Baja SAE Adaptive Suspension



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Team 7
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Executive Summary

The Michigan Baja Racing team competes in four different events during the Baja SAE competitions. These events are maneuverability, suspension and traction, 100 foot acceleration, and a four hour endurance race. Due to competition rules, the team cannot swap out any shock components in between events, so their current vehicles end up having a general tune in their shocks that works for all of the events. Therefore, the goal of our project was to provide the team with a way to modify the damping rate of their shocks to improve vehicle performance through different events and obstacles without changing or swapping out any components of the shock.

Some of our key requirements and specifications include adjustable damping of suspension with a specified range of 2000 Ns/m to 10000 Ns/m. Another requirement for our project is for the battery life to last an entire competition; specifically, greater than 6 hours. Our design needs to survive a max load case of 14 kN axially and an internal pressure of 1438 psi. Additionally, the mechanism failure mode cannot render the car undrivable. Our product needs to fit within the vehicle's packaging constraints, or be within a crash radius of 7". Finally, our system needs to be lightweight with a specification of adding no more than 1 kg to the existing shock.

Our final design concept was to add an adjustable external valve controlled by a motor to the side of the MBR shocks, which leads to an external reservoir in order to allow some shock fluid to bypass the shock piston. This concept was chosen due to its ease of packaging with our car and current shock, and it had no concerns with safety or power consumption. In order to prevent any modifications to the current shock body, an adaptor piece was manufactured using a lathe to allow the valve to be inserted into the shock. The valve, motor, and fittings were relatively inexpensive purchases, and the reservoir and housing for both the valve and electronic components were 3D printed.

In order to determine if our design met our requirements, we performed verification testing. First, we weighed our final design to confirm we were adding no more than 1kg to the existing shock. Next, we mounted our system to the Baja car and tipped it on its side to make sure it was within the roll radius of the car. Finally, we were able to take our system to Ford and utilize their shock dynamometer to measure the change in damping created by our system.

Some strengths of our system are that it is very robust, lightweight, and simple to operate. However, from the data collected at Ford, we found that our system only created a small change in damping, which did not meet our specified range. We also found that our design increased the unreliability of our shocks by creating cavitation and air pockets inside of our shock. We plan on continuing to work with the Michigan Baja Racing Team to help to mitigate these problems by making some changes to our design and increasing the overall range of damping our system can provide.

Table of Contents

Executive Summary 1
Table of Contents 2
1. Abstract 4
2. DR1 Material 4
    2.1 Project Introduction, Background, and Information Sources 4
    2.2 Design Process 7
    2.3 Design Context 9
    2.4 User Requirements and Engineering Specifications 12
3. DR2 Material 14
    3.1 Concept Generation 14
    3.2 Concept Selection Process 18
    3.3 Selected Concept Description 26
    3.4 Problem Analysis and Iteration 30
    3.5 Problem Domain Analysis and Reflection 32
4. DR3 Material 34
    4.1 Engineering Analysis 34
        4.1.1 On-Car Pressure Testing 34
        4.1.2 Shock Adaptor Pressure Vessel Calculations 35
        4.1.3 Pressure Vessel FEA 36
        4.1.4 Valve Aperture 37
        4.1.5 Motor Spec 38
        4.1.6 Battery Life Calculations 38
        4.1.7 Reservoir Sizing 38
        4.1.8 Packaging 39
        4.1.9 Weight 39
    4.2 Final Design Description 39
    4.3 Verification and Validation 44
5. Discussion 53
6. Reflection 54
7. Recommendations 56
8. Conclusion 56
10. References 58
11. Appendix 60
    11.1 Appendix A - Sample of Generated Concepts 60
    11.2 Appendix B - Downselection 61
    11.3 Appendix C - Analysis Calculations 63

Part 1: Shock adaptor stress analysis 63
Part 2: Bernoulli's equation for valve aperture 63
Part 3: Battery life calculations 64
Part 4: Reservoir volume 64
11.3 Appendix D - Part Drawings 64
12. Build Design Bill of Materials 65
13. Manufacturing/Fabrication Plan 66
14. Bios 68

1. Abstract

The Michigan Baja Racing team needs a way to modify the damping rate of their shocks to improve vehicle performance through different events and obstacles without changing any internal components of the shock. This semester, the team should develop an external mechanism prototype that can accurately control the damping rate of the shock. Once the prototype has been verified, the team should incorporate some open or closed-loop control system to actuate change in damping as a response to live input.

2. DR1 Material

2.1 Project Introduction, Background, and Information Sources

The Michigan Baja Racing Team (MBR) has tasked us with modifying the damping rate of their shocks. Our primary sponsor is MBR's suspension team who want shocks that can vary its damping rate between events.

Baja SAE competitions consist of multiple events across four days. The events we want to focus on in this project are the dynamic events: maneuverability, suspension and traction, sled pull, acceleration, and endurance. The maneuverability event is a slalom-like course that tests a car's ability to drift around tight corners and obstacles quickly. Cars are judged based on the overall time it takes them to finish the course. The suspension and traction event (S&T) can consist of a variety of possible obstacles, including logs, rock crawls, jumps, vertical walls, pits, tires, drops, and more. It is designed to break cars, and as such, teams are scored based on how far (measured in gates) their car makes it through the course. If multiple cars finish the entire course, they are then judged based on time. The sled pull event consists of a heavy sled connected to a tow hitch on the back of the car. The sled has a wedge that drags against the ground with increasing friction the further a car travels. Teams are judged based on distance completed. During some competitions, the sled pull event is replaced with a hill climb, where cars must drive up a steep hill, as far as possible. Scoring is similar to the suspension and traction event, where a tie in course completion is broken by time taken to complete the distance. In the acceleration event, teams are judged based on how quickly their cars can travel 100 feet starting from stationary. Finally, the endurance event is a wheel-to-wheel race between up to 100 different teams where vehicles attempt to complete as many laps as possible on a one to two mile course over four hours. This event is extremely demanding, and sees the most failures in vehicles.

The MBR suspension team is able to adjust the damping ratio of its current shocks by adjusting the shim stack inside it. Unfortunately, SAE rules prohibit the team from modifying the parts in any car during a competition, so MBR is unable to change the damping ratio during a competition. This results in the creation of a single suspension tune that is not optimized for any singular event, but rather sufficient in all of them. Being able to modify the damping rate between events, or better yet between obstacles, would allow MBR to have a shock tune that is

designed to excel in each and every event. Solving this problem would enable the car to do better in every dynamic event, ultimately giving the team more points and increasing the likelihood of winning the overall competition.

To modify a shock, we first talked to MBR's suspension team stakeholders to understand the mechanics of a shock; it is designed to compress at a roughly linear speed in response to an applied force. The force/speed is defined as the damping rate and can be measured in Newton seconds per meter and can be plotted against shock speed to obtain the shock's damping curve. As a shock compresses, the lower mount moves closer to the upper mount (the left moves closer to the right as shown in Figure 1 below).

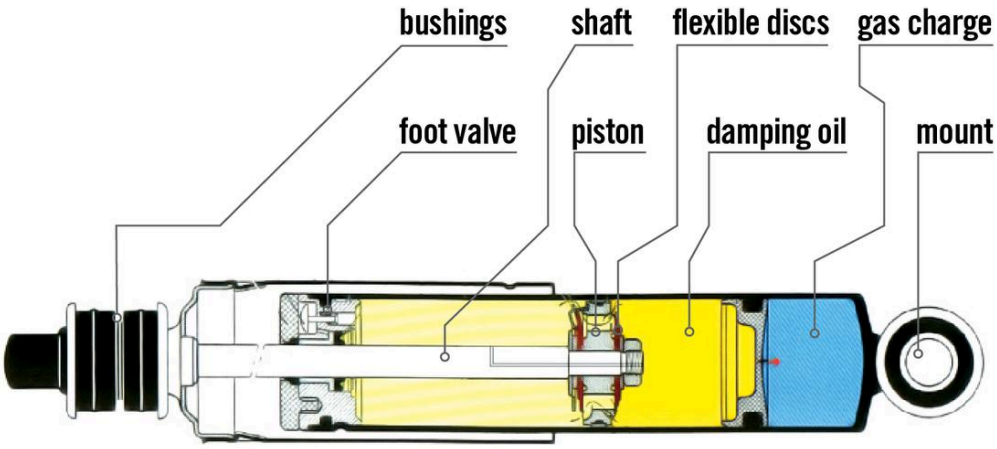


Figure 1: Overall shock geometry

This compression also causes the shaft and piston to move with the lower mount up through the overall shock body, which is connected to the upper mount. As the piston moves through the shock body, it must also pass through the shock oil. Resistance is created by fluid flowing through unidirectional holes in the piston and then deforming shims, or flexible discs that provide a reactive force on the fluid, as shown in Figure 2 below. The faster the shock compresses, the faster the piston moves through the fluid, and the more shims get deformed. The shims closer to the holes control the damping characteristics at low speeds, and the shims further out from the holes control damping at higher speeds. The same process happens during the shock's rebound, when the upper and lower mounts move away from each other, except fluid flows through the other set of holes in the piston. Shims can be taken out and replaced in order to get a specific tune, although it is a time-consuming and arduous process.

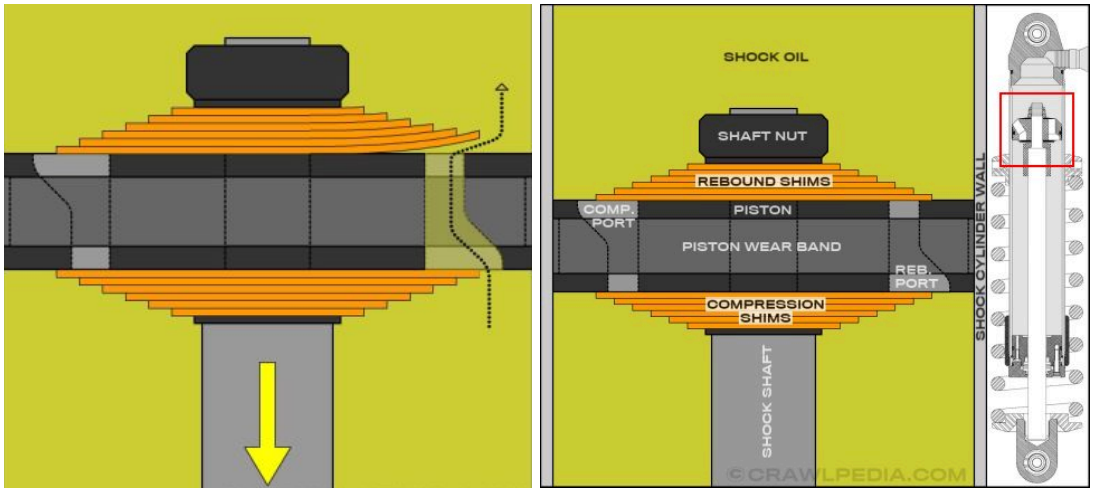


Figure 2: Shock piston mechanics

A successful project outcome would involve some modification to our existing Afco 64 series shock through which its damping rate would be variable through some user input. Additional major objectives and goals are outlined in the requirements and specifications section below.

In order to successfully define our problem and generate ideas, we benchmarked the problem by looking at previous attempts at solving the problem of variable damping rates in shocks, both successfully and unsuccessfully. The Afco 63 series shock allows for variable damping through a knob which opens and closes a valve in the piston. This valve allows additional fluid flow around the shim stack (Afco). Unfortunately, it is not adjustable by the driver, nor does it provide a wide enough range of damping rate. Other Baja SAE teams have successfully developed and implemented adaptive suspension systems in their vehicles, although there is no relevant documentation about their designs. A previous ME 450 team had attempted to solve the problem for MBR, ultimately seeing failure. The project attempt saw a prototype shock using magnetorheological (MR) fluid in combination with a wire coil housed in the piston. When current was passed through the coil, a magnetic field would be created, causing iron particles in the MR fluid to align, thereby the fluid's viscosity, and subsequently, the damping rate. After building a prototype, the team saw negligible change in damping rate and attributed the issue to insufficient current supplied (Garcia, Kaufman, Vainbridge, Backus). Many modern cars, such as the Audi A8, successfully use valves between the shock upper body and an external reservoir to limit fluid flow rate and thereby adjust pressure in the shock body ("Multifaceted Personality: Predictive Active Suspension A8 Flagship Model."). Other car manufacturers, such as Rivian, use air suspension to actively adjust the damping rate in their shocks ("Rivian Air Suspension: System Features - Rivian Support."). These mechanisms can be visualized in Figure 3 A full comparison of approximated relevant benchmark specifications can be found in Table 1.

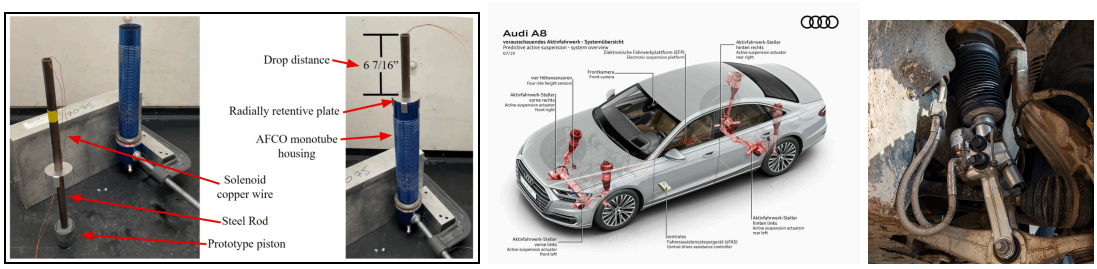


Figure 3: Adaptive suspension mechanisms from left to right, previous ME450 group, Audi AI, Rivian

Table 1: Comparison of approximated benchmark specifications. Different benchmark designs are compared to our most important requirements including: effective change in damping, conformance to Baja SAE rules, crash radius, cost, and weight. We will more closely research the solutions pursued by other Baja teams, and the Afco 63 series.

Benchmark	Range of damping (Ns/m)	Conforms to Baja SAE rules	Max. radius (in)	Cost per shock	Weight (kg)
Other Baja teams	2,000-10,000	Yes	5	$500	2.5
Afco 63 series	5,000-7,000	Yes	2	$400	1.37
Audi	20,000-100,000	No	10	$12,000	7
Rivian	20,000-100,000	No	10	$3,000	7
Previous ME450 attempt	0	Yes	2	$320	1.9

Most of the information we will use for our project comes from our current shock provider Afco, research papers and documentation on benchmarked attempts at adaptive suspension systems, and existing knowledge on the MBR team obtained through stakeholder interviews. Our project will have to fit the Baja SAE rule standards set, which all cars must do in order to compete. There is a rigorous technical inspection at the start of each competition, of which the result of failing is an inability to compete. We must ensure our product will not cause such failure.

2.2 Design Process

Following a structured design process is a critical component of a successful project. To this end, our group considered several different styles of design processes. After reviewing Wynn and Clarkson, we settled on a solution-oriented, stage-based design process with some cyclic

activities at each stage (Wynn and Clarkson, 36). The main exception to this is the prototype and testing stage of the process, as shown in Figure 4.

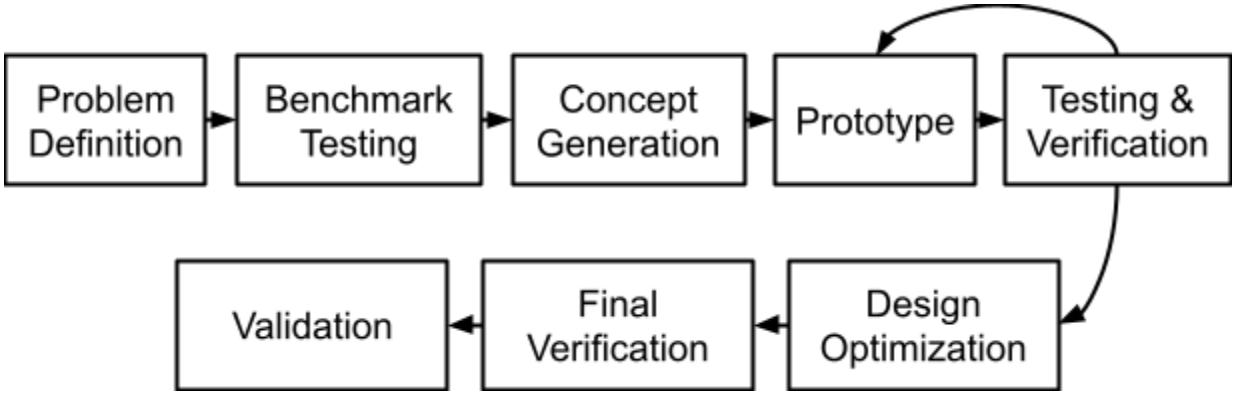


Figure 4: Our design process

The problem definition and benchmarking stages are not cyclic because these stages are very straightforward for our project. Our sponsor has done a very good job defining the need for an adaptive suspension system for their car and the benchmark designs are readily available. Benchmark testing is also non-cyclic for this project because we only need a few benchmark measurements including the current damping rate of the shock and the oil pressure inside of the shock. Concept generation will have a few cyclic brainstorming tasks as we individually generate ideas, but down-selection and final selection will be a one-time process. Based on our benchmarking discussed above, the different ideas should be fairly unique, allowing us to settle into a specific adaptive suspension concept without needing a cyclic process. Prototyping and testing are going to be an extremely cyclic process. Due to the unique type of driving that the Baja car sees, it is difficult to accurately predict some of the loads, inputs, and needed damping. Because of this, we are planning a cyclic process to ensure our design is very robust and to tune the damping to optimal values.

Moving to the second row, design optimization will allow us to focus on some of the secondary user requirements, including packaging and weight, to make sure we have a functional design that keeps the car competing at the highest levels. This step will be evaluating our now functioning design and finding any improvements we can make. Final verification is a quick step to make sure that our optimized design still meets the primary user requirements. The validation step will ensure that the final product is the best version and works for MBR.

Other models were considered, including a more activities-based model and a more problem-oriented solution. Within these other categories, different models had different distinct steps, but in general, they did not fit our project. Activity-based models fail to meet our time constraints as mentioned previously, and a problem-oriented approach does not fit our clearly

defined problem. Our process is quite different to that of ME 450, by comparison. We included a benchmark testing step to allow for a better problem definition and specifications. In addition, we took the solution development and verification steps from the ME 450 process and expanded them significantly. This was a necessary step for our project, since our main deliverable is a functioning prototype. As discussed above, we added prototyping and testing as a cyclic set of stages. After that, we have included a design optimization step to include manufacturing, assembly, and failure analysis. These are necessary steps since MBR has minimal support for our project internally. Final verification ensures these changes still leave us with a functional prototype. The final validation step returns to the ME 450 design process.

2.3 Design Context

After a thorough context analysis, we have identified any parties that may be affected by our decision-making. The primary stakeholders of our design include MBR's drivers, the MBR Team Captain, the Suspension Subsystem Leads, and other competitors in the Baja SAE series. Secondary stakeholders include material and stock providers, SAE rule-makers, Brakes and Halfshafts/Hubs Subsystem Leads, and our ME 450 team as MBR team members. Finally, tertiary stakeholders include the AFCO shock company, the Wilson Student Team Project Center (WSTPC), and Baja SAE competition organizers. The stakeholders can be visualized in Figure 5.

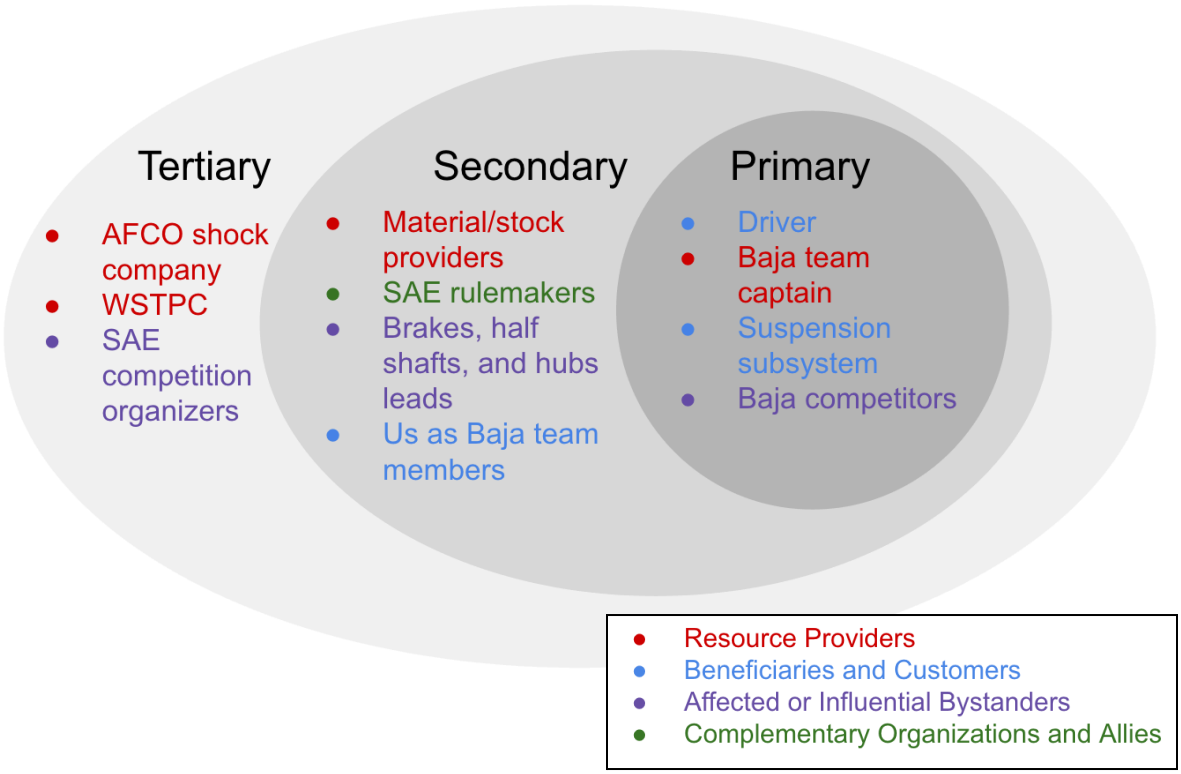


Figure 5: Primary, secondary, and tertiary stakeholders

Most of the stakeholders will be affected positively through our design. The team drivers, for example, will largely benefit from successful variation in our damping rate. An increased variation in damping will lead to a decrease in vibrations felt by the driver, allowing the driver increased comfort in the vehicle and an increased sense of ability to move through obstacles quickly. The MBR team at large will also be positively affected, including the Team Captain and Subsystem Leads: our design will allow for a faster and more capable vehicle overall, increasing the success of the team. There are some stakeholders, however, which may be negatively affected. Our success at Baja SAE competitions directly harms other competitors in the series, who may not be able to secure as many points or podium results. Additionally, the MBR material and stock providers may need to supply additional materials for the prototyping of our project. While this may not necessarily harm any specific company, the MBR team does receive those materials for free or at a large discount. Even though it remains up to the discretion of the company to provide this sponsorship, our prototype may have harmful economic impacts on any material providers. Finally, though our team drivers will benefit from the successful completion of the project, they may be harmed by failure. If our proposed mechanism fails at any time, it may ‘lock in’ an acceleration tune for a suspension and traction event, for example. In that case, any vibration not absorbed through the shock will be felt by the driver’s neck and back, leading to potential health impacts.

The main goal in completing this project is to increase MBR’s vehicle performance, leading to more points scored at competitions, and thus team success. Although this main driver largely stems from the interest of the sponsor, there is a social problem contributing to our design approach: driver comfort. In designing an adaptive suspension system, we also help the driver of our vehicle have an easier time with large obstacles. By reducing the vibrations felt by the driver, we can provide a smoother ride, leading to less negative health effects like myalgia and myositis. This social impact ranks low in the context of our project. The drivers of our vehicle experience little negative health effects with our current suspension system, and so the primary focus of our project is vehicle performance. Driver comfort will mainly be considered in conjunction with failure modes as described in the stakeholder analysis above. These priorities should positively affect the social impact of our project. Driver safety will increase upon the successful technical completion of our project, and so our top priority is successfully meeting our requirements and specifications.

There are no intellectual property requirements for our project. As such, our team owns all intellectual property created throughout the course of the semester. There are no protections applicable, however, as we are not the first group to attempt adaptive suspension. It has existed in the Baja series for at least two years. The primary intellectual property concerns in our project surround our benchmarking research, ensuring we give credit to the right people throughout the course of our reporting, and maintaining some sense of secrecy inside the Baja community.

Adaptive suspension remains a major way teams get an edge in competitions, and so ensuring that our ideas stay somewhat hidden throughout the design process will be essential in ensuring that MBR reaps the competitive benefits of our project.

Our project is extremely sustainable in use and disposal. We intend to use our designs on the competition vehicle for this season, meaning we will make exactly enough for one vehicle including spares. The design will remain on the vehicle assuming no component failure. These processes will likely consume aluminum, which is a finite resource. Although the project itself is not likely to emit any pollutants, we must be careful not to leak shock fluid in our processes. The less sustainable aspects of our design lay in its manufacturing, for which we will need to source materials like plastic and aluminum. We could make our project more sustainable by sourcing only sustainable materials or purchasing more exact quantities and dimensions of stock, both of which could come at a higher economic cost.

Examining our project for social, environmental, cultural, and economic impacts yielded the following conclusions. Social impacts largely consist of effects on our team driver. We have the potential to make our driver's experience more comfortable, but also, in the event of component failure, accidentally create more muscle strain. The most effective way to avoid this will be to carefully examine all failure modes of our design to ensure it will fail in a way that only 'locks' our normal damping ratio, rather than a largely stiff or soft one. Other social impacts will stem from how we allocate our materials. To minimize impacts on a larger society, we should use no conflict minerals and examine companies which we plan to source material from to ensure no involvement in conflict. Environmental concerns will come into play in failure modes. The only way in which our design may impact the environment is if our team leaks shock fluid. This could be harmful to the environment in several ways; depending on the area of the spill, we may introduce shock oil (a carcinogenic) into waterways. Any spills may affect local wildlife which accidentally ingest the oil, and waterway spills may contaminate drinking sources. To avoid negatively affecting the environment, we must examine the failure mode of our designs to ensure no leaking of shock fluid. As discussed previously, our project can be made more sustainable through the purchase and use of only sustainable materials and purchasing more exact quantities and dimensions of stock. After careful consideration, negligible cultural and economic impacts were found.

Team members of our ME 450 team are also project sponsors, and as MBR members, we are all stakeholders. Because our ME 450 team members have so many dual roles, and are also the most knowledgeable on the MBR team in the adaptive suspension area, the largest ethical dilemma we may face is making design decisions without considering all factors, especially in ethical, social, and environmental contexts. To manage this dilemma, we hope to have other MBR team members, including the Team Captain and Technical Director, thoroughly review our work. Our personal ethics are very similar to those we are expected to uphold by the University of Michigan

or a future employer. According to the National Society of Professional Engineers, “engineers shall acknowledge their errors and shall not distort or alter facts” and “engineers are encouraged to participate in civic affairs; career guidance for youths; and work for the advancement of the safety, health, and well-being of their community” (National Society of Professional Engineers). These are also part of our personal ethics code, and good examples of similarities between the different parties. Differences may stem from the size of companies, which may see more misconduct than from a personal ethics code.

Our project sponsor is a member of the ME 450 group, and so there are no noticeable power dynamics in this relationship. Our end users are drivers on MBR, including the Drivetrain Director and Team Captain, so there are no noticeable power dynamics there either. Finally, because our ME 450 team members all have leadership positions within Baja, the main power dynamics that exist amongst our team are no different than between any team. We will need to ensure that we are effectively collaborating with all involved parties and listening to all opinions, but we do not expect power to pose any challenges. In order to address other inclusivity problems that have not yet been identified, our team should ensure that others are checking over our work, potentially including past Baja members who no longer hold positions on the team. We could also attempt to get the input of others who drive our vehicle for testing, and not just the main competition drivers. Finally, we can conduct interviews with professionals in the automotive industry to ensure we haven’t missed any accessibility issues within our design.

2.4 User Requirements and Engineering Specifications

After interviewing multiple stakeholders, such as Baja’s driver, Captain, Manufacturing Director, Suspension Leads, and Logistics Director, we were able to combine their desires for the product into a list of non-technical user requirements. We then turned those into quantifiable engineering specifications with the goal of our product meeting all of them. All requirements, specifications, and the justifications behind them are listed below in Table 2. All requirements have been translated into specifications and no requirements or specifications have been omitted. All specifications have been quantified and reasonable to achieve.

Table 2: User Requirements and Engineering Specifications. This table contains our user requirements from various stakeholders translated into numeric engineering specifications. The last column justifies why the requirement is important for solving the overall problem. This table demonstrates that our design will only be focused on solving the direct problem and not unnecessary tasks.

User Requirement	Engineering Specification	Justification
Adjustable damping of suspension (Perl)	2000 Ns/m < Damping coefficient < 10000 Ns/m at 0.25 m/s shock speed	Primary requirement of the problem; adjustable shock improves vehicle performance
Driver/vehicle actuates change in damping (Perl)	> 3 presets for driver to adjust damping Vehicle responds to continuous input within 150 ms	At least three events would benefit from different damping rates
Battery life lasts one competition (Grover)	Battery life > 6 hrs	Allows consumable components to last a full competition
Shock survives max load case (Grover)	No yield in 14 kN axial force and 1348 psi internal pressure	No yield ensures no fluid leak and car driveable
Adjustment mechanism failure mode does not render car undrivable (Gariepy)	Mechanism failure modes result in 2000 Ns/m < Damping coefficient < 10000 Ns/m	Baja competitions are very rough on the car, and if it fails the car still needs to be driveable
Serviceable (Stack)	Internal components adjusted/replaced in 30-60 minutes	Not much time at competitions to service the car
Conforms to Baja SAE rules (Grover)	B.9.3 - Pinch Points and Entanglement, B.10.1 - Power Sources, B.10.2 - Wiring and Connectors	Must pass tech inspection to compete with car
Product fits vehicle packaging constraints (Grover)	Product doesn't interfere with vehicle chassis and is inside crash radius of 7"	If vehicle rolls, nothing breaks
Prototype satisfies the project budget (May)	< $650 for prototype ($250 is coming from the sponsor)	Needs to stay < budget given by ME450 and sponsor
Manufacturable (Hetrick)	All custom components are machinable using tools available in the WSTPC	End goal of building product ourselves in the machine shop
Lightweight (Grover)	Product weight < 1kg heavier than existing shock (2.37 kg)	Lighter car is faster
Product minimizes environmental costs (May)	Energy use costs < $0.10 per year of use Environmental use costs < $0.15 per year of use	Minimize societal impacts to protect those without input to our project

Our engineering targets were determined by first correlating user requirements into a quantifiable specification. Following this, the targets were checked with relevant stakeholders to ensure that the specification is, in fact, aligned with their intent in the corresponding requirement. For example, when given the requirement of making the product durable by the MBR Team Captain, we narrowed it down to mean lasting an entire Baja season Grover). Then, by adding together all the drive time over the course of the three competitions in a season, plus an extra several hours for testing and a safety margin, we landed on a required product lifetime of 30 hours. We also analyzed shock data from the MBR Suspension Leads (another stakeholder group) to determine the shock actuates approximately once per second, and therefore the shock would need to last around 100,000 cycles. After determining these technical specifications, we returned to our stakeholders, who confirmed the specifications fit the intention of their requirements.

Comparing these specifications to the other products we are benchmarking against, a few stand out. Our cost, size, and weight will be significantly less than other commercially available solutions that are used in full-scale cars, but will be roughly equivalent to other Baja teams' adaptive suspension systems. There is very little data on damping rate ranges in existing adaptive suspension systems in the automotive industry, but ours will likely be significantly less given how much lighter our vehicle is. Our system will likely be easily manufacturable in-house, just like other Baja teams' solutions and unlike many commercially available solutions.

Our most important requirement is the range of damping adjustability as that is the sole purpose of our project. The second critical requirement is that shocks follow all Baja SAE rules so that our car can compete (Baja SAE). Semi-important requirements include weight, battery life, total life, and manufacturability. The less the weight and power consumption of the mechanism, the faster our car, so our design should minimize both factors. Total part life and manufacturability are also not critical, as we could replace parts between competitions and outsource manufacturing, although this would increase the economic impact of our product. Our least important, although still very relevant requirements are the budget, environmental impact, and actuation time, as failure in achieving any of these wouldn't cause a total mission failure. The set of requirements that must be met consists of having a variable damping rate, meeting the Baja SAE rule set, and fitting vehicle packaging. All other requirements are wishes but are not mission-critical.

3. DR2 Material

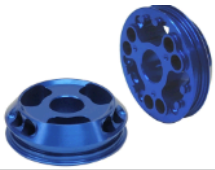
3.1 Concept Generation

During our concept generation process, we explored a wide variety of ideas by keeping an open mindset and preventing ourselves from evaluating concepts or being critical. At the beginning of this process, we spent time brainstorming individually. Each member of our team utilized a different concept generation process and came up with a list of twenty concepts. This gave our

team a total of eighty unique ideas to compare, and later down select into our top five design concepts. A sample of twenty of our more unique ideas can be found in Appendix A. The different concept generation methods that were utilized by our team included functional decomposition, morphological analysis, attribute listing, and design heuristics. These methods are described in detail below.

The first concept generation method used was functional decomposition. This process looks at the overall main function that needs to be accomplished by the system and decomposes it into different concept areas and components. The two components of a shock that were looked at using this method were the shock body and the piston. The concept areas that were used to build design ideas were magnetic shock fluid, fluid flow and pressure, and heat. As seen below in Figure 6, using the concept areas and components, six new ideas were generated. One of these ideas included a telescoping shock to change the pressure of the shock oil. As the piston in the shock compresses, the body of the shock would expand. This would decrease the pressure in the shock and in turn decrease the damping coefficient. Another concept generated using this method is a resistive heating coil in the pistons. Heating up the shock oil with the heating coil would change the viscosity of shock oil. This would allow the piston to move through the shock oil easier which would decrease the damping coefficient of the shock.





Concept Area	Shock Body	Piston
Magnetic shock fluid	Electromagnetic shock body	Electromagnetic piston
Fluid flow/pressure	Telescoping shock body to change oil pressure	Rotating star shims
Heat	Resistive heating coil around the shock	Resistive heating coil in the piston

Figure 6: Functional decomposition concept generation method

The next concept generation method used to come up with ideas for our project was morphological analysis. This process takes the main function of a project and breaks it down into many sub-functions. Morphological analysis often uses a chart or matrix to help identify which combinations of sub-functions and solutions might be most promising. The morphological method yields a matrix of functions and components. Each idea generated is unique to one of the

sub-functions. As seen in Figure 7, the three sub-functions used were adjusting the piston shim stack, fluid flow in the shock, and adjusting the fluid viscosity. An example of a concept that was generated using this method was putting a valve that would lead to an external reservoir. This valve would have variable settings based on how much it was open. Opening the valve more would reduce the pressure in the shock, allowing the piston to move easier through the shock oil, therefore reducing our damping coefficient.

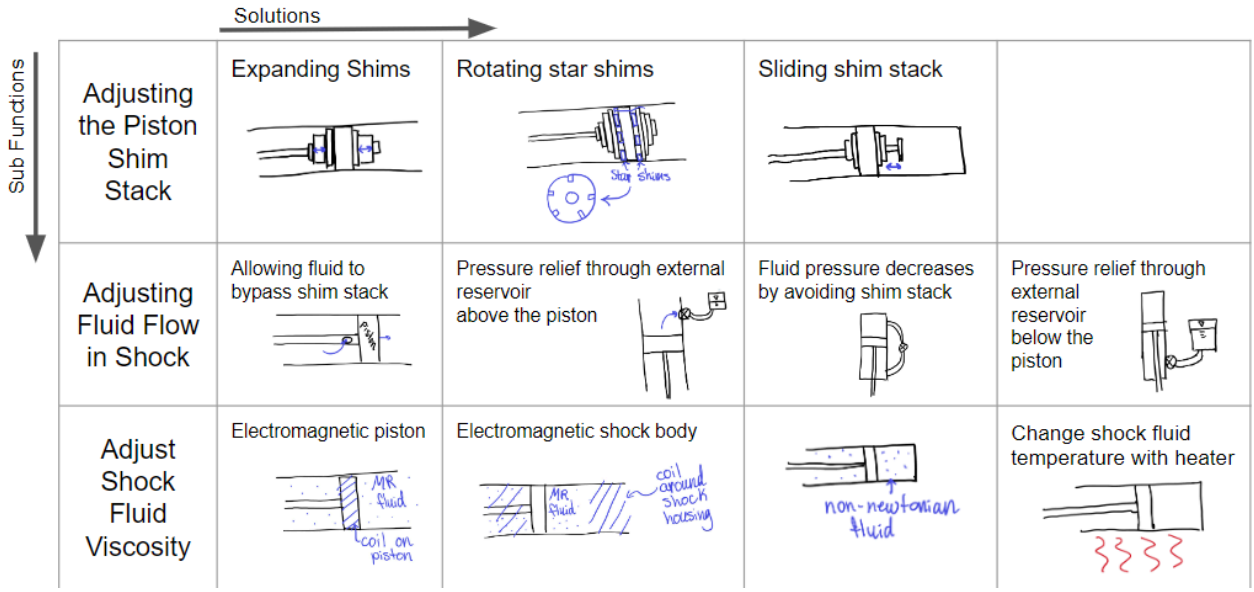


Figure 7: Morphological analysis concept generation method

Another concept generation method our group utilized was attribute listing. This method focuses on breaking down the problem into smaller problems to be solved by a potential design. This method starts off by listing attributes that are important to a system. In our case, as seen in Figure 8, the attributes included fluid flow, shim properties, and fluid properties. The concepts were then derived from one of the attributes. A concept that was generated using this method was expanding or adjustable shims. The shims in the shim stack on the piston are what determine your damping coefficient. Shims are different diameters and different thicknesses which determine how much resistance they provide to fluid flow. If the shims in the shim stack could increase in thickness or volume, the damping coefficient of the shock could be altered.

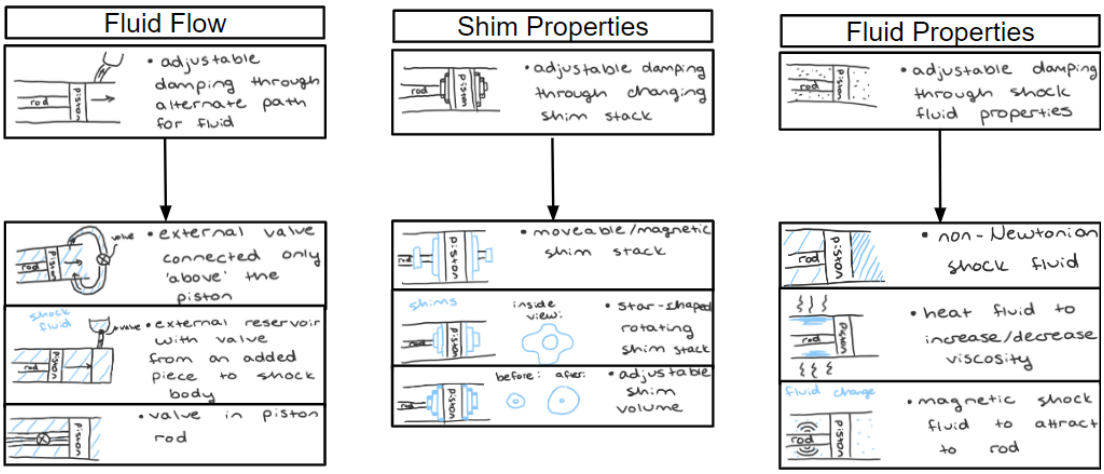


Figure 8: Attribute listing concept generation method

Finally, the last concept generation method our group used was design heuristics. This method promotes diverse idea generation by applying different design heuristics. As seen in Figure 9, examples of heuristics used during our concept generation process are expose interior, merge surfaces, different energy source, and bend. These heuristics enabled us to create new ideas using inspiration from previous concepts. An example of design heuristics being used to generate concepts can be seen using the different energy source heuristic. The two concepts that were generated were using magnetic shock oil with a magnetized piston and using magnetic shock fluid with a magnetized shock body. The piston or shock body would be magnetized using an electromagnetic field. As the magnetic field created by these components increased or decreased, the magnetic shock oil's viscosity would change, allowing the piston to move through the shock oil easier and decreasing the damping coefficient of the shock.

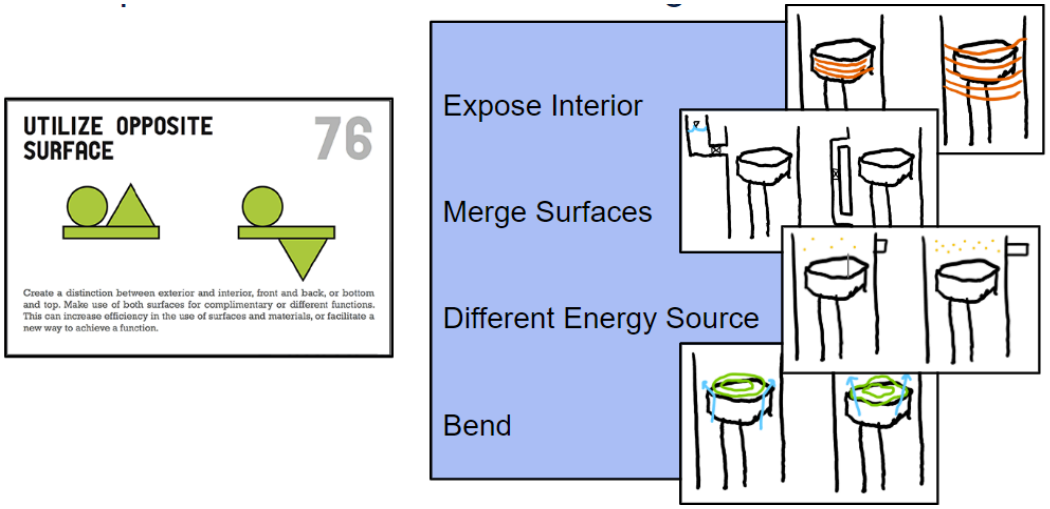


Figure 9: Design heuristics concept generation method

3.2 ***Concept Selection Process***

After concept generation, we had about eighty unique concepts to select from. The first step in this process was down-selecting to a more manageable five or six concepts. To do so, we started by eliminating designs that either didn't meet the original requirements or were physically infeasible. We then grouped the remaining concepts into four categories based on a general summary of the actuation method. These categories were external force, viscosity fluctuation through heat, viscosity fluctuation through electromagnetism, and fluid flow. We were able to eliminate the first three categories due to concerns with safety, power consumption, and our abilities to learn the relevant engineering topics in the course of this semester. This left us with just one major category, which is changing the damping of the shock through fluid flow. The full down selection process can be viewed in Appendix B.

Once we decided to use a concept that affected the fluid flow, we were left with the following five designs - the most promising of that category. The first concept relies on actively modifying the pressure inside of the shock during operation. The concept is sketched out below in Figure 10.

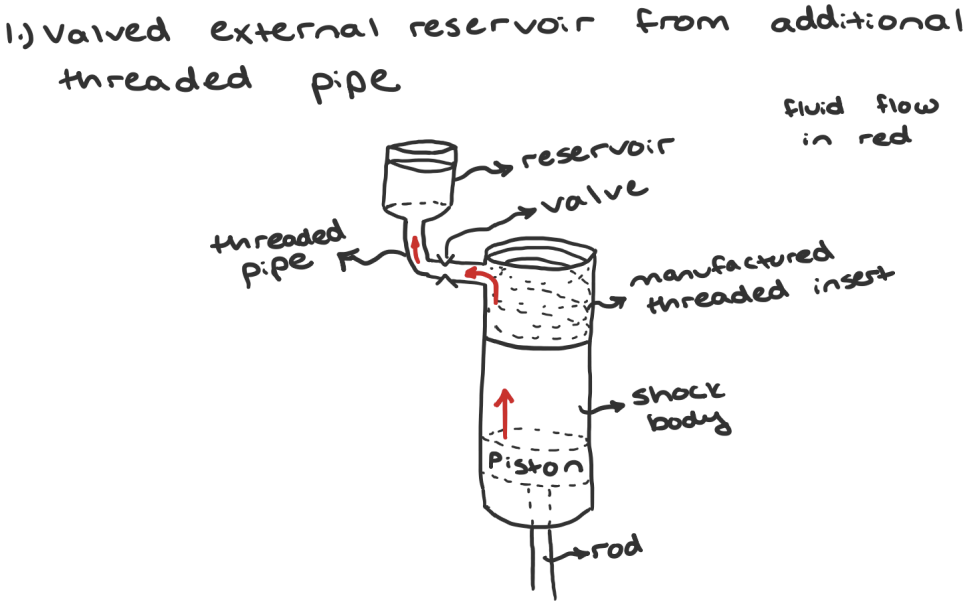


Figure 10: Design concept 1. This concept uses an external electronic valve and reservoir to regulate fluid and pressure inside of the shock.

As the shock compresses, the piston is pushed upwards into the upper region of the shock body. This movement causes the upper region of the shock fluid to be at a higher pressure. Under normal operation, the fluid flows down through the piston and is resisted by the shims, giving the shock damping. In this concept, some of the fluid under pressure is allowed to escape via an

electronic valve and into an external reservoir at atmospheric pressure. This would reduce the damping rate in compression. In rebound (shock extension), the upper region of the shock fluid is now at a lower pressure. This low pressure would pull fluid from the reservoir back through the electronic valve and into the shock, softening the rebound damping.

We then evaluated concept one against our user requirements of variable damping, driver actuatable damping, battery life, durability, safe failure modes, serviceability, packaging, manufacturability, weight, and social impact. Using a weighted scale by importance of satisfaction of each requirement and specification pair, we arrived at Table 3 for concept one.

Table 3: The weighted ranking of concept one. This concept scores well, especially in damping change, adjustability, and packaging. Weight is a concern.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	**Totals**
Max Points	10	8	5	3	6	2	7	4	6	1	45
Valved external reservoir from additional threaded pipe	8	6	4	2	5	1	6	4	3	1	40

Concept one scores well in this weighted ranking system. The mechanism will have good variability of damping due to simplicity of the design and mechanism. In addition, this design has advantages in battery life due to its low power consumption. Failure modes should be acceptable since most failures will result in the current damping rate becoming locked in place, and this design should be easy to package around the existing vehicle. The main disadvantage of this design is the potential weight gain by the addition of the valve and external reservoir in comparison to current shock.

The second concept uses an external valve as well, but in this case routes the fluid from one side of the shock into the other. This allows set amounts of fluid to bypass the shim stack and piston. Similar to concept one, concept two would see the inclusion of a valve. The amount ‘open’ the valve is would determine the amount of fluid able to bypass the shim stack and piston, then being routed from above the piston in the upper region of the shock body to the lower region. As shown in Figure 11, in compression, fluid at a higher pressure in the upper region of the shock body would be allowed to travel to the lower pressure area below the piston. This would reduce the pressure in the upper region, reducing the damping coefficient and resulting in a softer tune.

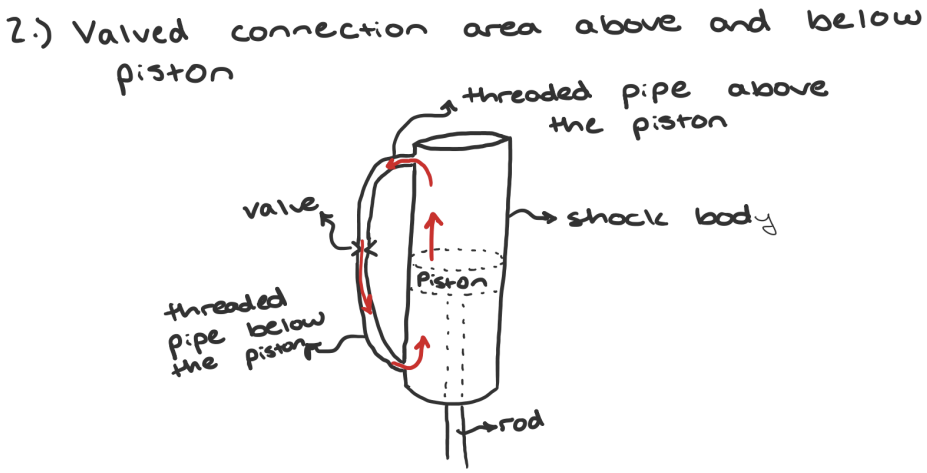


Figure 11: Design concept 2. This concept uses an electronic valve to route fluid from above to below the piston, thereby regulating pressure inside of the shock.

Concept two was also evaluated against our requirements and specifications. As shown in Table 4, concept two scores worse than concept one, specifically in the areas of failure mode and packaging constraints. Because the valved connection would need to be routed on the outside of the shock body, our team may run into conflict with exterior packaging. All MBR shocks are surrounded by springs, which see an equal compression to the shock itself. The valved connection would be routed through the springs so as the springs compress, they may clamp onto the connection. This may lead to a failure of the connection, potentially resulting in a leak of shock fluid. Not only would this render the shock unusable, but it could also harm the driver with no system left to absorb force into the vehicle. Finally, leaking shock oil is the only real impact our design could have on the environment. This should be avoided at all costs. Although concept two scores worse for these reasons, it has advantages over concept one. The elimination of the external reservoir also eliminates concerns about introducing external air into the shock fluid. Introducing air could be harmful to our design by leading to cavitation, or air pockets within the shock fluid, which harms shock performance.

Table 4: The weighted ranking of concept two. This concept has disadvantages in packaging and failure mode but is lighter.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	**Totals**
Max Points	10	8	5	3	6	2	7	4	6	1	45
Valved connection between area above and below piston	7	6	4	2	2	1	3	1	4	1	31

Concept three makes use of a moveable shim stack to create variable damping. In this design, some coil around the piston could induce a magnetic field inside of the shock body. This magnetic field would move the uppermost and lowermost shims above and below the piston respectively. Movement would result in separation from the rest of the shim stack, meaning fluid would have fewer shims to clear, thereby decreasing damping. The shims mainly provide resistance to the fluid as it moves, and so decreasing this resistance would result in a softer shock tune as the piston and rod are able to travel more freely through the fluid. A larger magnetic field would be able to move more shims, and likewise, further decrease damping. Once the current is no longer induced, shims would be able to return to their original position on the rod, returning damping to its original state. This design can be viewed in Figure 12.

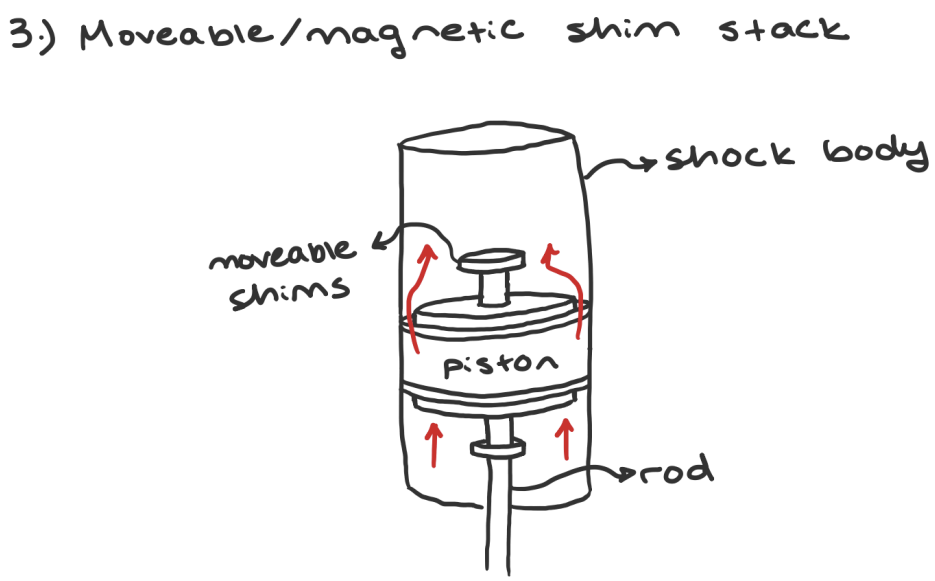


Figure 12: Design concept 3. Using an electric current, magnetic shims are allowed to travel up and down the rod, decreasing fluid resistance and damping.

When ranking the third design against our requirements and specifications, major benefits were found in external packaging. Since all components would be internal to the shock body, there would be no concerns about routing through the shocks or around the car. This idea is also lightweight, as the only real weight being added is the coil to induce a magnetic field. On the other hand, since all components are internal to the shock, serviceability would become next to impossible during a competition in the event of a failure. MBR is simply unable to take apart shocks during a competition as this process takes multiple hours. Since the endurance event is only four hours long, there is not enough time to take apart a shock. Because of this, any failure seen would render our concept unusable. This design also raises concerns about battery life. The

current would likely be turned on and off frequently, potentially draining battery life. More performance against requirements and specifications can be seen in Table 5.

Table 5: The weighted ranking of concept three. This concept would see easy external packaging, but harm to serviceability and battery life.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	Totals
Max Points	10	8	5	3	6	2	7	4	6	1	45
Movable/magnetic shim stack	8	2	3	0	5	0	7	0	5	1	31

Our fourth final concept involves the Afco 63 series shock. This shock has a hole inside of the piston rod which allows fluid to bypass the shim stack and piston itself. The tubing inside of the piston rod deposits fluid on the opposite side of the piston. The 63 series also has a separate rod inside of this tube. The rod, which is connected to a knob on the outside of the shock body, can cover the hole of the piston rod to varying degrees. By covering the hole in different amounts, a different amount of fluid is allowed to escape the shims and piston. A zoomed-in view of this idea can be seen on the right side of Figure 13. The rod inside of the piston rod is controlled via the knob. One click of the knob corresponds to a discrete amount of travel of the rod to cover the hole. Currently, MBR owns a set of these shocks for testing purposes, but the knob needs to be turned by hand. Our proposed design is to attach a servo motor to the knob, allowing for virtual control over the clicks of the knob.

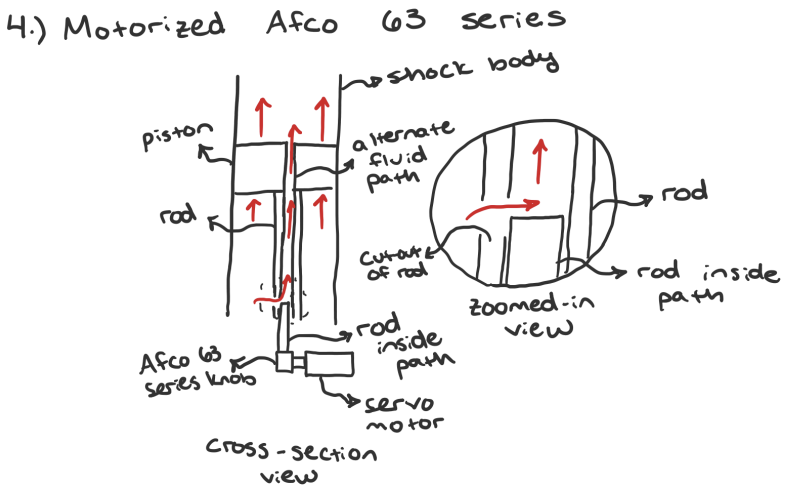


Figure 13: Design concept 4. A servo motor attached to the 63 series knob allows for different amounts of fluid to bypass the shim stack and piston.

This design has major advantages in manufacturing and cost. Since MBR owns a set of Afco 63 series shocks already, the only modification needed by our team is the integration of the servo motor. Minimal manufacturing would be required, and the only monetary cost to the team would be the servo motor and a motor controller. While this design may be easy to realize, the ability to vary damping is not as good as other ideas. Testing on the 63 series has been done already, and MBR does not see as large of a change in damping as we would like to create through this project. Additionally, any change in damping would be discrete - one click of the knob corresponds to a set amount of travel by the rod. One of the goals of our project is to create a continuous change of damping, which simply would not be possible with this concept. Table 6 shows the rest of concept four's performance against our requirements and specifications. Because adjustable damping is our most important requirement, concept four does not score as high as concept one.

Table 6: The weighted ranking of concept four. Advantages include manufacturability and weight, but the concept sees harm in adjustable damping.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	**Totals**
Max Points	10	8	5	3	6	2	7	4	6	1	45
Motorized AFCO 63 series	4	4	3	2	5	1	7	4	6	1	37

Our final concept makes use of rotating star shims. In the idea visualized in Figure 14, shims in the shim stack would have five circular cutouts matching the size of the holes in the piston. The shims would then be allowed to rotate around the rod via some motor or current. This rotation would allow for the holes of the shims to cover the holes of the piston in varying amounts. In a similar way to concept three, allowing more of the piston hole to be uncovered would create less resistance for the fluid to travel through the piston, leading to a softer tune. Once again, a path of less resistance allows the piston and rod to travel easily through the fluid, lowering the damping coefficient.

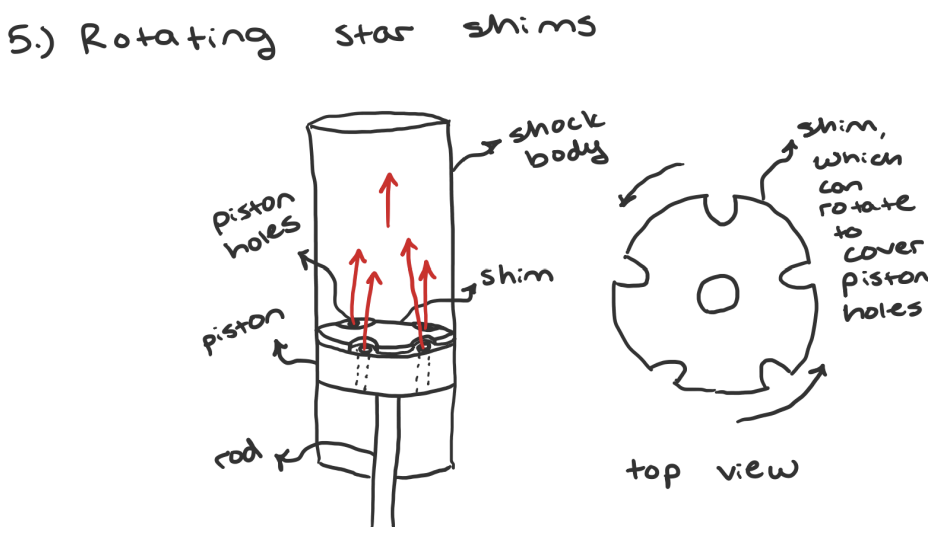


Figure 14: Design concept 5. Rotating star shims cover varying amounts of the piston holes, changing the resistance of the fluid, and therefore damping.

Concept five sees the worst performance against our requirements and specifications. Similar to concept three, manufacturability and serviceability are not as good in this design. Components are internal to the shock body, eliminating the ability to service failure at a competition. The manufacturing is the most difficult of our concepts since all parts would be small. Additionally, the mechanism that controls the rotation of the shims may drain battery life at competitions. Although this design has drawbacks in the aforementioned categories, it also has benefits in exterior packaging and weight, as shown in Table 7. Any weight addition would simply be from the mechanism controlling rotation. Finally, concept five would see no concerns in exterior packaging as all components would likely be internal to the shock body.

Table 7: The weighted ranking of concept five. The worst performing design, concept five has major drawbacks in manufacturability and serviceability.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	**Totals**
Max Points	10	8	5	3	6	2	7	4	6	1	45
Rotating star shims	3	4	3	0	5	0	7	2	5	1	30

Following the individual ranking of each proposed concept against requirements and specifications, results were compiled into one easy-to-read Pugh Chart, shown in Table 8. The

compilation shows concept one as the clear winner. It creates the greatest ability to adjust damping, which is truly our most important specification and the main point of our project. Additionally, concept one has few concerns with mechanism failure and fits into external packaging constraints reasonably well. As previously described, the major drawback to this concept is its added weight stemming from the adaptor, valve, external reservoir, and additional shock fluid to compensate for the increase in volume.

Table 8: Weighted rankings compared across all designs. This comparison shows concept 1 as the winner.

Requirement	Adjustable damping of suspension	Driver/vehicle actuates change in damping	Battery life lasts one competition	Durable	Adjustment mechanism's failure mode does not render car undrivable	Serviceable	Product fits vehicle packaging constraints	Manufacturable	Lightweight	No negative social impact	**Totals**
Max Points	10	8	5	3	6	2	7	4	6	1	45
Valved external reservoir from additional threaded pipe	8	6	4	2	5	1	6	4	3	1	40
Valved connection between area above and below piston	7	6	4	2	2	1	3	1	4	1	31
Movable/magnetic shim stack	8	2	3	0	5	0	7	0	5	1	31
Motorized AFCO 63 series	4	4	3	2	5	1	7	4	6	1	37
Rotating star shims	3	4	3	0	5	0	7	2	5	1	30

The Pugh Chart above led us to select concept one, the valved external reservoir. This was actually our initial idea as a team when we first met and discussed the project. This initial design was influenced by repeated previous discussions with the Baja team over the last year as we formulated this project. At face value, this might appear like an extreme fixation on the initial idea, but we fully explored the solution space. By benchmarking current solutions and a variety of concept generation techniques we were able to brainstorm a wide variety of concepts. Then via our down-selection process, we arrived at this region of the solution space, focusing on changing the fluid flow of the shock. From here we used the Pugh Chart above to fairly and quantitatively compare all of the concepts in this narrower solution space, eventually leading to our selected concept. Our selected concept will not benefit from more concept development at this stage, any changes will come from engineering analysis, prototyping, and testing. The solution space has been fully explored, and our initial idea best meets the user requirements and specifications.

3.3 Selected Concept Description

Our selected concept is a valved external reservoir from an additional threaded connector. In this design, our team will manufacture an extension adaptor piece which will thread into both sides of the shock. As shown in Figure 15, Afco 64 series shocks include a shock endcap, allowing the body filled with oil to be bolted to a vehicle. The endcap is attached to the shock body through mated threads.

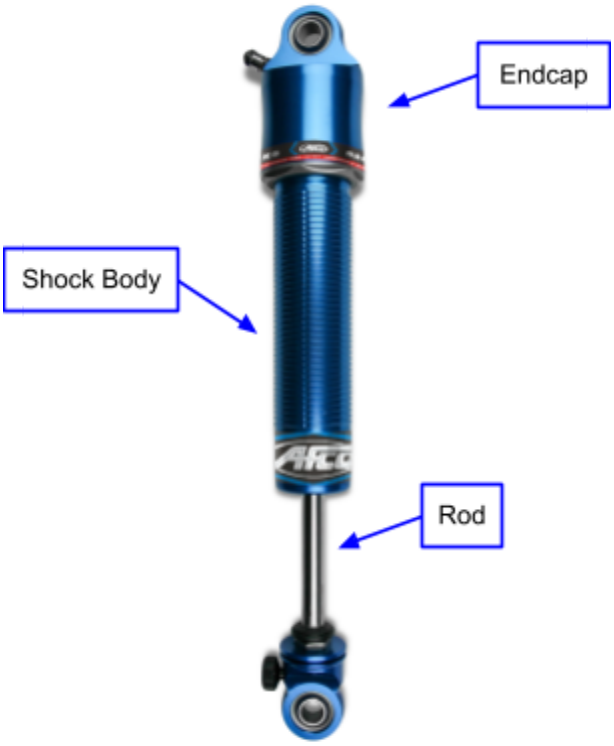


Figure 15: Afco 64 series shock diagram

Our extension piece will match these threads on both sides, allowing our piece to function simply as a volume/length extension piece. The initial CAD for this piece can be seen in Figure 16. The piece will then see a hole drilled into its side, as well as a flat surface surrounding the hole to ensure concentricity. Finally, the hole will be tapped to accommodate a male NPT valve, which is commonly used in the plumbing industry to encourage a proper seal around the hole.

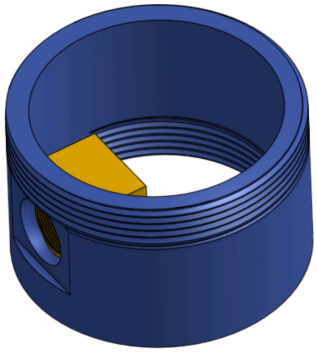


Figure 16: Initial CAD of the proposed extension piece

Following the completion of the threaded adaptor extension piece, the shock can be filled with fluid to accommodate the increase in volume. The valve will then lead to an external reservoir of shock fluid held at atmospheric pressure. A diagram of the integration of these different components can be seen in Figure 17.

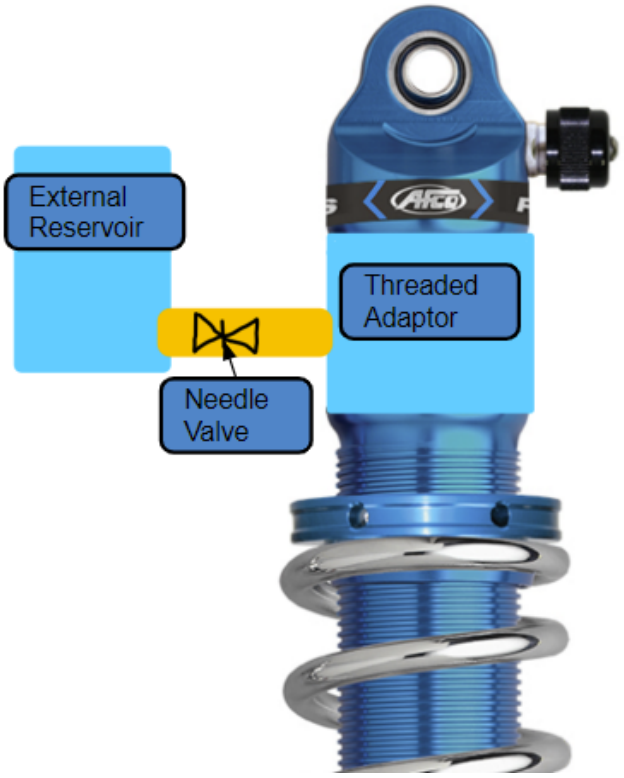


Figure 17: Integration of components for selected concept

This design will work through the amount ‘open’ that the valve is. In shock compression, a more open valve will allow for larger amounts of fluid to have an alternate path of escape through the external reservoir. That amount of fluid will be able to bypass the piston, reducing pressure in the upper part of the shock body and, by extension, lowering the damping coefficient. This lower damping coefficient would correspond to a softer tune, or the piston being able to move more easily through the shock fluid. A diagram of this path of fluid flow can be seen in Figure 18. Using a mechanical valve will allow our team continuous control over the amount ‘open’ the valve is, meaning we will have continuous control over the damping ratio. Theoretically, opening the valve all the way will correspond to the lowest possible damping ratio of our system in compression.

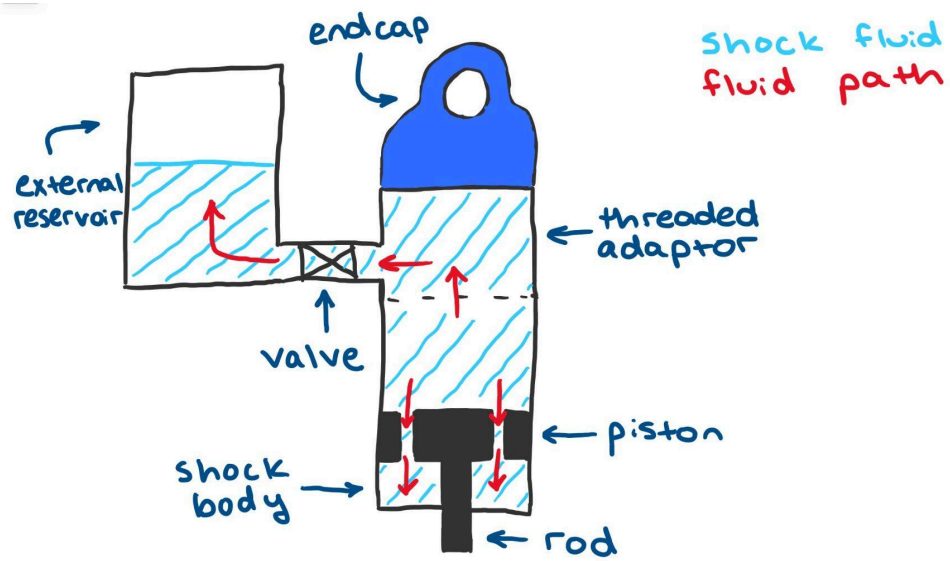


Figure 18: Path of compression fluid flow in selected concept

To meet our stretch goal of incorporating some control system into our design, we could modify our design hardware by simply attaching a stepper motor or servo to the valve knob. The motor would then be controlled such that damping can be adjusted via button, knob, preset, or sensor inputs. Once inputs have been defined, if the system determines a softer tune in compression is needed, the stepper motor would receive information to open the valve further. This actuation of the stepper motor would also be able to come from manual input, whether that’s pulling the car in before an event and updating software or driver input via buttons on the steering wheel or some other mechanism.

The selected concept satisfies our engineering requirements, including our most important requirement of allowing for adjustable damping of our suspension system. As described above, damping will be adjusted through the amount of ‘open’ the valve is. This concept also fits

external packaging requirements quite well, as the only components being added to the shock body would be the valve and reservoir. If needed for vehicle packaging, the reservoir could be routed to some other location via tubing. The addition of the extension piece eliminates the need to route any components through the springs that surround our shock, eliminating any concerns of component failure as a result of spring compression onto components. This idea can be seen in Figure 18 above, which shows that all components will be integrated above the springs. Any increase in shock length seen because of the threaded piece is not a concern, as it will not affect any other suspension points in our vehicle. The biggest downside to our selected concept stems from the weight addition onto the vehicle. Additional weight will come from the threaded extension piece and additional fluid to fill the increase of volume, valve, and reservoir.

The selected concept was chosen due to heavy sponsor influence, but only because we are our own project sponsor. Any influence from sponsors was due to our own personal biases. If there were external factors influencing our decision, it would likely be due to our benchmarking. We spent a lot of time at the start of our project researching past project attempts, industry solutions, and the solutions of other Baja teams. Most of our research pointed to an external valve being the optimal solution. During concept generation and downselection, it was sometimes difficult to ignore that an external valve is considered the “solved” method. While this may have impacted our initial concept generation, our objective selection process did not point a different way. No numbers in our Pugh Chart were “fudged” to meet the expectations set by the course. If anything, our deep research into the subject and benchmarking of other solutions led to a greater understanding of each of the final five concepts. This actually made it easier for our team to score designs objectively. While it is probably true that our biases impacted our final selection, our understanding of our design problem and other successful solutions of the problem allowed us to accurately score our concept’s performance against our requirements and specifications.

The selected concept is defined well enough to be analyzed rigorously using engineering concepts. Analysis will be required mainly to ensure our design will not see any limitations in fluid flow due to the size hole drilled into the side of our extension piece. Fluids calculations will be able to help us find an optimal hole size. We will also need to ensure that our extension piece will be able to withstand stress induced by the pressure of the shock oil in combination with external axial forces. Simple pressure vessel statics calculations will allow us to check for this failure. Additionally, results from these calculations can be verified using computational tools. Finally, we will need to ensure that the size hole we drill into the extension does not induce any additional stress causing failure in the piece. Stress concentration calculations will be sufficient in checking this constraint. It is in these ways that our selected concept is well defined. The project itself is only difficult to achieve within the constraints of ME 450. Given more time for verification and validation, our team would be confident in finding a viable solution to the problem. Because successful benchmark solutions are so well defined, however, the project itself does not seem difficult. The main difficulty with our project is simply the time constraints. There

are additional considerations within our stretch goal of closed loop control, but once again, successful benchmark solutions are very well defined. The most difficult part of incorporating control is determining the correct inputs, which more in-depth research should be able to help with.

3.4 Problem Analysis and Iteration

In order to ensure our selected design meets our engineering specifications, we first need to identify the relevant specifications to analyze. Our most important requirements include having a wide range of damping, low power consumption, being durable, fitting vehicle packaging, and being lightweight. Weight and size can both be easily analyzed in CAD, where assigning a material can tell us the product's weight. Placing the 3D model in an assembly with the entire car will validate whether it fits vehicle packaging constraints.

Before any serious analysis is undertaken, we need to ensure our idea will work. On a basic level, we need to validate that adding a valve to our shock that can vary the shock body's exposure to an external reservoir held at atmospheric pressure will vary the damping ratio of the shock. The parts used to construct the testing rig are outlined below in Figure 19. Although we explore the theoretical calculations needed to prove this later, this empirical test will give us concrete proof the idea will work, as well as a chance to construct a very crude prototype to help visualize the construction of a final product.

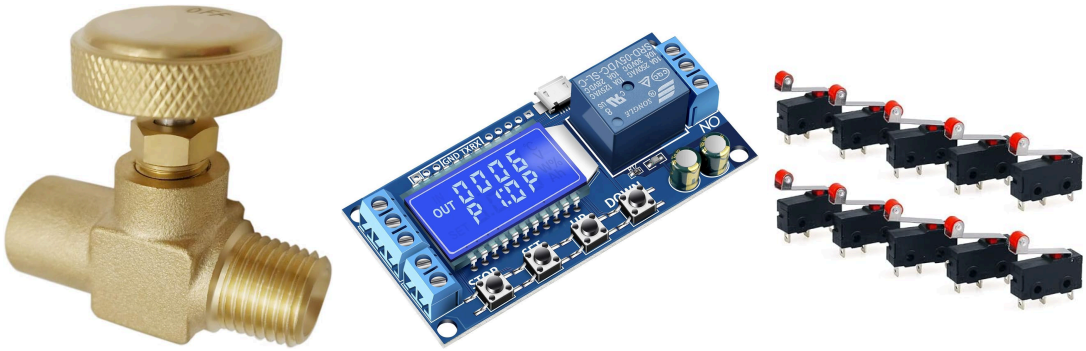


Figure 19: Initial test tools from left to right: manual needle valve, timer, limit switches

Ensuring the durability of the product will first require basic static calculations using combined loading of the car's weight under 3g's (simulating our maximum load case from a drop of six feet), as well as an internal pressure given by our shock's maximum pressure. These numbers, as well as additional variables like material properties, wall thickness, and hole size, can be plugged into a pressure vessel stress equation to ensure the stress seen by the part is under the tensile yield strength of the material, including a safety factor.

After these hand calculations are performed, a more accurate finite element analysis (FEA) will be conducted using 3D models of our parts and the same material properties and load conditions as in the hand calculations. We expect to see similar results when comparing the FEA and hand calculation maximum stresses. If they deviate by more than 20%, we may need to revisit our assumptions, loading conditions, and/or simulation setup to ensure the results are accurate.

Determining power consumption over the competition is a simple power equation which will ensure our battery life is greater than the 6 hour specification. Assuming we use four 21700 cells, one for each shock, our battery pack will weigh around 0.6lbs and have a total energy capacity of 72Wh (4 cells * 3.6V nominal * 5000mAh). That means that our actuation mechanism must have an average power draw of less than 12W over the competition (72Wh / 6 hours). Assuming we use an Adafruit mini stepper motor to turn our valve, and it is in constant use, we can expect to see a power draw of 9.36W (4 motors * 3.9V * 600mA). This means our batteries will have just enough energy to power our product for the entire rated period.

Next, we need to determine what valve opening corresponds to what damping coefficient. This will allow us to purchase an appropriately sized valve, as buying something with too small an opening would limit our ability to vary damping. On the other hand, a valve with too large of an opening would be heavier than necessary and harder to implement. It will also give us a good correlation to determine what position to set our valve to achieve certain damping rates. This will be done with Bernoulli's equation in Appendix C.

To gather the shock body pressure to use in our Bernoulli's equation and static analysis, we need to put a pressure sensor on our shocks. Empirical methods are required in this scenario because shock behavior is too complicated for hand calculations and a simulation is less likely to give accurate results. To gather the pressure data, we will hook up a pressure sensor as seen in Figure 20 to our shock and read the data with an Arduino Uno, both of which the Baja team already has. Since the pressure sensor operates at 10V, the Arduino reads data at 5V, and we will be powering this system using two 9V batteries in series, we will need to construct two voltage dividers. The first will be between the power supply and the pressure sensor using a 1kΩ resistor and several resistors summing to 800Ω. The second divider between the pressure sensor output and the Arduino will use two 15kΩ resistors. Finally, the Arduino will read data onto an SD card to enable portable data acquisition. Since sensor voltage is proportional to pressure, we can take one reading at atmospheric pressure and another at a known pressure using the Wilson Center's air compressor to get a baseline reading to convert future voltage outputs into pressure readings.



Figure 20: Pressure sensor

3.5 Problem Domain Analysis and Reflection

In our engineering specifications, we may face challenges in consistently measuring our damping coefficient. This difficulty will make it hard to measure our engineering specification of "2000 Ns/m < Damping coefficient < 10000 Ns/m at 0.25 m/s shock speed". The damping coefficient of a shock can accurately and consistently be measured on a shock dynamometer. This device records how much force is outputted by the shock and the velocity of the shock's piston travel. Unfortunately, our group does not have access to this equipment, so we will need to come up with a procedure to accurately measure these values in order to consistently measure the shock damping coefficient. One system we attempted to create involved hanging a known weight from the end of the shock and measuring the amount of time it took to travel a known distance between two photogates. This data could then be used to plot our damping coefficients against shock speed. However, while creating this testing rig, we realized the photogates provided extremely unreliable results, so we plan to revisit this solution using a timer and two limit switches.

Another anticipated challenge our group will face is the dimensional constraints of the shock. Not only will we need to design without interfering with the vehicle's chassis and within the crash radius of 7", but we are also limited by the current shock dimensions. These constraints will limit the area of fluid flow our mechanism will be able to utilize. This issue may be addressed by making sure our components are as small and lightweight as possible, in order to stay within the necessary dimensions. However, this could lead to size issues if larger areas for fluid flow are required. In order to solve this problem, we will need to review our knowledge of fluids, especially fluid viscosity and Bernoulli's equation as it relates to the interaction between flow rate, area, and pressure.

Additionally, our group may face problems in defining and testing failure modes. Given that none of our interviewed stakeholders had any experience building or using adaptive suspension systems, we don't know what possible failure modes exist, aside from shorting or disconnection

from the battery. This could lead to difficulty in certainty that no failure mode would render the shock useless, which is one of our most important specifications.

One more challenge we plan to tackle is the extreme forces our mechanism will have to go through. Not only will it be subjected to large forces coming from the car taking jumps and hitting obstacles, but also high pressures from shock actuation compressing and pressurizing shock fluid. As seen in Figure 21, Baja vehicles undergo massive forces that can cause component failure. These critical problems will be addressed with knowledge of statics including structural analysis, pressure vessels, and FEA.



Figure 21: Sample shock failure mode

Finally, in completing our stretch goal of a closed-loop controller for our system, our group may struggle to correctly define the controller inputs, as well as for the mechanism to respond before an obstacle is cleared. Knowing exactly what state a shock should be in, either for a given user input of ‘event mode’ in the case of adaptive suspension or sensor input in the case of semi-active suspension, will require a large amount of iterative testing and tuning.

Another domain that we need to review in order to solve our problem is that of communications protocol since we will need to adjust the damping based on either user or computed input. In order to solve all problems where information gaps exist, especially in the realms of

communication protocols and fluid dynamics, we will reach out to University of Michigan professors with relevant experience and ask for their advice and guidance.

4. DR3 Material

4.1 Engineering Analysis

In order to spec the components for our project, both for in-house manufacturing and online purchasing, we needed to conduct engineering analysis. To determine which type of analysis we needed to run on our components, we constructed Table 9 below.

Table 9: Analysis type for all components

Component	Analysis Type	Analysis Purpose	Justification
Shock Adaptor	Pressure vessel and FEA	Outputs max stress and safety factor	Ensure component meets stress specification
Valve	Bernoulli's	Outputs valve max required opening	Ensure product meets range of damping specification
Motor	Energy and power	Outputs battery life hours	Ensure product meets battery life specification
Reservoir	Volume	Outputs required volume	Ensure shock doesn't leak or get air bubbles
Full Assembly	Measure	Output total radius	Ensure product meets packaging constraint specification
Full Assembly	Weight sum	Outputs total weight	Ensure product meets weight specification

4.1.1 On-Car Pressure Testing

The first component we analyzed was the shock adaptor - the component that would allow us to insert our valve assembly into the existing shock without having to modify the shock itself. First, we needed to know the loads that this component would see. From previous Baja testing using a wheel force transducer, we knew that the maximum axial load on the shock, and therefore the adaptor, is 14kN. We also needed to know the maximum pressure inside the shock. Since determining this value computationally would be extremely complicated and well outside the scope of the class, we decided to test the maximum internal pressure empirically. As described in

section *3.4: Problem Analysis and Iteration* and shown in Figure 22, we hooked up a pressure sensor onto our shock.



Figure 22: Pressure sensor hooked up to our shock on car

We then brought the car to the track and used an Arduino to determine the maximum pressure seen in the shock in our maximum load case: taking the car off a six foot drop as seen in Figure 23.



Figure 23: Taking the Baja car off a six foot drop and measuring the max pressure load case

4.1.2 Shock Adaptor Pressure Vessel Calculations

The results of this test was a minimum pressure of around 0 psi and a maximum pressure of 1438 psi. Now that we had obtained the pressure, we could do a theoretical pressure vessel calculation

to ensure our shock adaptor meets the Baja car-wide safety factor of 1.2 as described in our specifications. For these calculations, we used a thickness of 0.4” to ensure proper thread engagement for our NPT fittings, an outer diameter (OD) of 1.8” to match the current shock body, a length of 2.82” to give our fitting adequate spacing and to accommodate threads on either end, and chose aluminum 7075 as our material since it could be provided by the Baja team. Looking at our calculations in Appendix C, Part 1, it is seen that we get a resultant maximum stress of 15,099 psi, which when compared to aluminum 7075’s yield strength of 21,000 psi, gives us a safety factor of 1.4. This safety factor meets the specified car-wide safety factor of 1.2, which justifies the thickness and material choice for the adaptor component.

4.1.3 Pressure Vessel FEA

Next, to double check our stress calculation results and get insight into maximum stress locations, we ran FEA on our shock adapter. The inputs were fairly simple: the end connected to the car gets constrained in all degrees of freedom, our maximum axial load is input into the bottom surface where the shock comes in contact with the adapter, and finally the pressure load is applied to the inside surface. These loads are summarized in Figure 24 below.

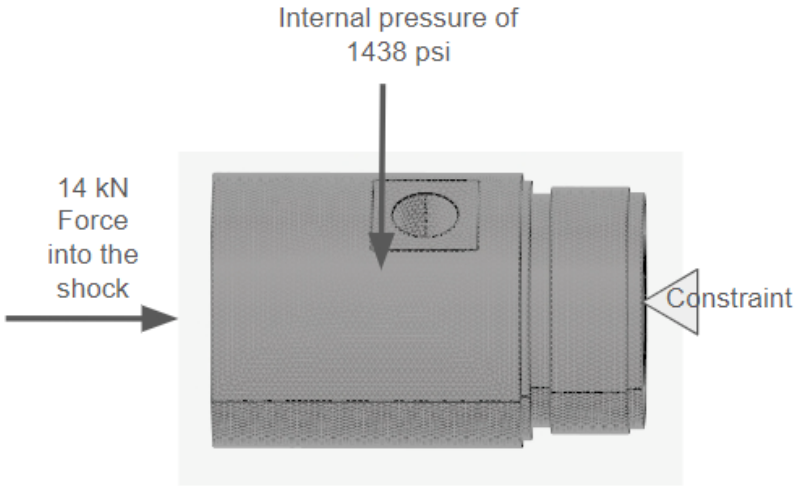


Figure 24: FEA loads and constraints on shock adaptor component

Using Hyperworks Optistruct, we ran our analysis and got a result of a maximum stress of 81MPa, as can be seen in Figure 25.

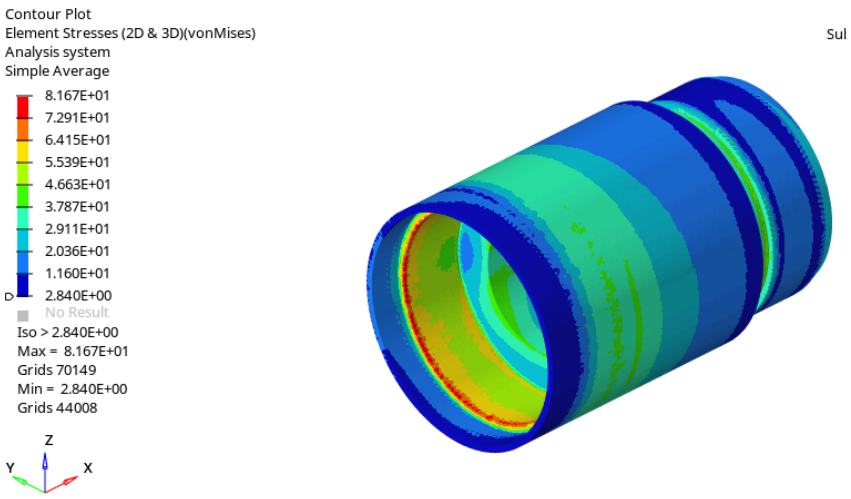


Figure 25: FEA results on shock adaptor component

This result of 81MPa, or 11748 psi, when compared to the 21000 psi yield strength of 7075 aluminum, gives us a final safety factor of 1.8. This is a fairly similar result to our theoretical calculations, so it validates our results. Looking at the contour plot of stresses, it can be seen that the maximum stress occurs where the adaptor comes in contact with the shock, and not on the outside of the adaptor. This is a promising result because it means that even if our shock fails, it will not leak.

4.1.4 Valve Aperture

The next component we needed to spec was the valve. We decided to purchase an existing valve, since constructing our own would be a very complicated process that is outside the scope of this course. This valve needs to have a removable knob so it can easily be mated to the motor for easy torque transfer. Our specification of surviving maximum load cases indicates that the valve needs to be rated for at least 1438 psi. Finally, the aperture, or the opening area of the valve through which fluid flows, needed to be determined. Our specification of having a range of damping occurs by varying the valve opening size. By setting up Bernoulli's equation with minor losses for the valve and ignoring gravity terms since they will be negligible, we arrived at a final equation that gave us the maximum valve aperture required. The full computations and variable definitions are outlined in Appendix C, Part 2.

$$A_2 = A_1 V_{piston} A_{shock} \sqrt{\frac{V_{piston} A_{shock} \sqrt{\frac{\rho}{1000(P_2 - P_1)}} + 1}{2P_1 a_1^2 - 2P_2 a_1^2 + V_{piston}^2 A_{shock}^2 \rho}}$$

This resulted in $A_2 = 0.022in^2$, which when assuming the valve opening is a circle, gave a diameter of 0.19". Since we need to use standard fitting size, we opted to use a ¼ NPT valve, since NPT fittings taper and would ensure fluid won't leak. Now that we determined thread size, pressure rating, and knob requirements, we were able to spec our valve as described in the BOM in section 4.2 below. Given the complexity of fluid systems, we do not have complete faith in this result but given the slight oversize in fittings (0.25" > 0.19"), we think this should account for any overlooked or unincluded aspects of this equation.

4.1.5 Motor Spec

To pick a motor for our project, we knew it needed to make several full rotations to turn the valve, be able to accurately and discretely stop at certain locations for our valve presets, and have enough torque to turn the valve. The requirement to make several full rotations rules out the use of a servo motor since we do not want to use any gearing that would add to the complexity of the model. The requirement to stop at discrete locations rules out the use of a simple DC motor. Based on this, we decided to use a stepper motor. Additionally, the motor we chose has a stall torque above the operating torque of the valve while still being as small as possible.

4.1.6 Battery Life Calculations

To ensure our motor and battery met the specification of battery life lasting a full competition of 6 hours, we needed to run a simple power calculation. Using four 21700 cells and four mini stepper motors (one of each for each shock), we will achieve a minimum battery life of 7.7 hours. This assumes the motors are run constantly at max power, so it is a very safe estimate. The calculations are detailed in Appendix C, Part 3.

4.1.7 Reservoir Sizing

To ensure our reservoir is large enough as to not leak fluid when the shock is fully compressed, or allow air into the shock when it is fully extended, it needs to be properly sized. To do this, we needed to make sure the volume of displaced fluid would be fully able to fill the reservoir. Since the volume of the piston that displaces fluid is $1.378\ in^3$, and the diameter of the reservoir needs to be $7/16\ in$ to fit a ¼ NPT fitting, the resultant length needs to be at least $9.167\ in$. Calculations are detailed below in Appendix C, Part 4. There are other contributors to the possible fluid overflow into the reservoir like added energy from piston velocity, so we oversized the reservoir. We also 3D printed the reservoir so if the volume is too small, it will be very simple to re-manufacture larger. Since there will be virtually no loading on the reservoir, the thickness is only relevant to ensure proper threads can be tapped. Material was selected as 3D printed resin to conserve budget and weight. The same can be said for the barb fittings and tubing we used, which are under virtually no pressure and as such were only selected to be cheap and match existing dimensions.

4.1.8 Packaging

To ensure our product meets the requirement of fitting vehicle packaging and specification of being less than 7” in diameter, we used the measure tool in CAD, which showed a maximum radius of around 6”. This ensures that our product will not collide with the ground in the case of a rollover. More detail is not needed in this analysis due to its simplicity as we are confident the design will survive a rollover.

4.1.9 Weight

Finally, to ensure our product meets its weight specification of being under 1kg, not counting the shock, we added the weights of all components as seen in Table 10 below. The primary contributors to our weight are the valve and shock adaptor, due to their large wall thickness to survive the high pressures they will see. Ultimately, the actual weight of 0.539kg is much less than our specification of 1kg per shock. This analysis is not highly detailed and neglects some minor components like wires, but since our weight is so far under the requirement, we are not worried about getting a perfect result.

Table 10: Constituent weights of all components

Component	Weight (kg)
Motor valve assembly	0.267
Weight of reservoir	0.026
Shock adaptor	0.155
Tubing + connectors + shock oil	0.091
Total	0.539

4.2 Final Design Description

The final design we chose for the solution to our project was an adjustable external valve leading to an external reservoir. When the piston in the shock compresses, the valve allows the internal pressure of the shock above the piston to decrease by allowing some fluid to escape out into the reservoir. The external valve will be controlled by a motor to turn to discrete positions, giving varying amounts of fluid an escape, and therefore allowing us to vary our damping coefficient. The main components of our system consist of a shock, custom shock adapter, valve, motor, housing, and reservoir. Our design is mounted through the shock adapter between two parts of the current shock, and the reservoir is attached to the side of the car’s frame. To get a better

understanding of our final design, Figure 26 below shows the final CAD of the adaptive shock on the car and an exploded view.

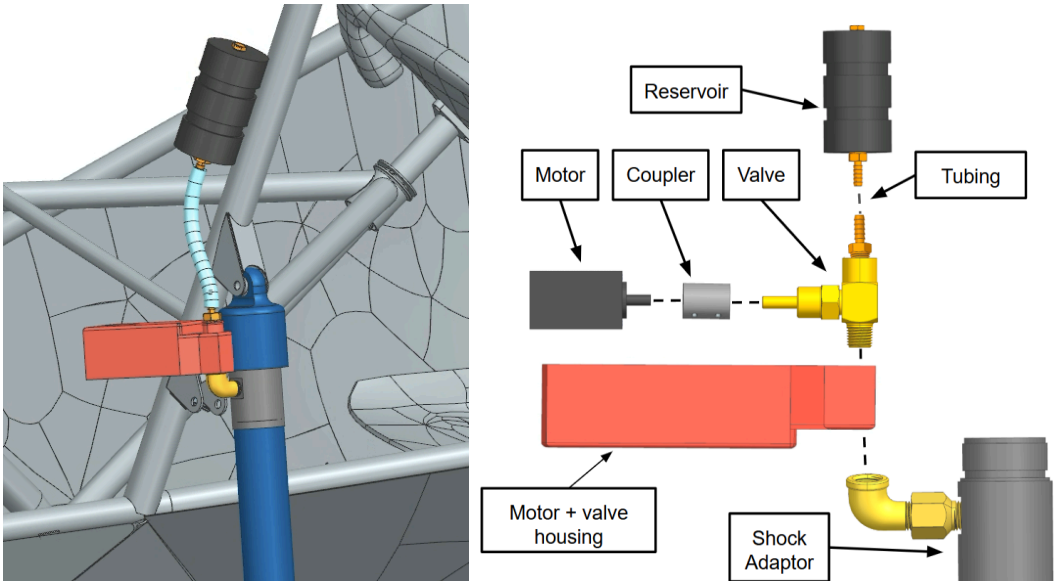


Figure 26: Figure A shows the full assembly mounted to the front left corner of the Baja vehicle. Figure B shows an exploded view. The shock adaptor attaches to the shock, and reroutes shock fluid out of the shock through a valve connected to a motor, and then to a reservoir holding fluid to atmospheric pressure.

The shock we are using for our design is an AFCO 64 series shock, seen below in Figure 27. We chose this component because it is the current shock used by the Michigan Baja Racing team, and they are providing us with it.



Figure 27: Michigan Baja Racing's current AFCO 64 series shock. This is also the shock we are using in our final design.

The shock adaptor was designed to be an extension of our shock. It provides us with a location to mount our system without drilling a hole in the shock body. As seen in Figure 28 below, we designed this component around the dimensions of the existing shock body while matching the thread size on the shock. The overall dimensions of the adaptor are about 3 inches in length and a maximum diameter of 1.8 inches. Additionally, we utilized the material Aluminum 7075 for this component because it was the same material that the shock body is made of, and the Baja team is able to provide the required stock. In order to prevent the adaptor from leaking, we also match the O-ring grooves that are on the shock body so that the shock O-rings will properly compress. We later validated that the material and design would hold to the loads experienced by the shock by running it in FEA. The results of this analysis can be found in section *4.1 Engineering Analysis.*

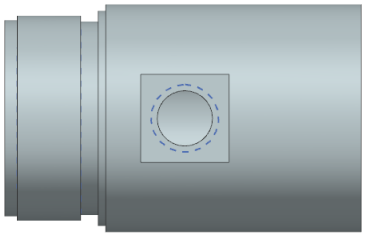


Figure 28: Custom shock adaptor

Next, the valve we chose for our project was a ¼ NPT needle valve. This component will be purchased due to the time constraints of our project and the required complexity to design and manufacture a valve. The main factors that led to this choice of valve was its pressure rating and its cross sectional area of the max hole size. The pressure requirement for the valve is the same as the maximum pressure inside the shock. This maximum pressure was obtained by putting a pressure sensor inside of one of the shocks on the Baja car and driving the car over multiple obstacles. More details about this testing process can be found in *4.1 Engineering Analysis*. In order to determine the maximum cross sectional area for the valve, we used Bernoulli's equation along with our maximum pressure value. More details about these calculations can also be found in *4.1 Engineering Analysis*.

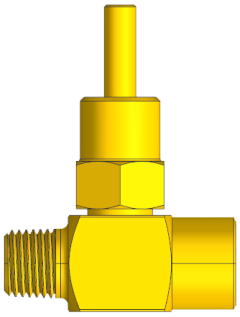


Figure 29: ¼" NPT needle valve.

The reservoir in our design will be 3D printed out of resin. The overall design can be seen in Figure 30, below. The internal volume of the reservoir is based on the volume of shock fluid displaced by the piston. The material we chose to use for this component is aluminum 6061 because it is lightweight, and the Baja team is able to provide the required stock. One key feature on our reservoir is the breather vent on the top. This vent is there to maintain atmospheric pressure inside of the reservoir while preventing any fluid from leaking out of our system. The breather vent is a purchased component and will be bought from Grainger.



Figure 30: Reservoir

Another major component we selected was our motor. The main requirements for our motor were the need to provide enough torque to spin the valve, to be able to spin several rotations, and stop at exact locations. Therefore the motor we chose was a stepper motor that is easily controlled with an Arduino motor shield.

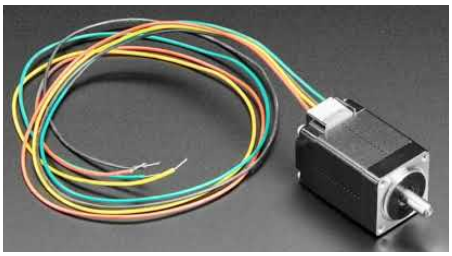


Figure 31: Stepper motor

Finally, our last designed component was a housing to hold our motor and valve. The goal of the housing is to keep any dirt or debris from getting into our system. This component was 3D printed out of resin.

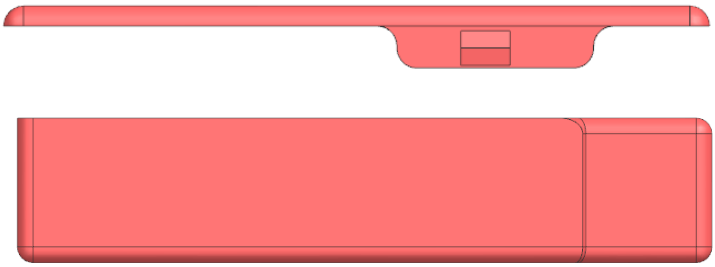


Figure 32: Motor and valve housing

The additional components needed for our design, as well as the components listed above, can be found in section *12. Bill of Materials*.

To verify our design, we built a full scale prototype as seen below in Figure 33. This prototype, assuming it meets all of the specifications, will become the final product since the Baja team is based on campus and has access to the same manufacturing resources that we do.

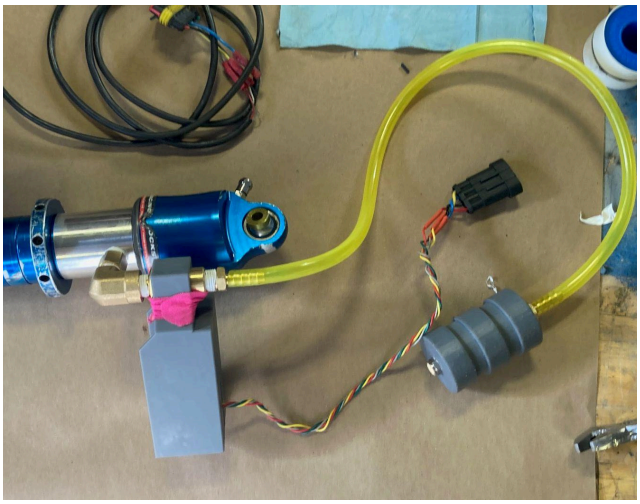


Figure 33: Final assembled prototype

Springs were then added to the prototype and it was attached to the Baja car as seen below in Figure 34. Connection points include the upper and lower shock mounting points using the same 5/16 bolts Baja already uses for shock mounting, as well as zip tying the reservoir to the frame.



Figure 34: Final prototype mounted to the Baja car

Now that the prototype shock was attached to the car, we could proceed with its verification and validation.

4.3 Verification and Validation

A verification plan has been identified for each of our requirements and specifications. The plans for each of our most important specifications will be described in detail, while the plans for each specification can be found in Table 13 below.

Table 13: Verification and validation plans for each requirement and specification. Our most important requirements are highlighted, and the corresponding plan will be described in detail.

User Requirement	Engineering Specification	Verification/Validation Plan	Results
Adjustable damping of suspension (Perl)	2000 Ns/m < Damping coefficient < 10000 Ns/m at 0.25 m/s shock speed	Re-run initial adjustable damping test with same rig and motorized prototype	Damping rate does not vary significantly
Driver/vehicle actuates change in damping (Perl)	> 3 presets for driver to adjust damping Vehicle responds to continuous input within 150 ms	Re-run initial adjustable damping test with button presets, receive driver feedback post-mock endurance race	7 button presets
Battery life lasts one competition (Grover)	Battery life > 6 hrs	Run motor setup for 6 hours	Motor ran >6 hours of constant use
Shock survives max load case (Grover)	No yield in 14 kN axial force and 1438 psi internal pressure	Attach prototype to vehicle, drive over 6-foot dropoff	Shock survived drop test
Mechanism failure mode does not render car undrivable (Gariepy)	Mechanism failure modes result in 2000 Ns/m < Damping coefficient < 10000 Ns/m	Manually cause software failure by disconnecting battery, test damping coefficient using adjustable damping testing rig	Damping rate maintained after power failure
Serviceable (Stack)	Internal components replaced in 30-60 minutes	Tear mechanism down to Afco 64 series, rebuild with timer	Shock rebuilt in 48 mins
Conforms to Baja SAE rules (Grover)	B.9.3 - Pinch Points and Entanglement, B.10.1 - Power Sources, B.10.2 - Wiring and Connectors	MBR Team Captain runs mock technical inspection using Baja SAE published tech inspection sheets	Mock inspection passed
Product fits vehicle packaging constraints (Grover)	Product doesn't interfere with vehicle chassis and is inside crash radius of 7"	Attach prototype to vehicle, manually 'roll' car by flipping it 90 degrees	Car rollover test passed
Prototype satisfies the project budget (May)	< $650 for prototype ($250 is coming from the sponsor)	Document all purchases, ensure final number is under $650	Total of $143.7 per mechanism
Manufacturable (Hetrick)	All custom components are machinable using tools available in the WSTPC	Throughout design process, only consider manufacturing which can be done in WSTPC	Used only WSTPC tools
Lightweight (Grover)	Product weight < 1kg heavier than existing shock (2.37 kg)	Weigh all components of final prototype	Final weight 0.84kg heavier
Product minimizes environmental costs (May)	Energy use costs < $0.10 per year of use Environmental use costs < $0.15 per year of use	Combination of 6-foot dropoff and electronic failure to ensure no shock fluid leaks, no harm to driver	Passed all tests

The first test conducted was a proof of concept, used to ensure that our design would yield different damping coefficients with the valve fully open vs fully closed. This test saw the rod of our shock fully compressed and the shock itself mounted to a shelf via the endcap. We selected a known weight, attached it to the shock rod, and released the rod, allowing the shock to extend and simulate the rebound region. Two limit switches, which were a known distance apart, were also used in the experiment. As the rod extended, it tripped the first limit switch, activating a timer. Near full extension, a second limit switch was activated to stop the timer. With a known distance traveled by the rod (the distance between the limit switches) and a known travel time (the timer results), the rod velocity was calculated. This velocity was plotted against the known force, the slope of which yielded a damping coefficient. The final piece of the experiment was the valve, which was screwed into our shock adaptor. The other end of the valve was connected to a water bottle, which simply served as a makeshift reservoir, one which would allow us to observe the behavior of the shock fluid. A diagram of our testing setup can be seen in Figure 33.

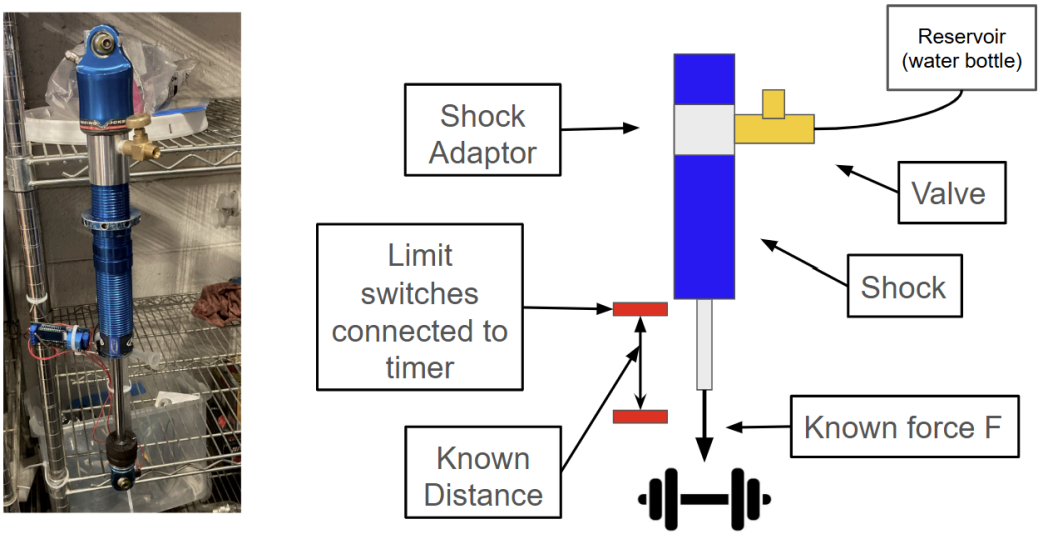


Figure 33: Diagram of proof of concept testing setup

The test was first performed with the valve fully closed, simulating the shock currently used on Baja vehicles. The valve was then fully opened, creating the maximum possible difference in damping seen in the rebound phase. With the valve fully opened, fluid behavior in the reservoir was also evaluated. The fluid level visibly dropped, indicating that the alternate path of escape of the valve had indeed been used. Results of the two tests can be seen in Figure 34.

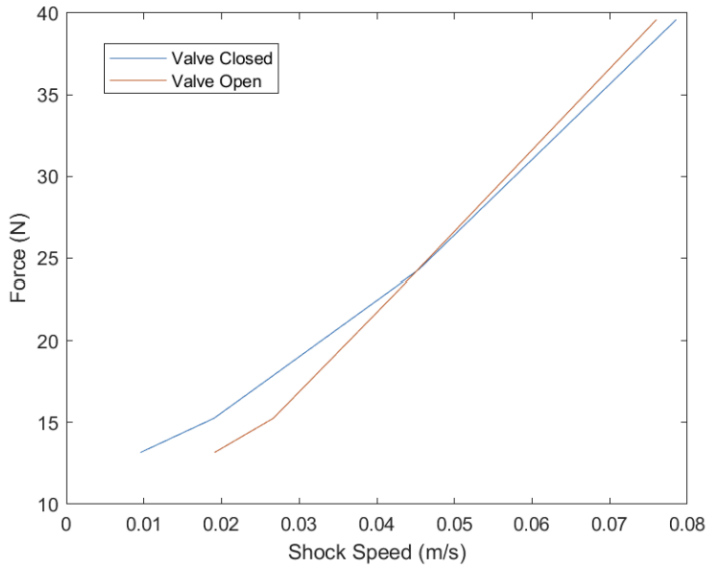


Figure 34: Damping test results of both valve closed and valve open. Damping is the relationship between force and velocity (Ns/m), and is the slope of the lines.

As shown in the figure, the two tests yielded different slopes, indicating that a change in damping had in fact been actuated. This, along with the movement of fluid in the reservoir, verified our external valve design. One limitation in this testing setup is the maximum shock speed attained. The weight used was not high enough to yield large shock speeds, especially in comparison to the speeds our shock sees on the Baja vehicle. Despite this limitation, we are somewhat confident in the results obtained. Theoretically, the difference in damping should be larger at higher shock speeds, so the difference should get more noticeable. While we are confident in saying that we have created a system which can adjust damping, we are not yet sure if we will be able to achieve the range laid out by our first specification (between 2000 and 10000 Ns/m).

The method above is not what will be used as final verification for the damping requirement. The inability to mount enough weight to the shock to reach the shock speeds actually seen by our car limits this testing setup. In addition, issues with the accuracy of the limit switches and timer setup also adds to the issues with the setup. Our final verification was done on an actual shock dynamometer which is discussed at length at the end of this section. This was done merely to validate that our concept was having an impact on damping.

Moving into verification for the rest of our most important requirements, we verified that the battery life of our mechanism will last one full competition, which is specified as 6 hours long. To test for meeting this specification, we ran the motor setup for a full 6 hours and ensured no electronic failure. The only potential limitation of this test is an inexact simulation of the amount of rotations the motor will need to turn in a competition, thus extracting more energy from the

battery. It is possible that in a competition setting, the motor may need to make more turns if the number of obstacles is higher, or if the motor/valve presets for any obstacle are far from each other. While this limitation is certainly something to consider, the actual number of motor rotations in competition will probably be much less.

To verify that our mechanism will survive the max load case stress, we attached the completed prototype to the vehicle and returned to the track. We drove the vehicle off the 6-foot dropoff, which is our maximum load case as previously identified. Our team is extremely confident in using this method to verify the survivability of our prototype. Since we have already run this test to determine the maximum pressure seen in the shock, as well as performed all calculations using the maximum axial force from the 6-foot dropoff, it makes sense to verify using the same loads. Our dropoff test with our shock mounted was a success, as no components saw failure. An image of this test can be seen in Figure 35.



Figure 35: The 6-foot dropoff used to determine 1438 psi pressure and 14 kN axial force maximum load case in the shock

To ensure that the adjustment failure mode does not render the car undriveable, we manually caused a software failure by disconnecting the battery. Software failure is the only failure mode of our mechanism we have control over, and, by running this verification test, our team ensured that a software or battery failure will ‘lock in’ a damping coefficient into the shock. This is because the valve would no longer be able to turn, and no extra amounts of fluid would be able to escape via the reservoir. While a ‘locked’ damping coefficient defeats the purpose of our project, the car would still be able to be driven. Additionally, our team wants to make sure that, in the event of a software failure, the ‘locked’ damping is the baseline, general tune normally used for all four competition events. This is for two reasons; the first is driver protection. The MBR team knows that the general tune does not lead to driver risk. To protect the driver, which is our main social concern, we would want to return to this tune. This also helps to satisfy our requirement as, if conditions are too unsafe for the driver, the car would be undriveable anyway.

While we are confident in using this test to meet our specification of a locked damping between 2000 and 10000 Ns/m, this test has a limitation in not verifying every possible failure mode of our mechanism. If any mechanical component were to fail, we would leak out shock fluid, rendering the car undriveable. Thankfully, this was verified with other tests, like the 6-foot dropoff verifying survivability.

Another important requirement and specification is that the product fits the Baja vehicle's packaging constraints. To verify this specification, we manually rolled the car 90 degrees and ensured that our prototype saw no impact with the ground. This is the best way to ensure that the prototype is inside the Baja car's 7" crash radius, as the crash radius can be difficult to measure manually. The easiest way to visualize this crash radius is to simulate a crash without any real impact, especially because the crash radius usually refers to rolled vehicles, the only real crashes that Baja cars see. This test is run on other parts on the Baja vehicle, and our team was given permission to perform it by MBR. We are extremely confident in its results. Since there is no interference between our product and the ground, our mechanism has satisfied the specification of being within the crash radius. An image of the experiment can be seen in Figure 36.



(a) (b)

Figure 36: (a) The Baja car rolled over in a previous competition. (b) A replicated rollover with the prototype shock.

Another important requirement and specification is that our prototype must not add more than 1 kg to the vehicle. Verifying this requirement is very simple; we weighed the prototype once everything was constructed as seen in Figure 37. Since the added weight is 0.84kg (below 1kg), we have satisfied the requirement to the highest degree of confidence. The rest of our verification plans can be found earlier in this section in Table 13.



Figure 37: To verify the prototype fits weight constraints, we weighed it

Our final, and most important, specification is that our shock supplies the specified range of damping rates. In order to do this, we brought our shocks to Ford's testing facility in Dearborn, MI and used their shock dynamometer (dyno). A shock dyno is the only reliable way to determine the damping rate of a shock, and since creating our own is an extremely intensive process and out of the scope of this course, we reached out to Ford. To prepare to test our shock, we built a makeshift, larger reservoir out of PVC to ensure no shock fluid leaked in their facility, as well as rebuilt our shock with a much stiffer tune to see a larger range of damping as the valve was opened.

Upon arrival, we used Ford's existing fixtures to set up our shock in the dyno, as shown below in Figure 38. The top of the shock mounted using a welded component that could bolt into our rod end with an M8 bolt, and the bottom mounted using a rounded component with an M12x1.25 thread tapped into it.

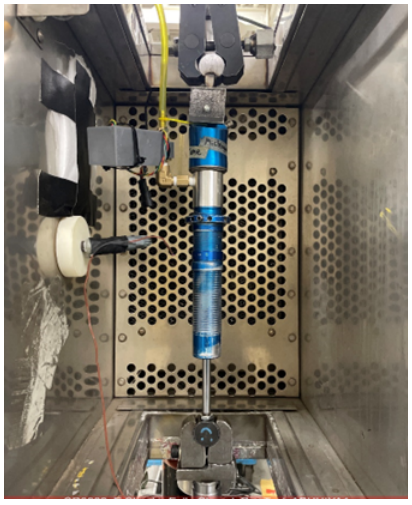


Figure 38: Our prototype shock mounted in Ford's dynamometer

After the shock was mounted, the bottom of the shock was vertically actuated using a hydraulic linear actuator while the top was held fixed. Linear actuator position was known, and a load cell connected to the top of the shock collected force output. We applied a sinusoidal input to the bottom of the shock with an amplitude of 2.5 inches (total range of 5 inches, slightly less than the shock's maximum range of motion of 7 inches). We linearly stepped the frequency from 0.1Hz to 4.5Hz, as shown in Figure 39, to hit all speeds up to the max speed our shock sees while driving.

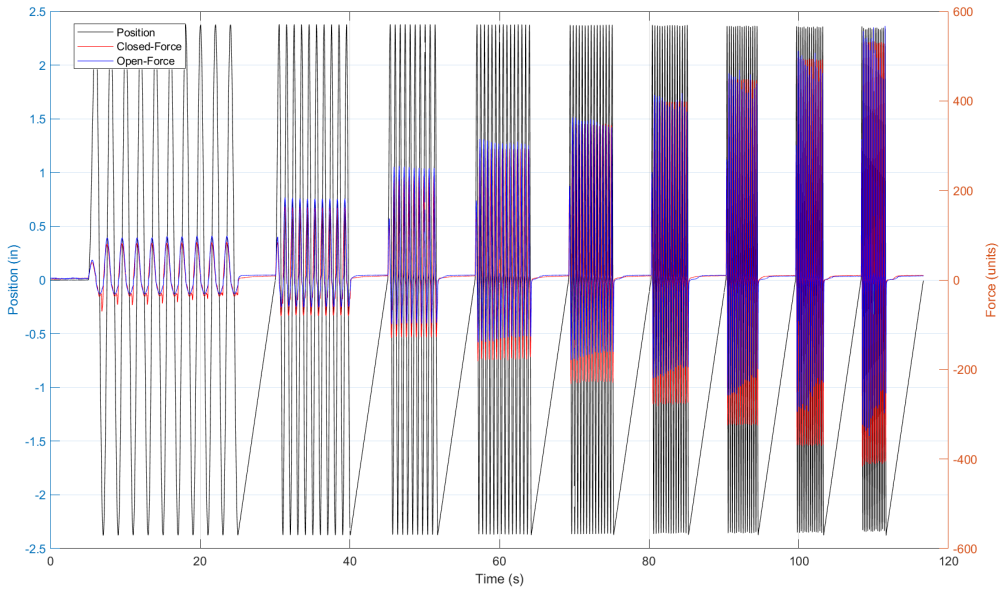


Figure 39: Our test setup displacement and force over time

We then re-ran this test at various valve apertures from fully closed to fully open, resulting in seven total tests. Each test output time, position, and force data. By deriving velocity from position and time, we could plot force vs velocity for all shock settings, yielding the characteristic damping curve of our shock at all settings as shown in Figure 40. Another plot of just fully open and closed runs is included for clarity.

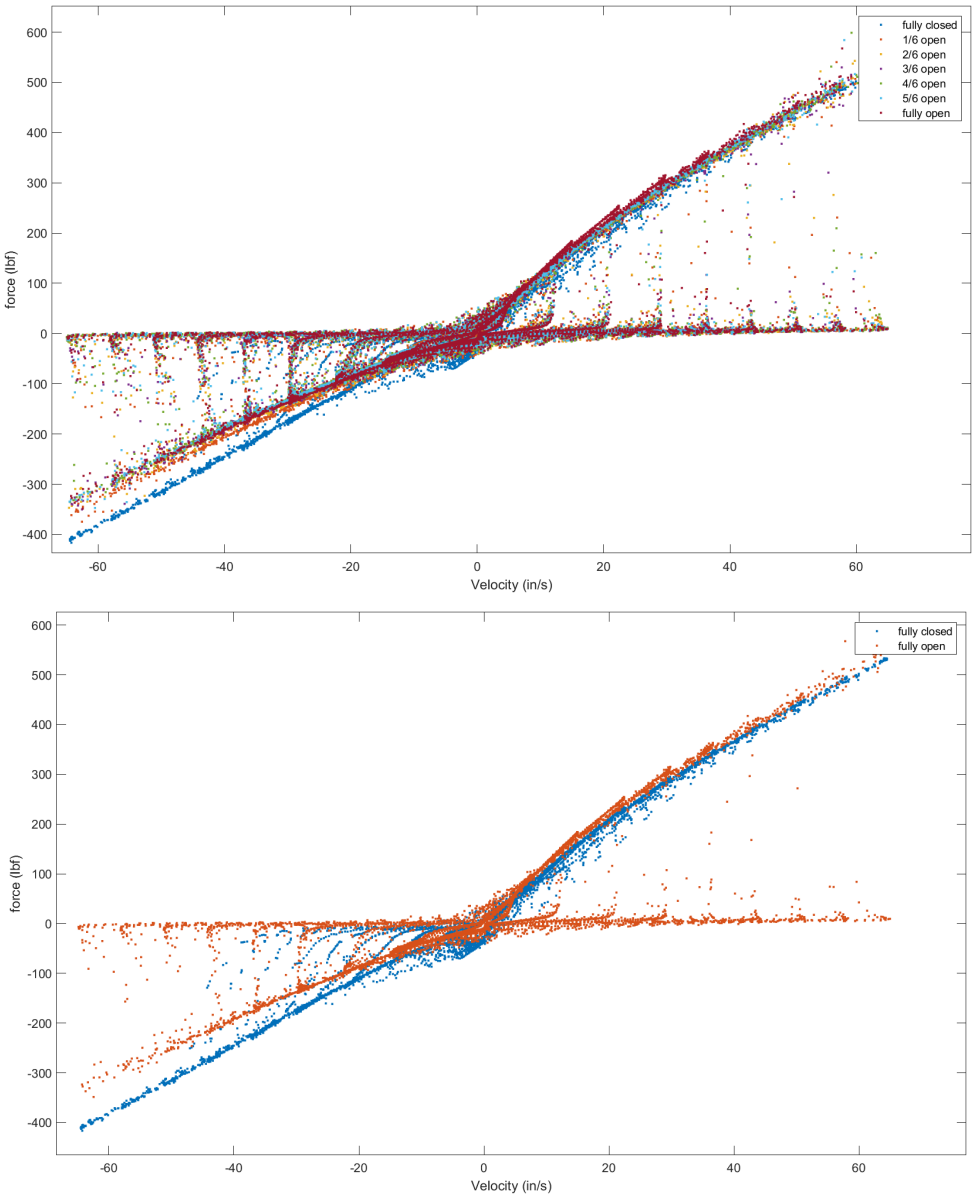


Figure 40: Characteristic damping curve at all shock settings

The results are not ideal. To hit our specification, the different lines would need to have vastly different slopes, representing different damping rates. Instead, the curves are all somewhat similar, meaning that our design did not succeed in the first requirement and specification to vary damping from 2000 to 10000 Ns/m. For perspective, the slopes seen in the plots above are all approximately 2000 Ns/m and do not vary more than 500 Ns/m from this value.

Another interesting finding from these plots are the noise and horizontal lines where force output is zero. Our fully closed plot, pictured in blue above, is a good example of what a damping curve should look like. All data points are close together along largely one line. All other curves from

tests with varying levels of valve position have a horizontal line at zero and much more noise. The horizontal line means there are instances where the shock is moving but not outputting a force. We believe this could be caused by cavitation, a phenomenon seen in shocks where extreme low pressure areas instantaneously convert shock fluid into gas. When the piston then moves through these air bubbles there is no fluid to resist, resulting in a high velocity and no output force. Shocks normally solve this issue by pressurizing the inside of the shock using a nitrogen pocket in the head of the shock. By venting our system to atmospheric pressure we have eliminated the effect of this nitrogen, and increased the chances of cavitation occurring.

Our team has also constructed a validation plan for our prototype. The end user of our product is the driver of the MBR vehicle. Validation will largely stem from testing of the mechanism with the driver. As such, we plan to integrate button presets on the steering wheel, which is how the driver will have control of the damping coefficient. Each button preset will correspond to a different valve position, allowing the driver to select his or her damping based on whatever event or obstacle is seen. After the buttons have been successfully integrated, we will run a 4 hour mock endurance race at Bundy Hill, an off-roading track which MBR frequently tests at. The endurance race is the longest event of the competition, and the one in which most components fail by fatigue. It is also the longest that a driver will be inside the car at any one time. Throughout the mock endurance race, our driver will have total control over the mechanism. After the mock race is over, we will be able to collect driver feedback on feel, comfort, and useability. As MBR and the driver, our two largest stakeholders, better understand our solution, it is possible that they could change their specifications. In that event, our team would be open to continue working to create a mechanism which best meets the stakeholders' needs.

5. Discussion

Our project is very well defined. The only aspect we would like to refine is the target range of damping. The number chosen was somewhat arbitrary, and now that we have tested the actual damping rate of our shocks and worked to better understand the results of changing damping, we have a much better picture of what a relevant range of damping would look like to be successful in competitions.

Our design is, for the most part, very robust and simple. It could be optimized for weight, but as is, it is already very light. Additionally, there are some key weaknesses in the design. At high pressures, the tube to barb fitting connection can disconnect, causing shock fluid to leak and causing a critical failure. The design is also not weatherproof, which is especially important for the mud and dirt in Baja competitions. Also, the handheld button unit the driver will use to actuate the shocks is unwieldy and will have too many wires if it needs to connect to all four shocks. Finally, our largest problem is the minimal change in damping rate our shock created, which we think is due to cavitation or air pockets introduced in the shock fluid. Potential solutions are discussed in the recommendations section below.

In our design process, we encountered many challenges, including minimal budget, underpowered motors, leaking shock fluid, packaging constraints, and lack of access to a dynamometer. In order to address these problems, we used a custom electronic valve instead of buying an expensive one, bought more powerful motors that could be used with the same motor shield, increased the reservoir size and added a water trap to it, used tubing and elbow fittings to properly orient all components, and utilized our connections to find someone that could let us use their shock dyno. Ultimately, the end-user's only risk with our current prototype is the non-secure barb to tube connection. If it failed, the shocks would lose all damping and the driver could get injured from hitting the ground or an obstacle too hard. This could easily be solved by directly mounting the reservoir to the valve.

6. Reflection

The Mechanical Engineering Department is committed to making the world work better, an important idea to be followed by all design projects and research opportunities. Public health, safety, and welfare is perhaps the most important factor in our project. Our prototype has the potential to improve the driving experience for anyone in the seat of our vehicle, but, in the event of failure, has the potential to lead to serious health complications. Because of the cavitation issues described in the previous section, we are currently unsure how we have affected driver experience and safety. For similar reasons, our current design would not be of benefit to a global marketplace. Once the problems with the design are solved, however, the technology could be used in road cars to improve driver experience. Currently, our prototype is intended for permanent use on only the Michigan Baja car, and so there are no economic or social impacts associated with disposal. Social impacts with use include driver safety, as previously discussed; impacts with manufacturing include sourcing of materials. The main material used in our project is aluminum, which is not a sustainable material. This could pose social impacts due to the dangers of working mines and refineries. Economic impacts associated with use are limited, while economic impacts regarding manufacturing include sourcing materials. Many of our materials were donated by Michigan Baja Racing, who received the materials as part of a donation from a company. Economic strain could be placed on the company if too many materials are requested in future production. To examine these contexts, life cycle costing and stakeholder maps were used.

Differences in privilege and identity influenced our team's approach to cost throughout the making of our prototype. Cost was a factor considered when thinking of solutions to our cavitation problems. Additionally, differences in experience on the Baja team affected group roles. Team members with more experience dealing with Baja sponsors lead more communication efforts on the team, while members with more experience on the steering, suspension, and brakes subteam had more formed opinions on the direction of our project. As we were our own sponsors, stylistic similarities with the rest of the Michigan Baja Racing team were the primary influences on our final design. MBR, as a sponsor, tries to avoid modifying the

shock body as much as possible due to high precision requirements and cost of shocks. This wish is shared by the team, and so adding a piece external to the shock body for modification was necessary. There were stylistic similarities outside of this example that guided our design.

There are power dynamics present between us and our stakeholders. For example, one stakeholder is the judges of the technical inspections in Baja competitions. They have the ultimate power to deem a design safe or unsafe, and so while one of our requirements was to produce a prototype meeting all Baja SAE rules, it is possible that our design could be refused from use in the Baja competitions. Another example is the Baja Team Captain, who has the ultimate say over what designs end up on the final vehicle. Although our design is not vehicle ready at this time, even if it was, it would be up to us to convince the Baja Team Captain to use our product for competitions. Team members who were previously involved with the suspension subsystem were more concerned with the benefits to vehicle performance, and prioritized decision-making with that in mind. Our end users were more concerned with vehicle handling, which guided different decisions. It was easy to balance these differing viewpoints as they are very complementary. A vehicle which handles better allows the driver to push it a little harder, which improves vehicle performance. Likewise, in the specific case of our project, better vehicle performance correlated to improved handling. In our project, a better performance is more horizontal velocity maintained. This usually corresponds to less vehicle vibration, which is a better feel for the driver. All opinions informed the project because the opinions are so complementary. There were many similarities in idea and experience between each team member and MBR as a sponsor, and so our team had an idea of what the design would look like before we really started generating ideas. Although finer details like motor selection, size of reservoir, and size of valve were determined through engineering analysis, the idea at the start of the project (valved reservoir) followed us throughout the design process.

The main ethical dilemma in the making of our project was sourcing materials and funding from companies which have the same mission and values as our team. Because our budget was so limited, we could not afford to be as choosy as we would have liked in selecting companies which align with our values. To manage this dilemma, we aligned with Michigan Baja Racing, sourcing materials and money from the same companies as MBR, knowing that our values are the same as the MBR team. If our product were to enter the marketplace, one other ethical issue which may arise is sustainability of materials. As our product becomes more large-scale, the sustainability of materials would become extremely important, and, as previously discussed, the primary additional material used was aluminum. Additionally, if our product were to enter the marketplace, it may have a shorter lifetime than the intended ‘on car forever’, and so social impact with disposal might become more important. Electronics are terrible to dispose of from both social and environmental aspects, and our product used a motor, Arduino, motor shield, and other electronics. Our team has learned almost all we know about engineering ethics from various classes at the University of Michigan, so it is reasonable to say that our personal ethics

are very closely aligned with the professional ethics expected at the University of Michigan. We will carry this ethics code through all engineering work and choose an employer which aligns with both our personal and professional ethics.

7. Recommendations

Given the intrinsic failure of our system to reach required maximum values of damping, as discussed in verification results, we would recommend completely revising the design concept before proceeding. In order to successfully vary damping to a much more extreme rate, some solutions could include a pressurized reservoir, a larger valve, and routing the fluid to the bottom of the shock instead of the reservoir. These can all utilize most of the components we already designed and should be relatively simple to implement. We would recommend creating a basic prototype of each and bringing them back to the dynamometer to test the range of damping, then move forward with the most promising solution.

Additional recommendations from project failures and learnings are as follows. Do not use barb fittings and PVC pipe, as these materials can disconnect at high pressure. Instead, directly connect the reservoir to the valve or, if absolutely necessary, use safety wire. The reservoir and motor mount can be combined into one part if the valve screws into the reservoir first and aligns with the reservoir vertically. Then, the motor could slide onto a built in track on the reservoir component. Since it is already printed out of resin, clear resin should be used instead so fluid levels are easier to track. We'd also recommend 3D printing a larger casing for the entire design in order to weatherproof the valve assembly. Finally, we would switch to a smaller microcontroller, like an ESP32, since the size of the Arduino is unnecessary. This would enable Bluetooth or WiFi control of the system, which would enable other team members (and not just the driver) to actuate the mechanism via their phones if necessary. It would also render the button and potentiometer control unit irrelevant, saving weight and creating easier packaging.

8. Conclusion

The Michigan Baja Racing team had tasked us with designing an adaptive suspension system that would vary the damping rate without changing any internal components. This would allow the car to change suspension tunes between competition events and obstacles, and thus excel in each event. After reviewing multiple design processes, we decided to use a solution-oriented stage-based design process with some cyclic activities, especially focusing on iterating between prototyping and testing. We also defined our requirements and specifications for our mechanism, including its need to vary damping, be durable, serviceable, lightweight, machinable, within budget, fit in the car, and obey all Baja SAE rules. Next, we generated numerous concept solutions using a variety of methods and then down-selected until we had five final concepts, all using the strategy of modifying fluid flow. Those concepts were then rigorously compared using a Pugh Chart until we landed on our final design concept of an external reservoir connected to

the upper shock body via a needle valve. We defined possible problems, including limitations in size, defining and testing failure modes, measuring damping, surviving large forces, and defining inputs for closed-loop control. We approached these challenges by reaching out to relevant professors and reviewing courses in fluid mechanics, statics, electrical engineering, and mechanical design. Testing and analysis of our design involves static analysis, FEA, pressure measurements, Bernoulli's equation for valve opening, and power consumption calculations. We built our prototype and verified some of the more critical user requirements including weight, machinability, budget, and exterior packaging. We then used a shock dynamometer at Ford to more accurately test the damping rate of our shock. This test showed our shock does not meet our user requirement of varying damping, and invalidated our design. We plan on continuing to work on this project to help the Baja team fulfill its goals.

9. Acknowledgements

We would like to thank everyone who helped us through this process. Prof. Wenda Tan guided us through the ME450 process and gave relevant and helpful feedback on our presentations and reports. Abdul Bhuiyan and the Ford testing facility team let us use their shock dynamometer, helped us use it, and gave feedback on our results. The entire Baja team gave us clear and relevant requirements and provided us with stock, tools, and some components. The Wilson Student Team Project Center allowed us to work on our project and use their tools.

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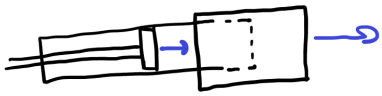
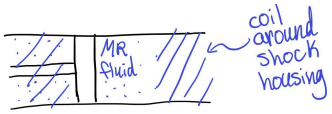
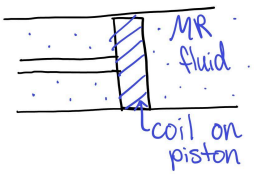
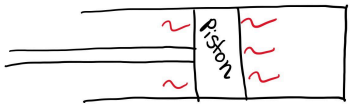
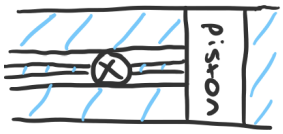
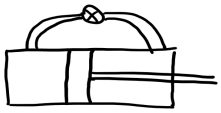
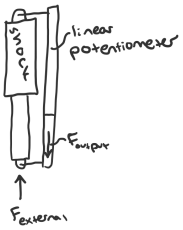
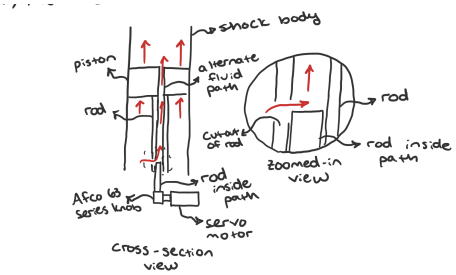
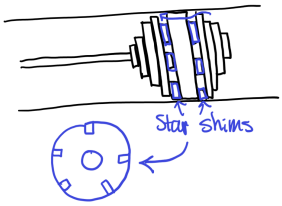
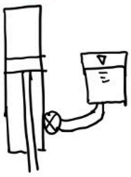
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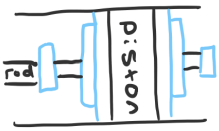
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11. Appendix

11.1 Appendix A - Sample of Generated Concepts

List of Ideas from Concept Generation Process:		
 Telescoping shock body	 Electromagnetic shock body	 Electromagnetic piston
 Resistive heating coil in the pistons	 • heat fluid to increase/decrease viscosity Resistive heating coil around the shock body	 Expanding shims
 Allowing fluid to bypass shim stack through a valve in the piston rod	 Pressure relief through external reservoir above the piston	 Fluid avoids shim stack externally
 Non-newtonian shock fluid	 Linear actuator to add a resistive or additional compressive force	 Motorized Afco 63 shock
		

Magnetic shock	Rotating star shims	Pressure relief through external reservoir below the piston
 Steel rod	 Sliding shim stack	 Air springs

11.2 Appendix B - Downselection

After completing our concept generation phase, we were left with about eighty different concepts for solving our problem. To get down to the final concept, we needed to start downselecting to converge to a certain region of the design space. To do so, we started by eliminating concepts that did not meet the original goal, were too advanced in an unknown engineering topic, or were physically infeasible. This is shown below in Figure 38.

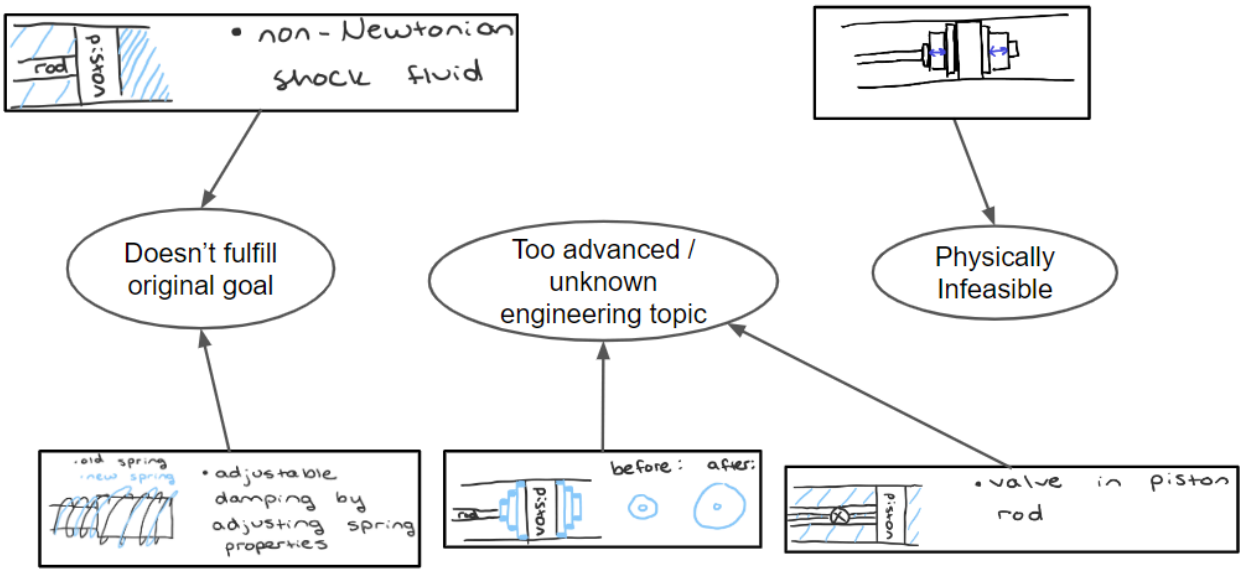


Figure 38: The first step in the down selection process. Concepts that did not solve the problem, were out of our realm of engineering, or were physically infeasible were eliminated.

Some examples shown in Figure 24 include a non-Newtonian shock fluid, which doesn't give an actuatable damping rate, shrinking/growing pistons, which are outside of our area expertise, and adjusting spring properties, which do not adjust the damping.

Once we had eliminated all of the unrealistic concepts we grouped the remaining concepts into general categories based on how the concept worked. We then pointed out some of the major issues with each category that would prevent it from being an effective solution. This is shown below in Figure 39.

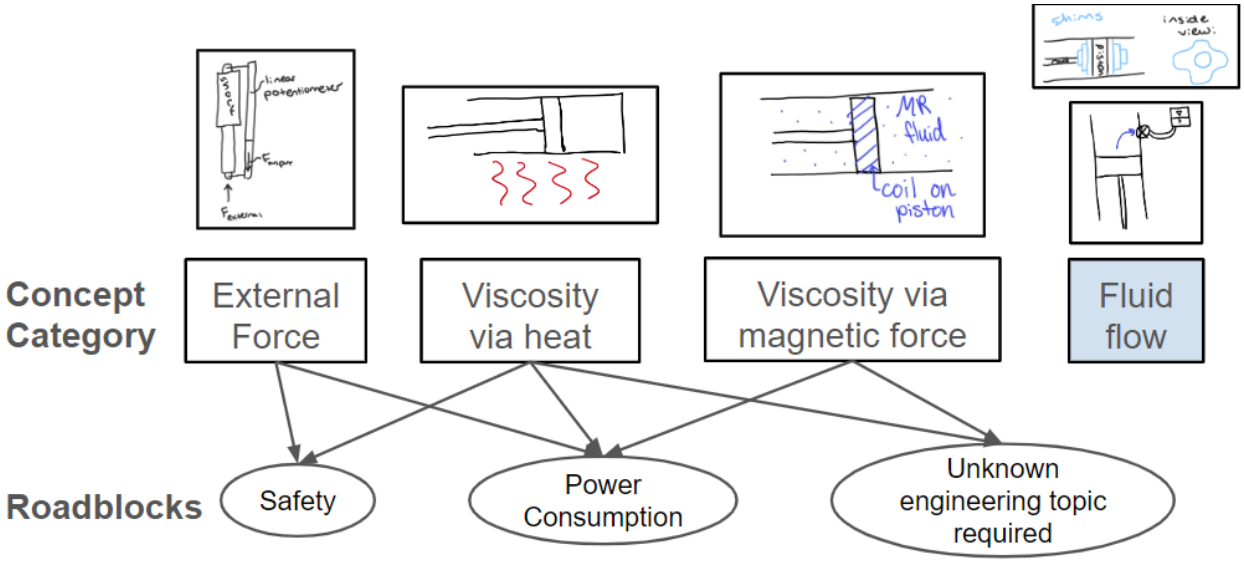


Figure 39: Each remaining concept was grouped by how it works. Concepts with an external force included a motor damper or linear actuator. Some concepts relied on changing the viscosity of the shock fluid by heating it up, other concepts changed viscosity via a magnetic shock fluid and an electromagnet. The final category was all designs that changed the fluid flow properties.

Some of these categories had some major issues with all of the concepts. External actuators require a lot of power to have a real impact on the loads of our suspension. In addition, they output a lot of force, which can be a safety hazard for both our driver and course workers. Both viscosity-related designs would require designing a shock fluid to meet the necessary properties, which is a topic in engineering we are unfamiliar with, and can't learn in the available time. Similar to external actuators, changing the fluid viscosity would require more power than we have readily available on the Baja car or would add a significant amount of weight in batteries. Changing the viscosity via heat would also cause our shock to get very hot, violating the SAE rules and creating a severe hazard to track workers and violating the SAE rules. This left only the concept of changing fluid flow, which, as discussed in section 3.2, was used in a Pugh Chart.

11.3 Appendix C - Analysis Calculations

Part 1: Shock adaptor stress analysis

$$\sigma_{zz} = \frac{pr}{2t} = \frac{1438\ psi \cdot 1.4"}{2 \cdot 0.4"} = 2,516.5\ psi$$

Hoop stress with stress concentration factor:

$$\sigma_{\Theta\Theta} = \frac{pr}{t} \cdot K_T = \frac{1438\ psi \cdot 1.4"}{0.4"} \cdot 3 = 15,099\ psi$$

Yield strength against un-heat treated Al 7075:

$$SF = \frac{\sigma_{yield}}{\sigma_{max}} = \frac{21,000\ psi}{15,099\ psi} = 1.4$$

Note that hoop and axial stress cannot be combined on the Mohr's Circle and therefore must be analyzed independently. Also note that the K_T factor of 3 in the hoop stress formula is to account for the circular hole in the side of our cylindrical shape.

Part 2: Bernoulli's equation for valve aperture

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + H_f$$

$$V_2 = \frac{V_1 A_1}{A_2}$$

$$H_f = \frac{1}{2} K_v \rho V_2^2$$

$$K_v = Q\sqrt{\frac{\rho}{1000(P_2 - P_1)}}$$

$$V_1 = \frac{Q}{A_1},\ Q = Q_{piston} = V_{piston} \times A_{shock}$$

$$P_1 + \frac{1}{2}\rho\left(\frac{V_{piston} \times A_{shock}}{A_1}\right)^2 = P_2 + \frac{1}{2}\rho\left(\frac{V_{piston} \times A_{shock}}{A_2}\right)^2 + \frac{1}{2}(V_{piston} \times A_{shock})\sqrt{\frac{\rho}{1000(P_2 - P_1)}}\rho\left(\frac{V_{piston} \times A_{shock}}{A_2}\right)^2$$

$$A_2 = A_1 V_{piston} A_{shock} \sqrt{\frac{V_{piston} A_{shock}\sqrt{\frac{\rho}{1000(P_2 - P_1)}} + 1}{2P_1 a_1^2 - 2P_2 a_1^2 + V_{piston}^2 A_{shock}^2 \rho}}$$

Known variables:

ρ - density of shock fluid = 62.4 lb/in^3

V_{piston} - shock speed = 3 ft/s

A_{shock} - interior shock area = 2.4in^2

A_1 - valve ID = 0.05in^2

P_2 - atmospheric pressure = 14.7psi

P_1 - shock body pressure = 1438 psi

Solved variable:

A_2 - required valve opening = 0.022in^2

Part 3: Battery life calculations

With 4 x 21700 cells (one in each shock), total energy is:

$$3.6\,V_{nominal} \cdot 5,000\,mAh \cdot 4cells = 72\,Wh$$

Stepper motor power consumption:

$$4\,motors \cdot 3.9\,V \cdot 600\,mA = 9.36\,W$$

Total battery life:

$$\frac{72\,Wh}{9.36\,W} = 7.7\,hours$$

Part 4: Reservoir volume

Piston displacement volume

$$V = \pi \times r^2 \times length = \pi \times (0.6)^2 \times 0.75$$

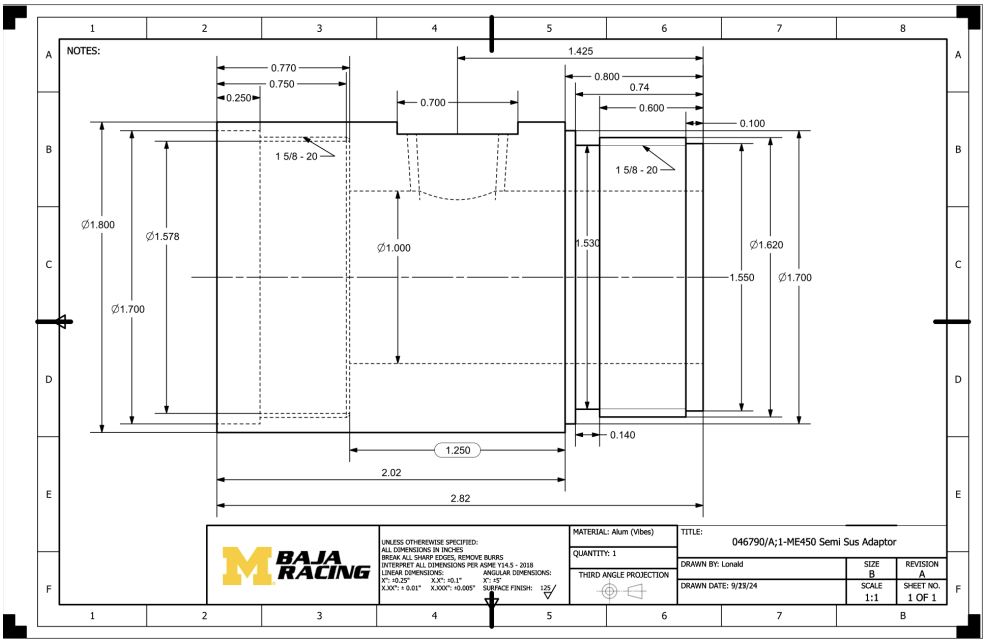
$$V = 1.378\,in^3$$

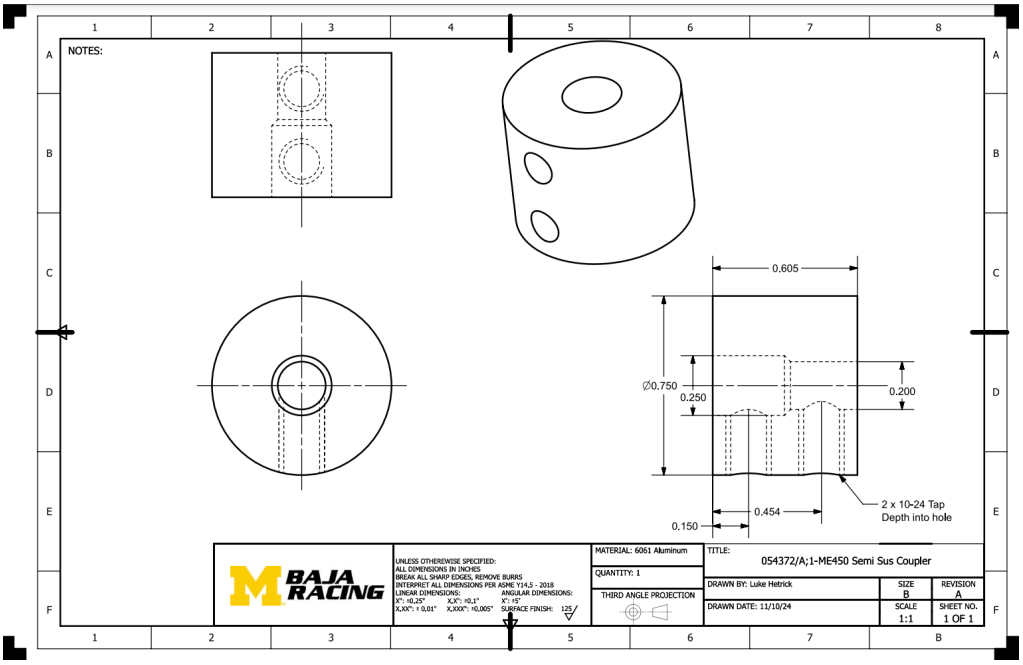
Reservoir length

$$L = \frac{V}{\pi \times r^2} = \frac{1.378}{\pi \times 0.219^2}$$

$$L = 9.17\,in$$

11.3 Appendix D - Part Drawings





12. Build Design Bill of Materials

Listed in the Bill of Materials is each component's price and quantity, and for the purchased parts, the manufacturer and part number.

Table 14: Bill of Materials. All components provided by the Baja team are denoted with an asterisk.

Item	Component Name	Part Number	Quantity	Cost
1	Arduino Leondardo	DigiKey 1050-1040-ND	1	24.90
2	Stepper Motor	DigiKey 1528-4411-ND	1	17.96
3	Motorshield	DigiKey 1528-1187-ND	1	19.95
4	Buttons	DigiKey 401-1995-ND	4	4.84
5	Elbow Connector	Grainger 1DGJ6	1	37.30
6	Breather Vent	Grainger 1EJT5	1	1.43
7	2 ft Tubing	Grainger 55YM11	1	3.43
8	Hose Fittings	Grainger 6AFH3	2	1.72
9	Male to Female NPT	Grainger 6AYX3	1	1.50
10	Valve	McMaster 7833K74	1	38.01
11	M2 Screws	McMaster 91292A831	2	0.19
12	AFCO 64 Shock	AFCO 64-7-SP-SP	1	259.99*
13	Resin	West System	0.05 lbs	0.02*
14	Aluminum 7075	Alro Steel	0.81 lbs	0.52*
* Coming at no cost to ME 450 team, provided by Michigan Baja				

Our budget is a combination of the standard $400 from ME 450 and an additional $250 allocated for our prototype from the MBR team. Should we decide to manufacture the eight actual shocks, we will meet back with the MBR Logistics Director stakeholder in order to allocate an additional manufacturing budget. This budget will not include any metal stock, wires, or other parts MBR already has in the Wilson Center. Given this, we expect to have enough people, time, and money to complete this project within our given budget and timeline.

13. Manufacturing/Fabrication Plan

In Table 15 below, you will find our manufacturing plan. This is an overview of how we plan on either making or purchasing the components we need for our design.

Table 15: Manufacturing plan

Component	Material	Manufacturing Plan
Shock Adaptor	Aluminum 7075	CNC lathe & Manual mill
Straight NPT Fitting	Brass	Purchased
Street Elbow NPT Fitting	Brass	Purchased
Valve	Brass	Purchased
NPT to Barb Fitting	Brass	Purchased
Tubing	PVC	Purchased
Reservoir	Resin	SLA 3D printed
Breather Fitting	Brass	Purchased
Motor Coupler	Aluminum 6061	Manual lathe
Motor	n/a	Purchased
Motor Housing	Resin	SLA 3D printed

The first component in the list, the shock adapter, was manufactured by the Baja team using a CNC lathe in the Wilson Student Team Project Center. On the lathe, it was turned down and bored to match the required outer and inner profiles, grooved, and threaded. The adaptor was then put on a mill and drilled and tapped for the elbow connector that attaches to the valve. The high tolerance surfaces are the threads and O-ring grooves because the adaptor needs to be able

to properly connect to the shock body without allowing fluid to leak out. A part drawing for this component can be found in Appendix D.

Next, the motor coupler, which is how we are transferring torque from the motor shaft to the knob on the valve, was manufactured using a manual lathe. It was turned down to size to the required outer diameter and then drilled to the diameter of the motor shaft. Next, it was flipped and drilled on the other end to match the diameter of the knob on the valve. The coupler was then drilled and tapped on the mill for set screws that allow it to be attached to the motor shaft and the valve knob. A part drawing for this component can also be found in Appendix D.

14. Bios

Marisa May is the Logistics Director for the Michigan Baja Racing team. Last year was her first full year as a lead on Baja, and she served as the Sponsor Outreach and Team Recruitment Lead, which provided valuable experience for her role this year. Marisa is from Marine City, Michigan, where she has lived her whole life. Growing up, she used to watch Formula One races with her dad every Sunday, and her dad helped her to realize that she could turn a passion for racing into a career. Then, during her school years, she became interested in engineering through her participation in STEM courses and Science Olympiad events including Mission Possible, Forensics, and Dynamic Planet. Marisa also became very interested in the intersection of art and engineering, completing the art program at her high school and entering several gallery showcases during her time in the program. Those passions lead to Marisa's interest in mechanical engineering. After graduation, she hopes to return to the University of Michigan for a SUGS master's degree in mechanical engineering. Then, she'll pursue a career in motorsports, specifically Formula One, Indycar, or IMSA Sportscar. For some additional fun facts, Marisa is almost fluent in Italian, and put her language skills to the test when she studied abroad in Berlin, Germany (but visited Rome) in the summer of 2023.

Rudy Lee is currently retired from the MBR team but served as its logistics director and steering subsystem lead his junior year and its composites team lead his sophomore year. He is from San Francisco, California, and grew up building and tinkering from a young age. He started building with Thomas the Tank Engine train tracks and moved on to legos, then duct tape, then woodworking, and finally into the engineering field. In high school, he, along with a group of friends, founded Flight Club Aerospace, a 501c3 trying to build an ultralight aircraft and educate younger students about aerospace. Although the plane didn't get built during his time in high school, the team is still going strong and working toward a successful first flight. He currently works as a contracted battery engineer for a startup called Humble based in Los Angeles, making large-scale (7kWh) batteries to be used in the entertainment industry for filming, concerts, and other events. He is also working on building a schoolie, which is a school bus converted into a tiny home. It is a 1995 Chevy G-30 with a Blue Bird body that is almost ready to be lived in! Its name is Cletus but may be renamed to Cleopatra. After graduating from undergrad, he plans to live in it while getting a SUGS master's degree in mechanical engineering at UMich and then travel the country while working remotely.

Luke Hetrick is currently the Manufacturing Director of MBR and has previously served as the kinematics and front suspension lead. He was born in Pennsylvania and moved to Michigan at the age of three. Growing up in Dearborn, home of The Ford Motor Company, he was surrounded by engineering for a young age. Luke always enjoyed helping with home DIY projects and figuring out how things work. His love for engineering really took off in middle school when he helped form the schools FIRST Tech Challenge robotics team. This introduced him into the world of engineering and was his first experience with the complete design process.

In high school Luke continued his love of robotics on the FIRST Robotics team, becoming captain his sophomore year. In college Luke thought he was going to pursue robotics, but instead fell in love with Baja. After graduation Luke plans to pursue a Masters degree in mechanical engineering through the SUGS program at the University of Michigan. A fun fact about Luke is that he loves to bake and is best known for his chocolate chip cookies and his homemade pizza.

Ana Ferrara is currently the Vehicle Dynamics Director and one of the Suspension Subsystem Leads on MBR. Last year, she was one of the Brakes Subsystem Leads, where she helped design and manufacture all of MBR's custom brake components. Ana has lived in southeastern Michigan her whole life. She is specifically from Oakland Township, MI, 32 miles north of Detroit. Ana's interest in Mechanical Engineering comes from her love of tractors. At a young age, Ana started going to summer camp at a farm, where tractors would pull all the campers on wagons down to the lake to swim everyday. Seeing the counselors drive these incredible machines inspired Ana to not only want to drive them but to learn how they worked. This, along with her love of her high school physics classes, is what inspired her to pursue a degree in Mechanical Engineering. Outside of school, Ana lives with her family on 20 acres where she gets to drive her family's John Deere every time she's home. Her interest in tractors has inspired her to pursue a career working with heavy machining after graduation. A fun fact about Ana is she has a dog, a cat, 38 chickens, and bees.