Baja SAE Brake Pedal

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Client Name: Queen’s University Baja SAE Design Team

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Executive Summary

The purpose of this project was to design a brake pedal for the Queen's Baja SAE team. Baja SAE, a sub-program of SAE International, is a competition that pushes engineering students to build an off-road vehicle to race against other universities through many variable conditions of rough terrain.

The pedal must be lightweight, strong, manufacturable, serviceable, and easy to replace. The pedal must also be able to withstand an applied force of 2000N with a minimum factor of safety (FoS) between 1.5-2.0. The design process for this pedal involved several iterations and ultimately, resulted in three major design concepts.

The first design concept featured a CNC-milled 7075 aluminum pedal assembly cut to the shape of an I-beam along the pedal shaft. It would have a smooth pedal face that uses adhesive grip material and attaches to the pedal arm with two screws and Loctite to keep them in place. The second design concept also used CNC-milled 7075 aluminum; however, rather than an I-beam, it introduced a layer of shallow material removal around triangular cutouts to minimize the mass of the pedal arm. The pedal face is attached with two flush flat-head screws with an abrasive CNC-milled grip pattern as opposed to the adhesive. This design offered more reliable performance in off-road racing conditions. Alternatively, the third design made use of two pieces of 4130 steel tubing, joined by welds with a steel plate pedal. This design allowed for a very strong shaft with very little heavy steel in the design. In addition, the pedal face was knurled to provide a better grip for the driver.

The three design concepts were then compared using a design evaluation matrix that compared them based on key criteria such as material, cost, weight savings, and functionality as seen in **Error! Reference source not found.**. The second design concept was evaluated to be the best of the three design concepts. The primary advantages of the second design concept were the strength-to-weight ratio of 7075 aluminum, the design freedom to create complex designs for weight savings with CNC-milling, and the reasonable pricing of materials and labour.

To further develop this design, several more iterations were made in SolidWorks, using topology optimization and finite element analysis (FEA), to continually improve weight savings while still being able to withstand the 2000N applied force with a minimum FoS objective of 1.5. However, after the design was completed, the static analysis of the assembly found in Figure 19 reported a minimum factor of safety of 3.5. The project scope did not include true physical testing due to limited machine access; however, the FEA figures include the stress, deformation, deflection, and FoS values that theoretically validate the testing requirements under load as discussed in **Error! Reference source not found.**. A model has been 3D printed as a visual demonstration which can be seen in Figure 20, Figure 21, Figure 22, Figure 23, and Figure 24.

The total material cost, including taxes and 1–2-day shipping, accumulated between \$112.24 - \$114.24. A detailed cost breakdown is provided below in Table 1.

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Part 1. Key Information for Clients

1.1 Problem Statement and Scope Definition

The project goal was to create a brake pedal that was light and strong and actuated a master brake cylinder on a Baja Racing Vehicle for the Queen's Baja SAE design team. The pedal body was required to be strong enough to withstand a specified minimum applied force while still being as lightweight as possible. Additionally, it needed to be easily serviceable, replaceable, and provide enough leverage to fully lock up all four wheels at once.

The brake pedal design for the Queen's Baja SAE team had to meet three metrics for optimal performance and safety. Firstly, the design had to actuate the brake master cylinder, creating efficient force transfer from the pedal to the braking system. Secondly, the design was required to withstand an applied force of at least 2000N as it is a test parameter of the competition. Lastly, the design needed to be optimized for minimum weight while maximizing strength, recognizing the importance of weight savings in performance racing. These requirements were demonstrated to be met with a static test of the assembly in SolidWorks of which the figures can be found in **Error! Reference source not found.**. A 1:1 scale prototype was necessary to be included as well.

The stakeholders involved in the design of the brake pedal include Queen's Baja SAE team, Baja SAE International, and Queen's University. Safety is vital for the brake pedal as failure could result in a collision. The entire Baja team put great effort into designing and manufacturing the car's components and brake pedal failure would risk destroying them. Additionally, the SAE International Association is a major stakeholder as it damages its reputation if any competitors get injured during the competition. SAE International also requires that all vehicles used in competition meet the United States Council for Automotive Research (USCAR) standards [1]. SAE International also requires that all vehicles used in competition meet the United States Council for Automotive Research (USCAR) standards [2]. Should any of these standards be outdated, resulting in injury, USCAR may hold responsibility as a stakeholder. Similarly, since Queen's University offers and facilitates the Baja team, its reputation and ability to acquire sponsorships are at risk. As the stakeholders have different priorities, there exist some conflicts of interest among them. The Queen's Baja team aims to reduce weight to perform better, whereas SAE International has implemented safety restrictions that increase vehicle mass to reduce liability. To address the conflicting interests of the two parties, FEA and topology optimization was performed on the model to achieve the highest possible strength-to-weight ratio, satisfying both requirements.

The brake pedal needed to be designed with the Queen's Baja Team's constraints in mind. This primarily included cost, and material use, as well as conforming to the allotted timeline and optimizing the part for manufacturability. The prototype was required to range from six to eight inches in length, with the pedal arm not being wider than the face of the pedal. The pedal must have also been made of steel or aluminum, as outlined by the Baja SAE rules [1]. Finally, the product had to be designed with ease of production and minimal cost in mind due to limited funding, as well as being completed by the end of Week 12 of APSC 103.

The brake pedal needed to withstand the minimum 2000N of applied force as stated earlier, in addition to being compatible with the current Baja vehicle pedal box area and the master cylinder to transfer the force from the pedal into the braking system. The pedal needed to have enough leverage for the force applied by the driver to lock all four wheels when at speed. These requirements were all necessary for the pedal to function safely and effectively while the vehicle was in use.

A brake pedal design has been created for the Queen's Baja SAE team that can actuate the brake master cylinder, withstand forces imparted by the driver, and was optimized for a maximized strength-to-weight ratio. The team has used their experience with CAD modelling within SolidWorks to develop a CAD model of the final design. This model will be presented to the client. Time constraints faced by the team include at least five hours per week dedicated to the project and completion by Week 12. The model has been 3D printed as making a 1:1 scale prototype using materials such as 7075 aluminum or steel would have been too expensive and time-consuming. With the timeline being close to four months for the project, the scope of creating a conceptual brake pedal design for the Queen's Baja SAE team was achievable between the time of the proposal presentation and the end of the Queen's University winter semester.

1.2 Background Information

1.2.1 SolidWorks FEA and Topology Optimization Guides

This project heavily involved the use of SolidWorks for creating brake pedal design models, specifically for strength and weight optimization. "Topology Study" by Dassault Systems provides step-by-step instructions for how to correctly use topology optimization in SolidWorks to optimize parts in terms of strength, weight, and materials. Each step of the optimization process is explained in detail, highlighting the purpose of each setting as well as where the icons can be found within the SolidWorks 2022 application [3]. Alongside the actual optimization of the model, it is important to check if the part still meets the strength requirements by using finite element analysis (FEA). A published document from West Virginia University walks the user through the process of using the SolidWorks simulation tool to perform a finite element analysis on a part [4]. If the FEA analysis is to provide accurate results, the process of meshing, assigning boundary nodes, choosing constraint types and their corresponding behaviours, as well as the ability to properly view and understand the results of the analysis must be well understood and completed in accordance with the dimensionality and shape of the part in mind. Once the initial FEA calculations are completed, the meshes must be refined to get a more accurate model of the part and therefore, achieve more precision in the final solution. Both sources will be crucial to producing an optimized brake pedal design.

1.2.2 Pedal Ergonomics and Implementation

Many aspects must be considered in the design process of a brake pedal. While not as obvious as material and weight, ergonomics play a huge role in the functionality of the pedal. The specific use of the pedal largely determines the parameters for the pedal position and shape. An article by the Texas Transportation Institute outlines various pedal types and recommended parameters for both accelerator and brake pedals. The shape of the pedal is often designed to adhere to certain human anatomy features such as the articulation of the ankle or toes, as well as a natural resting position for the heel. If the pedal is too short, or the pedal face is too small, it could ultimately hinder the ability of the driver to control the vehicle [5]. Similarly, "Design and Analysis of Composite Brake Pedal: An Ergonomic Approach" provides a good general analysis of ergonomic brake pedal implementation. While this source is not specific to this project, it still provides valuable insight into the impact that the structure of the control arm has on the braking system. This is primarily done through the demonstration of mass, volume, deformation, and stress on four different concepts of pedal arms, concluding that the I-beam concept is the most optimal. The I-beam is not necessarily the best design for this application, as the paper does not consider the weight of the design, an important consideration in competition vehicles [6]. Optimal pedal placement and adjustability are largely dependent on the mounting mechanism for the pedal arm. "Design and Analysis of Brake and Gas Pedal" discusses the operation and purpose of brake and gas pedals as well as the advantages and disadvantages of different mounting mechanisms. Some other design requirements that should be considered are the size, weight, safety, environment, pedal ratio, and balance due to their influence on both the driver and the functionality of the vehicle [7]. This information will be used for inspiration to mount the Baja brake pedal; however, the ergonomics in a Baja vehicle slightly differ from a conventional car due to the placement of the pedals requiring that the driver use both feet: one for the brake and the other for the acceleration, while conventional cars are often designed to only require the use of one-foot switching between the two pedals.

1.2.3 Baja and Racing-Specific Information

While much of the brake pedal design process is not unique to racing, it is also important to account for the unique conditions that a Baja racing brake pedal may experience. "Race Car Brake Pedal Study" includes a study of the brake pedal components, the data acquisition process, modelling, optimization, and manufacturing. Most competitive car teams have the same priorities such as cost-effectiveness, weight reduction, and strength, and as such the information from the article will be used to guide the design process. When it comes to the pedal arm, the article reflects on the importance that symmetry in the part may have on deformation, as well as the differing wall thicknesses for different sections of the arm [8]. Another very pertinent source for this project was "Force Analysis and Optimization of BSC Brake Pedal Based on ANSYS" from IOP Science from the Journal of Physics, which references the Baja China-SAE (BSC) rules which shares the same requirement with this project that the brake pedal must withstand 2000N of applied force. This publication covers pedal simulation optimization with 4130 steel and 7075 aviation aluminum, ultimately concluding that the aluminum provides the most benefits between the two due to the model's lower weight while still meeting the same work requirements [9]. As these are the two material options for the Queen's Baja racing team, the data will ultimately provide the information necessary to select the best material for the pedal.

1.2.4 Brake Pedal Mechanics

It is crucial to understand the mechanism of a brake pedal including the interaction of each component with one another. "Rapid Manufacturing of an Automotive Brake Pedal" discusses the manufacturing of a brake pedal, detailing the manufacturing, automotive components, and methodology behind it. The pedal bracket serves as the mounting point for the brake pedal assembly. It features a pit at its base for connecting the brake pedal to the brake pump. The pedal accelerator and brake pedal are positioned on the pedal bracket to establish their locations. The brake pedal functions as the interface for the driver to initiate braking. Its main part, the arm brake, is a substantial metal piece forming the pedal's core. A nut and bolt secure this connection [10]. Additionally, this source features a design like that of 2.1.3 Steel Tubing which was useful in the decision-making process for this project.

The mathematical modelling of a brake pedal is necessary to ensure that the pedal does not fail during use. The primary models that will be used are stress and strain models, which are used to analyze the stress and strain through the pedal giving insights into possible failure points, areas where material can be removed, and if the stress and strain are within their allowable range. These models can be produced using design software such as SolidWorks or ANSYS. Some equations can be used to determine the maximum allowable stress on the pedal [11]. While the equations often use simplified versions of the model due to the more complex shapes of some finalized designs, they will still be useful for this project during the initial stages of theoretical design testing to ensure that the Baja brake pedal will meet the leverage and strength requirements.

1.2.5 Brake Pedal Optimization and Analysis

While it is important to learn how to effectively use CAD to optimize a model to meet your desired requirements, it is equally important to take inspiration from others' trials. An article from the International Research Journal of Engineering and Technology (IRJET) covers topology optimization, specifically, the removal of excess mass from a brake pedal without compromising its functionality or strength. It highlights multiple methodologies including discrete, continuous variables, and commercial software as well as the basic functionality, physics, and mechanics of a brake pedal. SolidWorks can be used for both modelling and FEA simulation of a static brake pedal, for which boundary conditions can be set that allows the measurement of the stress and deformation experienced by the part both before and after topology optimization [12]. This IRJET article is useful for this project as instead of having to test various cut-out shapes for weight savings and then run it through FEA each time, it has already compared each approach with summarized mathematical figures.

1.3 Design Solution

The finalized 7075 aluminum design has both the pedal arm and pedal face being CNC-milled independently from each other but from the same block of aluminum (refer to Figure 8). The general structure of the arm is a straight bar with about a 150-degree curve near the pedal face interface. The weight optimization involves shallow cut-outs that are made alongside the triangular through-cut-outs to maximize weight removal without compromising the fundamental strength of the pedal arm. The stress analysis from the static test in FEA on the pedal assembly can be seen in Figure 2. The pedal face is rounded with a jagged grip pattern integrated into the face itself as illustrated in Figure 4, and Figure 5. A rounded face is a more common design for pedals in competition racing due to the ergonomic design that provides more grip and comfort for the driver, allowing for the foot to slide across the pedal naturally as the pedal arm goes through its travel. The grip pattern lowers the maintenance necessities for the brake pedal, due to the use of a CNC-integrated grip would be more durable and would not require replacement as often as a face made of rubber.

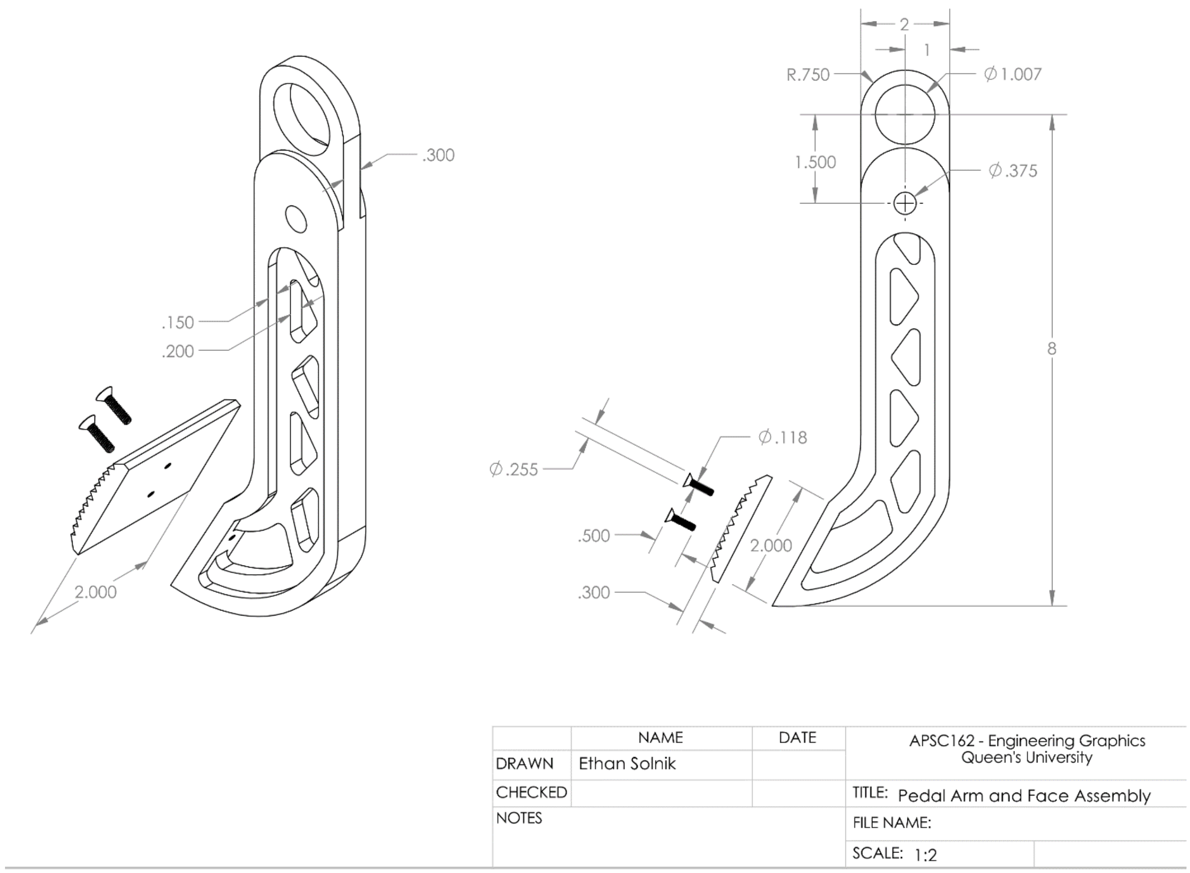

Figure 1: SolidWorks Drawing of Final Pedal Assembly Design

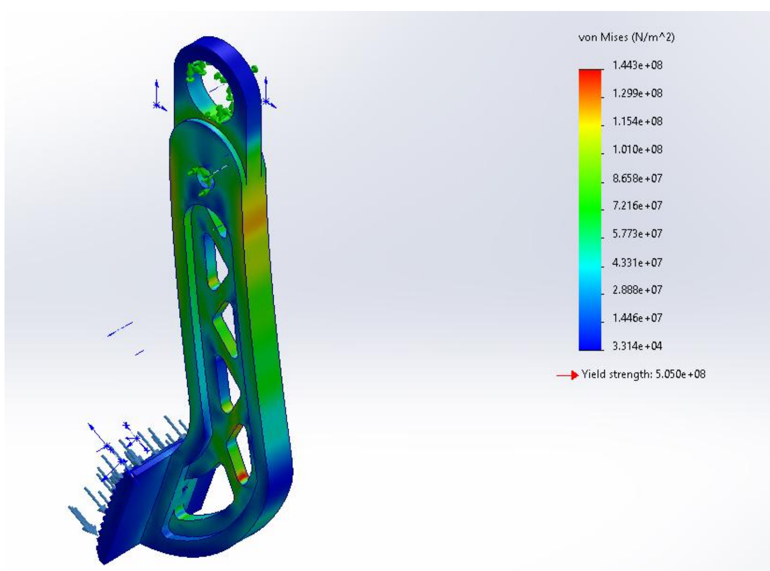

Figure 2: Von Mises Stress from Finite Element Analysis (Min = 3.314e+04N/m^2 | Max = 1.443e+08N/m^2)

Figure 3: Photograph of 3d printed pedal shaft.

Figure 4: Photograph of 3d printed pedal face with the grip pattern and bolt holes.

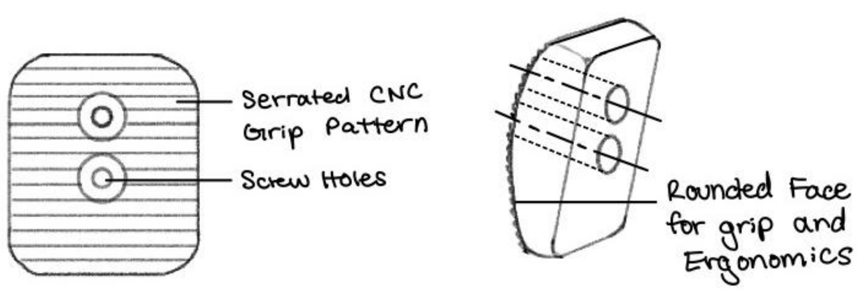

Figure 5: Sketches for revised Aluminum V2 with a CNC milled grip pattern instead of a smooth surface with adhered grip.

1.3.1 Design Proposal

The 2.1.2 Aluminum Version 2 pedal was designed to be constructed from 7075 aluminum, using a CNC machine to achieve a creative weight and stiffness-optimized design. Material removal included widespread shallow cuts and triangular through-cuts in the central part of the pedal arm. The exact locations of the cutouts were initially guessed, and then using topology optimization, adjusted to have more material where the pedal arm experienced more stress and strain, and less material in less critical places. The last topology study can be found in Figure 12 in Appendix III: SolidWorks Figures.

The resources that were necessary to produce the final product were split into 4 different sections: material requirements, software requirements, tools and machinery, and finally, labour time and assembly.

Table 1: Parts/Materials and Cost Breakdown

Parts:	Price	Shipping
High-Strength 7075 Aluminium Bar (1/2" Thick x 3" Wide x 1' Long)	$103.45	$6 - 8 (1-2 days)
316 Stainless Steel Hex Drive Flat Head Screw (82 Degree Countersink Angle, 4-40 Thread Size, 1/2" Long)	$2.79	
Total (+ Shipping)	$112.24 - 114.24	

*Prices from McMaster-Carr

The materials required for the product are a 0.5x3.0x12 inch 7075 aluminum block that the part will be CNC-milled from. One block should be used for this, one section for the pedal arm and the other for the pedal face. Less material will be lost by using one 12" block separated into two sections as the blocks are sold in larger lengths that would result in excess material if purchased. The only other material requirement for the final product is the screws that will be used to mount the face to the arm. The size of the screws is 82 Degree Countersink Angle, 4-40 Thread Size, 1/2" Long, using Loctite to ensure that the screws do not come loose during pedal operation.

The main software requirement for this was SolidWorks 2022/2023. SolidWorks was used to entirely model the pedal, for topology optimization, and finite element analysis, and is also compatible with the CNC machine to produce the final product. The results from the topology studies can be found in Appendix III: SolidWorks Figures. These include the mesh settings in Figure 11, the hinge and force parameters in Figure 11: Mesh network for topology optimization of final design before stiffness and weight optimization.respectively, as well as the displacement, strain, and minimum factor of safety in Figure 17, Figure 18, and Figure 19 respectively.

As such, no other programs were required; however, Mastercam may be used instead of SolidWorks for the machining due to the greater simplicity of the CNC milling functionality.

For tools and machinery, the primary necessity is a CNC machine, as it would be used to remove material, cut out the main shape of the pedal, and tap screw holes. In addition, minor adjustments might be required such as smoothing out sharp edges or altering the through holes using angle grinders or drills.

Finally, the physical labour requirements to produce the brake pedal would be minimal as most of the construction would be via machine and any subsequent adjustments that may be necessary should take a relatively short amount of time to complete. This ultimately brings the labour costs for the pedal to approximately 2 or 3 hours when considering the machine time, adjustments, and installation.

Decommissioning a 7075-aluminum brake pedal involves the safe removal from the vehicle and environmentally friendly drainage of brake fluid. To facilitate recycling, the aluminum pedal should be separated from any materials such as bushings, and gaskets, and stripped of any toxic lubricants. The team would contact local recycling facilities for proper aluminum recycling, considering the alloy type. Dispose of non-metal components according to local regulations, accounting for any hazardous materials. Maintain documentation of the decommissioning process, adhering to local waste disposal guidelines and choosing an appropriate disposal site. Seek professional assistance if needed, ensuring compliance with environmental regulations for the responsible and eco-friendly decommissioning of the brake pedal.

1.3.2 Modeling, Analysis, Testing and Evaluation

As stated in the problem definition, the brake pedal had to fulfill several key requirements. It had to withstand a force of 2000N applied to the pedal face which was evaluated using SolidWorks FEA. In addition, the brake pedal needed to stay within specific size ranges i.e. 6-8 inches in length and a minimum of 0.5 inches in width, with the pedal face being as wider or wider than the pedal arm.

The process of modelling this design began with creating detailed sketches for the shape, mechanism, and dimensions of the brake pedal assembly. Initial mathematical modelling of the pedal was done by hand, using equations for simplified shapes such as a comparable aluminum beam, to estimate stress, strain, and deflection figures given the 2000N applied force and a fixed hinge. These calculations were used for general design guidelines before finalizing dimensions in the SolidWorks modelling. Once all dimensions were finalized for the mounting and pivot points, topology optimization was used to locate the least critical areas of the pedal arm to remove mass while maintaining its strength. Finite element analysis was then used to test, analyze, and ultimately iterate the design until optimal. Table 4: Volumetric and material properties of the pedal arm and pedal face assembly provides all volumetric and material figures for the final SolidWorks assembly, including the material of each component. The supposed mass for the fully constructed pedal is 0.18kg.

Physical testing will not be possible due to the scope of the project. As stated, the time allotted was not enough to create a true material prototype and thus will be unable to conduct any physical testing. A 3D printed model was however produced as a visual representation.

A detailed testing and analysis rubric can be found in Table 8Table 8: Testing and Analysis Rubric.

1.4 Conclusions

The objective of this project was to create a strong and lightweight brake pedal for the Queen's Baja SAE team that is safe, easily manufacturable, serviceable, and replaceable. To do so, three conceptual design solutions were developed. The first idea was to use a block of 7075 aluminum and CNC mill the pedal arm and pedal face separately. The pedal face and arm would be connected via two screws. For weight reduction, this design would feature a series of circular cut-outs along the pedal arm (refer to Figure 6). The pedal face would have a smooth surface, and an adhesive grip pad would be used (refer to Figure 7). The next design idea was to use the same CNC-milled 7075 aluminum; however, for weight reduction, there would be shallow material removal surrounding either rectangular or circular cut-outs to maximize weight savings while still maintaining strength (refer to **Error! Reference source not found.**). Additionally, this design would feature a CNC-milled grip pattern on the pedal face as opposed to a smooth surface (refer to **Error! Reference source not found.**). The third design idea was to use two pieces of 4130 steel tubing, welded together with a steel plate pedal. The split pedal shaft (refer to **Error! Reference source not found.**, allows for a strong shaft design that will not deform under load while using minimal amounts of relatively heavy steel for maximum weight reduction. The pedal face features a knurled pattern to give the pedal a grip on the face (refer to Figure 10).

To choose which design was the best to move forward with, an evaluation matrix was created to compare each idea based on the key criteria for this project. This evaluation matrix compares each design based on its material, cost, weight savings, pedal face, and pedal arm, and then assigns an overall grade. After evaluating each design based on this set of criteria, it was determined that the second design option, 2.1.2 Aluminum Version 2, would be the best fit for Baja racing. The advantages to this design concept include the choice of 7075 aluminum for the material as it is much lighter than 4130 steel tubing and can still adequately withstand the 2000N of applied force with a factor of safety between 1.5-2.0 after being optimized for weight savings. Additionally, due to aluminum's lower density, it is more machinable, and therefore, costs less to CNC. With the alternative being steel tubing and tig welding, CNC machining can create complex patterns that minimize mass and maximize strength. Welds can act as weak points and steel tubing doesn't allow for as much design creativity. 7075 aluminum is also highly corrosion-resistant, whereas 4130 steel tubing is not. The brake pedal will be exposed to a lot of water and mud making this a desirable property of 7075 aluminum. However, 7075 aluminum is considerably more expensive, softer, and more prone to cracking than its steel alternative.

The process of modelling this design began with creating detailed sketches for the shape, mechanism, and dimensions of the brake pedal arm and face separately. The next step is to start creating models in SolidWorks with the proper dimensions for the pedal arm, pivot point, and mounting point. The model will then undergo topology optimization with the finalized dimensions to locate where weight savings can be made. Using finite element analysis, each iteration will be compared to decide which design is sufficient for the use of Baja racing while meeting the 2000N requirement and being as lightweight as possible. As stated previously, due to the scope of this project, physical testing will not be possible as a true physical model will not be produced. However, there will be testing using finite element analysis to prove that, in theory, the pedal would withstand the 2000N of applied force with a factor of safety of between 1.5 and 2.0 [9].

The materials that will be required to build this pedal include a 0.5x3.0x12 inch 7075 aluminum block as well as 2 flat head screws with an 82-degree countersink angle, 4-40 thread Size, and 1/2" long flat head; however, as previously mentioned, the screw size may be subject to change. These parts accumulate to between $112.24 - 114.24 including taxes and 1–2-day ground shipping (refer to Table 1: Parts/Materials and Cost Breakdown).

Through finite element analysis testing in SolidWorks, it was determined that the design was successful at meeting the design criteria. The pedal fits within the required physical design dimensions while maintaining a factor of safety of 3.5 (FoS), minimal deformation, and being lightweight. However, the design could have room for further optimization based on certain case-specific priorities. Referring to Figure 12, there is still some mass that has the potential to be removed. However, this mass would come at the expense of lowering the factor of safety closer to the minimum of 1.5-2. If the goal was to create the most lightweight possible pedal, one could analyze the stress and strain figures (Figure 2 and Figure 18 respectively) to locate areas of high stress and strain and add mass to these sections. This would better distribute the internal forces, allowing for extra mass to be removed in the non-critical locations. At this point, the design would be re-evaluated to decide whether the modified model would result in a better stiffness-to-weight ratio before proceeding.

While extensive simulative tests were performed on the design in SolidWorks, the design would have greatly benefited from experimental tests on a physical prototype; however, this was not within the scope of this project. Instead, only a 3D printed visual representation is possible, which would not replicate 7075 aluminum in a performance aspect. Subsequently, testing pedal ergonomics was also out of the scope of this project. Therefore, developing tests that can evaluate pedal ergonomics as well as gathering feedback from drivers would be another next step in developing and optimizing the pedal design.

Part 2: Technical Information

2.1 Conceptual Design Solutions

2.1.1 Aluminum Version 1

The CNC-milled pedal face and arm are crafted from 7075 Aluminum, chosen for its strength-to-weight ratio. The design uses an I-beam-inspired design for a strong but less bulky design structure as seen in Figure 5. The flat pedal face serves as a base and platform for mounting a rubber grip pad or similar textured material, prioritizing optimal contact and traction with the user's footwear. The pedal face as shown below in Figure 7 would be connected to the arm using 2 screws. Weight reduction is achieved through CNC-milling an I-beam shape to remove excess mass without compromising strength. Potential disadvantages include the cost associated with CNC milling and the use of premium materials. However, replicability due to a simplified assembly process may offset these initial costs. In summary, the CNC-milled pedal design prioritizes strength but lacks creativity in weight reduction and incurs greater costs due to the usage and milling of premium materials.

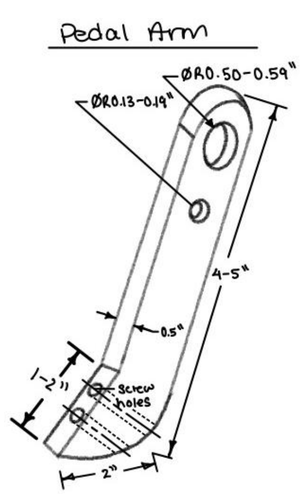

Figure 6: Sketches for Aluminum V1 showing general pedal arm design, and critical points.

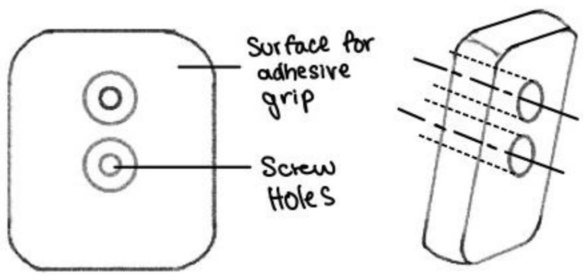

Figure 7: Sketches for Aluminum V1 pedal face with the proposed mounting mechanism. Features a smooth pedal face for an adhesive grip material.

2.1.2 Aluminum Version 2

The second 7075 aluminum design features much greater weight savings and ergonomics, with both the pedal arm and pedal face being CNC-milled from a block of 7075 aluminum. The general I-beam structure of the arm is shared with V1; however, most of the benefits result from a much more complex mass removal design and longevity. The use of FEA and topology optimization allows for the removal of mass from sections of the pedal area which do not experience great load during operation. This means that shallow cutouts were able to be made along semi-critical sections with through-cut holes to remove as much mass as possible where it would not compromise the strength. The last topology study that was performed before the final model was reached can be found in Figure 12. The second major benefit was the addition of a rounded pedal face with a CNC grip pattern integrated into the face itself as was shown in Figure 5. The rounded face is a more common design for pedals in competition racing due to the ergonomic design that provides more grip and comfort for the driver. The grip pattern also lowers the maintenance necessities for the brake pedal, as using a CNC-integrated grip would be more durable and would not require replacement as often as a face made of rubber.

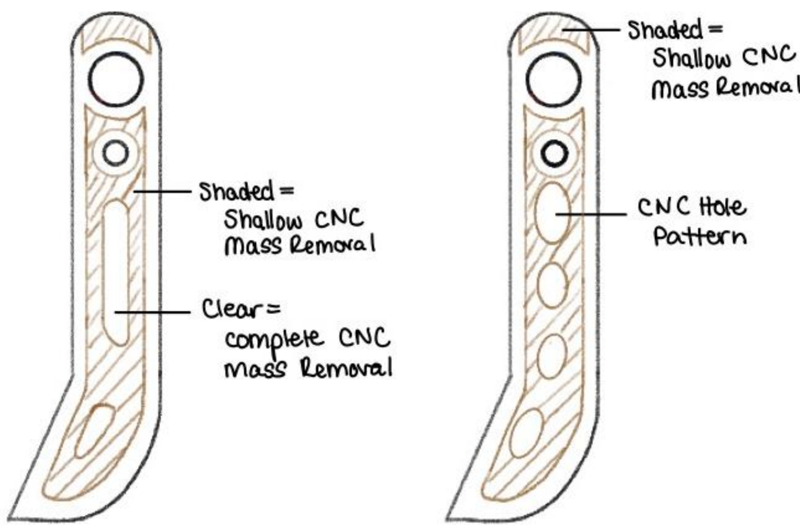

Figure 8: Sketches for revised Aluminum V2 with alternative weight savings approach. Features a CNC milled pattern with the addition of shallow material removal in addition to holes.

2.1.3 Steel Tubing

The steel tube pedal design features a pedal shaft crafted out of 4130 steel tubing and a pedal face made of 4340 steel plate. The design would utilize a main, lower tube shaft that spans from the mounting location with the master cylinder to the pedal face. The upper support bar would be welded from the bottom of the lower shaft to the upper half of the lower shaft to limit deflection in the lower shaft during operation. This shaft design creates a strong shaft out of a minimal material. A sketch of this can be found in Figure 9. This helps to offset the large density of 4130 steel tubing, making it an effective material. The pedal face consists of a steel plate that has been knurled to create a grip and then curved outwards slightly for ergonomics. The pedal face is attached to the lower shaft using TIG welds which are also used at joint locations to create a strong, rigid bond between surfaces. Sketches for the pedal face and weld locations can be found below in Figure 10. Advantages of this design include a lack of wasted material compared to CNC methods, strength due to tubular design and being made from 4130 steel, and design flexibility due to the pedal being attached on rather than integrated into the shaft. One of the designs' main disadvantages is the need to have a skilled welder to create effective TIG welds. The design is also more labour-intensive to manufacture compared to CNC manufacturing.

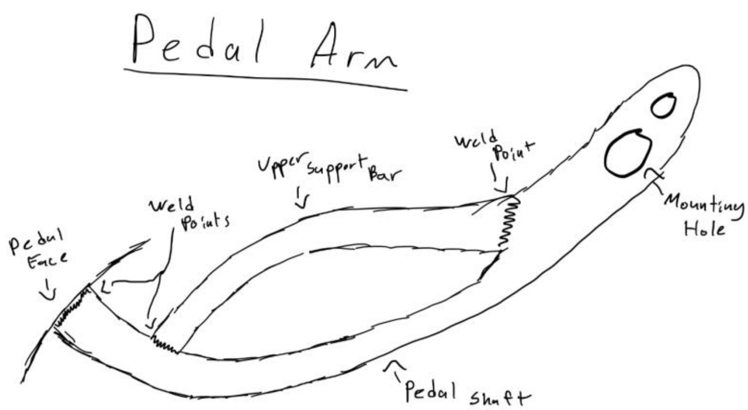

Figure 9: Sketches for Steel Tube general design.

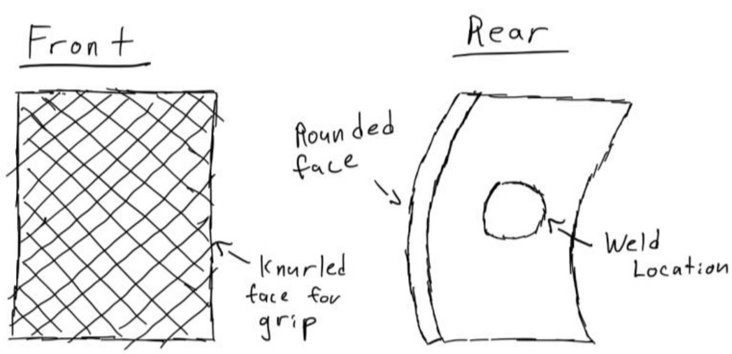

Figure 10: Sketches for welded steel design pedal face.

2.2 Decision Making

A detailed comparison and evaluation matrix for the three previously described design solutions can be found in Appendix VI: Design Evaluation Matrix. This evaluation matrix compared each design based on its material, cost, weight savings, pedal face, and pedal arm, and then assigned it an overall grade with the highest grade deemed the best design solution. After evaluating each design based on this set of criteria, it was determined that the second design option, 2.1.2 Aluminum Version 2, would be the best fit for the Queen's Baja Racing team.

2.3 Implementation

The procedure that was employed for this project began with general research into past brake pedal and BAJA vehicle models. Many of the articles and papers that were utilized included experiments or investigations into parameters that may be useful in designing this year's Queen's BAJA pedal. Additional information was also gathered from the BAJA team regarding the possible dimensions and the available machines for the manufacturing process. Following this, three design iterations were created using the constraints provided by the BAJA team as well as using the information gained through the research. To make the correct decision on which iteration to pursue the final design, an evaluation matrix, as seen in Table 7: Design Evaluation Matrix, was used to evaluate material, manufacturability, cost, pedal face, weight savings, and arm design. Each design was scored on a scale of 0 to 60, which ultimately led to the conclusion that the second design iteration would be the most effective solution. Once the base design had been chosen and modelled in SolidWorks, several series of tests were used to ensure that the design met the required factor of safety under the load of 2000N. This allowed any required changes to be made and ultimately produced the stress, strain, displacement, and factor of safety figures references for the final design.

One of the primary changes that was made in the design originally proposed in the Phase 3 report was the alteration of the structure of the pedal arm. This came in the form of mass reduction sections that passed through the side of the arm. In the original sketches from Phase 3, the holes were designed to be rectangular. This was mainly due to the prior research that was done in which several other articles demonstrated their models using circular and rectangular cutouts. While testing the prototype in SolidWorks however, it was decided that the triangular cutouts as seen in Figure 13: Mass and stiffness optimized SolidWorks assembly with parameters for finite element analysis. would produce a more optimal strength-to-weight ratio that would best align with the necessities of the Queen's BAJA team.

While there were no constraints directly from the BAJA team regarding the environmental impact of the pedal, Queen's University itself has policies regarding environmental protection. As such, the environmental impacts of the material were a major consideration when making the final design decision. Due to the BAJA SAE rules and regulations, the design was limited to what materials could be used for the brake pedal. Ultimately, 7075 aluminum was chosen due to its lightweight nature while still producing a safe and durable pedal, as well as its ease of recyclability compared to steel. Both materials can be recycled indefinitely; however, the process of melting and recycling aluminum requires less energy and thus makes it safer for the environment as fossil fuels are often used in the melting process.

To finalize the design, several different SolidWorks simulations were used. This included using FEA to simulate the static behaviour of the pedal under the 2000N, which provided stress, strain, displacement, and factor of safety as seen in **Error! Reference source not found.**, Figure 17: Resultant Displacement from Finite Element Analysis (Min = 0.000mm | Max = 1.507mm), Figure 18: Equivalent Strain from Finite Element Analysis (Min = 6.016e-06 | Max = 1.642e-03) and Figure 19: Factor of Safety from Finite Element Analysis (Min = 3.500 | Max = 1.542e+04) respectively. While these figures demonstrate the precise data for the final model, simplified calculations were performed by hand to better understand the fundamental stresses that the part would undergo to estimate if the design would align with the constraints and functional requirements. These figures and values ultimately show that the design would function per the BAJA team's requirements and is a viable solution to the problem that was presented.

The final aspect of the pedal's implementation is its incorporation into the actual vehicle and ensuring that it will function within its surroundings. The measurements made in the initial design process for the mounting holes were done using information from the client so that the pedal would be able to mount to both the chassis and the master cylinder without any issues. The pedal measurements were also made to fit within the BAJA vehicle's pedal box using the dimensions that were provided. This ultimately ensures that the pedal is not only strong enough to withstand the forces required by the BAJA team but also that it will function properly within the vehicle once it is implemented.

2.4 Project Plan

Refer to Appendix V: Gantt Chart for a detailed project timeline breakdown.

CAD software such as SolidWorks was required to design and create virtual preliminary pedal designs. This software was critical to creating potential designs to propose for Phase 3 and the final design for Phase 4. Structural analysis modelling software was used to test and evaluate potential designs for deflection, stress, and failure points. The simulation was all performed within SolidWorks. The prototype has been 3D printed and pictures can be found in Figure 20, Figure 21, Figure 22, Figure 23, and Figure 24. The printing was outsourced to another student with a 3D printer.

A breakdown of each team member's contributions to this deliverable can be found in Table 2: Individual Responsibilities This table indicates which person completed which component of Phase 4 and how much time was spent. Additionally, Table 6: Gantt Chart for Project Deliverables and Individual Tasks is a Gantt chart that tracks the status of all components of each deliverable, who was responsible, its extent of completion, when it was started, when it is due, and when it was actually completed.

If the team were to attempt this project again, a very similar approach would have been taken regarding the distribution of work, timeline organization, and time dedication. However, ideally, a physical prototype would have been within the project scope using the actual material proposed and not a replacement for visual representation. Stronger communication and coordination between team members for timing the completion of certain tasks would also be a potential improvement. Otherwise, the team was timely and kept track of which tasks were complete, and which required more work or improvement. All progress has been documented throughout this project and can be found in the Gantt chart as well as the individual contribution tables in each Phase deliverable.

2.5 Financial Analysis

The financial analysis of the 3D-printed model Baja brake pedal reveals a simple cost structure. Through a $100 budget financed by the team, the cost of the model brake pedal was achieved nearly within budget. With 17 meters of filament utilized and the brake pedal weighing 0.07 kilograms, the total cost of filament, priced at $30 per kilogram, amounts to $2.10. Other production expenses such as electricity and equipment maintenance are negligible, therefore the total production cost aligns with the filament cost, totalling $2.10.

The implementation of the brake pedal solution for the Baja racing team incurs material and shipping costs ranging from $112.24 to $114.24, using a high-strength 7075 aluminum bar and 316 Stainless Steel

Hex Drive Flat Head Screws. Financial benefits for the team primarily revolve around production costs and replicability, with potential advantages in streamlined manufacturing processes, reduced maintenance expenses, and improved component reliability over time. By prioritizing durability and reliability in design, the brake pedal aims to extend its lifecycle, further reducing environmental impact. The labour requirements to produce the brake pedal are very minimal. The pedal will be produced using a machine and minor adjustments that may be necessary should take a short amount of time to complete. This brings the labour costs for the pedal to approximately 2 or 3 hours when considering adjustments and installation of the pedal into the vehicle, as well as a safe process for those involved in the manual labour. Overall, the premium materials used in the brake pedal solution augment the price but should be balanced by the component reliability and replicability over time.

2.6 Evaluation

To evaluate the design, a series of static tests were performed in SolidWorks Simulation, all using a 2000N normal load applied to the pedal face, the pivot point set as a fixed hinge, and the master-cylinder mount set as fixed geometry. A factor of safety (FoS) of 3.5 was determined to be the minimum for the design. Using the yield strength of 7075 aluminum of 505 MPa, the maximum allowable stress can be determined with the equation: $\sigma_{Max} = \frac{\sigma_{Yield}}{FOS}$. Referring to the Von Mises stress test (Figure 2), the maximum allowable stress at any given point is about 144 MPa. Using the formula $FoS = \frac{\sigma_{Yield}}{\sigma_{Allowable}}$, it is found that the rough FoS is 3.507 which agrees with the SolidWorks Simulation value of 3.5 as shown in Figure 19. The maximum deflection of the pedal was determined using a deflection test using FEA. According to Figure 17, the maximum deflection was determined to be about 1.5mm. This deflection is small enough that it is negligible, meaning the pedal bends an allowable amount when under load. These applied force tests prove that the pedal design can withstand the required physical load while maintaining the required design integrity and safety. An area for improvement would be reducing the strain in the most critical points on the pedal. In the strain test (Figure 2), there was a region on the upper shaft that incurred a much larger stress than the rest of the pedal. This prevents extra material from being removed from this area. So, if the stress were to be reduced here, less material could be used elsewhere, possibly resulting in an overall more lightweight design. These optimizations likely would need to come at the expense of another specification such as the FoS or maximum allowable stress.

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Appendix I: Individual Tasks

Table 2: Individual Responsibilities

Task	Description of Activity	Activity Duration	Individual Responsible
SolidWorks FEA, Topology Study and Figures	All SolidWorks iterations and creation of figures for the final pedal	3-4 hr	Ethan Solnik
Sketches for V3	Creating detailed sketches for the steel pedal design	0.5 hr	Evan Gibson
Information Summary Updates	Updating and condensing the information summary based on feedback from Phase 3	1.5 hr	Gabriel Munante
Background Information Writing	General content writing	3hr	Group
Design Solution Writing	Updating design solutions to fit PM edits	1.5hr	Group
Modeling, Analysis, Testing and Evaluation	Updating appendices for analysis and testing	1 hr	Group
Updating PM revisions.	Updating bulk of writing from PM feedback + fixing tenses in writing, updating and implementing new figures, and Gantt Chart	2.5 hr	Ethan Solnik
Conclusion	Updating conclusions and putting them into section 1.4	1.5 hr	Evan Gibson
Implementation	Writing the implementation section of the phase 4 report and amending it with PM feedback	2 hr	Gabriel Munante
Project Plan	Updating project plan	30 min	Ethan Solnik
Financial Analysis	Provide analysis of costs and financial benefits for the brake pedal. Analyse prototype and recommendation design.	2 hr	Kiefer Olthafer
Editing the report	Editing and cutting down the report for concision and clarity.	3 hr	Ethan + Group
Evaluation	Writing the 2.6 evaluation	2 hr	Evan Gibson

Appendix II: Deliverables Timeline

Table 3: Deliverables Timeline

*Refer to Appendix V: Gantt Chart for a more detailed schedule.

Deliverable	**Due Date**	**Projected Team Timeline**	**Actual Timeline**
Phase 4: Final Project Report	04/01/24	3/26/24	03/29/24
Phase 5: Post-Project Audit	3/25/24	3/23/24	TBD
Final Presentation	Exam Period	TBD	TBD

Appendix III: SolidWorks Figures

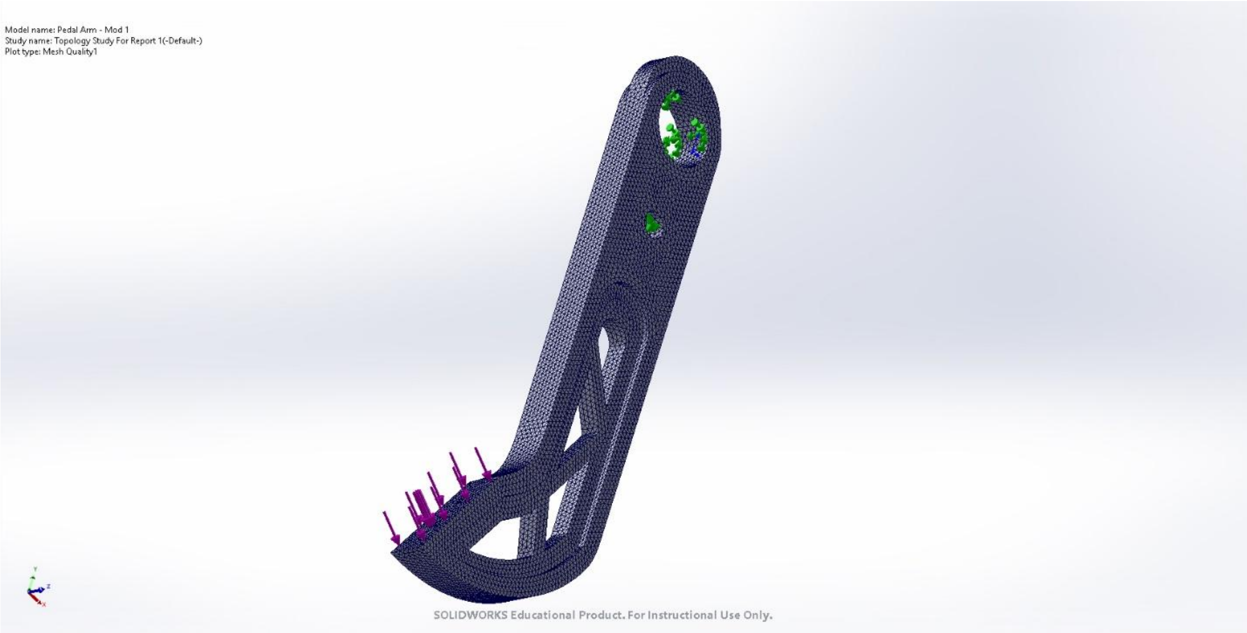


Figure 11: Mesh network for topology optimization of final design before stiffness and weight optimization.

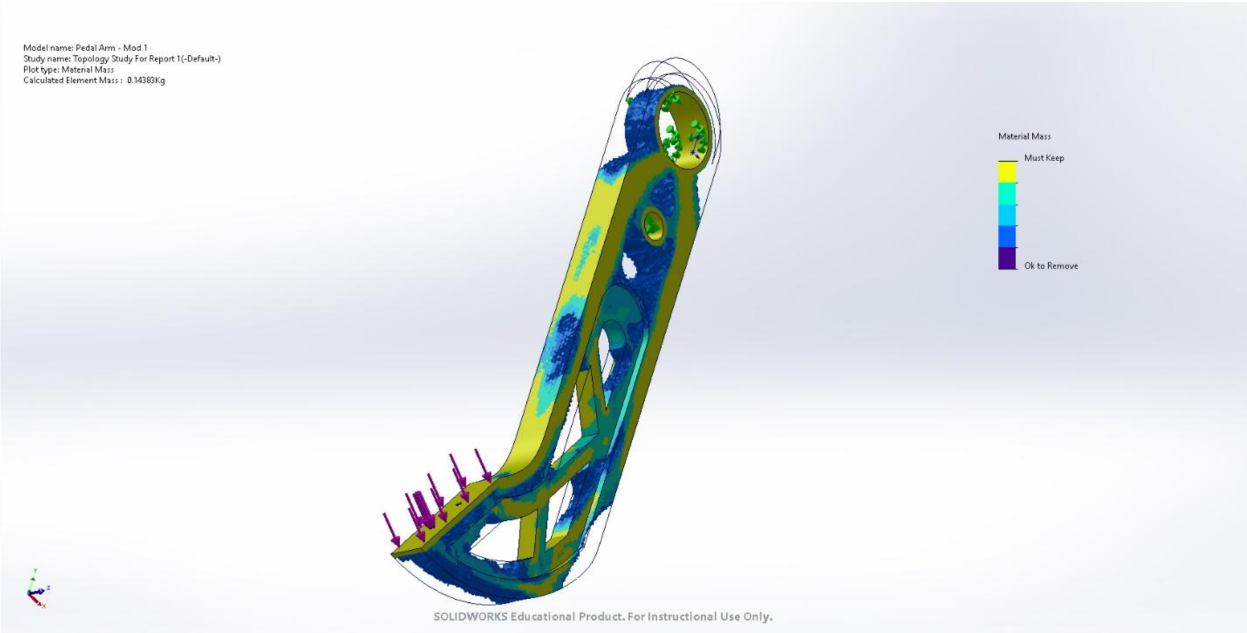


Figure 12: Topology-optimized design to find locations where the final design can be optimized for lower mass without compromising strength.

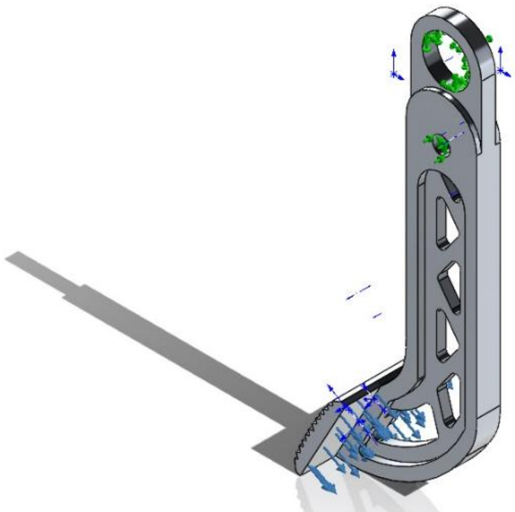


Figure 13: Mass and stiffness optimized SolidWorks assembly with parameters for finite element analysis.

Table 4: Volumetric and material properties of the pedal arm and pedal face assembly

Volumetric Properties		Material Properties	
Mass:	0.181561 kg	**Name:**	7075-T6 (SN)
Volume:	6.46129e-05 m^3	**Model type:**	Linear Elastic Isotropic
Density:	2,809.98 kg/m^3	**Default failure criterion:**	Max von Mises Stress
Weight:	1.7793 N	**Yield strength:**	5.05e+08 N/m^2
		Tensile strength:	5.7e+08 N/m^2
		Elastic modulus:	7.2e+10 N/m^2
		Poisson's ratio:	0.33
		Mass density:	2,810 kg/m^3
		Shear modulus:	2.69e+10 N/m^2
		Thermal expansion coefficient:	2.36e-05 /Kelvin

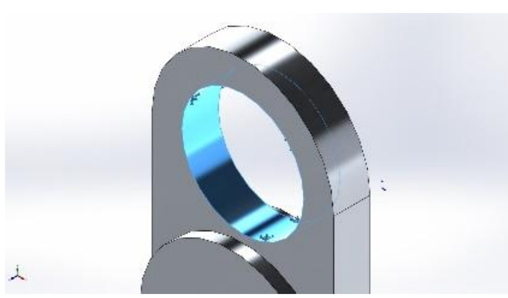


Figure 14: Fixed geometry interface to simulate maximum force on the arm as if the master cylinder were unable to compress or force was being applied while the cylinder was under full compression for Finite Element Analysis and Topology Optimization.

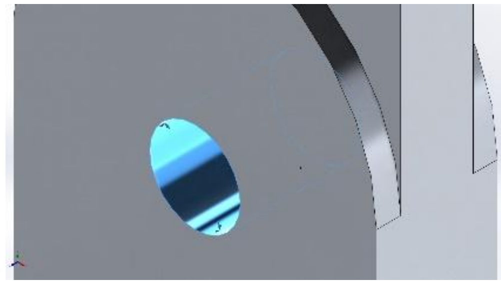


Figure 15: Fixed hinge interface to simulate the pivot point of the pedal arm for Finite Element Analysis and Topology Optimization.

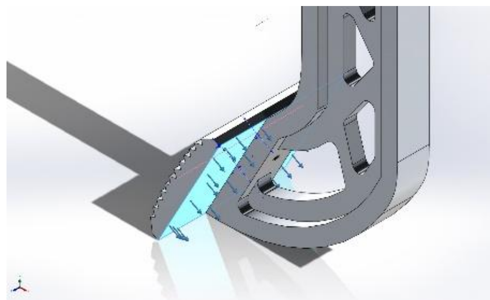


Figure 16: 2000N uniformly distributed normal force on pedal face for Finite Element Analysis and Topology Optimization.

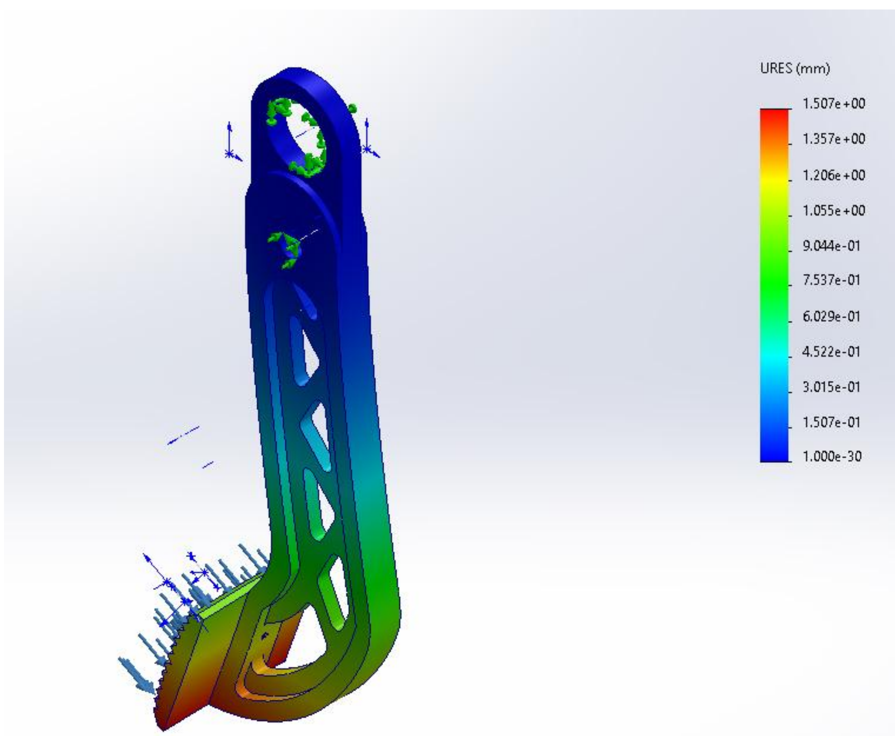


Figure 17: Resultant Displacement from Finite Element Analysis (Min = 0.000mm | Max = 1.507mm)

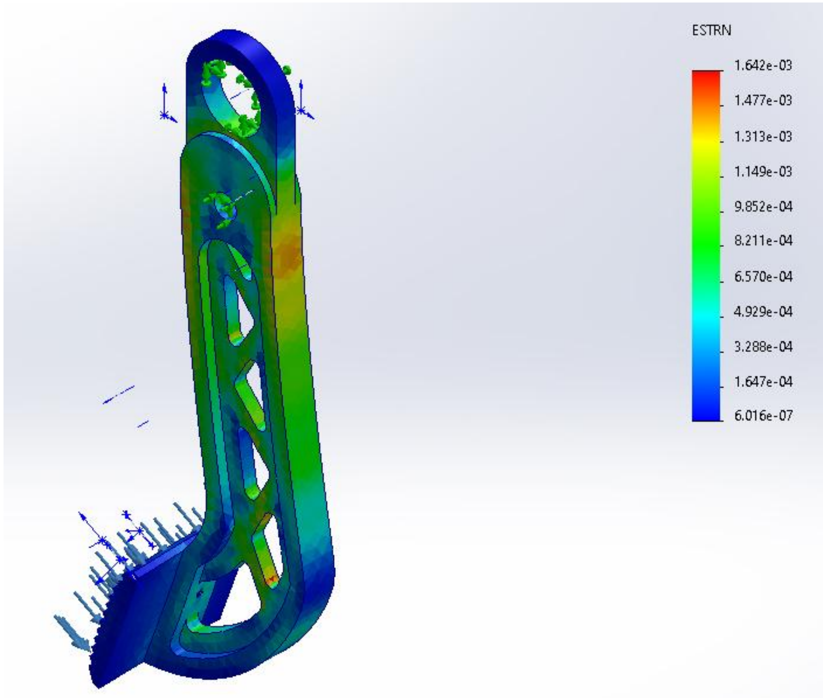


Figure 18: Equivalent Strain from Finite Element Analysis (Min = 6.016e-06 | Max = 1.642e-03)

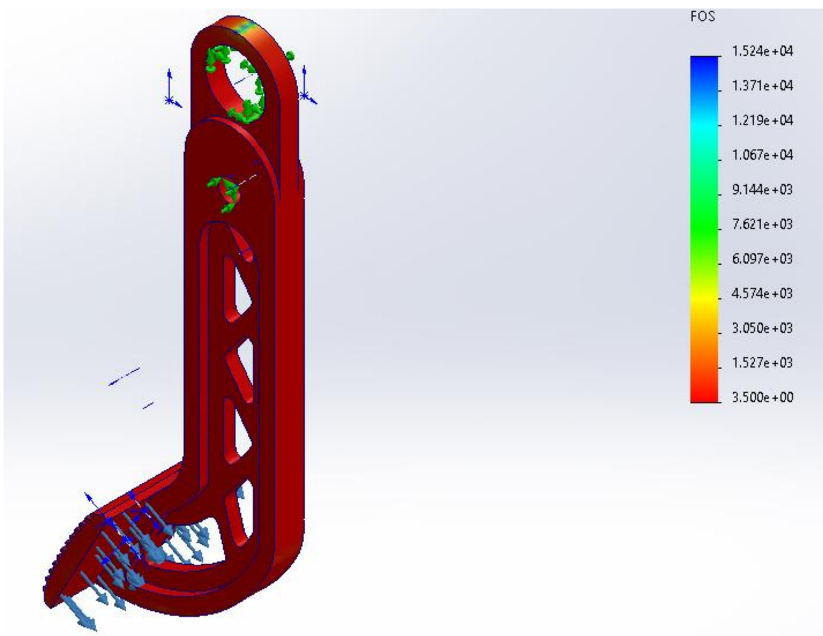


Figure 19: Factor of Safety from Finite Element Analysis (Min = 3.500 | Max = 1.542e+04)

Table 5: Bill of Materials for SolidWorks Assembly

Part Number	Part Name	Material	Quantity
1	Pedal Arm	7075 Aluminum	1
2	Pedal Face	7075 Aluminum	1
3	Hex Drive Flat Head Screw	316 Stainless Steel	2

Appendix IV: Photos of the Prototype.

Figure 20: Side view photograph of the 3d printed pedal shaft prototype.

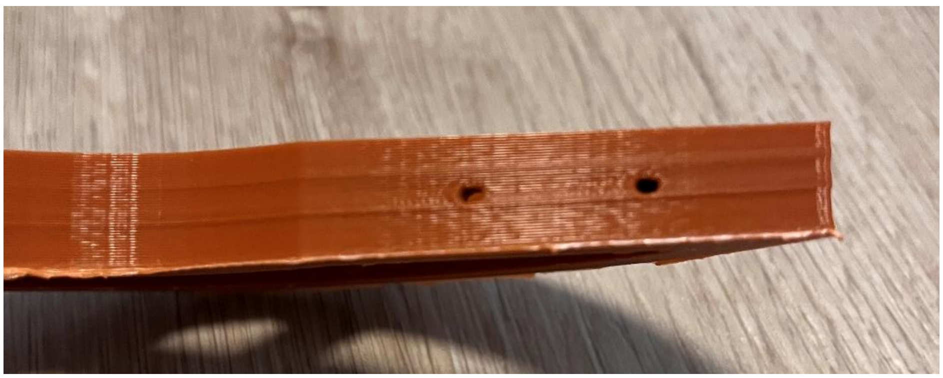


Figure 21: Side view photograph of the threaded bolt holes on the pedal shaft.

Figure 22: Front view photograph of the mounting points for the pedal shaft to the car and master cylinder.

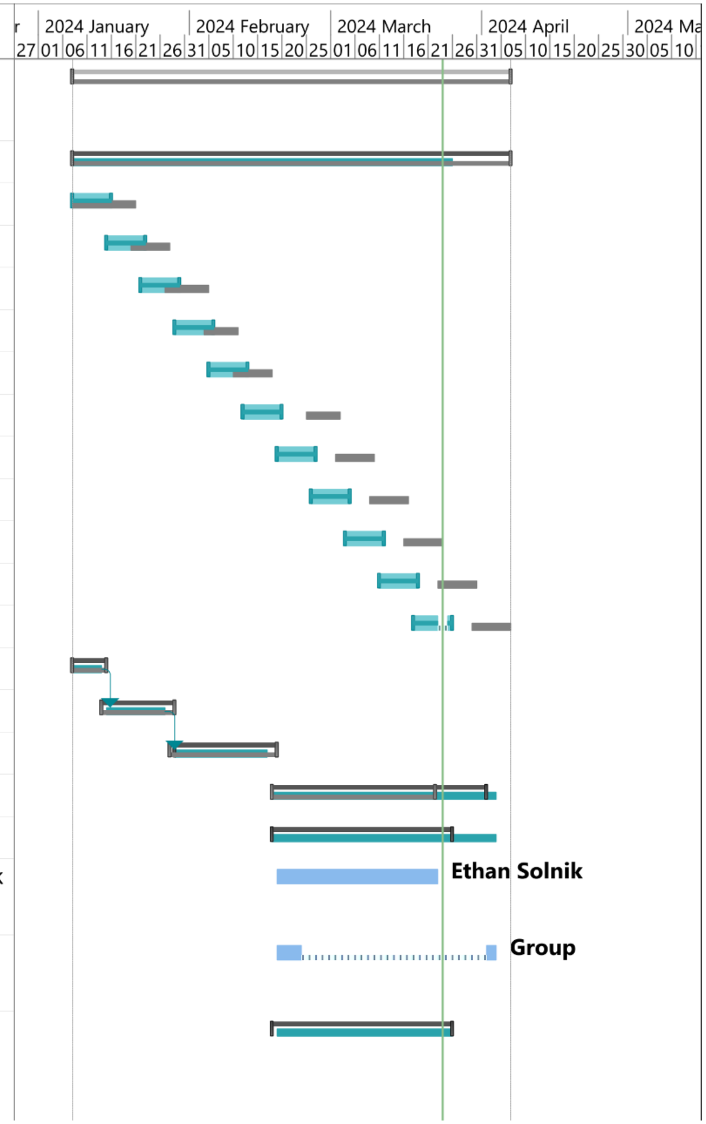
Figure 23: Orthographic view photograph of cutouts in the pedal shaft.

Figure 24: Front view photograph of the pedal face prototype.

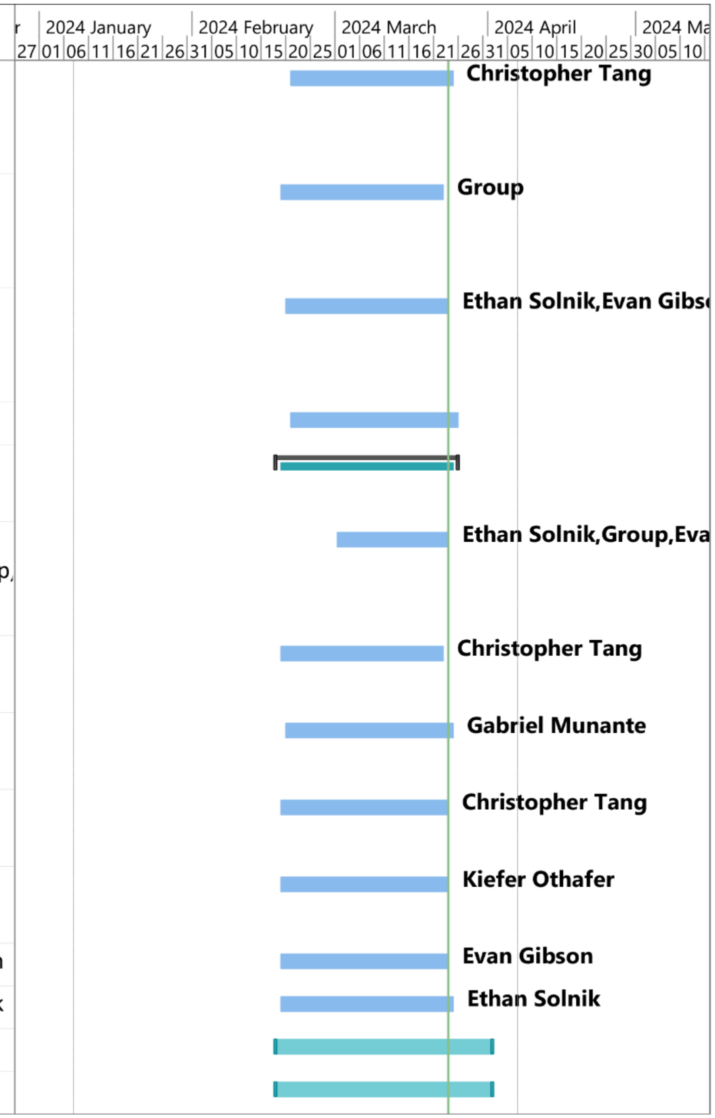
Appendix V: Gantt Chart

Table 6: Gantt Chart for Project Deliverables and Individual Tasks

ID	Task Name	Duration	Start	Finish	Resource Names
0	**Project Management for Baja Break Pedal**	**67 days?**	**Mon 24-01-08**	**Sat 24-04-06**	
1	**Status Reports**	**66 days**	**Mon 24-01-08**	**Sat 24-04-06**	**Group**
2	Week 2	6 days	Mon 24-01-08	Mon 24-01-15	
3	Week 3	6 days	Mon 24-01-15	Mon 24-01-22	
4	Week 4	6 days	Mon 24-01-22	Mon 24-01-29	
5	Week 5	6 days	Mon 24-01-29	Mon 24-02-05	
6	Week 6	6 days	Mon 24-02-05	Mon 24-02-12	
7	Week 7	6 days	Mon 24-02-12	Mon 24-02-19	
8	Week 8	6 days	Mon 24-02-19	Mon 24-02-26	
9	Week 9	6 days	Mon 24-02-26	Mon 24-03-04	
10	Week 10	6 days	Mon 24-03-04	Mon 24-03-11	
11	Week 11	6 days	Mon 24-03-11	Mon 24-03-18	
12	Week 12	6 days	Mon 24-03-18	Mon 24-03-25	
13	**Phase 1**	**6 days**	**Mon 24-01-08**	**Sun 24-01-14**	
19	**Phase 2**	**12 days**	**Sun 24-01-14**	**Sun 24-01-28**	**Group**
27	**Phase 3**	**16 days?**	**Mon 24-01-29**	**Sun 24-02-18**	**Group**
38	**Phase 4**	**34 days?**	**Sun 24-02-18**	**Mon 24-04-01**	**Group**
39	**For Project Manager**	**29 days?**	**Sun 24-02-18**	**Mon 24-03-25**	**Group**
40	SolidWorks FEA + Topology	25 days?	**Mon 24-02-19**	Fri 24-03-22	Ethan Solnik
41	Executive Summary	7 days?	**Mon 24-02-19**	Wed 24-04-03	Group
42	**Part 1: Key Information For Clients**	**29 days?**	**Sun 24-02-18**	**Mon 24-03-25**	**Group**



ID	Task Name	Duration	Start	Finish	Resource Names
43	Problem Definition and Scope Revision	25 days?	**Wed 24-02-21**	Sun 24-03-24	Christopher Tang
44	Background Information Revision	25 days?	**Mon 24-02-19**	Fri 24-03-22	Group
45	Design Solution	25 days?	**Tue 24-02-20**	Sat 24-03-23	Ethan Solnik,Evan Gibson
46	Conclusions	26 days?	**Wed 24-02-21**	Mon 24-03-25	
47	**Part 2: Technical Information**	**29 days?**	**Sun 24-02-18**	**Mon 24-03-25**	**Group**
48	Conceptual Design Solutions	16.67 days?	**Fri 24-03-01**	Sat 24-03-23	Ethan Solnik,Group, Gibson
49	Decision Making	25 days?	**Mon 24-02-19**	Fri 24-03-22	Christopher Tang
50	Implementation	26 days?	**Tue 24-02-20**	Sun 24-03-24	Gabriel Munante
51	Project Plan	26 days?	**Mon 24-02-19**	Sat 24-03-23	Christopher Tang
52	Financial Analysis	26 days?	**Mon 24-02-19**	Sat 24-03-23	Kiefer Othafer
53	Evaluation	26 days?	**Mon 24-02-19**	Sat 24-03-23	Evan Gibson
54	Appendices	27 days?	**Mon 24-02-19**	Sun 24-03-24	Ethan Solnik
55	For Faculty Advisor	34 days	**Sun 24-02-18**	Mon 24-04-01	
56	For Comm Assistant	34 days	**Sun 24-02-18**	Mon 24-04-01	



Appendix VI: Design Evaluation Matrix

Table 7: Design Evaluation Matrix

Proposed Idea	Material	Manufacturability	Cost	Pedal Face	Weight Savings	Arm Design	Overall Grade
Al Alloy Design 2	Aluminum alloy block has a high strength-to-weight ratio. Higher corrosion resistance than steel. (8/10)	Use of CNC milling and bolts. Welding is avoided using CNC which reduces failure points. (8/10)	CNC milling can be expensive. Aluminum is cheaper than steel per unit mass. (7.5)	The rounded pedal face is ergonomic. Integrated grip pattern through CNC. Less maintenance than a rubber grip. (7.5/10)	Shallow cutouts, not holes ensure higher strength while maximizing weight savings. (8/10)	I beam design for the arm. Ensuring strength, minimized deflection, and good durability. Strength will be tested in SolidWorks to 2000N. And the length will be 6-8 inches. (8/10)	**(47/60)**

Appendix VII: Testing and Analysis Rubric

Table 8: Testing and Analysis Rubric

Test #	Test Name	Objective	Method	Success Criteria
T1	Pedal Deformation Test	Validate the pedal's strength under the specific 2000N force as per Baja SAE requirements.	Simulate and apply a 2000N static force to the pedal face; measure deformation using FEA in SolidWorks.	Pedal arm withstands 2000N force with minimal deformation; meets Baja SAE safety criteria.
T2	Stress and Strain Test	Validate the pedal's strength under the specific 2000N force as per Baja SAE requirements.	Simulate an applied a 2000N static force to the pedal face; measure stress, strain, and FoS of pedal	Pedal arm withstands 2000N force with minimal stress and strain; meets FoS requirement