2019-2020 Baja SAE – Front End & Rear End

Preliminary Proposal

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DISCLAIMER

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BACKGROUND

1.1 Introduction

SAE Baja is a collegiate competition that tasks students to design and build a single-occupant, off-road vehicle that will be put through a series of dynamic and static events. These events can consist of an acceleration test, braking test, hill climb, endurance race, and other various inspections and tests. These vehicles must also adhere to a strict set of competition rules and guidelines set by SAE. These rules and guidelines will ensure and show that the students on the team are able to function as professional engineers. Furthermore, this competition provides the sponsor and other stakeholders a large platform for advertising and it will also validate that the team is able to produce a functioning and reliable off-road vehicle.

1.2 Project Description

The Baja SAE intercollegiate competition is a unanimous engineering design competition among undergraduate and graduate students. The primary goal is to design, build, test, promote and compete a fully function mini Baja within the constraints provided in the Baja SAE 2020 rules booklet. Provided below is a vital portion of the project description provided by the administration of the Baja SAE 2020 intercollegiate competition.

"Each team's goal is to design and build a single-seat, all-terrain, sporting vehicle whose driver is contained within the structure of the vehicle. The vehicle is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle which serves a recreational user market, sized at approximately 4,000 units per year. The vehicle should aspire to market-leading performance in terms of speed, handling, ride, and ruggedness over rough terrain and off-road conditions. Performance will be measured by success in the static and dynamic events which are described in the Baja SAE® Rules, and subject to event-site weather and course conditions." [1]

Based on this provided description, the Baja SAE 2020 team for Northern Arizona University has decided to fulfill the needed requirements by initiating a sub team division system. The sub teams are; Front-End, Rear-End, Drivetrain, and Frame respectively. Each sub team will initiate and design the allocated sections abiding by the rules of the competition. Based on the bonus point opportunity for this year, the teams will design their sections to facilitate a 4WD system. Once the sections are designed, the sub teams will combine their work and build the Baja merging the sections together while tweaking systems to be compatible with each other.

1.3 Previous Designs

1.3.1 NAU Car 52

The SAE Baja team that produced car 52 had some pros and cons of the design. For the front end, they designed a modified double wishbone suspension with a curved upper control arm to wrap around the shock. While the car looks very capable, the solid aluminum control arms added a lot of weight to the suspension making for a heavier front end. However, the suspension geometry looks very well researched and fabricated. For the rear end, the team went with a single control arm on the bottom with a shock acting as a McPherson strut. This suspension looks well but lacks the lateral stability for off-road racing.

The solid aluminum lower arm does add weight, but is the lightest type of rear suspension there is since they do not have heavy trailing arms or even an upper control arm. In Figure 1, car 52 side profile of front and rear suspension can be detailed.

Figure 1 – Car 52’s suspension side profile. [2]

1.3.2 NAU Car 44

The SAE Baja Team that produced car 44 has a lot of positive aspects. The front-end suspension was a simple tube style double wishbone system with a lower arm mounted shock for maximum dampening. The minimal components and simplicity of the design makes for efficient fabrication and a lightweight front end. As seen in Figure 2, the front suspension is clean setup, designed for the best of handling on the track.

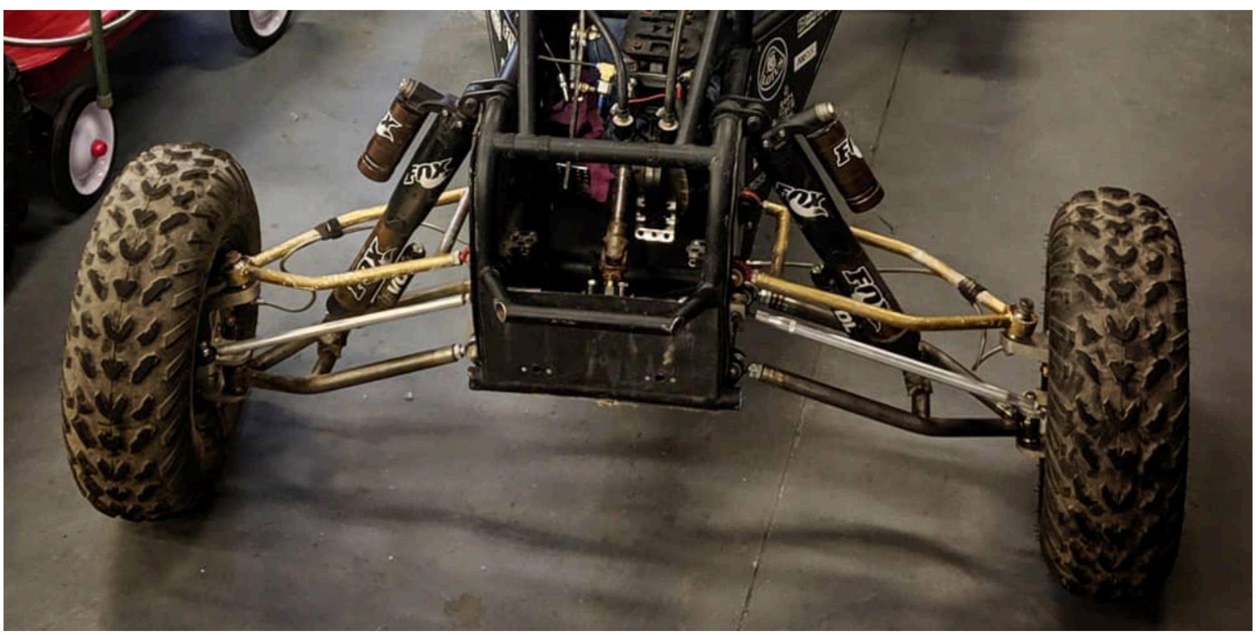

Figure 2 – Car 44’s front suspension view. [2]

The suspension in the rear was built for stability in mind as it features a long rigid trailing arm with two axial bracing bars connected to the rear of the frame. Pictured in Figure 3, the rear end design is shown. A con with this system is that the trailing arm is made from solid aluminum, making the rear have more weight than necessary further away from the center of gravity.

Figure 3 - Car 44's rear suspension design. [2]

2 REQUIREMENTS

The requirements that need to be met for this project is heavily based around the rulebook and our customer/client, Dr. Tester. After finding all the requirements needed, the team must convert those client needs to technical requirements that can be measured in a quantitative aspect.

2.1 Customer Requirements (CRs)

Part of the Baja competition is to pitch the design of the vehicle to a fictitious company for mass manufacturing. This company is our customer and requires that our vehicle can perform and pass different tests. These tests include an endurance race, a hill climb test, a braking test, an acceleration test, and others. From these tests, other requirements of the competition given in the rule book, and faculty advisors, a list of customer needs was generated and weighted. The weight of these requirements are from five, being the most important, to one, being the least important. Table 1 lists the needs as well as their weights.

Table 1: Customer Needs and Weights

Customer Needs	**Weights**
Reliable	5
Durable and Robust	5
Lightweight	4
Maneuverable	4
Low Cost (Within Budget)	5
Easy to Repair	3
Short Stopping Distance	4
Short Wheelbase	4
Ride Height	4
Track Width	4
Safe to Operate	5

A reliable design is one that will consistently pass repeated tests given to it. A durable and robust design will not break while performing the range of tasks it is designed for. Lightweight directly impacts the car's ability to perform well in the hill climb test. In addition, the maneuverability, the short stopping distance, wheelbase, ride height, and track width of the car will dictate how well it performs in the competition. Each of these requirements where found by comparing the winning teams' cars over the past few years of the competition. This data, from past years, was collected by students and provided to the team through one of our faculty advisors. Low cost for the car is crucial as the project is supplied with limited funds. In addition, the Baja vehicle is operated by a person inside the vehicle. Therefore, safety in operation is a customer need to ensure that the operator and others around the vehicle will not become injured. The last need to mention is for the vehicle to be easily repairable. This vehicle will be used by the SAE club on NAU campus for future years. Through this usage, it is inevitable that parts of the car will break over time or need to be replaced with upgraded models. Designing the car to be easily repaired will expand the overall life of the car and enable future teams to easily improve specific design components of the vehicle. Achieving these customer requirements, this vehicle that can exceed in the competition.

2.2 Engineering Requirements (ERs)

The engineering requirements found to be relevant for the sub-system suspension teams were based around the Customer Needs (CN's) given to us by the client and the competition rules itself. The purpose of the engineering requirements is to relate the CN's to technical requirements that can be measured. After discussing with both sub-teams, we concluded that our Engineering Requirements would include nine categories. Two of the more critical requirements include track width and ride height. These have become some of our technical requirements, because in order to achieve peak performance and maneuverability the team must design around a specific track width that can be measured in inches. For our specific purpose the track width goal is 53 inches. Ride height is also crucial to the entire vehicle, due to the axles and drivetrain, there is a required ride height of 10 inches. The Baja vehicle also needs to be able to stop within a certain distance of six feet, with a tolerance of 1-2 feet. For both front end and rear end, the total system is needed to stay within a budget of 7,000 dollars. The weight of the vehicle is another technical requirement, with more of a loose tolerance. As long as we stay within a weight of 450 pounds plus or minus 50 pounds. Another crucial requirement for the sub-teams involved in suspension is material properties to ensure the system does not fail when loaded during driving. The material being used can be measured by yield stress and tensile strength measured in Mega-Pascals or Kpsi. Each of these engineering requirements directly relates to designing a system that will be both reliable and durable.

2.3 House of Quality

The house of quality is a major part of the initial design stage. The Baja team has generated customer needs and engineering requirements in Sections 2.1 and 2.2. Those customer needs span the left side of the house of quality as seen in Table 2. The engineering requirements or technical requirements are listed at the top of the house of quality. With both the customer needs and engineering requirements generated they can then be compared to how well they align. The weighting for this includes values one, three, and nine. For example, if the vehicle is very reliable then it would have high cycles till failure, which awards the correlation with a nine. Whereas obtaining an optimal track width does not depend on decreasing the number of fasteners, which leaves that correlation blank.

Table 2: House of Quality

		Technical Requirements								
Customer Needs	**Customer Weights**	Cycles till Failure -->	Material Properties -->	Weight <--	Wheel Base <--	Cost <--	Fasteners <--	Stopping Distance <--	Ride Height *	Track Width <--
Reliable	5	9	9	1		3	3	9	3	3
Durable	5	9	9	1		3	3	3		
Lightweight	4		3	9	3	9	9	3		3
Manuverable	4			9	9	1		1	1	9
Low Cost	5	1	3	3	1	9	3			3
Easy to Repair	3	3		3	1	3	9			1
Short Stopping Distance	4							9		3
Short Wheel Base	4			9	9			3		
Ride Height	4			3					9	
Track Width	4			1				1		9
Safe to Operate	5		3	3	1			9		
Technical Requirement Units		#	kpsi	lbs	inches	$	#	feet	inches	inches
Technical Requirement Targets		150	50	450	60	7000	N/A	6	10	53
Absolute Technical Importance		104	132	169	97	124	108	169	55	93
Relative Technical Importance		5	2	1	6	3	4	1	8	7

The next step in completing the house of quality is creating target values for each of the engineering requirements. The targets were obtained through experiences at SAE competitions. For example, when in the rosy areas of the track it is optimal to have a high ride height and high material properties in case a rock makes contact with the suspension systems. If the vehicles does not have all wheels on the ground then there might be an increase in the impact taken by the shocks once it lands. This creates the target value of 450 pounds for the vehicle. The house of quality was able to assist the team in tabulating which engineering requirements are important in order for the team to do well at competition. For example, it is very clear from previous competitions that the lower the weight of the vehicle the better the team places. For that reason, the primary goal is to decrease the weight of the vehicle. Another important goal is to make the vehicle cost effective. To find the absolute importance the customer needs weights and how well they relate to the engineering requirements are multiplied and summed. The relative importance is simply which engineering requirement had the highest absolute importance in relation to the others.

3 DESIGN SPACE RESEARCH

Chapter 3 of the preliminary report presents a literature review performed by the team. It then discusses different systems and subsystems of the front and rear end of current Baja vehicles. After gaining a knowledge of the different areas of our project and current designs on the market, the team created black box and functional models for the front and rear end systems of the Baja vehicle.

3.1 Literature Review Front + Rear end

3.1.1 Will Preston (Brakes)

This student focused on examining the braking system of the Baja SAE vehicle. The first resource used for design research is the Brake Design and Safety textbook, which provides equations to evaluate forces exerted by the braking system. This includes equations that calculate pressure forces within the master cylinder and brake lines, and the corresponding clamping force generated by the hydraulic pressure [3]. This resource provided this student with the knowledge of forces within the brake system that must be considered to maximize system performance.

The second resource is a report from researchers at Inha University, where the effect of manufacturing processes on the development of stress cracks near cross-drilled holes of a brake rotor was examined. The findings indicated that despite a slight increase in average braking temperatures, stress relieving and ferritic nitrocarburizing decreased brake pad wear by 14%, and a 51.3% lower crack propagation rate near cross-drilled holes within a brake rotor [4]. This manufacturing process allows the cross-drilled rotor to be a viable concept, but such processes are not available at Northern Arizona University's machine shop and must be outsourced if this rotor design is chosen.

The third resource is a report from researchers at University Tenaga Nasional, which analyzed the optimum angle of internal cooling vanes in a ventilated rotor design. The findings from this report indicate that an internal cooling vane angle directed at 45 degrees in the clockwise direction improved the convective heat transfer coefficient by 51% and maximized braking performance and heat transfer [5]. These results introduced the possibility of implementing a ventilated rotor design into the Baja SAE vehicle, but in-house manufacturing capabilities may be limited.

The fourth resource, given by faculty advisor Dr. John Tester, analyzes vehicle chassis dynamics and weight transfer. This book primarily describes the effects of bushings, springs, alignment characteristics and chassis design, but this student focused on the topic of Weight Distribution and Dynamics described in Chapter 2. This chapter explained lateral weight transfer and cornering forces, which are experienced as the vehicle deceleration during braking. This chapter further contributed to the student's understanding of braking forces. [6].

The final resource examined is the 2020 Baja SAE competition rulebook. Section B.7.1.1 of the competition rulebook requires that the brake system for all Baja SAE vehicles "must be segregated into at least two (2) independent hydraulic circuits such that in case of a leak or failure at any point in one system, effective braking power shall be maintained on at least two wheels" [1]. The requirements for the braking system outlined in the competition rulebook must be followed to pass technical inspection and compete in dynamic events of the Baja SAE competition.

3.1.2 Michael Edirmannasinghe (Steering)

The primary focus by this student was on steering systems and geometry. The sources considered provides information on the pros and cons of steering geometries and calculations pertaining to different steering systems.

The first source considered is a thesis report specific to SAE Baja competition. It is an analysis which weighs the pros and cons of steering geometries, namely, the Ackermann steering geometry, Parallel geometry and reverse Ackermann geometry. According to this source, the Ackermann steering geometry allows ease of tight turns in lower speeds due to the difference in angles in the left and right tires. On contrast, parallel and reverse Ackermann geometries have the same turn angles in both wheels which would support turns in high speeds, but with larger turn radius. [7]

The second source outlines the designing process of a rack and pinion steering system specific to the Baja SAE project from a university in India. The design mentioned here uses SAE 9310 alloy steel tubing to build the steering system components and the calculations are done accordingly. The forces acting on the system is stimulated and the results and explained and discussed in detail in the sources. [8]

The third source is the textbook on Race Car dynamics. This book explains the needed steering systems in Chapter 19. The needed angle balance and the needed calculations that need to be done when designing the steering system is outlined based on the functionality of the vehicle. The steering gears that should be used and the relationship of steering box ratio is well explained for computation. [9]

The fourth resource is a book titled “Automotive Chassis”. This book had detailed manufacture and maintenance of various automotive systems. Chapter 17: Steering service has instances how the rack and pinion system could fail and how they can be remedied. This information is very useful for quick fixed in the Baja vehicle and would be highly considered when designing the system. [10]

The final source would be the SAE Baja 2020 rule book. This book has all the guidelines of designing all the components of the Baja vehicle. The team will move on to designing the components after examining all the rules and constraints [1].

3.1.3 Jacob Grudynski (Control Arms)

Jacob Grudynski dedicated his research to the control arms for the front suspension of the Baja vehicle. Many sources were used in gathering information for design research in the development of control arms for different off-road suspension setups.

The first sourced reviewed was a research paper written by A. Afkar, M. Mahmoodi-Kaleibar, and A. Paykani that detailed in every aspect of the optimization of a double wishbone suspension system. The various algorithms embedded into the paper are substantial evidence for the improvement of handling on the Baja vehicle. It gave in depth explanation of the geometry behind the control arms and the components mounted to them. Equations, charts and figures given in this report can help with the maximum performance of the suspension [11].

The second source reviewed was a website by “off road xtreme” that gave major incites on the fabrication process of control arms on an off-road vehicle. The types of mounts and mount locations of the control arm was explained for different types of suspension and applications. This article described several variations of joints of the control arm and focused on the best for off-road use. The geometry needed when fabricating the arms is crucial to a successful vehicle and the control arms not failing during operation [12].

The third source reviewed details a hydraulically dampened control arm with major variations from standard control arm setups. In the article, a suspension crankshaft is placed as the mounting bar of the upper control arm and had hydraulic dampeners affixed to the out sides laterally. Equations of how to design the control arms are given with the proper angles for off-road use in mind [13].

The fourth article reviewed is a website page from CarParts.com. The basic incites on standard control arm suspension are explained. This source gives information on the necessary components of the control arms and gives the locations of where to buy certain pieces on the control arm[14].

The fifth article reviewed is a page from RME4x4 that helps give important tips and tricks in the actual fabrication of the control arms. Pictures and captions explain the faults in most fabricating applications of these off-road suspension component. This article also outline the necessary tools in order to manufacture exceptional control arms [15].

3.1.4 Jesse Summers (Front-End Shocks)

This student focused research on the different types of shock absorbers that could be used and what type of shock absorber would be best for the needs of the vehicle and client.

The first source that was looked at focused on how suspension works. This article detailed some of the different mechanical aspects of how shock absorbers function, such as how the shock works with the spring and how the shock actually transforms the forces being absorbed into kinetic energy and then into thermal energy. This source could be very useful in finding shocks that would be effective and also evaluating different types of shocks that could be used on the Baja vehicle [16].

The second source this student found is focused on the physical mounting of the shock absorber. This article contains some valuable information on where is best to mount the shocks on the control arms and also how changing the angle the shock is mounted at will affect the damping effectiveness. This source can provide the team with very useful information and help decide on where and at what angle would be best to mount the shock absorbers [17].

The next source that was analyzed looked at the differences between monotube shock absorbers and twin-tube shock absorbers. This source is relevant because it has information concerning how both of these types of shocks actually work on the inside and how the fluids and gases are actually moving within the shock. This provides the team with valuable insight on which type of shock will be best to use for the SAE Baja competition [18].

The fourth source that was found also focused on the two types of shock absorbers, monotube and twin-tube. This source proved useful because it mainly focused on the positives and negatives of the performance of each type of shock. It also gave valuable information on how mounting angle can affect the shock performance [19].

The final source that was discovered looked at more of the differences between monotube and twin-tube shocks. This source provided more information about such things as ride stability and some of the common problems and issues that occur with each type of shock. This article also commented on how the two types of shocks compare in the area of responsiveness, which can be valuable for deciding on which type of shock to use [20].

3.1.5 Jacob Ruiz (Tires)

When it comes to looking at the environment that the Baja vehicle will be operating in, the tires selection needs to be considered. The first thing to consider is the type of tread that the wheels will have. For a competition in Arizona which is very hot and dry, there should be mostly hard ground or loose gravel. The tread pattern used has a lot to do with how the vehicle will gain traction. We will not be using a close tread pattern because it is mostly used for flat ground or in other words, daily driving [21]. The next thing to look at is the rims that the wheels will be attached to. For the application we are trying to decrease the weight of the vehicle and are limited in the rpms that the motor can supply to the wheels, because of that, the alloy wheels made of aluminum are the way to go [22].

The wheels must be connected to the vehicle and are done so though wheel hubs. The hubs are accompanied by a bearing. This bearing is used to allow the wheel to move freely compared to the static parts attached to the vehicle. 1A Auto did a great job at explaining how these worked and what it takes to repair/replace [23]. The next part that connects the hub to the output shaft of the engine is the CV axle. The CV axle is a constant velocity axle that provides the power to the wheels through a splined end connecting to the hub. The angle is able to vary which is necessary when using independent suspension [24,25].

3.1.6 Aaron King (Rear-End Shocks)

Aaron King focused on shock absorbers for the rear-end suspension system. In addition, Aaron researched general suspension systems and manufacturing of the systems to aid in the design of the rear-end suspension system.

The first source reviewed was a website by KYB. This website provided a brief explanation of twin-tube and mono-tube shocks. It also has a video demonstrating the two types of shocks and explaining their strengths and weaknesses. Twin-tube shocks are the conventional type and cost less than mono-tube shocks. Mono-tube shocks however eliminate the problem of the working fluid foaming and provide a smoother ride when compared to the twin-tube [26]. This helped the team to learn more about the types of shocks available and start to justify which shocks the team will use.

The second resource used was an article in a web archive. The archive is WayBack Machine, and the article is called “Monotube shocks – Don’t absorb shocks, but…”. This article describes in detail the monotube shock design and its advantages. Key points of the article include, mono-tubes designs only have one tube instead of an outer and inner cylinder. The elimination of the second outer cylinder enables the shock to be mounted in any position as opposed to the twin-tube which has to be mounted vertically, promotes greater heat diffusion since the heat generated through viscous and frictional forces in the shock only need to transfer through one cylinder, and it eliminates extra weight [27]. This article further increased the team’s knowledge of the mono-tube and aided in the decision-making process of which design would be best.

Next, Aaron reviewed Car and Driver’s website article, “Damper and Awe: Types of Automotive Dampers Explained.” This article discusses 6 different types of damper systems or shocks available and which cars they can be found in. The mono-tube damper is found in Audi A4. The twin-tube damper is found in Cadillac CT6. The internal-bypass damper is found in the Ford F-150 Raptor. The magnetorheological damper is found in Cadillac CTS-V. The spool-valve damper is found in the Chevrolet Camaro ZL1 1LE, and an electronically controlled damper is found in the Ford Focus RS [28]. This article was useful since it gave brief descriptions of many existing damper system designs. It also allowed the team to see what types of vehicles these designs were being used on. By analyzing the current applications of the designs and comparing them to the Baja vehicle design requirements, the team could quickly narrow down the concepts to what would work best.

The fourth source analyzed was a journal article in the Archive of Mechanical Engineering. The article title is “Design and analysis of an interconnected suspension for a small off-road vehicle”. This article describes the interconnected suspension for the University of Windsor SAE Baja vehicle. It also describes the multibody dynamic analysis of the system performed by an open source multibody software developed by the University of Windsor Vehicle Dynamics and Control research group. Based on their results it was concluded that the interconnected suspension offered a higher performance than the anti-roll bar configuration during high impact or amplitude scenarios but not in scenarios where the frequency is high [29]. This helped the team to learn from the tests and designs of another university participating in the competition in past years. Reading through the results and analysis of the article, it was determined that the interconnected suspension has advantages, but further research and analysis needs to be made on the interconnected system. his is due to the advantages experienced disappearing at high frequencies of cycling.

Lastly, Aaron reviewed a textbook written by Mikell P Groover. The title of the book is “Fundamentals of Modern Manufacturing”. This book describes many different manufacturing processes and equations for these processes [30]. The equations presented in the book aid in finding optimal design variables for fabrication of our design. As the team moves forward in the design concept generation it is important to keep in mind the manufacturing processes available to the team and the constraints it places on the materials and shapes of the designs. For example, certain materials are too brittle to be manufactured in the shop on Northern Arizona University campus and are too expensive to be manufactured elsewhere. In addition, some metals can be welded together, while others cannot. These are all important factors to consider when selecting design concepts.

3.1.7 Lucas Cramer (Semi-Trailing Arm Suspension)

The literature review done by this student lead to gathering information on how the semi-trailing arm suspension works, as well as the benefits/disadvantages of using such a system. The first source includes a blog specifically about semi-trailing arms and how they work. This source gives an insight into the exact differences between this system and a regular trailing arm system, and what aspects it uses from other types of suspension systems [31]. The second source focused more on the actual geometry of the system including diagrams, and pictures of the sub-components involved and what they do for the entire suspension system [32]. The third source was a report done by the University of Cincinnati’s Baja team from 2013, and they utilized a semi-trailing arm set-up and wrote a specific report detailing the load distribution and using this system to create under-steer. This report gives detailed explanations on why this team chose to use this set-up and how well it worked [33]. The final source used was a Journal from International Journal of Application of Engineering and Technology (IJAET), that had a dynamic analysis of this suspension system, when using specific material. The report also included a load diagram, but with the actual equations and numbers to support their findings [34]. Although, there are some benefits from using the semi-trailing arm suspension, the disadvantages seem to outweigh the benefits, causing our team to focus on other designs.

3.2 Benchmarking

For the Baja vehicle project, it is difficult to benchmark full systems because of how unique every Baja can be. The best benchmarking to be done for this project includes analyzing previous teams who have done well during the competition. Whether it be from simple well manufactured parts, to complex suspension geometries, analyzing previous teams gives us good insight as to what we should be aiming for and possible ideas we may have not considered. Furthermore, the benchmarking done for this project also included conversations with many off-roading companies via email or phone, to determine what type of material is best suited for our specific needs.

3.2.1 System Level Benchmarking

This section discusses current front and rear end design systems used in past Baja competitions. It highlights designs used by top performing teams in the competition. These teams are University of Michigan: Ann Arbor, Rochester Institute of Technology, and Oregon State University.

3.2.1.1 Existing Design #1: University of Michigan: Ann Arbor

3.2.1.1.1 Front End

The front-end suspension on the University of Michigan Ann Arbors Baja vehicle used a simple double wishbone system. This design would make the front-end light, strong and the best suspension set up for an off-road environment. As shown in Figure 4, the front end set up is clean and not complex. The shock is mounted on the lower control arm for maximum damping of the vehicle.

Figure 4– Ann Arbor's front-end design [35]

The tubular style wide framed a-arms are best for tuning and maneuverability when driving, as it gives the team very ideal suspension geometry for racing. This design makes for a race winning suspension.

3.2.1.1.2 Rear End

The rear end system involved in the Michigan Ann Arbor Baja vehicle was a more unique design than most. Instead of having multiple connecting pieces around the axle while mounting at multiple spots to the frame, this system utilizes a single trailing arm that sweeps around to the wheelbase and then back to the frame only needing two mounting points. This has benefits in being lightweight because of the single trailing arm, as well as having easy mounting due to only needing two mounting locations. However, because it is one single tube, it connects to the wheelbase in only one location, having less control over the toe and camber that can be created during testing/driving.

Figure 5 - Ann Arbor’s Rear End [35]

3.2.1.2 Existing Design #2: Rochester Institute of Technology

3.2.1.2.1 Front End

Rochester Institute of Technology’s RIOT Racing team received second place overall in the 2019 SAE Baja event hosted in California, yielding proficient scores in the Maneuverability and Suspension events of the competition [36]. These results inspired the Front End suspension design team to examine the front suspension geometry that contributed to RIOT Racing’s success. Figure 6 represents the front suspension geometry utilized by the competition vehicle, which is a double-wishbone setup with tubular control arms and a coil-over shock absorber mounted to the lower control arm. The top of the shock absorber is mounted over the nose of the vehicle, which minimizes stress on the lower control arm and allows for maximum suspension travel. In addition, this front end geometry features upper control arms that are shorter in length compared to the lower control arms. The difference in length minimizes the scrub radius of the vehicle and retains desired wheel alignment specifications under hard braking and cornering, which ensures vehicle stability and precise steering feedback for the driver. This configuration provided the front end design team with knowledge of shock absorber mounting points and geometry parameters that achieve optimal wheel alignment specifications.

Figure 6: Front End Geometry of RIOT Racing's Baja SAE vehicle [37]

3.2.1.2.2 Rear End

Rochester Institute of Technology placed 2nd at the SAE California competition. This prompts the research of what the team did for the rear end of the vehicle. What is modeled in Figure 7 shows that the team used trailing arms with two links to the rear end. The shocks on this model are mounted approximately at the halfway mark of the trailing arm. It should be noted that the mounting location if in a direct line with the mounting location of the frame. Although the location of the mounting points is determined based off the geometry and calculations, this is a common trend in vehicles to not cause additional stresses on the shock or members of the vehicle. The CV axle is also going directly through the trailing arm which likely has a bearing to reduce the friction of metal on metal. This design gives the group some great ideas of what works well and will work to incorporate into future designs.

Figure 7: Rochester Institute of Technology Rear End [38]

3.2.1.3 Existing Design #3: Oregon State University (OSU)

Oregon State University consistently places in the top five for the Baja competition [39]. Therefore, the team decided to use their vehicle as a system benchmark for the project.

3.2.1.3.1 Front End

Oregon State University's SAE Baja vehicle recently won first place overall at the SAE Baja Tennessee Event [39]. A key factor in this placing was their suspension setup. On the front end, the OSU team used a double wishbone setup, as can be seen in Figure 8.

Figure 8: OSU Baja Vehicle Front End [40]

Looking at Figure 8, the OSU team used simple, tubular upper and lower A-arms with the shock mounted on the lower arm [40]. This setup provides simple and strong A-arms that are easy to manufacture and can withstand any forces from the course. Additionally, the shock is mounted on the lower A-arm at a relatively high angle. This combination helps absorb the most force from the ground/course so that the A-arms do not have to withstand all of those forces.

3.2.1.3.2 Rear End

Oregon State University used a two-tube trailing arm with two rear lateral links for their rear end suspension system. These four links come together at the hub where they connect to the tire and their other ends attach to the frame as seen in figure 9.

Figure 9: OSU Baja Rear End [41]

The shock also attaches to the hub. From the hub the shock is mounted to the frame to oppose the travel the tire experiences from bumps and divots in the road. Advantages to this system are the simplicity of the design as well as the light weight. By using tubes as the arms and links of the system they can easily be scaled to fit different geometries, and the member's diameters can be changed in the design stage to increase their strength or decrease their weight. Another advantage is if a link breaks, there is another link to support the car. It also is easier to replace links one at a time as they break versus designs with a single trailing arm where when it breaks the whole arm needs to be replaced. Disadvantages of this design are the placements of each link in manufacturing of the suspension system. When using two links, both links need to be parallel with each other. If the links are not parallel it will decrease the maneuverability of the car by changing the toe angle during the up and down movement of the links during bumps and divots.

3.2.2 Subsystem Level Benchmarking

3.2.2.1 Subsystem #1: Geometry

The geometry sub-system is based around the connection from wheelbase to frame. This sub-system includes all arms and other types of geometry that can connect the wheelbase to the frame while housing the axle and many other sub-system connections.

3.2.2.1.1 Existing Design #1: Semi Trailing Arms

One of the current designs that exists on many vehicles is the semi trailing arm. This is a common geometry because of the ability to have one side of the vehicle act independently of the other side. Semi trailing arms also are one member instead of multiple working together which eliminates the possible collision of members when assembled. This also is a con to this system because if a member on the semi trailing arm breaks the entire system must be replaced or repaired. The unsprung weight of the vehicle is also decreased with semi trailing arms compared to geometries like double wishbone or twin I-beams [42]. An image of semi trailing arms on a SAE Baja vehicle is shown in Figure 10.

Figure 10 - Semi-Trailing Arms [43]

3.2.2.1.2 Existing Design #2: Trailing Arms

Another design that is currently used is the trailing arm suspension geometry. This is used on many vehicles including off road vehicles because of its ability to deal with bump travel well. Trailing arms typically need more members than the semi trailing arms because of needing more connection points. The downside to trailing arms is it only allows for movement up and down which restricts the movement side to side. This can also be a positive because if designed correctly the toe angle will not change which will increase maneuverability. In Figure 11 you can see a trailing arm set up used by NAU in the 2018-19 season.

Figure 11 - Trailing Arm [43]

3.2.2.1.3 Existing Design #3: Double Wishbone

The double wishbone suspension system is the most popularly using type of suspension for front end off-road racing vehicles. This type of suspension features two A or U shaped arms connected to a knuckle that mounts to the tire [11]. The shock absorber is mounted to one of the arms, usually the lower arm, to control the dampening of the vehicle when going over rough terrain. This system can be implemented on the rear end, but it is more uncommon. On this year's Baja Vehicle, a double wishbone suspension set up is going to be fabricated on the front-end for the best dampening and control of the vehicle.

3.2.2.1.4 Existing Design #3: MacPherson Strut

The MacPherson strut is one of the most commonly used types of independent suspension. This type of suspension combines a shock absorber and a coil spring into one, single unit [44]. This unit then replaces the functions of the upper control arm and shock in a double wishbone setup. The MacPherson strut is typically mounted completely vertically or very close to vertical. This aspect of the MacPherson strut would be very useful as the front end team needs to mount the shock as vertical as possible to absorb the maximum amount of the forces exerted on the suspension from the terrain. This design is also relatively lightweight and typically inexpensive to manufacture and buy [45].

3.2.2.2 Subsystem #2: Shocks

Shocks are another sub-system that will be utilized in both front and rear end. The twin-tube, mono-tube, and the external reservoir designs are presented and discussed in the following sections.

3.2.2.2.1 Existing Design #1: Twin-Tube

Twin-tube shocks differ from mono-tube shocks in many ways. The fundamental difference is that the twin-tube utilizes and inner chamber and outer chamber, the hydraulic fluid flows from the inner chamber to the outer chamber via valves along the system [46]. Due to the multiple chambers and the flow of the fluid, under extreme pressure or fast speeds it causes foaming in the system leading to rough ride quality. The twin-tube set-up is also not as responsive because of the multiple components and valves involved, not dispersing the load evenly. Twin-tubes are also harder to install, making them not an ideal candidate for our suspension systems.

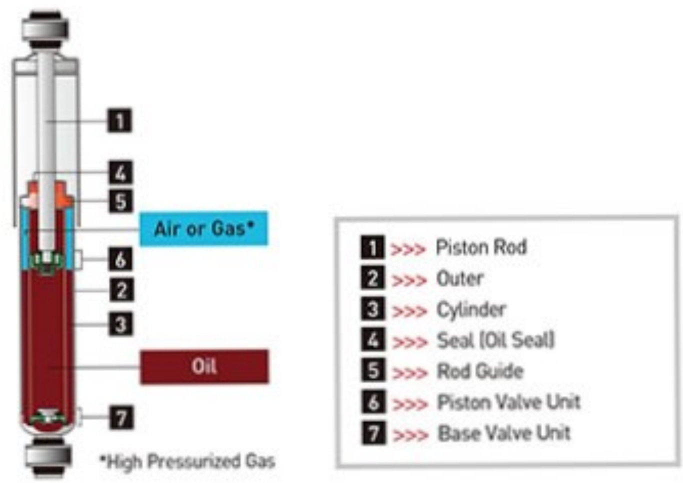

Figure 12: Twin-Tube Shock Design [46]

3.2.2.2.2 Existing Design #2: Mono-Tube

The Mono-Tube design consist of a piston inside of a cylinder. The cylinder is divided into two segments by a floating piston and seal. On one side of the floating piston is a fluid that the regular piston can cycle up and down through. On the other side of the floating piston is a high pressurized gas. This combination of fluid and high pressurized gas provides dampening to the system. On fast aggressive strokes of the piston the floating piston will be displaced by the fluid and it will compress the gas on the opposing side of the floating piston, providing extra dampening. This design is superior to the twin tubes since the gas is separate from the working fluid. This prevents mixing of the gas and fluid into a foam and provides more response from the shocks during fast, aggressive, and more frequent strokes. The disadvantage of this design is that the floating piston and seal are very precise parts that are difficult to manufacture. This raises the cost of the mono-tube design over the twin-tube design. Figure 13 illustrates a mono-tube shock design. [47,48]

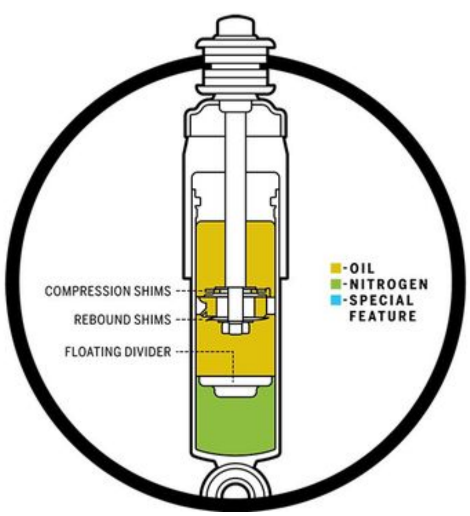

Figure 13 - Mono-Tube Shock [48]

3.2.2.2.3 Existing Design #3: External Reservoir

An external shock reservoir is a secondary tube that contains extra oil and gas for the main shock absorber to use. When a shock is preforming at an off-road level with longs of rough terrain the shock absorbers move a lot and from that movement heat up the oil inside and cause foam. This foam makes the shock lose its ability to dampen the suspension motion [49]. This results in a bouncy ride and terrible handling in rough sections. An external reservoir increases the oil capacity to help lower the shock temperature during lots of motion without having the shock performance suffer. There is two different style of external reservoir, the piggyback style, Figure 15 and the remote style, Figure 14 [49]. The piggyback style is an extra tube that is welded to the side of the main shock and connected directly to the main reservoir of oil inside the shock. A remote reservoir is a tube that is connected to the main shock by a tough composite tube; in this configuration the external reservoir can be mounted in different places, like open areas where wind can hit it to cool it down even more.

Figure 14 - Remote style external reservoir. Figure 15 - Piggyback style external reservoir.

3.2.2.3 Subsystem #3: Brakes

The brake system on the Baja SAE vehicle is designed to impart a friction force on a rotating disc connected to the wheel hub to reduce the kinetic energy of the vehicle. The braking process allows the operator to moderate the vehicle speed in competition and emergency situations, where the vehicle is required to lock all four wheels and stop in the shortest distance possible. The primary components of a braking system include the brake caliper, brake rotor and master cylinder. This section will examine existing designs of the aforementioned components.

3.2.2.3.1 Existing Design #1: Rotors

Brake rotors are discs designed to withstand frictional forces imparted by the brake pads. The friction between the pad and rotor surfaces generate high levels of heat that must be dissipated effectively to maintain efficient braking performance. Heat transfer between components will cause the brake fluid to boil or the brake rotors to deform from thermal and compressive stresses, which will significantly reduce the effectiveness of the braking system. Current automobiles utilize ventilated brake rotors, where two plates of steel are separated by internal cooling vanes that allow external air to flow through and reduce the operating temperature of the system. High performance automobiles utilize larger rotors with cross-drilled holes, dimpled holes, slots or a combination of these to quickly dissipate heat from the braking system. Figure 16 displays an example of a cross-drilled rotor. Maximizing heat transfer and braking performance will yield consistent and short stopping distances, and a reliable subsystem that ensures safety for the driver and pedestrians.

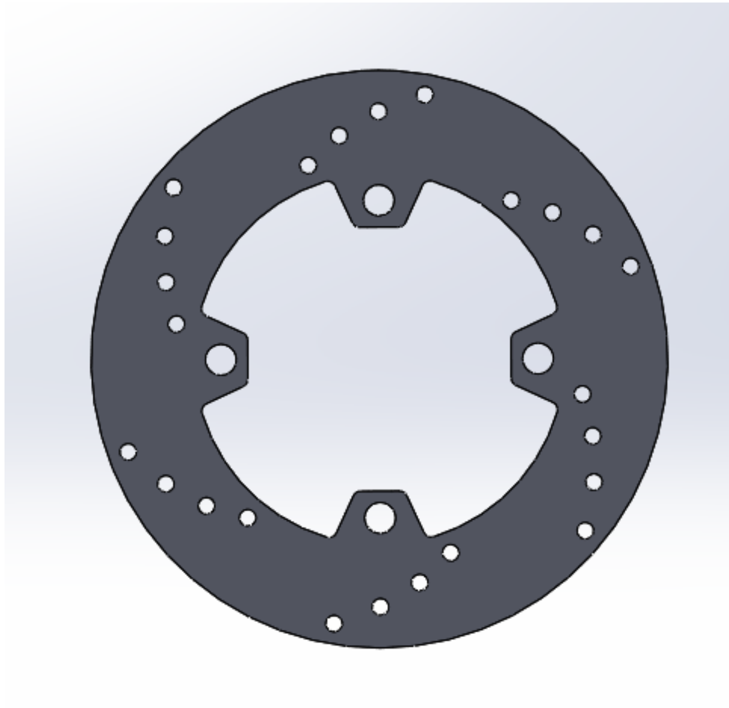

Figure 16 - CAD of simple brake rotor with cross-drilled holes

3.2.2.3.2 Existing Design #2: Calipers

The brake caliper is essential to the braking system, as it utilizes hydraulic pressure and frictional properties of brake pads to impart a clamping force onto the surface of the brake rotor and slow the vehicle. The two types of brake calipers used in current automobiles are fixed and floating calipers. Fixed calipers utilize pistons on the inboard and outboard side of the caliper, and both are displaced inward due to hydraulic pressure. This setup provides increased clamping forces compared to a floating caliper, where the caliper body is a two-piece system. Figure 17 represents the configuration of the fixed-type caliper.

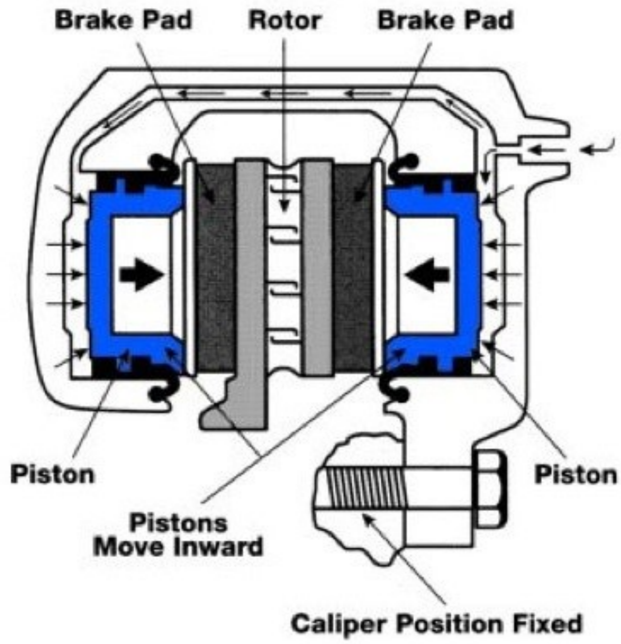

Figure 17: Schematic of fixed-type brake caliper [50]

In a floating caliper, a piston on the inboard side presses a brake pad to clamp the rotor against a stationary brake pad mounted on the opposite side of the caliper. This movement causes the caliper body to move along guide pins, which allows the brake pad being pushed by the piston to clamp the rotor against a fixed brake pad held on the opposite end of the caliper body. The layout of the Floating Caliper is displayed in Figure 18.

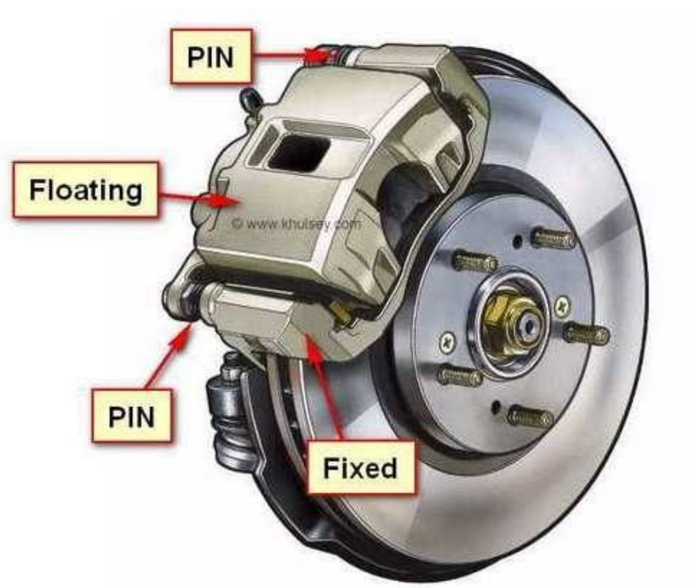

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Figure 18: Diagram of Floating Caliper with solid, ventilated brake rotor [51]

Brake caliper design is crucial for braking performance as it relies on hydraulic pressure to impart a frictional force large enough to stop the vehicle in the shortest distance possible, locking all four wheels in the process. The weight of the caliper and rotor system will also affect the gross vehicle weight, which determines the total stopping distance and required braking force. Therefore, it is critical to minimize the unsprung mass to maintain a short stopping distance.

3.2.2.3.3 Existing Design #3: Master Cylinder

The master cylinder of a brake system converts the pedal force imparted by the driver of the vehicle into fluid pressure via a pushrod connected to a moving piston and the brake pedal. The brake caliper utilizes the fluid pressure generated to apply a clamping force that decreases the speed of the vehicle. Current automobiles use a type of master cylinder known as a tandem master cylinder, which uses a dual piston system that sits in line to direct fluid pressure to the front and rear brake lines. However, the Baja SAE competition rulebook encourages the use of separate master cylinders to control the front and rear braking system. Figure 19 and Figure 20 represent the individual and Tandem master cylinder configurations, respectively.

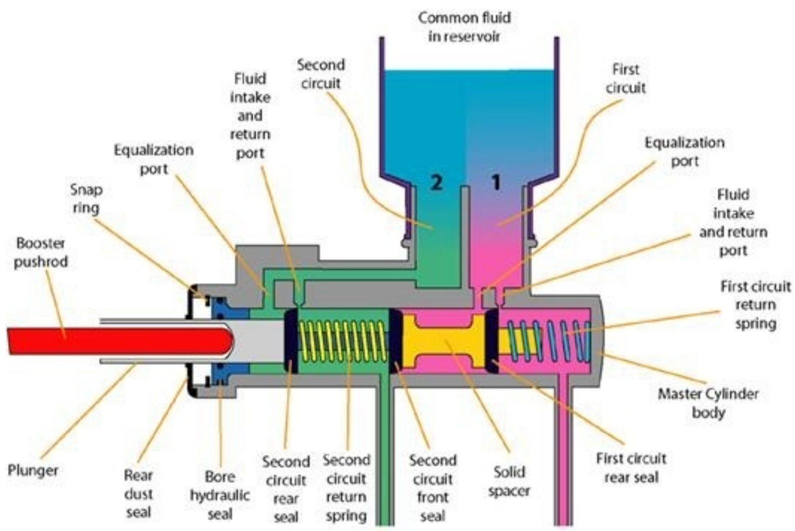

Figure 19 - Schematic of a Tandem Master Cylinder [52]

Figure 20 - Individual Master Cylinder [53]

3.2.2.4 Subsystem #3: Steering

The steering system of the Baja vehicle designed in this project plays a major role in the maneuverability of the vehicle. The steering system provides the ability to the driver to navigate the vehicle when in motion. Specifics of the vehicle such as wheelbase, track width and even wheel geometry must be adjusted based on the required turn angles and the speed in turning.

The primary focus on this subsystem is to identify the most efficient, reliable and durable method of converting rotating motion to linear motion and thus converting the human input energy to easily tilt the front tires as needed.

3.2.2.4.1 Existing Design #1: Steering Gearbox

The Steering Gearbox mechanism is a piston and gear that works as a rack and pinion. It is a vertical motion the connects an output shaft to a gear system the converts the tie rods to move linearly. The input shaft is connected to a piston that moves up and down with the support of high-pressure fluid and the rotation of the input shaft.

The input shaft is connected to a ball lead screw that allows the piston to move up and down when the input shaft is rotated. The piston is connected to a gear the further rotates the output shaft. The system is functioned by high pressure power steering fluid entering and exiting the chambers of the piston column.

Figure 21: Steering Gearbox

The benefit of using a steering gearbox is more applicable for larger vehicles that need more torque to move the steering links. The driver must exert lower torque in the steering column to get the needed turn in the wheels. The disadvantage of applying this system to the Baja vehicle is that the added components and the power steering system will add more weight and consume space during the assembly. With a 4WD system, it is not advisable to have more components to control the maneuverability of the vehicle. Efficiency is a key factor when designing functionality.

3.2.2.4.2 Existing Design #2: Rack and Pinion

The Rack and Pinion steering system is the basic system used in most cars today. The rotating torque coming in through the steering column is directly converted to linear motion. The gear controls the linear motion of the rack which controls the movement of the wheels through tie rods. Based on the dimensions and density of the material used when designing the rack and pinion, the intensity of the torque needed to be applied to the steering column varies. The pitch circle diameter of the pinion is proportional to the torque. A bigger pitch circle diameter compatible with the rack would ease steering torque.

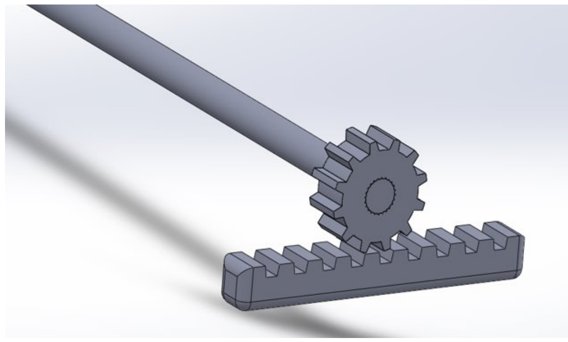

Figure 22: Rack and Pinion

The advantage of using this system is that it is light and easy to repair. The functionality of this system is simple and works effectively for a small Baja vehicle. The only drawback will be to steer the system in rough terrains. Yet, this would not be a concern since the Baja would be made specifically for known terrains. The torque needed for effective steering can be determined and the components can me manufactured as needed.

3.3 Functional Decomposition

3.3.1 Black Box Model

3.3.1.1 Front End

The primary function for the Front End subsystem of the Baja SAE vehicle is to control the displacement of the vehicle and support the vehicle weight. The driver must input Human Energy into the system to achieve this goal. Kinetic Energy due to shock forces translating suspension components (wheels, control arms, etc.) and Potential Energy due to vehicle weight forces must also serve as inputs. Visual and noise signals are interpreted by the driver as they operate the vehicle. These signals ultimately determine how the driver will proceed on the course and control the displacement of the vehicle. On the output end of the Black Box, Kinetic and Potential energies from the mechanical processes are conserved. In addition, noise and heat are also generated by braking, steering and dampening systems as they function. This model allowed the team to obtain a clear understanding of the end goal for the Front End geometry, including the vital physical concepts that achieve this goal. Figure 23 represents the Black Box Model for the Front End suspension geometry.

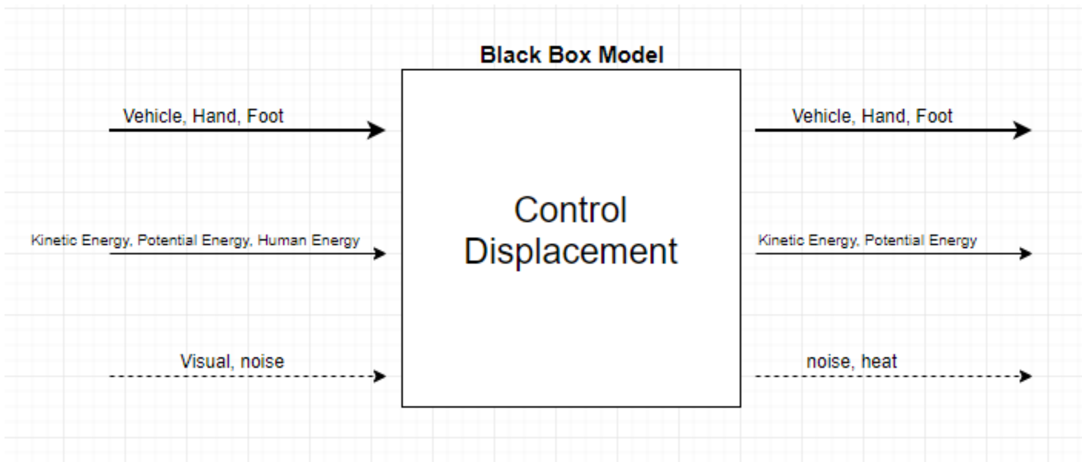

Figure 23 - Black Box Model for Front End Suspension Design

3.3.1.2 Rear End

The main goal for the rear end suspension system is to support the car. The kinetic energy of the movement of the car as well as its potential energy in relation to its position off the ground are inputted into the rear end suspension system. These energies are generalized to be a mechanical energy input as seen in Figure 24.

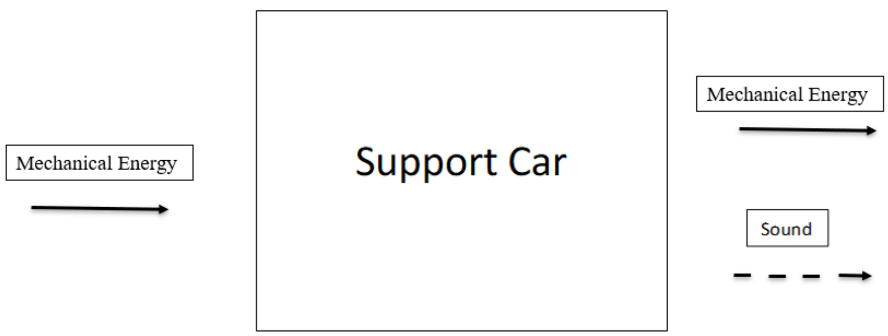

Figure 24 - Rear End Blackbox Model

From there the system produces mechanical energy to keep the frame of the car off the ground. There is also sound exiting the system. This sound signals the user on whether the system is working properly. This model demonstrated to the team that the objective of the rear suspension system was simple and that there would be many ways to accomplish this goal.

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

3.3.2.1 Front End

The Functional Decomposition model allowed the front end design team to further analyze the goal of controlling the displacement of the vehicle. This was accomplished by dividing the inputs and outputs from the Black Box model into essential processes that serve to achieve this goal. The team then applied this model to existing concepts of automotive suspension geometry to determine an ideal design that best meets the Customer and Engineering Requirements [Suspension Geometry and Computation]. The driver must input Human Energy for this process to occur, and this energy is converted into mechanical energy in two ways. The driver actuates the braking system via a foot-operated pedal, and this pedal force is subsequently converted into hydraulic pressure. This hydraulic pressure must be stored to maintain consistent braking performance and prevent total system failure. The hydraulic pressure then displaces a piston, which forces the brake pads to clamp against the surface of the brake rotor. The friction forces generate heat and noise, decreasing the kinetic energy of the vehicle in the process. The driver's hands actuate the steering system to change the relative angle of the front wheels and direction of the frictional forces between the tire and ground. This process allows the driver to further manipulate the direction of the vehicle. Lastly, a dampening system must be implemented to control vehicle handling dynamics and shock forces from rough terrain. Figure 25 displays the Functional Decomposition Model for the front-end suspension geometry.

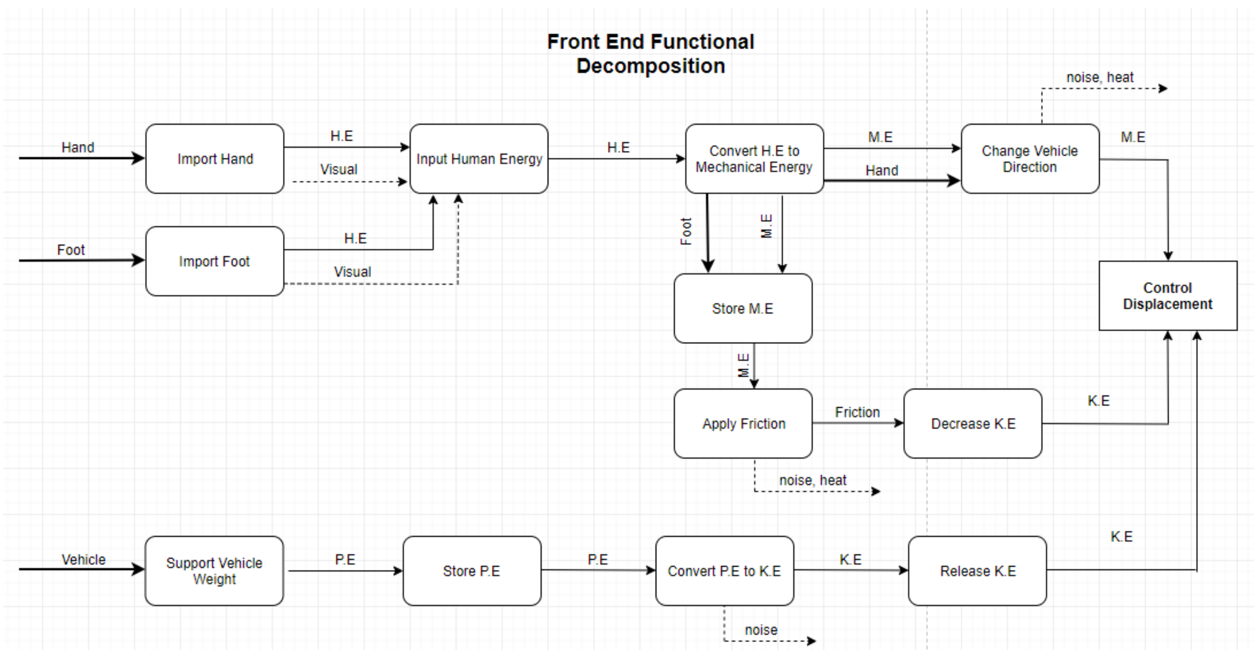

Figure 25 - Front End Functional Decomposition Model

3.3.2.2 Rear End

The rear end functional decomposition model was created by expanding on the black box model of the rear suspension system. This helped the team narrow down what was a necessary function that the system needed to perform and expanded our view on how these could be accomplished. Figure 26 illustrates our functional model.

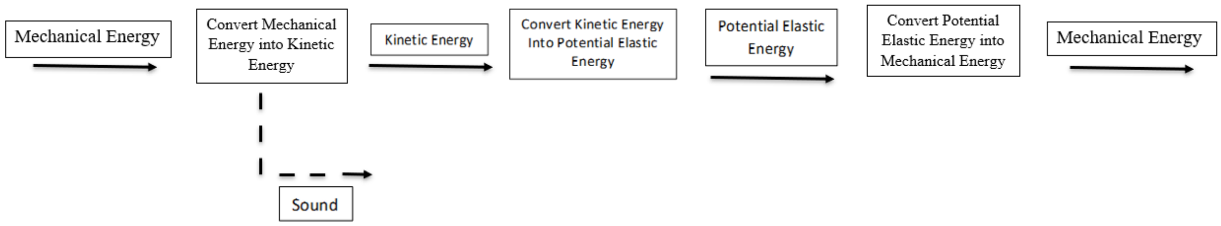

Figure 26 - Rear End Functional Model

After the mechanical energy of the car enters the system it is converted into kinetic energy. This kinetic energy is then transformed into potential elastic energy and leaves our system as mechanical energy. In past Baja competitions, teams would convert the mechanical energy into kinetic energy through moving control arms or links to the tires. When these arms moved they would compress shocks and created elastic potential energy. As these shocks decompressed kinetic energy and potential energy in the displacement of the car is what leaves the system as mechanical energy.

4 CONCEPT GENERATION

Chapter 4 of the preliminary report presents a concept generation section. In the concept generation, the team details different design concepts for the Baja Vehicle. Full vehicle design concepts as well as individual subsystem design concepts are explained.

4.1 Full System Concepts

4.1.1 Full System Design #1: Double Wishbone on Front and Rear End

The Double Wishbone concept is a primary concept when considering the suspension and stability of the entire Baja vehicle. However, there a separate pros and cons when considering this concept for Front and Rear End of the vehicle. The weight distribution and the component functions vary between the Front and Rear End. Therefore, the justifications do not apply equally.

With regard to the rear end, the expected function of the Double Wishbone arrangement is to support the rear end, mount the wheels and navigate the impact to the shock absorber. The wishbones connect the frame and the knuckles which then hold the hub, rotors and wheels. The shock is also mounted to upper wishbone preferably. The advantages are mainly the vertical movement of the suspension and support system. There is no unstable movement. However, the disadvantage would be to modify the frame horizontal members which would affect the structural integrity of the frame. The rear end consists of the engine, and the drive train which in turn adds most of the weight to the rear end of the vehicle. Therefore, the supporting components should be light weight and heavy duty at the same time.

When considering the front end, the double wishbone is the most common system used in Baja vehicles. The vertical motion and the ability to navigate the impact along the A-arms helps the structural quality of the system. The strength of the A-arm plays a major role since the impacts are absorbed directly into the shocks through the A-arms. The advantages of the double wishbone set up to the front end is the consistent alignment. The motion of the suspension system remains vertical since the mounted A-arms constraints any horizontal motion. With the 4WD system, the shock will be mounted on the upper A-arm and the top end of the shock will be mounted higher up on the frame.

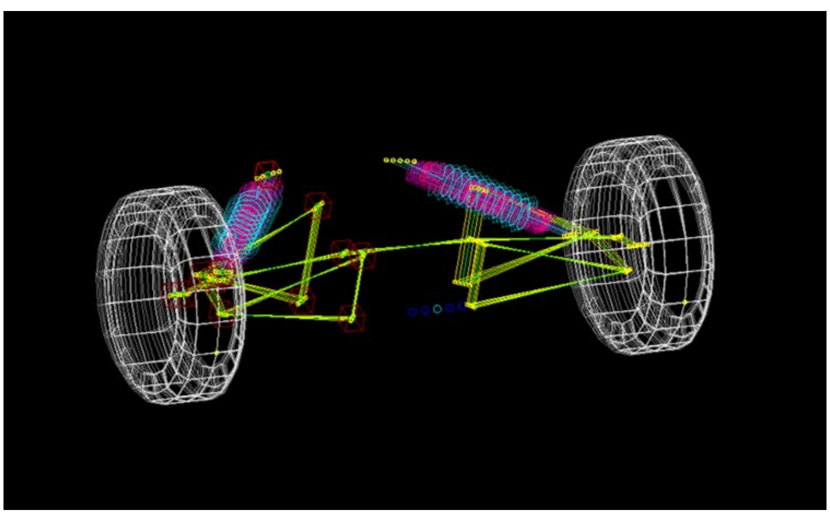

Figure 27 -Double Wishbone – Upper A-arm shock mount

4.1.2 Full System Design #2: Trailing Arms and Double Wishbone

The full system design discussed in this section included a trailing arm in the rear and double wishbone in the front. The advantages of having trailing arms in the rear end is that there is better travel over obstacles without worrying about the toe camber changing much. The con with the trailing arm is that the toe angle can significantly change with bump travel which decrease the maneuverability of the design. The goal for controlling the toe angle is to keep it within 3 degrees and have the wheel at 0 degrees at ride height. As for the front end, the double wishbone allows for good connection points as the mounting points can be on one plane level to the ground. The shocks for this design can also be mounted on the top A-arm, although not the best it allows for there to be more room for the CV axle due to designing for 4-wheel drive. Below in Figure 28, you can find a double wishbone geometry in the front and trailing arms in the rear.

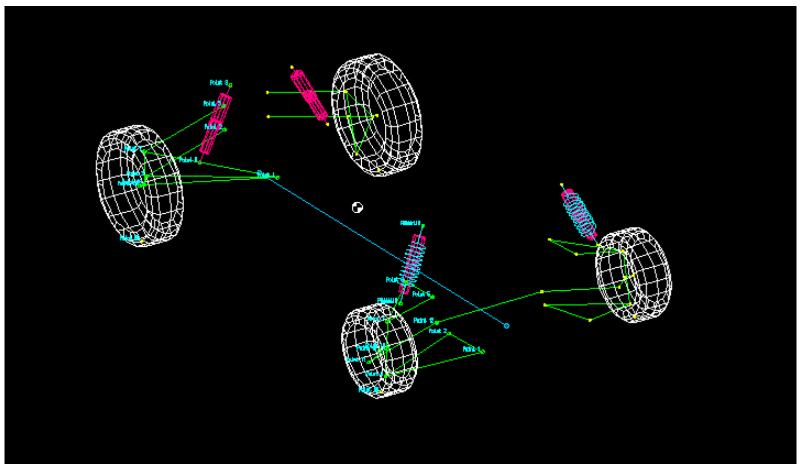

Figure 28 - Double Wishbone and Trailing arms

4.1.3 Full System Design #3: Semi Trailing Arms and Double Wishbone

The Semi-Trailing arm is almost a mixture of two different types of suspension. The semi-trailing arm design utilizes ideas from a trailing arm and a swing axle suspension, to create an independent suspension system on the rear end, so that a bump on one side will have no effect on the other side. This suspension system is extremely durable and reliable; however, it lacks in the performance category. Although the semi-trailing arm suspension is an independent system, every time one wheel turned because of a bump the toe and camber angle are subject to change causing steering problems. It also causes a complex mounting geometry for the axle housing, hub connection, and shock mounting. For the rear suspension, it appears the semi-trailing arm is less advantages than most.

The double wishbone suspension system is a more widely used type of system. This system is found in most off roading vehicles, the benefits of a system like the double wishbone lies within the mounting connections. It is mounted on the top and bottom keeping the toe and camber angles more fixed. This system is heavier than other systems but is also more reliable and durable. Depending on the set-up, the double wishbone can cause a complex geometry within the system. Utilizing both of these suspension systems will lead to a functional full system, but with many disadvantages lying within the rear end system due to the semi-trailing arm system.

4.2 Subsystem Concepts

4.2.1 Subsystem #1: Geometry

4.2.1.1 Design #1: MacPherson Strut

The MacPherson strut is designed to combine a shock absorber and coil spring into a single unit. This factor could be very useful in saving space, weight, and money. For this design, the Macpherson strut would essentially replace the functions of the upper control arm and shock absorber found in a double wishbone design. The strut would be mounted to the knuckle via two bolts at the bottom of the strut. The top of the strut would be more difficult to mount, though. A mounting plate would need to be added to the frame since the top of the strut consists of a mounting/camber plate with bolts that would fasten to the frame mounting plate. The pros of this design are that the MacPherson strut would save weight, reduce the number of parts, and would be cheaper in price. However, the cons of this setup are that a mounting plate would have to be added to the frame since the strut needs to be mounted vertically. Additionally, the MacPherson strut gives the team less control over such things as camber and this type of suspension is typically only used on front wheel drive passenger cars.

4.2.1.2 Design #2: Double Wishbone

For one of the concepts the team has considered to design is a double wishbone concept for the front suspension. This design features two control arms guide the wheel in the path for best dampening possible. A double wishbone system is the best for off-road compatible suspension for the front end. The pros of this system is that it is very adjustable and can be made for the best suspension geometry for any situation. A con of this system is that it is very tight tolerances for all the necessary components of the front suspension and must be designed to accompany these needs. Figure 29 shows the double wishbone CAD model on the front-end.

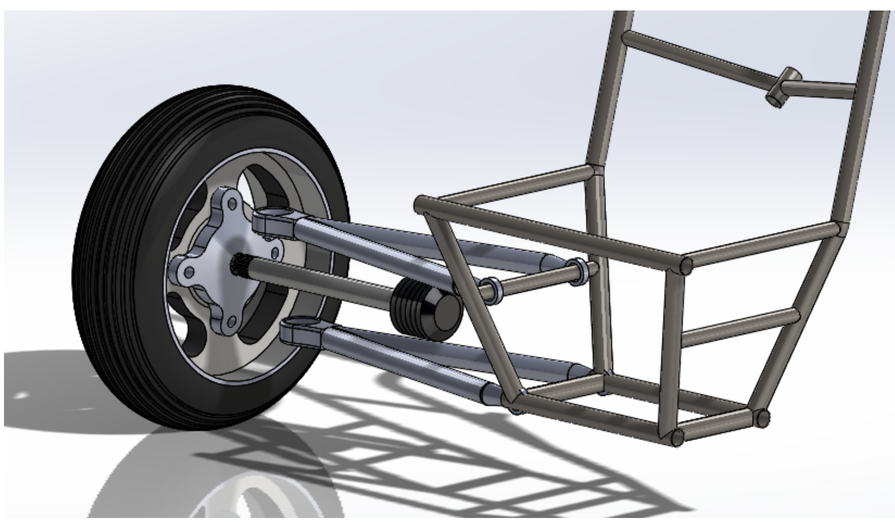

Figure 29 - CAD model of the double wishbone design for the front end.

4.2.1.3 Design #3: Trailing Arms

For one of the concepts that the team has considered to design for is the trailing arm suspension geometry.

For this there is one member that extends back and is connected to the rear by two rear lateral links that are parallel. There is also a CV axle that connects to the trailing arm which makes up a 4-point connection. As seen in Figure 30, there is a model of a concept made in solid works.

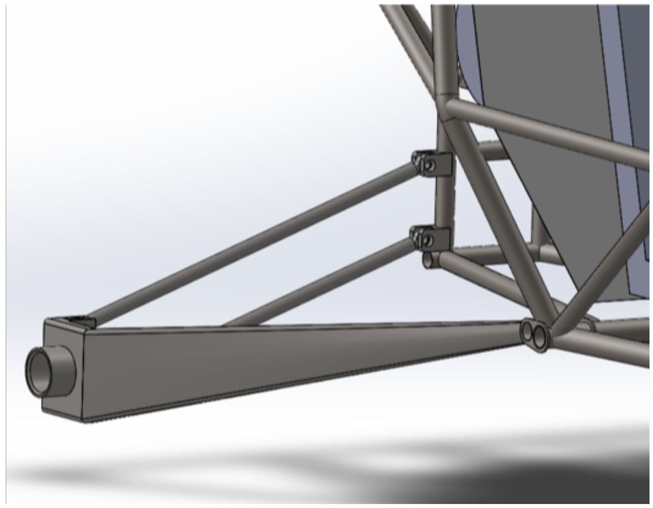

Figure 30 - Trailing Arm CAD model

The problem with this model is that it has very long rear lateral links. The stresses experienced on them will be very high and deform under any increased stresses. There is also a positive with having the trailing arms extend far out and that is better travel. This model was first created in Lotus to get mounting points and test how the toe angle and camber angle change through various situations. When the vehicle is moving over bumps the camber is going to change very little, but the toe angle will change more significantly. When modeling a roll scenario, the camber angle is going to be changing more than the toe angle. This can be validated by Figures 31 and Figure 32.

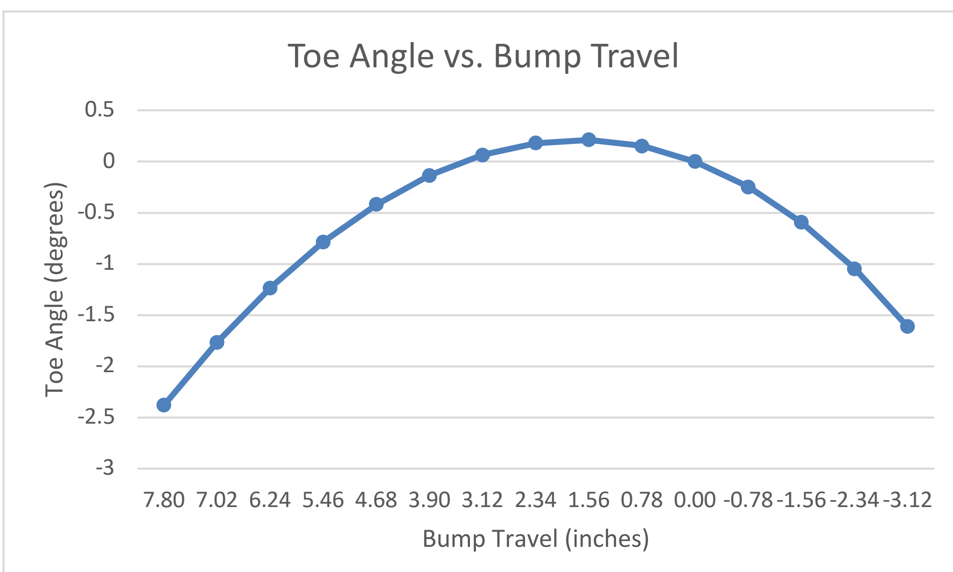

Figure 31 - Toe Angle vs. Bump Travel

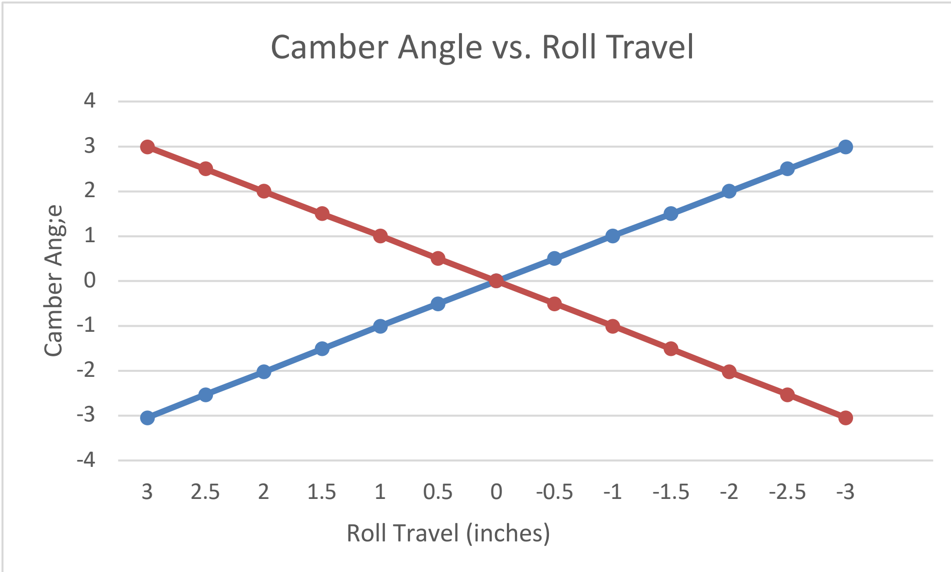

Figure 32 - Camber Angle vs Roll Travel

4.2.1.4 Design #4: Semi-Trailing Arms

The Semi-Trailing arm design is a mixture of two other type of suspension. It incorporates part of the trailing arm suspension as well as a swing axle suspension. This type of suspension geometry is based around the idea that the connection to the wheelbase is one-piece connecting to the frame with no lateral links. This system requires durable, thick material but also only utilizes half as much of the material because of only have only connection to the frame. Due to this geometry the toe and camber angle varies greatly over time, leaving a huge disadvantage. The benefits to using this system include a durable system with few weaknesses.

Figure 33 - Semi-Trailing Arm Suspension (Rear End) [43]

4.2.2 Subsystem #2: Shocks

4.2.2.1 Design #1: Mono -Tube Shock Directly Mounted to Frame

Design one incorporates the use of a mono-tube shock. This shock would be mounted directly to the frame of the vehicle. The main factor to consider with this design is the upper mounting point of the shock. In order to reduce the stress inflicted on the control arms and other suspension components, the shock needs to be mounted as high on the frame as possible so that it absorbs the majority of the vertical forces from the terrain being driven over. Based on this information, one con of this design is that the shock would need to be at a significant angle because of where the shock would be mounted. On the other hand, this is the design most commonly used on Baja vehicles, so it has been proven to be reliable and effective.

4.2.2.2 Design #2: Mono-Tube Shock Vertically Mounted to Frame Cross-Member

The second design considered, uses the same type of shock as design one. The main difference between these designs would be the upper mounting of the shock. For this design a cross member would be added to the nose frame that would extend the mounting point of the shock out over the knuckle/hub. This would allow the team to be able to mount the shock vertically over the knuckle thus increasing the amount of vertical force that the shock would be able to absorb. However, the downside of this design is that it would require additional fabrication to the frame.

4.2.2.3 Design #3: Twin-Tube Shock Directly Mounted to Frame

The third design that was considered consists of a twin-tube shock directly mounted to the frame rather than a mono-tube shock. The main differences between these types of shocks is how they separate the oil and gas within the shock. In a mono-tube design, there is simply oil on one side of the floating valve and some type of gas on the other side of the valve. In a twin-tube design, there is oil inside the inner cylinder with a gas filling the remaining space in the shock with no direct divider between the two. This type of shock, as a result, is much cheaper, however there are some cons that come with this. The main con to consider is that the gases in a twin-tube design can mix with each other, especially in bumpy, off-road environments. When this occurs the performance of the shock can greatly decrease.

4.2.3 Subsystem #3: Brakes

4.2.3.1 Design #1: Slotted and Ventilated Rotor with Fixed Caliper

The first design considered for the brake system consists of a fixed caliper and steel rotor utilizing a combination of multiple slots and cooling vents. The slots on the rotor surface allow for rapid dissipation of heat and gases generated by the brake pad as friction is applied to the rotor, while simultaneously maintaining structural integrity under high thermal and compressive stress. The fixed caliper provides a braking force from a piston on the inboard and outboard sides of the caliper, which implements a larger clamping force as opposed to a single piston or floating caliper. The primary disadvantage is the cost to manufacture these components, since the rotor possesses complex slot patterns and cooling vents that are necessary to maximize heat transfer. Manufacturing capabilities for this rotor design may not be available in house and must be outsourced, which could result in prolonged lead times. Lastly, the slots may increase the roughness of the rotor surface. This results in increased brake pad wear, resulting in increased maintenance costs for the system.

Figure 34 - Slotted and Ventilated Rotor with Fixed Caliper

4.2.3.2 Design #2: Cross Drilled Rotor with Fixed Caliper

The second brake system design considered utilizes a fixed type caliper paired with a cross-drilled steel rotor. This setup produces similar clamping forces and heat transfer characteristics compared to the first design, and further reduces weight by drilling holes through the rotor surface. The main disadvantage of this system is that repeated cycles of hard braking produce intense compressive and thermal stresses, which will cause stress cracks to develop on the edges of cross-drilled holes. This will result in total system failure if the stress cracks become larger in size..

4.2.3.3 Design #3: Solid Rotor with Floating Caliper

Compared to the aforementioned design solutions, this brake system design considers a floating caliper and a steel rotor without surface modifications that serve to dissipate heat. The diagram of this model is described in Figure 18 of Section 3.2.2.3.2. This design is a compact and cost-effective solution that is commonly used in current automobiles within the consumer market. The primary disadvantage of this system is increased weight due to the solid steel rotor, and reduced clamping force compared to a dual-piston caliper. Due to the lack of heat dissipation features on the surface of the rotor, inadequate heat transfer will impact the braking system under repeated cycles of threshold braking and cause brake fade, rotor deformation and increased brake pad wear.

5 DESIGNS SELECTED

Chapter five outlines how the team selected the concepts for the front and rear end systems of the Baja vehicle. The team identifies technical selection criteria and uses the criteria to select the best concept for the system. Each concept selected is then justified.

5.1 Technical Selection Criteria

The customer requirements and engineering requirements are predetermined in the Baja SAE project. Requirements like reliability, durability, easy of assembly are much needed when considering automotive components. However, requirements specific to the Baja SAE competition brings in the need for specific requirements to accommodate high performance at the competition. Ease of on field repair is a major factor to consider. The Baja must be durable, but in the same time, it could be inevitable that the Baja vehicle maybe damaged during competition.

When determining the aesthetics of the vehicle, the track width, ride height and wheelbase plays a major role in subordinating with other sub systems such as steering and suspension effects. The more variation applied to these values, the more the suspension system and the steering system imparts with respect to efficiency. One of the goals in designing a steering system is to provide quicks turns in a smaller turn radius. For that to be done, it is necessary to have an optimum wheelbase and track width.

The most variating sub system is the suspension. Also, the system that have an impact of the other subsystems on the frontend is the suspension system Therefore, the suspension system is iterated in different forms and analyzed through the Pugh chart and Decision matrix.

5.2 Rationale for Design Selection

5.2.1 Front End Design Selection

The front suspension geometry concepts considered were first evaluated using a Pugh Chart, Table 3 represented in Appendix A. This allowed the team to discover the top three suspension geometries with respect to the datum. The highest scoring designs were compared using a decision matrix, which utilized the customer requirements and weights determined from the House of Quality (HOQ). Each weight was multiplied by the respective raw score of the design, which was assigned based on the performance within each customer requirement. These values were subsequently summed to find the total weighted score of the geometry considered. According to the decision matrix, the Double Wishbone suspension geometry with the shock absorber mounted on the upper control arm is the optimal design.

The suspension geometries analyzed in the decision matrix, Table 4 in Appendix A, was stimulated using the Lotus suspension analysis software. Based on the results, the it was found that the Double wishbone suspension geometry with the suspension mounted on the upper A-arm had the reliable camber and toe angles. Shown below are the results of the chosen suspension design when analyzed in Lotus.

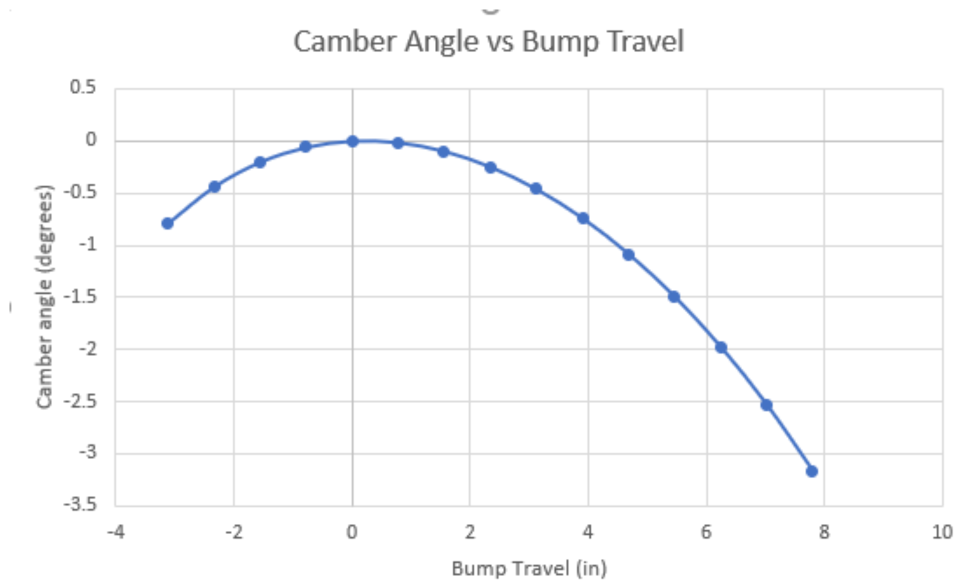

Figure 35: Camber Angle vs. Bump Travel

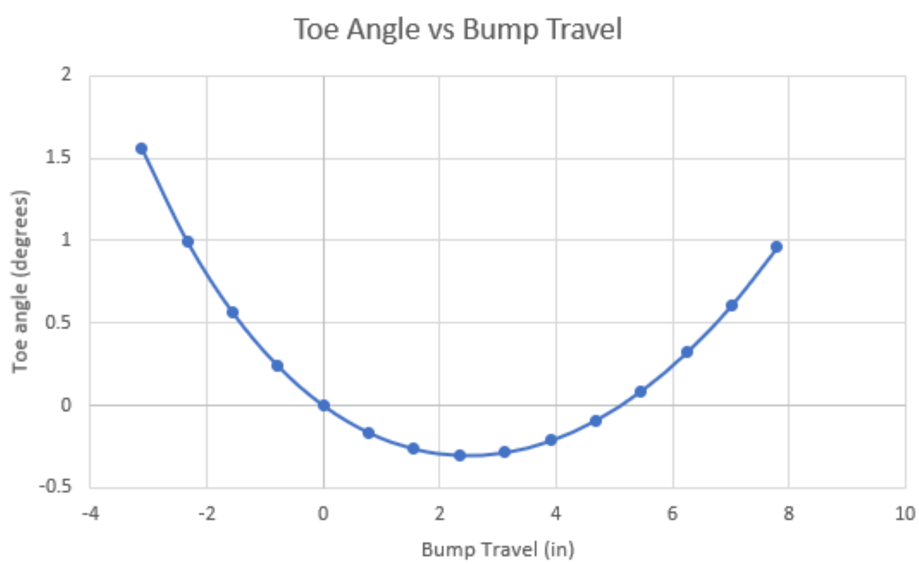

Figure 36: Toe Angle vs. Bump Travel

5.2.2 Rear End Design Selection

After analyzing the multiple different types of suspension systems with a Pugh chart, Table 5 seen in Appendix A, the team was able to narrow the concepts down to the top three design options. Using those three design options, a decision matrix was created to evaluate some customer needs for each design, Table 6 in Appendix A. After assigning weight percentages to each of the CN's, the more crucial needs having a higher weight percentage, the decision matrix weighed these three designs against one another leaving the best options with the highest scores. The two best options found for rear-end included the single-tube trailing arm, benchmarked by University of Michigan Ann Arbor's Baja team, and the single-trailing arm with two lateral links.

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7 APPENDICES

7.1 Appendix A: Figures/Tables

Table 3 - Pugh Chart Front End

Pugh Chart (Front End)				
Criteria	**CNC Solid Arm Double Wishbone (Datum)**	**Tube Double Wishbone - Top Control Arm Shock Mount**	**Tube Double Wishbone - Bottom Control Arm Shock Mount**	**McPherson Strut**
Track Width	0	0	0	+
Toe/Camber	0	+	-	-
Durability	0	+	+	-
Cost	0	+	+	+
Weight	0	0	0	+
Ease of Repair	0	+	+	-
Maneuverable	0	+	+	-
	Positives:	5	4	3
	Negatives:	0	1	4
	Total:	**5**	**3**	**-1**

Table 4 - Decision Matrix Front End

Decision Matrix (Front End)				
Customer Requirements	**Customer Weight**	**Double Wishbone - Top Control Arm Shock Mount**	**Double Wishbone – Bottom Control Arm Shock Mount**	**MacPherson Strut**
Reliable	5	4	5	3
Durable	5	4	4	3
Lightweight	4	3	3	4
Maneuverable	4	5	2	3
Low Cost	5	3	3	4
Easy Field Repair	3	3	2	4
Short Stopping Distance	4	4	4	3
Short Wheelbase	4	5	3	3
Ride Height	4	5	3	3
Track Width	4	4	4	2
Safe to operate	5	4	2	4
Total		**40**	35	36
Weighted Score		**172**	152	154

Table 5 - Pugh Chart Rear End

Pugh Chart (Rear End)					
Criteria	**Single-Tube Trailing Arm (Datum)**	**Semi-Trailing Arm**	**Double Wishbone**	**Trailing Arm- two lateral links**	**Four Link Suspension**
Track Width	0	-	+	+	0
Toe/Camber	0	-	+	+	+
Durability	0	+	+	+	-
Cost	0	+	-	-	-
Weight	0	0	-	-	-
Ease of Repair	0	-	-	-	-
Maneuverable	0	-	0	+	+
	Positives:	2	3	4	2
	Negatives:	4	3	3	4
	Total:	**-2**	**0**	**1**	**-2**

Table 6 - Decision Matrix Rear End

Decision Matrix (Rear End)							
Requirements	**Weight**	**Double Wishbone**		**Single Piece Trailing Arm**		**Trailing Arm Two Lateral Links**	
		Score	Weighted	Score	Weighted	Score	Weighted
Safe	15%	4	0.6	2	0.3	4	0.6
Durable	30%	3	0.9	2	0.6	4	1.2
Lightweight	20%	1	0.2	5	1	3	0.6
Ease of Production	10%	2	0.2	3	0.3	3	0.3
Performance	25%	4	1	3	0.75	5	1.25
Totals:			**2.9**		**2.95**		**3.95**