2019-2020 SAE Baja Capstone

Preliminary Proposal

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2019-2020

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DISCLAIMER

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2 BACKGROUND

2.1 Introduction

The Baja SAE design competition is a branch of SAE international's Collegiate Design Series. The objectives of these competitions are to enable students to design, build and test a real-life operable vehicle. The competitions are designed to give students hands-on engineering experience that requires teamwork, management, and budgeting among a slew of other valuable skills students will acquire through the trials of the design competition. **[1]**

The Baja SAE design competition requires teams to design a single seater mini baja vehicle capable of operating in a challenging off-roading. All teams are required to use a specified 10 horsepower engine from which they must design the vehicle. The vehicle must meet all rules and regulations and compete in a number of challenges to measure the effectiveness of the design. These challenges range from cost and design presentations to a four-hour long endurance race. **[1]**

Being a competition team, W. L. Gore has generously donated sponsorship funds of $6,000 to be used for design and fabrication purposes. W. L. Gore has a facility in Flagstaff and is part of the flagstaff engineering community they allotted sponsorship funds to all competition teams this year. The team will also be searching for additional sponsors that have an interest in giving back to the engineering community in Arizona. Team sponsors will be prominently displayed on the vehicle in addition to being featured in presentations and sponsor magazines. Major stakeholders in this project include all sponsors and the NAU engineering program, both of which will be represented by the success of the team's design.

2.2 Project Description

The following is the project description supplied by Baja SAE® at the beginning of the semester within the rule book.

> "Baja SAE® is an intercollegiate engineering design competition for undergraduate and graduate engineering students. The object of the competition is to simulate real-world engineering design projects and their related challenges. Each team is competing to have its design accepted for manufacture by a fictitious firm. The students must function as a team to design, engineer, build, test, promote and compete with a vehicle within the limits of the rules. They must also generate financial support for their project and manage their educational priorities." **[2]**

This description is still accurate at the time of writing this report.

2.3 Original System – Drivetrain

This section will go over the final design of the 2018-2019 Northern Arizona University's SAE Baja Capstone drivetrain design which includes the original system structure, original system operation, original system performance and the original system deficiencies. While the team placed 56th out of 100 teams they scored 44 percent overall at competition. After observing last year's team, the 2019-2020 Baja capstone have seen areas in improvement in the previous year's design. Below will outline the original system attributes that led to the low score seen in last year's competition.

2.3.1 Original System Structure

The previous Capstone team used a Gaged Continuously Variable Transmission (CVT). The CVT allows the vehicle to vary the gear ratio between the engine output shaft and the gear reducer input shaft. This effectively allows the vehicle to have more torque at certain engine conditions. This is done by the centripetal force exerted by the engine at different RPMs. In the figure below the gaged CVT is shown with the primary and secondary pulleys.

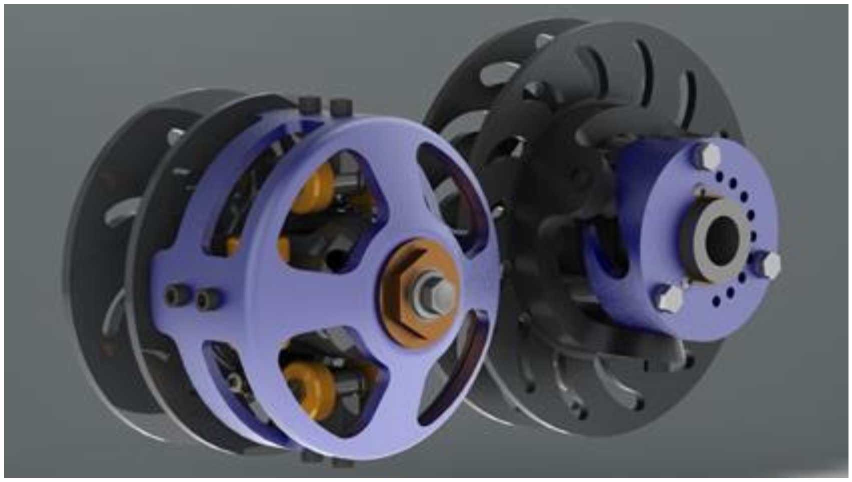

Figure 1. 2018-2019 Capstone Gaged Continuously Variable Transmission **[3]**

The primary disk connects to the engine output shaft and has weights and springs within to control the gear ratio. As the engine RPM increases the weights separate and drive the two disks closer together, making the effective diameter of the primary pulley larger, which in turn make the pulley of the secondary smaller. While the engine RPM decreases, the springs pulls the roller weights in which makes the primary pulley diameter smaller which puts slack in the drivebelt that decreases the tension in the secondary pulley which makes the diameter of the larger on the gear reducer input. The secondary pulley connects to the input shaft of the gear reducer. The secondary uses a spring to keep tension on the belt as it varies the ratio between the engine and gear reducer.

The engine is connected to CVT which is then connected to the gear reducer as previously mentioned. The gear reducer is the intermediate gearbox between the CVT and wheels. The purpose of the gear reducer is to reduce the number of rotations outputted by the engine to the wheels. 2019-2020 Capstone team used a 6.25:1 ratio spur gearbox that allowed the reduction of speed while increasing torque. In the figure below is a spur gear reducer.

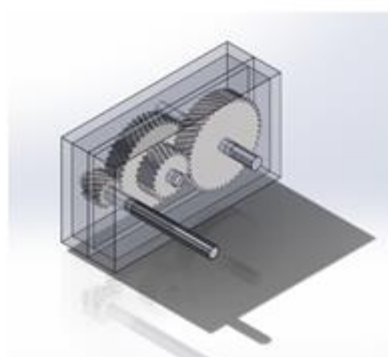

Figure 2. 2018-2019 Capstone Spur Gear Reducer **[4]**

The reason spur gears were used within the reducer was because of the performance that allowed for a higher than average driveline efficiency, compared to straight cut gear. Also, spur gears were used to the torque that can be transmitted through each tooth. The gear box uses metal on metal contact between gears and requires the use of lubricant. Because the reducer requires lubricant the housing requires high tolerance machining to allow for the lubricant to be contained.

2.3.2 Original System Operation

The 2018-2019 Capstone team used a Briggs and Stratton 10 Horsepower engine, which is required by competition rules. The competition does not allow teams to modify the engine. The engine drives the CVT which as a variable output speed which is a direct result of the engine RPM. The CVT is then connected by belt to the secondary CVT disk that is connected to the input shaft of the gear reducer. The gear reducer allows the vehicle to reduce the speed inputted by the engine and convert the speed into more torque based off the 6.25:1 gearing. The gear reducer is connected to the engine with a splined coupler on both sides of the gearbox going to the wheels.

The engine max rpm per competition rules is set at 3500 rpm, this is controlled by the throttle controlled by the drivers input. Based off last year's results in competition, the capstone team needed a different gear ratio

2.3.3 Original System Performance

Using the systems above in last year's vehicle, the team was able to go to competition and compete. While they were able to compete, they placed in 56 out of 100 other competitors. Their overall score was 437.63 out of 1000. In the table below, last year's team scores are shown. For drivetrain, the focus is on acceleration, maneuverability, hill climb and endurance.

Table 1. 2019 SAE Event Results for NAU Capstone

Events	Acceleration	Maneuverability	Hill Climb	Endurance
Points Scored	56.31	0	36.25	221.05
Total Points	75	75	75	400

As seen above the Capstone team preformed below average, the one exception is the acceleration event. The mild success in acceleration can be contributed to the gearing of the vehicle being at a 25:1 final gear output.

2.3.4 Original System Deficiencies

Last year design had two critical design flaws within the drivetrain system. The first design flaw found was the unreliable and low tunability of the CVT. The CVT was unreliable because without a tensioning system, the CVT belt would lose tension at lower speeds and disengage drive. The only way to reengage the drive was to increase throttle, but with increased throttle at lower speeds where torque is need over speed, the engine would lose power and was unable to supply the vehicle with enough torque. This leads into the low tunability of the CVT. With the only input to the CVT being the rotational speed of the engine, this did not allow the system to manipulate the gear ratio for a more efficient gear ratio.

The second flaw found within the drivetrain of last year's vehicle was the weight of the gear reducer. The gear reducer had solid metal gears, shafts, and gear casing. This was a disadvantage for the team because the engine had more mass to turn as well as making the vehicle heavier. Not only was the system heavier due to the material used, but also because of the lubricant needed. The gearbox needed oil to help with reducing the wear on the gears. This also made the gear reducer heavy.

2.4 Original System – Frame

The original frame designs from previous teams can be seen on the physical vehicles #44 and #52. The frame structure of #44 was the primary focus of the frame team. This design was analyzed and studied by the frame team to build upon or replicate the successful design aspects, and fix flaws the design may have had. A lot of the information in this section was gathered in conversations with members of last year's team.

2.4.1 Original System Structure

Vehicle #44 uses a rear braced frame structure (See section 5.2.2) which is one of the two common frame structures used in Baja SAE competitions. The frame is built from 4130 steel tubing of three different sizes:

primary tubing with a 1.25” OD and 0.065” thickness, secondary tubing with a 1.00” OD and 0.058” thickness, and tertiary tubing with a 1.00” OD and 0.049” thickness. The frame structure features a long cockpit, narrow overhead (ROH) members, a curved nose, and low-profile rear end. The frame was fabricated by team members in the machine shop here at NAU. The full frame structure of #44 is best represented in the drawing seen in **Figure 3. [5]**

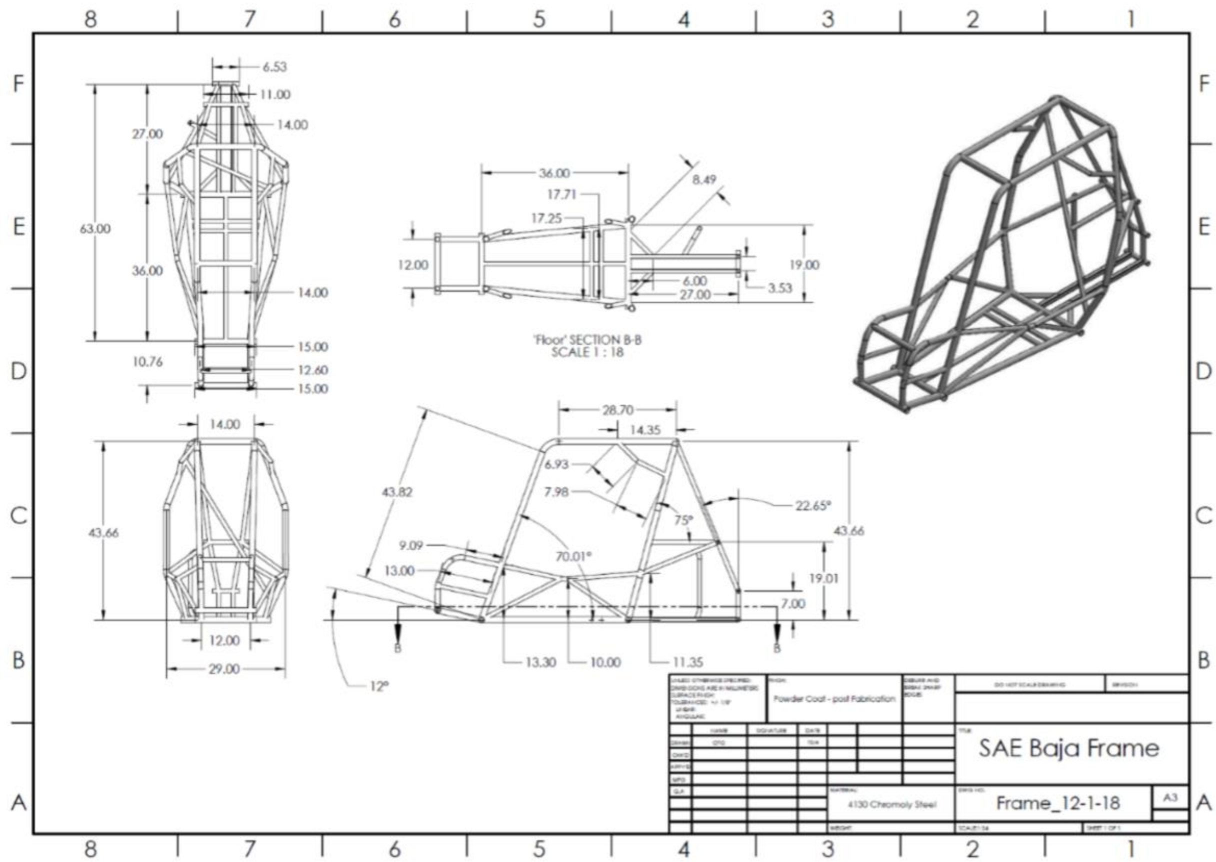

Figure 3. #44 Frame Design **[5]**

2.4.2 Original System Operation

The frame of #44 is currently still is good operating condition. The criteria for what classify as operating condition are outlined in the 2019 Baja SAE rule book and require the frame to maintain its structural integrity. This means the frame must be void of all cracks, kinks, breaks and any other physical deformities. The frame of #44 successfully held up through last year’s design competition by passing technical inspection and remaining in operating condition throughout the competition. The frame will continue to be used and tested upon throughout the semester by the team and members of the SAE club. An example FEA calculations that outline the forces the frame can endure can be seen in a load scenario (**Figure 4. [6]**) developed by the designers of #44.

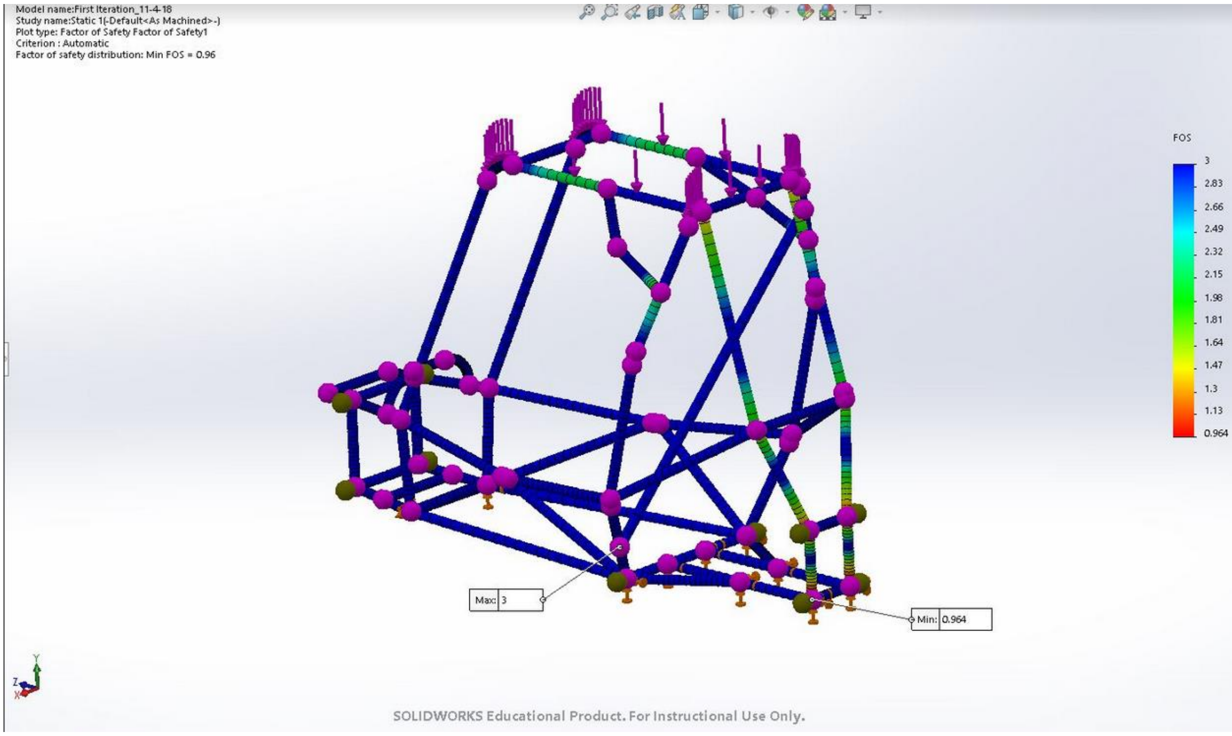

Figure 4. FEA Example on #44 **[6]**

2.4.3 Original System Performance

The purpose of the frame is to protect the driver and components it also serves as the mounting structure for any system in the vehicle. As such the performance of the frame is largely based on how long it has remained in operating condition. If the frame stays intact over a large expanse of time and trials it can be considered to have performed well. Other factors of the frame's performance include weight, ease of manufacturing, and ease of maintenance. The frame design can have a large impact on the accessibility of vehicle components which should be considered. The weight of #44's frame is 65.63 lbs. based on #44's CAD frame and vehicle maintenance was never heavily restricted by the frame.

2.4.4 Original System Deficiencies

While the frame has remained in good operating condition since its inception, two rule restrictions were not met before competition. The first condition failed to provide support to a bent structural member that was longer than 33". (Rule B.3.2.1) [Rulebook] This issue was simply missed in design and fabrication stages of the project. The second condition failed to provide 6" of clearance between the exterior lateral boundary of the frame and the driver's helmet. (Rule B.3.3.1) [2]. This issue was caused by inaccurate checking of this condition before all the driver seat components were implemented.

3 REQUIREMENTS

The requirements for the design competition are numerous and technical in nature. They are listed in their entirety within the 2020 Baja SAE rulebook. Competition requirements exist outside of the rules as well in the form of deliverable requirements for the competition. The customer for this project is technically Dr. Tester, but it is up to the team to decide how to best represent our school and sponsors. Due to the nature of this competition, very general customer requirements were created to encompass the scope of highly restrictive, and numerous, requirements detailed in the rules.

3.1 Customer Requirements (CRs)

The Baja vehicle needs to be designed to operate under harsh off-roading conditions. To match this need three customer requirements were required for reliability, durability and impact resistance. These three requirements are weighted to the max as those functions are the primary target of Baja SAE competitions. Three requirements were generated to cover the operating speed and handling of the vehicle. These requirements focus on the aspects that enhance the operating abilities of the vehicle. The operating abilities of the vehicle are still a focus and while not as critical as reliability and durability they are still of significant importance and are weighted at 6.

Ergonomics and safety are equally important. The vehicle will be driven in a four-hour long endurance race in which the comfort and safety of the driver will be tested. These important requirements will still be overshadowed by the reliability and durability of the design as a critical failure in either of those two categories will likely result in driver injury. The cost of the design must be within budget. If the design is not within the buget it cannot be made and building the vehicle is an absolute must giving this requirement the maximum weight.

1. Reliability [9]
1. Durability [9]
2. Low Weight [6]
3. Withstand Impact [9]
4. Ergonomic Cockpit [6]
5. High Torque Output [6]
6. High Power Output [6]
7. Operational Safety [6]
8. Cost Within Budget [9]

3.2 Engineering Requirements (ERs)

The engineering requirements were generated from the customer requirements through consulting the rulebook and benchmarked designs. Bending stiffness and torsional stiffness are dependent on the material type. These three requirements were obtained and calculated from information detailed in the rulebook and cover the reliability durability, weight, and impact resistance customer requirements.

The gear ratio engineering requirement is derived from torque and power output customer requirements through benchmarking an effective gear reduction was decided upon to meet desired torque and power. Safety and ergonomic customer requirements are incorporated into the egress time engineering requirement. Egress is how fast the driver can exit the vehicle in the case of an emergency and serves as a good measure for how the vehicle interacts with the driver. Weight and expense are engineering requirement that will be impacted by aspects of the vehicle design and applies to all subsystem and sub teams within the Baja team.

1. Bending Stiffness (greater than 2,620 Nm^2)
2. Torsional Stiffness (greater than 374 Nm)

3. Material Type
    a. Primary (1018 Steel Tubing 0.984” X 0.118”) (Or equivalent/greater material/profile)
    b. Secondary (Steel Tubing 1.00” X 0.035”)
4. Egress Time (within 5s)
5. Effective Gear Ratio (2.24:1 reduction)
6. Low Center Mass (below 20 inches)
7. Expense $6,000 to (dollars fundraised)
8. Weight (below 600 lbs.)

3.3 House of Quality (HoQ)

The House of Quality (**Table 2.**) is a tool that is used to relate engineering requirements to customer requirements. The strength of the relationship culminates in an absolute technical importance value intended to identify the relative importance of various engineering requirements. Again, these results are derived from very general customer requirements that are but a small sample of the true quantity of measurable parameters the team is required to meet.

The 2020 Baja SAE rulebook serves as the engineering requirement rubric. Many engineering requirements in these rules hold conditional and design dependent parameters that are difficult to represent as a single engineering requirement. For this reason, the House of Quality serves more as a presentation tool rather than a comprehensive list the team will utilize.

Table 2. House of Quality

Customer Requirement	**Weight**	**Engineering Requirement**	Material Ultimate Strength	Material Torsional Stiffness	Approximate Size (inches)	Weight of Material (lbs)	Driver Exit Speed (Seconds)	Cost of FR &DT (USD)	Highest Gear Ratio	Lowest Gear Ratio	Effective Gear Ratio	DT Component Location (inche
Reliability	9		9									
Durability	9		3	9	3	3						
Withstand Impact	9		3	3	9	3						
Low Weight	6				6	9						
Ergonomic Cockpit	6				3		9	3				
Operational Safety	6				3		9	9	3	3	6	6
High Power Output	6		6	6		3		3	9	3	6	
High Torque Output	6		6	6		3		3	3	9	6	
Low Center of Mass	3		3	3	3	9			3	3	3	9
Absolute Technical Importance (ATI)			216	189	189	171	108	108	99	99	117	63
Relative Technical Importance (%)			**16**	**14**	**14**	**13**	**7.9**	**7.9**	**7.3**	**7.3**	**8.6**	**4.6**
Target ER values					108x64x60	300	5	6000	3.9	0.9	2.4	36x48x24
Tolerances of ERs					MAX	MAX	MAX	MAX	MAX	MAX	N/A	MAX
Testing Procedure (TP#)			1	2	2	4	6	6	8	8	5	10

Approval (print name, sign, and date):

Team member 1: Kaleb Brunmeier
Team member 2: Riley Karg
Team member 3: Tye Jorgenson
Team member 4: Jacob Najmy
Team member 5: Jacob Kelley
Client Approval: Dr. John Tester

4 DESIGN SPACE RESEARCH

The following chapter details the research conducted by all five team members for the frame and drivetrain sub-teams. It includes a comprehensive description of referenced sources used, and explains the benchmarks used to inspire design concepts. Both the sources and benchmarks are categorized by subsystem to emphasis the unique processes, considerations, and design requirements for each field of study. Finally, a summary of the correlation between subsystems is described through use of black box and functional decomposition models.

4.1 Literature Review

In the following sections, each team member presents their five sources used for their literature review and gives a brief summary of the source while also noting the correlation to our design requirements.

4.1.1 Student 1 (Jacob Najmy)

Jacob focused on the design and implementation of the structure and code of the Electric Continuously Variable Transmission. He first focused on the design and function of how the ECVT worked. He has prior experience working with ECVTs from his Spring 2019 junior level design class where he designed a full concept of an ECVT. Although he and his team built a concept of an ECVT the system lacked the electrical control and testing needed to make the project a reality. Since then Jacob has been researching more in-depth designs and control methods.

In the first source being referenced, Jacob found an electric continuously variable transmission (ECVT) project done by undergraduate students from the California university, Berkeley. The students for their project used electric motors to increase and decrease the drive ratio. They were able to do this by connecting the primary drive pulley to a linear actuator. This seemed to work for them on the best bench, but mounting would have to be relocated for Capstone Project. The team controlled the system using an Arduino Mega, this was valuable research done by Jacob because the Capstone Project will also be controlled by an Arduino Mega. **[7]**

The second source Jacob reference was a Patent from the company Gates. The company patented a design that uses a DC motor and a gear system to move the system back and forth. This allowed Jacob to visualize a design that could be implemented into the final design of the system. Also discussed in the patent was the use of different modes that programed the ECVT to change gears with the press of a button, it was related to how an automatic transmission can be shifted using electronic paddle shifts in certain modes. This was helpful for Jacob to understand the different types of modes that can be used. **[8]**

The third source referenced during the design considerations helped Jacob understand the different efficiencies associated with electromechanical CVTs. During the design process the clamping force from the electric stepper motor wanting to be used needed to be sized. After understanding the difference in clamping forces based off the engine torque and angle of the pulleys helped Jacob with his search for a properly sized stepper motor. **[9]**

The fourth source reference by Jacob helped with the communication from human input to the electromechanically control of the effective diameter used to change gears. After the mechanical design of the ECVT was conceptualized Jacob needed to figure out the coding behind how the ECVT will interface with human input. Jacob searched the internet and found a human-machine interface (HMI) that allowed for the effective control of the ECVT. The HMI software was open-sourced and allowed Jacob to verify if the software would work. **[10]**

The last source Jacob reference was in part due to the finding of the Nextion HMI in the last source. The reference went into detail about how to interface an Arduino with a sensor (stepper motor), buttons, as well as the Nextion HMI. This allowed Jacob to have autonomous control and selectable control when needed. The article helped understand how to have the Arduino print messages to the HMI display while also allowing the Nextion display print values back to the Arduino. This allows for better control over the system in a dynamic environment. **[11]**

4.1.2 Student 2 (Tye Jorgenson)

Tye Jorgenson has focused most of his attention to all components relating to the 4WD system. This includes bevel gears, u-joints, driveshafts, bearings, and gear cases. This section includes a brief summary and discussion for five different sources that are relevant to the technical aspects previously mentioned.

The first source being referenced for his literature review is the 2020 SAE Baja Rulebook. This source contains all relevant information that our team as competitors must design in accordance to. More specifically, Article 9 of the rulebook contains information regarding all required guards for the drivetrain system as well as any limitations/requirements for driveshaft implementation for 4WD systems. This piece of literature is the most critical reference for all sub-teams of this project because designing in accordance with the rulebook will help ensure that the buggy will pass tech and be able to compete in all events. **[2]**

A simple google search on bevel gear designs led to the next useful literature resource titled "How to Design and Install Bevel Gears for Optimum Performance: Lessons Learned." This technical paper highlights the importance of correctly aligning bevel gear sets to ensure smooth running and optimal load distribution between gears. The correct process for determining the thickness range of shims in the design stage as well as their corresponding equations are also explained. This source is setup to where it provides the designer with enough knowledge to design any gearbox involving bevel gears and is currently being referenced in the current transfer case iteration. **[12]**

The third source used for benchmarking and design research was an article posted to the Chevy Hardcore website and is titled: "Driveshaft Angles: Why They Matter and How to Keep Them in Check." This source provides a good starting point for understanding the importance of driveline angles in both 2WD and 4WD applications. The 4WD system being implemented into this year's buggy will require the transfer cases to be mounted at an angle, therefore, this source is useful for understanding the fundamentals of minimum and maximum driveline angles allowed without sacrificing performance. **[13]**

For Tye's fourth piece of literature review, he selected a chapter from the Pearson HigherEd website called "Introduction to Drivetrains." This chapter covers the definition of torque, the relationship between torque and horsepower, gear types, gear ratios, and multiple different types of transmissions. Although this chapter does not provide in-depth calculations for drivetrain components, it provides a good overview for the most important drivetrain components and helps explain unclear concepts to any members on the team who may be confused about specific terminology. **[14]**

The last source used for literature review is the 10th edition of Shigley's Mechanical Engineering Design textbook. This source provides the necessary factors for computing bevel gear analysis using the AGMA standard as well as the corresponding material characteristics for common metals that are used in gear design. It also provides multiple example gear calculations for specific scenarios that is currently being referenced during the bevel gearbox design. This textbook is an excellent resource for the drivetrain sub-team and will continue to be referenced as the project progresses. **[15]**

4.1.3 Student 3 (Kaleb Brunmeier)

Kaleb Brunmeier researched different types of fixed speed reduction systems used to transmit rotational energy. There are several types of speed reduction systems including gear trains, chain drives, and belt drives. Research involved studying the different types of each system and comparing the advantages and disadvantages of each system.

The first source used to study the three most common types of reduction systems is Shigley's Mechanical Engineering Design textbook **[16]**. Several chapters of the textbook provided ample information about gear systems, including the difference between spur and helical meshes, and flexible drive components, which consist of both chain and belt drive references. The textbook shows examples of applicable scenarios for the different drive types, which has allowed the team to calculate and validate different reduction system concepts.

The second reference provided a more in-depth study of a chain drive. In it, chains are classified by their specific application. For example, the use of a chain drive to transmit rotational energy in a drivetrain is considered a power transmission chain drive **[17]**. It also revealed that the power transmission chains will not be ideal for the project as they typically deal with lower velocities or require chains that are too spatially demanding.

The third reference was the ideal reference for initial comparison of the gear, chain, and belt systems: Power Transmission Engineering **[18]**. They provide a generalized comparison of all three common reduction systems with descriptions and detailed lists of the advantages and disadvantages for each drive. The reference also provides a section for the most common applications of each speed reduction system. It was incredibly influential for concept selection and developing a knowledge base for the drivetrain team.

The fourth source is an eBook called "Design of Transmission Systems" **[19].** The reference explained in more detail the process for designing a chain, belt, or spur gear drive system. It was most helpful in designing a timing belt drive, as it provides resources for the design procedure as well as examples of design belt and pulley selection. With the eBook, validation spreadsheets for a timing belt drive were generated.

The fifth resource used is the technical resources of SDP/SI **[20]**. It illustrates major considerations and design processes for several gear type systems. The source benefits the team by describing not only the key differences between one-stage and two-stage gear trains but identifying the need for backlash in practical applications of spur gear trains. Most notably, it provides calculations for designing backlash into a gear train by manipulating the design to the gear teeth themselves.

4.1.4 Student 4 (Jacob Kelley)

Jacob Kelley directed his focus on the concept analysis portion of the frame. This included Finite Element Analysis (FEA) and material and profile selection of the members of the frame. The following five sources were found to be helpful to the above-mentioned technical aspects of the frame.

For Jacob's first literature review he used the Baja SAE rule book **[2]**. This is an important piece of documentation that applies to almost every part of the frame. Not only does it give rules on the structure of the frame but also on the requirements of the materials and profiles of the members. It gives an example profile and material and states that any primary members must meet or exceed the strengths of that example. Secondary members are only required to meet minimum profile restrictions. This is very important to the selection of the material and profiles of the members.

His second literature review was found in some initial research at **[21].** This report was done by a previous SAE Baja team at the Worcester Polytechnic Institute in 2017. It covers how they used FEA and some calculations to optimize their frame. This demonstrated how to make further design iterations based on the FEA results to improve upon weak portions of the frame.

Jacob then looked into resources on how to properly apply FEA on a Baja frame to accurately simulate real world scenarios. This led to a journal publication published in 2014 **[22].** This journal demonstrates how forces in FEA are applied and at what magnitude. It gives reasonings behind each decision for magnitude and what scenario is being simulated with the force and fixed-point positioning. This proved to be a very useful source in the analysis process.

Considering the frame is composed of mostly straight members and welded joints, the mechanics of materials course was very useful in understanding how the frame physically functions. The textbook **[23]** from that course was a crucial tool for this reason. Not only does it outline how members handle forces and torques but also how the profile of the members affects the strengths of the member. This aided in the material and profile calculations. It also gave a general understanding of how different design changes will change the overall system.

The last piece of valuable information Jacob utilized was from SolidWorks. The FEA simulation tutorial **[24]** built on his previous knowledge of the simulation tools in SolidWorks. This tutorial gave an understanding of how the simulation process could be automated to test many different scenarios at once. This skill was very useful for the purposes of the frame since we wanted to simulate many different impact scenarios. This greatly reduced the time to complete the analysis process compared to previous years.

4.1.5 Student 5 (Riley Karg)

Riley quickly learned how to use the weldment feature in SolidWorks to begin the iterative frame designing process. Riley focused heavily on repairing issues in #44's frame design. Most of these issues were caused by a lack of understanding the rules and a lack in communication with the rest of the team. To combat these previous issues Riley developed a strong understanding of the rulebook by reading it through multiple times and always referring to it before making any changes to the frame design. Riley also held small meetings to go over how the frame would be interacting with other subsystems. These meetings would continue as subsystem designs changed and the frame design would be adjusted to accommodate these changes.

The Baja SAE 2020 rulebook is Riley's main source for frame design as it should be. The rules are of utmost importance. If any rules are missed the vehicle will fail inspection. If a frame is designed using only the rulebook as a source the vehicle will pass inspection. Therefore, it is Riley's belief that the rulebook comes first and foremost trumping any other source. **[2]**

The frame could not have been designed without the use of design tools. Understanding the SolidWorks weldment features was crucial to obtaining a CAD model that could be easily interpreted for fabrication. SolidWorks also includes simulation features that can later be used on the model for FEA purposes. **[25]**

Some of the most useful material in designing the frame came from reviewing deliverables and technical documentation from last year's team. One such useful document was the Roll Cage Documentation Package. This package is a competition deliverable that outlines the sale's order, material invoice, material testing certifications, material strength calculations, and drawing with most frame dimensions. Not only is this a good starting point in terms of frame design, it also provides valuable information on what is needed from the material suppler. This will ensure that the frame team knows to request material certification along with the material. This documentation package must be filled out and sent in by the frame team in January. **[5]**

Wanting to design the frame to be successful Riley decided to study prominent features of other successful teams from last year's competitions. By viewing pictures of the top five highest ranking teams a spreadsheet (**Table 3.**) was made to document certain geometrical frame features to evaluate and emulate in the frame design.

Table 3. Example of Geometry Benchmarking Table

Rank (2019 California)	1	2			
Team/School	Uof Michigan Ann Arbor	RIOT RACING		Compairison	
Frame	RB	RB	Frame	60% RB	40% FB
RRH	Typical	Wide	RRH	60% Wide	40% Typical
RHO	One piece, wide	One piece, wide	RHO	100% Wide	
SIM	One piece, straight	One piece, bent	SIM	60% Bent	40% Straight
RHO angle	Steeper than RRH	Steeper than RRH	FBM angle	66% > RRH	33% = RRH
RRH to RHO Bracing?	Yes, straight member	Yes, bent member	RRH to RHO Bracing	75% Bent	25% Straight

One very comprehensive document on Baja SAE frame design came from Worcester Polytechnic Institute (WPI). The research paper provided a very in-depth analysis into the optimization of a Baja frame. While most of the information provided in the document comprises of information already known to the team, it does contain documentation of extensive design analysis using FEA in SolidWorks and provide good ideas for different FEA scenarios. However, the team will not be emulating the design featured in the WPI team's design report as it utilizes an overengineered, heavy frame that appears to be designed only for frame strength ignoring the negative impact such a massive and bulky frame could have on other areas of vehicle performance. **[21]**

4.2 Benchmarking

Now that Northern Arizona University has successfully competed in the SAE Baja Collegiate competition the last two years, the current capstone team now has two fully operational vehicles to use for benchmarking. Kaleb Brunmeier and Tye Jorgenson have been in contact with team members from the Spring 2019 NAU Baja team and plan on continuing to gain feedback from those who have relative experience in this field. There is also a fully operational Briggs and Stratton engine and CVT dyno that is now setup for system testing. Some of the biggest problems the capstone teams have encountered over the last two years is the lack of tuning of the Continuously Variable Transmission, improper final drive ratio calculations, as well as lacking originality within their design. With that said, these readily available systems will prove invaluable to this year's capstone team for solving problems such as the CVT tuning that have been encountered by previous teams. Dr. Tester is also a big reference for system benchmarking as he has extensive experience with the SAE Baja competition and is also the advisor for this project. Benchmarking for this project also include in-depth analyzation of designs that already exist and have similar requirements to this competition.

4.2.1 System Level Benchmarking

This year's team is analyzing three main existing designs that closely relate to the requirements and goals for this competition. The first existing design is NAU's #44 buggy. The second is the University of Michigan's Spring 2019 car. Lastly, the 2014 Polaris Razor 800 is analyzed and the correlation to our application is discussed.

4.2.1.1 Existing Design #1: NAU Baja #44

As mentioned in the introduction for this section, the current capstone team has access to last year's fully functional buggy and all related technical information. Therefore, the buggy is a useful resource for targeting weak points in the design and is currently being used for a benchmarking study. The frame is mainly constructed of 4130 Steel Tubing and has proved structurally durable on multiple instances. The drivetrain system in this car utilize a 6.25:1 spur gear reducer, gauged continuously variable transmission, two CV axles, and two corresponding hubs for interfacing the axles and wheels.

Figure 5. Lumberjack Motorsports Spring 2019 #44 & Comp Results **[26][27]**

Speaking with last year's team, current buggy testing, as well as referencing their competition results in **Figure 5.** above has helped this year's team determine the buggy's biggest flaws: Improper CVT tuning, lack of turn radius, excessive weight, and weak components in the rear end. This year's capstone team is actively completing a benchmark study by thoroughly testing the #44 car every Friday. This buggy directly relates to our system in all aspects other than drivetrain, because this year's team is implementing a completely new four-wheel drive system.

Existing Design #2: University of Michigan – Ann Arbor Baja

The University of Michigan Baja team is the prime example of a team that consistently meets all engineering and customer requirements for this competition. **Figure 6.** below shows Michigan's 34th buggy design that placed 1st overall in the SAE California competition in May of 2019. Using this design as a technical source for benchmarking is difficult because successful teams such as Michigan often keep design specific information confidential. However, the vast number of pictures on their website as well numerous teammates personally analyzing this buggy at the competition in May allows for a useful comparison. The actual degree to their success in the SAE California competition is shown in Figure # below.

Figure 6. Michigan Baja Racing Spring 2019 & Comp Results **[27][28]**

4.2.1.2 Existing Design #3: 2018 Polaris RZR 570

The 2018 Polaris RZR 570 shown in the figure below (**Figure 7.**) is a successful design that has been mass produced for consumer use since 2014. The specific UTV shown below is one of Polaris' smallest versions of their RZR. Although this design is outside of the requirements for the Baja competition, the four-wheel drive system orientation and setup is being analyzed to apply similar concepts to this year's design. Some of the biggest concerns for implementing a four-wheel drive system into this year's buggy are transfer case designs, driveline placement, and shock mounting to allow for another pair of CV axles in the front. With that said, this design is being referenced to help implement a fully operational system.

Figure 7. 2018 Polaris RZR 570 **[29]**

4.2.2 Subsystem Level Benchmarking

Benchmarking from a subsystem standpoint focused on three main components: the initial transmission of energy from the engine, the distribution of energy to all four wheels, and the translation of rotational energy to the wheels. The initial transmission of energy from the engine to the drive train is accomplished by the electronically controlled continuously variable transmission (ECVT). The distribution of energy to the wheels is performed by the transfer case. The translation of rotational energy from the ECVT to the wheels is accommodated by the speed reducer.

4.2.2.1 Subsystem #1: Electronic Continuously Variable Transmission (ECVT)

This year's Capstone team is focusing improving the function of the buggy, while also keeping the total weight below last year's design. Using an Electric Continuously Variable Transmission (ECVT) for the 2019-2020 design, this will allow the team to have a competitive advantage while keeping the weight below last season's weight. Before designing the ECVT the team investigated existing designs of the system. The iterations found all use different mechanisms to change the ratio of the ECVT disks. The first design looked at uses a DC motor connected to the side of the disk that uses a gear system to change the effective diameter of the pulley. The second existing design researched uses a pressure plate that uses the pressure of the v-belt to keep tension between a coned disk that rides on another cone disk on the back of the primary pulley. The final design researched uses a linear actuator to control the depth of the primary disk. This changes the effective diameter and allows for smooth operation of the transmission.

4.2.2.1.1 Existing Design #1: Gates Electronically Controlled ECVT

Gates electronically controlled ECVT is design specifically off-highway utility vehicles. It was designed to be a direct saw from conventional continuously variable transmission (CVT). The design uses gears between a primary pulley and an attached DC motor. This allows the DC motor to change the ratio of the primary ECVT by changing directions of rotation. Rotating counterclockwise allows the primary to fully open and clockwise to fully close. This design can be user controlled or automatically controlled. This is done with the use of a computer control system mounted directly to the side of the unit. Below (**Figure 8.**) is the Gates design ECVT primary:

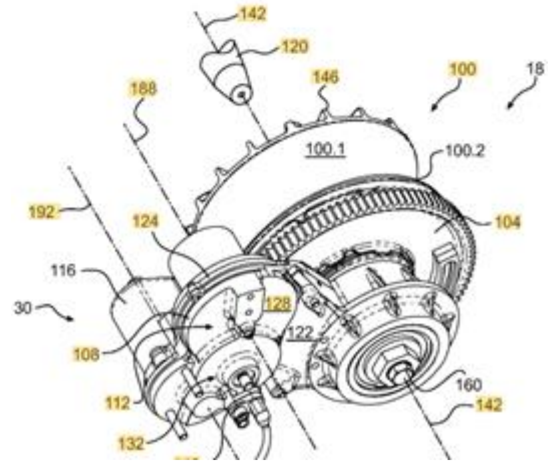

Figure 8. Gates ECVT Design **[8]**

An advantage of using this design is that it allows for direct replacement with no modification of the engine or drivetrain of the vehicle. This is something that the Capstone team would like to accomplish because if a critical failure of the ECVT happens during competition the team can swap out components easily without major modifications. This design also allows the secondary CVT pulley to stay in position, using the tensioning device within the design. This is another consideration that the Capstone team will use within the design. This allows for manipulation of the gear while keeping tension within the v-belt.

4.2.2.1.2 Existing Design #2: Pressure Plate Differentiable ECVT

The second design uses a cone shaped cylinder that uses the top of the cone to press on the cone another cone shaped cylinder to differentiate the effective diameter. In the figure below **(Figure 9**.), the system is fully close, largest effective diameter. This would be used for a high-speed gear:

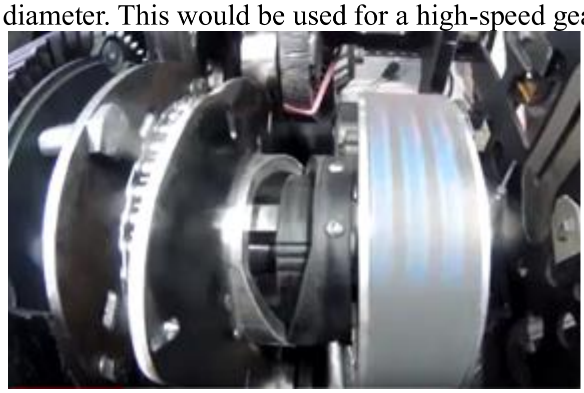

Figure 9. Electronic ECVT in Fully Closed Position **[30]**

The cone shaped cylinder pushes against the disk to change the effective diameter. It is held in place using the tension of the v-belt using down on the side of the primary disk. In the figure below **(Figure 10**.), the system is shown at a fully open position or neutral. The design can be considered in neutral because at fully open the tension is not enough to move the belt:

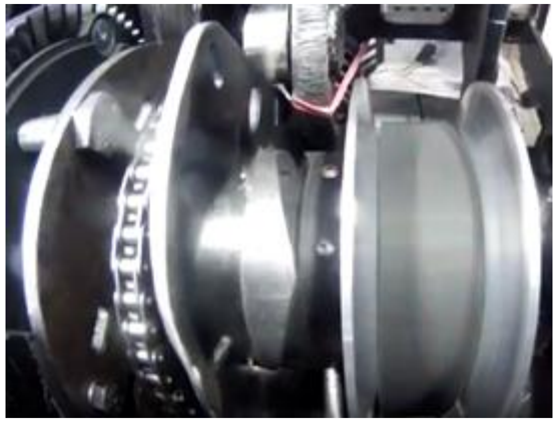

Figure 10. Electronic ECVT in Fully Open Position **[30]**

This design uses a chain drive and a stepper motor to move the coned cylinder back and forth to change the effective diameter. Unlike the previous design that used a gear and DC motor to change the diameter. The Capstone team would like to use a pulley belt drive using a stepper motor, this is because the tolerance needed to make the belt tight and aligned are low compared to what is needed for gear. This also allows the belt connecting the stepper motor to the primary ECVT to be changed out, as well as the stepper motor. Like the previous design, discussed this design only replaces the primary side of the CVT. Although this design does not allow for easy replace in case of critical failure.

4.2.2.1.3 Existing Design #3: Linear Actuated ECVT

The last existing design researched has been used by Cal Poly Pomona in 2017. This design used a linear actuator connected to a dog clutch that pushed the primary disks together to change the effective diameter. This design was considered because of previous SAE Baja usage. But, after more in depth research the design resulted in too much frictional force on the drive shaft that overheated the stepper motor. Below (**Figure 11.**) is the test bench setup of the linear actuated design:

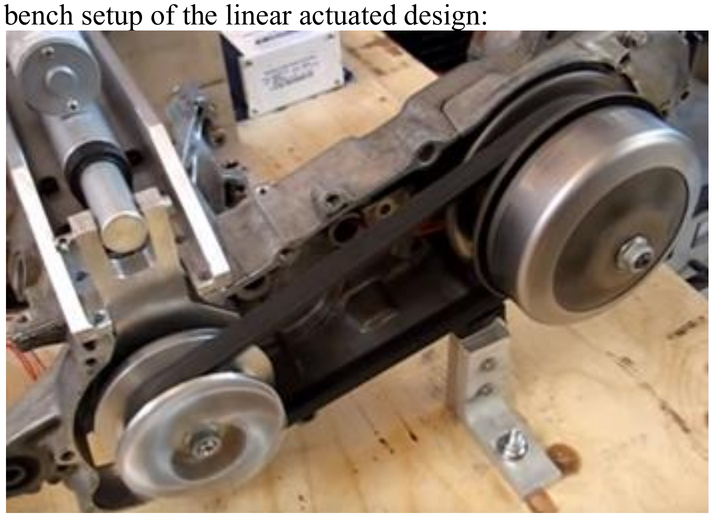

Figure 11. Linear Actuated Fork ECVT **[31]**

This design allows the buggy to use the same secondary CVT disks as years before by only actuating the primary side connected to the engine. This year's capstone team wants to use a design that can accommodate last year's secondary CVT disks, that is why this design has been researched. Although this design did not work in competition last year the design has need studied more in-depth dude to the overheating problem within the stepper motor. Capstone would like to avoid overheating the stepper motor because that is considered a critical failure of the drivetrain system.

4.2.2.2 Subsystem #2: Transfer Case/Gearbox

This specific subsystem is responsible for taking the power being outputted from the CVT secondary and transferring it to the wheels. The three existing designs being discussed for this subsystem are last year's spur gear reducer, a standard open differential, and a bevel gearbox.

4.2.2.2.1 Existing Design #1: NAU's Spur Gear Reducer

The figure below (**Figure 12.**) illustrates the gearbox that was designed and implemented into the NAU #44 buggy by last year's capstone team. This specific gear reducer provides an overall 6.25:1 gear reduction from the single input shown in the front of the figure below to the two output shafts at the rear of the case.

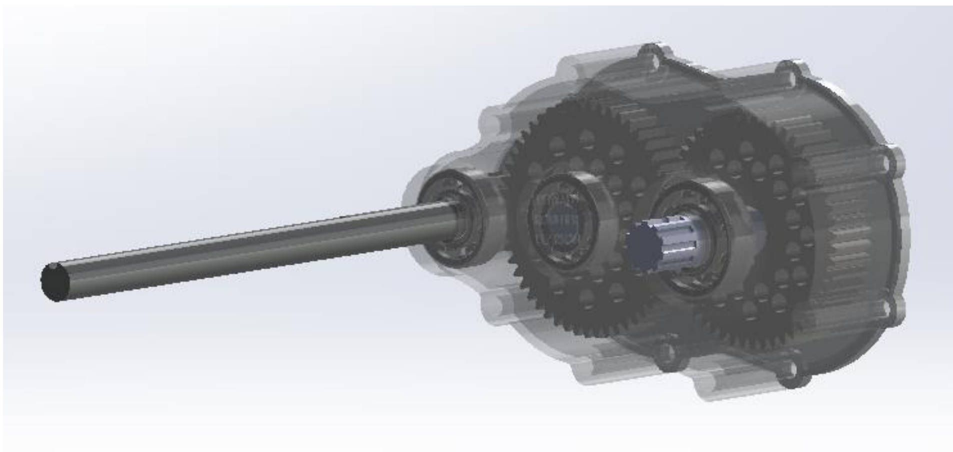

Figure 12. NAU Spur Gear Reducer **[32]**

This design has been operating successfully for the last five months; however, the new four-wheel drive system requires power to be transferred through intersecting shafts at 90 degrees. Therefore, this design is no longer relevant to the requirements for this year's design.

Existing Design #2: Open Differential

An open differential as pictured below (**Figure 13.**) is the starting point for most automobile drivetrain designs. This is because the design allows your wheels to turn at different speeds while going through corners; since the outside wheel must travel a longer distance at a greater rotational velocity than the inside wheel. However, a big setback for implementing a differential into a buggy is the amount of weight it adds as well as any loss in traction results in the entire buggy losing power being transferred to the ground. This can be avoided by implementing a limited slip into the differential, but at that point the complexity of the design surpasses the benefits from a limited slip.

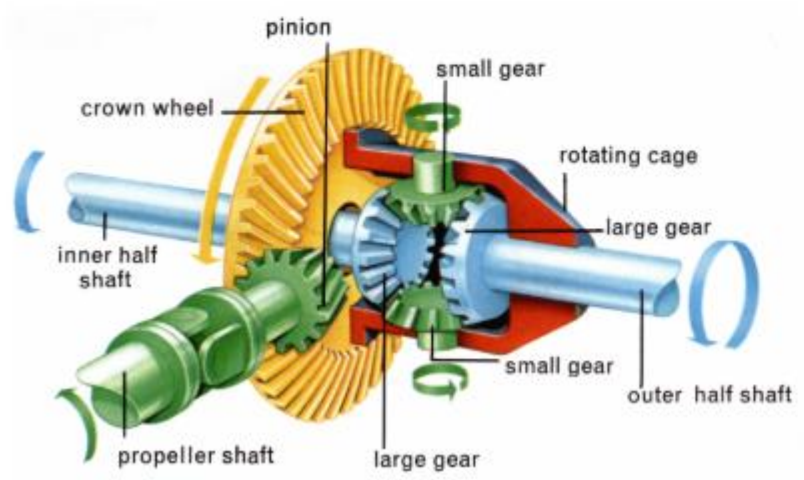

Figure 13. Open Differential **[33]**

4.2.2.2.2 Existing Design #3: Bevel Gearbox

The bevel gearbox shown below (**Figure 14.**) is a generic gearbox made by a company in the United Kingdom. This design utilizes two spiral bevel gears that are mated at a 90-degree angle. This design directly corresponds to the type of gearbox that is needed for this year's drivetrain system. This type of gearbox will allow for a driveshaft that transfers power to the front gearbox while also distributing power to the rear gear reducer. However, the gearbox cannot be a simple 1:1 ratio as in the design shown below and needs to accommodate for a specific desired final drive ratio.

Figure 14. Bevel Gearbox **[34]**

4.2.2.3 Subsystem #3: Speed Reducers

A speed reducer is a necessary component of any vehicle's drive train. Since an engine rotates much faster than the final wheel (used to propel vehicle), the rotational velocity must be reduced somewhere between the engine and the final wheel. While some reduction occurs in the transmission (and sometimes a transfer case), most of the rotational speed losses occur in the speed reducer subsystem. There are several ways to transfer rotational speed from a transmission to the wheels however the methods discussed include a spur gear system, a chain and sprocket system, and a belt-pulley system.

4.2.2.3.1 Existing Design #1: Spur Gear Train

A spur gear train is a common form of speed reducer. They use parallel teeth to mesh and are simple to design **[20]**. Due to their simplicity, it is common to design spur gears in a series of “stages” to either increase or decrease the rotational speed output of the system or change the rotation of the output shaft. **Figure 15.** provides an example of a two-stage spur reduction.

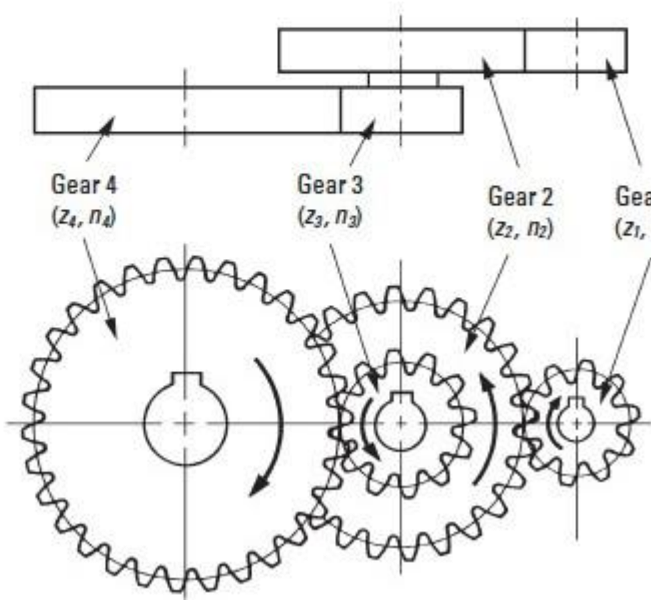

Figure 15. Typical Spur Gear Mesh (2-Stage Reduction) **[20]**

Intuitively the rotational speed introduced to the system at Gear 1 will be reducer compared to the output speed found at Gear 4 due to the difference in tooth count. Gear 1 will experience more revolutions per single revolution of Gear 4 thereby reducing the output rotation. The direction of shaft rotation will also change, as noted by the curved arrows in the figure. The spur reduction system is a reliable, robust system proven to perform adequately for the project’s application. The caveat is that spatial dimensions drastically increase as multiple stages are added, and weight of the system heavily depends on the material properties of the gears. To transmit the required torque and power generated by a 10hp motor for the required two days of racing, and time required for vehicle testing, through-hardened steel is the most cost-effective material for manufacture. For this reason, either the durability or the weight of the subsystem will suffer.

4.2.2.3.2 Existing Design #2: Chain Drive

The chain drive system is another simple design used to transmit power from one rotating shaft to another. It uses a specialized variation of a spur gear called a sprocket **[18]** with teeth that are designed to fit with into spaces in the chain. (**Figure 16.**) The chain itself is comprised of links that connect by roller bushings capable of simultaneous coplanar rotation. The teeth of the sprocket mesh with the spaces between these bushings, providing permanent contact between the chain and sprocket.

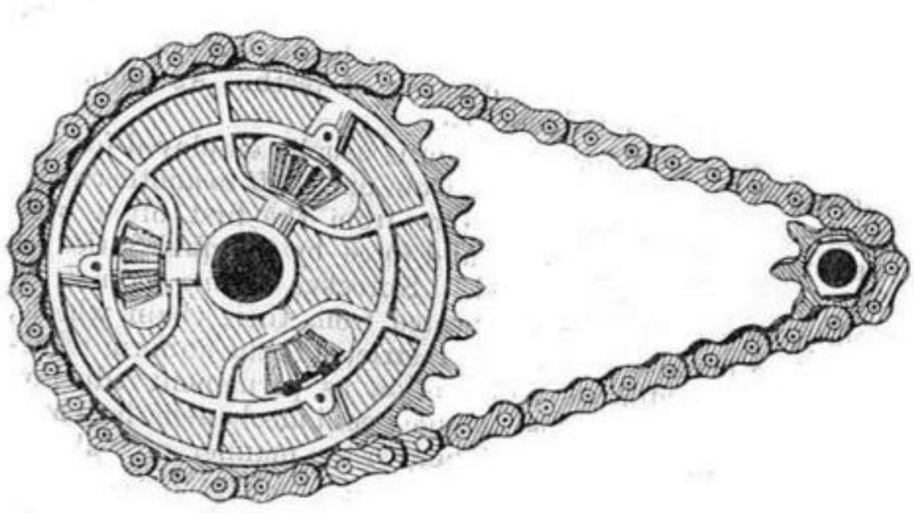

Figure 16. Chain and Sprocket **[18]**

The chain and sprocket designs are a light-weight option meant to mimic a spur gear train. As a result, they are capable of both speed reduction and accretion. The drawback to chain drives is that the need for components to be coplanar is paramount. If sprockets in the system are not sufficiently aligned, the chain will bind or derail, thus compromising the system.

4.2.2.3.3 Existing Design #3: Belt Drive

Belt drives come in several types including flat belts, round or wire belts, V belts, and timing belts. The belt is supported and actuated by a minimum of two pulleys. The pulleys are connected to various input, output, and intermediary shafts that import and export rotational energy to the system.

Figure 17. Timing Belt Drive **[35]**

While the design process is like a chain drive, each belt type requires specific considerations and varies in their efficiency of energy transfer. The main appeal for belt driven systems is their light-weight designs. For example, the timing belt system, shown in **Figure 17.**, illustrates qualities like a spur gear reduction system, while drastically reducing the weight. In return, the spatial dimensions of the system far exceed a spur gear system.

4.2.3 Subsystem Level Benchmarking (Frame)

For frame subsystem benchmarking, physical attributes from the frame functional decomposition (section 4.4) are broken down by benchmarking to existing designs and comparing the differences between them.

4.2.3.1 Subsystem #1: Member Material

The type of material the frame will be made from is a critical part of the frame design process. The material properties and profile will determine the structural integrity of the entire vehicle and special attention must be paid to this property of the frame. For this benchmarking breakdown three profiles of 4130 steel tubing will be examined.

4.2.3.1.1 Existing Design #1: Primary Members

The primary tubing is the strongest and most prominent profile on the frame. It is controlled by clear strength requirements in the Baja SAE rulebook. Last year's team along with almost all Baja vehicles from last year use a 1.25" OD and 0.065" thickness tubing. The rational for this will be shown later in section 7.2. The frame team has yet to discover a school that utilizes an alternative profile.

4.2.3.1.2 Existing Design #2: Secondary Members

The secondary tubing is a weaker profile can be used for any member not is not stipulated to be of primary material. The secondary members, like all parts of the frame structure, must be constructed of steel. However, unlike the primary material. It is restricted by a minimum profile size (1.00" OD and 0.035" thickness) rather than a strength requirement. Last year's team used a 1.00" OD and 0.058" thickness for their secondary material. The reasoning for the larger than required thickness in this case was due to the physical restrictions on bending thin wall tubing. Many secondary members needed to be bent for last year's frame and bending of a smaller wall thickness would result in kinking of the tube. (**Figure 18.**)

Figure 18. Example of a Kinked Tube

4.2.3.1.3 Existing Design #3: Tertiary Members

The tertiary tubing is a solution to the kinking issue. Bent secondary members can be manufactured with a larger wall thickness while straight secondary members can be replaced with a tertiary profile. Last year's team used a 1.00" OD and 0.049" thickness for non-bent secondary members. For clarification, all non-primary members are defined in the rules as secondary members. However, many teams utilize two different sizes of tubes that meet the requirement of a secondary member.

4.2.3.2 Subsystem #2: Member connection methods

The method in which structural members of the frame are connected impact the frame specs and performance. There are three-member connection methods outlined in the rulebook that give specific requirements for each method.

4.2.3.2.1 Existing Design #1: Weldments

Welding is the most common way to connect tubular members. Welds are simple to create and consume the least amount of weight of all other methods. Welds cannot be ground down, sanded or modified in any way. Any person who does any form of welding on the frame must be vetted with a welding sample that will be provided to tech inspectors at the competition. Last year's frame was fully welded and did not utilize any other member joining method.

4.2.3.2.2 Existing Design #2: Bolted Fasteners

Bolted member joints (**Figure 19.**) consist of two colinear members with welded on flanges. The flanges must be made of the same material as the members and must meet minimum radius and thickness dimensions. These members are then connected at the flanges by a minimum of three bolts. It is rare to see designs that utilize this connection feature as it is time consuming to fabricate and adds a large amount of weight for a connecting joint.

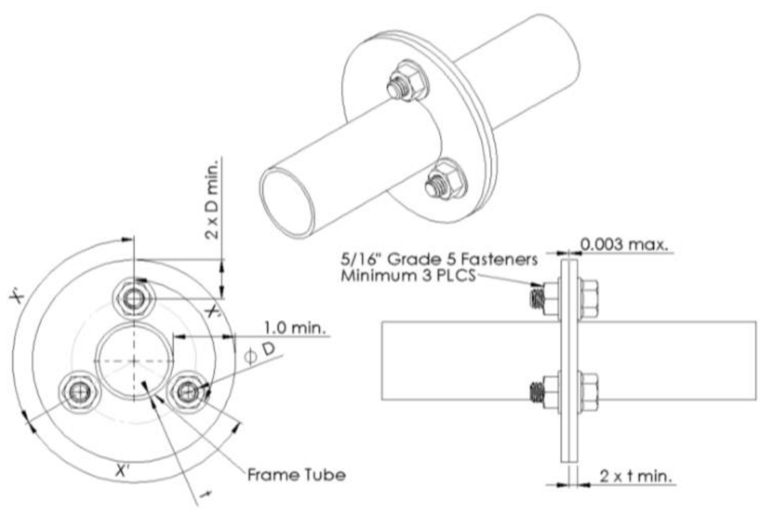

Figure 19. Bolted Roll Cage Member **[2]**

4.2.3.2.3 Existing Design #3: Butt Joints

Butt joints (**Figure 20.**) are an alternative method to the bolted. Like the bolted they join two colinear members. However, the use of bolts is avoided by welding both members to a tubular insert (sleeve) that goes inside of both members. The sleeve dimensions and welding method are detailed in the rulebook. This joining method is still quite rare as simple direct welding of members outclass butt joints in fabrication time and weight.

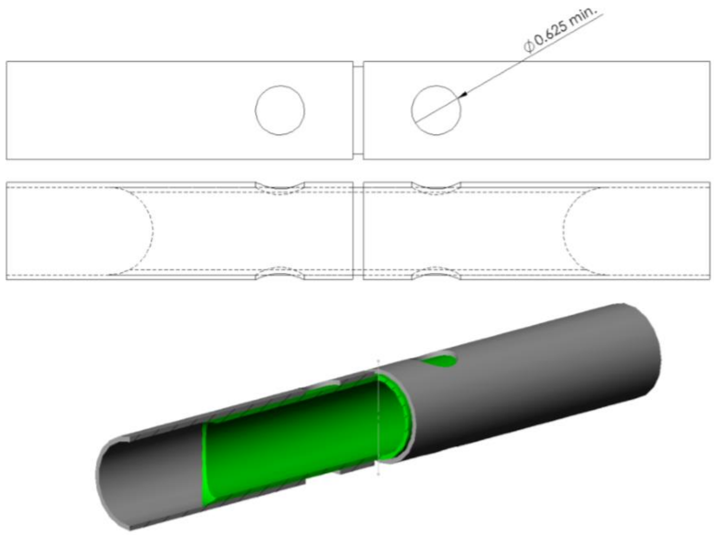

Figure 20. Butt Joint of Two Roll Cage Members **[2]**

4.2.3.3 Subsystem #3 (Chassis): Chassis

The chassis for the frame encompasses the overall geometry the frame will exhibit. There are three general frame geometries that teams are encouraged to design for. While other geometries can be implemented. They have even more restriction and special conditions that must be met. This results in almost all Baja SAE teams choosing one of the following three geometries.

4.2.3.3.1 Existing Design #1: Rear Braced Frame

Rear braced frames (**Figure 28.**) are one of the two common geometries chosen by Baja SAE teams. Around half of participating vehicles utilize this geometry including NAU's historic Baja vehicles. The geometry is notable for its close to vertical front bracing members (FBMs) that bend down from the roll hoop overhead (RHO.) This frame geometry is very successful and due to its use in last prior NAU teams give this team a good understanding of this geometry.

4.2.3.3.2 Existing Design #2: Front Braced Frame

Front braced frames (**Figure 27.**) is the other common frame geometry. This frame is historically just as successful as rear braced geometries. The front braced geometry can be noticed by more sloped FBMs that connect to the tip of the nose rather than the back.

4.2.3.3.3 Existing Design #3: Composite Bracing Frame

Composite bracing frames (**Figure 21.**) simply fulfill the requirements of both rear braced and front braced geometries. They are preferred by SAE officials as they are structurally very strong but are usually passed by other teams due to the added weight of this geometry. Due to the large impact weight has on vehicle performance it can restrict a team's success at competition.

Figure 21. Example of Composite Frame Geometry

4.3 Functional Decomposition (Drivetrain)

The purpose of a drivetrain system in a vehicle is to propel the vehicle. This is accomplished by converting human and chemical energy into different forms of mechanical energy, then converting that mechanical energy into linear motion. First, chemical energy is converted in the engine using internal combustion to rotational energy. That rotational energy is translated from the engine through the ECVT, transfer case, and speed reducer to the vehicle's wheels. The wheels convert rotational energy to linear motion due to traction between the wheels and the ground.

4.3.1 Black Box Model

The black box model shown in **Figure 22.** models the goal of the vehicle's drivetrain. The inputs will be a human and combustible chemical material, and an electrical signal. The system will output linear motion, thermal and vibrational signals, and excess combustible material.

Figure 22. Black Box Model of Drivetrain System

The model provides insight as to the drivetrain's purpose. Propulsion is essential to the function of the system. Normally the only consideration for input is the gasoline needed to run the engine, but the figure includes consideration for the human required to crank the engine and continue to actuate it. The electrical signal is unique as it will actuate the initial transmission system, which controls the translation of rotational energy through the entire system.

4.3.2 Functional Decomposition Model

The sole function of the drivetrain is to transmit power from the engine to the wheels. It is accomplished by burning materials with a high chemical energy and converting that chemical energy into rotational (mechanical) energy. After several translations of rotational energy, it is converted into linear motion through the wheels. Human input is required to begin the chemical energy conversion by converting human energy to mechanical energy through initiating the pull cord and actuating the throttle pedal.

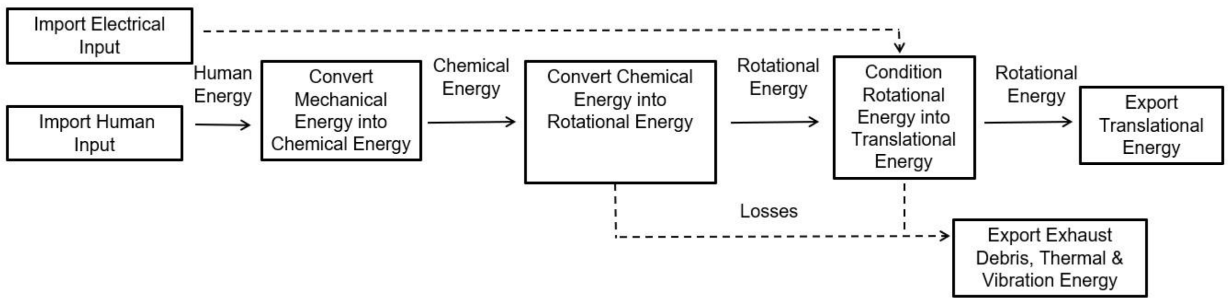

Figure 23. Functional Decomposition of Drivetrain System

Figure 23. shows the breakdown of energy conversion throughout the drivetrain system. Clearly, human input is required to initialize the entire process. The exported materials are the human and expended chemical particulates. The exported energy is linear motion, heat, and vibrations.

4.4 Functional Decomposition (Frame)

The frame's main function is to handle many different forces in different ways. A black box model and functional decomposition model is used to help in the design function clarification process. For the black box model, the three input types were individually considered. For the materials, the member types were selected. For energies, various forces that the frame will experience were used. There were no other significant energies that could be considered. For the signal input, the suspension forces were used since they had a varying input that also gave a varying output. Some of the other forces considered in energies could also have varying input but since they always had the same output, they were not a meaningful signal. Each input was then given an appropriate output that corresponded to the input. When the functional decomposition model was put together, the inner workings of each of these input-output pairs were broken down. Since all of the energy and signal inputs directly interact with the frame, the material input applied to all the other inputs. The intermediate steps directly tracked each change in energy form until it reached the output. For this section it was difficult to focus on the subsystems mentioned above because the frame is one continuous part that overall performs the same functions.

4.4.1 Black Box Model

For the frame, the black box model (**Figure 24.**) was mostly dealing with forces being applied to the frame. For the material input, the primary secondary and tertiary members were used. The frame by itself only consists of these members at this stage in the design process. The energy inputs consist of various forces from outside factors. This includes vibrations from the drivetrain, impact forces, and the weight of the driver and drivetrain. All these forces are handled in different ways. The signal inputs for the frame are the suspension forces since they are a varying input that the frame responds to in different ways depending on the configuration of the forces. For example, when all four suspension subassemblies transmit the same force, the frame holds its position. If the two left subassemblies transmit more force if it goes up a curb, the frame rolls to the right until the forces balance again.

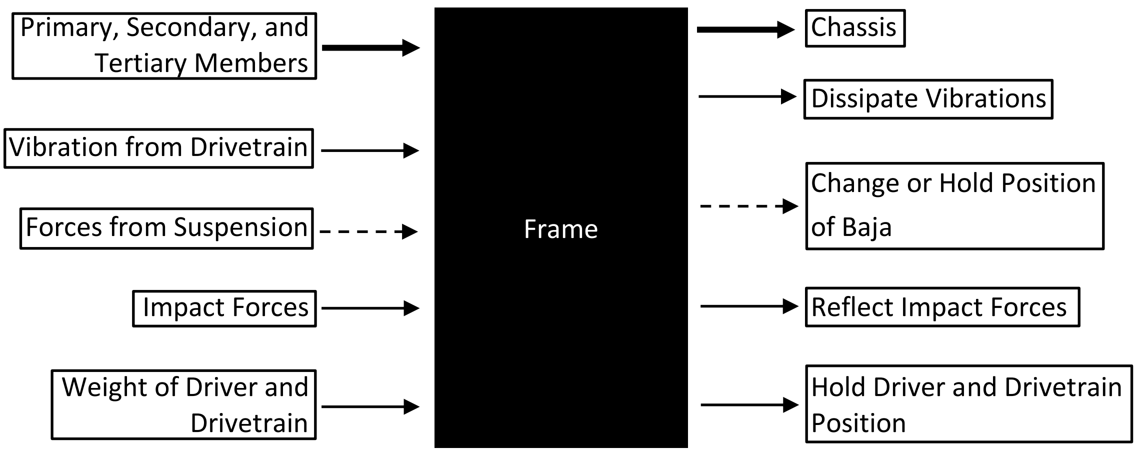

Figure 24. Frame Black Box Model

The black box model helped clarify the essential functions that the frame must perform. This allowed us to keep designs on track with these functions. In the initial frame design methods, some of these functions were left out. For example, the suspension forces having varying loads was not initially considered. This black box model helped us understand everything that the frame needs to do.

4.4.2 Functional Decomposition Model

For the frame, we decided to go with a functional decomposition model shown in **Figure 25.** This built off the black box model and expanded on how it got from the inputs to the outputs. The material inputs were used in conjunction with every other input. Together, the primary, secondary and tertiary members create the chassis as the material output. The vibrations from the drivetrain are transmitted throughout the frame but ultimately are canceled by each other or absorbed by the internal frictions of the material involved with the oscillating stresses. The forces from the suspension are transmitted throughout the frame and are relayed to all other components of the Baja. This causes the entire Baja to either hold or change its position in space. Any Impact forces experienced by the frame is first converted to elastic energy in the frame members and then an opposing force arises from the strained members. This in effect, reflects any impacts assuming they do not yield the members. Lastly, the weight of the driver and drivetrain are first converted to elastic energy in the members. Again, this causes an opposing force to be generated. This holds the driver and drivetrain in position relative to the frame.

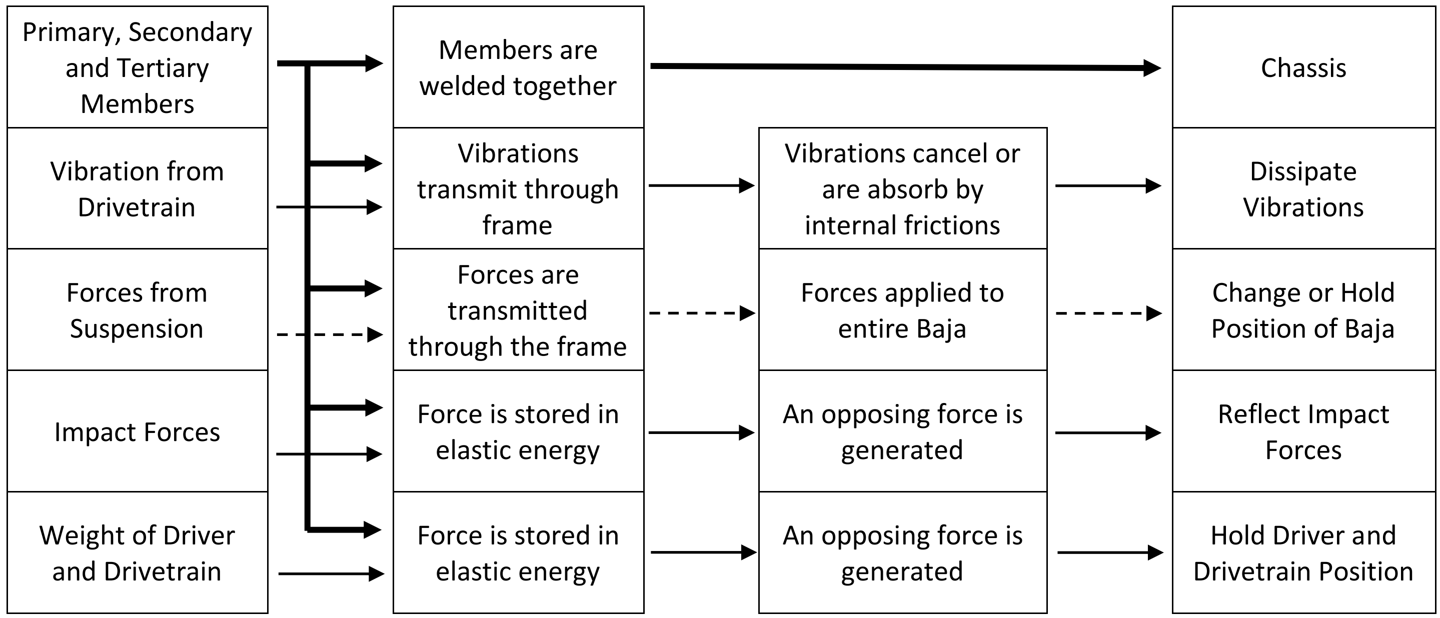

Figure 25. Frame Functional Decomposition Model

The functional decomposition model helped the frame understand what the frame was doing to accomplish the functions of the black box model. This ensured that we selected the correct material that could satisfactorily perform the broken-down steps in the model. This led us to choose 4130 steel instead of the recommended 1018 steel because of its higher yield point and thus more storage of elastic energy without damaging the members.

5 CONCEPT GENERATION

The following sections are full system design concepts that are a product of the benchmarking processes discussed in sections 4.2-4.3 of this report. A simple technical analysis has been completed for each system and discusses the advantages and disadvantages of each concept. Although these designs are new concepts generated from group brainstorming, the basis for many of these designs are like systems that already exist.

5.1 Full System Concepts: Drivetrain

While researching and studying drivetrain designs, three solutions were found. Some research was done before the official rules were released, which allowed the team to receive a 15% bonus in competition points if the team decided to develop a four-wheel-drive system. The first design considered was using a dual Electric Continuously Variable Transmission (ECVT) directly connected to the gear reducer. The second drivetrain system concept uses a gaged CVT as previous years have done, that connects to the transfer case which allows the system to have four-wheel-drive. For the final concept researched, an ECVT connected to the motor directs power to a transfer case that allows motion travel perpendicular to the engine and connects to two separate gear reducers in the front and rear. This allows the vehicle to travel in four-wheel-drive while having the tunability of an electronically controlled transmission. In the next three section the design of these three systems will be explained in detail.

5.1.1 Full System Design #1: ECVT Direct to Spur Gear Reducer (2WD)

In Junior level design class, two of the three Capstone drivetrain sub team members designed an Electronic Continuously Variable Transmission (ECVT) that used a stepper motor to change the diameter of the pulleys. This design was the first full system concept design of a working ECVT. The engine output shaft connected to the ECVT primary pulley which was connected through a V-belt to the ECVT secondary which was mounted to the gear reducer. This design allowed for a gear ratio that could be manipulated at different RPMs. In the figure below (**Figure 26.**) the ECVT is seen connected to the engine with the primary and secondary.

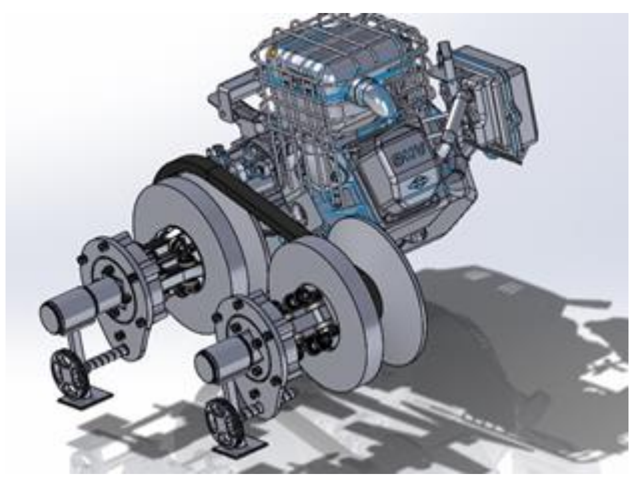

Figure 26. EGR-386W ECVT Design Concept **[8]**

This design allows for independent control of the primary and secondary CVT pulleys, in testing the design needed to compensate for slack between the primary and secondary. This reduced the ability for the system to fully use both primary and secondary. The table below (**Table 4.**) outlines the advantages and disadvantages of the design.

Table 4. EGR-386W ECVT Advantages and Disadvantages

EGR-386W ECVT Advantages	
1.	Allows for manipulation of gear ratio dependent of the engine's output speed
2.	Low initial cost, using no specialized parts
3.	Ease of manufacturing that allows for inhouse machining
EGR-386W ECVT Disadvantages	
1.	Design uses two ECVT pulleys for primary and secondary, with no advantage
2.	Large moment on threaded stepper motor arm that will bind the linear motion of the assembly
3.	Robust Shaft design that requires additional support due to the weight of the design

This system concept allows for only four-wheel-drive, because the secondary ECVT pulley connects to a spur gear reducer that does not allow the vehicle to transmit the power perpendicular to the engines output drive shaft.

5.1.2 Full System Design #2: Gaged CVT to Transfer Case to Spur Gear Reducer (4WD)

Design 2 is comprised of a pre-manufactured CVT, two fixed rotational transfer systems, and two spur gear speed reduction systems. The CVT is made by Gaged Engineering and comes fully functioning using a 6-inch drive and 8-inch driven cam system to put out a 3.9:1 bottom end and 0.9:1 top end speed reduction ratios for a final reduction (at the CVT output) of 4.33:1. **[3]** It is the same CVT system that has been used by past NAU Baja teams. The transfer case systems will consist of simple spiral bevel gear meshes with a 3:1 reduction ratio for a combined total of 9:1 reduction. They will provide direct drive to the front wheels. The CVT output will also connect to a two-stage spur gear reducer with a reduction ratio of 9:1. It is critical to have equivalent reduction ratios to provide power to the front and rear wheels, as it will avoid efficiency losses. The advantages of the system include high torque output to the wheels and high efficiency in power transfer between the engine and the wheels. However, the components of the system will be extremely heavy, which will decrease the maximum speed of the vehicle. In addition, the factory made CVT is difficult to tune and prone to efficiency losses if not tuned properly.

5.1.3 Full System Design #3: ECVT to Transfer Case to Belt Drive Reducer (4WD)

Design 3 considers the possibility of a custom built, electronic CVT (ECVT), fixed rotational transfer cases, and a belt-driven speed reducer. The ECVT will have a final reduction ratio of 4:1 using a 6-inch by 8-inch cam system but will be programmable. This allows the driver to adjust how the vehicle is "geared" like a manual transmission found in full-size vehicles. The ECVT will go to the front and rear wheels using different methods. To the front, a two-stage direct drive reduction using two spiral bevel gear meshes (transfer cases) is used. This will provide a direct drive but cannot be disconnected. The rear wheels will use a timing belt-driven speed reducer. A belt system will reduce the weight of the vehicle when compared to a spur or helical gear mesh at the cost of increased volume. The full system is the lightest possible solution but is also the highest spatially demanding design.

5.2 Full System Concepts (Frame)

In this section, three different frame designs are considered. These designs are dictated by the rules but allow for three different designs. These include front braced, rear braced, and a combination of both front and rear braced. The rule book recommends the combination design for extra strength.

5.2.1 Full System Design #1: Front Braced Frame

The front braced system shown in **Figure 27.** involves bracing members from the end of the nose to the front of the roll hoop overhead members. There are no required members rear of the roll hoop in this design, so the additional strength comes from these front bracing members. While this design doesn't require any members rear of the roll hoop, the engine still has to be behind the roll hoop so structural members will have to be placed there anyways.

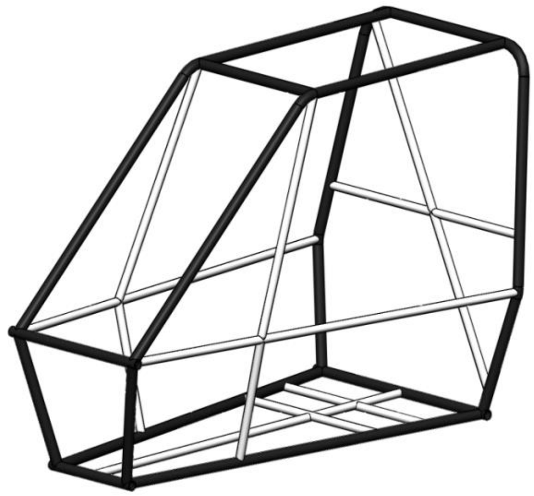

Figure 27. Front Braced Frame **[2]**

Pros:

- Medium weight frame
- Shorter wheelbase

Cons:

- Would require all new design from previous years
- Not as strong
- Prone to rolling
- Weighted towards the front

5.2.2 Full System Design #2: Rear Braced Frame

The rear braced system shown in **Figure 28.** involves bracing members from the rear of the roll hoop that attach to rearward required members. This design does not have bracing members between the nose and the roll hoop overhead members.

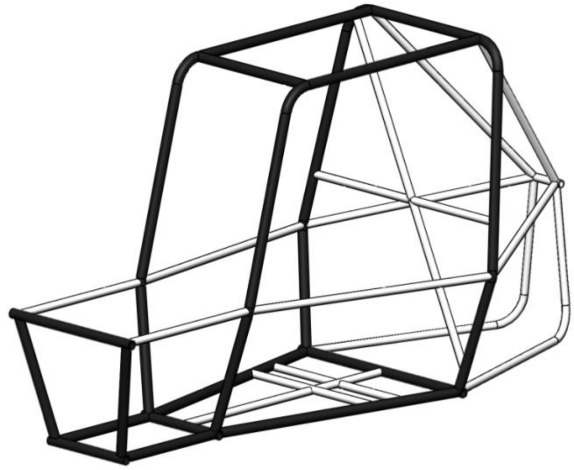

Figure 28. Rear Braced Frame **[2]**

Pros:

- Can work off previous years proven designs
- Stable
- Light weight frame

Cons:

- Not as strong
- Longer wheelbase
- Weighted towards the rear

5.2.3 Full System Design #3: Front & Rear Braced Frame

The combination front and rear braced design takes the bracing methods from both previous designs and combines them. Like the front braced design, there is a member between the nose and the roll hoop overhead members, but it also is braced from the rear of the roll hoop. The rules suggest this design since it is the strongest of the two designs.

Pros:

- Strong
- Very stable
- Even weight distribution

Cons:

- Heavy
- Long wheelbase

5.3 Subsystem Concepts (Drivetrain)

5.3.1 Subsystem #1: Electronic Continuously Variable Transmisson

During the design iteration phase of the project the Capstone Drivetrain sub team investigated three different designs for the electronic continuously variable transmission (ECVT). The first design researched was improving the design of Spring 2018 ECVT design with dual disk setup. The second design concept was based off research done by online searches, which resulted in an electric toroidal concept. Lastly, the third concept iteration uses a specialized linear bearing with grooved shaft that allows power to be transmitted parallel to the engine, but at the same time allowing the disk to change effective diameter.

5.3.1.1 Design #1: Modified Spring 2019 ECVT Concept

During last year junior level design class, part of the Capstone drivetrain team designed an ECVT concept that used over 30 bearings. This was for the dual system that after further research would not work. This year's Capstone team researched previous years design and found a few faults. Instead of using two ECVT systems, one for the primary and one for the secondary, the team could instead implement only the primary side of the ECVT and use the previous year's secondary. In the figure below (**Figure 29.**) is the design iteration of the primary ECVT:

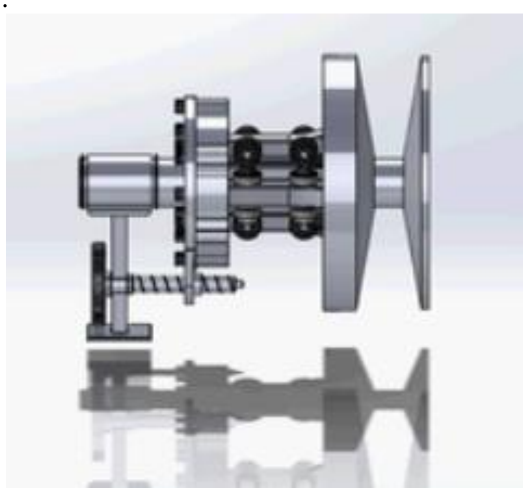

Figure 29. Modified Spring 2019 Primary ECVT

The design of a modified single primary ECVT connected to a tensioner allows the belt to stay in tension while still allowing for the belts diameter to change. Outlined below are the advantages and disadvantages of the design.

<u>Advantages:</u>

- Ease of manufacturing
- Low initial cost
- Robust design

<u>Disadvantages:</u>

- Bearing intensive with 17 bearings to control movement
- Large moment on stepper motor frame
- Heavier than previous year's design

5.3.1.2 Design #2: Toroidal ECVT Concept

After modifying the previous design to work with a last year's Capstone secondary ECVT. The team looked at industry ECVT designs that are new to market. One design found was a high torque toroidal system. This uses four parabolic cones and 4 roller disks on swivels the design allows for the transmission to vary based on which part the disk is touching. It would be controlled by a linear actuator connected to a rod connecting all disks. Below is the concept drawing: (**Figure 30.**)

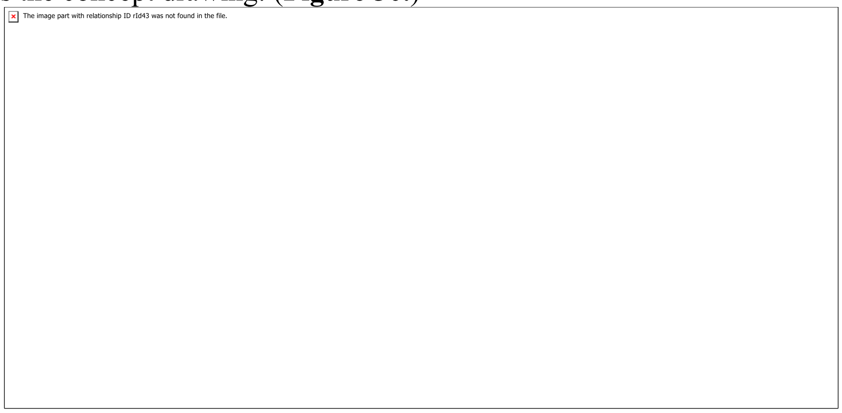

Figure 30. Toroidal ECVT Concept

This system requires very high tolerance allowing the disks to mesh with the plate. The two disks in the middle connect with an intermediate shaft, that transmits the power from one side to the other. Below are the advantages and disadvantages of the system.

Advantages:

- Allows for very high torque output without slipping
- Requires a linear actuator that easily controlled

Disadvantages:

- Very high tolerances need for meshing of cones and disks
- Long dimensions require larger footprint on the buggy
- Heavier than previous year’s design
- Output direction in opposite than what is needed

5.3.1.3 Design #3: Linear Bearing ECVT Concept

The last design iteration the team focused on was reducing the number of moving parts by using a specialized bearing that allows the assembly to move back and forth on the engines output shaft while also being able to transmit torque. This is done by incorporating a linear bearing in the center of the assembly that will allow for a main hub for mounting as well as the mechanism needed to move the disks apart. Below (**Figure 31.**) is the design iteration of the design.

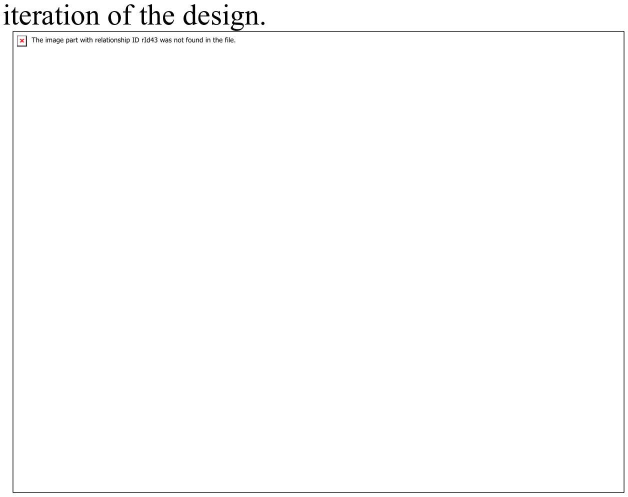

Figure 31. Linear Bearing ECVT Concept

This design allows for the use of a hallow shaft that is fitted with a threaded rod which allows the system to move back and forth. Below is a list of advantages and disadvantages of the design concept

Advantages:

- Centralized design allows for the center of mass to stay within the shaft

- Low friction linear bearing allows for back and forth motion while transmitting torque to the wheels
- Small footprint allows the design to be mounted to the side of the engine
- Stepper motor with remote location allows for heat dissipation

Disadvantages:

- High cost for linear bearing
- High tolerance needed for linear bearing

5.3.2 Subsystem #2: Bevel Gear Reducer

Subsystem #2 is a bevel gear reducer that will be used to transfer power in orthogonal directions for the four-wheel drive system. For this section, three different concepts for bevel gear reducers are discussed along with a pros and cons list for each.

5.3.2.1 Design #1: Open Bevel Gear Concept Iteration

The first full system concept uses a 1:1 pair of miter gears, a dog clutch for driveshaft disengagement, and a u joint for driveshaft connection. This full system does not accurately depict the needed gear ratios to achieve the final drive ratio of 36:1 because of the 1:1 gearset used. The input shaft on the bottom left of the figure below (**Figure 32.**) is connected to the secondary CVT and goes all the way through the gearbox to the other side; where a second gear reducer is connected. The dog clutch shown in the figure uses a spring that applies a constant force; keeping the dog clutch engaged and transferring power to the driveshaft. This full system design is purely conceptual and is shown as a dry system without the proper linkages. Advantages for this design would include ease of assembly, but it is not practical for our application.

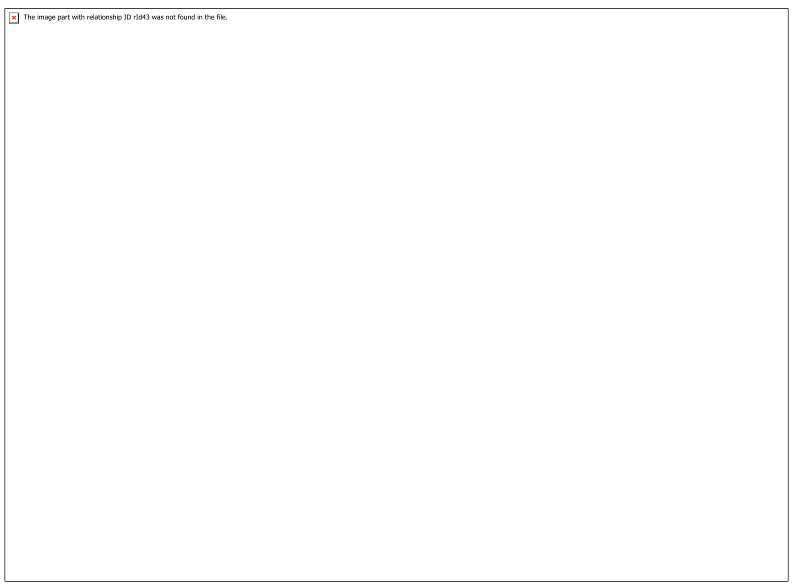

Figure 32. Simple Gearbox for 4WD

A list of pros and cons for this concept is shown below:

Pros:

- Simple geometry
- Minimal power loss from friction

Cons:

- Complex linkage needed
- Single plane mounting orientation

- Unstable

5.3.2.2 Design #2: 3:1 Bevel Gear Reducer with Flanges

The design shown below (**Figure 33.**) is a simple bevel gearbox reducer that utilizes a 3:1 gear reduction going to the driveshaft. This design is a wet system that receives power input from the secondary CVT and is transferred to the driveshaft as well as the opposing side of the gearbox.

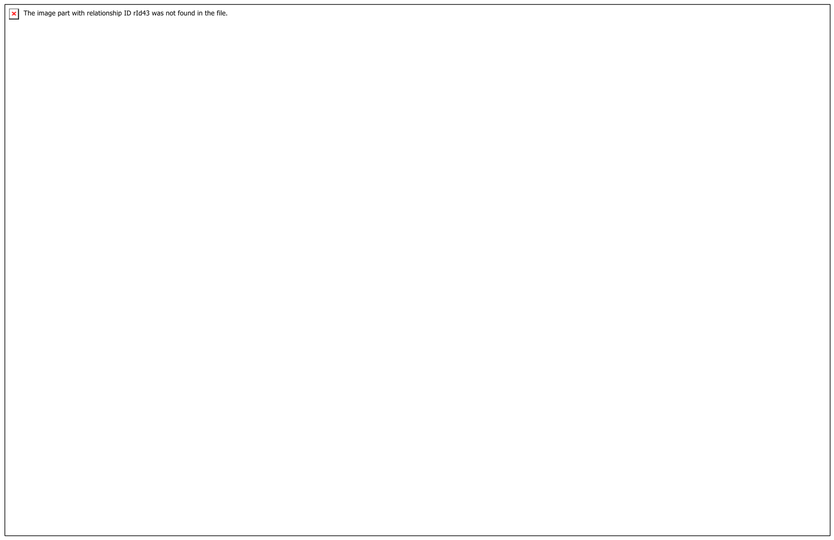

Figure 33. Bevel Gear Reducer with Flanges

A list of pros and cons for this concept is shown below:

Pros:

- Compact
- Durable
- Heat Resistant

Cons:

- Gear reduction is only seen by bevel gear output
- Impractical for manufacturing
- Different shaft sizes
- Lack of bevel gear support

5.3.2.3 Design #3: 3:1 'Split Case' Bevel Gear Reducer

Although the figure shown below (**Figure 34.**) does not accurately depict a split case bevel gear reducer for our application, it still gives a good example of the overall concept of this design. The design consists of a bevel gear and pinion, and when together achieve a 3:1 reduction. This concept is currently being iterated for our application and will be included in the next capstone presentation.

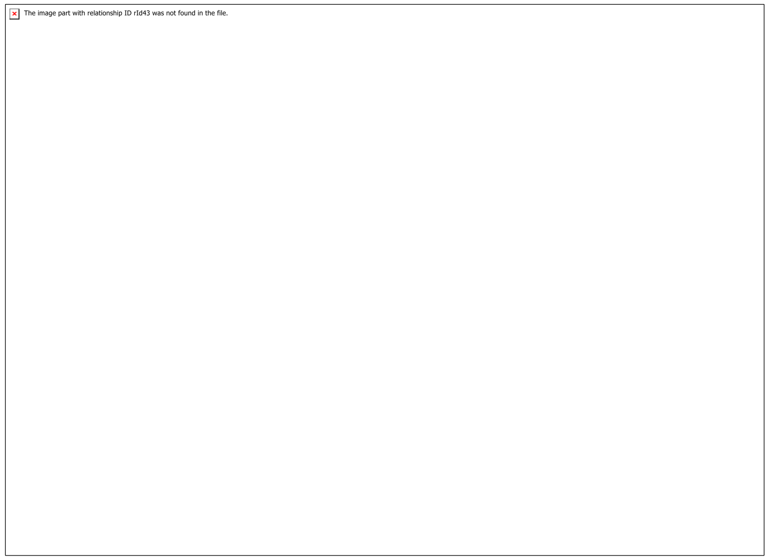

Figure 34. Split Case Bevel Gearbox **[TJ14]**

A list of pros and cons for this design is shown below:

Pros:

- Ease of manufacturing; case can be made in-house
- Minimizes size
- Easily assembled

Cons:

- Complex case sealing
- High tolerances for end bearings

5.3.3 Subsystem #3: Speed Reducers

The three design concepts evaluated by the drive train team are a two-stage spur gear train, a two-stage chain drive, and a two-stage belt drive. Each subsystem is meant to incorporate two stage reduction to minimize the strain on rotating components and increase the lifespan of the system, as well as reduce the size of all components.

5.3.3.1 Design #1: Spur Gear Set

The spur gear train would use two pairs of gears and three different shafts. The input shaft introduces rotational energy translated by the transmission and drives Gear 1. The intermediate shaft supports Gears 2 & 3 and translates rotational energy between the two gear meshes. The output supports Gear 4 and translates the converted rotational energy to the rear wheels. (**Figure 35.**)

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Figure 35. Spur Gear Concept

The benefits of the spur gear system are that it is the most compact design, has been validated by previous teams' designs, and is easily manufacturable. The issue is that premade gears will be made of heavy material and hinder propulsion of the vehicle.

5.3.3.2 Design #2: Chain Drive System

The chain drive will use the sprocket connected to the CVT Input shaft to translate motion to the intermediate sprockets. These sprockets are fixed to one another, so the pinion sprocket will convert rotational motion to the sprocket connected to the Output shaft. (**Figure 36.**)

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Figure 36. Chain Drive Concept

The biggest advantages of the chain drive are its low weight and high transmission efficiency (98%) **[17]**. The downside is that the volume of the system increases dramatically, and the alignment of the system requires tighter tolerances than a spur gear or timing belt system.

5.3.3.3 Design #3: Timing Belt Drive System

The timing belt system will use toothed pulleys to move a grooved belt along a plane. Looking at **Figure 37.**, the input shaft will rotate the driving pulley (top left corner) to rotate the intermediate shaft. The intermediate pulleys are fixed to one another and will convert and translate motion to the pulley on the output shaft (bottom right corner). This will drive the final wheels and propel the vehicle.

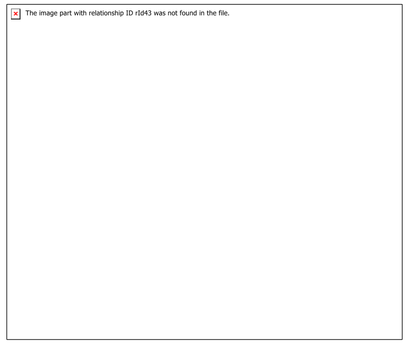


Figure 37. Timing Belt Drive

The benefits of a timing belt systems are the ease of design, being very close to design of a spur gear train, and the efficiency comparable to a chain drive system. Unfortunately, the transmission efficiency is only 95-98% at its best and will decrease as the belt experiences wear over time **[17].**

5.4 Subsystem Concepts (FRAME)

For the frame subsystems, different features of the frame were selected since the frame technically has no sub-systems. The three features chosen include the nose, the cockpit, and the roll hoop. These were selected because of their less restrictions from the rules.

5.4.1 Subsystem #1: Nose

The nose subsystem involves different geometries that build off the front bracing members. Since our bracing members narrowed towards the bottom, the nose had to fit that profile on the rear of the nose. The nose also interacts with the front-end team. This makes the nose geometry important for the ease of their design adaptation. It is also important to keep the nose shorter if possible so that the overall wheelbase is shorter which helps with turning radius. A narrower nose can also help with turn radius. However, space is needed for the front differential in the 4WD system this year.

5.4.1.1 Design #1: Bent Rectangular

The first nose design in **Figure 38.** uses bent members to narrow the top of the nose to be parallel and equal width as the bottom of the nose. The front of the nose is a rectangular shape. This nose is longer than the others since it attempted to have a decent amount of parallel section on top of the nose for the front end to utilize.

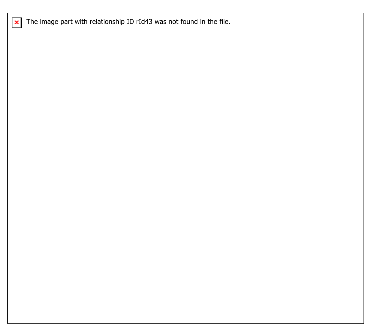


Figure 38. Bent Rectangular Nose from Drive Perspective

Pros:

- Easy for front end to mount to
- Narrower for turn radius

Cons:

- Longer
- Heavier
- Harder fabrication
- Weaker
- Less space inside nose

5.4.1.2 Design #2: Straight Rectangular

Design two, seen in **Figure 39.**, for the nose also has a rectangular nose but instead has straight members on the top. Since the front is narrower than the rear, this causes the top members to not be parallel. This allows for the nose to be shorter. To get those bars closer to parallel the bottom was widened. This makes it wider than the other designs but has a lot of space in the nose.

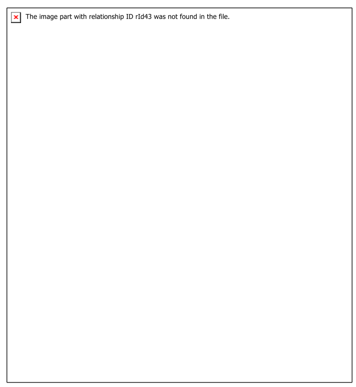


Figure 39. Straight Rectangular Nose from Drive Perspective

Pros:

- Shorter
- Lighter
- Easy fabrication
- Stronger
- More space inside nose

Cons:

- Difficult for front end to mount to
- Wide

5.4.1.3 Design #3: Straight Trapezoidal

The last design keeps all the bars parallel but instead it has a trapezoidal front end (**Figure 40.**). This mad it easier for front end to mount to and keep it short. This makes the top wide but keep the bottom narrow.

This ended up with an amount of space between the two previous designs.

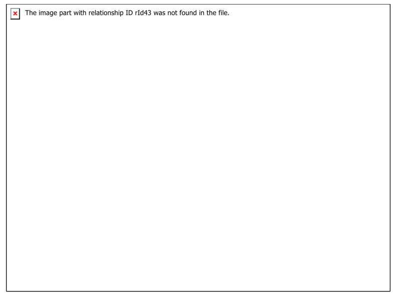


Figure 40. Straight Trapezoidal Nose from Drive Perspective

Pros:

- Shorter
- Lighter
- Easy fabrication
- Stronger
- Easy for front end to mount to

Cons:

- Wide

5.4.2 Subsystem #2: Cockpit

The cockpit variances include the front bracing members (FBMs) and the side impact members (SIMs). Both straight and bent versions of these are considered. These differences contribute to the space inside the cockpit area. Having a larger cockpit is useful for the fitment of the driver and ease of ingress and exit of the driver. Previous years designs were tight and compact making it uncomfortable for taller people. While the rulebook does specify to design it to be used by a wide variety of people sizes, many teams try to minimize weight by making it smaller than comfortable for above average sized people.

5.4.2.1 Design #1: Straight SIMs, Straight FBMs

The first design option for the cockpit involves both straight SIMs and FBMs. This is the simplest design for fabrication. This is very narrow for the cockpit area. This design is also not as strong in a side impact as the later designs since the SIMs do not require supporting members unlike the bent SIM designs. It is stronger in a top impact scenario since it has straight FBMs. (**Figure 41.**)

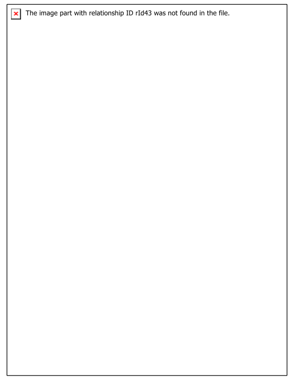


Figure 41. Straight SIMs and Straight FBMs from Top Front Perspective

Pros:

- Simple fabrication
- Strong top impact resistance
- Light weight

Cons:

- Narrow
- Weak side impact resistance
- Uncomfortable riding position

5.4.2.2 Design #2: Bent SIMs, Straight FBMs

Adding a bend to the SIMs allows the cockpit to be wider and thus more comfortable for the driver. This is the previous year's design. The rule book dictates the bends in the SIMs have to be braced. This makes it stronger in a side impact but heavier. However, the bends can only have a maximum angle of 30^{o}. This forces the bend to be further back than desirable. When the driver sits in the cockpit, their knees are further forward than this bend position. The bend would preferably be at or in front of the knee position to make the driver ingress, exit and comfort better. (**Figure 42.**)

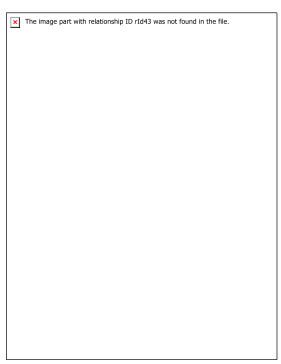


Figure 42. Bent SIMs and Straight FBMs from Top Front Perspective

Pros:

- Strong top impact resistance
- Wide
- Strong side impact resistance
- Comfortable for driver

Cons:

- Heavy
- Complicated fabrication
-

5.4.2.3 Design #3: Bent SIMs, Bent FBMs

To move the SIM bends further forward while keeping within the 30° bend rule, design three widens the front of the SIMs by adding a bend in the FBMs. This allows for the most space in the cockpit area. However, it weakens the top impact scenario. Again, the bent SIMs are braced making it heavy but making it stronger in the side impact scenario. This became the most favorable design regarding the driver comfort and ingress/exit. This does make it the most complicated to fabricate. (**Figure 43.**)

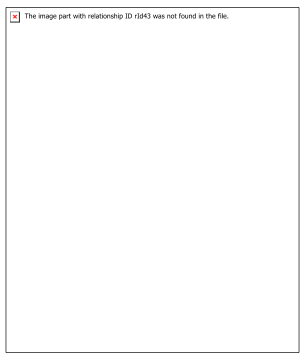


Figure 43. Bent SIMs and Bent FBMs from Top Front Perspective

Pros:

- Wide
- Strong side impact resistance
- Most comfortable for driver

Cons:

- Heavy
- Weak top impact resistance
- Most complicated fabrication

5.4.3 Subsystem #3: Roll Hoop

The roll hoop is an important structural member of the frame. it gives most of the strength in a roll over scenario. Last year's Baja team had to make some fixes to their Baja at competition because of some bends in the roll hoop that had to be braced. We decided to focus on the roll hoop for this reason.

5.4.3.1 Design #1: Bent Roll Hoop Sides, Narrow Top

The first design is like last year's design. The extra bend in the sides allows it to be wider around the shoulder height. This is useful since there are restrictions on spacing around the driver enforced at competition. It narrows at the top because the head section does not have to be as wide. This also saves weight in the roll hoop. However, the extra bend means it must be braced from the rear which adds unnecessary weight to the overall frame. (**Figure 44.**)

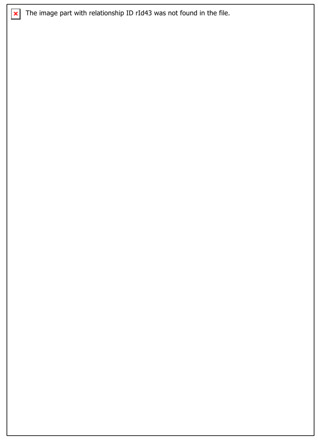


Figure 44. Bent Sides Narrow Top Roll Hoop

Pros:

- Stronger rear bracing
- Good driver clearances

Cons:

- Heavier
- Weaker top impact resistance
- Harder fabrication

5.4.3.2 Design #2: Straight Roll Hoop Sides, Narrow Top

The next design eliminates the bend in the sides of the roll hoop. This makes the driver clearances tighter near the shoulders. The straight members do not need extra bracing which greatly reduces weight. This also lends to simpler fabrication process and stronger top impact resistance. (**Figure 45.**)

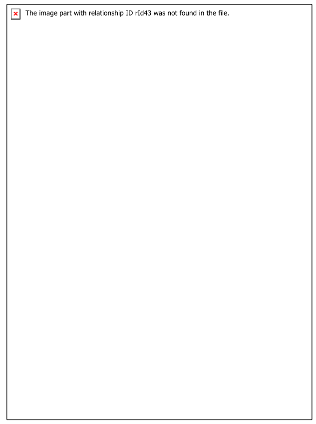


Figure 45. Straight Sides Narrow Top Roll Hoop

Pros:

- Lightest
- Strong top impact resistance
- Easy fabrication

Cons:

- Tight driver clearances

5.4.3.3 Design #3: Straight Roll Hoop Sides, Wide Top

The last design uses the straight sides from the previous design but instead widens the top to get the shoulder clearances bigger. This design is heavier than the last design but still significantly lighter than the first design. This also retains the strength in top impact scenarios. The only problem with this design is the added drag from the firewall compared to the last two designs. The firewall must completely close off the inside of the roll hoop according to the rules. (**Figure 46.**)

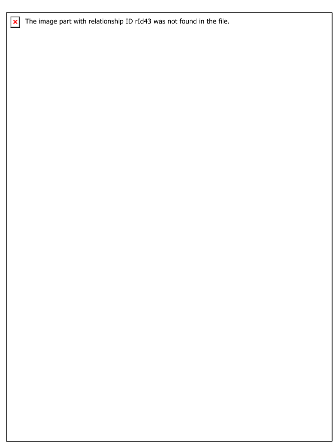


Figure 46. Straight Sides Wide Top Roll Hoop

Pros:

- Light
- Strong top impact resistance
- Easy fabrication
- Big driver clearances

Cons:

- Higher drag from firewall

6 DESIGNS SELECTED – First Semester (Drivetrain)

The full system selection for the drivetrain subsystem will be the use of an ECVT, split case (simplified) bevel transfer case, and timing belt driven speed reducer. The selection process for the final decision is described in this chapter. It includes descriptions of the major design criteria that influenced the decision, and rationale for ruling out infeasible design concepts.

6.1 Technical Selection Criteria

The selection process for a full drivetrain system was based several factors. Most notably, weight of the system was a major consideration throughout the design process, along with the size and transmission efficiency of each subsystem. Rationale for both the transfer case and speed reducer are discussed using a Pugh Chart (**Table 5.** and **Table 6.**) and a Decision Matrix (**Table 7.** and **Table 8.**). Criteria for each table was generated from benchmarking and interviewing past design teams. Decision matrices criteria was weighted based on expected contribution to vehicle positive performance.

6.2 Rationale for Design Selection

Since the CVT concept comparison considered only two options, the ECVT was chosen for its potential to gain added user control while operating the vehicle. This leaves selection for the speed reducer and the transfer case subsystems. The several speed reducer designs were generated from benchmarking and literature research. The concepts were inserted into a Pugh Chart, as seen in **Table 5.** The benchmark design was the concept used by the previous competition team, the spur gear reduction system. The highest scoring concepts for the speed reducer were the spur gear and timing belt reduction systems.

Table 5. Speed Reducer Pugh Chart

Speed Reducer Pugh Chart

Criteria	Spur Gear	Timing Belt	Helical Gear	Chain Drive	Direct Drive
Weight	0	+	0	+	+
Approximate Width	0	-	0	+	+
Approximate Height	0	0	0	+	+
Approximate Length	0	-	0	-	+
Efficiency	0	+	-	-	-
2-stage reduction capable	0	+	0	-	-
Thermal E. Generation	0	+	-	+	-
Audible Volume	0	+	+	-	-
Maintenance	0	+	0	-	-
TOTALS					
Positives	0	6	1	4	0
Negatives	0	2	2	5	5
Final:	0	44%	-11%	-11%	-56%

The transfer case subsystem also generated many design concepts. The following Pugh Chart depicts the top six designs for transfer cases.

Table 6. Transfer Case Pugh Chart

Transfer Case Pugh Chart

Criteria	Classic Transfer Case	Classic Differential	Simplified Bevel	Diff. Concept 1	Diff. Concept 2	Diff. Concept 3
Weight	0	-	0	+	-	-
Approximate Width	0	-	+	+	0	0
Approximate Height	0	-	+	+	0	0
Approximate Length	0	-	+	+	0	0
Efficiency	0	+	+	-	-	-
Reduction Capable	0	+	+	+	+	+
Thermal E. Generation	0	0	0	-	-	-
Audible Volume	0	0	0	-	-	-
Maintenance	0	-	0	0	0	0
TOTALS						
Positives	0	2	5	5	1	1
Negatives	0	5	0	3	4	4
Final:	0%	-33%	56%	22%	-33%	-33%

The top two designs were the simplified bevel system and unique differential concept. These scored well based on the benchmarked classic transfer case system due to their reduced weight and compact sizes. They also require just as little maintenance as a normal transfer case setup, whereas most design concepts either were not spatial viable or too complicated to maintain.

Table 7. Speed Reducer Decision Matrix

Speed Reducer Decision Matrix					
Criteria	**Weight**	**Concept**			
		Spur Gear		Timing Belt	
		score	total	score	total
Weight	33	3	90	5	150
Approximate Width	6	3	21	2	14
Approximate Height	3	3	15	2	10
Approximate Length	10	4	40	3	30
Efficiency	20	3	75	4	100
2-stage reduction capable	15	4	40	4	40
Thermal E. Generation	7	3	21	2	14
Audible Volume	1	1	1	3	3
Maintenance	5	2	10	2	10
TOTALS	100		313		371

The decision matrices compared the top two designs for speed reducers and transfer cases. As the design criteria suggests, weight and spatial dimensions are very heavily considered for the project's application. Thus, the timing belt system was selected for its superior light-weight design. It also performed well in the transmission efficiency category, as the grooved belt and pulley design allows it to behave similarly to a spur gear reducer. Full breakout of weighted criteria scores can be found in **Table 7**.

Table 8. Transfer Case Decision Matrix

Transfer Case Decision Matrix					
Criteria	**Weight**	**Concept**			
		Simplified Bevel		**Diff.Concept 1**	
		score	total	score	total
Weight	30	3	90	4	120
Approximate Width	7	2	14	2	14
Approximate Height	5	3	15	2	10
Approximate Length	10	5	50	3	30
Efficiency	25	5	125	3	75
Reduction Capable	10	3	30	4	40
Thermal E. Generation	7	4	28	1	7
Audible Volume	1	3	3	2	2
Maintenance	5	4	20	3	15
TOTALS	100		375		313

The final decision matrix describes the transfer case selection given the top two design concepts of the corresponding Pugh Chart. As with the speed reducer selection, considerable criteria include the weight, transmission efficiency, and size dimensions of the subsystem. The simplified bevel drive will be the final transfer case because of its high efficiency and low size requirements.

7 DESIGNS SELECTED – First Semester (FRAME)

The design selection process for the frame is unconventional; a conventional D4P design process approach does not apply very well to the process needed to design a frame compatible with all other subsystems. This section outlines some of the desired criteria and selection procedures, but also explains why many decisions manifested by the criteria were unable to be applied in later and final designs.

7.1 Technical Selection Criteria

The design selection process for the frame is incorporated into the actual frame design process. The only time the frame design was selected upon occurred during the start of the design process. This initial design was made to closely mirror that of last year's frame while altering minor features and fixing prior issues. These features are detailed in section 5.4 and their advantages/disadvantages were discussed upon in frame sub team meetings to determine an optimal choice. The rational and quantifiable criteria incorporated in these discussions are detailed in the frame decision matrix (**Table 10.**) and frame Pugh chart (**Table 9.**) The criteria in these matrices were largely developed through benchmarking.

7.2 Rationale for Design Selection

The frame sub team has already decided on and fully designed the frame for this year in SolidWorks. The team is currently in the process of obtaining quotes for the coping and bending of the structural members. The team desires the frame to be made in fabrication shops with laser notching and CNC bending capabilities. The top two designs be the last (**Figure 47.**) and second to last (**Figure 48.**) iterations in the frame design process. Pugh chart and decision matrix results (**Table 9.** and **Table 10**.) were initially implemented at the start of the design process, but almost immediately scraped due to the nature of the frame design process. Since the frame must interact with and connect all other sub team systems, a majority of the previously made decisions were overridden by spatial and mounting needs of the other subsystems. This in conjunction with the rulebook forced the frame into its final form through constraints rather than decisions. The only design goal of the frame team quickly became a game of creating the smallest profile frame possible allowed by the rules and sub teams. This simply involved decreasing member lengths as the frame geometry and shape were locked in by the restrictions.

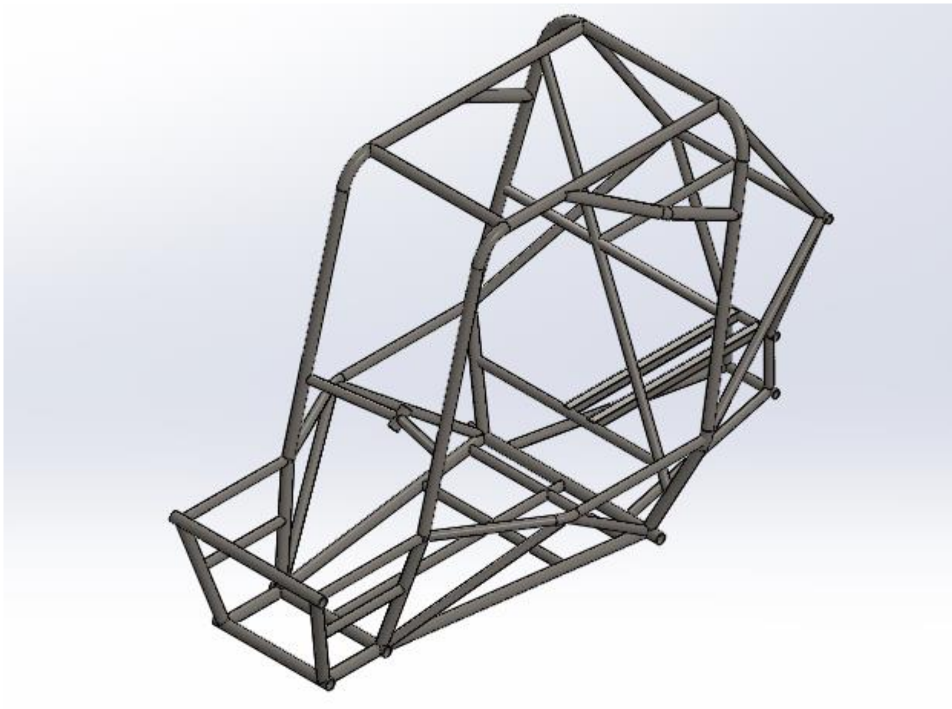


Figure 47. Final Frame Design V2.1

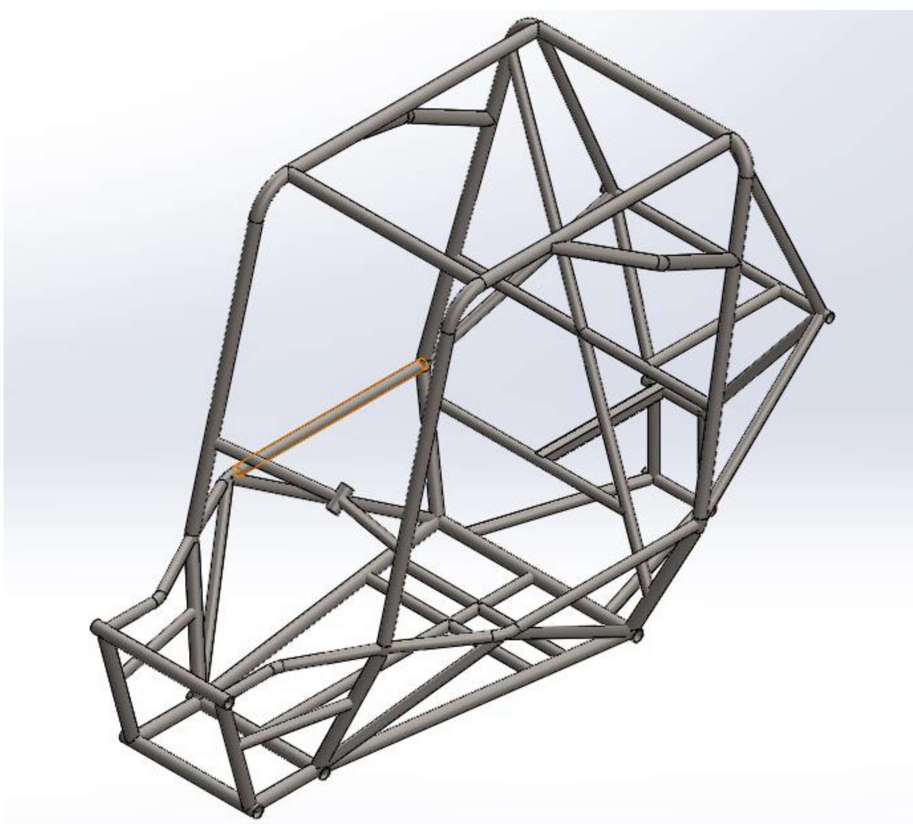


Figure 48. Frame Design V1.7

Table 9. Decision Matrix

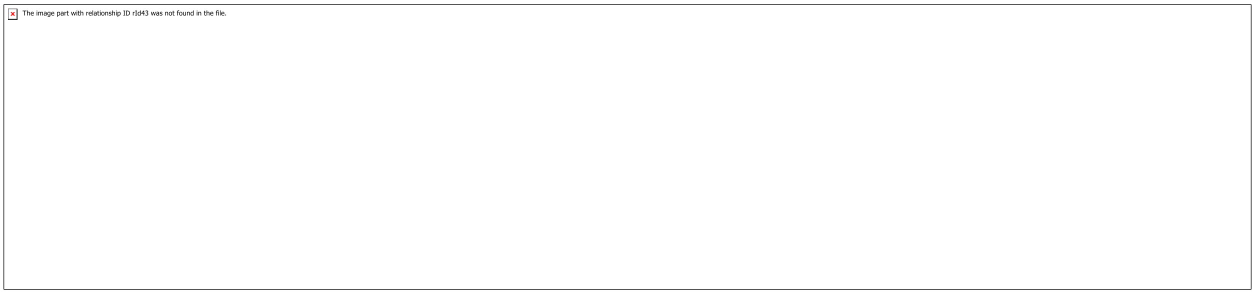
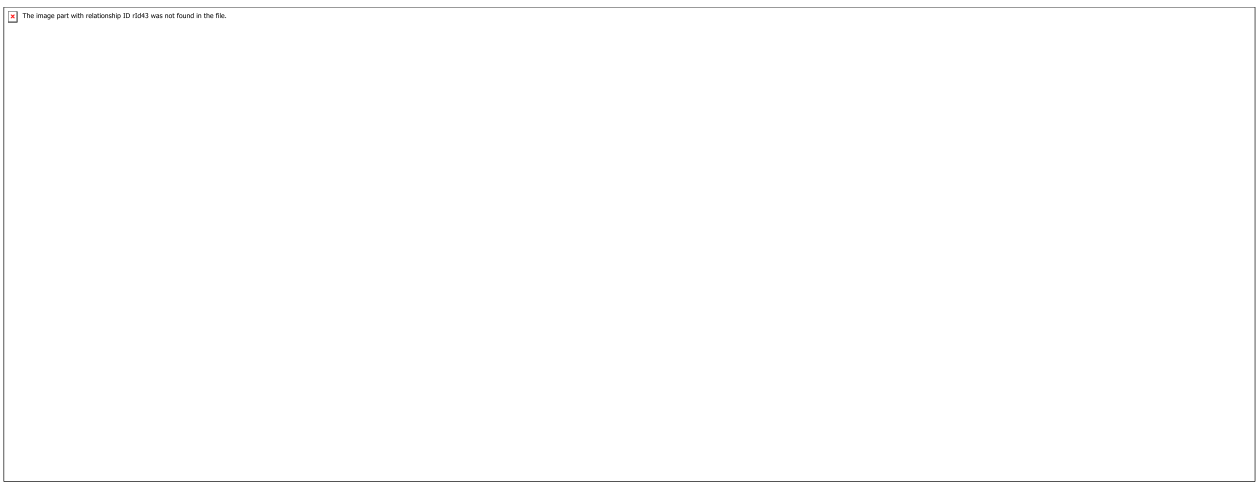


Table 10. Pugh Chart



Justification of the resulting design mostly involved thoroughly checking every individual member with any and all rules that could possibly dictate the dimensions of that member. Material justifications were presented in the form of bending and torsional stiffness calculations (**Table 11.**) and tubular profile dimensions.

Table 11. Frame Material Calculations

	Required Tubing by Rules	Our Proposed Primary Tubing		Our Proposed Secondary Tubing
material	1018 steel	4130 steel		4130 steel
OD (in)	1	1.25		1
Wall thickness (in)	0.12	0.065		0.035
carbon content (%)	0.18	0.3		0.3
E (kpsi)	29700	29700		29700
I (in^4)	0.032710765	0.042602298		0.012367468
k_b (klb * in^2)	971.5097313	1265.288253	293.7785	367.3138007
S_y (kpsi)	52.9388	63.1		63.1
c (in)	0.5	0.625		0.5
S_b (klb*in)	3.463337331	4.301128015	0.837791	1.560774466
density (lb/in^3)	0.284	0.284		0.284
weight per foot (lb)	1.130611444	0.824671841	-0.30594	0.361613651

Another method used to justify our frame design was finite element analysis (FEA). For this method, we used the SolidWorks Simulation add-on. This allowed us to model the frame under different loading scenarios. For the purposes of designing a reliable frame, we overestimated the forces that were applied in the simulation. We used four different forces in different combinations. These forces include the driver weight estimated at 1000N, side impact forces at 1500N and a top front and top rear impact force both applied at 3000N. Fixed points were placed at locations where the suspension will be supporting the frame. We simulated nine scenarios for our preliminary testing. The first scenario is just the driver weight applied downward. This was to get a baseline to gauge the severity of the other applied forces. For the other three forces, each one was tested by itself and with the driver weight applied. Lastly the two top impact forces were applied simultaneously with and without the driver weight. In the scenarios with a top impact and the driver weight, the driver weight was directed upwards simulating a roll over situation. For each scenario, the factor of safety (FOS) was tracked. In **Figure 49.** the FOS for scenario 5 is shown because it had the lowest FOS of all the scenarios at 1.65. This scenario involved the top front impact with the inverted driver weight. The minimum FOS was at a point on the side of the roll hoop where the additional bracing connects from the roll hoop overhead members.

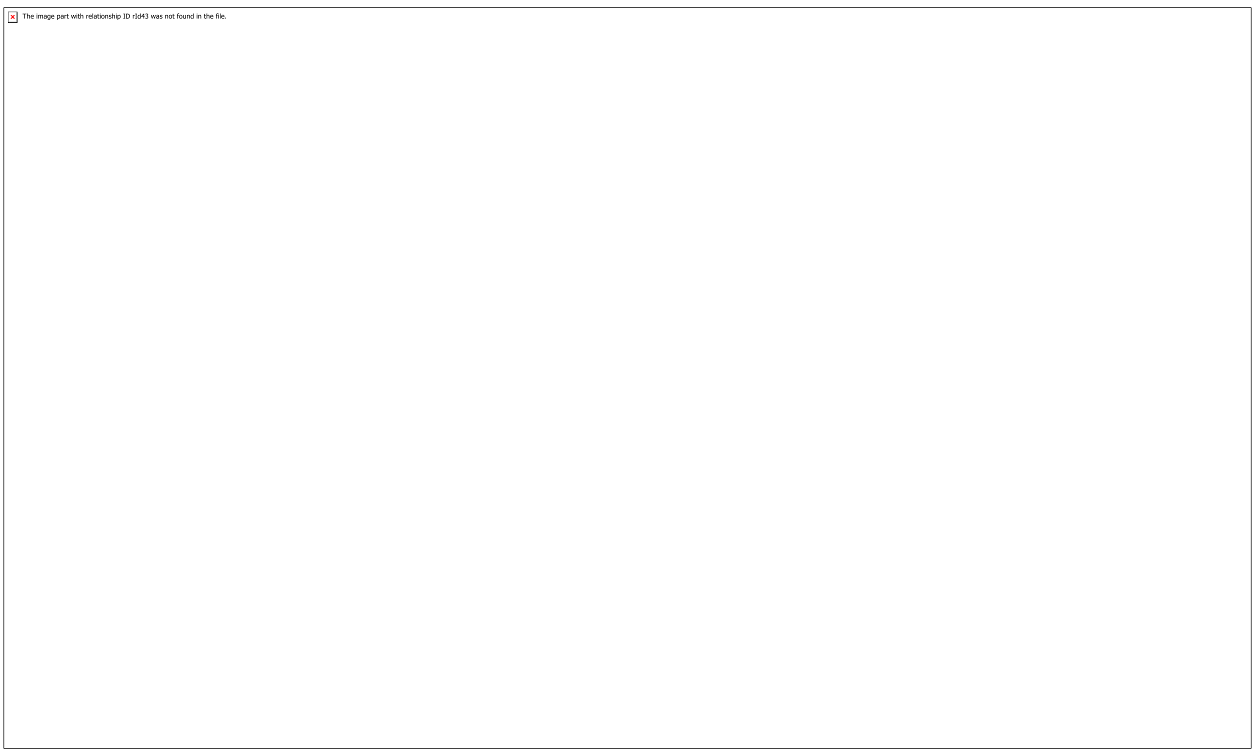


Figure 49. Frame FEA Analysis

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9 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report. These can contain engineering calculations, engineering drawings, bills of materials, current system analyses, and surveys or questionnaires. Letter the Appendices and provide descriptive titles. For example: Appendix A-House of Quality, Appendix B- Budget Analysis, etc.]

9.1 Appendix A: Descriptive Title

9.2 Appendix B: Descriptive Title