A, T

A list of the specifications that were chosen, reasoning behind them, and compliance testing are as follows:

1. **Max Allowable Pressure**
   This requirement specifies the pressure at which the caliper will fail. It was established based on the pressure rating of fittings and other components anticipated to be used in the braking system. Failure can occur due to component yielding, fluid leakage, pad damage, or any other factor that compromises the functionality of the caliper. This requirement can be evaluated through a simple static pressure test.

2. **Lockup Pressure (Tarmac)**
   This requirement sets the maximum pressure at which the caliper will lock the vehicle on a concrete surface. Testing was conducted to determine the maximum pedal force that the strongest and weakest drivers could exert on the system. The pressure generated per pedal force was then calculated to ensure that the strongest driver could not exceed the maximum pressure of the braking system with a 1.3 Factor of Safety (FOS) applied. The requirement was ultimately based on the maximum pressure that the weakest driver could generate. To evaluate this requirement, a brake check can be performed with the vehicle while recording data using pressure transducers.

3. **Lockup Pressure (Dirt)**
   This requirement defines the target pressure at which the vehicle will lock on a dirt surface. It needs to be a target because the driver should be able to operate the brakes within a comfortable range of pedal force. The range of pedal force was determined by analyzing the forces applied by drivers during the endurance race, as well as conducting static testing where drivers were asked to apply a braking force they considered to be at the maximum end of a comfortable range. To convert this pedal force into a pressure requirement, testing was conducted to determine the maximum pedal force that the strongest driver could exert on the system. The pressure generated per pedal force was then set to ensure that the strongest driver would not exceed the maximum pressure of the braking system with a 1.3 FOS applied.

4. **Max Allowable Rotor Temp**
   This requirement specifies the maximum temperature that the caliper must endure without experiencing component failure, such as overheating of pads, boiling of brake fluid, or unacceptable loss of heat treatment. The exact value for this requirement will be determined based on data from the Baja SAE Oregon endurance race. However, due to time constraints, the data has not yet been processed. To test this requirement, a heat gun can be used to raise the rotor's temperature to the desired level while the brake caliper is clamped onto it. It is important to note that this test method may lack accuracy as it does not apply tangential load to the caliper and the rotor remains static. Nevertheless, it is expected to prevent unexpected fluid boiling or catastrophic pad degradation during operation.

5. **Mass**
   This requirement defines the maximum allowable mass of the caliper. It is established by considering the weight of the formula minicross calipers, as the team found their mass to be satisfactory and they almost met the reliability requirements for the Baja SAE vehicle. It is anticipated that by using improved pads designed for lower temperatures, vehicle-specific mounting, and more advanced manufacturing methods, a significantly more mass-efficient design can be achieved compared to the Formula minicross calipers. To evaluate this requirement, the caliper can simply be weighted in both CAD and with a scale.

6. **Pad Life**
   This requirement defines the minimum duration of vehicle operation that the pads must be able to last. This requirement can be tested by running the vehicle until the pads noticeably impact the driver’s lap times.

7. **Caliper Life**
   This requirement defines the minimum duration of vehicle operation that everything on the caliper except the pads must be able to last. This requirement can be tested by running the vehicle until a caliper becomes damaged. In competition or more dangerous than average situations, the calipers should be swapped out for fresh calipers and then the test calipers swapped back on for further testing of the caliper life.

8. **Footprint**
   This requirement defines the maximum bounding volume that the calipers can occupy. For now, we want something in the size range of the Formula mini-cross calipers. As of right now, a reasonable amount of front caliper redesign is expected. Not enough packing studies for the 2024 vehicle have been completed to say what amount of space will be left for calipers. We expect to refine and quantify this requirement by having further discussion with next year's suspension leads over the summer of 2023. This requirement is easy to evaluate via CAD.

9. **Pad Acquisition Method**
   This requirement defines how pads are acquired for our calipers. It has been set to comply with the Baja team's goal of not bringing in any manufacturing in house unless it is a necessity or significantly improves vehicle performance. This is easily evaluated by inspection.

10. **Piston Manufacturing Method**
    This requirement defines how pistons are acquired for our calipers. It has been set to comply with the Baja team's goal of not bringing in any manufacturing in house unless it is a necessity or significantly improves vehicle performance. This is easily evaluated by inspection.

11. **Bleed Port Location**
    The bleed port must be located such that it is at the highest point of the hydraulic passages of the caliper. Therefore, the bleed port must be above the caliper pistons, brake line fittings, and internal fluid routing within the caliper. This is to ensure that air bubbles in the system will not be trapped and will instead find their way to the bleed port where they can be extracted.

12. **Cost**
    Caliper cost is important because to make this option sustainable for the team, we need to make sure it is affordable. This can be measured after manufacturing and validation.

13. **Time to Manufacture**
    The team consists of a significant number of members, reducing concerns about manufacturing time. However, considering the finite availability of CNC machining resources, a maximum limit of 30 hours per year has been established for student machinists to dedicate to the production of custom calipers. This limit is based on an estimated 1600 CNC machine shop hours available per year for the Baja team, as well as approximately 50 major components or assemblies that require machining. The goal is to ensure that the calipers do not require more work time than the average component on the vehicle. To evaluate this requirement, the manufacturing time of each caliper component can be tracked.

14. **Mounting Style**
    The mounting style we choose, whether it be axial or radial, is important because it determines the shape of both the caliper and what it mounts to. In the case of the CPX '23 Baja SAE car, the calipers are axially mounted because this allows for a lower profile upright and gearbox mount. This is advantageous both because the object the caliper mounts onto can be smaller and because this means that a larger rotor can be used due to the packaging constraint for the brake assembly being inner wheel diameter.

15. **Caliper Stiffness**
    This requirement establishes the amount of piston travel that occurs per pound of caliper clamp force once the brake pads have made full contact with the rotor. This metric is crucial to ensure that the driver experiences minimal pedal deflection during braking, enabling better control over the vehicle. Pedal deflection can result from various factors, including pedal stiffness, master cylinder/pedal mounting stiffness, line stiffness, and caliper stiffness. In the 2023 system, we plan to measure the deflection and analyze the contribution of each factor to the overall pedal stiffness. Based on this testing, we intend to set a target for caliper stiffness, ensuring that the pedal stiffness requirement can be met at a system level. This requirement can be evaluated using a dial indicator and measuring braking force with a pressure transducer.

The specifications that we had that had a high risk of being met are design life, cost, and time to manufacture. The design life is difficult to validate because of the time required to prove that the requirement has been met. Cost and time to manufacture are very difficult to predict and thus any requirement that is set will most likely be somewhat arbitrary and too easy or difficult to meet.

4. Concept Design

The design of brake calipers is already well defined, so ideation is focused on specific design choices rather than entirely different types of systems. To start, we researched many existing brake caliper design variations. In addition, we came up with a few design changes that are not seen in existing calipers, such as using a leaf spring to retract the piston. These ideas are compiled in a Pugh matrix, which is included as appendix D.

The ideas in the Pugh matrix are combined into 4 feasible system level designs. Preliminary sketches and explanations of the designs are shown below.

4.1. Concept Design Ideas

4.1.1. One-Piece Caliper Body with Fixed Axial Mounting

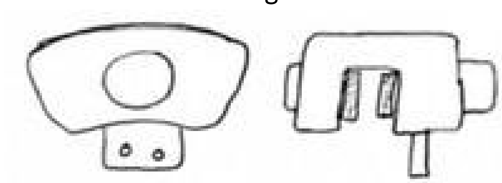


Figure 10: Concept sketch of one-piece fixed caliper.

This system level design uses a body that is made from a single piece of machined aluminum. Piston retraction is achieved through flexible seals. Off the shelf pistons are used, and seal groove geometry is designed to match existing calipers and pistons, as developing original return seal groove geometry requires extensive R&D. As the body is one piece, the piston bore and fluid channels are machined through the entire calipers, and then machined caps are used to plug the holes. The caliper would be axially mounted, which means that the mounting bolts are aligned axially relative to the wheels. A one-piece body would be difficult to manufacture, but may be easier to seal, as the sealing interface between body halves would be eliminated.

4.1.2. Two-Piece Body with Fixed Axial Mounting

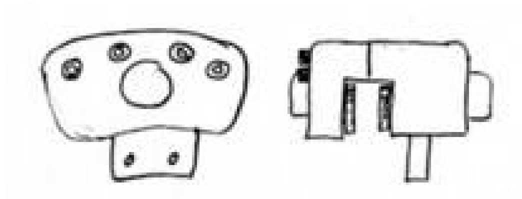


Figure 11: Concept sketch of two-piece fixed caliper.

This design is identical to the previous concept, except that the body would be comprised of two halves that bolt together. This reduces manufacturing complexity and changes the sealing methods used. Instead of using caps to plug holes, fluid and piston bores are machined from inside the caliper halves, and then a sealing interface is used when the calipers are assembled. If located above the neutral axis, the sealing interface would be compressed upon braking, making this design fairly robust. This is the system level design that many production calipers use.

4.1.3. One-Piece Body with Floating Mount

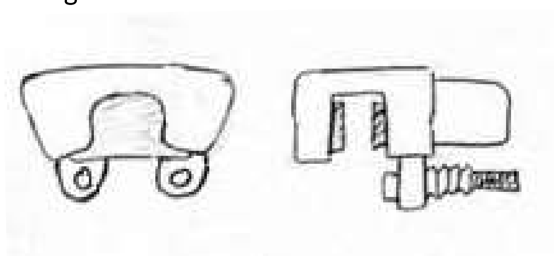


Figure 12: Concept sketch of floating caliper with one-piece body.

While the previous two designs use two pistons to simultaneously clamp on the rotor, this design used only one piston. In order to evenly clamp on the rotor, the entire caliper body can slide axially. When the one piston extended, the body self-aligns until the clamping force on each brake pad is the same. This design still uses the same piston and sealing geometry as the previous two designs, but for this design, only one piston and seal is necessary. Internal fluid channels across the caliper are unnecessary, so the body geometry is greatly simplified. Due to the simplified geometry, a one-piece body is used. The biggest concern with a floating mount is that the sliding mechanism adds complexity and is prone to wear.

4.1.4. Two-Piece Body with Fixed Mounting and Return Spring

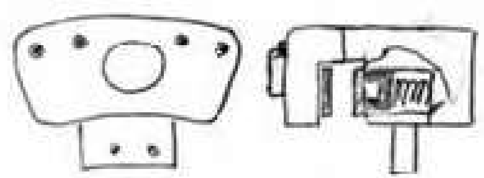


Figure 13: Two-piece body with piston return spring.

This design uses a spring rather than a seal for piston return. As the seal isn't used for retraction, it can slide along the piston, which means that piston seal geometry is less critical. However, with sliding between the piston and seal, seal wear is more of a concern. The rest of this design is the same as concept 2.

4.2. Design Decision

The 4 designs above are compared in a weighted decision matrix. Ease of mounting and ease of manufacturing are the highest weighted criteria.

Ease of mounting is important because mounting is one of the current issues we have with our calipers. Small calipers and ease of alignment both make calipers easier to mount.

Manufacturability is critical because of the time constraints of this project. If multiple iterations are necessary, it is important that calipers can be produced relatively quickly.

Size reduction is important, both for packaging and mounting.

Service life and ease of maintenance are not the highest priorities because the Baja car is a competitive vehicle that emphasizes performance over convenience. However, a short service life will become a problem if it starts cutting into testing time or keeps the car from completing a 4-hour endurance race without being serviced. Similarly, lengthy maintenance will cut into testing time, or keep us off the track longer than necessary during competition.

Cost effectiveness is important because we are a student team with a limited budget. We have good in-house manufacturing capabilities, but if too much out of house manufacturing is needed, the cost could become prohibitive.

Braking performance is important but is mostly used as a benchmark to make sure that we do not reduce braking performance. Our current calipers perform very well, so it is desirable to keep the same braking performance while improving in other areas.

The decision matrix below uses the criteria discussed above to compare the 4 possible system level designs.

Criteria	Weight	System Level Designs							
		One piece body, axially mounted, two off the shelf pistons, with copied seal groove geometries and a return seal.		Two piece body, axially mounted, two off the shelf pistons, with copied seal groove geometries and a return seal.		One piece floating body, axially mounted, with copied seal groove geometries and a return seal.		Two piece body, axially mounted, two off the shelf pistons, with sliding seal and piston return spring	
		Score	Total	Score	Total	Score	Total	Score	Total
Ease of manufacturing	0.2	3	0.6	9	1.8	5	1	10	2
Ease of mounting	0.2	7	1.4	7	1.4	10	2	7	1.4
Size reduction	0.15	8	1.2	7	1.05	8	1.2	6	0.9
Service life	0.1	9	0.9	9	0.9	7	0.7	8	0.8
Cost effectiveness	0.15	7	1.05	8	1.2	9	1.35	8	1.2
Ease of maintainance	0.05	7	0.35	10	0.5	9	0.45	6	0.3
Braking performance	0.15	10	1.5	10	1.5	5	0.75	10	1.5
Total	1	**7**		**8.35**		**7.45**		**8.1**	

Figure 14: Weighted decision matrix comparing 4 feasible designs.

The two-piece caliper with a return seal and fixed mounting scores the highest in the decision matrix. This agrees with intuition, because that design keeps manufacturability high while providing good braking performance. It also happens to be by far the most popular system level design used on production vehicles. This is the design direction we moved forward with.

4.3. Testing to Determine Requirements

Before starting the design of the calipers, it is essential to understand the requirements for stopping the Baja car. One of the requirements is the ability to lock the wheels on pavement. To determine the torque required to break traction on pavement, we conducted testing using our current brakes. When a tire generates force in the direction it rolls, it must slip relative to the ground. To characterize this phenomenon, it is possible to create a longitudinal slip ratio versus effective coefficient of friction curve for the tire.

To conduct this testing, we utilized the CPX 2023 vehicle and removed the rear brake caliper. By braking with only the front calipers, we were able to determine where most of the force that slows down the car is being generated. To calculate this force, we considered the mass and acceleration of the vehicle. The acceleration was measured by differentiating the measured rear wheel speed. Also, the speeds of the front and rear wheels were compared to determine the front tire's slip ratio. With this data, we established both upper and lower bounds for tire performance and developed a curve representing the average performance. This testing allowed us to gain insight into the requirements for the caliper design by understanding the necessary torque to achieve wheel lock on pavement.

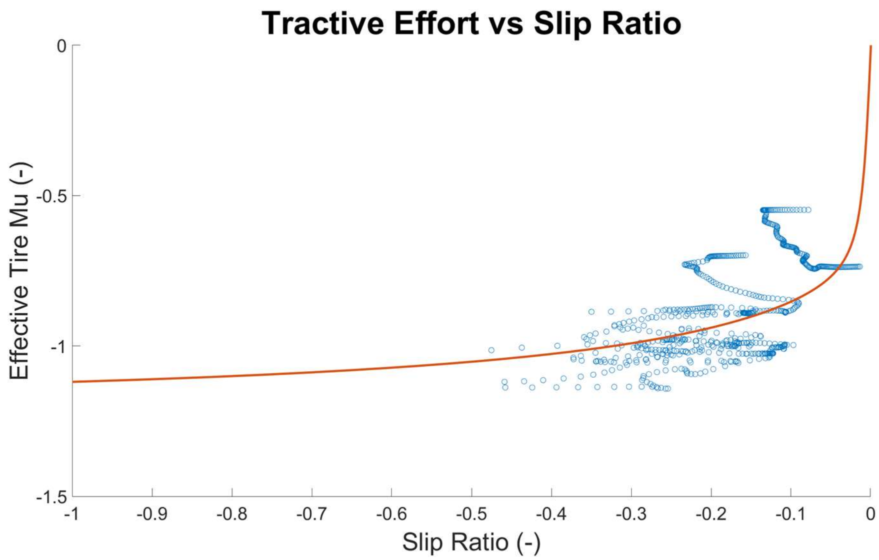


Figure 15. Test data for Cal Poly Baja tire on concrete – fit with magic tire formula.

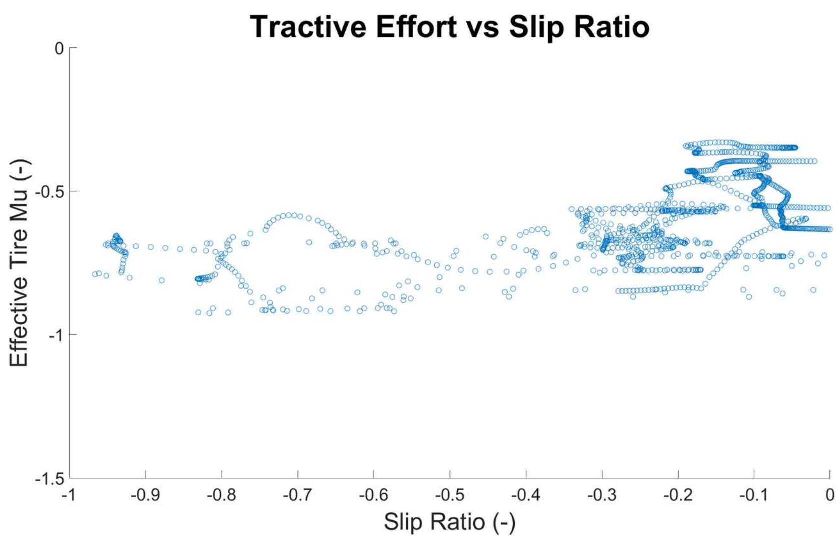


Figure 16. Test data for Cal Poly Baja tire on dirt.

4.4. Initial Design

To begin our initial design, we researched the pad materials available for brake pads. The most important pad parameter when designing a caliper is the coefficient of friction between the pad and the rotor. This is highly dependent on the temperature that the brakes operate at so often the friction coefficient is plotted against temperature. In 2023 the Baja SAE team used Composite Metallic pads from Willwood and the plot of friction versus temperature for these pads are shown below.

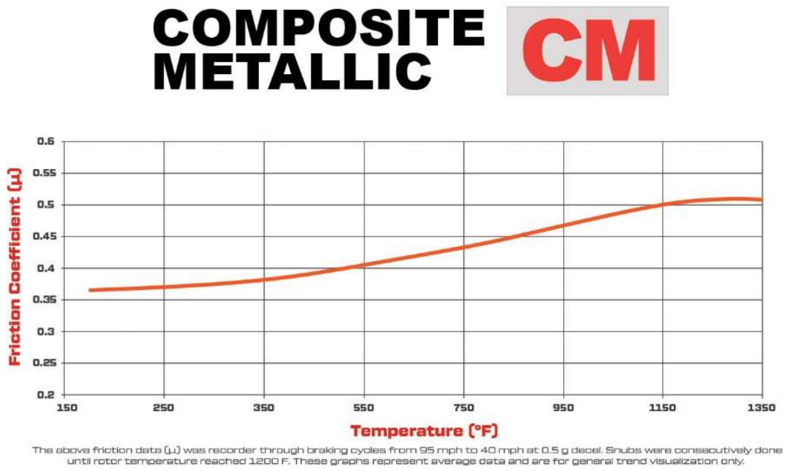


Figure 17. Cal Poly Baja SAE 2023 brake pads fiction data.

These pads were selected because they are compatible with the Willwood PS-1. However, this pad material is not ideal for the Baja SAE vehicle. Due to the low power and high drag environment of Baja SAE, the brakes rotors do not see high temperatures. Because of this, a low temperature pad material can be selected that has a lower maximum temperature rating but a higher initial coefficient of friction. Most low temperature pads can achieve friction coefficients in the range of 0.5 to 0.6, so for conservativism, 0.5 was used in all initial analysis.

Our initial analysis of the calipers primarily focused on the system-level design of the braking system for the Baja SAE car. This approach is crucial as the system design determines the requirements for the caliper. To facilitate this analysis, a spreadsheet was created, incorporating vehicle and braking system parameters. The spreadsheet calculates the required piston bore diameter for both the front and rear calipers. Two load cases were considered in this tool: braking on dirt and braking on concrete.

It's important to note that this tool adopts a conservative approach. For the front caliper, it assumes load transfer, while for the rear caliper, it assumes no load transfer. We believe this assumption is reasonable since historically, the rear wheels of the Baja car have always had a more difficult time locking than the fronts. We attribute this behavior to the non-negligible time required for load transfer to occur, resulting in a rear that is more challenging to lock than our previous analysis indicated.

By using this tool, we vary vehicle parameters and braking system requirements within reasonable ranges. This allowed us to select front and rear piston diameters that would be robust against minor modifications to the vehicle and braking system. Consequently, we chose a 22mm bore for the front caliper and a 28mm bore for the rear caliper. Given that the Willwood PS1 already has a bore size close to 28mm, we have decided to aggressively pursue the design of a 22mm bore front caliper initially. We will reevaluate the design and manufacturing of a custom rear caliper if time permits.

Overall, this initial analysis provided valuable insights and enabled us to make informed decisions regarding the caliper design for the Baja SAE car.

4.5. Concept Prototype

Figure 18. CAD and 3D Print of Concept Prototype.

The prototype shown in figure 18 was created to help us get a sense of scale for the caliper body, pistons and pads, and mounting tabs. It also helped us to explore how we could bolt the two halves of the caliper together while also allowing fluid to pass across the seam between the two halves. We found that routing fluid passages was more challenging than we had initially expected as the bolts holding the caliper halves together tended to get in the way. This led us to realize we could use a banjo bolt to connect the two caliper halves and transport fluid from one half to the other. The model also ended up being larger than expected and we realized that we will likely need to reduce the number of bolts holding the caliper halves together to meet our size goal.

4.6. Design Hazards

We have identified several potential hazards associated with our design. The primary hazards are the fluids used in a brake system. Both brake fluid and brake cleaner are toxic to humans, and flammable. Brake cleaner is particularly flammable, and when burnt, creates phosgene gas, which is a poisonous gas that was used during World War I. Phosgene can be fatal in extremely low doses, so it is imperative that brake cleaner is never combusted. The most common way brake cleaner is accidentally burnt is when it is used to clean metal parts that get welded. To address these hazards, we will wear rubber gloves when working with both fluids, wear safety glasses, and keep fluids away from spark sources such as grinders. We will also store brake cleaner in a flammables cabinet and make sure it is clearly labelled to mitigate the risk of it being used to clean metals.

Another hazard is the danger associated with brake failure on a moving vehicle. This didn't fit into any category on the checklist because the danger isn't directly due to our component. However, the inability to bring a 500 pound moving vehicle to a stop is dangerous enough to warrant mentioning. Our calipers will be tested off the car; however, we need to assume that there is always some risk of on-car failure. This is addressed by the team's practice of always handling the car as if brake failure is possible. The driver is relatively well protected in the case of a collision, so the more significant danger is that of collision with bystanders. As a rule, drivers are instructed to never drive directly towards people, and when it is necessary, the car is moved at very slow speeds. Bystanders are also instructed not to walk in front of the car when the engine is running. These practices greatly reduce the risk of injury due to caliper failure. Finally, if all else fails, the transmission is equipped with engine braking so the vehicle would still be able to slow down, even if it was going down a gentle incline.

The rest of the hazards we identified are included in the design hazard checklist, which is included in Appendix E.

4.7. Concerns

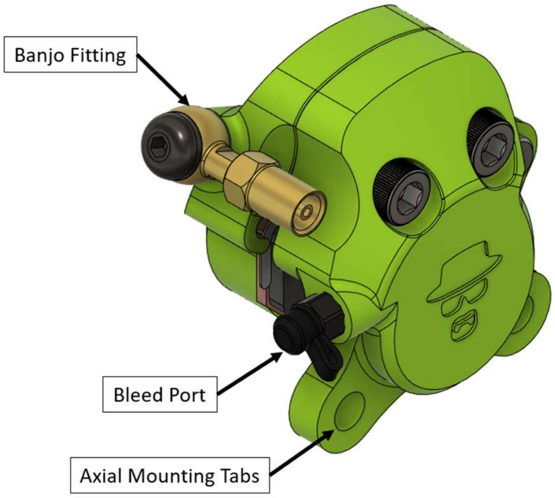
The primary concern with our design is that it will be very difficult to implement a working piston return seal. Accurate analysis of a lubricated rubber seal will be extremely difficult, so trial and error will likely be the most practical way to find working geometry. We do not know how many iterations it will take to create a working design, so the best we can do is to develop a prototype as soon as possible so we have ample time to iterate.

Another concern is the manufacturability of the seal geometry. It is possible that we will need custom tools to machine the seal groove, which would significantly increase time between iterations. Once again, the effects of this concern can be reduced if we move through the design process quickly so we can begin making informed decisions about manufacturing.

5. Final Design

5.1. Design Overview

Our brake caliper's final design consists of two 7075-T6 billet housing halves fastened together with two 1/4-28 socket head cap screws. Fluid enters the caliper via a banjo screw and then flows directly behind the outboard piston. From there, the fluid is routed through holes that let it flow to the top of the caliper and then back down and around to the backside of the inboard piston. At the top of the caliper where the 2 fluid channels intersect there is a seal. Finally, a bleed port is placed on the inboard caliper half and routed directly behind the inboard piston. All seals in the caliper are made from EPDM rubber and as such the caliper is compatible with DOT 3 or DOT 4 fluid. Additionally, pistons selected for this caliper are off-the-shelf Shimano 22mm ceramic pistons and the caliper is compatible with aftermarket pads that fit the formula mini-cross caliper used in previous years. These pads were selected as they have a reasonable thickness and do not wear quickly, while still being small and easy to integrate into our design. The caliper is mounted using tabs that are integrated into the inboard half of the body. Each tab has a hole for a fastener which is orientated axially along the bore of the caliper and along the axis of the wheel in the final mounting orientation.



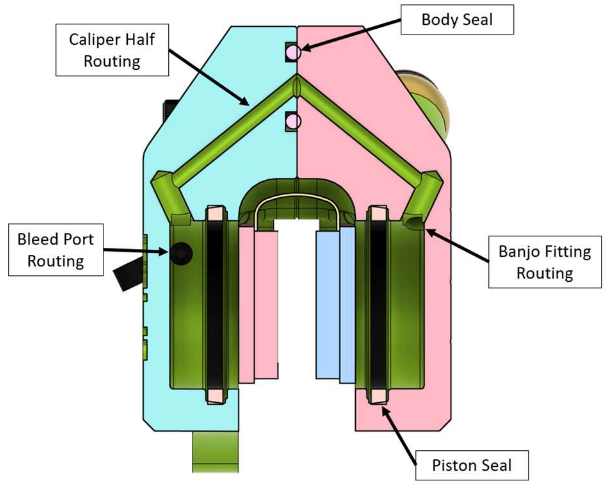


Figure 19. Caliper design overview.

5.2. Design Details

The main feature that makes the caliper function as intended is the piston seal groove. The groove geometry is designed to deform a square seal such that it will retract the pistons when pressure is not applied to the caliper. The seal acts like a return spring for small displacements of the piston but only if the groove geometry is correct. We copied the groove geometry from an existing Shimano Deore XT caliper to avoid having to iterate through groove designs and ideally get the groove to function as intended on the first try. We chose the Shimano Deore XT BR-8000 caliper since it had 22 mm pistons which we determined were the best size for our design. To measure the Shimano groove geometry, we cut a Shimano caliper in half and inspected the groove cross section using a CMM with a vision system. This groove cross section profile was then used in our caliper design.

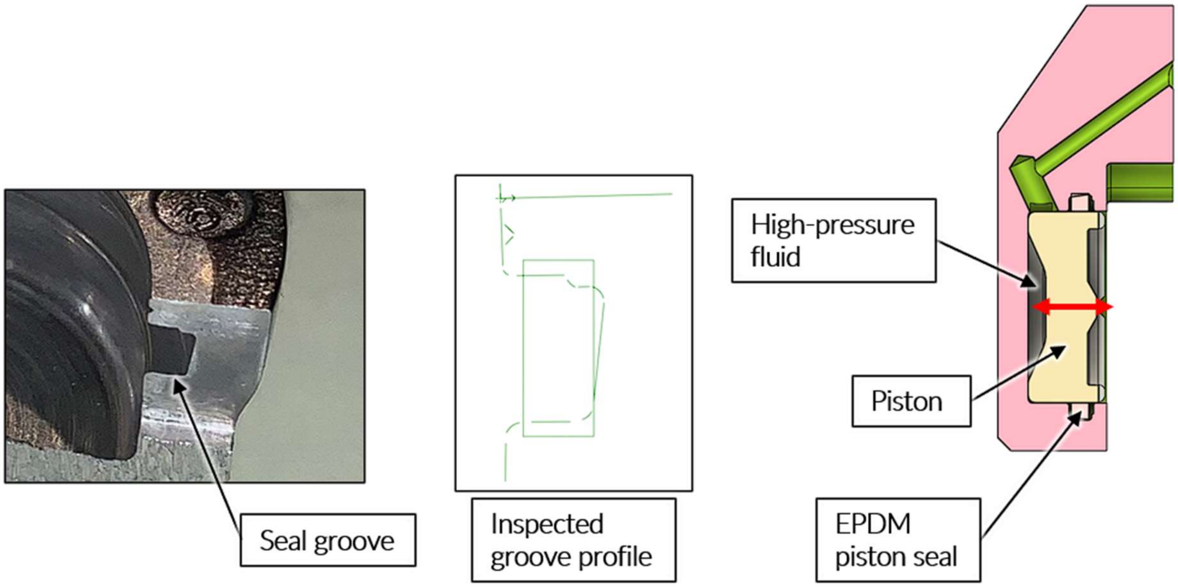


Figure 20. Seal groove cross section.

The fluid passages were designed to be drilled into the body using multiple intersecting holes. The fluid enters the caliper at the banjo fitting which is threaded into a tapped hole in the outboard half of the caliper body. This hole intersects a smaller fluid passage that is drilled at an angle through the tapped hole and intersects with the piston bore of the outboard half. Fluid is then routed from the outboard piston to the inboard piston through passages that intersect the bores and connect the two body halves. The passages on each half are created by drilling two holes that intersect just above the piston bores. The passages in the right and left halves of the caliper meet at the centerline where the two halves intersect, and an O-ring face seal is used to seal the interface.

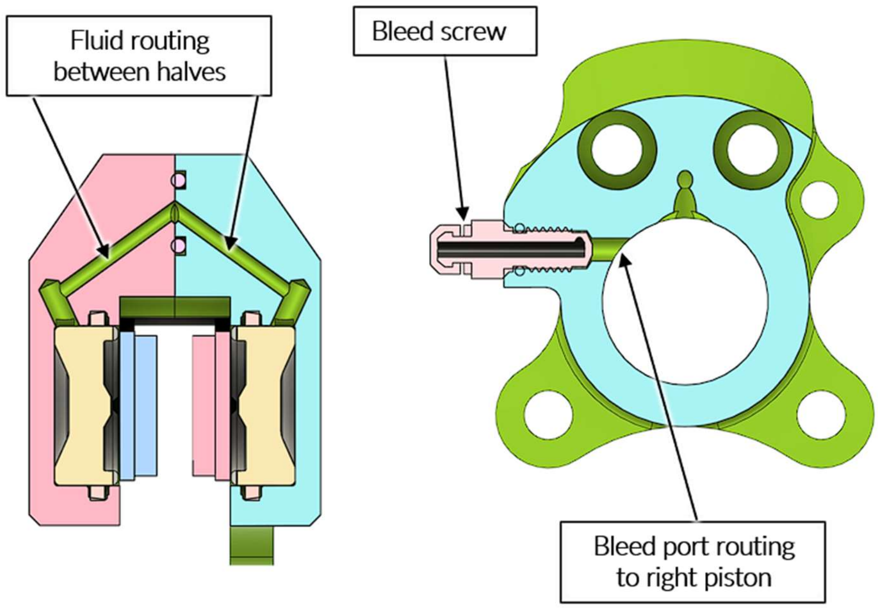


Figure 21. Fluid routing cross section.

When bleeding the caliper, fluid and air flow out the open bleed screw which is located on the inboard side of the caliper, opposite the banjo fitting. The bleed screw is an off the shelf part that is also used in the Shimano Deore XT BR-8000 caliper. The bleed screw is threaded into a tapped hole in the caliper that has a tapered face at the end. A smaller hole is drilled coaxially to the tapped hole and intersects with the inboard piston bore. This diameter reduction leaves a tapered area where the tapered end of the bleed screw can seal when it is fully seated and tightened. When the bleed screw is loosened, fluid can flow from the piston bore, past the tapered sealing area, and into the hollow center of the bleed screw through a hole in the side. Thus, fluid and air can exit through the bleed screw without fully removing it.

Two socket head cap screws are used to fasten the caliper body halves together. The screws thread into the outboard body half and the inboard body half has counterbored clearance holes. The threads in the outboard half are reinforced with threaded inserts so that more preload may be applied to the screws. About 0.5" of material is kept above the bolts to react the moment resulting from the piston clamping forces. When the pistons press the pads against the rotors, the bottom halves of the caliper bodies are forced apart and the material above the bolts should be pressed together if enough bolt preload is applied. The face seal between the caliper halves is located above the bolts to always maintain seal compression and avoid gapping between the halves that could cause the seal extrude out between them.

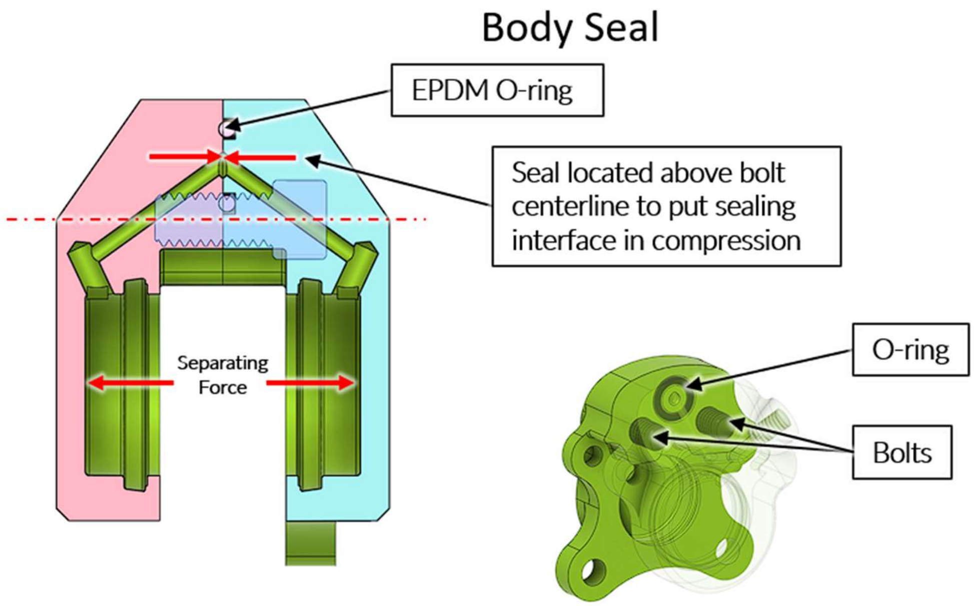


Figure 22. Body seal and fastener cross section.

5.3. Integration and Assembly

The caliper attaches to the front uprights of the car with an adaptor plate (not pictured). The adaptor plate will be finalized once the new upright design is complete and upright mounting points are chosen. For now the 2023 upright design is shown for reference and the position of the caliper with respect to the upright and rotor is depicted below.

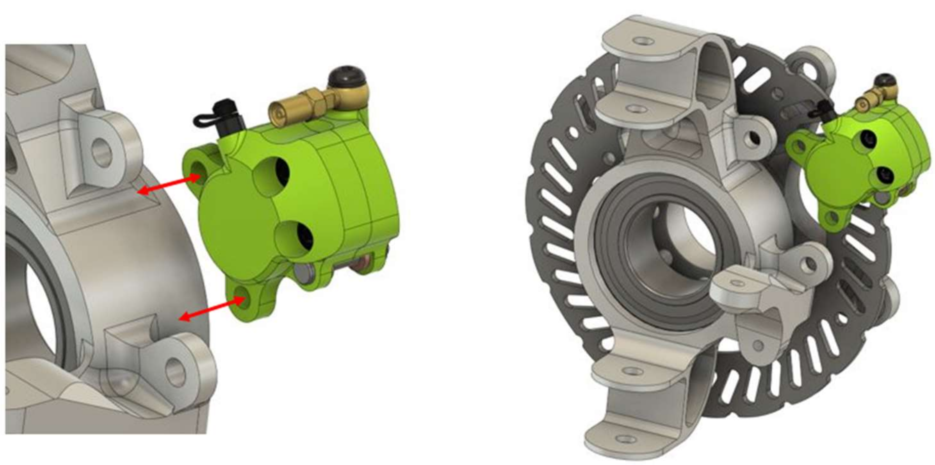


Figure 23. Caliper mounting position with respect to upright

The caliper must be able to fit over the rotor and still fit inside the wheel without rubbing. With a 7 in rotor, our caliper fits inside the wheel with 0.2” of radial clearance. This is more clearance than the calipers on the 2023 car have and should not rub under normal circumstances. The caliper is designed to function with rotors smaller than 7 in so if necessary we can reduce the rotor diameter to gain more clearance with the wheel.

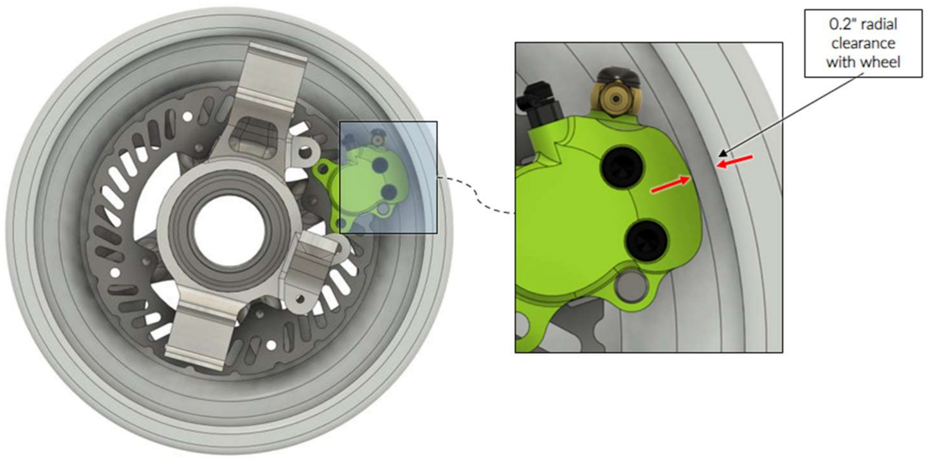


Figure 24. Radial clearance between caliper and wheel

The caliper has over 0.2” of radial and axial clearance with the 2023 front hubs. This is more clearance than the calipers on the 2023 car have and it is unlikely that this clearance will need to increase.

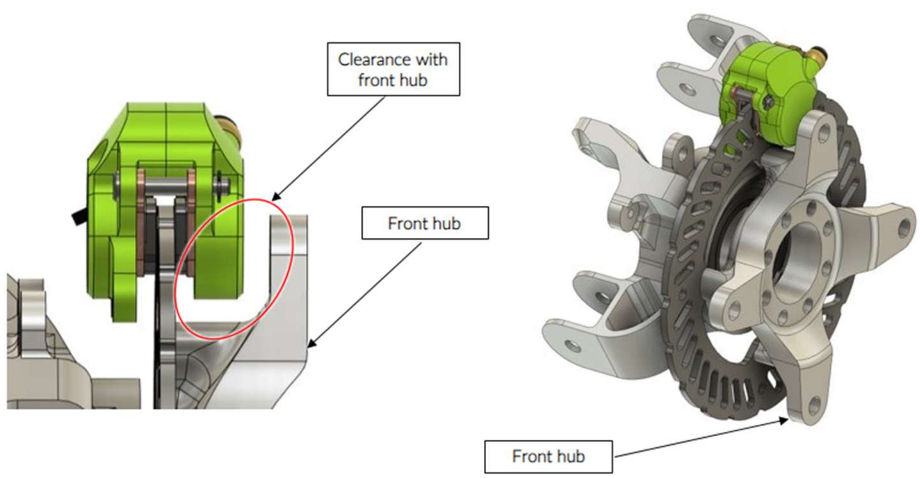


Figure 25. Clearance between caliper and hub

Assembly steps are as follows:

1. Install threaded inserts into outboard body
2. Install pistons and piston orings into caliper body halves
3. Install oring face seal between caliper halves
4. Connect halves with ¼-28 socket head cap screws – apply Loctite 243 and torque to 160 in*lbf
5. Slide pad retention spring over both pads and insert pads into caliper
6. Install clevis pin through caliper body and pad carrier holes, attach E clip to secure pin in place
7. Insert bleed screw into inboard caliper threaded port and tighten till snug
8. Insert banjo bolt through banjo fitting and tighten into outboard caliper threaded port till snug

5.4. Structural Analysis

Our structural analysis's goal is to ensure there is a high chance of meeting our strength and stiffness targets. The analysis we completed consists of hand calcs for the fastener forces and resultant margins and a FEM to predict the stress state and fatigue life of the body halves.

To begin, we created a spreadsheet that allowed us to size the fasteners and determine how much material to put above the fasteners. It is conservatively assumed that the moment applied from the piston pressure is reacted via a force applied through the center of the bolts and the centroid of the material that is above the fastener. Then, standard Shigley's analysis was completed to determine a margin on yield. A 1.25 factor of safety was selected as fastener yield would likely cause a loss of preload after the load is relaxed. This would likely cause a fluid leak and thus the failure mode is catastrophic. The resultant fastener selection is a ¼-28 bolt with 160 in*lbf of torque applied to it. A K factor of 0.17 was selected as the bolts will be retained with Loctite 243 which acts as a lubricant prior to cure. A lower margin of joint separation than yield was selected via applying a lower amount of torque to the fastener. This is because a small amount of leakage at high pressure is preferred to having the caliper have a chance of not sealing at low pressures.

Inputs

Parameter	Value	Units	Alt Value	Alt Units
Piston Diameter	22	mm	-	-
Max Pressure	3000	psi	20.68428	mPa
Bolt -> Piston	22	mm	-	-
Bolt -> Top	5.7875	mm	-	-
Thickness 1	8	mm	-	-
Bolt Length	0.625	in	15.875	mm
Fastener Diameter	0.25	in	6.35	mm
Thread Pitch	28	tpi	0.9071428571	mm
Washer Diameter	0.375	in	9.525	mm
Fastener K Value	0.18	-		
Fastener Torque	160	in*lbf	18077.57264	N*mm

Calculated Geometry

Parameter	Value	Units
Piston Area	380.1327111	mm^2
Fastener Nom Area	31.66921744	mm^2
Fastener Tensile Area	23.74895249	mm^2
Thread Shear Area	71.82691621	mm^2
Pitch Diameter	5.760810714	mm
Threaded Length	19.05	mm
Unthreaded Length	0	mm
Shear Length	6.35	mm
Pressure Length	3.175	mm

Fastener Stifness

Parameter	Value	Units
Grip Length	11.175	mm
Eff Thread Leng	11.2	mm
Eff UnThread Leng	0	mm
K_thd	402947.8	N/mm
K_shank	-	N/mm
K_bolt	402948	N/mm
Frustum Thickness	5.5875	-
K_Frust	1032963	N/mm
K_m	516481.6	N/mm
Stiffness Const (C)	0.438	-

Calculated Forces/Moments

Parameter	Value	Units
Max Piston Force	7862.8	N
Top Side Force	29888.7	N
Fastener Ext Load	18875.74611	N

Fastener Max Forces

Parameter	Value	Units
Preload	15815.9	N
Fastener Load	24088.4	N
Joint Sep Ext Load	28155.1	N
Thread Shear Fast Load	43745.9	N
Thread Shear Ext Load	63729.5	N
Fast Yeild Fast Load	33407.8	N
Fast Yeild Ext Load	40140.5	N

Fastener Properties

Parameter	Value	Units	Alt Value	Alt Units
E	27500	ksi	189605.9	mPa
Proof Strength	140	ksi	965.2664	mPa
Yeild Strength	153	ksi	1054.89828	mPa
Ult Strength	180	ksi	1241.0568	mPa

Fastener Margins Forces

Parameter	Value	Units
MS_Shear	1.701009526	-
MS_Yeild	0.7012505921	-
MS_Sep	0.1932825444	-

Caliper Body Properties

Parameter	Value	Units	Alt Value	Alt Units
E	10000	ksi	68947.6	mPa
Yeild Strength	35	ksi	241.3166	mPa

Fastener Margins

Parameter	Value	Units
MS_Shear	1.701009526	-
MS_Yeild	0.7012505921	-
MS_Sep	0.1932825444	-

Figure 26. Fastener calculations and resultant margins

After this was completed a CAD model was created and we moved into FEM. Due to the fast meshing and solving times, no further hand calcs were done as it was considered acceptable to iterate through design ideas and part sizes in FEM space.

A model was set up in ANSYS using solid TET10 elements. A bilinear isotropic hardening material model was selected as low to no plastic strain is expected in a functional design and the load will not be cycled more than a single time in the FEM. Linear geometry was selected as the plastic strains and elastic deformations are all expected to be low, and buckling is not a concern. Contacts were modeled using a small sliding penalty formulation. Friction and viscous contact effects were not considered.

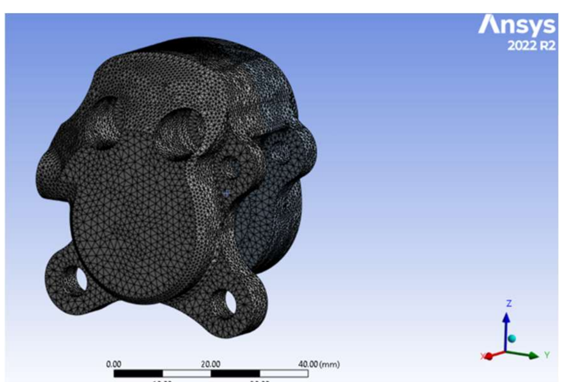


Figure 27. FE model of the brake caliper.

Boundary conditions consisted of 6 DOF springs at the caliper mounting location. The mounting holes were rigidized. The spring stiffness was selected based on the Huth equation for representative bolted joint stiffness as well as some approximations of upright stiffness.

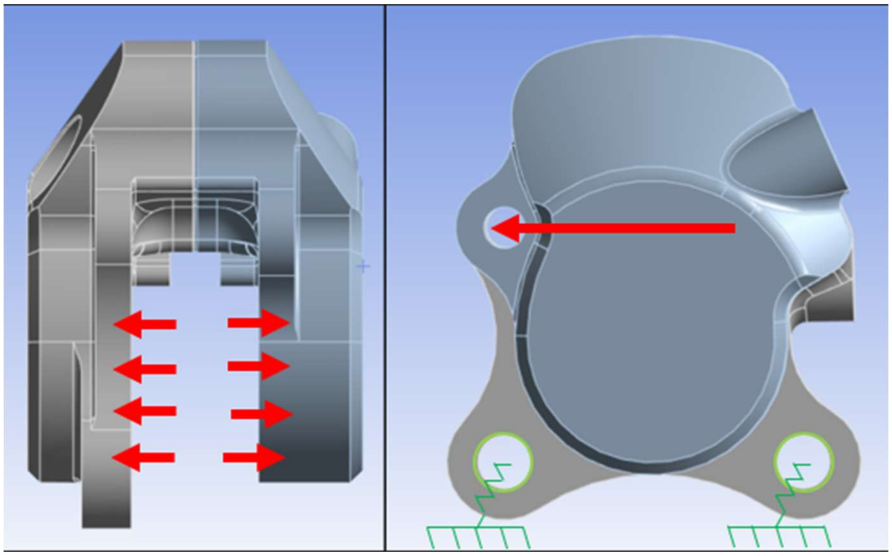


Figure 28. Boundary conditions and loads applied to the model.

Three load cases were considered, an abuse case, tarmac lockup case, and a dirt lockup case. The requirements in each case are different. The abuse case corresponds to 3000 psi and a tangential pad load that corresponds to the max coefficient of friction we expect to see on concrete. This load is expected to occur only a few times over the lifespan of the calipers so as such, plastic strain that does not cause detrimental deformation after the load is relaxed is allowed. The tarmac lockup case corresponds 1280 psi which is the expected pressure to lock with a 1.2 coefficient of friction on the tire and a 0.5 coefficient of friction for the pad. In this case, yield is not allowed, however as this is not the nominal operating conditions fatigue is not considered. Finally, the dirt lockup case (i.e. threshold braking) is the nominal operating condition and as such fatigue must be considered.

Load Case	*Pressure*	*Tangential Load*	*FOS Yield*	*FOS Ultimate*	*FOS Fatigue*
Abuse	3000 psi	3400 N	-	-	-
Tarmac Lockup	1280 psi	3400 N	1.1	1.25	-
Dirt Lockup	700 psi	1860 N	1.1	1.25	1.4

Figure 29. Loads applied to the caliper and required factors of safety.

In the abuse case when the model was run with linear material properties, stress past yield was observed. As such, a non-linear material model was used. A small amount of plastic strain is seen on the inside corner of the inboard caliper. To determine if this was acceptable, the load was applied to the caliper, then taken off, and the final deformed shape was inspected. There was not a significant enough change in the caliper's form to affect its performance (i.e. bring any features out of spec) and as such, the yielding in this corner is considered acceptable.

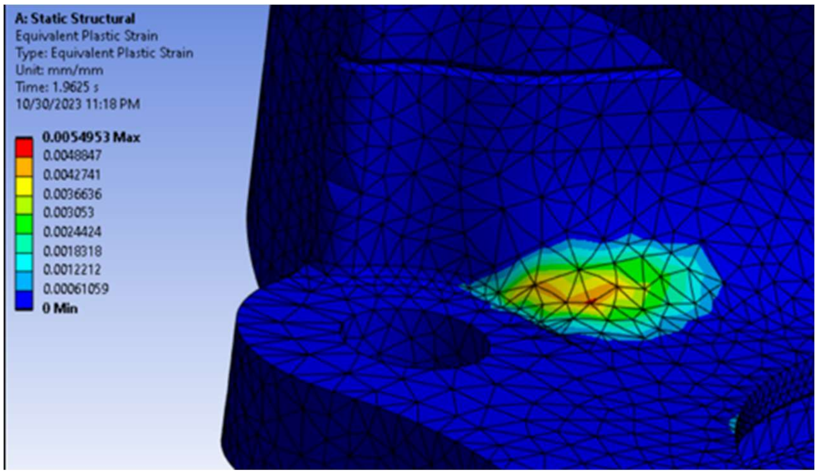


Figure 30. Plastic strain on the brake caliper while the abuse loads are applied.

Next, the tarmac lockup case was run. In this model, no yielding occurred. With the factors of safety shown above, there is a 4.5% margin on yield and a 3.6% margin on ultimate. We feel that this low FOS and margin can be considered acceptable. This is because this load is applied infrequently, and prior analysis has shown that the resulting yield is non-catastrophic. Additionally, all material properties were evaluated at 212 F, but this case only ever occurs as a one-time load during a brake check test where the calipers will not have time to get up to temperature.

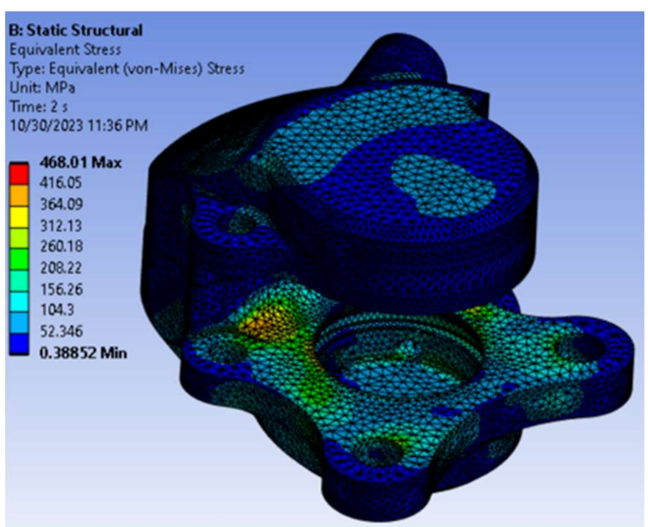


Figure 31. Caliper stress state during the tarmac lockup case.

Additionally, during the tarmac lockup case we were able to derive a caliper piston to piston stiffness in N/mm. We found that the stiffness of our design is around 67000 N/mm which easily exceeds our target of 30000 N/mm which was driven by allowable pedal compliance. Finally, the gap at the contact surface was evaluated. All elements around the body seal remained in contact during the tarmac lockup base and overall gapping of the surface was minimal. As such, we do not expect fluid to leak during normal operating conditions.

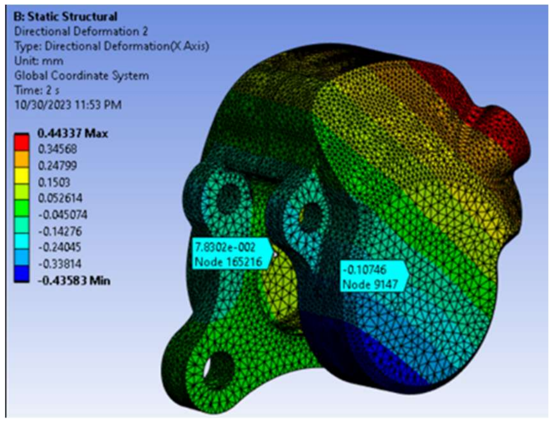


Figure 32. Caliper deflections during tarmac load case.

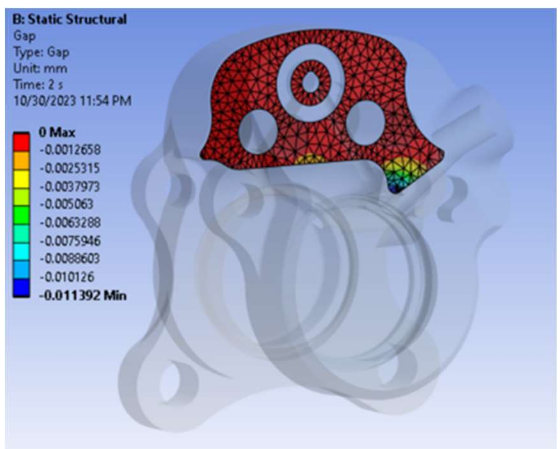


Figure 33. Gap at contact surface during tarmac load case.

Finally, we looked at the nominal operating case, which is threshold braking on dirt. With this load case, we have very high margins of 74% on yield and 72% on ultimate. Additionally, with this load case we evaluated the fatigue life of the brake caliper. Our requirement for fatigue life is 20,000 cycles which is based on a 90-hour life with about 3 brake actuations per minute. The Gerber criteria was selected to correct for mean stress and to account for temperature effects. The SN curve was scaled based on the ECF for ultimate strength at 212 F. Notch sensitivity was conservatively neglected in this analysis. With this, a minimum FOS of 1.54 was observed, which exceeds our 1.4 FOS requirement.

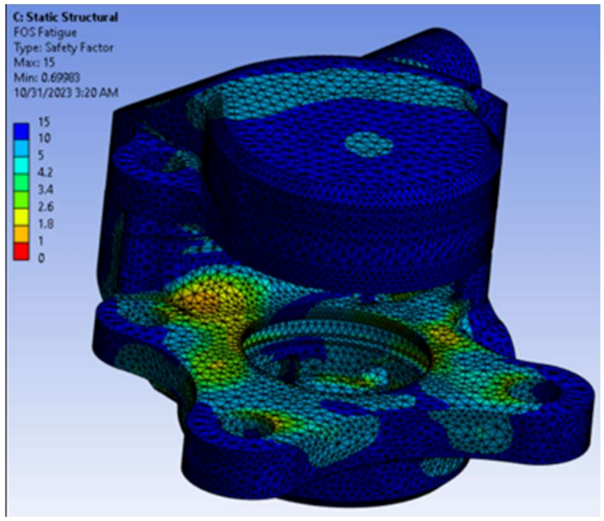


Figure 34. FOS on fatigue using the Gerber criteria.

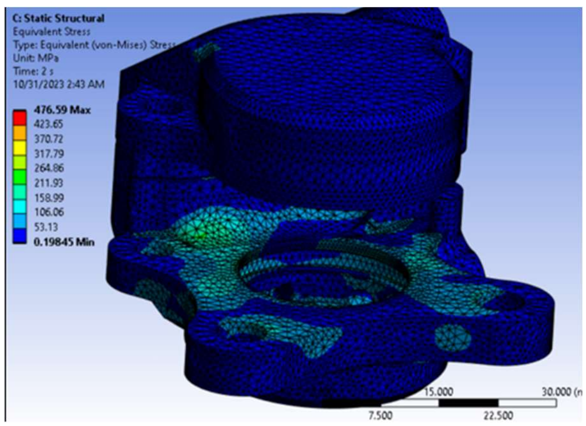


Figure 35. Stress state during threshold braking on dirt.

5.5. Costs

A detailed BOM and cost breakdown can be found in appendix G. To summarize, one caliper is expected to cost $110, and if we can get 7000 series stock for free, which is likely, the cost is reduced to $90. The largest contributors to the total cost are the specialized piston O-rings and pistons, which make up $45 of the total cost. We could potentially cut costs by buying O-rings in bulk, and machining our own pistons, but that isn't a big focus, as our current cost is already in line with off-the-shelf options, and will provide higher performance.

5.6 Post-CDR Design Changes

We manufactured the first prototype exactly as presented in CDR. The only issue we discovered is that fluid slowly leaked from the bleed port under pressure. We determined that the taper under the bleed screw head was bottoming out in the countersink before the taper on the end of the bleed screw was fully pressed into the fluid passageway. We fixed this on the prototype by using a deburring tool to expand the countersink in the caliper, and we adjusted our design to make the countersink half a millimeter deeper.

Figure 36. We determined that the bleed screw was unable to be installed deep enough to press into the sealing taper based on the non-uniform aluminum residue on the bleed screw taper. It appears that only about 2/3 of the taper was making adequate contact with the caliper-side taper.

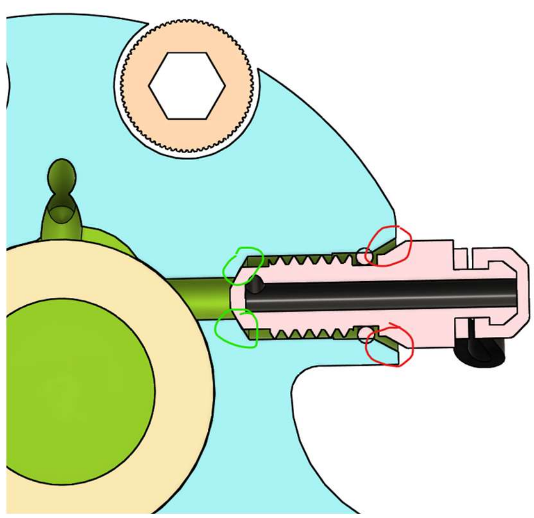


Figure 37. Cross section after adjustment. Note that there is clearance at the outer countersink, and contact at the inner sealing taper.

6. Manufacturing

Overall, there were largely no issues with the manufacturing of this design. The project followed the projected budget, minus the tooling cost which can all be reused for other Baja projects and future production runs of more calipers. The manufacturing methods worked exactly as expected and the desired forms were created within the desired tolerances. In the future it is recommended that the caliper is designed to be symmetric on the left and right sides of the car, this would greatly reduce the programming time and result in an easier to manufacture system.

6.1. Final Budget

It is hard to know the total amount spent on calipers because we are operating in conjunction with the Baja team, so we or other team members may purchase additional spare parts off our BOM without meticulous tracking of each order. Our project did not have a strict budget, as we were essentially creating a product to replace off-the-shelf brake calipers, which could be manufactured in the quantity desired by the Baja team. The best cost metric for us is cost per caliper, which has not changed since CDR. All the items on our BOM in appendix G are still used in the current caliper iteration, and the total cost per caliper comes out to $110.66, which is competitive with existing calipers. This number drops to $89.88 when we consider that the Baja team has plenty of donated 7075-T6 stock which is essentially free to use.

6.2. Manufacturing

This section discusses the various manufacturing methods for the most challenging and complex parts required to complete this project.

6.2.1. Grooving Tool

To machine the complex groove geometry described in section 5.2, a custom HSS tool was created. The tool consisted of an arbor and an insert. The insert is attached to the arbor via two set screws.

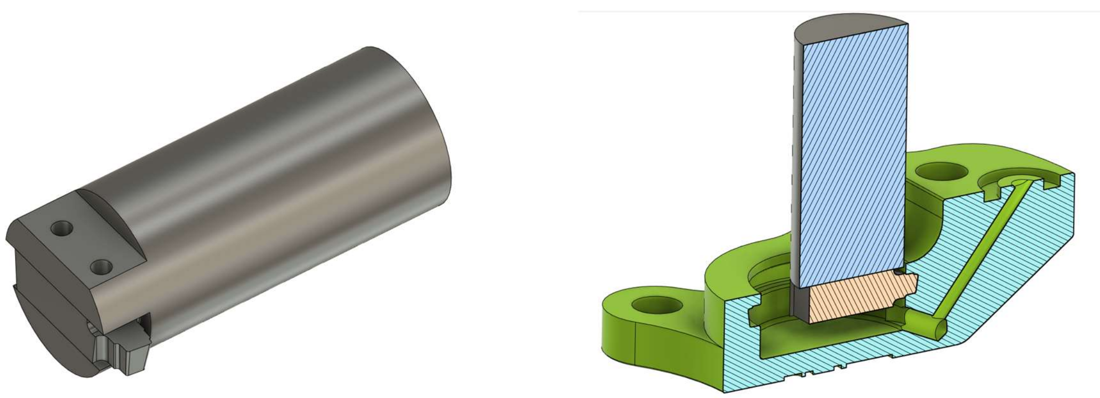


Figure 38. Grooving tool design.

The arbor is made from ETD-150. This material was selected due to its easy machinability, acceptable strength, and on-hand availability. The insert is made from A2 tool steel. A large variety of alloys were considered for the insert. It was crucial that the selected alloy was easy to heat treat with in house equipment and that this process will not significantly alter the dimensions of the insert. The hardness of the alloy was not a driving factor in material selection. Any tool steel alloy will have sufficient hardness after heat treating to machine a limited quantity of grooves in soft aluminum. A2 tool steel was selected because it can be treated at reasonable temperatures and is air hardening which simplifies the process and results in minimal warpage.

To manufacture the arbor, a 5/8” diameter rod was put into a manual milling machine using a collet block with the axis of the rod aligned with the Z axis of the machine. From here, the required slots and flats were created. Then, the part was placed with the axis of the rod aligned with the X axis of the machine. From here, holes were drilled and tapped for the set screws.

Figure 39. Grooving tool manufacturing

Figure 40. Grooving tool arbor manufacturing.

To manufacture the insert, .25 x .25 A2 tool steel bar stock was loaded into a 5-axis milling machine. From here, the insert was machined down to have a .20 x .20 square shank that fits into the arbor. Then, using small bull nose endmills the cutting profile and relief geometry were created.

Figure 41. Machining of the inserts on a VF2-SS with TRT-160.

After the inserts were machined, they were heat treated. To do this, the inserts were first thoroughly cleaned of all oils and then placed into a stainless-steel heat-treating bag along with a small piece of paper. Once the bag is sealed and placed into the furnace, the paper will burn and consume all the oxygen in the bag, creating an inert environment that prevents mill scale buildup on the inserts. A very standard process for treating A2 tool steel was used, the exact details of which are specified in Bryson's *Heat Treatment, Selection, and Application of Tool Steels*. The temper was performed at 400 F targeting HRC 60. A lower hardness is likely desirable to improve the inserts toughness, but this was the maximum temperature of the oven used to temper these parts.

Figure 42. The finished inserts along with the oven used to preheat and soak (austenitize) the inserts.

6.2.2. Caliper Body Halves

The body halves are machined from 7075-T6 aluminum which was procured from existing Baja stock inventory. Each piece of stock is approximately 3" x 2" x 1" and is cut from 1" x 2" bar stock.

The body halves are CNC milled using the shop's VF2-SS with TR160 5th axis trunnion attachment. The first machining operation is a stock prep operation where a dovetail is cut into the stock so that it can be held in a dovetail vice for the second operation. The second machining operation is where the bulk of the machining takes place and is performed with the 5th axis mill. A rough list of the machining steps is as follows.

1. Roughing toolpaths are used to rough out the shape of the caliper without cutting any surfaces to final dimension. This is done with a 0.375" or 0.5" carbide endmill.

2. Each caliper half has a few holes drilled at angles to its surfaces so areas normal to the holes will be spot faced to ensure drills will not wander when entering the material. High speed steel drills are used so spot drilling is necessary after spot facing and prior to drilling. Some holes do not require spot-facing but are still drilled. Threads for the body screws and ports are also created using form taps.

3. The piston seal groove is roughed out to a rectangular profile using a key seat cutter and then finished using a miniature fly cutter with a custom edge profile. This form tool cuts the finished groove to the final shape and is not used for large amounts of material removal. The seal groove geometry is inspected with a CMM and fine-tuned by creating test parts with half the bore machined away so that a cutaway of the groove profile may be viewed. The grooves on the final caliper bodies are not inspected so test cuts must be made each time the bodies are machined. Once the groove geometry is machined into the bore, the inner diameter of the bore is finished with an endmill.

4. Once the critical features are machined, finishing toolpaths are used to finish outer surfaces and a ball endmill is used to surface the curved features that cannot be cut with simple contours.

5. At this point the body is mostly machined except for the material that is being held in the vise. A tab off operation is performed in order to remove most of the material attached to the machined body to the leftover stock being held by the vise. At the end of this operation, the body is only connected by a few small tabs that can easily be broken by hand. This is the last operation performed since the tabs do not provide good support for machining any other features.

Before that caliper halves can be bolted together, threaded inserts must be installed in the outboard half of the caliper. Once they are installed, ¼-28 socket head cap screws are used to bolt to two halves of the caliper together.

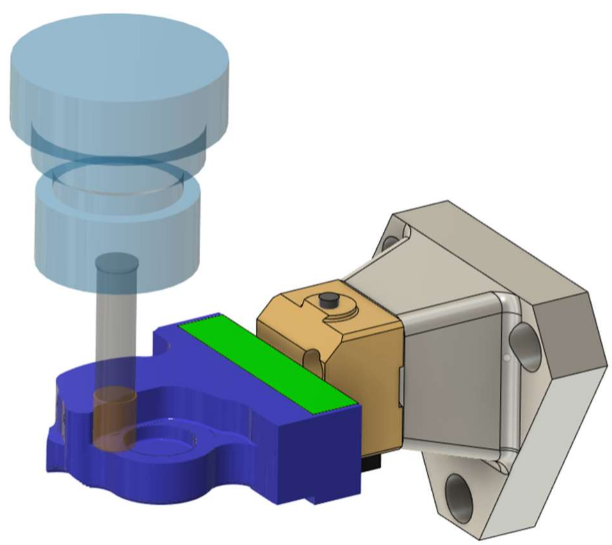


Figure 43. Simulation of the machining, currently the machine is roughing with a ½” RN endmill.

Figure 44. Caliper with cut made to reveal the internal fluid routing and sealing grove geometry. The surfaces were polished and optically inspected with a CMM.

Figure 45. Finished caliper half held onto the machine with two tabs.

Brake Pad Retention Spring

The pad retention spring is made of 0.015” thick spring steel sheet which is purchased from McMaster-Carr. The spring is waterjet out of steel sheet and bend into shape. A 3d printed jig is used to help when bending the spring into its final shape. The bending is done using a small arbor press. The pad retention spring slides over the friction material on the brake pads and then both pads and the spring are inserted into the caliper body.

Figure 46. Final assembled product.

7. Design Verification

After completion of our verification prototype, we will need to prove that our design meets our many requirements. The requirements are restated below for clarity.

Requirement	Value	Test Needed (Y/N)
Max Pressure	3000 psi	Y
Max Lockup Pressure (Tarmac)	1280 psi	Y
Max Lockup Pressure (Dirt)	700 psi	Y
Normal force at lockup pressure (Tarmac)	13600 N	N
Normal force at lockup pressure (Dirt)	7300 N	N
Max allowable rotor temp	375 C	Y
Caliper Stiffness	30000 N/mm	Y
Maximum Caliper Mass	280 g	Y
Pad Life	8 hours	Y
Caliper Life	90 hours	N
Footprint	<120% vol. formula caliper	Y
Fluid Compatibility	DOT 4	Y

Figure 47. Breakdown of requirements that require verification testing

7.1 Planned Testing

While most of the requirements require verification testing, a few do not.

The normal force requirements do not need to be tested because clamping force is coupled to pressure. Normal force values are useful during the design stage, but are difficult to test, and redundant because we will be testing lockup pressures on different terrains.

The required 90-hour caliper life is something that would be tested in a perfect world, but it is almost certainly not feasible to get 90 hours of on car testing before we need to start design of the second iteration. While any fatigue calculations are based on a 90-hour life, we will have to take the risk of not putting this requirement to the test. Fortunately, a failure to meet this requirement will cause inconvenience and extra labor (more service and manufacturing of spares) rather than complete failure at competition. We will certainly be able to validate our caliper above the 4-hour endurance event time, so worst case we can still be confident that a new caliper set will last through endurance.

The footprint requirement also does not require physical testing but can be verified for compliance with analysis. It is a simple check that can easily be confirmed in CAD.

Compatibility with DOT 4 fluid is a requirement that dictates the use of EPDM rubber for all seals but is not something that needs to be tested directly. We have sourced the proper seals and can verify that they EPDM via inspection.

The tests to verify the rest of the requirements are included in Appendix F. To summarize, pressure related tests will either use a pressure gauge or a pressure transducer. The max pressure test will be static, and it will be used to verify the structural integrity of the calipers before any on car testing is performed. A pressure gage will be connected to the brakes system, and the system will be pressurized to 3000 psi. Any fluid leaks or mechanical failure will be a failure to meet the requirement. During this test, the deflection of the caliper can be measured. The max deflection and max pressure can be used to calculate the stiffness of the caliper. The pressure (Pa) times the piston area (m^2) divided by deflection (mm) will yield the stiffness, which must meet the stiffness requirement.

After verifying that the calipers can take the max pressure of 3000 psi, we will perform on-car testing. Using wheel speed sensors and pressure transducers, we will be able to determine the pressure at lockup on both tarmac and dirt and compare these numbers to our requirements.

We can find the maximum rotor temperature by driving a representative test course with a temperature sticker on the rotor. After many laps we will be able to see how hot the rotor got.

To check caliper mass, we can simply weigh an assembled caliper on a food scale that has 1 gram precision. We have a good mass estimate from CAD, but it is worth confirming in real life, as the masses of purchased components in CAD might not match real life.

To confirm that pad life is at least 8 hours, we will need to track drive time, and after 8 hours we can repeat lockup pressure tests on dirt and tarmac. The calipers pass if the pressure needed to lockup hasn't increased.

7.2 Actual Testing

Pressure and Deflection Testing

We pressure tested a caliper by connecting it and a pressure gauge to the 2023 Baja car's brakes system. We used a digital caliper to measure deflection under pressure by zeroing the digital caliper on the undeformed brake caliper and then pressurizing the caliper. The testing setup is shown on the following page. We achieved a pressure of 3400 psi, which exceeds the 3000 psi requirement. We observed 0.027 inches of deflection. When converted to N/mm, this gives a caliper stiffness of 129938 N/mm, which greatly exceeds the required 30000N/mm.

Figure 48. Caliper pressure and deflection testing. The calipers withstood 3400 psi and deflected a maximum of 0.027 inches.

Mass

The fully assembled caliper weighs about 215 g, which meets the requirement of less than 280.

Max Rotor Temperature

We were not able to test the maximum rotor reached during use, however, we had no issues with rotor warping or accelerated pad wear during testing or competitions, so rotor temperature is likely not an issue.

Lockup Pressure (Tarmac & Dirt)

We did not get around to measuring lockup pressures because the car was not in a driving condition until shortly before competition, and the car was almost exclusively used for driver training until competition. However, the drivers were comfortable applying the necessary braking force to lock all four wheels to pass brake check.

Pad Life

We did not directly test pad life, but the car was driven for more than 8 hours of testing and then around 4 hours at Gorman competition before we finally had to swap pads to pass brake check at Pennsylvania Competition.

8. Project Management

Working calipers must be delivered by go/no-go, which is the date during winter quarter that the car must be completed by. Successful completion of this project will require us to adhere to an ambitious timeline.

The milestones below include all major steps we achieved. Our second run of calipers was manufactured just one week before our first competition, but by that point we had already confirmed that our design worked, and we just needed more spares for competition.

Milestone	Date	Done (Y/N)
Requirements Set	5/18/23	Y
Piston Size Chosen	6/02/23	Y
Find and Order Caliper with Appropriate Piston Size	07/01/23	Y
Deconstruct Piston and Inspect Seal Groove	08/01/23	Y
First Revision of Final CAD Complete	09/21/23	Y
Machine Custom Groove Tool	11/13/23	Y
First Functional Prototype Manufactured	12/18/23	Y
Complete First round of Testing	12/25/23	Y
Adjust Design Based on Testing	2/9/24	Y
Manufacture Second Iteration	4/20/24	Y
Pass Brake Check at Gorman Competition	4/26/24	Y

Figure 49. Fall/Winter/Spring quarter milestones.

9. Conclusions & Recommendations

This report covers the design of a custom brake caliper intended to suit the needs of Cal Poly's Baja SAE team. Our background research led us to the conclusion that existing calipers are either too bulky and overbuilt, or too small and prone to failure. With our design, we are aiming for a middle ground, with a caliper that is compact enough to integrate well into the outboard assembly, but sturdy enough to withstand the clamping forces needed to stop the car.

At the end of our project, we have designed and made brake calipers that suit the needs of the Baja SAE team. Our calipers are light and compact but stiff enough to deliver the required braking force. Caliper packaging was significantly easier than last year thanks to the decreased size. We were able to pass brake check at both competitions this year, and there were no brakes failures during either competition.

We have created a design that could be used in its current state indefinitely, but if the team wishes to improve the design, we have the following recommendations:

1. Create a symmetric caliper design. We designed left and right calipers with conveniently located line routing and bleed screws located at the highest point in the caliper. However, this makes manufacturing more time consuming, as the number of unique CNC parts that need to be programmed is doubled. A symmetric design that has a bleed screw on either side would reduce the number of parts that need to be manufactured while still allowing for easy bleeding of the calipers.

2. Integrate caliper mounting into the upright. We currently use an adapter plate between the upright and the caliper. This made sense when we were not positive that our design would work, because the use of an adapter plate means that if our custom calipers did not work, we could have used a different adapter plate to mount off the shelf calipers. However, now that our design is validated, it makes sense to redesign the caliper and upright mounting interface to bolt the calipers directly to the uprights. This reduces part count and will potentially result in a slight weight reduction. The mounting stiffness may also be higher if the number of bolted connections is reduced.

3. Attempt to source piston O-rings in bulk. Our piston O-rings must be EPDM to withstand DOT fluid, and we were only able to find a single source of 22mm ID by 2mm square EPDM O-rings. The source is a motorcycle caliper O-ring kit on Amazon that contains 2 O-rings and costs $24.01. It may be possible to purchase bulk O-rings directly from the manufacturer. It also may be possible to use O-rings made of a different material due to the short design life of these calipers. We think it would be worthwhile to try to find an alternative to the $24 O-ring kit, as that one kit comprises around 25% of the cost of a custom caliper.

4. Change the brake line interface. The banjo fitting we used to connect the brake lines to the calipers requires mountain bike brake lines and adds complexity compared to a simple off the shelf automotive brake line with a threaded fitting. A simple threaded port on the inboard side of the caliper would allow the use of simpler automotive brake line and would decrease the number of adaptor fittings needed to accommodate the mountain bike brake lines. This change that was requested by 2023/24 brakes lead.

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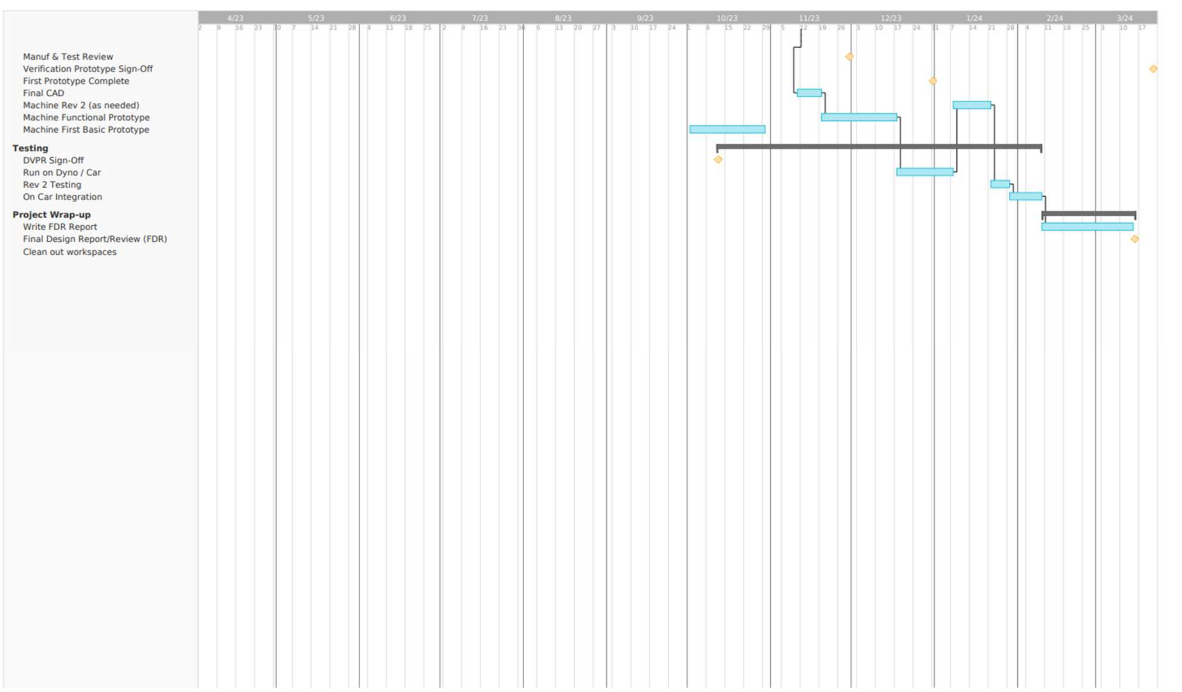
Appendix A: Gantt Chart



Appendix B: Quality Function Deployment

Correlations	
Positive	+
Negative	–
No Correlation	

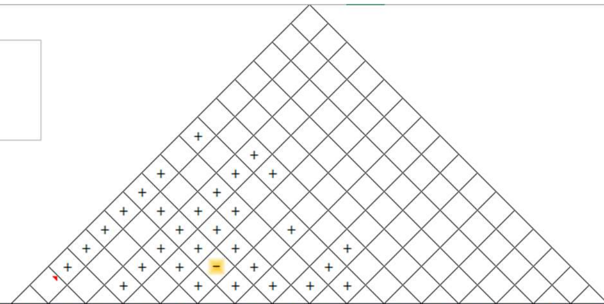
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: SAE Brake Calipers

Revision Date: 5/5/2023



								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers							Direction of Improvement	◇	◇	▼	▼	▲	◇	◇	▼	▲	▲	▼						NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Brakes Lead	Sus Lead	Service Leads	Machinists	Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Clamping force at failure	Bleed port location	Mass	Footprint	Design Life	Pressure at failure	Clamp Force @ Design Life	Cost	Pad temp. at caliper overheat	Caliper temp. at overheat	Time to manufacture						Wilwood PS1	Formula Calipers	Guide Calipers	Competitor #3: *Product Name*	Competitor #4: *Product Name*	Row #
1	III	6%	10	1	10	1		Easy to bleed	▽	●	▽	▽	▽	○	▽	▽	▽	▽							3	1	4			1
2	II	4%	3	5	1	1		Reduced mass	○	▽	●	●	●	○	▽	○	▽	○	●						0	4	5			2
3	III	7%	7	7	2	2		Reduced size	○	▽	○	●	●	○	○	○	○	●	●						0	5	4			3
4	III	8%	6	1	7	7	9	Long service life	▽	▽	▽	▽	●	○	○	▽	○	○	▽						5	1	3			4
5	II	5%	8	1	8	1	9	Long pad life	●	▽	▽	▽	●	○	●	▽	●	●	▽						5	4	1			5
6	III	6%	7	7	1	1	3	Easy to mount	▽	▽	▽	○	▽	▽	▽	▽	▽	▽	○						2	2	2			6
7	II	5%	5	1	9	1	3	Quick to install	▽	▽	▽	○	▽	▽	▽	▽	▽	▽	▽						4	2	3			7
8	II	5%	5	1	9	1	3	Quick to remove	▽	▽	▽	○	▽	▽	▽	▽	▽	▽	▽						4	3	3			8
9	I	3%	8	1	1	1	9	Reasonable operating pressure	●	▽	▽	▽	●	●	○	▽	▽	●	▽						4	0	2			9
10	III	6%	10	1	10	1	9	No overheating	○	▽	▽	▽	●	▽	○	▽	●	●	▽						5	3	3			10
11	III	6%	8	3	2	4	9	Uses standard fittings	▽	○	▽	▽	▽	▽	▽	●	▽	▽	○						5	1	1			11
12	IIII	8%	9	6	9	1	9	Convenient port locations	▽	●	▽	▽	▽	▽	▽	▽	▽	▽	○						2	3	2			12
13	III	8%	5	1	1	10	9	Easy to manufacture	▽	▽	●	○	▽	▽	▽	●	▽	▽	●						N/A	N/A	N/A			13
14	IIIIIII	16%	10	10	10	10	9	Pass brake check	●	▽	▽	▽	▽	●	○	▽	▽	▽	▽						5	1	5			14
15	II	5%	6	1	8	1	9	Easy to mantainance	▽	●	▽	▽	▽	▽	▽	▽	▽	▽	▽						3	3	3			15
16	I	2%	5	1	1	1	9	Inexpensive	▽	▽	○	▽	▽	▽	▽	●	▽	○	●						3	3	4			16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	TBD	TBD	TBD	TBD	270 hours (3 seasons of testing)	TBD	TBD	TBD	TBD	TBD	TBD					
	Max Relationship	9	9	9	9	9	9		9		9	9					
	Technical Importance Rating	328	264.7	212.6	234.5	365.9	312.9		252.2		299.3	309.9	0	0	0	0	0
	Relative Weight	13%	10%	8%	9%	14%	12%		10%		12%	12%	0%	0%	0%	0%	0%
Curr. Products	Wilwood PS1	5	3	1	1	4	5		3		4	N/A					
	Formula Calipers	2	2	4	4	1	2		3		2	N/A					
	Guide Calipers	IDK	3	5	5	3	4		4		IDK	N/A					
	Competitor #3: Product Name																
	Competitor #4: Product Name																
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix C: Caliper Data Sheets/Product links

Wilwood PS1 caliper data sheet

https://www.wilwood.com/PDF/Flyers/fl40.pdf

Formula caliper product page with specs

https://www.rideformula.com/products/moto-brakes/minicross/

Sram guide caliper product info

https://www.sram.com/en/sram/models/db-gde-t-a1

Appendix D: Pugh Matrix

Function	Importance	Possible Solutions				
Mounting	7	Radial	Axial	Multiple calipers		
Clamping	10	One piston	Two pistons	Multiple pistons per side		
Bleeding	10	Bleed screw	Bleeding ball valve	Bleed nipple		
Fluid Transport Sealing	10	Two piece body with interface that gets compressed during clamping	One piece with plugs sealing manufacturing holes and piston bore			
Pads	8	Custom pads	Purchased pads			
Thermal Management	9	High resistance wafer between pads and piston for thermal resistance	Fins on caliper body			
Enclosure	7	One piece	Two piece			
Fluid Transport	7	Internal channels	External tubes			
Piston Sealing	9	Square o-ring	Round o-ring	Really tight slip fit		
Piston Retraction	10	Seal deformation	Compression spring for return	Spring loaded brake pedal to pull pistons back.	Extension spring return	Leaf spring return
Pad Retraction	6	Bond pad to piston	Magnet pad to piston	Torsion springs at pad mount		

Appendix E: Design Hazard Checklist

Y	N	
✔		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	✔	2. Can any part of the design undergo high accelerations/decelerations?
✔		3. Will the system have any large moving masses or large forces?
	✔	4. Will the system produce a projectile?
	✔	5. Would it be possible for the system to fall under gravity creating injury?
	✔	6. Will a user be exposed to overhanging weights as part of the design?
	✔	7. Will the system have any sharp edges?
	✔	8. Will any part of the electrical systems not be grounded?
	✔	9. Will there be any large batteries or electrical voltage in the system above 40 V?
✔		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
✔		11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✔	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
✔		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✔	14. Can the system generate high levels of noise?
✔		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✔		16. Is it possible for the system to be used in an unsafe manner?
	✔	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	**Planned Corrective Action**	**Planned Date**	**Actual Date**

The brake pads clamp on the rotor with upwards hundreds of pounds of force.	The pads will be contained by the caliper body, which will be designed to support the clamping load.	Summer 2023	
The piston force will be hundreds of pounds.	The piston will be contained by the caliper body, which will be designed to support the clamping load.	Summer 2023	
The brake fluid will be under high pressure.	The caliper body will be designed with a significant factor of safety. Seal integrity will be tested at lower pressures before operating at full pressure. Fittings and lines used will be rated for pressures higher than operating pressure.	Summer-Winter 2023	
Brake fluid is moderately flammable. Brake cleaner is highly flammable.	Fluids will be kept away from spark sources such as grinders or welders. Fluids will be stored in appropriate containers and kept in fireproof cabinets when not being used.	Fall-Winter 2023	
Brake fluid and brake cleaner are toxic to humans.	Fluids will be used only in well-ventilated spaces. Safety glasses will always be worn.	Fall-Winter 2023	
Braking can develop high temperatures.	Thermal analysis will be conducted to ensure high temperatures do not cause mechanical failure. Care will be taken to not touch the caliper immediately after use.	Summer 2023	
The system could spray high pressure fluid if improperly assembled.	Safety glasses will be worn whenever we are working on the system. An assembly manual will be created to reduce the risk of improper assembly.	Fall 2023	

Appendix F: Design Verification Plan

DVP&R - Design Verification Plan (& Report)											
Project:	Baja SAE Brakes		Sponsor:	Cal Poly Racing						Edit Date:	11/3/2023
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Max Pressure - 3000 psi	Attach a pressure gauge to the brakes system on the car and pressurize to 3000 psi. This should require significant effort from the person sitting in the car, but is possible.	pressure [psi gage]	no leaks, no mechanical failures	Baja car (any year will work) Hangar/shop tools	Working custom calipers, brake line, pressure gauge, banjo fitting/bolts, brake fluid	Colin	12/18/2023			
2	Tarmac lockup pressure - under 1280 psi	Install custom calipers on a baja car with a pressure transducer installed in the brakes system. Wheel speed and brake line pressure must both be logged. Drive the car at top speed on tarmac, and press the brakes hard enough to lock the wheels.	brake line pressure (psi), wheel speed (rpm)	Wheels lock before brake line pressure exceeds 1280 psi	Baja car with pressure transducer and wheel speed sensors installed.	Working custom calipers, brake line, pressure gauge, banjo fitting/bolts, brake fluid	Ben	12/18/2023			
3	Dirt lockup pressure - under 700 psi	Install custom calipers on a baja car with a pressure transducer installed in the brakes system. Wheel speed and brake line pressure must both be logged. Drive the car at top speed on dirt, and press the brakes hard enough to lock the wheels.	brake line pressure (psi), wheel speed (rpm)	Wheels lock before brake line pressure exceeds 700 psi	Baja car with pressure transducer and wheel speed sensors installed.	Working custom calipers, brake line, pressure gauge, banjo fitting/bolts, brake fluid	Ben	12/18/2023			
4	Max allowable rotor temp - 375 C	Install temperature stickers on the rotors. Drive a few representative laps of a test course, until it can reasonably be assumed that caliper temperature will have reached its max value at some point during testing.	Max temp (C)	Max temp is below 375 C	Functional baja car	Temperature stickers, working custom brake calipers, banjo fittings, brake lines, brake fluid	Carter	12/18/2023			
5	Caliper stiffness - at least 30000 N/mm	Measure the distance between caliper halves. Insert a sheet of steel the same thickness as a rotor between the brake pads. Pressurize the caliper to 3000 psi (using a baja car brake system), and measure the gap between caliper body halves at the bottom of the caliper. Calculate stiffness by dividing pressure times area by deflection in mm.	Distance between caliper body halves (mm)	Caliper stiffness is greater than 30000 N/mm	Baja car with functional brake system. Calipers (measuring, not brakes)	Working custom calipers, brake line, pressure gauge, banjo fitting/bolts, brake fluid	Nathan	12/18/2023			
6	Caliper mass - under 280 g	Weigh an assembled caliper. Exclude banjo fitting, but include other fasteners and brake pads.	Mass (g)	Mass is less than 280 g	Small scale (food scale)	Assembled custom caliper	Nathan	12/18/2023			
7	Pad life - at least 8 hours	Measure brake pad thickness. Install custom calipers on the car. Track driving time until the car has been driven for 8 hours. Examine pads and measure thinnest pad region. Repeat tests 2 and 3 to confirm pads still perform as intended.	pressure [psi]	Brakes performance at 8 hrs of use matches performance of fresh brakes	Baja car with pressure transducer and wheel speed sensors installed.	Working custom calipers, brake line, pressure gauge, banjo fitting/bolts, brake fluid	Carter	12/18/2023			

Appendix G: Project Budget

	Part Description	PN	MFG	Supplier	Qty Needed	Qty/pkg	Pkg Cost	Unit Cost	Total Cost	Link
Hardware	Pad retaining pin	92735A154	-	McMaster	1	1	$ 6.25	$ 6.25	$ 6.25	https://www.mcma
	Structural Bolts	90128A365	-	McMaster	2	25	$ 6.44	$ 0.26	$ 0.52	https://www.mcma
	Body Seal O-Ring	1289N333	-	McMaster	1	50	$ 4.84	$ 0.10	$ 0.10	https://www.mcma
	Banjo O-Ring	1289N306	-	McMaster	2	50	$ 3.05	$ 0.06	$ 0.12	https://www.mcma
	Helicoil	91732A515	-	McMaster	2	10	$ 6.95	$ 0.70	$ 1.39	https://www.mcma
	Piston seal	-	-	Amazon	1	1	$ 24.01	$ 24.01	$ 24.01	https://www.amaz
Purchased components	Brake pad set	-	Formula	Xmotorstore	1	1	$ 21.15	$ 21.15	$ 21.15	https://www.xmot
	Banjo bolt	SM-BH60	Shimano	Foothill Cyclery	1	1	$ 3.00	$ 3.00	$ 3.00	-
	Banjo fitting for soft line	-	Off brand	Ebay	1	1	$ 13.03	$ 13.03	$ 13.03	https://www.ebay.
	Pistons		Shimano	Ebay	2	1	$ 10.16	$ 10.16	$ 20.32	https://www.ebay.
Stock	1"x2.5"x2.5" 7075 T6	9055K18	-	McMaster	1	9	186.95	$ 20.77	$ 20.77	https://www.mcma

Total	$ 110.66
Total (free stock)	$ 89.88

Appendix H: Initial Caliper Sizing Spreadsheet

Inputs

Parameter	Value	Units	Value	Alt Units	Notes
Wheel Base	59	in	1.4986	m	
CG Height	18.14	in	0.46076	m	
Total Vehicle Mass	370	lbm	167.829	kg	
Brake Check Driver Mass	120	lbm	54.431	kg	
Endurance Driver Mass	180	lbfm	81.6466	kg	
Front Percent	0.45	-			
Rear Percent	0.55	-			
Front Radius	21.5	in	0.5461	m	
Rear Radius	20.8	in	0.52832	m	
Concrete Tire Friction	1.1	-			Conservative
Dirt Tire Friction	0.8	-			Need to process test data
Pad Friction	0.5	-			
Min Rotor Diameter	5.5	in	0.1397	m	
Max pedal force	200	lbf	889.644	N	Non-conservative, apply FOS
Brake check pedal force	100	lbf	444.822	N	Conservative, all drivers under 72" can apply this
Comfertable pedal force	50	lbf	222.411	N	Force to reach traction limit on gravel, need testing
Max line pressure	5000	psi	3.4E+07	Pa	Based on flex line breaking
Number Pistons Front	4	-			
Number Pistons Rear	2	-			
Factors of Safety	Yeild	Ultimate			
Structural	1.1	1.3			
Driver inputs	-	1.3			

Pressure Requirments

Parameter	Value	Units
Max Pressure (nominal)	5000	psi
Driver force at max pressure	260	lbf
Pressure / Pedal Force (design)	19.230769	psi / lbf
Max Brake Check Driver Pressure	1923.0769	psi
Max Comfertable Driver Pressure	961.53846	psi

Selected Design

Parameter	Value	Units
Front Piston Design Size	22	mm
Rear Piston Design Size	28.6	mm

Braking on Dirt

Before Load Transfer

Parameter	Value	Units	Value	Alt Units
Max Comfertable Pressure	961.53846	psi	6629576.9	Pa
Total Vehicle Mass	249.4756	kg		
Max Accel	7.848	m/s^2		
Front Weight	1101.31	N		
Rear Weight	1346.0456	N		
Total Tang Force	1957.8845	N		
Rear Tang Force	1076.8365	N		
Rear Calip Tang Force	4072.3998	N		
Rear Calip Norm Force	8144.7996	N		
Min Rear Pist Area	0.0006143	m^2		
Min Rear Pist Diam	0.0279665	m	27.966451	mm

Post Load Transfer

Parameter	Value	Units	Value
Max Comfertable Pressure	961.53846	psi	6629576.9
Total Vehicle Mass	249.4756	kg	
Max Accel	7.848	m/s^2	
Front Weight	1703.2766	N	
Rear Weight	744.07907	N	
Total Tang Force	1957.8845	N	
Front Tang Force	1362.6212	N	
Front Calip Tang Force	5153.1858	N	
Front Calip Norm Force	10306.372	N	
Min Front Pist Area	0.0003887	m^2	
Min Front Pist Diam	0.0222451	m	22.245136

Braking on Concrete

Before Load Transfer

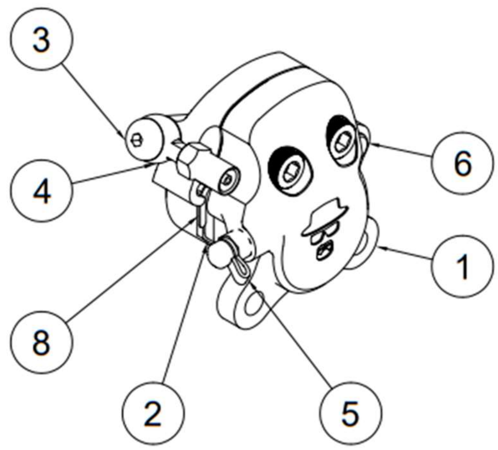
Parameter	Value	Units	Value	Alt Units
Max Comfertable Pressure	1923.0769	psi	13259154	Pa
Total Vehicle Mass	249.4756	kg		
Max Accel	10.791	m/s^2		
Front Weight	1101.31	N		
Rear Weight	1346.0456	N		
Total Tang Force	2692.0912	N		
Rear Tang Force	1480.6502	N		
Rear Calip Tang Force	5599.5497	N		
Rear Calip Norm Force	11199.099	N		
Min Rear Pist Area	0.0004223	m^2		
Min Rear Pist Diam	0.0231886	m	23.188556	mm

Post Load Transfer

Parameter	Value	Units	Value
Max Comfertable Pressure	1923.0769	psi	13259154
Total Vehicle Mass	249.4756	kg	
Max Accel	10.791	m/s^2	
Front Weight	1929.014	N	
Rear Weight	518.34163	N	
Total Tang Force	2692.0912	N	
Front Tang Force	2121.9154	N	
Front Calip Tang Force	8024.6983	N	
Front Calip Norm Force	16049.397	N	
Min Front Pist Area	0.0003026	m^2	
Min Front Pist Diam	0.0196289	m	19.628925

Braking on Concrete

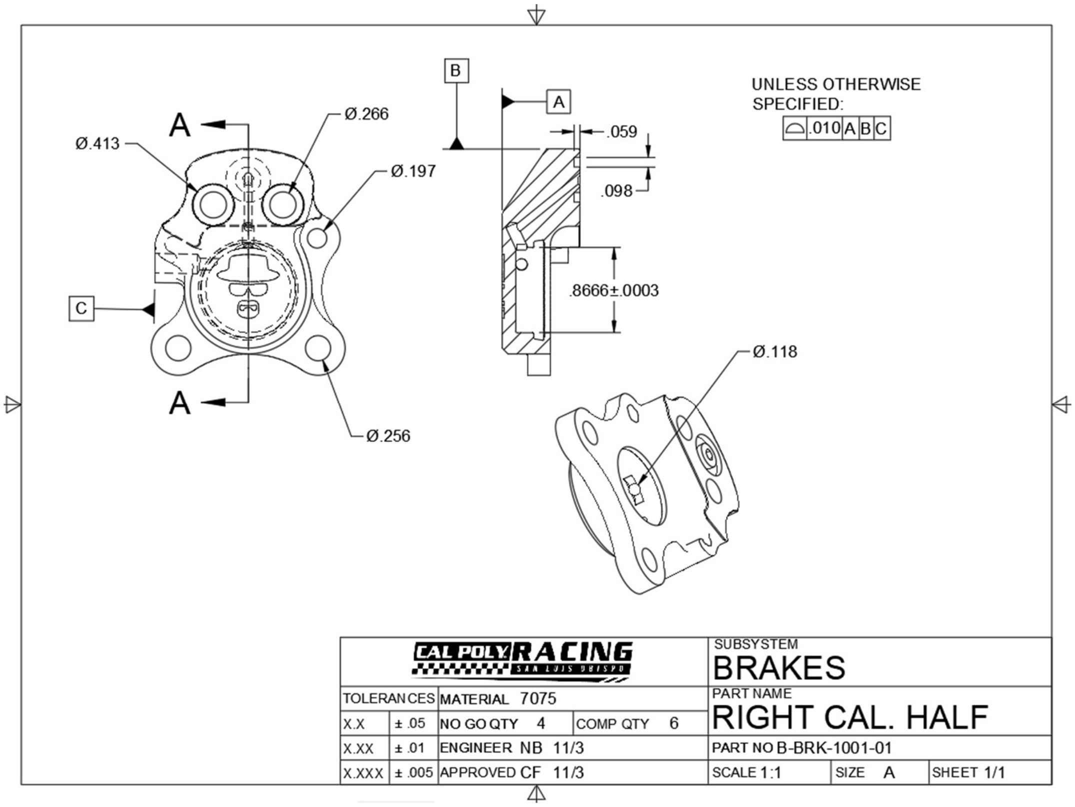
Appendix I: Part Drawings

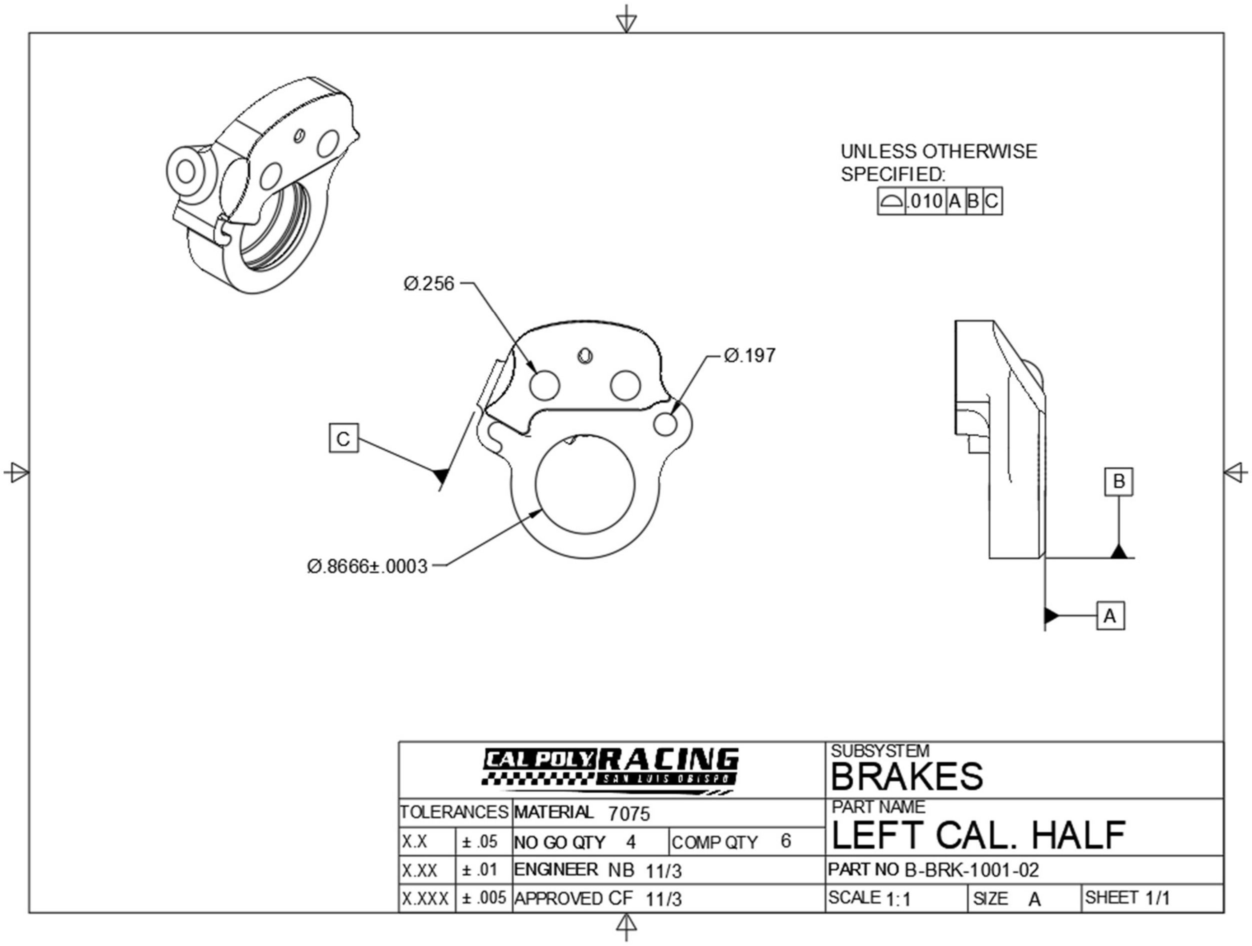


ITEM	QTY	PART NUMBER
8	1	PAD SPRING
7	2	SHIMANO 22MM PISTON
6	1	HARDWARE
5	1	SHIMANO BLEED SCREW
4	1	BANJO FITTING
3	1	SHIMANO SM-BH60 BANJO BOLT
2	1	FORMULA MINI CROSS PAD
1	1	CALIPER BODY

PARTS LIST

TOLERANCES		MATERIAL		SUBSYSTEM BRAKES
X.X	± .05	NO GO QTY 4	COMP QTY 6	PART NAME BRAKE CALIPER
X.XX	± .01	ENGINEER NB 11/3		PART NO B-BRK-1001
X.XXX	± .005	APPROVED CF 11/3		SCALE 1:1 / SIZE A / SHEET 1/3


UNLESS OTHERWISE SPECIFIED:
.010 A B C
A
A
B
A
C
Ø.413
Ø.266
Ø.197
Ø.256
.059
.098
.8666±.0003
Ø.118
CAL POLY RACING
SAN LUIS OBISPO
SUBSYSTEM
BRAKES
PART NAME
RIGHT CAL. HALF
TOLERANCES
X.X ±.05
X.XX ±.01
X.XXX ±.005
MATERIAL 7075
NO GO QTY 4
COMP QTY 6
ENGINEER NB 11/3
APPROVED CF 11/3
PART NO B-BRK-1001-01
SCALE 1:1
SIZE A
SHEET 1/1


UNLESS OTHERWISE
SPECIFIED:
.010 A B C
Ø.256
Ø.197
C
B
A
Ø.8666±.0003
CAL POLY RACING
SAN LUIS OBISPO
SUBSYSTEM
BRAKES
PART NAME
LEFT CAL. HALF
TOLERANCES
MATERIAL 7075
X.X ± .05
NO GO QTY 4
COMP QTY 6
X.XX ± .01
ENGINEER NB 11/3
PART NO B-BRK-1001-02
X.XXX ± .005
APPROVED CF 11/3
SCALE 1:1
SIZE A
SHEET 1/1