Cal Poly Supermileage Vehicle

Braking System

Final Design Report

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Abstract

The Cal Poly Supermileage Vehicle (SMV) team has requested this team to design the braking systems for the 2021 Supermileage vehicle in accordance with the 2020 Shell Eco-marathon rules, weight restrictions, and team budget. A braking system consists of the front brake pedals, front pedal mount, cable management to the brake calipers, and the rear caliper mounts. This report outlines the concept design that our project group has developed for the redesign braking systems. Background research, objectives, and concept design developments, final design, manufacturing notes, and design verification testing data are documented for the project sponsors.

Background research of the Shell Eco-marathon rules, current Supermileage braking systems, and bicycle braking systems shaped the scope of this project. Many design parameters lie within the regulatory needs of the vehicle in order to compete. The specified scope and design parameters allowed for our team to generate several concept designs for the braking systems, all of which are detailed in this report. From this point, our team configured the final design solution by optimizing function, weight, and cost. The design was manufactured and tested, and all information is included in the final design report.

A final design for the 2021 Supermileage braking system is proposed and shown to meet each of our design objectives with calculations and failure modes and effects analysis (FMEA). Models of this design are illustrated using Computer-Aided Design (CAD). Manufactured products are pictured in figures (listed above). This report outlines the project completed by this senior project team. All further modifications will be performed and documented by Cal Poly's Supermileage Vehicle club

1. Introduction

This section of the report has been updated from the Critical Design Review (CDR). Major changes include additional information added to manufacturing and design verification to accommodate for changes since CDR.

Problem Statement: The Supermileage vehicle team has requested a new braking system for the 2021 vehicle. Shell Eco-marathon competition regulations require vehicles to have two independent hydraulic braking systems, one per axle. Each braking system must have a foot pedal and both systems must be able to be actuated simultaneously. Additionally, while each braking system may have a maximum of two master cylinders, they must act on a single hydraulic circuit to ensure a proper balance between the right and left wheels. The previous system does not meet these standards, as well as creates energy losses through rubbing and is not ergonomic for the driver. Our team has developed an efficient and ergonomic system that meets competition regulations.

The goal of our project is to redesign the braking system of Cal Poly's Supermileage vehicle (SMV) to comply with new competition standards and to improve efficiency and driver ergonomics. The previous SMV braking system, installed on the Delamina, has been identified by current team members as uncomfortable and difficult to operate. It also is suspected of providing unwanted drag, reducing the vehicle's gas mileage by an estimated 100-200 mpg. Furthermore, Shell Eco-marathon competition rules recommend that all brakes to operate hydraulically. The previous system operates with a mechanical system; therefore, a complete overhaul is required for the next SMV to be competition-legal. Our team installed bicycle hydraulic brakes to the vehicle and developed the interface for custom foot pedals that are comfortable for the driver to operate.

The goal of this report is to explain our design process and document our manufacturing, installation, and testing in order to keep information accessible to future brake teams. The final design review will also include an oral presentation to further explain our design. In this report, the background section summarizes the research we have gathered thus far and includes our personal thoughts on possible solutions. The objectives section establishes our design specifications and requirements, as well as our original plans to implement each feature and the risks associated with each decision. The concept design describes our concept development process, and includes ideation notes, decision matrices, sketches, computer models, and analysis of our design. The final design will clearly define our overall conclusions of the project, and it include detailed drawings of the final deliverables. The manufacturing plan will go into further detail of the final design, and clearly label our methods of manufacturing and reasoning for material choices. The design verification will detail our testing plans and include results to confirm the product works as intended and meets safety requirements. The project management section demonstrates our decision-making process and outlines current project timelines.

2. Background

This section has updates from the PDR, with regards to rear brake selection.

With the variety of rotational systems in use today there is large assortment of braking solutions available. The existing Cal Poly SMV consists of two disk brakes for each front wheel and one rim brake for the rear wheel. There are two braking systems in the vehicle, front brakes and rear brake, that are operated individually operable via cable actuation from separate foot pedals. Each front brake is 2-piston, and the 140 mm disks are substantially perforated out to minimize weight. The rear rim brake is a simple bicycle rim brake that applies friction to the wheel rim to create braking force. The rules of Shell Eco-marathon state:

> *The effectiveness of the braking systems will be tested during vehicle inspection. The vehicle will be placed on a 20 percent incline with the driver inside. Each brake system will be activated separately, and each individual brake system must keep the vehicle immobile.*

The current system has several problems. The new Shell Eco-marathon rules recommend hydraulic front brakes for all Supermileage Vehicles by 2020. The existing cable-actuated system can pass the inspection testing, albeit with difficulty. This suggests the system has no room for degradation before failing inspection, thus requiring a new system. Finally, the current system requires the operator to depress the pedals nearly 90 degrees to fully actuate. This is not ergonomic for the driver and can pose as a safety hazard in race conditions.

The rear brake presents a unique challenge because transitioning to a disk-caliper system is incompatible with the current drivetrain. The wheel has no upright on which to mount a caliper and installing a rotor would require a new hub to be installed in the wheel. The current drivetrain is left-hand drive, which is not standard for bike wheels. The SMV drivetrain senior project team is designing a hub that would allow for easier mounting of a brake rotor, so a rear disk brake may be considered for future designs. Our design must be compatible with the current Supermileage vehicle, so this may not influence our design.

A rim brake update has advantages for this application over a disk brake. It is very easy to ensure zero friction when the brake is not applied and there is no additional rotational inertia from a disk to accelerate. If a rim brake is utilized, we would transition to a hydraulic high-performance model, which would provide much more braking power than the mechanical system currently on the vehicle.

2.1 Customer Wants

From communicating with the Supermileage team, we have gathered this list of wants, along with their justification.

- **Hydraulic brakes –** The transition from cable to hydraulic will allow for an immediate increase in brake force and stop time, as well as allow for reduced foot travel during actuation.

- **Foot operated –** The Shell Eco-marathon rules require the front brakes to be foot operated and applying this to the rear brakes allows the driver's hands to be free for steering and throttle control.
- **Independent operation of front/rear brakes –** Required by Shell Eco-marathon rules.
- **Each system immobilizes vehicle on a 20° slope -** Required by Shell Eco-marathon rules.
- **Braking distance-** Braking system must be able to stop within 4 meters when traveling 24 kph according to the SAE Supermileage Contest Rules.
- **Deceleration-** System must decelerate car from 24 kph at greater than 0.25 g according to the SAE Supermileage Contest Rules.
- **Zero drag when not in use –** Drag on misaligned rotors is a waste of energy and reduces effective mileage.
- **Light weight –** The lower the weight, the less mass the engine needs to propel.
- **Non-adjustable by driver during motion –** Required by Shell Eco-marathon rules.
- **Fits in current and future prototypes –** This system should be compatible with both the current prototype, and future versions, as it is intended to last more than one competition year.
- **Rotors fit within uprights –** Adequately sized rotors should provide necessary braking moment, but not too large to fit in the uprights without interference.

2.2 Existing Products

Because the existing system is capable of meeting Shell Eco-marathon inspection requirements with low-performance cable bicycle brakes, we didn't believe it was necessary to upscale to small vehicle brakes. Rather, our search focused on high performance bicycle brakes.

Figure 1 Magura MT5 four-piston disk brake caliper and lever.

Figure 2 Magura MT4 two-piston hydraulic disk brake caliper and lever.

Figures 1 and 2 show two possible models of brakes that could be installed onto the front wheels. Magura is not the only manufacturer option but is used as an example because their product line is high performance, low maintenance, reliable, and compatible with electronic systems. The decision between two and four pistons will be made after analysis of required brake force is complete. The four piston models provide more brake force, but the extra force may not be necessary factoring in additional weight and cost.

Figure 3 Magura HS33 hydraulic rim brake caliper and lever.

Figure 3 shows a high-performance rim brake, also by Magura. This model, or a similar one is substantially more powerful than a cable-mechanical rim brake. Because the existing model can meet the Shell Eco-marathon requirements, an upgrade like this would be able to outperform and outlast a mechanical replacement.

Both the front and rear brakes would require modification to operate in the Supermileage vehicle. Primarily, the stock hand levers would need to be deconstructed, and their master cylinders would need to integrate into the pedal system. There are a variety of foot operated hydraulic pedals available, but these all incorporate their own master cylinder, as seen in figure 4, or require a full-sized master cylinder to attach to. Due the differences in hydraulics between manufacturers, it would likely be difficult to purchase a product that would circumvent the stock master cylinder.

In research we found a book by Jean Jacques Santin, who helped design the Pac-Car II, a hydrogen cell car that operated at 12666.31 miles per gallon equivalent. We noted that his design team opted to use Magura disk brakes for two reasons. The first was their much lighter construction than other bicycle brakes available. The second was the calipers ability to retract to full clearance on every brake cycle, avoiding rotor drag.

Although a rim brake has these advantages, there are potential conflicts with the sprocket that drives the wheel. In order to optimize gear ratios for efficiency, the sprocket is nearly as wide as the rim itself and is located immediately adjacent. This placement makes mounting the rim brake very challenging, so a disk brake may be necessary.

Additionally, we've found two patents, numbers 20140109567 and 20140041379 that describe the master cylinder actuation of Magura brake levers. These patents, however, were not published in English, and the technical drawings have proven difficult to find on English websites, though there are thorough descriptions. Further attempts will be made to find the full texts, as they should provide valuable insight into design of the pedal box, and may allow us to perform more accurate analysis of brake forces.

Figure 4 AP Racing 3-pedal box.

To properly implement the braking system, pedals will need to be designed and fabricated to imitate the lever to master cylinder interaction seen here. Key design elements to consider are: force ratio from pedal to master, stiffness, weight, return mechanism, and connection from pedal to hand-brake master cylinder. Technical details of this design can be found in Appendix A and will serve as a starting point for design. This pedal box is a floor mounted model, which is what the vehicle needs. The carbon fiber monocoque won't be stiff enough to handle top-mount, as the new chassis is being designed 'skateboard' style, which makes the floor a much stronger mounting location.

Figure 5 Bicycle disk brake rotors.

One final area to consider is rotor sizing. Mountain bike rotors come in various sizes, the most standard being 140, 160, and 180 mm. As rotor diameter increases, the braking moment created by caliper friction also increases. Selecting a larger rotor has the potential to create stronger braking, but also increases the likelihood of over-braking, which is detrimental to the efficiency goals of the competition. The current SMV uses 140 mm rotors to avoid over-braking. Calculations can be done to select an optimal rotor size, but these rely on knowledge of the caliper force applied, which is unavailable for many brake models. Once the prototype stage is reached, testing can be performed to determine if the rotor size should be changed.

3. Objectives

This section has been updated from the Preliminary Design Review (PDR). The new 2020 Eco-marathon regulations and change in scope of our project to accommodate only the 2021 SMV has resulted in adjustments to the final design.

The front braking system now consists of a single piston-cylinder with a split cable that actuates both front wheel brake calipers per the 2020 Eco-marathon regulations. This change in design also resulted in a need for larger brake rotors which are listed in Table 1.

Change in scope of our project to the 2021 car resulted in a change in our rear braking system design. The SMV Drive Train team designed a rear hub with an integrated brake rotor, so our team has changed our design to include a rear disc brake rather than a rim brake. This change in design also requires our team to design a rear brake caliper mount.

Additional information was added to this section to clarify the design choices our team made. The braking systems specifications now include pedal interface details such as average pedal force and pedal travel. A design for an adjustable pedal mount and hub interface to mount rotors were added and the wheel size was removed from the specifications.

Specifications of wants and needs for the Cal Poly 2021 Supermileage vehicle braking system were obtained through technical research and sponsor input. These specifications form the problem statement for the project and are used to define measurable engineering specifications for the braking systems to be designed to. The list of wants and needs for this project is in Section 2.1.

3.1 Problem Statement

The Cal Poly Supermileage team needs a front and rear braking system that is low drag, light weight, and ergonomic. The braking system must meet the 2020 Shell Eco-marathon contest rules and provide better control, be more robust, and be more ergonomic than the current 2019 Cal Poly Supermileage car. Specific Shell Eco-marathon rules that our system must comply with are that the vehicle must have two independent hydraulic braking systems, one per axle. Each braking system must be actuated with a foot pedal, and both systems must be able to be engaged simultaneously. Additionally, a maximum of two master cylinders are allowed per axle, but they must act on a single hydraulic circuit to ensure proper balance between the left and right wheels. Our SMV senior design group will design, analyze and select hydraulic brakes for all three wheels of the vehicle within the constraints of budget, weight, adjustability, and ability to be retrofitted into future vehicle prototypes. Additionally, we will design, analyze and manufacture mounting systems for the brake pedals and calipers.

3.2 Specification Table

The Quality Function Deployment (QFD) chart is used to evaluate the Supermileage team requirements for the braking system. SAE and Shell Eco-marathon contest rules highlighted most of the project requirements and the engineering measures of the requirements derived the table of specifications.

Table 1 displays the leading project specifications. These specifications are measurable and required for the success of the project. Each task in the table has an associated risk factor that indicates the difficulty of reaching the goal (Low, Medium, and High). The compliance column shows the method used to measure each specification and ensures that it meets the target. The methods are Testing, Inspection, and Analysis.

Table 1 SMV Braking Project Specifications

Spec. #	Specification Description	Requirement or Target	Tolerance	Risk	Compliance
1	Braking Force	140 lbf	± 10	M	A, T
2	Deceleration	0.3 g	Min.	M	T
3	Brake Drag	0 lbf	Max.	L	I, A, T
4	Weight	5 lbf	Max.	M	A, T
5	Cost	$300	Max.	L	A
6	Pedal Travel	30°	± 5	L	T
7	Average Pedal Force	20 lbf	± 5	M	A, T
8	Rotor Size	160 mm	Std.	L	A
9	Hub Interface	6 bolt	Std.	L	A

Specification Target Descriptions

1. **Braking Force** – Braking force will be measured by measuring the vehicle's top speed (around 24 kph), total weight and the distance the vehicle requires to come to a complete stop from that speed. The braking force is between the ground and wheel and must be individually attainable by the front and rear braking systems. Calculations are attached in Appendix G.
2. **Deceleration** – Deceleration will be measured by measuring the vehicle's top speed (around 24 kph) and the distance the vehicle requires to come to a complete stop from that speed.
3. **Brake Drag** – Brake drag will be measured by comparing deceleration rate between vehicle without braking system and vehicle with the braking system (unapplied).

4. **Weight** – The weight of the braking system will be obtained by weighing all components, such as pedals, cables, fluid, calipers, rotors, and master cylinders.
5. **Cost** – The treasurer will record team spending throughout the year. The cost includes total amount of money spent by the senior project team and SMV team on the braking system of the SMV (research, materials, installation, tools, etc.)
6. **Pedal Travel** – Brake pedal will rest at 90° from the horizontal and modulate brakes within 30° of resting position. Pedal travel will be measured by inspection of resting and fully engaged brake pedal locations.
7. **Pedal Force** – Driver will test ergonomics of brake pedals and lever ratio will be adjusted accordingly.
8. **Rotor Size** – Rotor size refers to the diameter of the rotor and will be determined by the braking force required on each wheel for the vehicle to make a full stop in 4.0 meters from a 24 kph speed.
9. **Hub Interface** – 6 bolt rotor to hub interface will be used because the current rotor and hub have a 6 bolt connection.

The table of specifications contains only one high-risk target; maximum brake pedal force. This force is between the operator's foot and pedal and is pertinent in creating an ergonomic and efficient user interface. Determining optimal braking force will be a challenge that requires research, prototyping and testing. Once a braking force has been decided upon, a second challenge will arise to design and manufacture the system to work under said optimal conditions.

The wheel size will be determined by the Supermileage Team by October 2019. Most specifications will be tested for compliance using analysis (e.g. FEA and calculations) prior to purchase and assembly of parts. After brake system installation is authorized, specification compliance will be confirmed via testing and inspection.

4. Concept Design

A section was added to discuss ideation for front brake pedal, as a result of unexpected geometry of the ordered part.

4.1 Ideation Processes

After extensive background research, multiple ideation exercises were used to develop design concepts for the Supermileage vehicle braking systems. There are three main components to design for the braking systems: the pedal structure, brake actuation mechanism, and the brakes. Team members brainstormed ideas for each component both individually and as a group. After discussing our initial design ideas, our group also performed a brainwriting exercise and a rapid ideation activity to expand on those ideas. Results from the activities are in Appendix H**.**

Next, we developed our design ideas by sharing and discussing the ideas with each other, our sponsor, and the Cal Poly Supermileage team. Each gave feedback on the concepts, so we could highlight the advantages and disadvantages of each idea. Pugh matrices shown in Appendix E were used to subjectively quantify the strengths and weakness of each design idea in accordance to our design criteria. This narrowed down our ideas to our top six design concepts described in Section 4.2.

4.2 Top Design Concepts

These design concepts are identical to our PDR report. It is important to document all ideas generated. Since PDR, the only significant change is that we are going to follow through with the "split line" idea because competition rules now require it. We either will branch the line of the MT4 brakes or buy an already-split Magura brake set. Communication with Bike Builder's about the possible discounts will drive the final decision.

Pedal Structure

Pedal structure design regards the number of pedals, mounting location, pedal geometry and material, and manufacturing.

Three-Pedals

Contest rules require independent front and rear brakes, with a separate pedal for each system. Our team questioned if two brake pedals would make the vehicle less natural to control, so we discussed implementing a three-pedal system shown in Figure 6. Two pedals would independently operate the front and rear brakes. A third pedal between the front and rear brake pedals would push both pedals simultaneously when pressed. Therefore, competition regulation would be met, but the driver would also have the option to use only one pedal to actuate both systems for the actual competition.

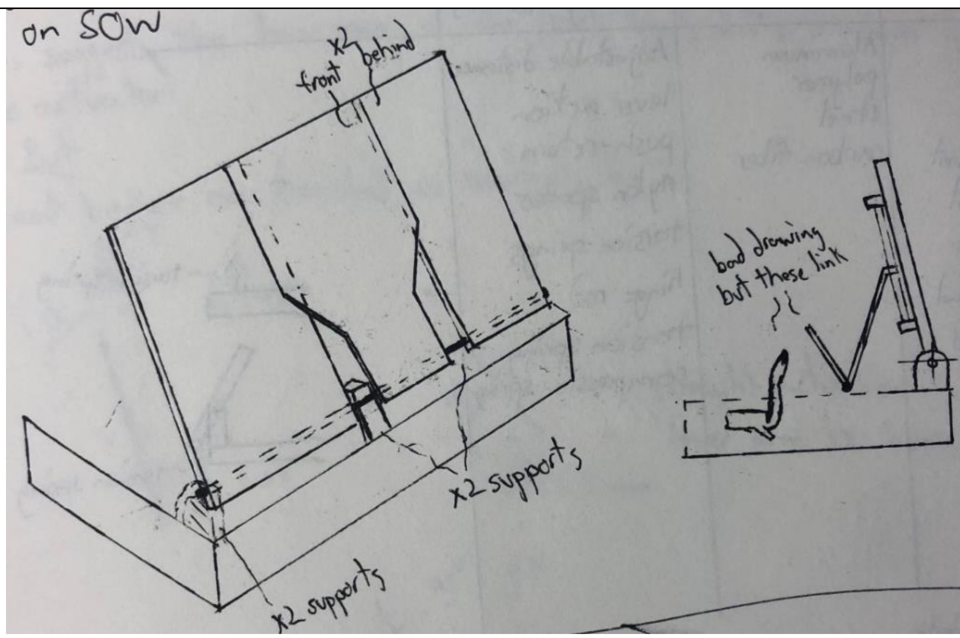

Figure 6 Three-pedal brake system sketch..

Piston Mounting Location:

The master cylinders can be actuated either ‘above-the-hinge' or ‘below-the-hinge'. The sketch in Figure 7 shows the primary distinction in the direction of the actuation force of the piston. Mounting the piston cylinder above the hinge results in the actuation force to go towards the front of the car, so the piston must be in front of that lever arm for the force to depress the piston into the cylinder. Oppositely, the below-the-hinge configuration results in the actuation force to go in the opposite direction toward the rear of the vehicle. In this case, the master cylinder must be mounted in front of the pedal for the actuation force to depress the piston into the cylinder. Both methods can work, but below-the-hinge actuation creates problems with packaging, as it forces the master cylinder to sit lower, and on the same side as the driver’s foot.

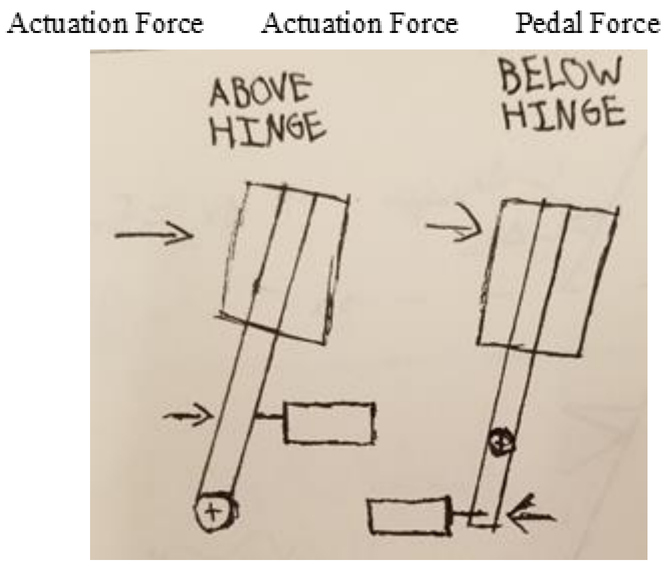

Figure 7 Sketch of piston-cylinder connection above the hinge (left) and below the hinge (right).

Two-Part Pedal:

Our first 3-D printed pedal-lever prototypes were all one solid part, but the final pedals will be machined from aluminum. In order to make the manufacturing process simple, we plan to make the pedal from two parts. The lever will fit onto the master cylinder hinge to activate the piston, and pedal top will be fastened to the top of the lever for the driver’s foot to press. The advantage of this concept is that both pieces can easily be milled from blocks of metal and complicated geometry and cuts are eliminated. The pieces can be welded or bolted together.

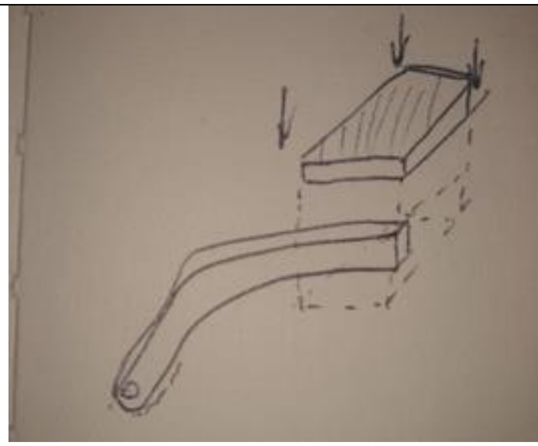

Figure 8 Sketch of two-part pedal.

Brake Actuation Mechanism

The brake actuation mechanism regards how the pedal lever arm will thrust the piston into the master cylinder.

Split-Line Master Cylinder for Front Brakes:

In order to brake both front wheels, we need to install two sets of calipers and rims for the front. If we use stock bicycle brakes, we will also need to install two cylinders. With a third for the back wheel, there may be too many pieces in the front of the vehicle. Therefore, we have conceptualized a single front brake cylinder that splits across two brake lines and goes to both front calipers at the same time. There are several advantages to this concept- equal force applied to both (front) calipers, less mass and volume taken up, and lower cost. However, there is no standard adapter for brake lines, so we would need to manufacture a custom-fit T-joint. As well, by splitting the fluid, each caliper would only receive half the force as they would if independent.

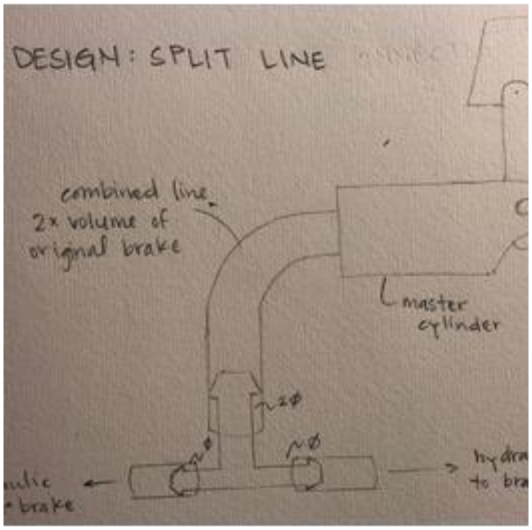

Figure 9 Split line connection for two front brake lines.

Dual Master Cylinder-to-Pedal Connection for Front Brakes:

The dual cylinder-to-pedal connection shown in Figure 10 utilizes custom made lever arms for both front brakes. These levers will be fastened to the back of a pedal top as described in the two-part pedal design concept. This will allow for both front brakes to be actuated simultaneously and reduce the amount of custom parts and manufacturing needed in comparison to any other design.

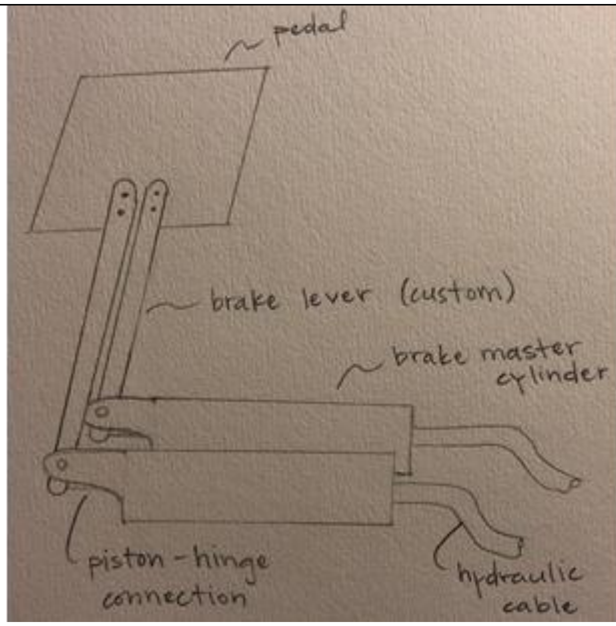

Figure 10 Direct actuation of both front brakes via pedal. There are 2 levers, two master cylinders and two hydraulic cables connected to the pedal.

Cam Follower:

This piston actuation concept regards the optimal force ratio between foot-pedal force and piston-actuation force. In order to mimic the modulation sensitivity of a hand brake, the foot-pedal force must be applied approximately five times further from the center of rotation than the piston is actuated. Additionally, the piston must be depressed roughly 5 mm to fully actuate. The issue is that the lever ratio resulted in an optimal pedal-force distance that is unreasonably short. This design concept shown in Figure 11 attempts to solve this problem by creating a cam-type profile on the pedal that would allow for 5 mm of piston travel while putting the optimal pedal force location at a reasonable distance.

The assumption behind the lever ratio calculations, however, assumes that the brake lever had no further travel after brake pad engagement, which means that all the modulation must occur via driver foot pressure control. After examining other hand brakes, we establish this is not the case, and after caliper engagement, modulation still occurs as a function of lever travel. This leads us to believe that the force lever ratio is less important, as the driver will be able to modulate effectively just by pedal travel

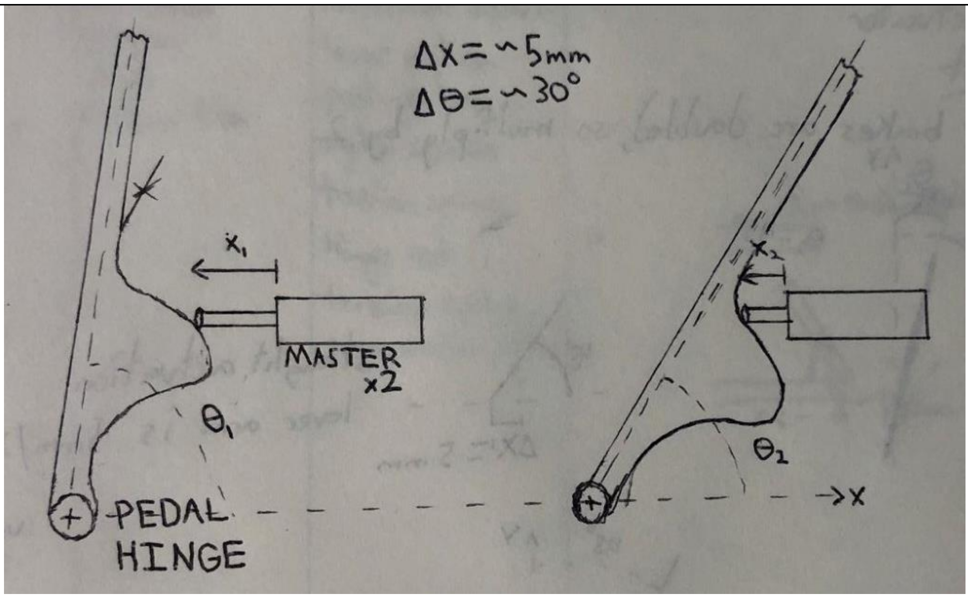

Figure 11 Cam follower brake pedal sketch.

Brakes

Rear Disk Brake:

It is generally accepted that disk brakes are better than rim brakes. Disk brakes dissipate heat more effectively and have more braking force than rim brakes. However, due to the left-handed hub attachment of the rear wheel, a disk does not fit on the rear wheel. Therefore, the current SMV has a rim brake at the rear wheel. We considered trying to install a disk brake, but ultimately decided that it is more work than necessary. A big deciding factor is that the rear brake is rarely used in competition, and only is required to qualify for the Shell Eco-marathon.

Update: Scope of work has been adjusted to only include next year's vehicle, which will only be compatible with a disk brake in the rear, so that is the design choice.

Disk Brake Clip/Spacer:

In the event of the rotor continues to rub against the calipers, and no amount of bending or repositioning manages to solve the issue, we will consider using clips or spacers shown in Figure 12 to help separate the brake pads further. Therefore, slight warps in the rotor will not touch and rub against the caliper. The downside to adding spacers is that more force is required on the pedal to activate the brakes. This is a last choice solution.

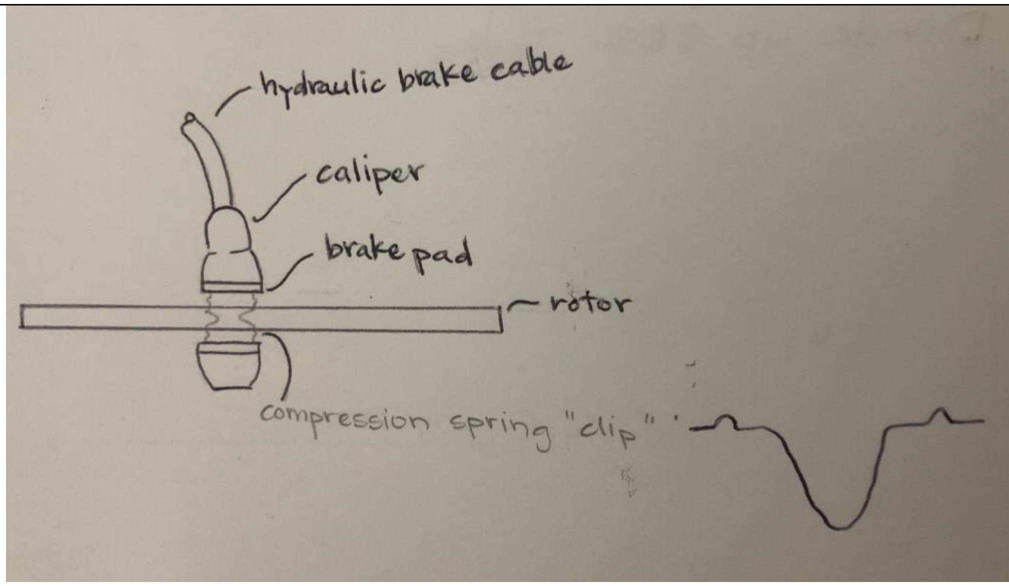

Figure 12 Drag reducing brake clip sketch. Two clips connect on opposite sides of the caliper.

Rear Caliper Mount

The design of a mount for the rear disc brake caliper was added to our team's scope this quarter. The sketch in Figure 13 shows a rough idea of a caliper mount that attaches to the outside end of the axle and rests on top of the drop-out mount. This design allows for the caliper to move longitudinally with the wheel as it adjusts in accordance with chain length. This will keep the caliper properly aligned with the brake rotor. Additionally, this design minimizes the distance between the distance between the mount and the caliper which greatly reduces the possibility for vibrations and rubbing between the rotor and caliper.

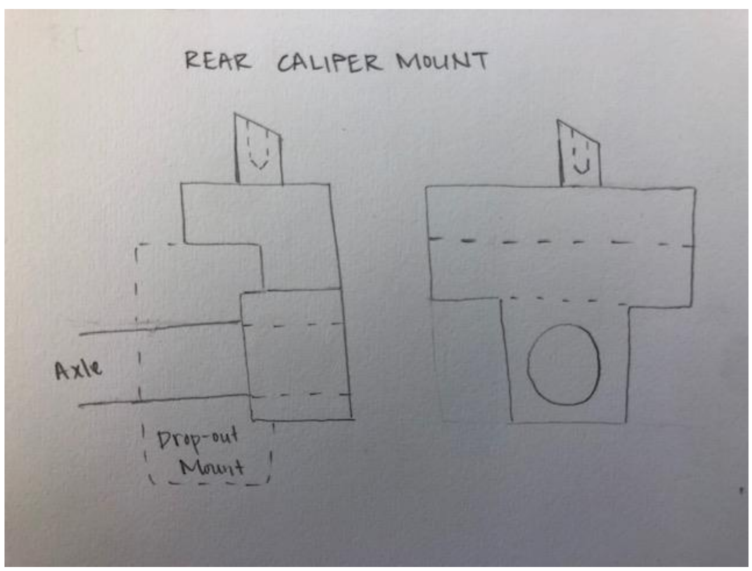

Figure 13 Rear caliper mount concept design.

Front Brake Pedal

The front braking system came with a lever much different than the expected MT4 lever, as well as a much larger master cylinder. These differences made mounting to the base plate in the same way as the rear brake impossible. The sponsor established two requirements quickly, which shortened ideation. The first requirement was horizontal actuation, the second was direct mounting to an L-bracket. A design for a pedal was needed, as it was the last day 3D printing was available. The resulting design did not go through as stringent of an ideation process, instead functionality was highly prioritized. The final design, pictured below, is a 3D printed pedal face, with a hole protruding, allowing for a lever to be inserted, along with epoxy. This design was chosen to allow for an acceptable strength pedal head that was adaptable to multiple lever styles, and forgiving of design oversights.

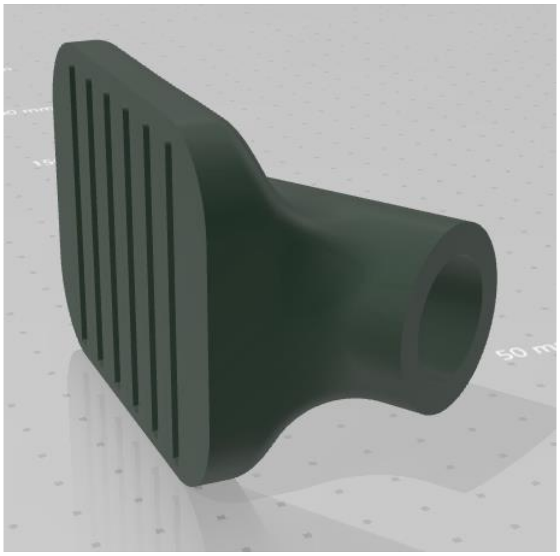

Figure 14 Front brake 3D printed pedal attachment.

4.3 Design Selection

The preliminary designs for pedal structure, brakes, and brake actuation mechanism were determined by comparing results of the Pugh matrices, continued research, and team discussions with the Cal Poly SMV team and sponsor about manufacturing, cost, installation, and intuitions. Results from these discussions are summarized in this report, leading to the selected design. Results from these discussions were used to create a decision matrix in Table 1 for the top design concepts. The matrix weighed concepts based on cost, weight, ergonomics, and manufacturability.

Table 2 Decision Matrix for Braking Components of Cal Poly Supermileage Vehicle.

Concept		Weight	Cost	Ergonomics	Manufacturability	Total
		3	**5**	**2**	**4**	
Actuation Mechanism	Cam Follower	4	1	2	1	25
	Split-line Master Cylinder (Front Brakes)	4	4	5	4	58
	Dual Master Cylinder Pedal Connection (Front Brakes)	5	5	4	5	68
Pedal Structure	Two Pedals	5	5	5	4	66
	Three Pedals	2	4	3	3	44
	Piston Above Hinge	5	5	5	4	66
	Piston Below Hinge	5	5	1	3	54
Brakes	Rear Disc Brake	5	5	5	1	54
	Rear Rim Brake	5	4	4	5	63

Two concepts were considered for the pedal structure of the braking system: the number of pedals and the location of the master cylinder relative to the pedal hinge. As discussed above, a three pedal design was considered for driver ergonomic reasons. Upon talking with the Cal Poly SMV Team about this design concept, Esther relayed to us that the rear braking system is only used for the pre-competition brake test, but never in the actual race. This completely eliminated the need for a three-pedal structure, so our final design will only include two brake pedals. Secondly, our team weighed the advantages of the brake piston-cylinder location relative to the hinge. Both concepts are equal in terms of cost, weight and manufacturability, but it quickly became clear that designing with the piston above the hinge is much more ergonomic. This is because the brake master cylinder would be in front of the pedal if installed below the hinge, resulting in having the piston-cylinder directly under the driver's foot where it is unprotected from adjustments by the driver. This is against Shell Eco-marathon rules and not ergonomic, so the master cylinder will be installed above the hinge.

Designing how the brakes will be actuated was the most difficult because there aren't any stock parts to adapt a bike brake lever to foot pedal. We had to design around this and think our how to use stock parts and manufacture custom parts. As aforementioned, the front braking system poses a unique challenge because two master cylinders for each wheel need to be assimilated in the brake pedal. Two of the top design concepts addressed this challenge. The first idea was a split-line piston and the second idea was to have direct actuation of both pistons from the pedal. The split-line piston would be difficult to manufacture and install because we would need to find a split-line adapter with a perfect two-to-one ratio for the hydraulic cable size and the bike master cylinder would likely be unable to displace twice the amount of brake fluid than designed for. For these reasons we chose to include the direct actuation of both pistons from the pedal in our preliminary design. Direct actuation of both pistons greatly reduces the number of custom parts we need to make, and therefore reduces uncertainty and alterations to stock brakes. Actuation of the piston via cam follower was also considered, but manufacturing a part with the correct track profile would be extremely difficult and require a lot of trial and error.

Lastly, brake type for the rear wheel and brake clips were considered for the brake design. Currently, the rear wheel has a rim brake because the rear hub is not compatible with a rotor and there is no upright or abundance of space for disc brake calipers. Because of this, our team will continue the use of a rim brake. Brake clips were also considered for drag reduction. Current mountain bike brakes are designed to have no rubbing between the caliper and rotor when unapplied. As long as the rotors and calipers are aligned properly upon installation, drag should not be a problem. If there is drag, after market brake clips can easily be purchased and connected to the calipers.

4.4 Selected Design Concept

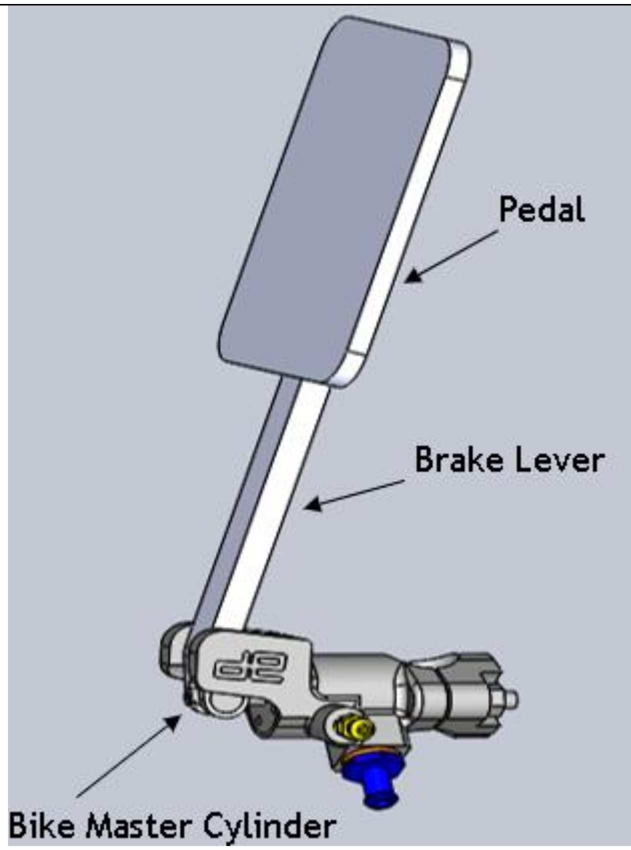

Figure 15 Preliminary pedal assembly design model.

The brake will be manufactured from two parts. The pedal will be cut from a thin piece of aluminum (low-weight), and the lever will be machined on a mill. The hinges and pistons will be taken from the purchased Magura part. Once the MT4 is in our possession, we can create a detailed drawing of the lever with properly spaced holes that will fit on the MT4.

The cylinder will be mounted to the SMV by attaching vertical rods to the floor of the vehicle, and tightening the cylinder around the rods, similarly to how they attach to normal bike handlebars. This will prevent the brake master cylinder from moving. In application, the driver's foot will press the brake pedal causing a forward (toward the front of the car) displacement in the lever arm below the hinge that will push the piston into the master cylinder. This displacement in the piston-cylinder results in the activation of the calipers closing on the brake rotor for the front brakes and wheel rim for the rear brake.

Additionally, we will experiment with an adjustable pedal placement system, in which the rod will be attached to a separate base plate that can be moved to adjust the pedal location to be most comfortable for the driver.

4.5 Preliminary Analyses and Tests

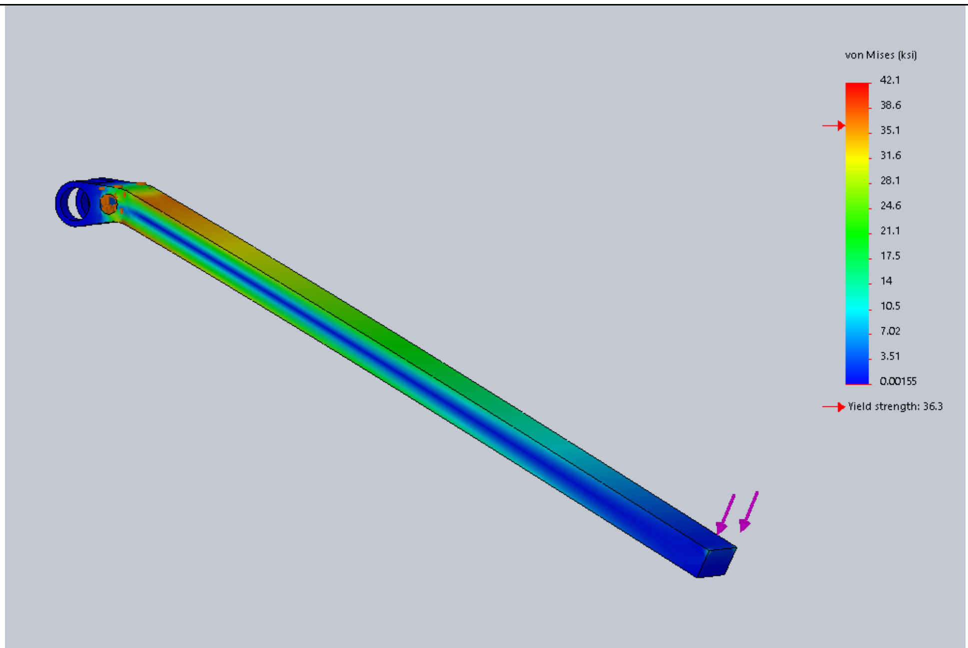

Figure 16 SolidWorks FEA to determine pedal geometry optimization.

In a worst-case scenario, the driver will need to be able to slam the brakes to stop the vehicle as quickly as possible. In this instance, it is important that the pedal does not snap or bend; otherwise, the brakes may be unusable. Therefore, the pedal geometries (thickness) are determined by estimating the stress caused by locking-up the brakes. According to online research, rider will apply (at maximum) half of their weight's force to a brake pedal. Assuming a 120lb driver, then she will apply 60 pounds to the pedal. See Appendix F for further detail on calculations. A hand-calculated estimate of stress was found, and the SolidWorks FEA confirmed these results seen in Figure 15. These calculations will be re-performed when the Magura is obtained and better details of hole geometries can be measured. The resulting length and thickness of the brake lever that will be used in our design are illustrated in Figure 16.

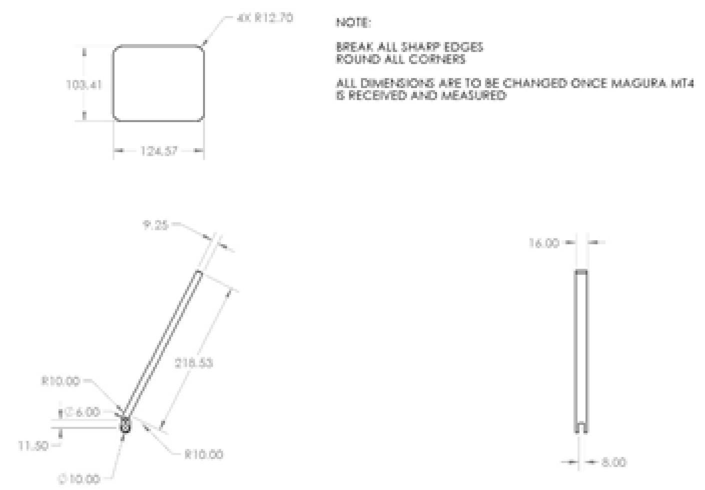

Figure 17 Finalized pedal geometry after conducting stress analyses.

4.6 Current Risks and Challenges

While a full-scale design hazard checklist is not in the scope of this report, there are some obvious design risks that must be addressed. Obviously, brake failure of any sort could be disastrous to the rider and vehicle's safety, so failure must be prevented at all costs. The most likely forms of failure would come from mechanical failure (snapping of manufactured pieces), loss of brake fluid within the lines, bolt shear at rotor hub connection, failure at knuckle caliper connection, or disconnection of the master cylinder from the attachment fixture. Most of these failures are difficult to analyze numerically and will be tested against once the brakes are installed. An additional concern is that we must ensure that the brake calipers and rotors are aligned properly when mounted to avoid any drag when brakes are not in use. The system will be pushed beyond competition requirements during testing in order to ensure rider safety.

5. Final Design

The final design for the 2021 SMV braking system consists of three subsystems: front brakes, rear brake, and pedal mount. This braking system design will meet the specifications to meet 2020 Shell Eco-marathon regulations and keep the driver safe. Each braking system will individually be able to prevent vehicle from moving or sliding down a 20% incline per Eco-marathon rules and provide at least 0.3g of braking deceleration per recommendation by FSAE. Additionally, brakes will be hydraulic, and the front braking system will have a converging fluid cable per the 2020 Eco-marathon rules. The braking system all together will be less than 5 pounds to reduce weight in the vehicle and calipers will properly align with rotors to will eliminate drag. The braking components in this system are all commercial bike parts to reduce cost, manufacturing and unknowns in our design. Commercial bike brakes have been designed with high factors of safety and tested time and again for effectiveness and safety. For this reason, we find mountain bike brakes to provide more than enough braking power to ensure the safety of the Supermileage vehicle and its driver. The braking system pedal mount is in Figures 17, 18 and 19.

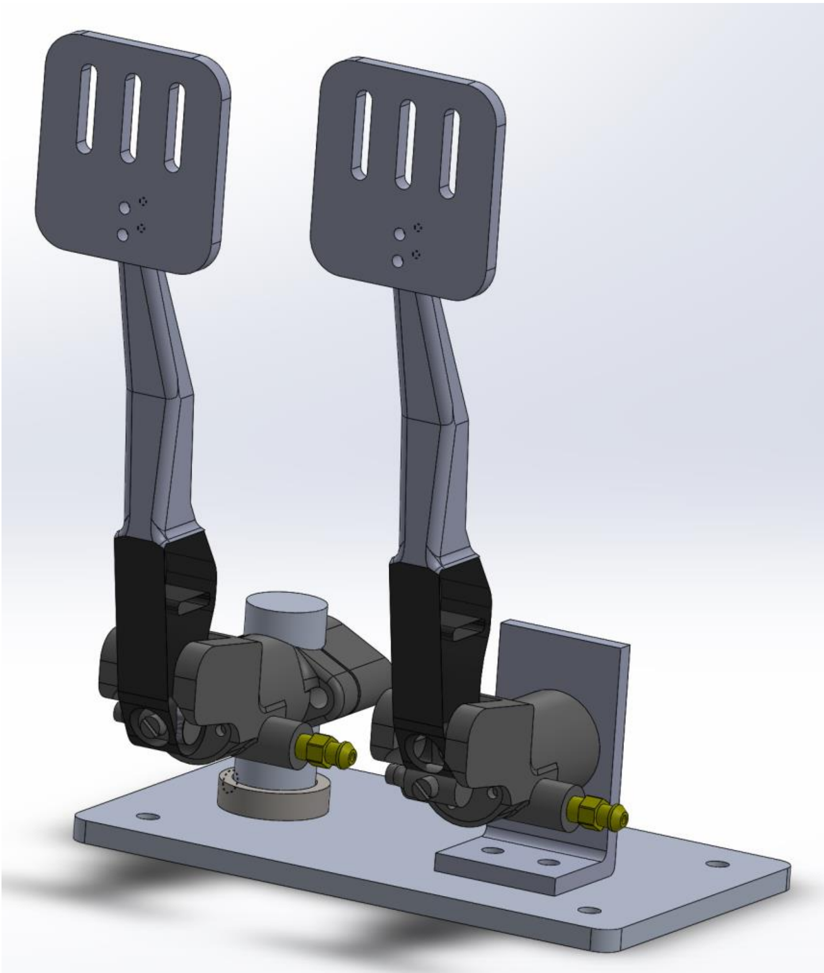

Figure 18 Supermileage vehicle brake levers and pedal mount.

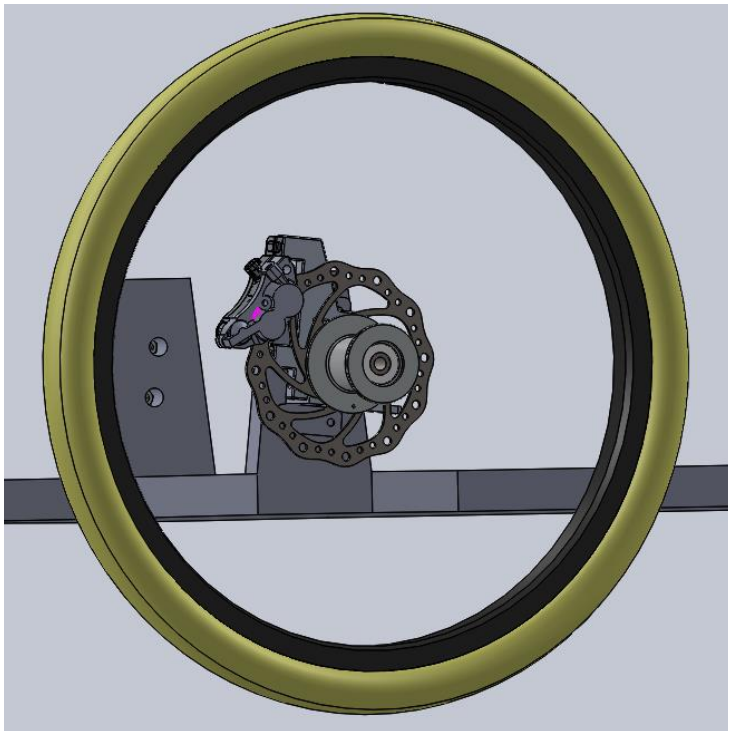

Figure 19 Front brake caliper is mounted to the steering knuckle.

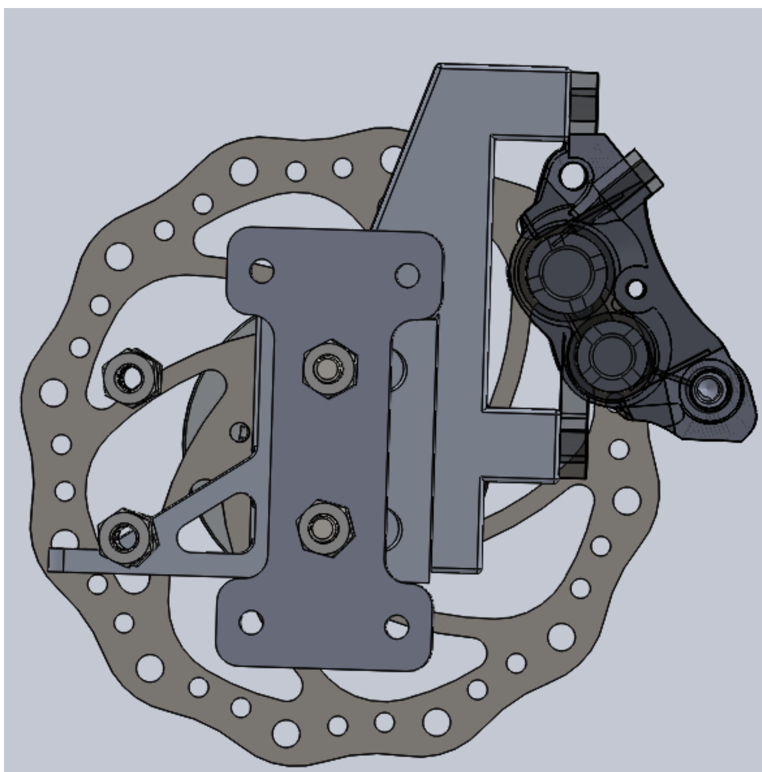

Figure 20 Close-up image of caliper mounted to the steering knuckle.

5.1 Final Design Changes

Two major design changes were made to the braking system after the CDR in November: the rear brake pedal design and front brake pedal design.

Rear Brake Pedal

Once our team acquired the rear MT4 brake, we were able to design the brake pedal. Initially, we planned to design and fabricate a whole lever from aluminum to replace the stock MT4 lever. The geometry and rigidity of the stock brake lever led us to utilize the existing lever instead. We decided to cut off the top centimeter of the brake lever and design a 3D printed pedal head attachment, shown in Figure 21, that slides onto the existing brake lever and fastens to it with a composite wrap. The overall rear brake pedal design is shown in Figure 18. This design reduces weight, manufacturing time and error because the need to redesign of the piece that actuates the piston was eliminated. Our team worked with Professor Mello and Maddy from the Supermileage team to composite wrap the brake lever.

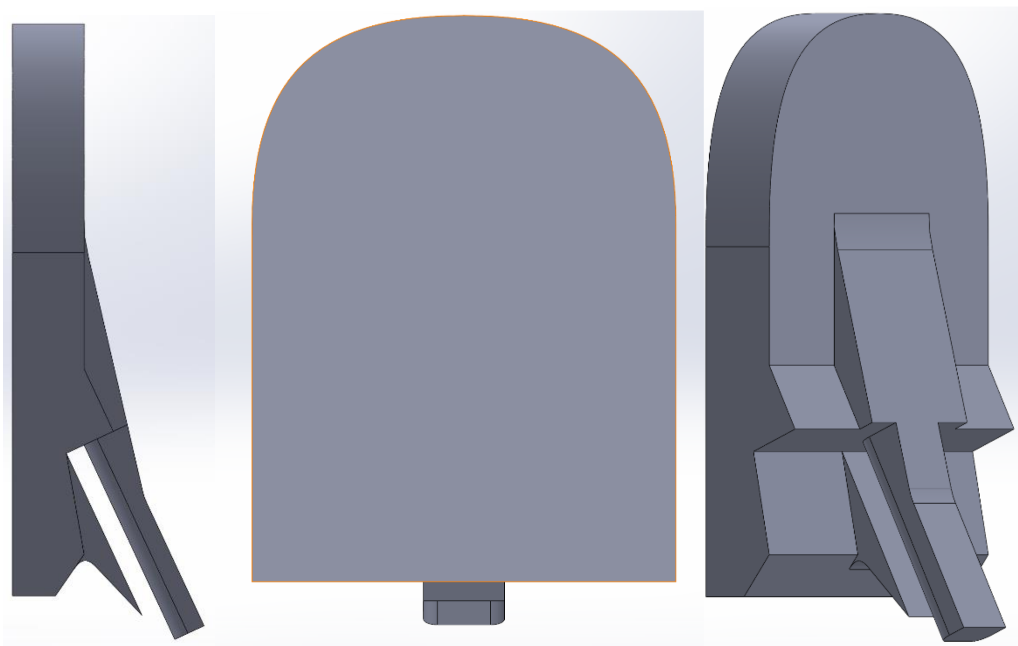

Figure 21 Rear brake pedal 3D printed pedal head side (left), front (middle), and isometric (right) views. The slot cut in the level attachment slides onto the existing stock MT4 lever.

Front Brake Pedal & Mount

The other major design change involved developing a completely different pedal design for the front brake. Unfortunately, the Magura Big Twin brake that's used for the front braking system has a vertical master cylinder orientation unlike the MT4 brake as shown in Figure 22.

Figure 22 The Magura Big Twin brake (left) has a vertically oriented master cylinder, whereas the Magura MT4 brake (right) has a horizontally oriented master cylinder.

This means that we had to change the design for the interface between the master cylinder and pedal mount plate. With the help of Crystal and Maddy from the Supermileage team, we decided to mount the pedal sideways so the master cylinder could be oriented horizontally. This allows for the front and rear brake pedals to be level with each other and retains most of the original pedal mount design. Additionally, this design is easy to manufacture because we can use our scrap to make a right-angle bracket, Figure 23, that fastens to the plate and bolt the master cylinder to it with its existing holes. This updated configuration is shown in Figure 18.

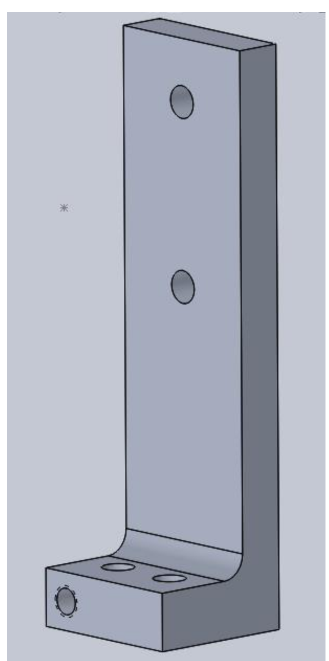

Figure 23 Front brake pedal mount. Angle bracket machined from aluminum scrap.

Due to the geometry and material of the Big Twin brake lever, the same 3D printed pedal head could not be used. Our team design a larger, stiffer 3D printed pedal head, Figure 24, that slides over the existing brake lever and is adhered with epoxy. This more robust design with serve well in the pre-competition brake tests, during the competition, and in the case of emergency.

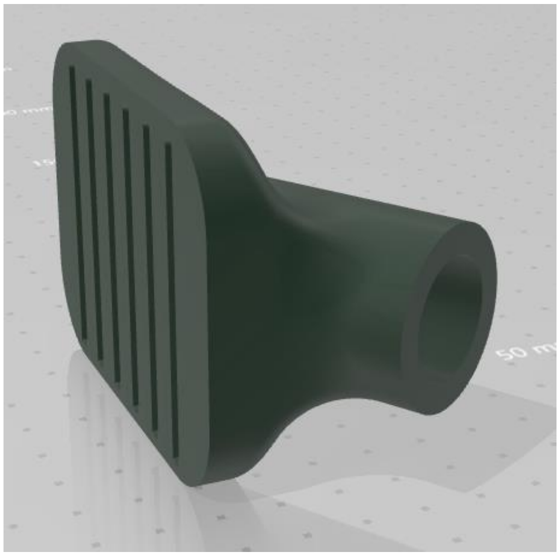

Figure 24 Front brake 3D printed pedal head attachment. Adhered to lever with epoxy.

Front Brake Caliper Mounts

The front brake caliper mount design was also adjusted to accommodate the Magura Big Twin I.S. mount calipers. Originally, we worked with the SMV Steering Team to develop a caliper mount for a post mount brake. Since the Magura Big Twin brakes are no longer in production, our team was unable to acquire detailed specifications on the brakes. When we received the Big Twin brakes in February we realized that the calipers were I.S. mount, not post mount. First, we attempted to obtain a post-to-IS disc brake mount adapter so we could still use the existing caliper mounts that the Steering Team designed and manufactured. Unfortunately, this type of adapter does not exist, so we worked with the Steering Team to design and manufacture a new caliper mount shown in Figure 25 that accommodates an I.S. mount for a 160 mm rotor.

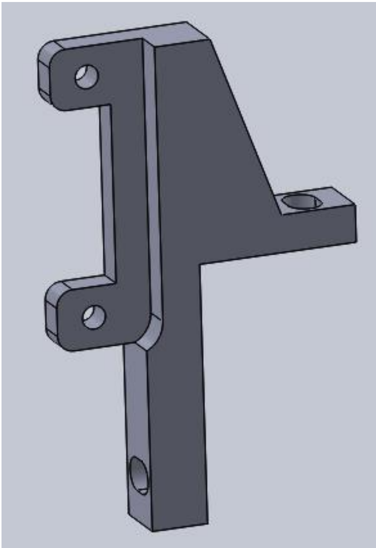

Figure 25 Front Brake caliper mount. Mount designed for an IS caliper on a 160 mm rotor.

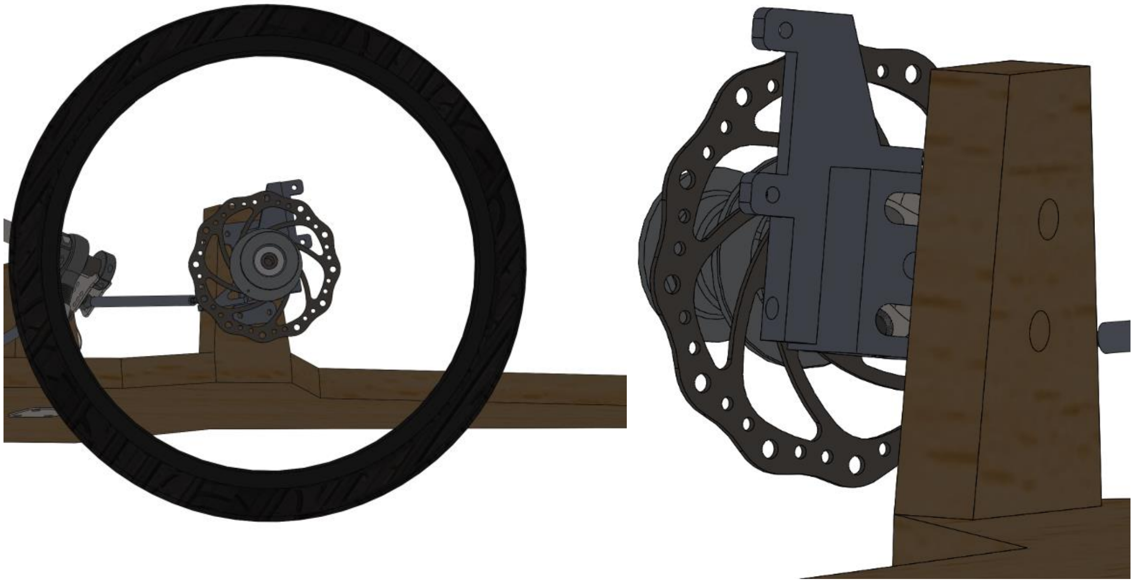

Figure 26 Front brake caliper on front wheel assembly.

Rear Brake

Lastly, the incorrect rear brake was ordered through the Bike Builders Club. The system requires a hydraulic, single piston, post-mount brake. We received a flat mount brake instead which cannot be accommodated to fit to a post-mount frame. For this reason, the Magura MT4 FM brake must be exchanged through Bike Builders for a Magura MT4 post-mount brake or other suiting brake. Since the brakes had such a long lead time, our team was unable to exchange the brakes by the end of the quarter, so the MT4 FM brake, a spare lever, and its box were left with the SMV team to be returned at the start of next quarter.

5.2 Front Braking System

The front brakes consist of one pedal, one master cylinder, brake cable, one split-line connector, two rotors and two calipers (one per wheel). The front braking system will be attached to the pedal mount at the front of the car and allow the driver to decelerate the front wheels of the vehicle. This system is shown in Figure 20.

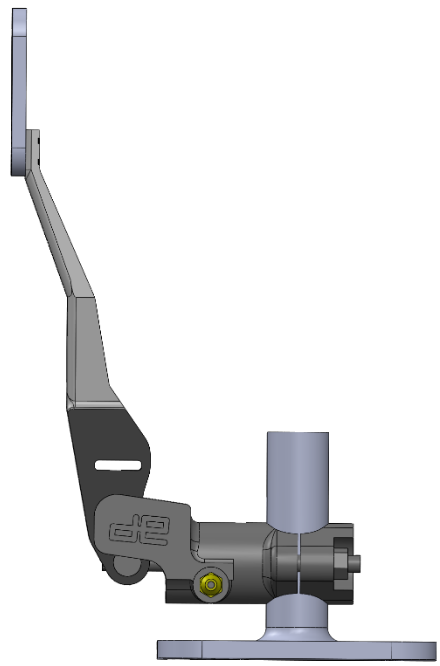

Figure 27 Side view of pedal and master cylinder on pedal mount plate. Master cylinder is clamped onto rod like it would mount onto bike handlebars.

The lever arm of the pedal will replace the bike hand-brake lever to meet the driver's ergonomic needs. Like the hand-brake lever, the foot pedal will include a pushrod that actuates the brake piston and a hinge to rotate about when actuated. When the foot pedal is pressed, it will rotate about the hinge pin and the pin will move transversely to depress the brake piston through the master cylinder. This creates a displacement in fluid that travels through the hydraulic cable. After about 6 cm the hydraulic line will split into two lines that lead to brake calipers on each front wheel. Pressure and braking force will be conserved despite the split in the brake line, but changes in fluid volume must be considered to ensure enough pedal travel can fully actuate brakes. For this reason, our team has selected a commercial dual caliper brake with a single master cylinder. This system manufactured by Magura was designed to account for the changes in volume throughout the system, so brake force is conserved and at its potential by ensuring there is enough fluid for the calipers to fully engage. Additionally, this dual caliper system has a larger piston than standard bicycle brake systems to move the necessary amount of fluid. Here, the displaced fluid also displaces the caliper pistons causing them to squeeze the brake rotor. This creates friction and decelerates the car. To a certain extent, the more the brake pedal is depressed, the more friction between the pistons and rotor is created so the vehicle decelerates faster. The brake calipers are mounted to the uprights using a post-mount adapter designed by the SMV Steering Team. Please refer to their report for a detailed design justification.

The master cylinder is rotated 90 degrees from its standard working position to the Supermileage vehicle's working position. This creates concern for the functionality of the master cylinder in a new orientation because it can allow air into the metering hole of the master cylinder which can eventually travel through the hose to the caliper. This can be detrimental to the system if left unaddressed because the working fluid at the caliper is not incompressible if there are air bubbles, so braking power is lost. Our team contacted a Magura representative to address this question and we were informed that the brake will function properly in an orientation other than its standard position. The representative also informed us that the system must be filled completely with brake fluid to minimize air bubbles. Brakes should be bled and filled at least every 6 months to eliminate air bubbles that enter the system. If the team notices a drop in braking power of the vehicle, it is a sign that the brakes should be bled and filled.

As shown in our braking calculations in Appendix G, the selected Magura brakes will provide enough braking force for the Supermileage vehicle. Each brake will provide approximately 240 N of braking force and altogether provide a total braking force of about 720 N. The required force to prevent the 200-pound vehicle from moving on a 20% incline in its pre-competition evaluation is 175 N. The front braking system provides 480 N of braking power and has a safety factor of 2.75. The rear braking system provides 240 N and has a safety factor of 1.4. The braking force required to decelerate the vehicle at our specified 0.3g minimum is only 270 N – only one-third of the braking force our system can provide. Our optimum braking deceleration is 0.8g, which allows for the Supermileage vehicle to make a complete stop within 2.8 m from an initial speed of 24 kph. This exceeds our second need for the vehicle to stop within 4 m from an initial speed of 24 kph. Please note that the calculations used to determine these values used estimates of certain values including master cylinder area, caliper piston area, and pedal arm pivot lengths because our team does not have detailed dimensions of Magura's brakes.

Lastly, we conducted Finite Element Analysis (FEA) on the brake lever to determine the minimum thickness of the lever for there to be less that 1 mm of deflection. We also used FEA to analyze the von Mises stress along the brake lever to optimize geometry, so the lever doesn't fail. This analysis will have to be performed again after we obtain the Magura brakes and adjust the geometry to suit their master cylinder, but the analysis methodology can be found in section 4.

5.3 Rear Braking System

The rear braking system consists of one pedal, one master cylinder, brake cable, one rotor and one caliper. The rear braking system shares the same pedal mount with the front braking system.

All functionality between the front and rear braking systems remain the same except for the brake cable, which is not split. There is only one rear wheel in the car, so the brake cable does not need to supply two calipers like it does in the front braking system. This results in a simpler design for the rear brake because pressure-volume changes through multiple lines does not need to be accounted for. Unlike the front braking system, our team was given the additional task to design a rear brake caliper mount shown in Figure 21.

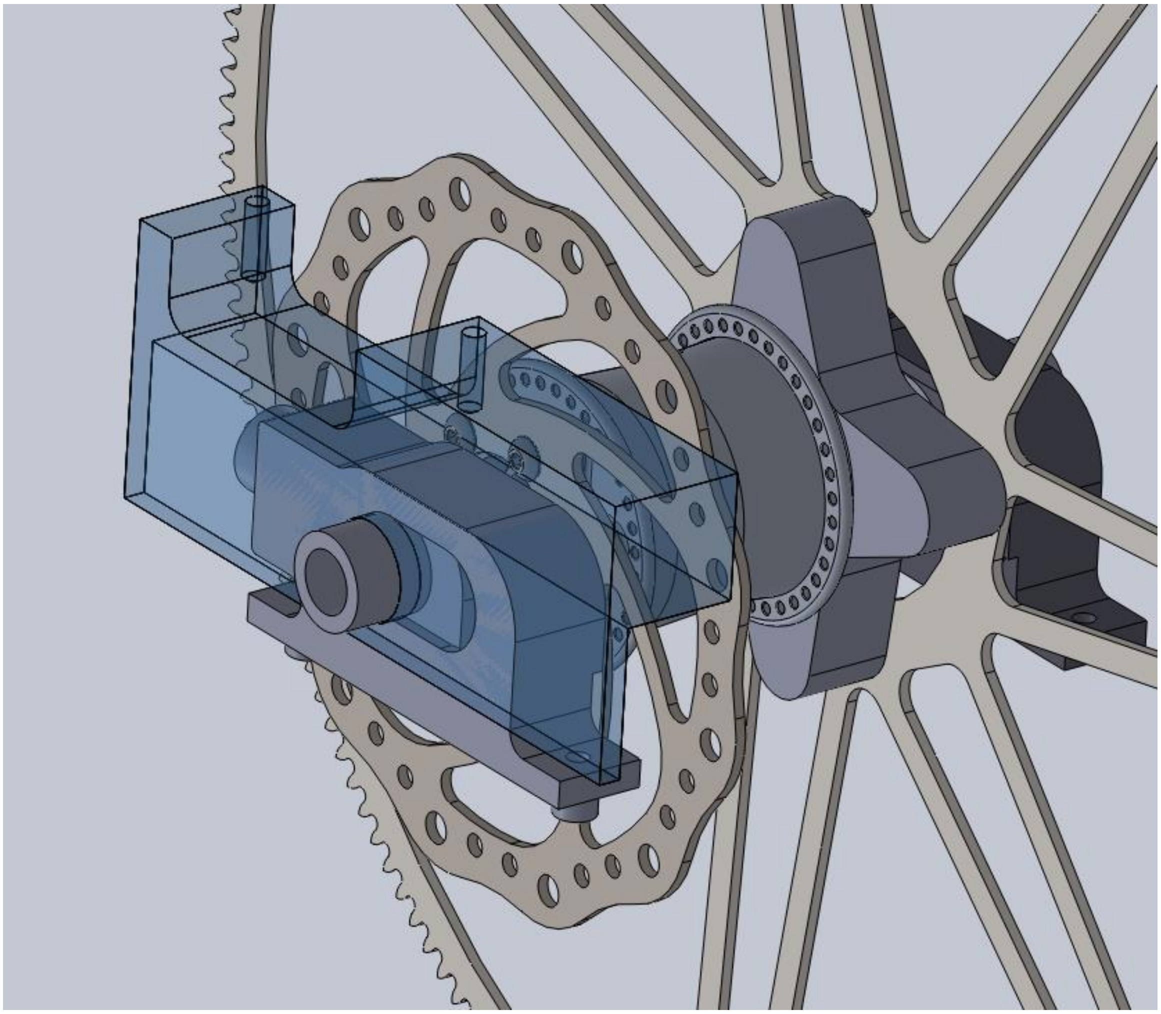

Figure 28 Rear brake caliper mount assembly.

The rear caliper mount will fasten to the rear axle drop-out mount to minimize distance between the mount and caliper. This will ensure rigidity between the caliper and rotor which will reduce the effects of vibrations on the caliper and prevent the brakes from dragging. This is our main design consideration because it directly affects the vehicle's fuel efficiency. The rotor is rigid relative to the axle, so by connecting the caliper mount to the axle, overall rigidity is maximized. This presented a difficult challenge however, because there is no room on the axle to mount it and the axle is threaded outside the drop-out mount. The longitudinal position (along the length of the car) of the rear wheel changes when the drive train chain length is adjusted. This poses the requirement for our design to keep the rear caliper in-line with the wheel axle to ensure that the calipers remain aligned with the rotor. Our team decided to design the rear caliper mount to the drop-out mount for this reason because it moves longitudinally with the axle. The current design shown in Figure 22 is in the concept design phase, so part analysis and material minimization have yet to be performed.

Our design utilizes the dropout body to resist braking moments. The part will be machined from a 2.5”x1.25”x6” aluminum block, which is the closest size to the minimum dimensions needed for the part.

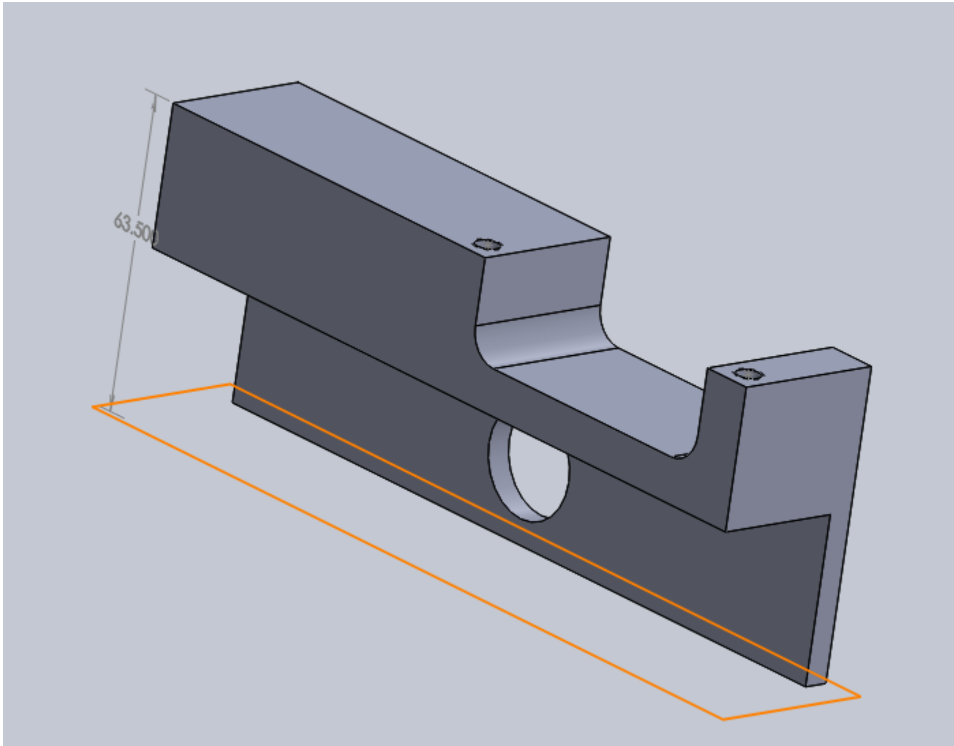

Figure 29 Rear brake caliper mount concept design. This part will attach to the drop-out mount so the calipers move with the wheel axle and stay in-line with the brake rotor.

As discussed in section 5.1, the rear brake will meet our design specifications and provide more than the required braking force for this vehicle. The design is for standard 140mm post-mount, but regular post-mount adaptors allow it to accommodate larger rotors. Analysis of the rear caliper mount will be conducted this quarter and a final design will be presented to the SMV team.

5.4 Pedal Mount

The front and rear braking systems are made complete with the pedal mount shown in Figure 17 and the original concept design is shown in Figure 24. Magura’s master cylinders are made to mount onto bike handlebars with a clamp. This mounting style prevents the master cylinder from sliding or rotating about the handlebar. Our pedal mount uses a similar design that incorporates the same diameter rods for the master cylinders to fasten onto shown in Figure 23. These rods are fastened to the mounting plate which bolts into the car chassis.

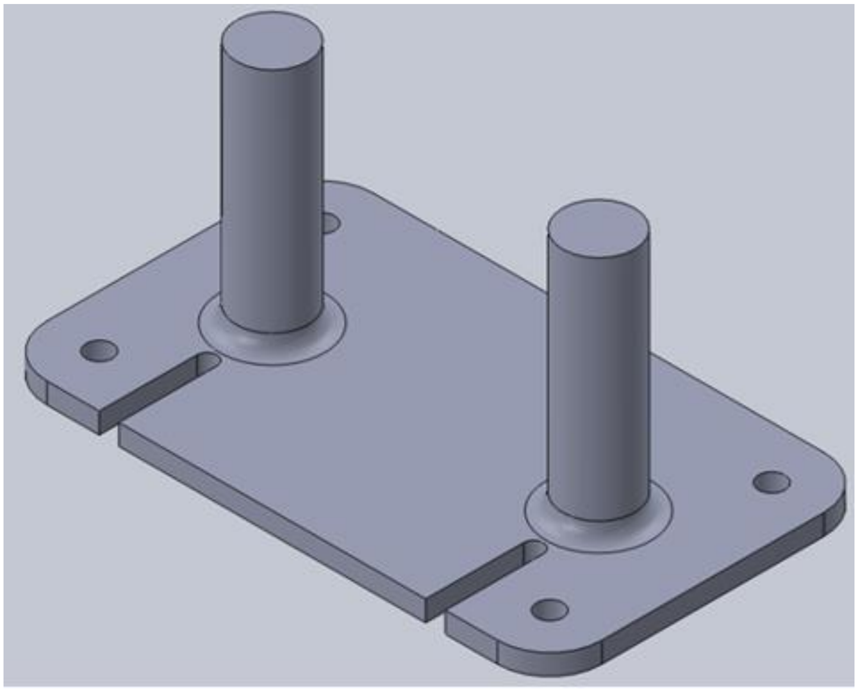

Figure 30 Isometric view of pedal mount plate without pedals attached.

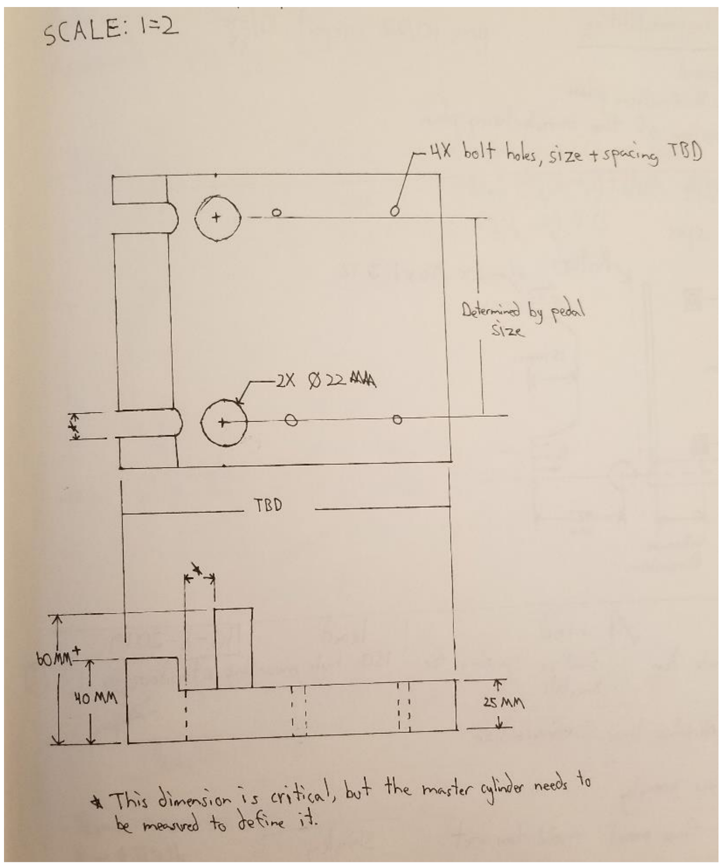

Figure 31 Concept design for pedal mount plate.

Additionally, this pedal mount has been designed to be adjustable for varying driver heights. The mount plate has a hole on each corner for a bolt and nut to fasten it to the chassis. The chassis will have a hole pattern that repeats every 1.3 inches to create three different height settings for a total of 4 inches of play. The hole pattern in the chassis can be altered or added to depending on the driver's needs. The two slots in the plate are for the hydraulic cable to drop through to prevent crimping the cable.

For this design, it was decided that the max strain condition and thus failure should be avoided by a large factor of safety. First, from an ergonomics standpoint, it was important that the driver feel that the brakes are stiff, and not bending noticeable amounts during normal use. Also, unexpected forces might occur, such as a kick. We believed it was unreasonable expect that the force of a small female driver's calf muscles would cause failures in shear or compression of either the 22 mm rod or the 5/16" plate, but that it would be worth analyzing the bending moment amplified by the distance between where pedal force is applied and the base plate. Using a pedal force of fifty pounds, a conservative estimate, moments were calculated and applied to the base plate modeled as a beam simply supported by the steel fasteners used to secure the plate to the chassis. Even with multiple overly conservative assumptions, the factor of safety found was is the tens of thousands, alleviating concerns about this failure mode. Calculations can be found in Appendix I.

5.5 Safety and Maintenance

The safety of the driver in the Supermileage vehicle is dependent upon the reliability of our braking system. Braking system safety is ensured by design analysis, regular checks, and proper maintenance. Design analysis was discussed earlier in this section and design verification discussion is in section 7. Maintenance and regular safety checks will be reviewed in this section.

Upon installation, check that screws on brake lever, brake caliper, mounting socket, rotor, and hose connections are tight. Check these screws for tightness periodically after installation as well. The bolts that fasten the pedal mount plate to the chassis must be tightened upon installation and every time the pedal mount plate is relocated for height adjustment.

During the first use of the brakes it is pertinent to bed in the brakes. The goal of bedding in the brakes is to bring the brakes to their full potential. This is done by driving with the brakes engaged (one braking system at a time) so the rotor and brake pads get hot enough for the top layer of glazing to break up. This allows for the pads and rotors to shape to each other, so they share more surface area and therefore provide more braking power.

Braking checks should be conducted prior to every ride. Follow the brake line from pedal to caliper to look for any leaks. Observe the calipers to makes sure they are centered around the rotor. Then engage each braking system and make sure both calipers make contact with the rotor. While engaging the brakes for this check, check a second time that no brake fluid leaks from any part of the system.

More periodic brake checks include checking the brake pads and rotors for wear. Refer to the Magura Owner's Manual for more specific information, but as a general rule pads should be a minimum of 2.5 mm thick and rotors should never be less than 1.8 mm thick prior to replacing. Additionally, brakes need to be bled every six months, sometimes more often if the vehicle is not used frequently. All brake parts are stock from Magura, so information on bleeding brakes, brake fluid, cleaning, repairs, and part replacement can be located in the Magura Owner's Manual. Lastly, it is common to remove wheels during vehicle maintenance and transport. Never pull the brake lever when the wheel is removed unless an insert is placed between the calipers.

The pedal mount is solid aluminum, so it is unlikely that this part will need any repairs or maintenance. This plate is adjustable to driver height and can be moved about the car chassis or even between cars. Because of this, it is important to ensure the bolts that fasten the mounting plate to the car are tightened after each adjustment.

5.6 Failure Modes & Effects Analysis

Most failure modes of our braking system occur during installation. These failure modes include failure of pedal actuator pin to line up with master cylinder piston, actuator pin breaking, failure of calipers properly aligning with and centering around the rotors, and failure of fluid to displace properly due to leaks or improper cable fittings. These problems can be resolved through 3D print prototyping. By 3D printing caliper mounts, we can ensure the best geometry for each caliper, so they properly align with rotor and prevent drag. The brake pedal levers can also be 3D printed to determine the best geometry that is both ergonomic for the driver and ensures alignment of the actuator pin and piston. Proper alignment of the pin and piston will help prevent the actuator pin from breaking. Additionally, the pin is a separate piece from the pedal level so it can easily be replaced if it breaks during testing. If it does break, our team with analyze the cause to determine how to change the pedal or pin geometry to prevent future breaks. Testing brake lines consistently throughout installation and using commercial bike cable fittings will prevent brake line leaks. A copy of our Design Hazard Checklist is in Appendix J.

5.7 Project Cost & Weight

The cost and system weight of this project was divided into the three subsystems of this braking system: the front brakes, rear brake, and pedal mount. Magura brakes and additional brake cable will be purchased through the Cal Poly Bike Builders Club for a discounted price. Fasteners and aluminum will be purchased through a hardware store. Aluminum 6061 was selected to manufacture the pedal mount, master cylinder rod mount, pedal, and brake lever because of its machinability, rigidity, and low density relative to other metals.

A simplified bill of materials for the entire braking system is in Table 3. See Appendix J for a more complete bill of materials. Please note that the current total cost and weight of the system excludes the rear caliper mount because it is still in the concept design phase. The total cost of the SMV braking system is $361.16 and the expected total weight of the system is 1.7 kg, or 3.8 pounds. We exceeded our goal of creating a braking system of 5 pounds or less but went over our expected project budget.

Table 3 Simplified Bill of Materials for Whole Braking System.

Subsystem	**Cost**	**Weight (g)**
Front Brakes	$127.02	618
Rear Brake	$151.28	676
Pedal Mount	$82.86	433
	$361.16	1726.92

5.8 Part Drawings

A complete set of part drawings for the Supermileage braking system is attached in Appendix K. The brake lever geometry is subject to changes based on the geometry of the Magura master cylinders. The rear brake caliper mount design is also subject to change because it is in the concept design phase.

6. Manufacturing Plan

The following section has changes from the CDR. Outdated manufacturing plan elements were removed, and a final manufacturing section was added.

6.1 Original Plan

The original manufacturing plan is listed directly below. Underneath is an updated plan that includes use of a water jet for precision and simplicity.

There are three parts that need detailed manufacturing plans: the base plate, the pedal adapter, and the rear caliper mount. All material can be ordered from McMaster for less than $50 total, and all machining can be performed on campus for free. The most significant cost of the project will be the Magura parts.

Base Plate:

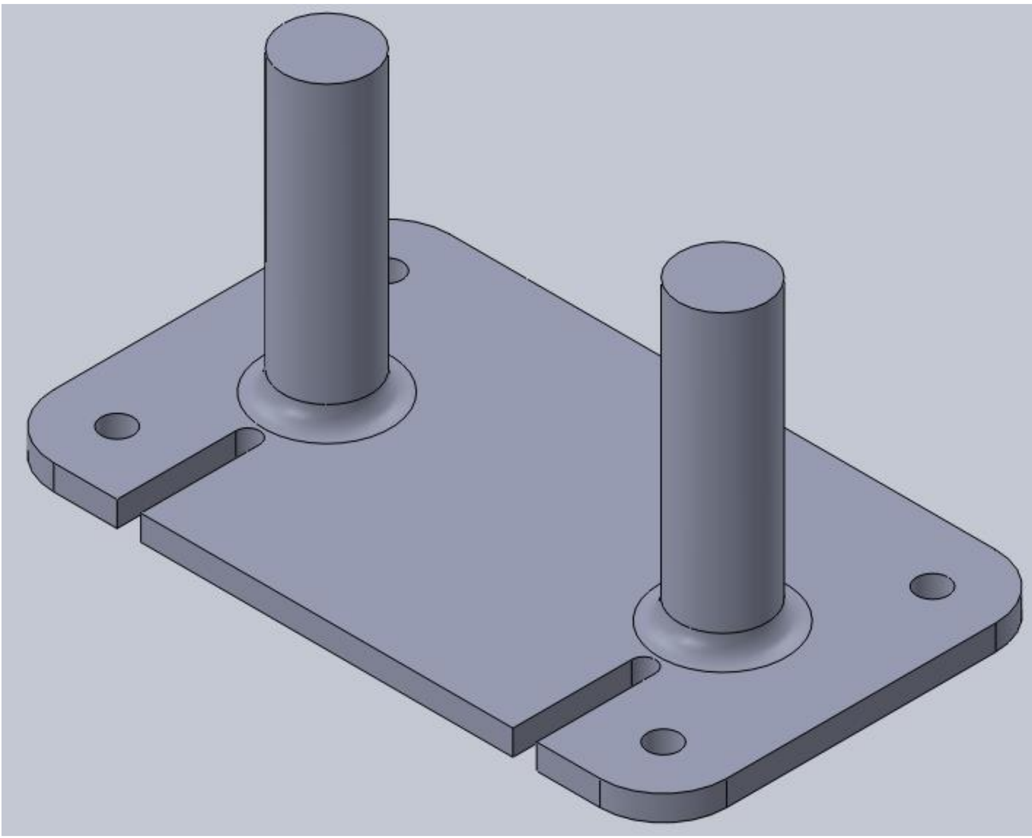

Figure 32 Pedal mount plate.

The base plate shown in Figure 25 will be built from a milled aluminum sheet and two aluminum cylinders welded on. The material will be ordered from McMaster-Carr. If cylindrical rods are significantly more expensive, then a rectangular bar can be purchased for cheap and lathed to a cylinder. The plate can be milled easily when our final hole-callouts are determined. It will be important that the holes match what is drilled into the SMV chassis. The piece will be mounted to the chassis with nuts and bolts, and big washers to distribute the force because the carbon fiber body should not be put in high stress concentrations.

Anticipated manufacturing time: 5 hours

Completion date goal: December 10th

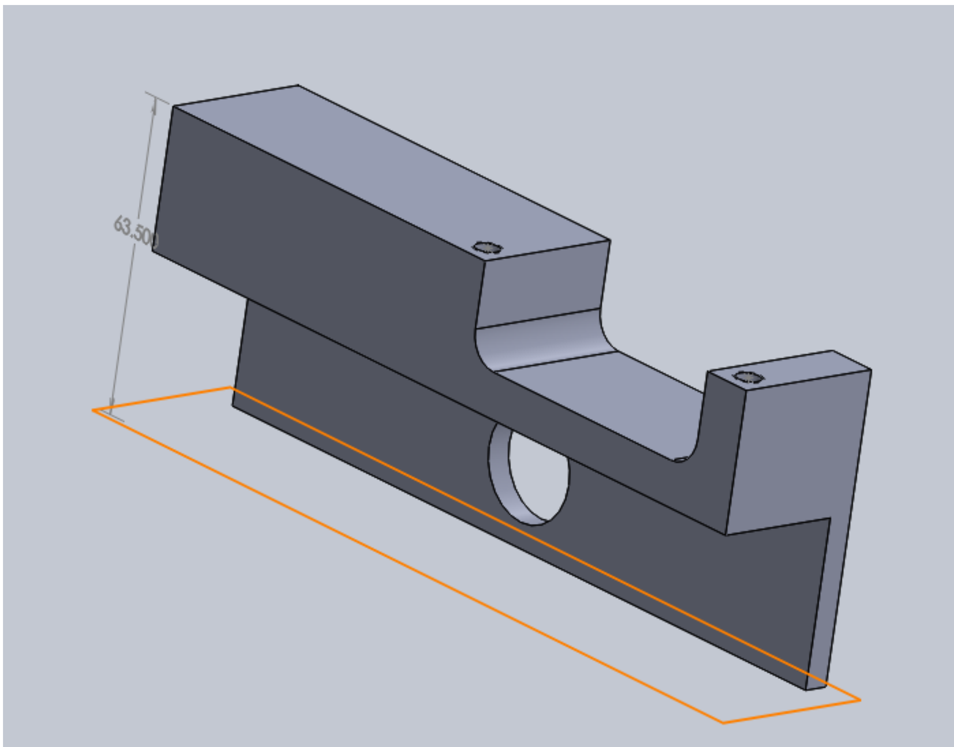

Figure 33 Rear brake caliper mount.

The mounting caliper shown in Figure 28 will also be milled from a 2.5x1.25x6 in block. Our team still needs to conduct analysis on the part, so final dimensions are not provided in this report. The piece will be fastened to the rear drop-out mount. The mount will be placed a few millimeters from the brake rotor to reduce the length and thus the bending stress on the system. The advantage of this is the increased rigidity of the steel axel, which is less prone to rubbing between the caliper and rotor.

Anticipated manufacturing time: 5 hours

Completion date goal: February 10th

Updated Plan:

Note: The final design only utilizes the base plate manufactured from the plan below. Other components were not needed.

The pieces we want to manufacture will come from an aluminum sheet and an aluminum rod. See the drawing in Figure 26 to verify that the parts will fit in a 6”x12” sheet and 1’ long rod. (Total Cost: $36.42)

Table 4 Raw Material Costs

Multipurpose 6061 Aluminum Sheet, 5/16" Thick, 6" x 12"	9246K464	$21.67
Multipurpose 6061 Aluminum Rod, 1-1/4" x 1-1/4", 1’ length	9008K15	$14.75

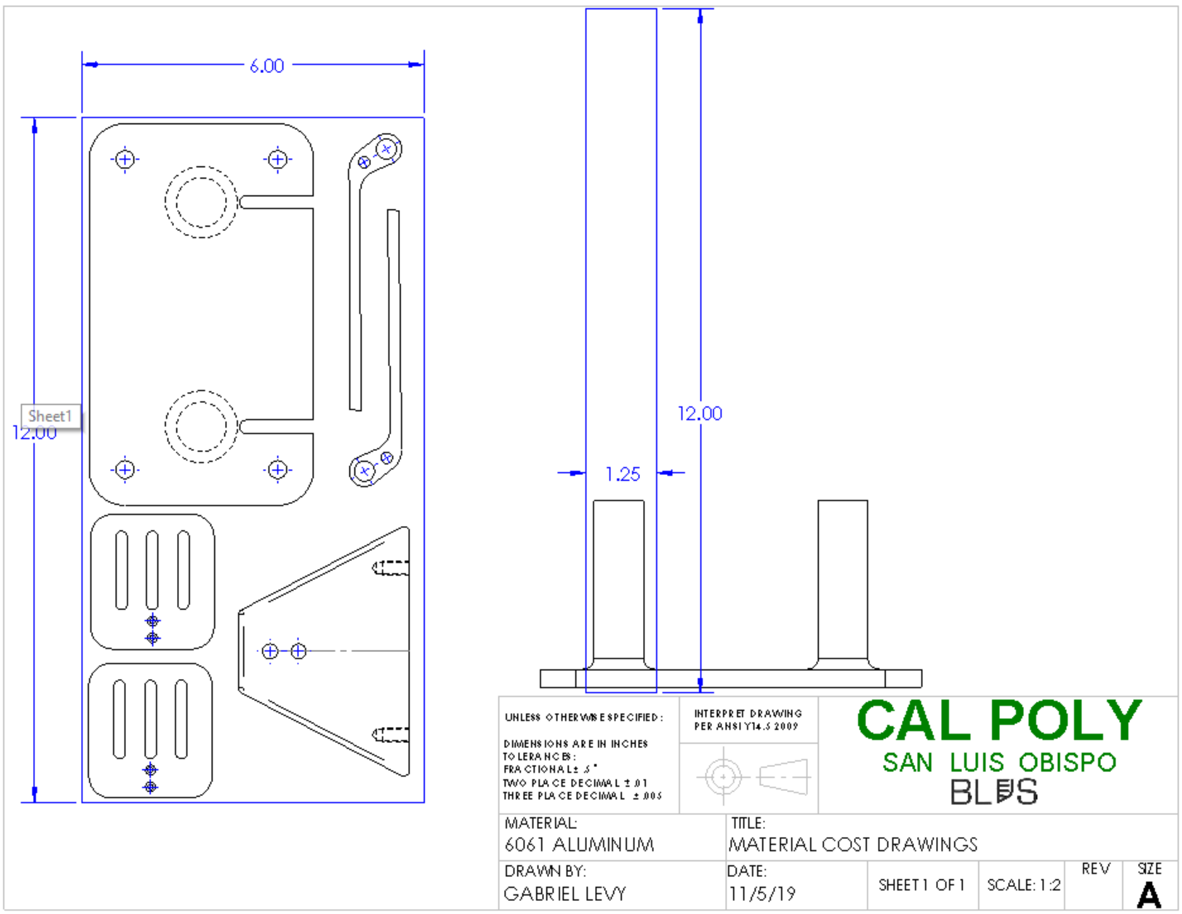

Figure 34 overlay of machined parts on stock material

The sheet will be cut with a water jet, then each hole will be milled in Mustang 60. The bar will be lathed to a cylinder.

The base plate and cylinders will be milled with a counterbore hole-shaft configuration and fit together mechanically. A collar clamp will be used to prevent the shaft from slipping out of the hole. This modification was recommended during CDR presentation when it was pointed out that welding aluminum reduces its material strength. The press fit configuration eliminates the need for welding.

In addition, we will need to order the Magura breaks. That request will come later, but we estimate a cost of $160.

The current dimensions of the pedal lever is not determined yet. Once the Magura parts arrive, we can hand measure the geometries and design the lever from there. However, there should be plenty of material remaining.

6.2 Final Manufacturing

Aluminum for the base plate, mounting cylinders, and rear brake mount were ordered from McMaster Carr. Magura MT4 and ‘Big Twin’ brakes were received, along with three 160 mm brake rotors. Fabrication of two mounting cylinders, the base plate, and the rear brake was done according to the specified plan. Alterations to the plan follow.

Manufacturing of the pedals and their mounts faced several challenges and required design changes as discussed in prior sections. The final design, pictured below, required fabricating an L-bracket and 3D printing a pedal to allow horizontal actuation of the front Magura ‘Big Twin’ dual brake. The rear brake also required a pedal to be 3D printed, which was designed to interface with the Magura MT4 brake lever cut off at the end. Once press-fit, the pedal was bonded to the lever with epoxy, and wrapped with carbon fiber to lower bending stresses and prevent cracking failure. 7/8” collar locks were purchased from Amazon, one of which was used to fix the mounting cylinder to the base plate. The assembled rear brake pedal/master cylinder was then affixed to the cylinder using the brakes included mounting bracket.

Figure 35 Final brake pedal mount assembly. Front brake pedal (left) and rear brake pedal (right).

As seen, the necessity for the L bracket is due to the larger than expected master cylinder. As such the post on that side was removed, and two 6 mm countersink holes were put in the bottom of the base plate, aligned with two 6mm holes drilled in the L-bracket. Two #10 flat head machine screws were put through the base plate and L-bracket, with nuts used to secure them. The lever and master cylinder were fixed to the L-bracket using the same M6 bolts that originally came with the brake handle bracket. For the pedal, the ‘Big Twin’ lever was shortened with a saw, and the plastic was scored. The hole in the pedal was filled with JB WetWeld 900 PSI epoxy, and the lever was pressed in, forming a permanent attachment.

The base plate was secured to the testing rig similarly to how it will be secured to the skateboard style chassis of next year’s vehicle. This involved drilling 3/16” holes at the location of the corner mounting holes, then bolting #10 button head machine screws on with flat washers on bottom and lock washers on top.

Added to our manufacturing were IS 2000 mounting brackets for the front uprights. Originally, the steering team designed these brackets, but we had anticipated post-mount brakes, so they were redesigned when the brakes arrived. These were designed to the IS rear-brake standard, as this allowed them to fit natively on 160 mm rotors, where if they were designed to front-brake spec, 180 mm rotors would be required. The steering team had the shape laser cut, and we machined M6 brake mount holes, upright mounting slots, and faced the brake mounting location to the proper thickness for alignment. These mounts are pictured in Fig. 31 in the next section.

Finally, the rear brake mount was fabricated according to the original plan, with excess material removed, a choice supported by FEA. The component fit on the dropout as expected, and the brake was attached along with a +20 post mount adaptor, allowing for a 160 mm rotor. Fabrication of this component took longer than anticipated, and a failed first attempt was later used to form the L-bracket.

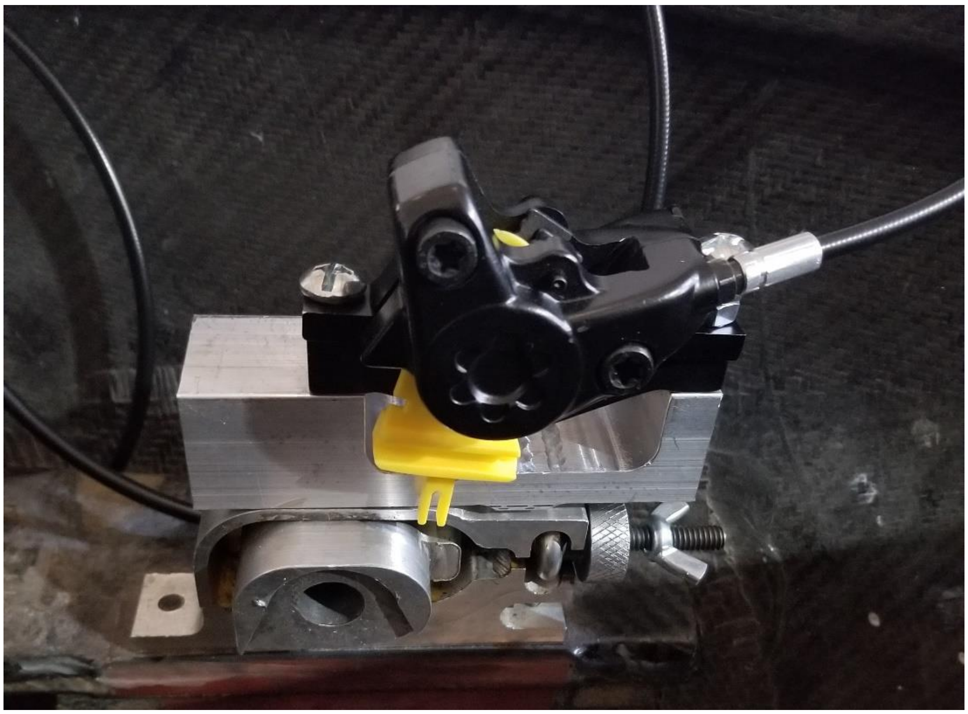

Figure 36 Final rear brake caliper mount with Magura MT4 brake and +20 PM adaptor.

7. Design Verification Plan

The team has designed and performed three tests for design verification. Because the total vehicle is not fully assembled, we cannot perform the Shell Eco-marathon tests yet. Future teams will be required to do these tests before the 2021 competition.

Weight test: Each component is individually weighed and tabulated as in Table 3 (Bill of Materials). The overall weight of the braking system is 3.81lb, which is well below the 5lb target weight. Future team members can evaluate values and find areas to reduce weight.

Brake test: Sytems is lifted onto blocks so that wheels can spin freely. The wheels are manually spun, then the brakes are activated to confirm brake pad contact and activation. Confirmed that the brakes work.

Brake Drag Test: While the system was lifted as mentioned previously, brakes were left unactuated and wheels were manually spun again. Teammates observed and listened for any pad-rotor contact to confirm there is no unwanted drag. Some drag was experienced, but the brakes were not finely tuned and installed carefully, as they were on temporary mounts until the actual vehicle is complete. Once properly installed, we recommend the team test again and adjust from that data.

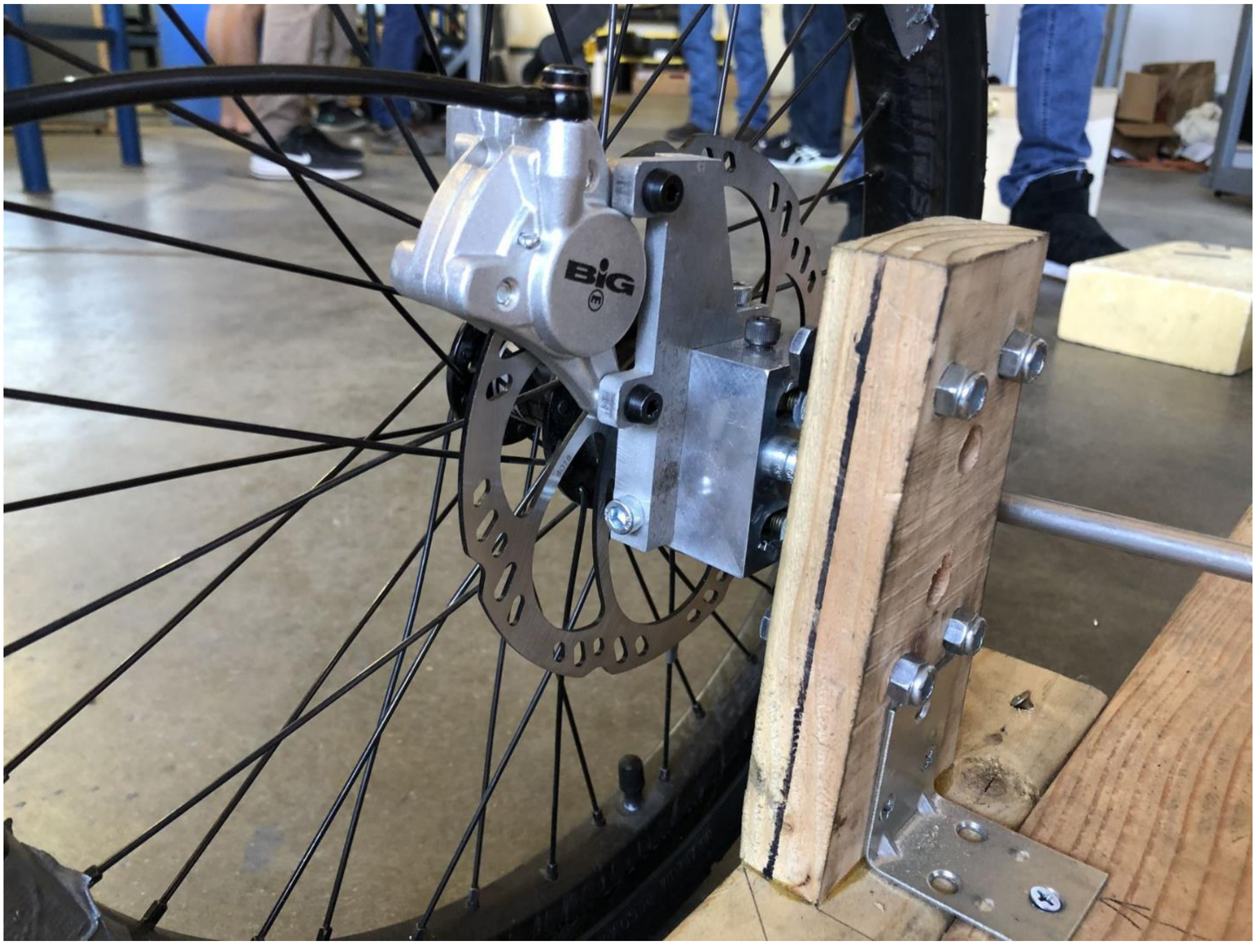

Figure 37 Front brake IS caliper mount.

We suggest that the Supermileage Vehicle club conducts two additional tests prior to competing in Spring 2021. The additional tests are the Shell Eco-marathon tests: independent braking systems on 20% incline and deceleration rate.

Independent braking system test on 20% incline: The vehicle has to be able to hold itself steady with both separate brakes (front and rear) on a hill at a 20% incline.

Deceleration rate test: The vehicle has to stop from a speed on 24 kph in a space distance of 4 meters.

Both of these tests require the vehicle to be in operational order before they can be performed, so they are out of the scope of this senior project team.

8. Project Management

Anneka, Ian, and Gabriel found a natural division in team responsibilities. Specific roles are assigned to each member in accordance to their specialties in order to benefit the success of the project. Anneka, having the best technical writing abilities, is our communication officer, editor, and secretary. Ian, who is detail-oriented and organized, oversees planning and testing. Gabriel, who enjoys hands-on work, is lead manufacturer and treasurer. By dividing the roles evenly, the team hopes to create leaders for each step of the project; therefore, creating a management system that can guide the team to success. Of course, the roles are not absolute, and any individual who sees a lack of completion in any task is expected to communicate with the team and help organize a plan that leads to satisfactory work. Because the team size is small, it is easy to communicate between each other and collaborate in order to achieve the best results. Ultimately, the team worked very well together and had no major quarrels. Any disputes in design choices were solved diplomatically and with empirical data to validate decisions. The team formed a close bond, and are sad to be parting ways.

The team worked together to write and sign a team contract, which states procedure for communication, conflict resolution, and penalties for poor teamsmanship. The contract can be viewed in Appendix C. The contract is approved by our advisor, Professor Mello, and binds each team member. In the event of catastrophe or absolute defiance of the contract, outside consultation will be sought to resolve any internal problems. The contract was a good backup, but it was never used during this project.

Scheduling for this project is carefully monitored by each member in order to prevent project progress from falling behind. A quarter-long timeline on TeamGantt.com is regularly updated as new developments are made. The timeline keeps team members accountable and clearly presents deadlines for every aspect of the project. As the preliminary research stage is moving past, we begin early modeling and prototyping. Upcoming weeks will be spent dissecting different models of hydraulic brakes and experimenting with foot-pedal modulations. See the GANTT chart in Appendix D for further detail. The chart currently stops at the team's preliminary design review date, but it will be extended into next quarter's activities when an updated schedule is presented. The Gantt chart was helpful as a vague outline for our plans, but rarely were the tasks met at the expected times or followed through at all, due to changes in plans and unforeseen delays.

An important topic to discuss is Gabriel's absence for of winter quarter. He has no other classes to complete his degree, and therefore does not anticipate on being in SLO. The team has discussed the matter and came to the agreement that if he puts in effort to finish most of the manufacturing during the fall quarter, and then works remotely on the final design review, he can stay abroad. He plans to return to SLO in order to finalize the product and present his work by the end of the quarter, if requested by the team. Gabriel put in his fair-share of work, and he remained a valuable team member despite his physical absence.

9. Conclusion

The conclusion's upcoming plans has changed from the CDR report.

After reading this document, our sponsor should have a clear outline of the project. As requested, we designed and installed the braking system of the 2021 SMV with a hydraulic brake. Our work done is as follows: researched and purchased the optimal bicycle hydraulic brake, replaced the current rotor and caliper system, designed a foot pedal to replace the stock brake hand-lever, and performed a series of tests to confirm that the vehicle meets competition requirements.

After much research and gathering of user input from the previous SMV driver, our team has pin-pointed several important requirements. Driver ergonomics is a priority; the brakes must be comfortable to reach and easy to maneuver. The current brake system is awkward and requires a lot of ankle flex from the driver, which limits her ability to comfortably operate the vehicle. Brake fit will be optimized by properly aligning rotors with calipers during installation to prevent rubbing and drag, as seen in the current system. This will prevent the large energy losses and improve the gas mileage of the vehicle.

9.1 Recommendations

Our team successfully achieved in building, assembling, and testing a hydraulic brake system for the 2021 SMV vehicle. Magura bicycle brakes are retrofitted with custom levers and mounts to activate via foot motion by the driver. Each part will be discussed at length to determine what corrections were required, and how the process would be done differently.

Caliper Mounts: Both the front and rear brake caliper mounts work exactly as intended. Manufacturing and installation were straightforward, and the devices work as intended. No changes recommended.

Front Brake: The front brake took a long time to deliver, and it is shaped differently than expected. It requires a different orientation to operate than originally thought, so our mounting system had to change to mount it vertically. The newly designed L-Bracket was bent and machined from a spare sheet of aluminum, but should have been an already-bent, stock angle bracket.

Pedal Lever: Instead of removing the stock lever and replacing with a custom shaped piece, we were recommended to 3D-print a shell that fits over the lever and adhere it with epoxy. This was a much simpler manufacturing process, but the method reduces our ability to manipulate the lever angles. Therefore, it is more awkward for the driver to use the brake pedals. Custom shaped levers would be longer, so they would require more travel distance in order to actuate the brakes. They also can be shaped at an angle to fit the driver's foot and ankle resting position better. To improve these levers, we need access to a waterjet cutter, which was not reasonably obtainable to us.

Rear brakes: We could not install rear brakes due to ordering errors/administrative mistakes. We requested post-mount brakes but received flat mounts. The order was returned through Sara Passatino with Bike Builders, and Magura MT4 post mount brake or other compatible hydraulic brakes have been recommended for future teams.

Pedal Mount Plate: The mount system works as intended. There is one additional hole in center than needed due to design changes, but functionality is not lost. An SMV teammate suggested that the part could be 3D printed in order to reduce weight. It is possible that a 3D part would break under emergency braking forces, so stiffness and strength calculations are recommended before the conversion is made.

The biggest struggle with our project was part delivery time. We had to go through several organizations to obtain the desired parts as cheaply as possible, and the excessive waiting time resulted in a shortened assembly and testing period. We did not have time to fix some errors, such as the incorrectly ordered part. This project taught a valuable lesson about working for a large organization.

Next Steps:

1. SMV should order the correct (post mount) rear brakes and attach them to our caliper mounts.
2. We recommend that SMV replaces the brake levers with custom-shaped, waterjet-cut levers that orientate to a comfortable angle for the driver.
3. Reevaluate brake drag and look at possibilities of fine tuning the system. The pedal mounts are designed so that calipers can be moved to optimal position. The calipers can be tuned by hand as well.

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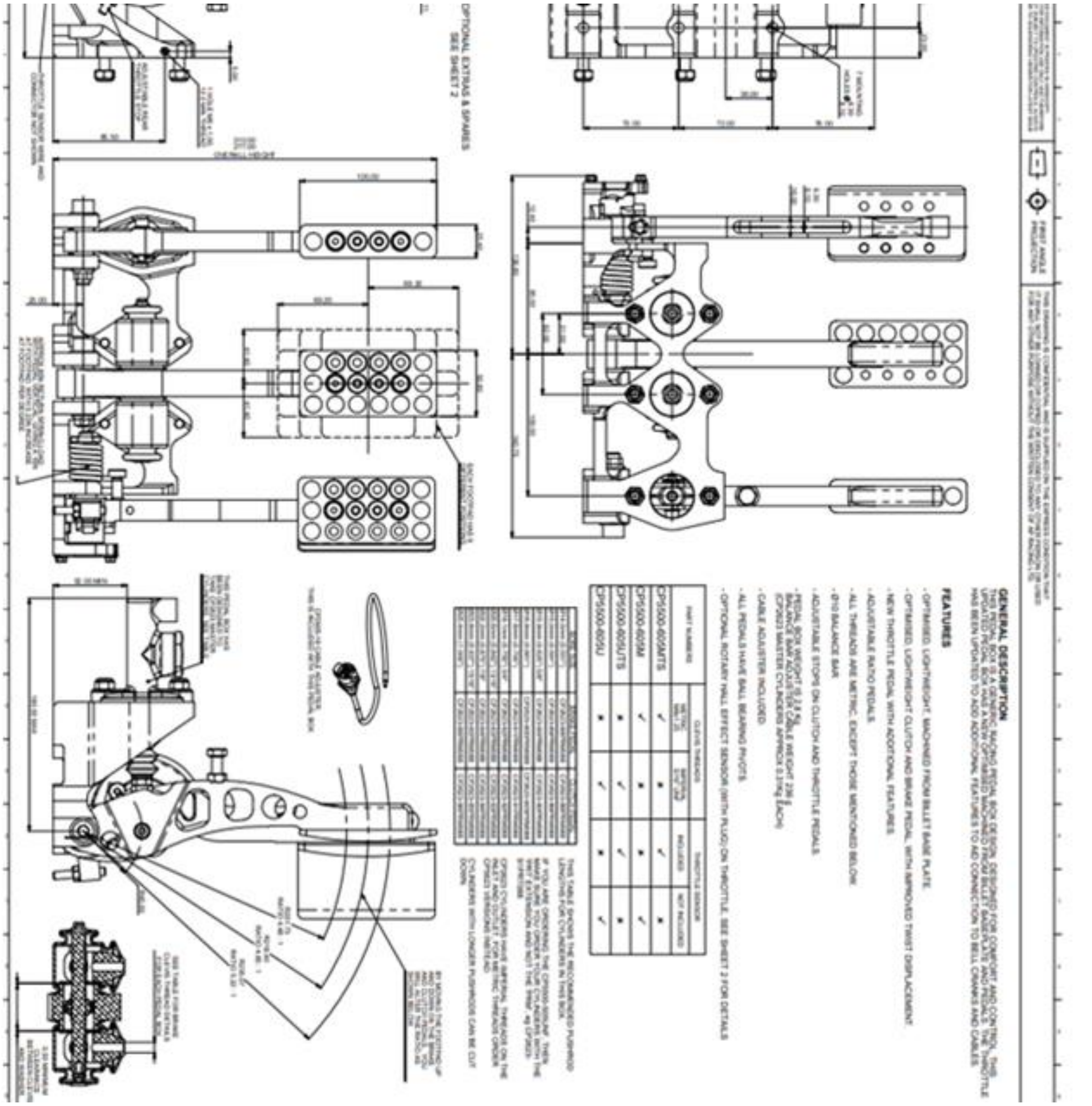
Appendix A

AP Racing 3 pedal brake box



Appendix B

Quality Function Deployment (QFD)

◎ ○ △ □ ▽ ◇

Customer: Cal Poly SMV

Dr. Mello (Sponsor), Lucas Kensinger (SMV President), Crystal (SMV Driver)

Item No.	Requirement	Importance	A Weight	B Cost	C Friction in unapplied	D Brake pedal force	E Braking force	F Deceleration	G	H	I	J	K	L	M	N	O	1 (Bad)	2	3	4	5 (Good)
1	Two front hydraulic brakes	10					◎	◎											C			P
2	One rear hydraulic brake	10					◎	◎											C			P
3	Individual brake systems immobilize vehicle on 20° incline	10					◎													C		P
4	Brake systems are individually operated by foot pedal	10	◎			◎												C				P
5	Zero friction between unapplied pad and rotor	8			◎																C	P
6	Light weight	6	◎				△	△												C		P
7	Non-adjustable by driver	10			△															C	P	
8	Under $1000	6		◎																P		C
9	Fits in current and future prototypes	8		○															P	C		
10	Rotors fit within uprights	9			○															P	C	
11	Pedals activate braking at 45° angle	7				△												C		P		
12	Ergonomic & driver compatible	6			△	△																
13	Two piece disk brake	3	△		△																	
14																						
15																						
	Targets		5 lbf	$300	0 lbf	50 lbf	100 lbf	0.3 g														
	Weighted Importance		4	3	5	4	3	2										21				
	% Importance		19	14	24	19	14	9.5														

Company Ratings: Good 5, 4, 3, 2, Bad 1

Relationship Strength: Strong - 9 ◎, Medium-3 ○, Weak - 1 △

C - Cal Poly 2019 SMV
P - Pac Car II

Appendix C

SMV 2019 Braking Systems Team Contract

The basic working group in industry is the project team. Team environments foster efficient interdisciplinary interactions and create a desirable setting for innovation. Hence, the ability to function effectively as a member of a team has become essential. A team contract identifies the goals and processes that the team will follow to achieve success. The purpose of this Team Contract is to communicate rules of operation to members of your senior project design team.

Mission:

The mission of this team is to design, prototype, and test two independent hydraulic braking systems for Cal Poly's Supermileage Vehicle Team. This will be done through collaboration of team members with each other, other senior project SMV teams, their sponsor, and their advisor.

Section 1—Name

Our team name is **Supermileage Vehicle 2019 Braking Systems Team**.

Section 2—Roles & Responsibilities

A. Members of the team are: Gabriel Levy, Ian Kennedy, Anneka Cimos
B. No member shall purport to represent the team unless so authorized by the team.
C. Each member shall be provided a copy of the team contract.
D. Officers of the team shall include those listed below with their designated responsibilities.

1. **Communications Officer** – Anneka Cimos
    a. Main point of communication with sponsor
    b. Coordinates meeting with sponsor
2. **Treasurer** – Gabriel Levy
    a. Maintain team's travel budget
    b. Maintain team's materials budget (planning & tracking)
3. **Secretary** – Anneka Cimos
    a. Organize information repository for team (i.e.. OneDrive and team binder)
4. **Manufacturing –** Gabriel Levy
    a. Coordinate build activities
    b. Arrange materials/equipment
5. **Testing** – Ian Kennedy
    a. Coordinate test activities
    b. Arrange facilities/instruments
6. **Editor** – Anneka Cimos
    a. Ensure documentation is complete, well-written, and timely

7. **Planner** – Ian Kennedy
    a. Organize project plan/tracking
    b. Create and distribute weekly meeting agenda prior to meeting
    c. Create and distribute weekly action items list after each meeting

Section 3—Decision-Making

A. Decisions will be made by consensus
B. When the method of consensus for decision-making has broken down (ie. team members still not willing to agree), decisions will be arbitrated by a third party. This party will likely be the SMV Steering and Uprights Team or by Professor Mello.

Section 4—Team Communications

A. All affairs of the team shall be governed by courteous manners.
B. Normal communications outside of meetings will be held through GroupMe.
C. Team members must check and respond to GroupMe messages within 1 day and be more responsive within 24 hours of a due date.
D. All files will be shared and stored on OneDrive
E. Meetings shall be held Thursdays from 4:30 – 6:00 pm.
F. Unless otherwise noticed, all meetings will be held at Building 192 (whichever room is open).
G. Special meetings of the team may be called by Anneka at least 24 hours in advance.
H. Attendance is mandatory unless an approved excuse such as illness or family emergency is provided. In most cases the meeting will be moved to a time and date when all three members are able to meet.
I. Meeting discussions will be conducted in a conversational format with special regard for a dialogue that is respectful and considerate of all members in attendance.
J. Ian Kennedy will create a meeting agenda, distributed at least 24 hours in advance, that will guide meeting topics and timing.
K. The length of meetings shall be stated in advance by Ian Kennedy.
L. All team members are expected to be punctual.
M. Violation of team meetings will be publicized to members using phone calls, team websites, e-mail, and texting prior to the beginning of the meeting.
N. Notices shall be distributed no less than 24 hours before the meeting date.
O. Violation of team rules will result in violator bringing snacks to the next team meeting after each offense and revisiting the contract terms after multiple offenses.

Section 5—Sponsor Interactions

A. Meeting time and location will be set with the sponsor within a week prior to the meeting.
B. A meeting agenda will be created and distributed by Ian Kennedy at least 3 hours prior to the meeting
C. Anneka Cimos, the sponsor contact, will initiate all discussion and follow-up queries via email with the sponsors. All members will be copied on correspondence.
D. Anneka Cimos will follow-up with sponsor within a week if sponsor doesn't respond.

Section 6—Conflict Resolution

A. Minor disagreements shall be deliberated until a unanimous decision is made
B. In the event of an agreement not being made, one day shall be allowed to gather more evidence and form final arguments.
C. If no conclusion is reached, the advice of Mello will be requested, and ultimately the decision will be determined by majority will.

Section 7—Violations of Contract

A. All meetings will operate on "Poly Time"
    a. Sessions begin 10 minutes after agreed upon time, i.e. 3 pm meeting will meet at 3:10 pm
B. It is acceptable to be up to 15 minutes late to a meeting; tardiness beyond that will be considered disrespectful.
C. One tardy excuse will be allowed to each team member a quarter. Beyond that, tardiness or absence not cleared ahead of time will require the following actions:
    a. 15 minutes late to meeting: bring a snack next meeting
    b. Missed meeting: bring a meal next time
D. Missed deliverables are unacceptable. In the event of an individual being unable to complete an assignment in time, he/she is expected to give the group at least two days' notice, and request help when necessary. Failure to properly warn the team of an upcoming deadline that will not be fulfilled will result with severe consequence.

Section 8—Amendments

A. This document is "living" and subject to change at any time.
    a. A change can be initiated by anyone, but it must be unanimously agreed upon. In the event of conflict, mediation through Mello will be sought.
B. Quarterly reviews of this document will be performed by the group members
C. Advisor will be informed of document changes via email. These emails will count as legal proof of change to contract.

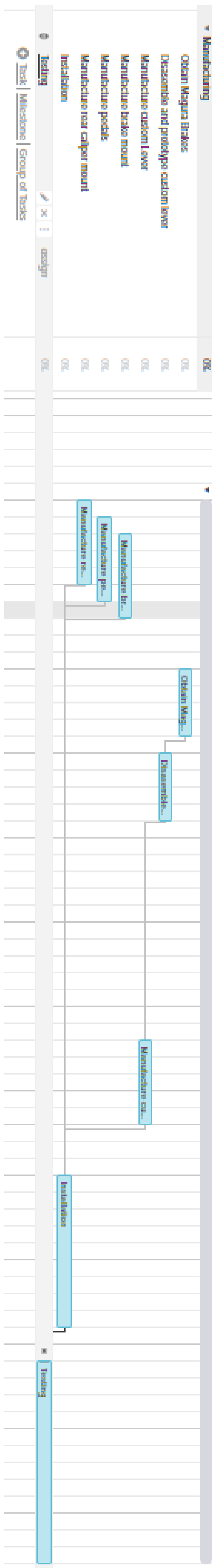
Section 9—Effective Date (Required)

A. This contract of the Supermileage Vehicle 2019 Braking Systems team shall become effective on April 11, 2019.

B. Dates of amendment must be recorded in meeting minutes at which amendments were approved, together with a revised set of bylaws.

Appendix D

Team Gantt Chart



Appendix E

Pugh Matrices

Table 3. Pugh Matrix for Front Hydraulic Disk Brakes.

Brake choice (Front)	Concept:	Magura MT 4		Sram Guide T		Avid Code R	
Criteria		+/-	Value	+/-	Value	+/-	Value
Cost		1	$ 100.00	1	$ 105.00	-1	$ 150.00
Weight		1	230 g	0	280 g	-1	395 g
Force		1	MTB	1	MTB	1	MTB
E-brake compatibility		1	yes	0	no	0	no
Unapplied friction		0	no	0	no	0	no
Mounting		-1	PM adaptor	-1	PM adaptor	1	IS Adaptor
Rotor Size		0	140/160	0	140/160	-1	160/180
Easy Bleed Tubing		1	Yes	1	yes	-1	no
Pad Material		1	choice	0	organic	0	Organic
# of pistons		0	2	1	4	1	4
Sum		5		3		-1	

Table 4. Pugh Matrix for Rear Hydraulic Rim Brake.

Brake choice (Rear)	Concept:	Magura HS33		Sram	
Criteria		+/-	Value	+/-	Value
Cost		1	$78	-1	$250
Weight		0	480 g	1	405 g
Force		1	MTB	-1	Road
E-brake compatibility		0	no	0	no
Unapplied friction		1	no	1	no
Mounting		0	Cantilever EVO 2	0	Cantilever
Lever Blade Material		0	Aluminum	0	Aluminum
Lever Blade		0	2 finger	0	2 finger
Easy Bleed Tubing		1	yes	1	yes
Sum		4		1	

Table 5. Pugh Matrix for Brake Pedal Structure.

Pedal Structure	Below Hinge Actuation	Above Hinge Actuation	Adjustable Plate
	+/-	+/-	+/-
Cost	0	0	-1
Weight	0	0	-1
Stiffness	1	0	0
Reliability	-1	1	0
Adjustability	0	1	1
Convenience	-1	1	1
Sum	-1	3	0

Table 6. Pugh Matrix for Brake Actuation Mechanism.

Actuation Mechanism	Hinge-piston (straight)	Hinge-piston (angled)	Cam-follower
	+/-	+/-	+/-
Cost	1	0	-1
Weight	0	0	0
Adjustability	-1	0	1
Reliability	1	1	?
Sum	1	1	0

Appendix F

Pedal Thickness Calculations

Pedal Thickness Calcs

going to use FEA to optimize pedal size

Assume

1) ~~Max~~ MAX brake compression 300 N (60lb) (~~gen~~ people press brakes half their weight in car break lockup

120 lb girl → 60 lb force

2) ~~simple connected~~ ~~rigidly connected~~ simple beam model

3) Force applied entirely at tip (conservative)

4) stress max at hinge → rectangular bar, traverse hole

5) shear negligible, bending only

Shigley A-15-2

Appendix G

Brake Force Calculations

BRAKING FORCE

SAE brake test:

decelerate from 24 Kph to 0 kph in 4.0 meters at a rate greater than 0.25g

Vehicle weight ≈ 80 lbf = 36.5 kg

driver weight ≈ 120 lbf = + 55 kg

91.5 kg

weight FS = 1.25

CONSERVATION OF ENERGY

$$W = KE_{INITIAL} - KE_{FINAL}$$

$$= \frac{m V_{INITIAL}^2}{2} - \frac{m V_{FINAL}^2}{2} \quad (V_{FINAL} \rightarrow 0)$$

$$= 91.5\ kg\ \frac{\left(24\ \frac{km}{hr} \cdot \frac{1000\ m}{3600\ s}\right)^2}{2} = 2033.3\ N\text{-}m$$

$$W = F \cdot d$$

$$F_{Brake} = \frac{W}{d} = \frac{2033.3\ N\text{-}m}{4\ m} = 508.3\ N$$

Design

$$1.25 \times F_{Brake} \cong 640\ N$$ (total brake force)

BRAKE ROTORS -- FRONT WHEELS

F_B is braking force from each rotor (front wheels)

$$F_B = \frac{F_{Brake}}{2} = \frac{640\ N}{2} = 320\ N$$

BRAKING CALCS

CAR

$$KE = \frac{1}{2} m v^2$$

$$= 2035 \text{ N-m}$$

m = car + driver mass
= 92 kg

V = car speed
= 24 kph (SAE design req)

$$KE = m_b c_p \Delta T_b$$

↑ car ↑ brake sys

* Ideal case
assumes no energy losses

m_b = mass braking sys.
c_p = spec. heat of brake
ΔT_b = temp. rise in rotor

PEDAL

$$F_{bp} = F_d \times \frac{L_1}{L_2}$$

$$= 250 \text{ N} \times \left(\frac{10 \text{ cm}}{4 \text{ cm}}\right)$$

$$= 625 \text{ N}$$

F_{bp} = output F of brake pedal
= ?

F_d = force applied to pedal — really closer to 200N
= 250N

L_1 = pedal arm pivot to output rod clevis
= 10 cm

L_2 = pedal arm pivot to pedal head
= 4 cm

MASTER CYLINDER

$$P_{mc} = \frac{F_{bp}}{A_{mc}}$$

$$= \frac{625 \text{ N}}{2.85 \times 10^{-4} \text{ m}^2} = 2.19 \text{ MPa}$$

A_{mc} = master cyl. area
$\cong 2.85 \times 10^{-4}$ m²

CALIPERS

$$D_{cal} = 0.026 \text{ m}$$

$$A_{cal} = 5.31 \times 10^{-4} \text{ m}^2$$

$$P_{cal} = P_{mc}$$

$$F_{cal} = P_{cal} \times A_{CAL}$$

$$= 2.19 \times 10^6 \text{ Pa} \times 5.31 \times 10^{-4} \text{ m}^2$$

$$= 1164.36 \text{ N}$$

$$\cong 260 \text{ lbf}$$

CLAMPING FORCE

$$F_{clamp} = 2 \times F_{cal}$$
$$= 2328 \text{ N}$$

$$F_f = \mu_{bp} F_{clamp}$$
$$= 0.4 (2328 \text{ N})$$
$$= 931.49 \text{ N}$$

ROTOR

$$T_r = F_f \times R_{eff}$$
$$= 931.5 (0.07875 \text{ m})$$
$$= 73.35 \text{ Nm}$$

R_{eff} = effective rotor rad.
= 78.75 mm
T_r = torque gen. by rotor

TIRES

$R_{wheel} = 0.305$ m

$$F_{wheel} = \frac{T_t}{R_{wheel}}$$
$$= \frac{73.35 \text{ N-m}}{0.305 \text{ m}}$$
$$= 240.5 \text{ N / wheel}$$

⟶ ~53.95 lbf/wheel

$$F_{total} = 3 \times F_{wheel}$$
$$= 721.5 \text{ N}$$

DECELERATION CASE

$$F_{req\ tot} = (92 \text{ kg})(0.3 g)$$
$$= 270.8 \text{ N}$$

BRAKING DISTANCE

$$d = \frac{v^2}{2a_v}$$
$$= \frac{24 \text{ kph}^2}{2(7.84 \text{ m/s}^2)}$$
$$= 2.83 \text{ m}$$

BRAKING RATE

$$a_v = \frac{F_{total}}{m} = \frac{721.5 \text{ N}}{92 \text{ kg}}$$
$$= 7.84 \text{ m/s}^2$$
$$\doteq 0.8 g$$

Appendix H

Ideation Sessions

BRAINSTORMING SESSION: PEDALS

Number of Pedals-

* * 2
* 3 (Ian's Idea)

Moonting-

* * floor
* ceiling
* side wall

Material-

* Al → fatigue
* Plastic → fatigue
* Wood → weight, maching
* Steel → weight
* * Mix plastic & steel parts

Shape-

* low SA, solid pedal, small
* high SA, perforated, large
* direct master cyl. actuation? (button pedal)
* low SA, somewhat perforated, medium

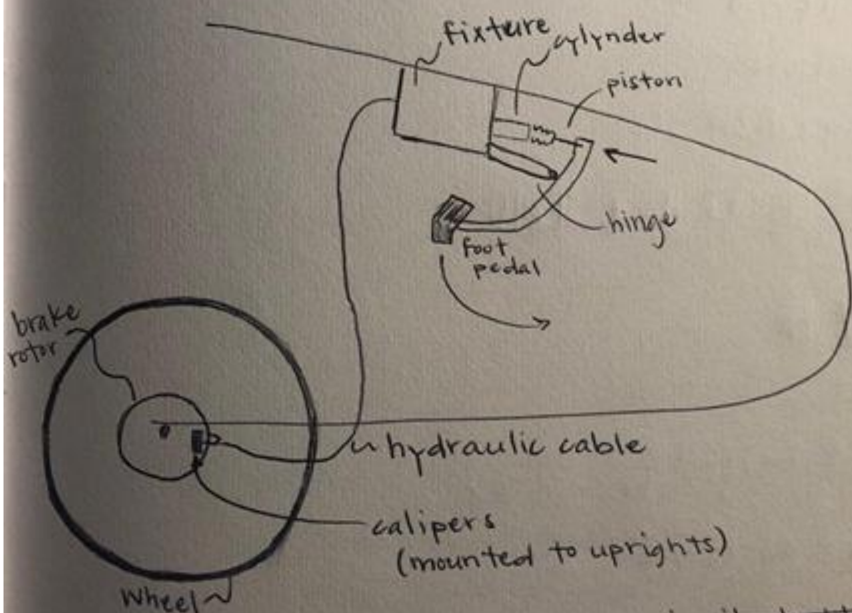
* indicates preferred idea

ENTRY: 5/7/2019

IDEATION SESSION #2: Pedal-cable connection

- how to fix cylinder to vehicle
- how to connect piston to pedal

CAR FRONT:



*mount to floor instead of ceiling because floor is stiffer.

*adjustable pedal mount

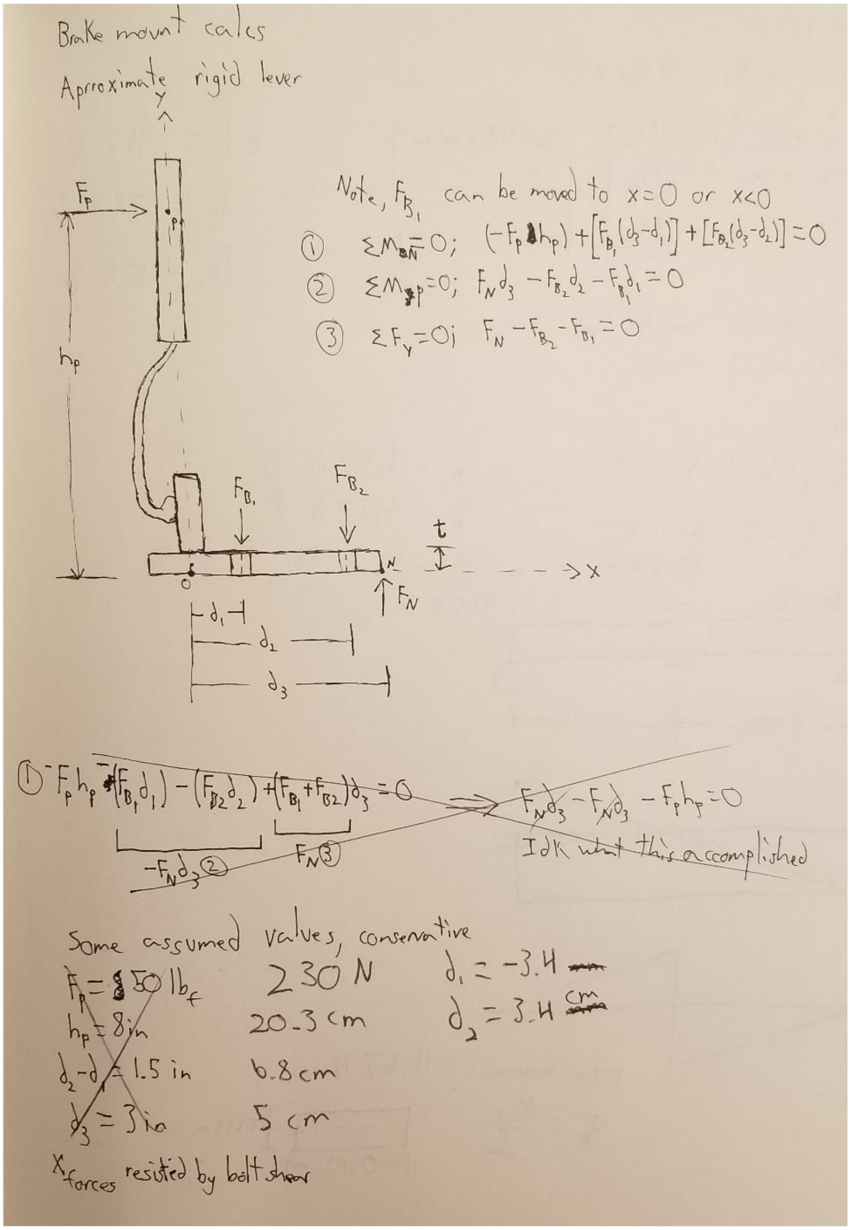
~~is it better to mount to the floor? stiffer?~~

fixture ideas:

bracket?

Appendix G

Base plate bending moment calculation



9 10-15-19

solvin equations ① ② & ③

$$\begin{bmatrix} 0 & 0.084m & 0.016m \\ 0.05m & 0.034m & -0.034 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} F_N \\ F_{B_1} \\ F_{B_2} \end{bmatrix} = \begin{bmatrix} (230N)(0.203m) \\ 0 \\ 0 \end{bmatrix} \rightarrow$$

$F_N = -467\ N$

$F_{B_1} = 577\ N \downarrow$

$F_{B_2} = 110\ N \downarrow$

Normal force can't be in tension
- calc w/ 0 $force_N$

$\Sigma M_o = 0$

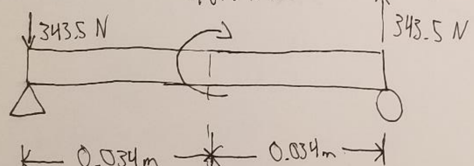
$$\begin{cases} -F_p h_p + F_{B_1}(d_1) + F_{B_2}(d_2) = 0 \\ F_{B_1} + F_{B_2} = 0 \end{cases} \Rightarrow$$

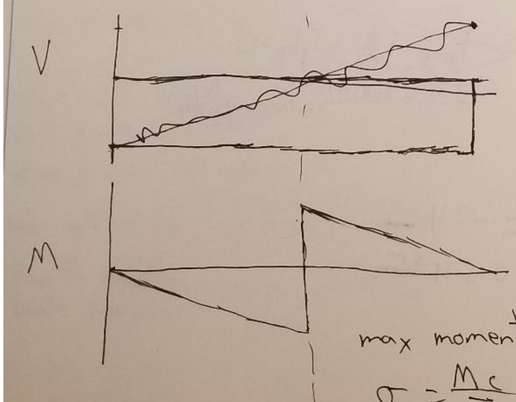
$F_{B_1} = 687\ N \downarrow$

$F_{B_2} = 687\ N \uparrow$

divide by 2 for 2 sides

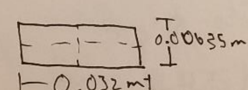
23.35 ~~46.7~~ N-m





max moment = 11.67 N-m

$\sigma_b = \frac{Mc}{I}$



$$\sigma_b = \frac{11.67\ N\text{-}m \cdot \left(\frac{0.00635}{2}\right)}{\frac{1}{12}(0.032^2 + 0.00635^2)}$$

$\sigma_b = 417\ Pa$

σ_y aluminum $\approx 270 \times 10^6\ Pa$

should be good

Appendix I

Design Hazard Checklist

ME 428/429/430 Senior Design Project 2019

DESIGN HAZARD CHECKLIST

Team: SMV Braking 2019 Faculty Coach: Mello

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 (No) 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.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure 4: Design Hazard Checklist, Page 1

Appendix J

Bill of Materials

Note: Please contact our team for further information on listed products.

Rear Brake

Part	Quantity	Cost/Unit	Total Cost	Weight/Unit (g)	Total Weight (g)	Vendor
Magura MT4	1	$64.47	$64.47	290	290	Magura
Spare Brake Lever	1	$16.84	$16.84	N/A	0	Magura
160 mm Brake Rotor	1	$15.54	$15.54	134	134	Magura
Rear Brake Pedal	1	$-	$-	N/A	0	Cal Poly Innovation Sandbox
Rear Caliper Mount	1	$27.93	$27.93	200	200	McMaster-Carr
Rear Caliper Mount Screws	2	$0.75	$1.50	9	18	Home Depot
Rear Brake Caliper Adapter	1	$25.00	$25.00	34	34	Art's Cyclery

Pedal Mount

Part	Quantity	Cost/Unit	Total Cost	Weight/Unit (g)	Total Weight (g)	Vendor
Rear Brake Rod Mount	1	$10.04	$10.04	64	64	McMaster-Carr
Rod Mount Collar	1	$12.92	$12.92	82	82	Amazon
Pedal Mount Plate	1	$21.67	$21.67	124	124	McMaster-Carr
Pedal Mount Plate - Screw	4	$0.59	$2.36	9	36	Home Depot
Pedal Mount Plate - Nut	4	$0.43	$1.70	1	4	Home Depot
Pedal Mount Plate - Washer	4	$0.65	$2.60	0.73	2.92	Home Depot
Front Pedal Mount	1	$27.95	$27.95	100	100	McMaster-Carr
Front Pedal Mount - Screw	2	$0.59	$1.18	9	18	Home Depot
Front Pedal Mount - Nut	2	$0.63	$1.26	1	2	Home Depot
Front Pedal Mount - Washer	2	$0.59	$1.18	0	0	Home Depot

Front Brakes

Part	Quantity	Cost/Unit	Total Cost	Weight/Unit (g)	Total Weight (g)	Vendor
Magura The Big	1	$90.17	$90.17	350	350	Magura
160 mm Brake Rotor	2	$15.54	$31.08	134	268	Magura
Front Brake Pedal	1	$-	$-	N/A	0	Cal Poly Innovation Sandbox
Epoxy	1	$5.77	$5.77	N/A	0	Home Depot

Part Vendor Information

Part	Vendor	Vendor Part Number/SKU	Invoice Number
Magura MT4	Magura	2701633	418506
Spare Brake Lever	Magura	2700529	418506
Magura The Big	Magura	0551238	190960
160 mm Brake Rotor	Magura	2700928	190960
Front Brake Pedal	Cal Poly Innovation Sandbox		
Epoxy	Home Depot		
Rear Brake Pedal	Cal Poly Innovation Sandbox		
Rear Brake Rod Mount	McMaster-Carr	8974K16	
Rod Mount Collar	Amazon		
Pedal Mount Plate	McMaster-Carr	9246K464	
Pedal Mount Plate - Screw	Home Depot		
Pedal Mount Plate - Nut	Home Depot		
Pedal Mount Plate - Washer	Home Depot		
Front Pedal Mount	McMaster-Carr	8975K961	34736905
Front Pedal Mount - Screw	Home Depot		
Front Pedal Mount - Nut	Home Depot		
Front Pedal Mount - Washer	Home Depot		
Rear Caliper Mount	McMaster-Carr	8975K961	36030903
Rear Caliper Mount Screws	Home Depot		
Rear Brake Caliper Adapter	Art's Cyclery		

Appendix K

Part Drawings

Brake Pedal Mount Assembly

Pedal Mount Plate

Master Cylinder Rod Mount

Rod Collar

Brake Lever

Pedal