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Date: 02/14/20

Subject: ER & TP Revamp Memo

The SAE Baja capstone allows students involved to go through the process of creating a safe and well performing off road vehicle. This vehicle has strict requirements set by the SAE organization and as well by the team itself. This is to ensure that the vehicle is safe and reliable, and will also perform well during competition. Up to this point, the only engineering requirement which has been modified is the material strength requirement. This requirement was changed by slightly lowering the minimum material strength, but was justified by an increase in tubing wall thickness.

1 Customer Requirements (CRs)

1.1 Frame and Drivetrain

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, below.

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

1.2 Front End and Rear End

Table 2. FE & RE Customer Requirements

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

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

2 Engineering Requirements (ERs)

The engineering requirements for the Baja team were based directly from the customer requirements. More specifically, the engineering requirements being discussed here are track width, ride height, stopping distance, cost, weight, and material strength. These are key ER's since many of them are translated directly from customer requirements and, additionally, these ER's will ensure that the team's buggy performs well and is safe to operate with repeated use and abuse.

2.1 ER #1: Track Width

2.1.1 ER #1: Track Width Target = 53 inches

The target track width, or the center-to-center distance between the tires on a given axle, was selected based on vehicle data from past competitions provided by the faculty advisor, including an Ackerman angle analysis that accommodates varying track widths. The track widths for the front and rear end of the vehicle determine the angles of the front wheels relative to each other and the optimal turning radius for maximum maneuverability.

2.1.2 ER #1: Track Width Tolerance = +/- 3 inches

This tolerance accommodates differences in suspension geometry for the front and rear of the vehicle and defines the suitable range for an optimal turning radius. By remaining within 3 inches of the desired track width, a tight turning radius can be achieved.

2.2 ER #2: Ride Height

2.2.1 ER #2: Ride Height - Target = 10 inches

A ride height of 10 inches was chosen based on vehicle data from previous competitions provided by the faculty advisor. The ride height of the vehicle is critical in rough terrain as it provides clearance between debris and the vehicle frame, protecting moving and structural components from damage.

2.2.2 ER #2: Ride Height - Tolerance = +/- 1 inch

The suspension geometries and shock absorber settings between the front and rear suspensions may differ slightly to suit dynamic characteristics including cornering behavior and ground clearance.

2.3 ER #3 Stopping Distance

2.3.1 ER #3: Stopping Distance - Target = 6 feet

The team expects the stopping distance of the vehicle to be 6 feet using a high-friction brake pad compound with proper bedding procedures, with the addition of new 22x7-10 all-terrain tires set to optimal pressures and operating temperatures. Engine braking due to adjustable gear ratios from the 4WD system will also provide additional braking force on all four wheels.

2.3.2 ER #3: Stopping Distance - Tolerance = +/- 2 feet

Variations in track surface conditions and available grip are accounted for with this requirement tolerance, since the environment will affect the braking distance of the vehicle.

2.4 ER #4 Cost

2.4.1 ER #4: Cost - Target = $7,000.00

For this project, the team aims to stay within a total cost of $7,000. This will be achieved through the use of off-the-shelf parts to reduce material and labor costs, and in-house manufacturing will also reduce labor costs.

2.4.2 ER #4: Cost - Tolerance = +/- $350.00

The maximum cost of this project is set at $7,350, but the team is designing to achieve a cost of $7,000 or less. Additionally, this buffer was set to try and account for potential fundraising.

2.5 ER #5 Weight

2.5.1 ER #5: Weight - Target = 450 pounds

With the addition of four-wheel drive, the team is expecting the buggy to weigh in around 450 pounds. This is a higher number than some previous years since four-wheel drive differentials add a considerable amount of weight.

2.5.2 ER #5: Weight - Tolerance = +/- 50 pounds

Additionally, the team has set a buffer of 50 pounds for the weight. This was done to account for potential weight differences in drivers.

2.6 ER #6 Material Strength

2.6.1 ER #6: Material Strength – Target Minimum = 290 MPa

The rear end team was able to achieve the material strength engineering requirement by using 6061 – T6 Aluminum which has and ultimate strength of 310 MPa. [1] The material used for the front-end team is 4130 steel which has an ultimate tensile strength of 670 MPa. [2]

2.6.2 ER #6: Material Strength – Target Max (Changed from fall) = 700 MPa

The rear end team achieved a material property above the target minimum, while the front-end team achieved material properties under the target max.

2.6.3 ER #6: Material Strength – Change Justification

The ER for material strength was changed to accommodate a difference in wall thickness between the front and rear end. Using aluminum allows for a lighter overall weight and with an increased wall thickness from steel, its justified to have a wider range of overall strength.

3 Testing Procedures (TPs)

Testing procedures for the Baja team were split up into front end, rear end, frame, and drivetrain sections. This was done to ensure that each of these subsystems is performing to its maximum capacity and will be able to perform at that level for the duration of the vehicle's life. Additionally, testing will also have to be done to the vehicle as a whole, once all of the subsystems have been completed.

3.1 Front End Testing Procedures

3.1.1 Testing Procedure 1: Brake System Test

3.1.1.1 Testing Procedure 1: Objective

The objective of this test is to assess the durability and performance of the braking system by replicating the conditions expected in a competition environment. The design team will measure the system pressure with the brake pedal actuated and the vehicle at rest, and subsequently test the braking system with the vehicle traveling at maximum speed to determine if all four wheels lock in the shortest possible stopping distance. The team will measure the stopping distance of the vehicle to determine if the engineering requirement for stopping distance is satisfied. Testing the hydraulic pressure of the braking system ensures the system is operating at maximum efficiency to lock all four wheels and provide optimal deceleration. In addition, the driver will conduct repeated cycles of hard braking to bed a layer of the pad material onto the rotor, which will improve the clamping force between the rotor and caliper. The repeated compressive and thermal stresses from hard braking will also assess the endurance limit of the rotor. This test will be conducted on service roads and asphalt roadways to examine if all wheels will lock on dirt and asphalt.

In addition, the brake pedal assembly is required to withstand a maximum force of 450 lbf per competition rules. After a Finite Element Analysis (FEA) of the Wilwood 7:1 aluminum pedal is conducted to analyze stresses and expected deformation, the brake pedal will be actuated at rest with the brake system fully bled and installed on the vehicle. The driver will exert the maximum force allowed at the allowable thigh and knee angle when sitting in the vehicle. The corresponding angles will be measured and the test will then be replicated on a digital scale to measure force outputs provided by the driver. This test will prove that material strength requirements are satisfied. A prolonged application of the maximum expected force will also test the ability of the master cylinders and brake lines to withstand high system pressures expected from calculations. All components will be examined for deformation and redesigned if necessary.

3.1.1.2 Testing Procedure 1: Resources Required

The system pressure test required a brake force analysis to be evaluated in Excel, which provided values of expected system pressures and braking forces required to lock all wheels. In addition, this test requires a driver to fully depress the brake pedal and a Bourdon Tube gauge to be connected to the bleeder valve of the brake caliper, which can be performed when the brake system is installed onto the vehicle. The Bourdon Tube gauge kit will be ordered online or borrowed from the Experimental Methods lab equipment with permission from faculty. This leak down test will determine the total brake system pressure, allowing the design team to verify the measured pressure with the expected value from the analysis and troubleshoot the brake system for leaks. The dynamic braking test will be conducted on sections of service roads and asphalt roadways of at least 100 feet to allow the vehicle to reach maximum speed and lock all wheels on dirt and asphalt. The design team will mark the sections of road in increments of ten feet and determine the point at which the driver applies the brakes. Spotters from the front and rear end sub teams will measure the distance between where the driver applied the brakes to where the vehicle comes to rest, which will be used to conclude if the stopping distance requirement is satisfied.

3.1.1.3 Testing Procedure 1: Schedule

The braking system testing procedure requires a force analysis to be evaluated and programmed in Excel, which has been completed. The brake calipers, rotors, master cylinders, brake lines and pedal are also required to be installed on the vehicle for testing, which will be completed no later than March 15^{th}. These parts, including the front hubs which have mounting holes for the front rotors, will be acquired from aftermarket suppliers or manufactured in house and will be received by the end of February and early

March. The initial system pressure test can be conducted when stationary and does not require the vehicle to be fully assembled, which means it can be completed during the construction of the vehicle. However, the break-in procedure for the pads and rotors and subsequent dynamic braking test requires the vehicle to be fully assembled and operational, including a full day of testing time. The design team expects to complete vehicle fabrication and assembly no later than March 30th.

3.1.2 Testing Procedure 2: Maneuverability Test

3.1.2.1 Testing Procedure 2: Objective

The maneuverability test is designed to assess the reliability of the steering system in situations that require swift reactions by the driver. This test also assesses the maneuverability of the vehicle when the driver is required to navigate tight corners and around stationary objects that hinder the vehicle's path. The design team will be able to adjust the front end and rear end suspension alignment for optimal cornering performance, including the steering tie rods while conducting this test. This allows the vehicle to swiftly change direction for sharp turns and maintain stability under hard cornering, ensuring success in the maneuverability event of the competition. Additionally, the vehicle will travel at low speeds with the steering at full lock to one direction, and a spotter will mark the starting and ending points when the vehicle completes a 180° turn. The corresponding radius of the path will then be measured. This allows the design team to determine the turning radius and further optimize the suspension geometry and dimensions to satisfy the engineering requirement for maneuverability. Lastly, the design teams will conduct a slalom test, where the driver will be required to swiftly maneuver the vehicle at speed between evenly spaced cones or markers.

3.1.2.2 Testing Procedure 2: Resources Required

The front end and rear end design teams utilized an analysis of past successful competition vehicles and an Ackerman Angle analysis to determine the optimal wheelbase and ride height of the current design, including front and rear track widths**.** This allowed the design team to optimize the engineering requirements for track width, ride height and wheelbase of the vehicle to satisfy the desired turning radius. The design teams will utilize the dirt service lots located behind Building 98C to construct a course that includes a continuous set of corners that switch direction and gradually increase in radius. A tape measure will be acquired from the machine shop to measure the turning radius of the vehicle at low speeds.

3.1.2.3 Testing Procedure 2: Schedule

Tentatively, this test would be one of the last to be performed. This is because the vehicle will need to be fully assembled before any of these tests are able to be completed or even performed.

3.2 *Drivetrain Testing Procedures*

3.2.1 Testing Procedure 1: 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 known, 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.

3.2.1.1 Testing Procedure 1: 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.

3.2.1.2 Testing Procedure 1: 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.

3.2.1.3 Testing Procedure 1: 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.

3.3 Frame Testing Procedures

3.3.1 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

3.3.1.1 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.

3.3.1.2 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.

3.3.1.3 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.

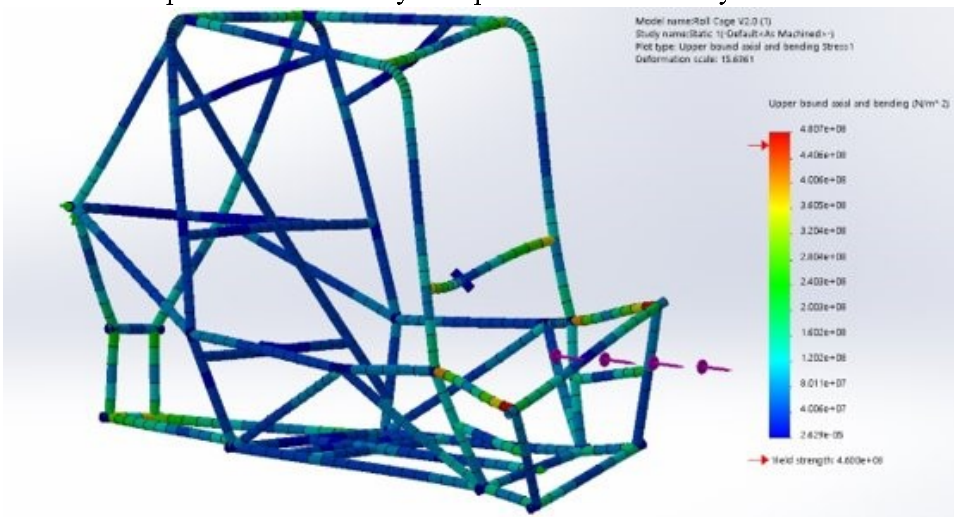

Figure 5. Frame Torsional Test FEA

3.4 Rear End Testing Procedures

3.4.1 Testing Procedure 1: Bump, Roll, and Drop Test

3.4.1.1 Testing Procedure 1: Objective

This testing procedure will analyze how the rear trailing arm will react to various loading. The testing will involve attaching the trailing arm to a Baja vehicle. Once the arm is attached loading will be applied to the rear end in an up and down motion to imitate bump travel. Likewise, loading will be applied in a side to side motion to imitate roll travel. For the drop test the vehicle will be fixed with a hinge connection from the front. The rear end will then be elevated approximately two or three feet and dropped to visualize how the trailing arm reacts. This testing procedure will test the strength of the material, and there will also be an opportunity to visually inspect the track width and ride height.

3.4.1.2 Testing Procedure 1: Resources Required

To test the bump, roll, and drop the team will need to acquire material and fabricate a single trailing arm. The dimensions shall be adjusted to fit onto a previous years Baja vehicle. To apply loading team members will apply body weight to the rear and sides of the vehicle.

3.4.1.3 Testing Procedure 1: Schedule

The schedule for testing will begin with fabricating a trailing arm. Due to this being the first trailing arm to be manufactured the team shall be allotted two weeks to complete. Once the arm is manufactured, there will be one day which the team will attach and test the trailing arm.

4 References

[1] ASM, "ASM Aerospace Specification Metals Inc.," [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6. [Accessed 13 February 2020].
[2] ASM, "ASM Aerospace Specification Metals Inc.," [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=m4130r. [Accessed 13 Feburary 2020].