Final Proposal

19F08 – SAE Baja FR&DT

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DISCLAIMER

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EXECUTIVE SUMMARY

Every year SAE runs a collegiate competition program that tests engineering students of their full engineering design evaluation and fabrication skills. This year Northern Arizona University's mechanical engineering department has formed a team of 12 dedicated students to compete in this competition. They call themselves the Lumberjack Motorsports Team. The competition will be held in Tucson Arizona in April of 2020. The task is to design a Baja vehicle that can run in many different tests, both dynamic and static. These include suspension tests, hill climb, four-hour endurance race and many more. This year they are rewarding an extra 15% to the overall score if they can successfully show up with a four-wheel drive system. previous years only required two-wheel drive. The Lumberjack Motorsports Team has decided to go for the four-wheel drive system this year. There is a set of strict rules the Baja must follow to be able to pass tech inspection at the competition. With that in mind, the lumberjack motorsports team has been rigorously designing subcomponents for the last two months. These subsystems include the frame, drivetrain front suspension, and rear suspension. This report focuses only on the frame and drivetrain components.

The frame is a major part of the entire Baja vehicle. It connects and holds every other component together while also allowing the driver to operate the vehicle safely. The safety of the driver is held paramount in this project and thus abides by the most rules in the entire Baja. There are many members in the frame that are mandated by length, bend profiles joint types and more. The frame is mostly finalized and almost ready for fabrication. The frame will be built using 4130 steel tubing of various diameters and wall thicknesses. Along with the tubing, many different mounts and brackets will be added to connect with the other subcomponents. Extensive design and analysis have taken place on the frame to work in the final adjustments.

For the engine, we are required to use a Brigs and Stratton 10 hp motor. This is mandated by the rules to attempt to level the playing field for all the competing teams. After the motor however is fairly loos in terms of restrictions on further power transmittance to the wheels. They have decided to go with an electronic continuously varying transmission, also known as an ECVT. This system involves two sets of adjustable cone plates that have a v-belt running in between them. By adjusting these cone plates, you can effectively run through different gear ratios between the engine and the later driveline components. These plates are controlled with a stepper motor that will be controlled with an Arduino system. a simple user interface will be displayed on a screen in the cockpit of the Baja that will allow the driver to select effective gears, terrain type or just put it in automatic mode.

After the ECVT, further gear reduction is still needed to be able to be have appropriate speeds and torque in the competition. this is where a gear reducer comes in handy. Originally they were going to use a belt reducer type setup but after some analysis decided to go with a spur gear reduction box. The belt system was to heavy and required a lot of space. The cases for the gear box will be machined out of aluminum in house. Additional analysis will be required to select an oil grade.

Finally, for the drivetrain, we will use differentials to further reduce the speed and direct the power outwards. Differentials were initially going to be designed and fabricated in house. This proved to be too much design work and they decided to buy off the shelf differentials from a Yamaha Rhino 660. This is both front and differentials. These differentials only vary in that the front differential is electronically unlockable while the rear one is always locked. This works perfect for our application and can be trusted to operate as they are intended. They have already ordered and received the differentials since they are one of the early parts to be finalized.

Throughout this report, the team demonstrates their design, analysis and evaluation that they are undergoing. It starts with the engineering requirements that are set by the rulebook and ends with selected designs. Many steps are taken in between to ensure quality engineering practices and work are being carried out.

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1 BACKGROUND

1.1 Introduction

The Baja Society of Automotive Engineers (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 environment. 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]**

The benefits of competing in the Baja SAE competition go far beyond the trophies and recognition given to top performing teams. The learning experience gained from participating in this form of difficult and restrictive design challenge will reinforce the fundamentals of the design process. Participants will also encounter unforeseen design challenges that are often unique to a certain situation. These roadblocks will begin to craft a custom knowledge bank that will serve the engineering student in the future when encountering similar situations. The competitions are also a great location to meet with recruiters and representative of various companies associated with SAE. Recruiters at SAE competitions will often place a higher level of interest on the competition participants as they are shown to not only be able to complete a rigorous engineering curriculum, but also apply their knowledge to design, and fabricate a robust design capable of undergoing rigorous trials. Lastly NAU's future teams will benefit from the lesson's and experiences of this year's Baja SAE team.

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.

1.2 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 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.

2.1 Customer Requirements (CRs)

The generated customer requirements for this project were weighted on a 3, 6, 9, scale. This scale is used to symbolize the large importance difference between requirements, with each weight being greater than the former by a value of 3. For this application the base weight (3) is never applied to any customer requirements. This is meant to signify the heightened importance of all the requirements.

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 budget it cannot be made and building the vehicle is an absolute must giving this requirement the maximum weight. A list of all customer requirements and their respective weights can be seen in **Table 1.**

Table 1. Customer Requirements

No.	Customer Requirment	Weight
1	Reliability	9
2	Durability	9
3	Low Weight	6
4	Withstand Impact	9
5	Ergonomic Cockpit	6
6	High Torque Output	6
7	High Power Output	6
8	Operational Safety	6
9	Cost Within Budget	9

2.2 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.

Tolerances were generated from benchmarking values, rule specifications and supplier specifications. Bending stiffness, torsional stiffness, and egress time all have inequality tolerances specified by the rulebook. The values for bending and torsional stiffnesses are calculated using the minimum tubing profiles given in the rulebook. These profiles are under the material type engineering requirement. The tolerances for the tubing profiles are not detailed in the rules, but any tubing used in structural elements must be detailed in a material properties packet that confirm the profile meets the rules. For this reason, the tolerance for tubing profiles will be per the supplier's tolerance range. Thus, the tolerance of (+/-) 0.005" was acquired from the supplier's website. **[3]** Center of mass and weight tolerances were generated from benchmarking. The tolerances are listed as inequalities that present a limit that top performing cars in the benchmarking data did not exceed. The effective gear ratio does not have a tolerance. The listed gear ratio is a target gear ratio that will be exactly met. Gear ratios are generated by the number of teeth on the pinion and drive gear. Because the ratio is created by a counted number and not a measured value, it does not have a tolerance. Any attempt to apply a tolerance to a target gear ratio would be nonsensical. The last tolerance for expense is clear to understand seeing as the team started with an initial donation of $6,000 and can fundraise an unlimited additional amount. A list of all engineering requirements and their respective units/tolerances can be seen in **Table 2.**

Table 2. Engineering Requirements

No.	Engineering Requirment	Value	Units	Tolerance
1	Bending Stiffness	2620	Nm^2	greater than
2	Torsional Stiffness	374	Nm	greater than
3	Material Type	1018 Steel Tubing 0.984 X 0.118 (Primary)	in	(+ or -) 0.005"
		Steel Tubing 1.00 X 0.035 (Secondary)	in	(+ or -) 0.005"
4	Egress Time	5	seconds	less than or equal to
5	Effective Gear Ratio	2.24:1	speed reduction	NaN (gear ratios are exact values)
6	Low Center Mass	20	in	less than
7	Expense	6000	dollars	(+ funraised amount) (- 0)
8	Weight	600	lbs	less than

2.3 Functional Decomposition

2.3.1 Drive train

The drivetrain system has expanded on the black box model and functional model. After some design changes of the processes involved and finalizing designs, a more detailed version of these are available. The main function for the drivetrain is to provide power to the wheels. This energy mainly comes from gasoline as an input. A better understanding of black box models has led to corrections and elaborations on the inputs and outputs as compared to the preliminary report model.

2.3.1.1 Black Box Model

The black box model for drivetrain is shown in **Figure 1.** The inputs include the four main components of the drivetrain for materials: the engine, the differentials, the gear reducer, and the CVT system. Energy inputs are electric batteries and gasoline while transmission control and on/off are signals. These are sent into our black box and this results in outputs of exhaust as a material, useable rotational energy, heat and vibration as energies, and gear position as an output signal to the driver.

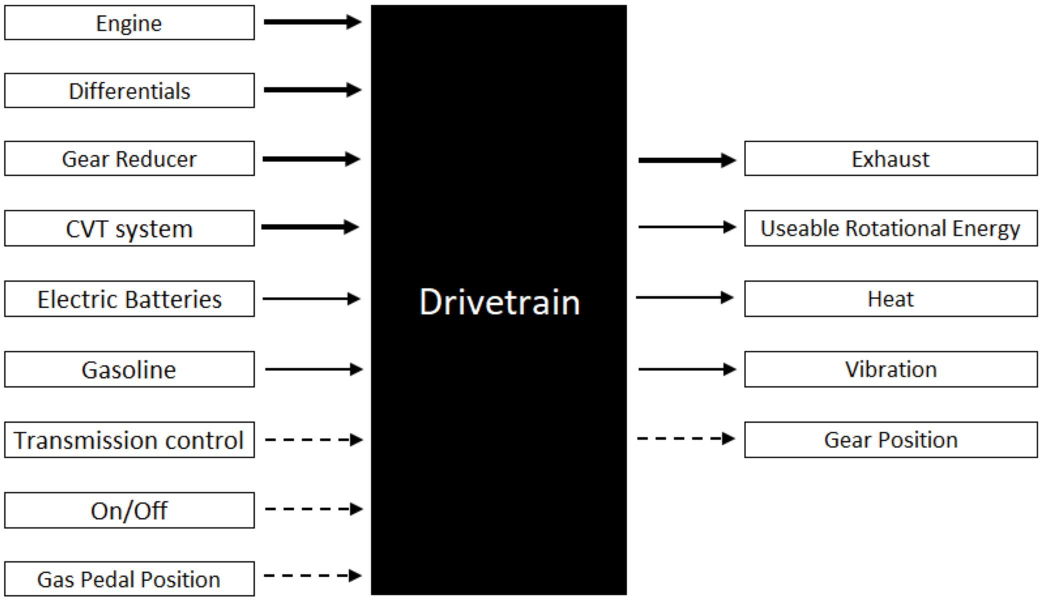

Figure 1. Black Box Model of Drivetrain System

This model helps to clarify the purpose of the drivetrain system. As we designed components for the drivetrain, we were reminded of the overall purpose of the entire system. This helped to keep designs simple and not overly complicated. Gasoline could have been considered a material but because it is essentially the energy source for the non-electrical components, it was considered an energy.

2.3.1.2 Functional Model

The overall function of the drivetrain is to produce useable rotational energy. However, this process is comprised of many different sub-processes. The functional model seen in **Figure 2.** demonstrates these steps. Each input is sent through one of the many processes and through the progression and interaction of these processes will result in all the outputs from the black box model. Some of these outputs, such as exhaust, heat and vibrations, are unintended but inevitable outcomes of some of the processes. The useable rotational energy is the primary outcome while the gear position is more used for informing the driver of the CVT state.

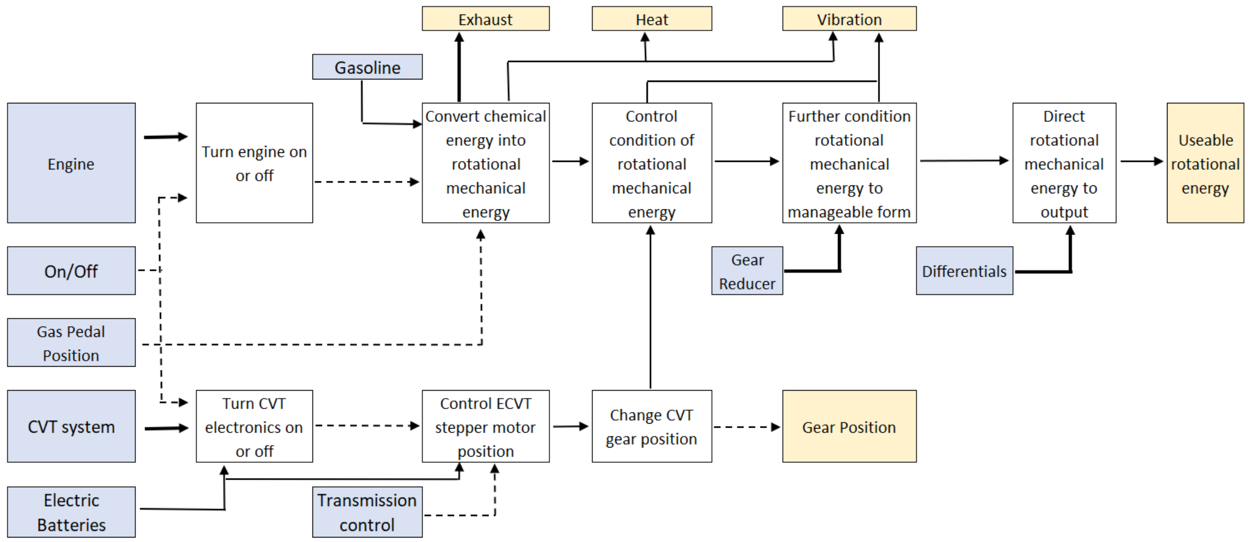

Figure 2. Functional Decomposition of Drivetrain System

This decomposition of the processes helps to identify exactly what each subcomponent should be doing in terms of the supplied inputs and the desired outputs. This kept our systems as simple as possible while achieving their function efficiently.

2.3.2 Frame

For the frames black box model and functional model, nothing has changed. The frame team had completed early variations of a complete frame early in the semester. The only changes have been made to accommodate the other sub-team components but functionally has remained the same. The same black box model and functional model are presented below. The frames overall function is to handle various forces in different ways. The force management results in keeping the Baja together and keeping the driver safe. The frame is a single static part which results in a relatively small functional model.

2.3.2.1 Black Box Model

For the frame, the black box model (**Figure 3.**) 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.

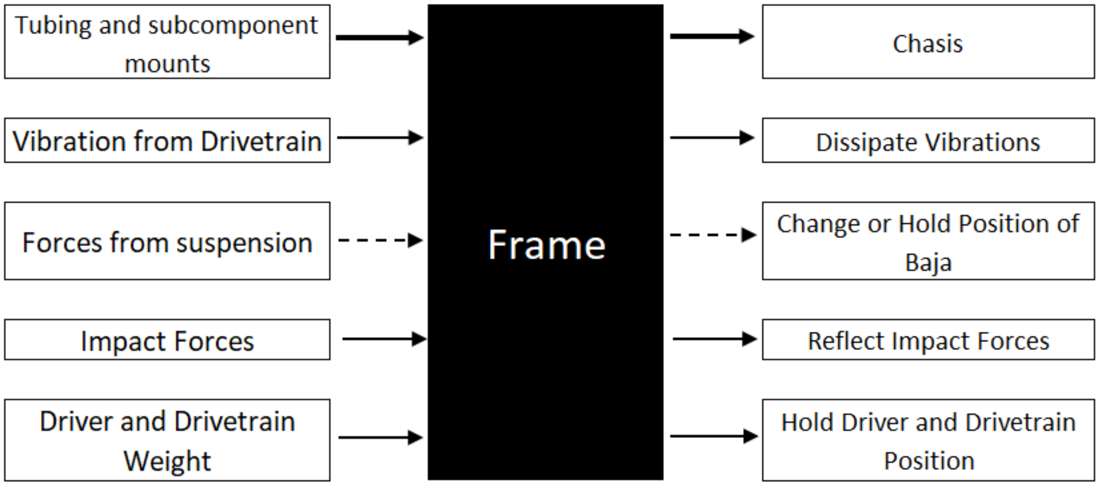

Figure 3. Frame Black Box Model

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.

2.3.2.2 Functional Model

For the frame, we decided to go with a functional decomposition model shown in **Figure 4.** 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.

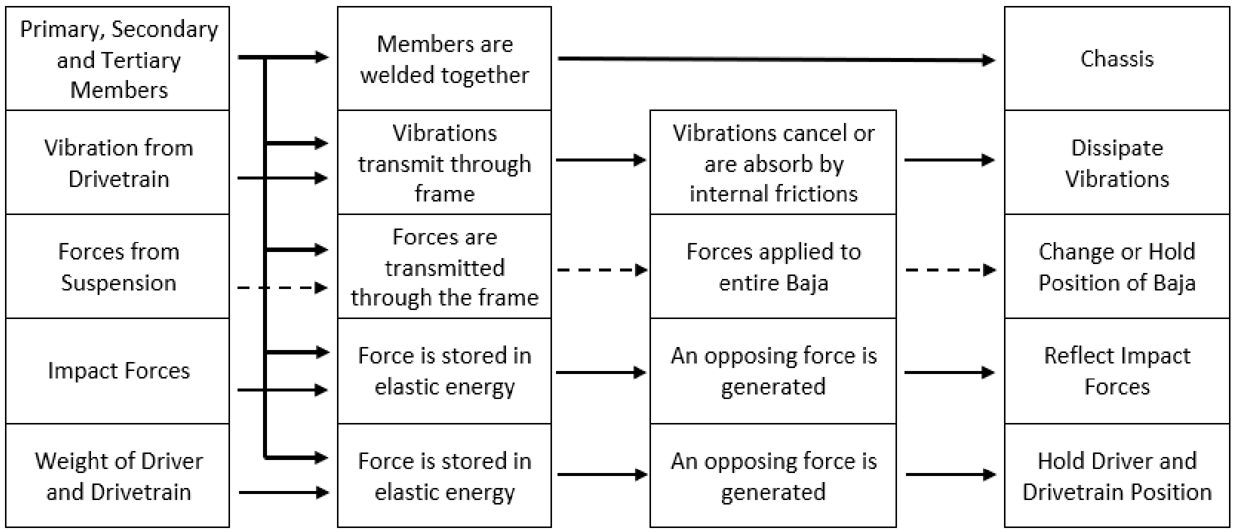

Figure 4. Frame Functional Decomposition Model

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.

2.4 House of Quality (HoQ)

The House of Quality (**Table 3.**) 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 3. 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

The engineering requirements will be tested using four procedures. A torsion test will analyze the frame material's strength and stiffness, which will determine the size and weight of the tubing used. A cost analysis of individual subcomponents will be used to determine the viability of reusing parts from previous years. A gear ratio test at the ECVT will determine the optimal ratio for power and torque outputs of the drivetrain system. A dimensional test will determine the minimum volumetric requirements of the drivetrain subcomponents to minimize the frame volume. Each testing procedure will be discussed further in Section 3 or this report.

2.4.1 Standards, Codes, and Regulations

Due to the vast number of materials used to build a mini Baja buggy, there are at least thirteen standards/codes/regulations that directly apply to this project. The table below (**Table 4.**) provides the title of each standard as well as a brief description of its correlation to our project. The upcoming Individual Analysis assignment for this class will likely increase the number of standards being referenced

Table 4. Standards of Practice as Applied to this Project

Standard Number or Code	Title of Standard	How it applies to Project
IFI 2018	Industrial Fasteners Institute Book of Fastener Standards	Compilation of the most common used English unit fasteners for all sub-systems

ANSI/AGMA 2001-D04 & 2101-D04	American Gear Manufacturers Association	Spur gears being used for gearbox this year are designed and analyzed using AGMA standards.
AISI 4130	American Iron and Steel Institute	Frame material properties are based on AISI standards
ANSI H35.2-2017	Aluminum Mill Products	Helps in wall thickness determination for aluminum gear casing
AWS D1.4/D1.4M:2018	American Welding Society Structural Welding Code	All frame welding is performed in house and includes welding of 4130 steel and 6061 aluminum
AA	Aluminum Design Manual	Proper feed rates for aluminum milling and turning operations found here
ASME Y14.5-2009	Dimensioning and Tolerancing	All part drawings for the buggy reference GD&T to ensure proper design interpretation from the machinist
ASTM	American Society of Testing and Materials	Minimum ASTM material properties are used in excel calculations
ABMA 9:2015	American Bearing Manufacturers Association	Load ratings and fatigue life for ball bearings being used in rear gearbox
IEEE	Institute of Electrical and Electronics Engineers	All citations are in IEEE format
ISO 9001:2008	International Organization for Standardization	Relevant international standards that includes test methods, codes of practice, guideline standards, and management systems standards that can be used for all sub-systems
SAE Rulebook and J966_201911	Society of Automotive Engineers Rulebook/Test Procedure for Measuring Car Tire Revolutions Per Mile	Entire buggy must be built within limits of the rulebook. Test procedure will help compare theoretical and realistic vehicle speeds
NIST	National Institute for Standards and Technology	Advanced manufacturing guidelines

3 Testing Procedures (TPs)

For the frame and drivetrain systems, various testing procedures were constructed to verify the engineering requirements were satisfied. Some of these requirements can be directly measured while others require a test procedure to verify the requirement. These tests include a frame torsional test, a cost analysis, an ECVT gear ratio test, and a drivetrain dimensions verification test.

3.1 Testing Procedure 1: Frame Torsional Rigidity Test

For the frame, a torsional rigidity test will be completed once the frame is fabricated. A torsional test is one of many widely accepted forms of vehicle chassis testing, especially in race applications. This test shows how stiff the frame is twisting front to back. While the frame deflection is more important for on road racing, the stresses that are calculated during Finite Element Analysis is going to be important information for our off-road application. This will be able to show that material ultimate strength and torsional stiffness engineering requirements are met. The Baja vehicle will be put into situations where the suspension is flexed in such a way to create the same stresses that a torsional rigidity test creates. We can initially perform FEA on the final frame design within SolidWorks and capture deflection and stress data. Then we can physically test for the same deflection amount to verify our FEA was correct. Then we can safely assume the stresses are also correct. Most of this will take place next semester

3.1.1 Testing Procedure 1: Objective

The FEA process will take place in SolidWorks. The simulation will attempt to model as close as possible to what can actually be done on the final frame. Once the frame is fully assembled, we will use the machine shop, building 98c, on campus as a workspace. The rear end of the frame will be mounted to one of the tables in the classroom. Using a metal rod to slide through one of the nose lateral members, one end of the rod will be placed on top of another table while the other end is free floating. From there, careful measurements will be taken to get a baseline for the untortured frame. These measurements include the angle of the nose and the angle of the rear end. A weight will be hung off the free end of the rod to provide the torque on the frame. The same measurements will be taken again to see the difference from the applied torque. These measurements will be compared to our FEA predictions.

3.1.2 Testing Procedure 1: Resources Required

For this procedure, we will require SolidWorks on a capable computer, the completed frame, frame mounting brackets for the rear end, a steel rod, some weights, tape measure, level and angle finder. Jacob Kelley from the frame team will perform the FEA on his home computer. The frame will be fully fabricated but will not have any other components attached. This is to be consistent across the FEA simulation and the real procedure. The frame mounting brackets will be fabricated and mounted to the table using clamps. The steel rod will have to be small enough to fit inside the lateral nose tube but still thick enough to be able to apply the required torque. Ideally, it will have to be as close in length as the width of our wheelbase. In the shop, there is already a steel bar that fits this profile. For the weights, simple workout weights can be used in conjunction with some rope to tie to the end of the rod. This procedure will require three to four people to lift the frame to be mounted and one or two people to make the measurements.

3.1.3 Testing Procedure 1: Schedule

The FEA has already been performed on the current frame model as seen in **Figure 5.** but will be performed again once the frame design is finalized. This will more than likely be in January next semester. The frame is planned to be mostly fabricated by the end of winter break. That means torsional testing can be completed soon after the FEA is finished. We aim to do this by the end of January. The mount fabrication and test procedure will likely take place on the same day one weekend.

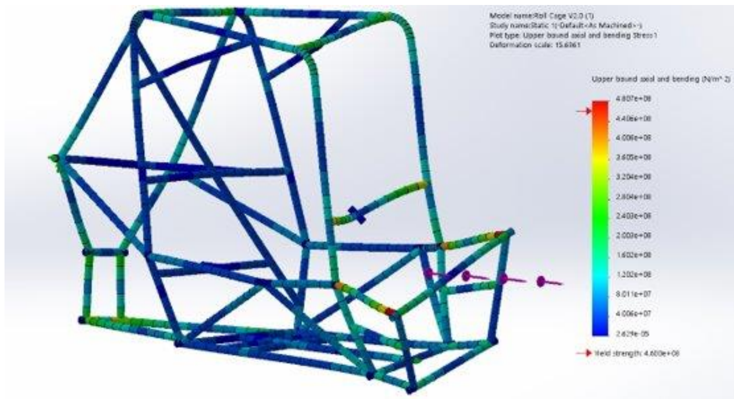

Figure 5. Frame Torsional Test FEA

3.2 Testing Procedure 2: Cost of Frame and Drivetrain

A test procedure will be run to test if the cost of the vehicles subsystems frame and drivetrain meet the expectations of the engineering requirement [6] will be tested by using baseline evaluation of subsystems versus previous years subsystem vehicles. After this test procedure is successfully run the team will have a better understanding of the cost required to build a competition read vehicle, while keeping the vehicle's subsystems cost lower than the previous year. Although this year the NAU SAE Baja Capstone team is preforming a complete overhaul of the drivetrain subsystem, the comparison will be based on existing drivetrain components. This procedure will include the cost breakdown of last year's gear reducer, continuously variable transmission (CVT) and frame. The schedule for this testing will be dependent on a finalized bill of material (BOM), and cost to manufacture. Based off the deliverables for the capstone class the testing will be able to start beginning of December.

3.2.1 Testing Procedure 2: Objective

The objective when running the test procedure is to understand the cost effectiveness of the different subcomponents of the vehicle baselined off last year's vehicle. This procedure is important for this year's team to run because with the information gathered the team will be able to find different manufacturers or different suppliers of material to help reduces the cost of the subcomponents.

First, the frame and drivetrain sub-teams will need a complete and finalized bill of material for the frame, electric continuously variable transmission (ECVT) and gear reducer. The challenging part for frame will be the finalization of the BOM and vendor for tube and tube bending services. The BOM will be challenging for frame because the changes from other sub-teams affects the design and supporting structures of the frame. After the three other sub-teams have finalized the designs, frame will be able to finalize the CAD model as well as the BOM. After the frame's BOM is finished the team will send their design to the vendor selected and given a quote.

The drivetrain, once final design of the subcomponents is finalized the bill of material can be made. This requires drivetrain to find quality parts while baselining prices off the previous year's BOM. This will allow the drivetrain to baseline while building the subsystem. The design of this year's vehicle is unique compared to last year's design based off the in-house manufacturability of the design of the ECVT. Last year ran an off the shelf CVT.

After drivetrain and frame have finalized the price of manufacturing and material, the sub-teams will run a cost analysis based off last year. This will be an in-depth analysis basing the cost of each component based off last year. While going through last year and this year's BOM the team will look for ways to lower the price of current components if possible. The team will keep in mind that the goal of the cost analysis is to lower the cost by at least 15%. The purpose of lowering the cost a minimum of 15% is to help increase the cost event score compared to last year. Last year the team scored a 15%.

Finally, once the in-depth cost analysis is completed, frame and drivetrain will report the findings to the entire team. The goal for the entire team is to lower the cost at least 20-25% overall. For this procedure this is an achievable goal, even with the extra challenge of making the system four-wheel-drive. The capstone team thinks this will be achievable since more of the parts are going to be bought and integrated into the vehicle rather than using raw material and manufacturing the components like last year did.

3.2.2 Testing Procedure 2: Resources Required

The cost analysis procedure will help the team provide an accurate cost comparison to last year's team with little outside resources. The outside resources that are required are the finalized CAD and BOM of last year's vehicle which has been handed down from the previous year's team. Once the current Baja buggy BOM and CAD are finalized the team will be able to do a direct cost comparison. This will require one engineer and at the minimum 6 engineering hours. This can be minimized using another engineer. One engineer from the sub-team drivetrain and another from frame to split the work up. No tools are needed for this analysis or faculty advisor, this will be student led and completed.

3.2.3 Testing Procedure 2: Schedule

The testing will begin at the beginning of December. For this testing to be completed the team must finish the BOM and CAD packages. This is necessary because of the analysis and baselining of cost with last year's Baja team. Depending on setbacks in frame vendor selection this may be completed over winter break or next semester. However, this will impact the schedule of the team ordering certain components necessary to finish the manufacturing of certain systems. This means the earlier the team can finish the BOM and CAD files the better performing the team's budget will be.

3.3 Testing Procedure 3: Electronic Continuously Variable Transmission Gear Ratio Test

This test procedure will cover the Electronic Continuously Variable Transmission's (ECVT) effective gear ratio. This will test the gear ratio at the closest together the two primary disks can go as well as the farthest apart the two primary disks can spread. This will allow the drivetrain sub-team better understand the gear range between the top end and low end of gears. Similarly, the effective gear ratios will be tested to understand at what axial distance is required for certain gear ratio such as a 4:1, 3:1, 2:1, and 1:1. With this information know this will help the team to better understand the process of shifting, torque outputs and different environments to use these ratios. This will help satisfy the engineering requirements 7,8, and 9, which are highest gear ratio, lowest gear ratio and effective gear ratio, respectively. This testing will take place after the ECVT is built. If the desired time to reach desired gear ratio is not achieve fast enough the drivetrain sub-team will be able to make small changes to achieve desired time to ratio required. This will take place early December which will allow for testing and tuning well before competition in mid-April.

3.3.1 Testing Procedure 3: Objective

The objective of the ECVT Gear Ratio Test is to help better understand and accurately tune the ECVT for optimal performance during competition. This will be specifically testing the electromechanical integration of components that make the ECVT system that changes the primary gear ratio which changes the desired output gear ratio. This will be achieved with the described test procedure below.
After the manufacturing of the ECVT is complete the drivetrain sub-team will start testing by first measuring the stroke length of ECVT Shaft. This will allow for a rough estimate of the four desired ratios as mentioned above. Once the stroke length of the shaft is found, the length will be divided into four different measurement which will correspond to the different ratios. After the measurements have been taken the ECVT till be mounted to the dynamometer and belt attached to the ECVT primary and gaged

secondary.
After mounting to the dynamometer and connecting the v-belt and gaged secondary CVT, the primary ECVT assembly will be slowly rotated on the engine shaft. While rotating the ECVT, the ECVT threaded actuator will be actuated to first the 4:1 ratio and then the primary will be turned to count the number of rotations of the gaged secondary CVT. If the ratio is actually a 4:1 ratio the location of the actuator will be note and the test will continue. This test will be repeated until the all the ratios have been measured.
After the initial location on the stroke have been verified the torque output will be tested as well as the full motion of gear ratios. This will require the ECVT to be connected to the engine and the engine turned on. Once the engine is turned on and is at idle speed, the ECVT will be turned through the gear ratios. The ratio at the high speed will not be able to be counted manually. Instead the team will use two hall effect sensors that measure the rotation of the engine. This will be hooked up to an Arduino and speed comparison will be viewed on the serial monitor and verified that the ratio even at speed will be correct. This will be tested for all gear ratio and timed to see the amount of time needed to shift through the specified gears. This test method will also be repeated at different engine RPMs until the engine is at maximum RPM.
The final testing that will be connected is the time it takes to change gear ratios from gear to gear and through the entire gear range. This is required to stay in competitive advantage with the gaged CVT ran previously on the last year's vehicle. If the time to change between the desired gear range is longer than the time for the gaged CVT to change gear, minor modification can be made to the ECVT adjust for faster gear selection. This can be done by changing out the six-inch-long threaded rod to a threaded rod with a more aggressive pitch than previously used.
Once testing is complete on the dynamometer the testing can be conducted on last year's vehicle with no medication necessary. Once the testing is complete the team will have a fully functional ECVT that has been properly tuned for the competition. In the next section, the complete list of required resources and personnel will be outlined.

3.3.2 Testing Procedure 3: Resources Required

For this test procedure to be executed the ECVT system must be complete. This includes the hardware and software for the ECVT. Once the ECVT hardware and software have been build and assembled the team can start testing. For the test the team will use the dynamometer in the machine shop. The Baja team will be working with the shop manager for the duration of the testing.

3.3.3 Testing Procedure 3: Schedule

The schedule of testing is dependent on the availability of the shop manager and the time required to manufacture the ECVT. After talking with the shop manager, the team has estimated 2 weeks to manufacture the ECVT and another week to receive parts and assemble. The testing will begin last week in November and will continue to through January on the dynamometer. After the dynamometer testing the ECVT can be added to last year's buggy which will allow for real world testing and tuning of the ECVT.

3.4 Testing Procedure 4: Drivetrain Dimensional Testing

This test procedure will help with drivetrain and frame better integrate the two sub-teams. Without proper fitment of drivetrain components in the frame the team will lose the competitive advantage because of the added weight due to the space added. This test procedure will help validate the engineering requirement [8] in the house of quality. This testing has begun with first measuring drivetrain components. The testing will be complete after before the manufacturing of the frame. This will help the team better adapt the final frame structure before the frame is built.

3.4.1 Testing Procedure 4: Objective

The first part of testing has already started mid-November and will continue until mid-December. This testing includes the measuring of the front and rear differentials, the reason differentials were purchased first before the finalization of the frame and other drivetrain components is because of the necessity of accurate measurements that were not available online or through the manufacture's website.
Now that the differentials have been accurately measured and mounting location and tabs added to the CAD module the frame can be adjusted to be as form fitting as possible to help cut down on weight. The next step of the testing procedure for the design of the drivetrain components is the finalization and dimensioning of the frame. Most of the design testing will be conducted in CAD rather than physical testing because it will help the team optimize the design rather than build and change designs.
After the finalized designs the frame sub-team will use the interference tool on SoildWorks to make sure that the movement of the components will not collide while moving. This will also be done through visual inspection of components in the CAD model.
After this design testing procedure is complete the start of manufacturing frame will start. This will help the SAE Baja team reduce weight and cost of the system.

3.4.2 Testing Procedure 4: Resources Required

For this test procedure to be completed the team will need to be able to access the CAD model final dimensions on all parts that will be directly mounted to the frame. This testing will also require all physical subcomponents to be dimensioned and entered in CAD. The testing of dimensions does not require any physical testing besides the measuring of the physical drivetrain components in house.

3.4.3 Testing Procedure 4: Schedule

This start of this test procedure is reliant on the final CAD packages of the individual sub-teams. Without the CAD packages the frame sub-team will not be able to do final tolerancing and interference checks. The schedule is set to start testing the beginning of December and through winter break if necessary. This will require one frame sub-team member to do a final check.

3.5 Testing Procedure 5: Frame Weight and Dimension measuring

To satisfy the engineering requirements of approximate size and material weight, we will conduct testing to measure the size and weight of the frame. This test will involve measuring the length of each member of the frame to verify it matches our designs. The frame will also be weighed on a scale. Since we are having our tube bending and notching outsourced, this will be important to verify that the parts we receive are correct to the design we have. The frame design theoretically already meets the engineering requirement, but we will need to verify the fabricated frame also meets these requirements.

3.5.1 Testing Procedure 5: Objective

The design process has already been underway for the frame within SolidWorks. The design meets the desired dimensions. The weight can also be evaluated within SolidWorks by selecting the material we will be using and going to mass properties. The objective is to get as low a weight as possible. Of course, since we are doing a four-wheel drive system this year, it will be very difficult to make it lighter than previous years Bajas. The weight evaluation will help us predict if our frame is close to what we want or too heavy.

3.5.2 Testing Procedure 5: Resources Required

When carrying out this procedure, we will have to have a scale that is capable of measuring up to 1000 lbs. and tape measures. Both of these items are already in the machine shop. Previous years Baja vehicles have weighed around 600 lbs. wet with the driver inside. The wet weight represents the weight of the vehicle with all the fluids and is generally regarded the maximum a vehicle can weigh without passengers and cargo. From previous Baja vehicle we know the weight of the frame to be about 65 lbs. This was our target in designing the frame and initially it was around 60 lbs., but with recent changes and the addition of many mounting brackets, we are closer to 65 lbs. which is still on target with last year. The extra weight will mostly come from the 4wd drivetrain

3.5.3 Testing Procedure 5: Schedule

This testing will have to be completed after the frame is fully fabricated. The frame dimension measuring will take the longest since there are so many measurements while the weight measurement will be fairly quick. This can be done in a single day in the workshop.

4 Risk Analysis and Mitigation

For our mini team, we performed a risk analysis and mitigation using a Failure Modes and Effects Analysis table. We identified at least 10 failure modes for all four of our subcomponents. All 40 failure modes can be seen in **Appendix A**, **Table A.** We have selected the top 10 failure modes based on the Risk Potential Number (RPN) to talk about in the sections bellow. A table showing the top 10 can be seen in **Table 5.**

Table 5. Top 10 Failure Modes

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls	Detection (D)	RPN
Frame contain and protect driver while holding together all other subcomponents together	Fatigue failure	broken members leading to unfunctional parts of the frame or entire Baja	8	repeated high stress situation	7	Over design the frame	9	504
ECVT modulates and transmits power from the engine to the gear reducer	stepper motor overheating	ECVT would be stuck in gear	7	improper cooling	7	ensure proper cooling is designed	7	343
	electrical shortage	ECVT would be stuck in gear	6	improper soldering	6	use quality soldering techniques	9	324
	bearings overheat	bearings get stiff and cause high losses and potential jamming	7	improper lubrication	7	properly lube the bearings	7	343
Gear Reducer transfers power from ECVT to the front and rear differentials	Case Puncture	oil leaks and contamination of the gears causing overheating and grinding	8	rock hitting case	8	design protection around case	8	512
	overheat	gears loose proper temper and cause extra friction and potentially snap teeth	8	wrong or no oil	5	use correct oil	10	400
Differentials takes power from the gear reducer and splits it between the left and right tires	front case puncture	oil leaks and contamination of the gears causing overheating and grinding leading to loss of power in the front	8	rock hitting case	6	design protection around case	7	336
	rear case puncture	oil leaks and contamination of the gears causing overheating and grinding leading to loss of power in the rear	8	rock hitting case	7	design protection around case	7	392
	rear case dent	potentially leaks from seal and contacts internal parts leading to lockup in rear wheels	7	rock hitting case	6	design protection around case	8	336
	overheat	gears loose proper temper and cause extra friction and potentially snap teeth	8	wrong or no oil	5	use correct oil	10	400

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Frame Fatigue Failure

For the frame, one of the critical failure modes include member fatigue. Over the course of the Baja's life the frame will be put under repeated stresses. This can cause a member to fail from fatigue. If this occurs, a member or joint would break resulting in an improper functioning. This is generally considered to be a severe failure that affects the function of a chassis in the long term. For the purposes of our project we are not as concerned with the long-term life of the Baja as some of the other immediate concerns. This does not mean we have not designed to mitigate this failure, but we have not done as much research and analysis into the subject. To mitigate this form of failure, thicker tubing wall and stronger welds will reduce the risk of fatigue failure. The main reason this failure mode had a high RPN number from the FMEA table was because it was very difficult to detect before a fatigue failure would happen.

4.1.2 Potential Critical Failure 2: ECVT Stepper Motor Overheating

During the endurance leg of the April 2020 SAE Baja Competition the vehicle will be driving through different conditions for four hours with minimal down time while fueling the vehicle in the pits. The process of speeding up and slowing down will be assisted by the stepper motor which drives the movement of effective diameter on the ECVT. The stepper motor under load will generate heat as well as being close proximity to the engine will also heat the stepper motor. This can cause the stepper motor to fail due to the high temperatures the stepper motor will see. If the stepper motor fails, the movement of the effective disk diameter will stop, and the vehicle will be locked in the last gear selected before the stepper failed. This critical failure can be mitigated by using heat shielding around the stepper motor. This will allow the motor to be shielded from the engine's heat produced during the race. Another way to mitigate the excess heat is to have a small computer fan attached to the housing to help eliminate the buildup of heat.

4.1.3 Potential Critical Failure 3: Electrical Shortage.

An electrical short within the ECVT computer system is possible if a wire is pinched in a collision with an obstacle or another vehicle. Another cause of electrical shortage is heavy vibration the vehicle will experience during the competition. The effect of a shortage in an electrical connection within the computer would cause a catastrophic failure and my result in a fire or the vehicle to be rendered useless. To help mitigate the possibility of an electrical failure due to collision the installation of the wiring harness will be carefully and thoughtfully connected to the frame. It will be connected in a way where all wires are within the vehicles frame and away from any potential pinch points. To help mitigate the possibility of the vibration of the vehicle harness vibrating loose, all connections will be soldered. With the help of solder holding the connection onto the Arduino board the team will also use adhesive heat shrink for an added layer of protection on every electrical connection made.

4.1.4 Potential Critical Failure 4: CVT Bearings Overheat

During the endurance leg of the race at competition the ECVT will be running for 4 hours with minimal fuel breaks to refuel, but most of the time the engine will be turning between 1500-3800 RPM. The design of the ECVT uses a coupled shaft that has bearings inserted into the shaft that spin at the same rpm as the engine. The ball bearing will need to be able to withstand the 4 hours of continuous usage as well as the heat generated by the frictional forces and the engine. The potential of a bearing overheating and seizing up will cause a critical failure of the ECVT. To help mitigate the potential of the ECVT bearings from overheating and seizing the correct bearing design must be selected. Choosing the right bearing to withstand the engine temperature as well as the RPM is critical to the success of the ECVT.

4.1.5 Potential Critical Failure 5: Spur Gear Reducer Case Puncture

During the competition in April of 2020, the SAE buggy that is currently being designed will be challenged with crossing rock beds, climbing hills, and maneuvering through rough terrain. To minimize the mounting height of the driveshaft that will run through the cockpit for this year's four-wheel drive design, the team is mounting the two-to-one spur gear reducer as low as the rear differential input allows. With that said, the bottom of the spur gear reducer will be protruding an inch and three-quarters out from the bottom of the frame. Therefore, a substantial impact force from hitting a rock or bottoming-out on the terrain could result in critical failure number six: a punctured case. The depth of the puncture would determine the severity of this failure. A puncture that only penetrates the cases' wall would result in oil leakage and eventually gear failure but could be repaired at competition. However, if the puncture was deep enough to penetrate the gear teeth, it would result in immediate failure of the buggy and require a new gearbox. This failure will be mitigated to the best of the team's ability by fabricating a sloped gearbox guard using both steel and carbon fiber.

4.1.6 Potential Critical Failure 6: Spur Gear Reducer Overheats

The Arizona location of the 2020 SAE Baja competition will present a challenge this year. The competition will take place in Tucson, Arizona in mid-April, which means the environment temperature will be excessively high. When the vehicle runs for an extended time period such as a four-hour endurance race, friction generates between the spur gears. That presents the possibility of overheating the spur gear reducer. Heat generated in the gear reducer must dissipate to avoid excessive wear on the internal gears and bearings. This phenomenon is mitigated using gear oil in the casing to lubricate the gears and bearings. The strategy will also account for higher environmental temperatures at the cost of efficiency in heat diffusivity.

4.1.7 Potential Critical Failure 7: Front Differential Case Puncture

The front differential has the potential to be punctured by a rock that hits it at high speed. A punctured case would result in loss of differential fluid and possible jamming of the gears by fragments of the shattered case material. This would be a catastrophic failure that would result in immobility of the entire Baja. One way to mitigate this failure is to design a stronger case. In our case, we have decided to buy an off the shelf front differential that is plenty strong enough to handle this situation. The front differential will be encased in the nose of the Baja which is covered in body panels. This also greatly reduces the risk of this happening.

4.1.8 Potential Critical Failure 8: Rear Differential Case Puncture

Like the front differential, the rear differential has the potential to be punctured by a rock that hits it at high speed. A punctured case would result in loss of differential fluid and possible jamming of the gears by fragments of the shattered case material. This would be a catastrophic failure that would result in immobility of the entire Baja. One way to mitigate this failure is to design a stronger case. In our case, we have decided to buy an off the shelf rear differential that is plenty strong enough to handle this situation. The rear differential will be mounted in the rear cage section of the frame which is not covered by body panels. However, the likelihood of a rock being able to avoid hitting any component further forward on the Baja and then hit the rear differential is very low.

4.1.9 Potential Critical Failure 9: Differential Oil Contamination

The SAE competition is known for testing the capabilities of each school's design by implementing numerous terrain conditions such as mudholes, rock gardens, and wood stumps. The front and rear differentials both have vent tubes that allow the cases to breath as well as prevents excessive internal pressure buildup. These vents, if not properly placed, could result in oil contamination from the water/mud that inevitably gets on the buggy due to the tube's direct path into the casing. Oil contamination would result in excessive gear wear and eventually result in complete differential failure from worn gear teeth. Detection of oil contamination is low unless a CV axle is pulled to inspect the differential internals. This failure can be mitigated by extending the differential ventilation hoses towards the top of the frame and placing the tube within a secondary member to protect the inlet from potential contaminants.

4.1.10 Potential Critical Failure 10: Differentials Overheat

Similar to overheating a spur gear reducer, the front and rear differentials have the potential to generate heat in the internal bevel gear mesh. Friction between gears creates heat by cycling for long time periods. The differentials will cycle constantly whenever the driver operates the vehicle since they transfer rotational energy from the spur gear reducer to the wheels. Heat diffusion from the gears will be mitigated using gear oil in the differentials. This will lubricate the ring and pinion gear set to reduce friction.

4.2 Risks and Trade-offs Analysis

Critical failures 6-10 are all related to transmitting power to the wheels through gears. Any one of those critical failures that occurs may result in complete power transmission failure depending on the severity. As mentioned in the failure descriptions, ways to mitigate/reduce chance of gear case failures include adding additional support members and covers to sufficiently protect these components, or by increasing the wall thickness of the gearbox cases being used. However, implementing either one of these ideas results in an increase of overall weight and makes mitigating critical failure one (Frame Fatigue Failure) more difficult. The more weight that the frame must support, the higher the repeated stresses are and the more likely the frame will eventually fail. SAE rulebook uses their own standards and regulations for minimum frame requirements, therefore, critical failure one's risk is lower than failures 2-10 but still directly correlates to all subsystems within the buggy. This is due to SAE's notably high strength material requirement that the FEA analysis has proven it can withstand impact forces from all directions.

Critical failures 2-4 can result in complete drivetrain failure but are also independent from the other critical failures. Mitigating these failures have no adverse effects on any other drivetrain components because any necessary additions to the electronic control system will have no significant increase in weight. Although the Electronic Continuously Variable Transmission has more components subject to failure, the risks of using the ECVT are small because any critical failure of the ECVT can be easily bypassed by swapping it with a primary gauged CVT.

Do you need this?

5 DESIGN SELECTED – First Semester

The designs for both the frame and drivetrain subsystems are still undergoing changes. Recent revelations during a design meeting three weeks ago prompted the drivetrain subsystem to be radically altered upending progression plans, and other subsystem designs. This section will detail current designs, their calculations, and prototypes. Designs that are still unmade or undecided will be mentioned with sufficient information.

5.1 Design Description

5.1.1 Design Description (Frame)

The frame of the vehicle is a rear braced 4130 chromoly tubular steel structure consisting of three different tubular profiles. Calculation justification for the bending and torsional stiffness of the chosen primary material and profile can be seen in **Table 6.** The two other profiles are restricted only by profile, provided they are made from some form of steel and therefore do not require any calculation justification.

Table 6. Primary Frame Tubing Profile Calculations

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

The overall geometric pattern of the frame design has remained unaltered since the preliminary report. However, the frame continues to undergo length changes in certain sections to allow for previously unmodeled components. The frame design is still not solidified and is subject to change. More detailed information on why the frame design is currently in a state of limbo will be detailed in section **5.1.2.** The current state of the frame can be seen in **Figure 6.**

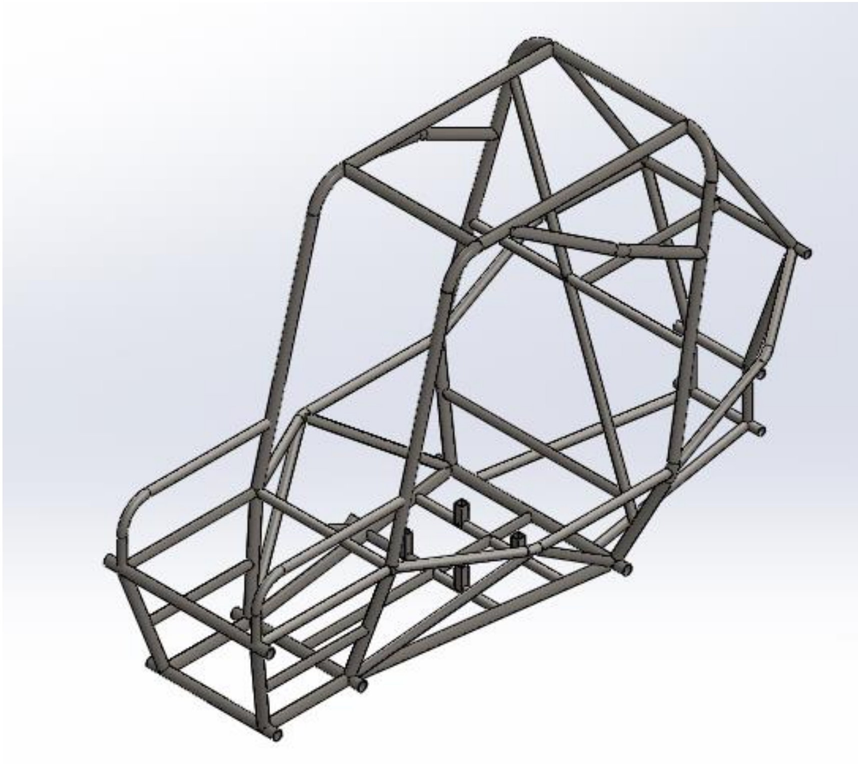

Figure 6. Frame Design V2.4

The frame prototype is a garden wire and hot glue structure made on a 4:1 scale. (**Figure 7.**) This prototype was built to satisfy the rubric requirements for the final presentation and served no purpose beyond existing as a visual prop. Prototypes of frames generally serve no purpose as they are static structures designed to withstand loads. Scale models of a frame could be used in scaled simulations of the frame under stress, but this type of testing would require time and resources outside of the team's ability. There was no learning at any point in construction or completion of this prototype. Necessary design changes to the frame had to be put on hold as the making of the prototype sapped roughly five hours of potential design time. No, changes to the frame were made as a result of the prototype.

Figure 7. Frame Prototype

5.1.2 Design Description (Drivetrain)

The drivetrain of the vehicle will utilize a 4WD system capable of powering all four wheels. The drivetrain will include all components of a classical 4WD system: engine, transmission, gear reduction, front/rear differentials, and driveshaft. Since the preliminary report the drivetrain has undergone a drastic change. After a design meeting where the feasibility of designing and fabricating custom differentials was analyzed the drivetrain sub team decided to change the design to utilize differentials from commercial off-roading vehicles. The cost and time reduction resulting from this decision is likely far less than if the existing design plan had proceeded.

As a result of the decision to use commercial differentials, many changes need to be made to the existing design. The most major change involves rotating the engine 90 degrees to direct the output shaft towards the firewall. This is due to the direction most commercial differentials accept shaft input. The differentials chosen are from a Yamaha Grizzly 660 ATV. The team has purchased and received a front and rear differential belonging to this model (**Figure 8.**) Other design changes include a new gear reducer/transfer case design. (**Figure 9.**) The ECVT (**Figure 10.**) thankfully did not require any major design changes outside of shortening its length. The frame was also slightly impacted by the shifted position of the engine requiring a reevaluation of the rear roll cage section. Calculations for the gear reducer and driveshaft can be seen in **Appendix B** and **Table 7.** respectively.

Figure 8. Yamaha Grizzly 660 Rear Differential

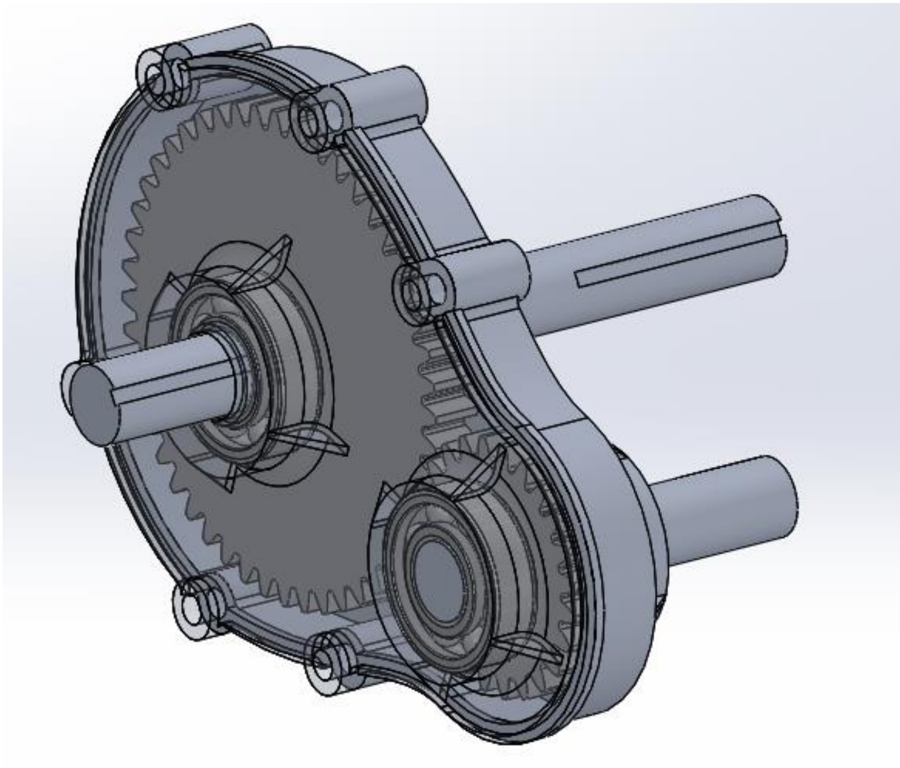

Figure 9. Gear Reducer Design

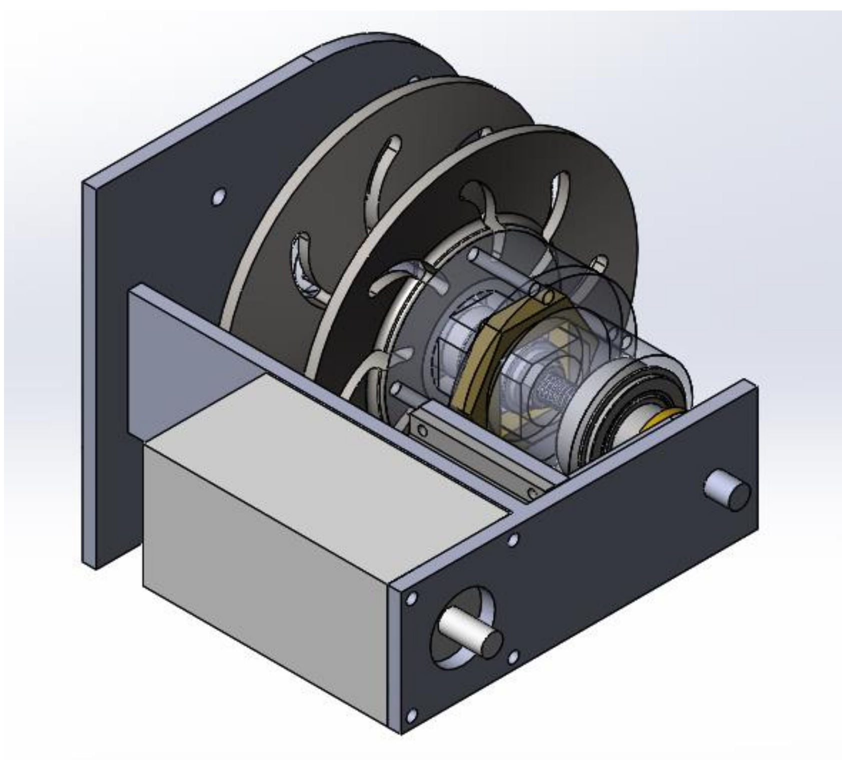

Figure 10. ECVT Design

Table 7. Driveshaft Shear Stress Calculations

T shaft (ft*lbs) (in*lbs)	2016	7200
D (in)	1	
d (in)	0.93	
R (in)	0.5	
J (in^4)	0.024735	
Stress (psi) (Mpa)	40752.08	280.9758
Yield Stress 4130 steel (psi) (Mpa)	63100	435
thickness (in)	0.035	
T motor (ft*lbs) (in*lbs)	14	168
Reduction	12	
T output (ft*lbs)	2016	
Weight/length (lb/1 in)	0.030028	
Density (4130 steel) (lb/in^3)	0.283	
cross sectional area (in^2)	0.106107	

Two of the most challenging issues created by this design change involve the height of the driveshaft, and ability to insert and remove the engine. Solutions to these issues are still being evaluated, but some insight into these dilemmas can be provided. Due to the size of the differentials and newly designed gear reducer the height of the driveshaft will be elevated. This will require the driver seat to raise in order to accommodate the driveshaft passing beneath it. Raising the height of the drive will make the vehicle's high center of gravity only higher and should be avoided if possible. This can be fixed by redesigning the gear reducer to incorporate an idler which would eliminate one size issue, but the size of the differentials will still severely restrict the ability to lower the drive shaft. Another solution is to lower the gear reducer and differentials below the frame. However, this will risk damaging the components if left unprotected. The components can be protected with additional frame material, but this will add weight to the design. The last solution is to simply leave the driveshaft at an elevated height and sacrifice a potentially lower center of gravity. The tradeoffs of these potential pathways forward are still being discussed.

The ability to insert and remove the engine is also an area needing special attention. The new position of engine and ECVT cause the two components to be sandwiched between the firewall and rear end of the frame. Assembly and maintenance of the vehicle will require these two components to be separated which is impossible when they are sandwiched together. The decided upon solution to this problem involves the creating of bolted frame members in the rear of the frame to allow the rear wall of the frame to be removed. This change can then be incorporated with a sliding engine mount allowing for smooth removal and insertion of the engine output shaft into the ECVT.

The drivetrain prototype is a 3D print and ball bearing assembly of the ECVT. (**Figure 11.**) The prototype was made on a 1:1 scale and was made primarily for tolerancing of the engine output shaft. It can be used as an accurate placeholder for the ECVT in the vehicle during the assembly process. No design changes or learning experiences resulted from this prototype.

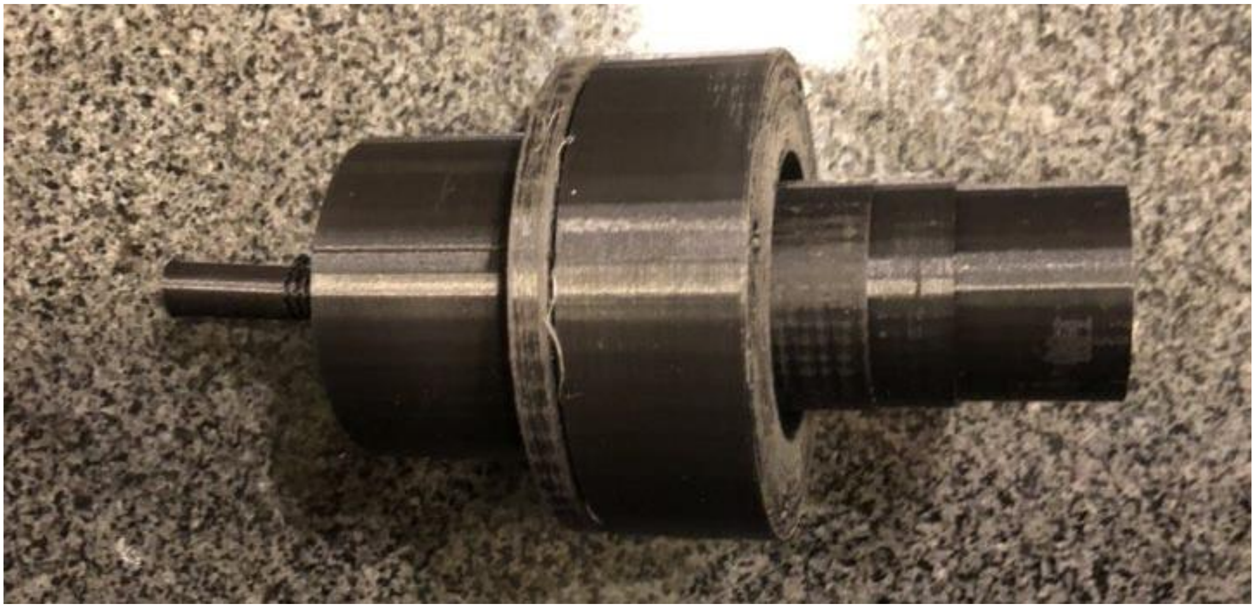

Figure 11. ECVT Prototype

5.2 Implementation Plan

The frame and drivetrain design systems shown in **Figure 12.** will be implemented in three phases: simulation, prototyping, and manufacture. Major resources include the NAU campus machine shop, sponsorship companies, and team fundraising. The total project budget is $4003.17 to complete the frame and drivetrain systems. A complete breakdown of the team's budget can be found in **Appendix C**. The estimated time for manufacture completion will be three months based on lead times for the team's sponsored partners.

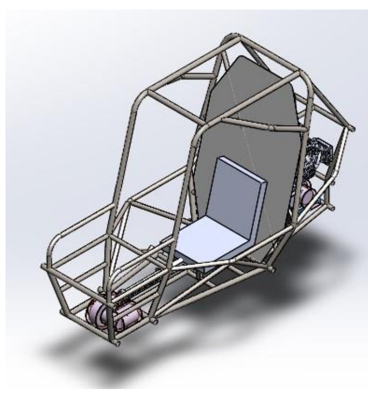

Figure 12. Frame and Drivetrain Full Assembly (Isometric View)

Simulation will consist of finite element analysis on the frame, spur gear reducer, and ECVT using SolidWorks. The frame will simulate torsional loads and impacts from multiple directions. The spur gear reducer will simulate bending loads on gear teeth, torsional loads generated by the rotational input and output shafts, and bearing loads generated by the input and output shafts. The ECVT will simulate the bending loads applied to the primary shaft by the tensioned v-belt.

Prototyping has already begun by modelling the frame to one fourth scale and comparing it to similarly scaled models of previous years' frames to grasp the spatial disparities between designs. The spur gear reducer (**Appendix D**, **Figure D2.**) has been 3D printed to model the volumetric constraints in relation to the engine, ECVT, and differentials. The ECVT input shaft, threaded rod, bearing actuator, and sheaves have been 3D printed to verify tolerancing requirements based on its mechanical counterpart. A full breakout of the ECVT is illustrated in **Appendix D**, **Figure D3**. The insights gained from prototyping subcomponents have improved the vehicle's subcomponent alignment to resemble the configuration displayed in **Figure 13.** and given rise to mounting locations for each system.

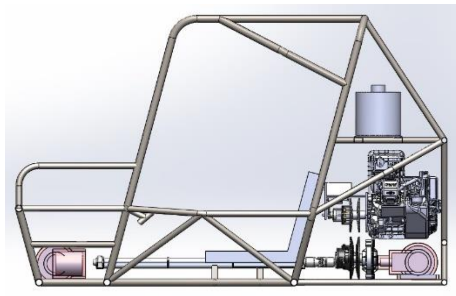

Figure 13. Frame and Drivetrain Full Assembly (Side View)

The manufacture phase will take place in the NAU campus machine shop. The frame member and driveshaft tube material, bending, and coping processes from VR3 Engineering will occur in December and the structure welding will take place in the machine shop during the first week of January. Material for the spur gears and casing and wire EDM processing will be donated from Ping Engineering **[4**] during December. Bearings will be bought from SKF **[5]**. Gearbox assembly will occur in the machine shop and be completed by the end of January. Differentials are bought from Amazon **[6]** and will require no manufacturing processes. ECVT mechanical elements will be built using excess machine shop material and machined in house, while electrical components will be bought from Amazon. ECVT wiring will take place in December and January to allow for ample testing time in February. The ECVT secondary pulley, gas tank and seat will be recycled from the 2018 SAE Baja team's vehicle.

6 CONCLUSIONS

This report compiles all information from the design process that the SAE Baja frame and drivetrain sub-teams have determined thus far. The critical requirements for this project are to design a fully functional, single seat, all-terrain vehicle within the limits of the SAE rulebook. All completed calculations that support our designs were determined using common engineering standards and codes to ensure credibility of the results from their analysis. Testing procedures, risk and trade-off analysis, and an implementation plan are all discussed within this report and provides a good idea of where the frame and drivetrain sub-teams currently stand. Designs for the drivetrain assembly have changed numerous times to accommodate for the first ever four-wheel drive NAU Baja design. However, the designs for the frame and drivetrain sub-teams are near finalization and ready to begin manufacturing. The final solution proposed in this report includes all frame members being coped and bended by outsourcing, an in-house machined ECVT assembly, in-house spur-reducer casing, and two ready-to-go Yamaha Rhino differentials. The full-assembly CAD proves that all components are contained within the buggy and there are no spatial interferences between them. This semester has proven to the frame and drivetrain sub-teams that the amount of time-commitment to the SAE Baja capstone project cannot be underestimated. Now that most all designs are nearing finalization, the team must remain fully committed to Baja to successfully manufacture/purchase all necessary components. The team is on an accelerated schedule and the manufacturing complexities cannot be overlooked.

7 REFERENCES

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[4] "Arizona Wire Specialists," Wire EDM http://azwireedm.com/

[5] "Self-Aligning Ball Bearings," SKF Bearings. Accessed November 14, 2019. Available: https://www.skf.com/us/products/bearings-units-housings/ball-bearings/self-aligning-ball-bearings/self-aligning-ball-bearings/index.html?designation=1205%20EKTN9&unit=imperialUnit

[6] "maXpeedingRods Complete Rear Differential for Yamaha Rhino 660," Amazon. Accessed November 15, 2019. Available: https://www.amazon.com/maXpeedingrods-Differential-Yamaha-2004-2013-Complete/dp/B07DJB4QCG

8 APPENDICES

8.1 Appendix A: Failure Mode and Effects Analysis

Table A. Full Failure Mode and Effects Analysis

Lumberjack Motorsports Baja Vehicle		Frame and Drivetrain Mini-Team				Page No 1 of 1			
Baja Vehicle						FMEA Number 2			
Frame and Drivetrain						Date: 11/14/2019			
Frame, ECVT, Gear Reducer, Differentials									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls	Detection (D)	RPN	Recommended Action
Frame contain and protect driver while holding together all other subcomponents together	Weld Failure	Members will become detached and frame will warp under normal loading. If any severe impact occurs, the frame will be severely damaged and endanger the driver or lead to accident.	9	High Stress Concentratio n	6	Design to distribute loads evenly, strong materials and welds	5	270	Design to distribute stresses
				Poor Welding	2	Quality control in the fabrication process, using a highly skilled welder	3	54	use a qualified welder
	Font End Impact	Nose could have bent member or completely collapse	7	Ramming into another vehicle	5	Avoid hitting another vehicle	3	105	Use a qualified driver
	Side Impact	SIMs bend	6	Rolling onto side	3	Drive carefully	4	72	Use a qualified driver
	Rear Impact	Rear cage bends or collapses	7	Another vehicle rear ends the Baja	5	don't slam on brakes while another vehicle is close behind	3	105	Use a qualified driver
	Roll Over	Bend in FBMs or RHO members	7	Taking a ramp incorrectly	5	power through any ramps, or take them slow	2	70	Use a qualified driver
				taking a turn to fast	7	slow down before curves	2	98	Use a qualified driver

	Torsion from Suspension	permanent deformation in the twist of the frame	4	The entire Baja balancing on two wheels	6	Design for the entire weight on two wheels	6	144	Stiffen the frame
	Frame Buckles in Hard Landing	Entire Baja is immobile and unable to function at all	10	Hard landing	1	Design for a heavy load and large FOS	1	10	nothing
	Bottom Impact from Rocks	Bent USMs	4	landing on a tall rock	7	Design frame to withstand this situation	7	196	nothing
	Fatigue failure	broken members leading to unfunctional parts of the frame or entire Baja	8	repeated high stress situation	7	Over design the frame	9	504	use quality materials
	Driveshaft Fails	no power to the front or potential lock up of the front	6	High torque on the driveshaft	2	use a stronger shaft than needed	4	48	perform testing on drive shaft
ECVT modulates and transmits power from the engine to the gear reducer	stepper motor overheating	ECVT would be stuck in gear	7	improper cooling	7	ensure proper cooling is designed	7	343	perform endurance type testing
	belt wear failure	power not transferred between ECVT and secondary	6	incorrect pulley alignment	3	align pulleys	6	108	nothing
	output shaft bends	further damage to gear reducer and high fatigue to secondary parts	8	high moment on shaft	1	properly mount drivetrain components	8	64	nothing
	input shaft bends	fatigue to ECVT parts	8	high moment on shaft	1	properly mount drivetrain components	8	64	nothing
	electrical shortage	ECVT would be stuck in gear	6	improper soldering	6	use quality soldering techniques	9	324	test connections
	programmi ng malfunctio n	ECVT would be stuck in gear	5	improper testing	5	test run many times in many scenarios	8	200	nothing
	actuation belt tear	ECVT and primary would be out of sync	7	high stress on belt	6	design for proper tension on belt	6	252	ensure specs are met
	secondary helix bends	Secondary would not properly grab the belt	7	high forces on secondary	3	properly install the cvt system	8	168	nothing

	secondary spring fails	Secondary would not grab the belt at all	7	spring over compresses	2	use correct spring	7	98	nothing
	bearings overheat	bearings get stiff and cause high losses and potential jamming	7	improper lubrication	7	properly lube the bearings	7	343	perform destructive testing on bearings
Gear Reducer transfers power from ECVT to the front and rear differentials	Case Puncture	oil leaks and contamination of the gears causing overheating and grinding	8	rock hitting case	8	design protection around case	8	512	ensure case is strong
	gasket leak	oil leaks and gears overheat	5	poor sealing procedure	6	use correct parts and installation procedure	3	90	pressure test
	mounting bolts shear	gear box dismounts and potentially breaks other parts	7	high forces on the case	1	design strong enough bolts	7	49	nothing
	overheat	gears loose proper temper and cause extra friction and potentially snap teeth	8	wrong or no oil	5	use correct oil	10	400	temperature testing
	case impact	Case dents and potentially leaks from seal and contacts internal parts leading to lockup	7	rock hitting case	7	design protection around case	6	294	ensure case is strong
	oil contaminati on	grinding gears	6	improper seal and handling	3	properly seal and fill the oil	8	144	consider an oil filter system
	pressure relief valve contaminati on	relief valve doesn't operate properly	4	improper handling and covering	4	use debris shields	9	144	nothing
	pressure valve overflow	valve won't properly release pressure	2	overfilling oil	5	use proper amount of oil	6	60	nothing
	bending failure in gears	additional friction in gears and potential to break teeth	8	high forces through reducer	2	design strong gears	7	112	nothing
	compressiv e failure in bearings	bearing seizes up	7	high forces on bearings	2	use strong bearings	8	112	nothing

Differentials takes power from the gear reducer and splits it between the left and right tires	front case puncture	oil leaks and contamination of the gears causing overheating and grinding leading to loss of power in the front	8	rock hitting case	6	design protection around case	7	336	use quality body paneling
	rear case puncture	oil leaks and contamination of the gears causing overheating and grinding leading to loss of power in the rear	8	rock hitting case	7	design protection around case	7	392	Protection
	front case dent	potentially leaks from seal and contacts internal parts leading to lockup in front wheels	7	rock hitting case	5	design protection around case	8	280	use quality body paneling
	rear case dent	potentially leaks from seal and contacts internal parts leading to lockup in rear wheels	7	rock hitting case	6	design protection around case	8	336	design stronger case
	front case gasket leak	loss of oil and overheating of gears	5	poor sealing procedure	5	use correct parts and installation procedure	3	75	nothing
	rear case gasket leak	loss of oil and overheating of gears	5	poor sealing procedure	5	use correct parts and installation procedure	3	75	nothing
	front mounts shear	differential dismounts and potentially breaks other parts in the nose	7	high forces on case	1	design strong enough mounts	8	56	nothing
	rear mounts shear	differential dismounts and falls out of Baja	7	high forces on case	1	design strong enough mounts	8	56	nothing
	oil contamination	gear grinding	7	improper seal and handling	5	properly seal and fill the oil	8	144	consider an oil filter system
	overheat	gears loose proper temper and cause extra friction and potentially snap teeth	8	wrong or no oil	5	use correct oil	10	400	temperature testing

8.2 Appendix B: Calculations for the Gear Reducer

		Pinion	Gear			
Number of Teeth	N	24	48	teeth		Bending factor of safety
Diametral Pitch	P	8	8	TPI		
Transmitted Load	Wt	200	200	lbf	Eq. 13-35	Wear factor of safety
Pitch-line velocity	V	3800	3800	ft/min	Eq. 13-34	
Material		Through-hardened G1	Through-hardened G1		Fig. 14-2	
Brinell hardness	HB	275	275	HB		
User-specified bending stress	St	0	0	ksi		
User-specified contact stress	Sc	0	0	ksi		Circular pitch
Quality number	Qv	7	7			tooth thickness
Overload Power/driven		Uniform-uniform	Uniform-uniform		Fig. 14-17	
Face width	F	0.375	0.375	in		
Centered?		TRUE	TRUE		Eq. 14-33	
Adjusted?		FALSE	FALSE		Eq. 14-35	
Condition		Commercial	Commercial		Table 14.9	
Fatigue model		250 HB	250 HB		Fig. 14-14	
Load cycles		1.00E+07	5.00E+06			
Reliability		95	95			Length Check:
Pitch Diameter	d	3	6	in	Eq. 13-1	Total Length
Addendum	a	0.125	0.125	in		CtoC
Deddendum	b	0.15625	0.15625	in		
Bending stress slope		77.3	77.3	psi/HB		
Bending stress intercept		12800	12800	psi		
Contact stress slope		322	322	psi/HB		
Contact stress intercept		29100	29100	psi		
Bending stress	St	34.0575	34.0575	ksi	Figure 14-2	
Contact stress	Sc	117.65	117.65	ksi	Figure 14-5	
Geometry factor	J	0.354	0.399		Figure 14-6	
Speed ratio	mG	2.0000	2.0000		Eq. 14-22	
Load-sharing ratio	mN	1	1		Eq. 14-23	
Surface geometry factor	I	0.1071	0.1071		Eq. 14-23	
Elastic coefficient	Cp	72.435	72.435		Eq. 14-13	
	B	0.7310	0.7310		Eq. 14-28	
	A	65.0638	65.0638		Eq. 14-28	
Dynamic factor	Kv	1.6278	1.6278		Eq. 14-27	
Maximum velocity	Vt,max	4769.80	4769.80		Eq. 14-29	
Overload factor	Ko	1	1			
Lewis factor	Y	0.3375	0.401		Table 14-2	
Size factor	Ks	0.9830	0.9876		Sec 14-10 (a)	
Load Correction Factor	Cmc	1	1		Eq. 14-31	
F/10d		0.0500	0.0500			
Pinion Proportion Factor	Cpf	0.0250	0.0250		Eq. 14-32	
Pinion Proportion Modifier	Cpm	1	1		Eq. 14-33	
Mesh Alignment Corr. Factor	Ce	1	1		Eq. 14-35	
	A	0.127	0.127		Table 14-9	
	B	0.0158	0.0158		Table 14-9	
	C	-0.000093	-0.000093		Table 14-9	
Mesh Alignment Factor	Cma	0.1329	0.1329		Eq. 14-34	
Load-distribution factor	Km	1.1579	1.1579		Eq. 14-30	
Hardness-ratio factor	CH	1	1.0000		Eq. 14-36	
^^(for Pitting Resistance)^^	HBP/HBG	[redacted]	1.0000			
	A'		0.000000		Eq. 14-36	
SCF for Bending Strength	YN	1.0000	0.9856		Fig. 14-14	
	YNmult	1.6831	4.9404		Fig. 14-14	
	YNexp	-0.0323	-0.1045		Fig. 14-14	
SCF for Pitting Resistance	ZN	1.0000	1.0396		Fig. 14-15	
	ZNmult	1.4488	2.466		Fig. 14-15	
	ZNexp	-0.023	-0.056		Fig. 14-15	
Reliability factor	KR	0.8854	0.8854		Eq. 14-38	
Temperature factor	KT	1	1		Sec 14-15	
Rim-thickness factor	KB	1	1		Eq. 14-40	
Allowable bending stress	σ,all	38.468	37.914		Eq. 14-17	
Allowable contact stress	σc, all	132.884	138.139		Eq. 14-18	
Bending stress	σ	22.310	19.882		Eq. 14-15	
Contact stress	σc	127.012	127.306		Eq. 14-16	

	Pinion	Gear				Pressure Angle	phi	0.34906585	20 deg pressure angle
SF	1.72	1.91		Eq. 14-41			Esteel	30000	ksi
(SH)^2	1.09	1.18		Eq. 14-43			nusteel	0.3	
SH	1.05	1.09		Eq. 14-42			TRUE		
							FALSE		
			Abbreviations						
p	0.393		SCF	Stress Cycle Factor					
t	0.196								
			Calculations made using AGMA Method as described in "Shigley's Mechanical Engineering Design - 10th Ed."						
9	in								
4.5	in			interference check:	**We Good**				
				Pinion Teeth	24				
		0.020833333		Equation Check	16.94181163				

8.3 Appendix C: Bill of Materials

Initial Bill of Materials: Drivetrain and Frame								
Item No.	Description	Qty.	Vendor	Cost Range		Link	Notes	Billed Cost
1	B&S 10 HP Vanguard Engine	1	Briggs & Stratton	$ 546.30	$ 546.30	Briggs & Stratton	Price subject to change based on availability	$ 290.00
2	Fuel Tank	1	Pyrotect	$ 225.00	$ 225.00	Fuel Tank	New aluminum fuel tank required for all competing teams	
3	Fuel Line	1	Napa Auto	$ -	$ -	1.5 ft of Fuel Line	Donated by Napa/Excess from last year	
4	Kill Switches	2	Parker SportsCenter	$ 51.00	$ 51.00	ParkerYamaha	2 kill switches per rulebook requirements	
5	Primary ECVT Pulley	1	In-house	$ -	$ 400.00	N/A	Price dependent on 6061-T6 Aluminum donations	
6	Linear Bearing for Splined Shaft	1	McMaster-Carr	$ 278.89	$ 278.89	ECVT Main Bearing	ECVT component that allows linear and rotational movement	
7	Gaged Secondary CVT Pulley	1	Gaged Engineering	$ -	$ -	Gaged CVT Specifications	Secondary from previous capstone teams	
8	Nema 23 2.8A Stepper Motor	1	StepperOnline	$ 26.00	$ 26.00	Stepper Motor	Arduino controlled stepper motor for ECVT primary	
9	US5881 Hall Effect Sensor	2	SainSmart	$ 7.98	$ 7.98	Arduino Sensor	Used to detect engine output RPM	
10	Arduino Components	TBD	Arduino	$ -	$ 40.00	Arduino	Prototyping may effect cost	
11	Spur Gears	2	TBD	$ 100.00	$ 400.00	Bevel Gear Sets	Ongoing bevel gearbox design iterations	
12	Gear Manufacturing	2	Ping	$ -	$ -	N/a	Wire EDM	
13	Transfer Case Material	1	SpeedyMetals	$ -	$ 500.00	6x10 6061-T6	Case material may be donated	
14	Transfer Case Manufacturing	2	Ping	$ -	$ -	N/A	Investment Cast	
15	5/8 Hollow Steel Tube	1	SpeedyMetals	$ 27.36	$ 27.36	5/8 OD Steel Tube	4 ft hollow steel tubing for custom driveshaft	
16	Closed Cell High Density Foam	1	USAFoam	$ 22.36	$ 22.36	1/2 x 23 x 108	Composite floorboard	
17	Safety Covers	2	SpeedyMetals	$ 54.32	$ 54.32	1/8 in. Aluminum Sheets	1/8" 6061 aluminum covers required for exposed components	
18	Misc. Hardware	TBD	Copper State	$ 20.00	$ 150.00	Copper State Bolt & Nut	Hardware for assembly	
19	ECVT Electronic Components	N/A	N/A	$ 513.66	$ 567.96	N/A	Electronic hardware	$ 600.00
20	Yamaha Rhino 660 Rear Diff.	1	maXpeedingrods	$ 240.00	$ 240.00	Rear Differential	4-10 day Lead Time	$ -
21	Yamaha Rhino 660 Front Diff.	1	maXpeedingrods	$ 266.00	$ 266.00	Front Differential	4-10 day Lead Time	$ 687.35
22	Contingency Fund	N/A	Any	$ -	$ 200.00	N/A	Accounting for potential unforseen expenses	
23	Frame Material/Fabrication	N/A	VR# Engineering	$2,000.00	$2,000.00		11-19 day Lead Time	
24	4130 Steel Tubing 1.25"x0.065"	56ft	SpeedyMetals	$ -	$ 660.00	speedymetals		
25	4130 Steel Tubing 1.00"x0.058"	30ft	SpeedyMetals	$ -	$ 300.00	speedymetals		
26	4130 Steel Tubing 1.00"x0.035"	40ft	SpeedyMetals	$ -	$ 416.00	speedymetals		
27	4130 Steel Square Tubing 1.00"x0.035"	10ft	SpeedyMetals	$ -	$ 128.00	speedymetals		
28	4130 Steel Plate 0.125"	3ft^2	Metals Depot	$ 75.00	$ 75.00	metalsdepot		
29	4130 Steel PLate 0.250"	2ft^2	Metals Depot	$ 125.00	$ 125.00	metalsdepot		
30	Dzus Fasteners	50	Summit Racing	$ 87.00	$ 87.00	summitracing		
			Total:	$2,378.87	$4,003.17			$(1,577.35)

8.4 Appendix D: Assembly Views

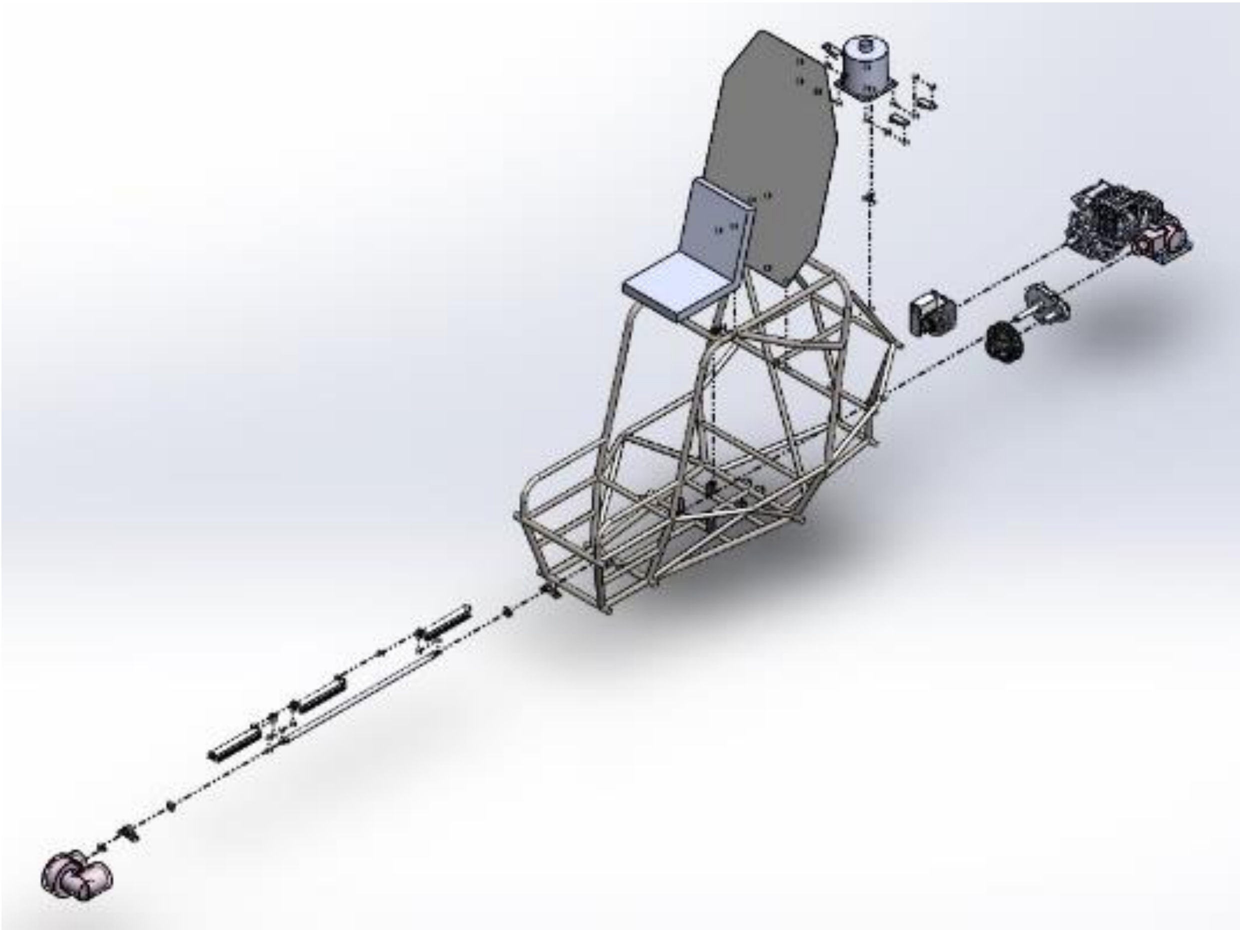

Figure D1. Frame and Drivetrain Full Assembly (Exploded View)

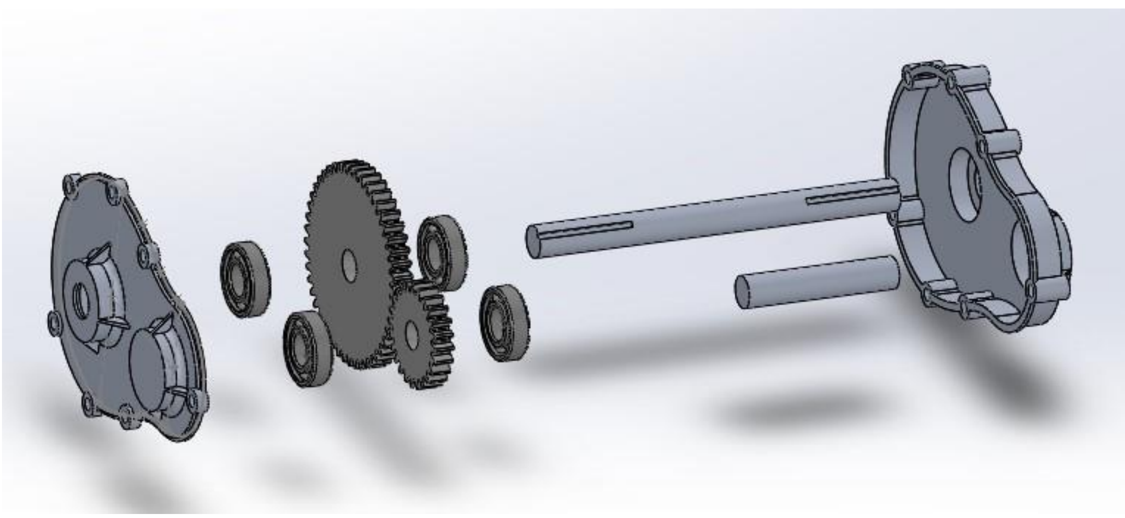

Figure D2. Spur Gear Reducer Assembly (Exploded View)

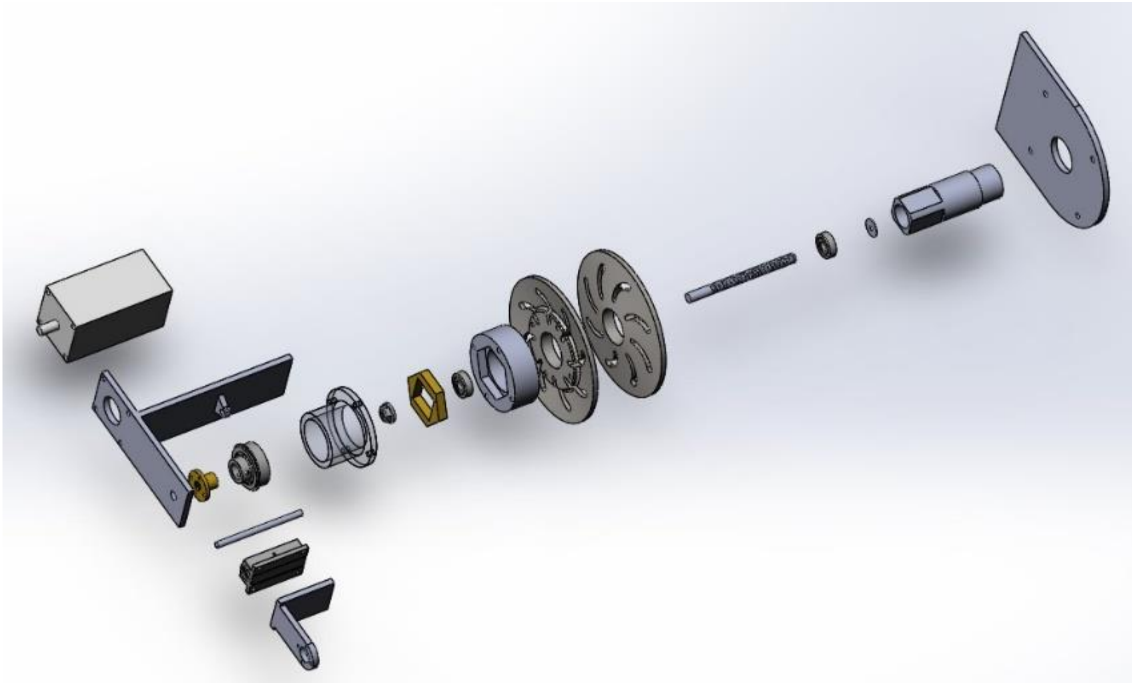

Figure D3. ECVT Assembly (Exploded View)