Department of Mechanical Engineering
SAE Baja 24
ME486C - 001

To: David Willy

From: SAE Baja 24

Date: 03/22/2024

Re: SAE Baja Finalized Testing Plan

The goal of this memo is to present each subteam's plan for testing their respective designs. The test plans generated during this process will adhere to the customer/engineering requirements that were established in the fall and will produce quantitative results. These results will be presented in a final specification sheet in a subsequent document to assess the success of each subteam's design.

Design Requirements Summary

In the initial design conceptualization stage, each subteam generated a series of customer/engineering requirements based off benchmarking research, client meetings with Professor Willy, and the SAE Baja rulebook. These requirements are outlined by subteam in the section below.

Front End

Aside from requirements established by the SAE, the team generated some general customer/engineering requirements (hereby referred to as "CRs" and "ERs") that governed the design of the front end sub-system. Since the front end of the vehicle only has a single strict requirement established in the rulebook, many of these CRs are inferred based on desirable vehicle attributes and from extensive benchmarking research.

- CR1: Vehicle must comply with the dimensions of the SAE Baja course
- CR2: Vehicle must have adequate ground clearance
- CR3: Vehicle must have adequate traction across all terrains
- CR4: Vehicle must be capable of safe operation over rough land terrain
- CR5: Vehicle must have agile maneuverability
- CR6: Front suspension components must be robust in design (i.e. control arms, hubs, knuckles, tie rods, etc.)

For each CR, a corresponding ER was generated with a quantifiable metric.

- ER1: Decrease Vehicle Width
    - Max Vehicle Width = 64"
- ER2: Increase Ride Height
    - Front Ride Height Minimum = 10"

- ER3: Increase Tire Traction
    - Scrub Radius = ~0”
- ER4: Increase Capability in Rough Terrain
    - Wheel Travel = ~12” total (3:1 bump to droop)
- ER5: Increase Turn-In Angle
    - Pro-Ackerman = 40-60%
- ER6: Increase Crash Durability
    - Max Survivable Collision Speed = 20 mph

Engineering requirements allowed the front end to guide their geometric design and better communicate design desires with other sub-teams during integration phases. Many of these engineering requirements must serve dual purposes: meeting the engineering requirement and satisfying SAE BAJA rules/regulations.

Rear End

A testing plan has been developed to test the subsystems performance of how accurately the suspension has been designed to fulfill customer and engineering requirements. The CRs are mainly from the SAE rulebook. In addition, the team has decided to add a few requirements based off team discussions with and without the client. These CRs have been previously determined mainly during the benchmarking portion of the project.

- CR1: Vehicle should be reliable and safe over different obstacles
- CR2: Vehicle’s rear suspension shall be low cost
- CR3: Vehicle must maximize the amount of traction when vehicle is moving
- CR4: Vehicle must have agile maneuverability
- CR5: Vehicle must have the ability to be tuned/adjusted as needed for different events at competition
- CR6: All components must be robust in design

To ensure the CRs would come true the team came up with quantifiable requirements that would ensure the CRs would be true. Below are the ERs.

- ER1: Decrease vehicle weight
    - Rear Suspension subassembly under 75 pounds
- ER2: Increase rearward axle path
    - Axle path to be over 1 inch
- ER3: Increase linkage radii
    - Camber links =~ 20” (pivot to pivot)
- ER4: Decrease CV axle angle
    - 20 degrees of angle change
- ER5: Vehicle width
    - Maximum track width under 62”
- ER6: Increase ground clearance
    - Minimum ground clearance = 8”
- ER7: Decrease camber link angle
    - Angle 15 degrees from centered

- ER8: Increase camber gain
    - Allow design for =~ 2” longer upper camber links

These requirements allowed the team to dictate the fundamentals of the suspension that has been design thus far. Moving forward, the team’s goal is to refine the requirements based off these CRs and ERs by test verification and measurements.

Drivetrain

The drivetrain team has generated both customer and engineering requirements that has guided the team in designing a robust drivetrain. The testing plan developed will determine the performance of the drivetrain and it meeting its customer and engineering requirements.

- CR 1: High top speed
- CR 2: Maximum efficiency
- CR 3: High torque
- CR 4: High service life
- CR 5: Low weight
- CR 6: High transmission range

The CRs are used to generated ERs that will reflect the performance of the drivetrain.

- ER 1: 40mph Top Speed
- ER 2: 80% Drivetrain Efficiency
- ER 3: 400lb-ft of Torque to the Wheels
- ER 4: 100-Hour Service Life
- ER 5: Total Drivetrain Weight (Without Engine) of 60lbs
- ER 6: 1:4.5 Total Transmission Range

Using these constraints will help the team better understand the design of the drivetrain and the important aspects of meeting the SAE Baja regulations and adhering to the customer requirements as well.

Frame

The frame team has generated Customer requirements to ensure the project will satisfy the customer in an efficient and effective manner. From these customer requirements, engineering requirements are propagated and quantify the meeting of customer requirements. In order to validate the engineering requirements testing must be preformed for each of the sub teams and driver integration.

Customer Requirements

- CR 1: Frame must satisfy SAE BAJA Rules
- CR 2: Frame must be designed for manufacturing

- CR 3: Frame must be rigid
- CR 4: Frame must be lightweight
- CR 5: Frame must be maneuverable
- CR 6: Frame must be aesthetically pleasing
- CR 7: Frame must be durable
- CR 8: Vehicle must be fast
- CR 9: Frame must be stable
- CR 10: Frame must be cost-effective

Engineering Requirements are derived from the customer requirements and quantify the testing.

- ER 1: Decrease Weight
    - Target weight: Under 65 lbs
- ER 2: Decrease Body Length
    - Maximum Wheelbase = 64 inches
- ER 3: Decrease Body Width
    - Maximum Body Width = 64 inches
- ER 4: Decrease Cost
    - Cost of 4130 CD Steel
        - IMS Sponsorship
        - Primary 1.25” OD x 0.065” thickness
        - Secondary: 1.00” OD x 0.035” thickness
- ER 5: Increase Strength of Frame
    - Optimize Yield Strength
- ER 6: Optimize Suspension
    - Place tabs so suspension is 95% accurate to CAD
        - Track width
        - Travel
        - Suspension geometry
- ER 7: Integrate Drivetrain Accurately
    - Ensure tab placement is 95% accurate to CAD

Top Level Testing Summary

To assess these CRs and ERs, several experiments will be conducted on the subteam’s designs. These experiments, along with their relevant design requirements, are outlined below.

Front End

For the front end, there is a large focus on dimensional compliance from several key aspects of the design. Attributes such as ground clearance, wheel travel, and maneuverability determine the success of the car during a race. As such, a multitude of dimensional assessments (static and dynamic) must be performed on the front end to ensure the build will be successful. In addition, durability testing must be performed on the parts most prone to catastrophic failure (i.e. knuckle). The scheduled experiments are outlined below for the front end and will be described in detail in *Detailed Testing Plans.*

Table 1: Front End Testing Summary

Experiment/Test	Relevant DRs
Ex1 - Trackwidth Assessment	CR1, ER1, CR6
Ex2 - Ground Clearance Check	CR2, ER2, CR3, CR4, ER4
Ex3 - Scrub Radius Measurement	CR3, ER3, CR4, CR5, ER5
Ex4 - Wheel Travel Verification	CR4, ER4, ER2, CR2, ER6, CR6
Ex5 - Ackerman Angle Test	CR5, ER5
Ex6 - Knuckle Strain Test	CR6, ER6, CR2, CR4

Rear End

The Rear End team is focused on getting the suspension system to where the team designed the suspension to be. Since the team designed with the idea of optimizing the suspension for a variety of competition events that will take place in Gorman, California, the idea is to test and see what works best for each event to be competitive. For the testing plan the verifications have been split up in to either static or dynamic testing. The static testing will verify many of the design goals the team had during concept development and design phase. The dynamic testing will act to verify many of the FEA elements and prove to the team parts will be strong enough for competition. Dynamic testing will also serve to educate the team on what setup will perform the best for the different events at competition.

Table 2: Rear End Testing Summary

Experiment/Test	Relevant DRs
Ex1 - Trackwidth Assessment	CR1, CR4, CR5, ER1, ER3, ER5, ER6
Ex2 - Ground Clearance Check	CR1, CR3, CR4, CR5, ER1, ER5, ER6
Ex3 - Wheel Angles Verification	CR1, CR3, CR4, CR5, ER1, ER2, ER5, ER6
Ex4 - Shock Setup Testing	All DRs are relevant here
Ex5 - FEA Accelerometer Confirmation	All DRs are relevant here

Drivetrain

The drivetrain team is focused on getting all drivetrain components functioning and optimized for the competition. To make sure that the drivetrain system is functioning properly for the competition, it will be imperative to test the output of the system relative to the output of the engine. This will be accomplished by testing the driving capability of the car with a top speed test and the dyno test. Testing the vehicle's top speed and performance on the dyno will provide us information on how the systems on the vehicle transfer power from the engine to the wheels, and how efficiently/effectively it accomplishes this. A 4WD test will ensure that the front-end functions as it should, and weighing the components of the drivetrain before they are installed will provide us reference information for how optimized the parts were in the drivetrain. Further, any testing that involves the wheels spinning will provide us information about the service life of the vehicle. If in pre-competition testing, we have component failures then we know that the service life requirement of the vehicle was not accomplished, and component alterations may need to occur for the competition.

Frame

The focus of the frame team is integration and optimization. By helping other subteams integrate their components as close to the design as possible, the integration should be straightforward. By using CAD as a baseline, the frame team can work with other subteams to adjust component placement as appropriate. No component is manufactured exactly as designed and so there must be adjustments made in the assembly and tuning of the vehicle. Another strong focus of the frame team is to continue manufacturing all frame components. Paneling and driver safety/integration are the two largest concerns within this area. These are the final few steps that will allow the frame team to completely focus on testing and tuning of the vehicle.

To ensure that the frame team has satisfied all primary customer and engineering requirements, 5 tests will be performed. Firstly, a technical inspection must be performed to prove that the car will be able to race at competition. Then the ergonomics of the car will be assessed through driver fatigue and egress times to ensure that the driver will perform optimally and safely. Thirdly, suspension geometry validation must be performed. This will help optimize the handling of the car and mitigate any unwanted stresses through the components. Similarly, the drivetrain integration must be validated. This will make tuning the drivetrain more streamlined and efficient. Lastly, to ensure driver safety, all deformation and deflection in impact and roll cage members should be documented.

Table 3: Frame Experiments and DR's

Experiment/Test	Relevant DRs
Ex1 - Technical Inspection	CR1, ER 1, ER 2, ER 3
Ex2 - Ergonomic Assessment	CR8, CR 9
EX3- Suspension Inspection and Evaluation	CR 5, CR 8, CR 9, ER 6
Ex 4-Drivetrain Compatibility and Safety	CR 1, CR 8, CR 9, ER 7
Ex5- Member Deflection Assessment	All DR's are relevant

Detailed Testing Plans

For each test presented in *Top Level Testing Summary*, an experimental summary, procedure, expected results, and conclusion will be presented to give the reader a better understanding. These detailed testing plans can be seen below.

Front End

Six experiments will be featured in the front end's testing plan, each of which will directly assess a different attribute of the build. These experiments were introduced in *Top Level Testing Summary* and will now be explained in detail.

Experiment 1 – Trackwidth Assessment:

- Test/Experiment Summary:
  The SAE Baja rulebook directly states that no vehicle is to exceed 64" in width, which gives little room in the design for dimensional error. Once the front end is built, the front shocks will be aired out to an appropriate stiffness for ride height sag. This experiment requires a tape measurer, a shock pump, and the car itself. Track width will be measured and checked against the stated value to confirm compliance. This test will be relevant towards CR1, ER1, and CR6. In this experiment, the track width of the car at ride height will be isolated and measured. No calculations follow this measurement.

- Procedure:
  1. Air up the front end tires to optimal operating pressure (7-8 psi)
  2. Air out the front shock absorbers to facilitate 30% compression of the shock body at ride height (start at 150 psi in the small chamber and 65 psi in the large chamber and reduce until satisfied)
  3. Verify that the car is on a flat surface and the wheels are pointed forward
  4. Take a tape measurer and measure the distance between the outer sidewall of the passenger side tire and the outer sidewall of the driver side tire

- Results:
  The trackwidth measured in this experiment is expected to land at or near 63" based on the team's CAD modeling, with a lower value being preferred. Expected variation in this value could range from 60"-64" based on frame mounting tabs and discrepancies between designed parts and manufactured parts. A larger track width translates to a larger pivot arm for the suspension and, thus, more travel for the wheels. However, too large of a track width will prevent us from competing.

- Conclusion:
  This experiment is the only one for the front end that will directly determine if the team competes in April or not. A successful completion of this experiment, with a desirable result, will permit the front end team to relax at tech inspection. If the track width is above 64", tab relocation and clever engineering will be paramount to resolve the issue.

Experiment 2 – Ground Clearance Check:

- <u>Test/Experiment Summary:</u>

  The SAE Baja competition will feature a variety of off-road obstacles including rocks, telephone poles, and elevated/ramped surfaces. To perform well over these obstacles, having adequate ride height is crucial. This experiment requires a tape measurer, a shock pump, and the car itself. The ride height of the car will be measured and checked against the previously established engineering requirement for ride height (10” +6”/-0”). This test will be relevant towards CR2, ER2, CR3, CR4, and ER4. In this experiment, the ride height of the car at normal driving height will be isolated and measured. No calculations follow this measurement.

- <u>Procedure:</u>

  1. Air up the front-end tires to optimal operating pressure (7-8 psi)
  2. Air out the front shock absorbers to facilitate 30% compression of the shock body at ride height (start at 150 psi in the small chamber and 65 psi in the large chamber and reduce until satisfied)
  3. Verify that the car is on a flat surface and the wheels are pointed forward
  4. Take a tape measurer and measure the distance between the lowest point of the front-end assembly (likely the lower control arm rear mount location) and the ground

- <u>Results:</u>

  In this experiment, the ideal result is a simple measurement above 10” but below 16”. Since the rear is designing for 12” of ride height in the back, we want to stay around that value if possible. Exceeding this value by too much will lean the car back and lead to possible stability issues for the driver over jumps or large obstacles. Landing under the 10” mark will tilt the car forward, leading to dive issues under hard braking and, again, lack of stability for the driver. Shock adjustment can compensate for discrepancies between the front and rear ride height, but the ideal case is a front ride height that lands within the stated engineering requirement tolerances.

- <u>Conclusion:</u>

  Proper ride height on the front end of the vehicle will allow the driver to approach large obstacles head on and not worry about approach angle limitations. In addition, an appropriate ride height will keep the suspension components away from course hazards and hopefully extend the lifespan of the front end (especially control arm tabs, tie rods, and control arms).

Experiment 3 – Scrub Radius Measurement:

- <u>Test/Experiment Summary:</u>

  One attribute of off-road suspension design that can be overlooked during the design stage is the scrub radius of the knuckle assembly (the distance between the axis of the tire centerline and the axis of the control arm mounts on the knuckles when they intersect with the ground). This experiment requires chalk, a tape measurer or digital caliper, a shock pump, a long/straight object exceeding 2’, and the car itself. The scrub radius of the front-end assembly will be measured and checked against the design value/engineering requirement (0” +/-1”). This test will be relevant towards CR3, ER3, CR4, CR5, and ER5. In this experiment, the scrub radius of the car at ride height will be isolated and measured. No calculations follow this measurement.

- Procedure:
    1. Air up the front-end tires to optimal operating pressure (7-8 psi)
    2. Air out the front shock absorbers to facilitate 30% compression of the shock body at ride height (start at 150 psi in the small chamber and 65 psi in the large chamber and reduce until satisfied)
    3. Verify that the car is on a flat surface and the wheels are pointed forward
    4. Take a tape measurer and measure the width of the driver side tire, marking the center point on the ground in front of the wheel with chalk
    5. Take a long, straight object (taught string, thread-all, etc.) and move to a “front view” position of the driver knuckle.
    6. Align the straight object with the upper control arm ball joint and the lower control arm ball joint, making sure this straight object contacts the ground as well
    7. Using chalk, mark out the point where this knuckle axis, created by the straight object, intersects the ground
    8. Measure the distance between this mark and the mark previously made at the tire with a pair of digital calipers or a tape measurer
    9. Repeat steps 4-8 on the passenger side knuckle assembly to verify scrub radius continuity between sides

- Results:
  From this experiment, the front end is hoping to get a simple scrub radius measurement on the magnitude of 1” or less. An ideal scrub radius for an off-road vehicle to promote proper camber gain and suspension performance is 0”. Any deviation from this point will change how the wheels gain camber and maintain traction during a compressive event (high-speed corner, bump over obstacle, etc.). Modification of this attribute in the team’s suspension software Lotus *Shark* negatively impacted camber gain at values of 1.5” and above, meaning this design point must be taken seriously. The front end’s CAD leads the team to expect a value near 0.25” but, as always, discrepancies between the designed parts and manufactured/assembled parts exist.

- Conclusion:
  The scrub radius of each knuckle assembly is a critical design feature that must be verified in the real-world build. This experiment will help identify the scrub radius of each knuckle assembly and verify if they are in alignment with the engineering requirement established above. Failure to satisfy this engineering requirement will not lead to catastrophic failure but will lead to compromised suspension performance for the driver during the race, impacting placement amongst the competing vehicles.

Experiment 4 – Wheel Travel Verification:

- Test/Experiment Summary:

In addition to the previously mentioned off-road attributes, wheel travel is another design point that is necessary for proper vehicle functionality over rough terrain. The front wheel assemblies must be able to articulate vertically to compensate for sudden collisions with obstacles and to protect the suspension components from rigid impact. This experiment requires a tape measurer, a shock pump, a solid resting location for the frame of the vehicle, and the vehicle itself. The total wheel travel of the front end knuckle/wheel assemblies will be measured and checked against the design value/engineering requirement of 12” +/-2”. This test will be relevant to CR4, ER4, ER2, CR2, ER6, and CR6. In this experiment, total wheel travel of the car will be isolated and measured. No calculations follow this measurement.

- <u>Procedure:</u>
  1. Air up the front end tires to optimal operating pressure (7-8 psi)
  2. Air out both chambers of the front shock absorbers completely to allow the shocks to be compressed with minimal force application
  3. Move the front end of the vehicle onto a solid resting location (i.e. spare wheels/tires) to isolate frame movement, ensuring that the tires are just barely contacting the ground and that the shocks are fully extended
  4. Have one person stand to the outside of the driver side wheel and extend the tape measurer from the ground to roughly 2 feet above the ground
  5. Have another person securely hold the frame to the solid surface and ensure no rotation occurs in the frame during the next few steps
  6. Have a third person note the height of the bottom of the tire using the extended tape measurer (should be flush with the ground at 0”)
  7. Using a fourth person, compress the driver side shock/wheel assembly upwards until full compression of the shock is reached
  8. Have the third person take a note of the position of the lowest point of the tire relative to the tape measurer
  9. Subtract the extended value from the compressed value to obtain the total wheel travel for the driver side
  10. Repeat steps 4-9 on the passenger side

- <u>Results:</u>

  In this experiment, we are looking for positive values (indicating vertical wheel travel) on the order of 12” +/-2”. In the event of a full shock compression, the high end of that tolerance would have the frame nearly bottomed out on the floor with a ride height that lands in the middle of our 10”-16” tolerance. This could be problematic but, depending on shock resistance via air pressure, we can mitigate this failure from occurring. The greatest advantage of high wheel travel would be added stability during corners to counter body roll and proper handling of unilateral obstacles to always keep the driver vertical/stable. Design goals point towards 12” of expected wheel travel but limitations from shock stroke length could limit this (or exceed this depending on orientation).

- <u>Conclusion:</u>

  Wheel travel is another critical design point that can enhance or destroy the performance of this vehicle during competition. A car with ample wheel travel will be able to comfortably handle all obstacles and rough terrain while not placing excessive strain on the driver. The driver comfort factor will become increasingly important during the 4-hour endurance race in the SAE competition.

Experiment 5 – Ackerman Angle Test:

- Test/Experiment Summary:
  As this Baja vehicle will rarely see speeds over 20 mph and will spend most of its life between 5-15 mph, low speed maneuverability is key. To enhance this attribute, a design point referred to as "Ackerman steering" has been induced in the team's design. This allows the inside wheel to turn more during a turn than the outside wheel, helping with turn in angle at low speeds. This experiment requires a tape measurer, chalk, a digital (or analog) angle gauge, a shock pump, and the car itself. The Ackerman angle will be measured and checked against the design value/engineering requirement (50% +20%/-10%). This test will be relevant towards CR5 and ER5. In this experiment, the steering of the car will be isolated at ride height and the steering angle of the inner/outer wheels will be measured at neutral and full lock positions. From here, the Ackerman formula will be used to calculate the pro-Ackerman percentage being achieved by the car.

- Procedure:
  1. Air up the front end tires to optimal operating pressure (7-8 psi)
  2. Air out the front shock absorbers to facilitate 30% compression of the shock body at ride height (start at 150 psi in the small chamber and 65 psi in the large chamber and reduce until satisfied)
  3. Verify that the car is on a flat surface and the wheels are pointed forward (adjust tie rods as needed until wheels are at zero toe)
  4. Use a tape measurer and a piece of chalk to mark out the center line of each front tire and draw a line extending 12" forward from each centerline directed parallel to the tire centerline
  5. Without moving the car, turn the steering wheel to full lock towards the driver side
  6. Repeat step 4 making sure to draw the centerline marks as parallel to the tire centerline as possible for an accurate angle calculation
  7. Move the vehicle back and use a tape measurer or straight edge to extend the chalk lines of each tire back until the pairs intersect each other
  8. Use an angle gauge to measure the inner wheel angle (higher angle) and the outer wheel angle (lower angle) and note these values
  9. Repeat steps 4-8 while turning the steering wheel full lock towards the passenger side to verify consistency between angles

- Results:
  The inner wheel angle should be roughly 45 degrees, which will conveniently be the functional limitation of the cv axle in the 4WD system. The outer wheel, if everything was constructed properly, should be roughly 30 degrees to achieve a 50% Ackerman steering percentage. With these real-world values, the Ackerman calculation can be performed to verify against design metrics:

$$Ackerman\% = \frac{\theta_{inner} - \theta_{outer}}{\theta_{inner}} * 100$$

Equation 1: Ackerman Steering %

Any values between 40% and 70% are considered acceptable and will yield good low speed performance during the maneuverability and suspension/traction events.

- Conclusion:
  During the manufacturing stage, extra care was taken to construct the steering system identically to the design plans with special consideration towards the steering geometry being crucial. The low-speed maneuverability of this vehicle will allow it to succeed during competition and this experiment will help bring peace of mind to the front end design team that the vehicle will perform as intended during operation.

Experiment 6 – Knuckle Strain Test:

- Test/Experiment Summary:
  Ensuring the structural integrity of critical componentry is important for keeping the vehicle safe for the driver and competitive in competition. To improve upon our knowledge of the vehicles ability to absorb impact without permanent deformation or component failure, strain gauges and accelerometers will be fixed to multiple locations of concern on the vehicle for the duration of testing. The gathered data on the forces and strain experienced at these locations will help assess whether the components can perform to the required level for competition. Evaluations of the components will be relevant towards meeting the requirements of ER6, CR6 CR4, and CR2.

- Procedure:
  1. Affix strain gauges to locations deemed concerning in FEA simulations.
  2. Affix accelerometers to knuckle and frame of vehicle.
  3. Collect data during vehicle testing
     - Driving vehicle over obstacles like those seen at the Gorman raceway
  4. Interpret accelerometer data to ensure forces seen during testing align with forces used for FEA simulation
  5. Interpret strain data to ensure knuckle strain does not exceed calculated and expected strain during use.

- Results:
  Strain gauges should report a lower strain than expected values on the driver knuckle. Lower than expected values would help to validate proper FEA simulations and will ensure the knuckle will not fail due to impact. Accelerometer data will be used to back calculate impact force the vehicle will see during testing. This calculated force value will be compared against the 2300lbf impact force used for FEA simulation. If the impact force value is below the 2300lbf value used for FEA, the knuckle and all associated hardware will be capable of withstanding impact failure.

- Conclusion:

  Collecting strain and impact force data will stand to validate all previous calculations and FEA simulations. Validating all calculations and simulations helps to ensure the vehicle is safe to operate and will remain intact for the duration of the race competition.

Rear End

To evaluate the Rear suspension setup the team has plans to execute 5 tests/experiments. This will verify the vehicle can perform highly at competition. These plans are explained below.

Experiment 1 – Trackwidth Assessment:

- Test/Experiment Summary:

  This static assessment is similar to the front-end team's assessment. As the Front team stated the SAE rules state that no vehicle is to exceed 64." From many conversations with the front team, we decided to run close to 2 inches less in rear. For this measurement, the team will estimate the amount of weight to be on the system, and then dial in the shocks. This will be done so that at the proper ride height the trackwidth is within compliance of both team and SAE expectations. The materials needed for this are the SHARK software, a tape measure, and the vehicle.
- Procedure:
  1. Air up the rear end tires to optimal operating pressure (7-8 psi)
  2. Air out the rear shock absorbers replicate ride height of 8 inches off the ground (this is most likely what the orientation will be during tech inspection)
  3. Verify that the car is on a flat surface and the camber/toe angle are aligned with SHARK's expectations
  4. Take a tape measurer and measure the distance between the outer sidewall of the passenger side tire and the outer sidewall of the driver side tire

- Results:

  The expected value for this measurement is 61 inches, based off of CAD articulation, SHARK analysis, and prototyping. However, after manufacturing this value is expected to fall within the range 58 inches to 62 inches.

- Conclusion:

  After this assessment the team will also verify that the rear suspension is in compliance with SAE's rules. This is the main rule that would prevent the car from competing for this subsystem. The measurement will also verify to the team that we are running 2 inches more narrow in the rear.

Experiment 2 – Ground Clearance/Rear Suspension Travel Check:

- Test/Experiment Summary:

  This static test verifies the expected design travel measurements for the team. For this procedure, a series of measurements will be conducted at ride height, max compression, and max droop to verify the travel of the rear end of the vehicle. For this check, a tape measure, a shock pump, the SHARK software, and the car will all be necessary.
- Procedure:
  1. Air up the rear end tires to optimal operating pressure (7-8 psi)

2. Air out the rear shock absorbers replicate ride height of 8 inches off the ground (this is most likely what the orientation will be during tech inspection)
3. Verify that the car is on a flat surface and the camber/toe angle are aligned with SHARK's expectations
4. Compress the shocks on both sides until both shocks are fully compressed
5. Have another member use the tape measure and measure the distance from the frame to the ground (this is the compressed clearance measurement)
6. Next, use the shock pump and air the shocks up until the shocks are at full droop
7. Conduct another clearance measurement (this is the droop clearance measurement)

- Results:

These measurements will work to confirm the teams expected numbers for droop and compressed clearance (17 and 5, respectively). In addition, the team will also be able to calculate the vehicles travel by using the formula:

$$Travel = Droop\ Clearance\ -\ Compressed\ Clearance$$

Equation 2: Travel formula

Knowing the vehicle travel will help to determine what setups will be ran for different events at competition. The travel the team expects to see based off of CAD articulation is 12 inches. However, this is expected to be in the range of 11-13 inches.

- Conclusion:

Wheel travel is critical to maximizing traction on the wheels as the vehicle rolls over rough terrain, optimizing friction. As well as ensuring driver comfort as the car goes over jumps and rocks.

Experiment 3 – Wheel Angle Verification:

- Test/Experiment Summary:

This static test verifies the expected design camber angle, toe angle, and rearward axle path are aligned with the CAD. The materials required for this test is a tape measure, protractor, and the car.

- Procedure:

1. Verify the vehicle is at proper ride height the wheel orientation can be optimized.
2. For 3 through 6 verify the values are as expected. Adjust the camber links as needed for the suspension.
3. At ride height the wheel values should be -3 degrees for camber angle and 0 degrees for toe angle.
4. At full compression the wheel values should be -8 degrees for camber angle and -1 degrees for toe angle.
5. At full droop the wheel values should be 3 degrees for camber angle and 1 degree for toe angle.

- Results:

The measurements should all be within the range of ±2 degrees inches for these measurements. There are no calculations following this verification.

- Conclusion:

The camber and toe angle of the rear end of the vehicle are critical to the robustness of the design. They will help to maximize the amount of traction that will be produced in the wheels with the ground.

Experiment 4 – FEA Accelerometer Confirmation:

- Test/Experiment Summary:

  This testing is the first of the dynamic testing. This will be conducted once the vehicle is driving. The idea is to do a sanity check proving that all the components will hold up to common loads the car will see at competition. The team rather have parts of the car break here rather than at the competition in Gorman. For this test an accelerometer will be used to generate values the team can then calculate forces the components see. The materials needed for this will be some Arduino code that stores data from the accelerometers, accelerometers themselves, a running vehicle, and a scale.
- Procedure:
  1. First an accurate weight of the vehicle will be weighed using the scales (this will be the mass value, m)
  2. Next up will be to finalize the code of the Arduino to store values of the common accelerations
  3. Now load the code to the Arduino for the eCVT. (This should be able to do both)
  4. Hook up the accelerometer to the component being tested (should be placed near critical design points)
  5. To collect data the car will be taken around the track behind the bus station.
  6. Collect data for the hub, trailing arm knuckle, trailing arm shock point, both camber links.
- Results:

  These results will then be used with the equation below:

  $$Force = mass * acceleration$$

  Equation 3: Equation to calculate expected forces

  The team will then use these forces to compare to the forces used for FEA. The idea is to have the test forces be less than the expected forces.
- Conclusion:

  This verification will allow the team to have some ease at competition. As we will know the components will be strong enough to endure anything the track makers throw at the team while ensuring the robustness of the vehicle.

Experiment 5 – Shock Setup Testing:

- Test/Experiment Summary:

  The purpose of this dynamic testing will be to identify the best performance of the vehicle for each event. At Gorman's competition the team is expecting to adjust the shocks and camber based on which event is going on. This will hopefully optimize the cars performance in each event, resulting in better placement. The relevant events are, acceleration, maneuverability, sled pull, suspension, and endurance
- Procedure:
  1. The acceleration event is most likely going to be a straight away seeing how fast the vehicle is. For this event the team will mock race behind the bus station. We time the car and adjust until the car consistently performs well.
  2. This will be repeated for maneuverability, sled pull, suspension, and endurance.

3. Each time the suspension geometry will be written down so the setups can be easily repeated for competition.

- Results:
  The results from the testing will allow for the team to become prepared for competition. This allows the car to perform the best at competition. There are no calculations following this test.
- Conclusion:
  In conclusion this will make the team remain competitive with top tier teams.

Drivetrain

Experiment 1 – 4WD Test

- Test/Experiment Summary: One of the competition requirements is for the vehicle to be four-wheel drive. The way to test this ability is to lift up the rear wheels of the vehicle onto blocks leaving the front wheels on the ground. Then, by accelerating the vehicle the team will know whether or not the front wheels are receiving power. If the car does not accelerate off the blocks, then the four wheel drive system is not working properly, and steps must be taken to correct this for competition.
- Procedure:
  1. Jack the rear wheels of the car off of the ground leaving the front wheels on the ground.
  2. Gently accelerate the car to test whether or not the car accelerates forwards off of the blocks.
- Results: The result of this simple test will indicate to the team whether the four-wheel drive system is operating as expected.
- Conclusion: The functionality of the four-wheel drive system is required for the competition. If the vehicle does not have a functioning four-wheel drive system, then the team will not pass inspection and will not compete. For this reason, it is necessary to ensure that the system is functioning properly.

Experiment 2 – Weigh Components

- Test/Experiment Summary: To see if the subteam has met the goal of keeping the components of the subsystem under a total of 60 pounds, not including the engine, we will need to measure each of the components of the subsystem. Since the scales on hand at the machine shop are inexpensive analog bathroom scales, it is important not to directly measure the weight of the part on the scale because the scales are inaccurate in the lower range. To get a more accurate reading it helps to stand on the scale with the part and measure the difference in weight between holding the part and not.
- Procedure:
  1. Zero out one of the shop scales using the dial.
  2. Step onto the scale without the component in hand and record weight.
  3. Pick up the component and record total weight.

4. Subtract the total weight from initial body weight to obtain the weight of the part being measured.

- Results: The results of this test will show the team whether or not we have met the initial design goal of keeping the total wight of the system below 60 pounds.
- Conclusion: It is imperative to optimize parts for weight in a racing vehicle. The performance of the vehicle depends largely on the weight of the vehicle which means that minimizing weight of the drivetrain components can go a long way towards improving performance at competition.

Experiment 3 – Top Speed / Acceleration Test

- Test/Experiment Summary: The top speed and acceleration of the vehicle are important performance indicators of the car. The acceleration event at competition measures the vehicle's ability to, from a stop, cover a distance of 100 or 150 feet. The top speed of the car will have an impact on other dynamic events at the competition. Testing both of these parameters will indicate how successful the sub team was in designing a drivetrain that is capable of transferring power from the engine to the wheels. The terrain of the acceleration event at competition may "vary from pavement to loose dirt" so it is important that the team test on a variety of surfaces.
- Procedure:
    1. Find locations with long, straight, and ideally flat paths of varying terrain.
    2. Measure of distances of 100 and 150 feet from a designated starting line.
    3. Time the vehicle on how long it takes to cross the measured distances, and then continue driving until the vehicle stops accelerating to find the top speed of the vehicle.
    4. Repeat this test on the varying terrains to measure the values for all competition possibilities.
- Results: The results of this test will be indicative of the design success of the drivetrain team. We hope to have designed a car that is capable of
- Conclusion: The top speed of the car is an important performance indicator. The team may also consider testing acceleration of the vehicle as it is a competition event.

Experiment 4 – Dyno Test

- Test/Experiment Summary: Testing the vehicle on the dyno available at the machine shop will provide the team with a large sum of testing data. The dyno available is a chassis dyno which measures output from the wheels of the vehicle. The output of the test will show us the power and torque output at the wheels of the vehicle which gives the team valuable information about the efficiency of the drivetrain system. Further, it will provide valuable data on the performance of the vehicle as power is transferred through the system. The setup of this system is likely to be more difficult and have more tuning than is outlined below, but the basics are outlined.
- Procedure:
    1. Setup the dyno according to manufacturer instructions and protocols.

2. Hookup a laptop to the output of the dyno to collect the data outputs for torque and power.
3. Run the vehicles rear and front wheels on the dyno separately to see how torque and power are transmitted through the drivetrain system.
4. Interpret the results of the test and adjust the CVT and four-wheel drive system accordingly.
5. Retest the vehicle as necessary.

- Results: The team will use the results of this test to determine how the system is performing and whether or not any changes need to be made to the eCVT or the four-wheel drive systems.
- Conclusion: The data the team will collect from the dyno test will help us to determine how much power and torque is being delivered to the wheels which will inform us to competition performance.

Frame

To validate that the manufactured frame has met the engineering and customer requirements, The frame team will preform 5 tests/experiments. This will verify that the frame has been manufactured to optimize performance at competition.

Experiment 1 – Technical Inspection:

- Test/Experiment Summary:
  This static test will be a walk through with the client, Dr. Willy, to verify that the frame meets the technical requirements specified by the SAE BAJA Technical Inspection Sheet. Included in this is geometry verification, driver clearances, and driver safety requirements.
- Procedure:
  1. Verify that the car is ~100% complete
  2. Coordinate a meeting with Dr. Willy
  3. Perform member measurements and angle measurements
  4. With our largest driver in the car, verify driver clearances
  5. Inspect all safety systems to ensure compliance
- Results:
  The results of this experiment will be notes specifying any necessary improvements or modifications necessary to meet the technical requirements of the car and improve driver safety.
- Conclusion:
  This verification will allow the team to focus on other aspects of the car if the frame meets all requirements. Having to readjust the frame would set back frame and other subsystems and is not conducive to remaining on schedule.

Experiment 2 – Ergonomic Assessment:

- Test/Experiment Summary:
  This test has both static and dynamic components. Without driving the car, the driver seating position, steering wheel position, and pedal placement will all be assessed statically and in the field.
- Procedure:
  1. Coordinate meeting with all three drivers.

2. Seat each driver in the car and critique the seat positioning, steering wheel positioning, and pedal placement within the car without the car running.
3. Have each driver perform 5 full egress trials by exiting the vehicle after being fully secured by safety equipment.
4. Each of the 3 drivers will drive a test course in the car and give feedback about the steering wheel, seat, and pedals.

- Results:
  From the driver notes the frame team will modify the seat, steering wheel, and pedal placement, within reason, to accommodate the drivers to the highest degree possible.
- Conclusion:
  This testing will result in a higher performance at competition. Drivers will have longer endurance and improved performance because the ergonomics of the car allow them to focus on driving and not a lack of comfort.

Experiment 3 – Suspension Inspection and Evaluation:

- Test/Experiment Summary:
  This test will verify the suspension geometry through the travel and provide any improvements that the team might need to make to both the front and rear suspension subsystems.
- Procedure:
  1. All shocks will be pressurized to ~50% sag.
  2. Cameras will be positioned perpendicularly and parallel to the wheels for both the rear and front suspensions.
  3. 200lbf will be applied to the front of the car.
  4. 200lbf will be applied to the back of the car.
  5. All videos will be analyzed for any undesirable suspension movement.
- Results:
  Frame team and the respective suspension team will create and execute a plan to correct the undesired suspension characteristic. The test will be run until the wheel path and movement is desirable for both suspension teams.
- Conclusion:
  These results will ensure the car will be tuned and tweaked to optimal performance. This will increase handling, minimize component failure, and decrease driver fatigue. This should enable to drivers to perform better at competition and earn a better placement.

Experiment 4 – Drivetrain Compatibility:

- Test/Experiment Summary:
  This test will reflect the team's ability to integrate the drivetrain into the frame. This test will be static, but help the drivetrain tune their eCVT and the 4 wheel drive.
- Procedure:
  1. Ensure that the drivetrain is installed into the car
  2. Measure the tab and component placement relative to a significant member
  3. Compare measurement to CAD, ensure the difference between CAD and reality <%5
- Results:

These results will help us best optimize the drivetrain by staying true to design. Once we know we are accurate in our drivetrain integration, then we can begin to adjust measurements to best optimize components such as tensioner pullies.

- Conclusion:
  By using CAD as a baseline and optimizing for the manufactured car, the drivetrain tuning will become more efficient and streamlined. This will increase vehicle handling and driver integration in the car. This will also allow us to record drivetrain component placement and validate that each component is optimally placed if the drivetrain needs to be serviced.

Experiment 5 – Member Deflection and Deformation:

- Test/Experiment Summary:
  This test will be one of the few dynamic tests of the frame. Other than driver safety equipment, the roll cage and impact members ensure driver safety in the event of a crash. By analyzing the condition of members through deformation and deflection, we can verify members that undergo the most stress and validate the magnitude of their deformation.
- Procedure:
  1. Identify all roll cage and impact members.
  2. Perform impact testing at 30 mph.
  3. Denote any significant signs of deformation, specify member or joint and include visual documentation.
  4. Perform end-over-end roll at reasonable speed for testing ground.
  5. Denote and significant signs of deformation, specify member or joint and include visual documentation.
- Results:
  These results will validate the members and joints likely to undergo the greatest stresses. In doing so, we can compare our FEA CAD analysis with actual observation. The benefit of this comes in that we will work out any alarmingly deformed members before the Gorman competition, not during.
- Conclusion:
  In following SAE BAJA guidelines, we have verified that the characteristics of both primary and secondary members meet the requirements for each respective member category. The testing will prepare us for competition by testing the safety of the roll cage and impact members in a worst case scenario.

Specification Sheet Preparation

The CRs and ERs presented in are critical to the design and successful operation of the vehicle during competition. Each subteam will present summary tables in preparation for a formal specification sheet to be used as metrics of client satisfaction and engineering success.

Front End

The front end of this vehicle was built with some specific CRs/ERs in mind, which helped guide the design to a high standard of engineering performance. The summary tables of these CRs and ERs, as well as engineering/client satisfaction assessments for an eventual specification sheet, are included in the tables below.

Table 4: Front End CR Summary Table

Customer Requirement	CR Met? (✓ or X)	Client Acceptable (✓ or X)
CR1 - SAE Course Compliant		
CR2 - Adequate Ground Clearance		
CR3 - Adequate Traction		
CR4 - Safe Operation Over Rough Terrain		
CR5 - Agile Manuverability		
CR6 - Robust Design		

Table 5: Front End ER Summary Table

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met?(✓ or X)	Client Acceptable (✓ or X)
ER1 - Decrease Vehicle Width	64"	+0" / -4"			
ER2 - Increase Ride Height	10"	+6" / -0"			
ER3 - Increase Tire Traction (Zero Scrub Radius)	0"	+/- 1"			
ER4 - Increase Capability in Rough Terrain (Wheel Travel)	12"	+2" / -2"			
ER5 - Increase Turn-In Angle (Ackerman %)	50%	+20% / -10%			
ER6 - Increase Crash Durability (Collision Speed)	20 mph	+10 mph / -5 mph			

Rear End

The CR and ER summary tables represented in *Table 6* and *Table 7* will be used to assess if that requirement is met during the experimental testing phase. Maintaining these standards that were outlined at the beginning of the project will ensure that the client is happy with their final product and that all design requirements were addressed.

Table 6: Rear End CR Summary Table

Customer Requirement	CR Met? (✓ or X)	Client Acceptable (✓ or X)
CR1 - Reliable and Safe		
CR2 - Low Cost		
CR3 - Maximize Traction		
CR4 - High Maneuverability		
CR5 - Adjustable		
CR6 - Robust		

Table 7: Rear End ER Summary Table

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met?(✓ or X)	Client Acceptable (✓ or X)
ER1 - Decrease Vehicle Weight	50 lbs	±5 lbs			
ER2 - Increase Rearward Axle Path	1"	±1"			
ER3 - Increase Linkage Radii	20"	±2"			
ER4 - Decrease CV Axle Angle	20°	±5°			
ER5 - Vehicle Width	60"	±2"			
ER6 - Increase Ground Clearance	11"	±3"			
ER7 - Decrease Camber Link Angle	15°	±5°			
ER8 - Increase Camber Gain	2"	±1"			

Drivetrain

The CR and ER tables generated below will be used to determine if the requirements are met during testing and if the client is satisfied with the results.

Customer Requirement	CR Met? (✓ or X)	Client Acceptable (✓ or X)
CR1 - High Top Speed		
CR2 - Maximum Efficiency		
CR3 - High Torque		
CR4 - High Service Life		
CR5 - Low Weight	ü	ü
CR6 - High Transmission Range		

Table 8 : Drivetrain ER Summary Table

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met?(✓ or X)	Client Acceptable (✓ or X)
ER1 - Top Speed	40 mph	+/- 5mph			
ER2 - Drivetrain Efficiency	80%	+20% / -5%			
ER3 - Torque to the Wheels	400 lb-ft	+/- 25 lb-ft			
ER4 - Service Life	100 Hours	+/- 5 Hours			
ER5 - Total Drivetrain Weight (wo/ Engine)	60 lbs	+2.5lbs / -20lbs			
ER6 - Total Transmission Range	01:04.5	+/- 0.25			

Engineering Requirement	Target
ER1 - Top Speed	40 mph
ER2 - Drivetrain Efficiency	80%
ER3 - Torque to the Wheels	400 lb-ft
ER4 - Service Life	100 Hours
ER5 - Total Drivetrain Weight (wo/ Engine)	60 lbs
ER6 - Total Transmission Range	01:04.5

Engineering Requirement	Target
ER1 - Top Speed	40 mph
ER2 - Drivetrain Efficiency	80%
ER3 - Torque to the Wheels	400 lb-ft
ER4 - Service Life	100 Hours
ER5 - Total Drivetrain Weight (wo/ Engine)	60 lbs
ER6 - Total Transmission Range	4.50

Engineering Requirement	Target
ER1 - Top Speed	40 mph
ER2 - Drivetrain Efficiency	80%
ER3 - Torque to the Wheels	400 lb-ft
ER4 - Service Life	100 Hours
ER5 - Total Drivetrain Weight (wo/ Engine)	60 lbs
ER6 - Total Transmission Range	01:04.5

Engineering Requirement	Target
ER1 - Top Speed	40 mph
ER2 - Drivetrain Efficiency	80%
ER3 - Torque to the Wheels	400 lb-ft
ER4 - Service Life	100 Hours
ER5 - Total Drivetrain Weight (wo/ Engine)	60 lbs
ER6 - Total Transmission Range	4.50

Frame

The ER and CR tables shown below will be used to assess the requirements of the frame design. Successful testing of the designated requirements will ensure a properly functioning vehicle and maximize client satisfaction.

Table 9: Frame CR Summary Table

Customer Requirement	CR Met? (✓ or X)	Client Acceptable (✓ or X)
CR1 - Satisfy SAE BAJA Rules		
CR2 - Design for Manufacturing		
CR3 - Rigid		
CR4 - Lightweight		
CR5 - Maneuverable		
CR6 - Aesthetically Pleasing		
CR7 - Durable		
CR8 - Fast		
CR9 - Stable		
CR10 - Cost Effective		

Table 10: Frame ER Summary Table

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met?(✓ or X)	Client Acceptable (✓ or X)
ER1 - Decrease Weight	60 lbs	+5 lbs / -15lbs			
ER2 - Decrease Body Length	62"	+/- 2"			
ER3 - Decrease Body Width	62"	+/- 2"			
ER4 - Decrease Cost	$700	Maximum $800			
ER5 - Increase Strength	53 Kpsi	Minimum 53 Kpsi			
ER6 - Optimize Suspension	Accurate to CAD	+/- 5%			
ER7 - Integrate Drivetrain Assembly	Accurate to CAD	+/- 5%			

QFD

A House of Quality/Quality Function Deployment diagram allows engineers to link CRs to ERs and determine which tested ERs link to specific CRs (and even other ERs). A QFD for each subteam is presented below with ER/CR correlations and brief comments as necessary.

Front End

Several CRs and ERs are linked together due to relevance towards each other via shared engineering principles, resulting in the creation of a QFD. The front end's QFD allowed for the proper correlation of ERs/CRs and the optimization of experimental protocols. Please see the table below of a copy of this QFD.

Table 11: Front End QFD

System QFD

Project:	SAE Baja '24
Date:	09/18/2023

#	Technical Requirement	1	2	3	4	5
1	Decrease Vehicle Width					
2	Increase Ride Height					
3	Increase Tire Traction	-3				
4	Increase Capability in Rough Terrain	3	9	6		
5	Increase Turn-In Angle				3	
6	Increase Crash Durability	6	-3		6	

Legend	
A	NAU #74
B	Baja ETS
C	Cornell Racing

#	Customer Needs	Customer Weights	Decrease Vehicle Width	Increase Ride Height	Increase Tire Traction	Increase Capability in Rough Terrain	Increase Turn-In Angle	Increase Crash Durability	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
1	Comply with track dimensions	4	9									A	BC
2	Adequate ground clearance	2		9	6	9		3			A	C	B
3	Adequate traction	3	3	3	9	6	3	3			A		BC
4	Safe operation over rough terrain	3	6	6	3	9		9				ABC	
5	Agile manuverability	4	6	3	6	3	9					A	BC
11	Robust design	3		3		3		9			BC	A	
	Technical Requirement Units		Inches	Inches	Degrees (Scrub Rad)	Inches (Wheel Travel)	Degrees	mph					
	Technical Requirement Targets		64	10	0	12	40-100	40					
	Absolute Technical Importance		87	66	72	84	45	69					
	Relative Technical Importance		1	5	3	2	6	4					

The QFD reveals that several of the CRs and ERs work towards the same goal (ratings of 6 and 9) while others tend to work weakly or inversely with each other (ratings of 3 or -3, not considered relevant at this point). These interaction effects are addressed based on engineering requirements and the associated experimental test plans below:

Experiment 1 – Trackwidth Assessment:

- Tested ER/CR: CR1, ER1
- Impacted ERs/CRs: CR6
- Comments: Trackwidth assessment is obviously highly related to the first ER/CR pair seeing as that is the reason for this experiment in the first place. The only other CR that relates to this experiment would be the need for robust design. A narrower car means more lateral clearance between obstacles and a more compact assembly that keeps a tight distribution of forces. The ER of collision speed has no relation to trackwidth.

Experiment 2 – Ground Clearance Check:

- Tested ER/CR: CR2, ER2
- Impacted ERs/CRs: CR3, CR4, ER4
- Comments: Ground clearance check, like experiment 1, is a highly specialized test that targets the second ER/CR pair closely. However, there is some overlap between ground clearance and the desire for a car that has superior traction and safe operation over rough terrain (including wheel travel). More clearance allows wheels to stay planted over obstacles without the risk of bottoming the frame out and allows more articulation out of the suspension before frame bottom out as well.

Experiment 3 – Scrub Radius Measurement:

- Tested ER/CR: CR3, ER3
- Impacted ERs/CRs: CR4, CR5, ER5
- Comments: Scrub radius measurement is purposefully designed to test a small aspect of suspension design covered in the third ER/CR pair. Though, this requirement of "adequate traction" has some overlap into the desire for safe operation over rough terrain as well as increasing the turn-in angle of the car (and associated Ackerman percentage). A good scrub radius keeps the wheels planted, leading to safer driver operation, and ensures that the tie rod pivot point is in a favorable location to induce Ackerman steering.

Experiment 4 – Wheel Travel Verification:

- Tested ER/CR: CR4, ER4
- Impacted ERs/CRs: ER2, CR2, ER6, CR6
- Comments: Wheel travel verification is an experiment to measure the vertical articulation of the front suspension, testing the fourth ER/CR pair directly. However, wheel travel is closely related to the desire for ground clearance and crash durability, the second/fourth ER/CR pair. A car with more suspension travel generally allows for more ground clearance and can avoid rigid obstacle collisions at a higher speed.

Experiment 5 – Ackerman Angle Test:

- Tested ER/CR: CR5, ER5
- Impacted ERs/CRs: N/A

- Comments: The Ackerman angle test is a unique assessment of the vehicle's steering system concerning angular difference between the inner and outer wheels. As such, this experiment is only relevant to the fifth ER/CR pair.

Experiment 6 – Knuckle Strain Test:

- Tested ER/CR: CR6, ER6
- Impacted ERs/CRs: CR2, CR4
- Comments: The knuckle strain test is designed to assess the robust design of a critical part of the front-end assembly, closely related to the sixth ER/CR pair concerning collision speed durability. This testing can also link to the need for increased ride height (CR2) and increased capability in rough terrain (CR4). A more durable off-road vehicle generally has more ground clearance and, therefore, more capability in rough terrain.

Rear End

The QFD for the Rear suspension is as shown.

1	Decrease weight						
2	Increase strength	-3					
3	Increase rearward axle path						
	Increase linkage radii	-1					
4	Increase ground clearance	-6	3	1			
5	Vehicle width	1	3		6	2	
6	Decrease CV axle angle		3	-2	1		

Legend	
A	CWRUM
B	RIOT Baja
C	ETS BAJA

			Technical Requirements							Customer Opinion Survey				
	Customer Requirements	Customer Weights	Decrease weight	Increase strength	increaseward rear axle path	increase linkage radii	Increase ground clearance	Vehicle Width	decrease CV axle angle	1 Poor	2	3 Acceptable	4	5 Excellent
1	Tunability	2	2	3	8	7	3	2	7	C	A			B
2	Servicability	2	2	6						A		BC		
3	Reliability	5	3	9	3	2			7			A	B	C
4	Ease of manufacturing	3	6	7	1	1		1	1		C	A		B
5	Low cost	5	9	9	3	3		1	3			A	C	B
6	Maximum Traction	2	7		8	8		3	1				B	AC
7	Maneuverability	4	5	1	8	6	5	7	1				AB	C

8	Technical Requirement Units	lb	Psi	in	in	in	in	degrees
	Target Requirements	<50	NA	<1	20	>8	<64	180
10	Absolute Technical Importance	120	133	97	82	26	46	73
11	Relative Technical Importance	2	1	3	4	7	6	5

Experiment 1 – Trackwidth Assessment:

- Tested ER/CR: CR1, CR4, CR5, ER1, ER3, ER5, ER
- Impacted ERs/CRs: ER5

- Comments: Trackwidth assessment is highly related to the first ER/CR seeing as that is the reason for this experiment in the first place. The other CRs/ERs that relate to this experiment would be the need for robust design. A narrower rear end means more lateral clearance between obstacles and a more compact assembly that keeps a tight distribution of forces.

Experiment 2 – Ground Clearance/Rear Suspension Travel Check:

- Tested ER/CR: CR1, CR3, CR4, CR5, ER1, ER5, ER
- Impacted ERs/CRs: CR1, CR3, CR4, CR5, ER1, ER5, ER
- Comments: Ground Clearance/Travel check assessment is highly related to the most of the ERs/CRs seeing as that the test is a basic function of suspension is to keep the car off the ground.

Experiment 3 – Wheel Angle Verification:

- Tested ER/CR: CR1, CR3, CR4, CR5, ER1, ER2, ER5, ER6
- Impacted ERs/CRs: CR1, CR3, CR4, CR5, ER1, ER2, ER5, ER6
- Comments: Wheel angle verification is critical to most ERs/CRs. Getting the angle of the wheel throughout the travel right is critical to the disperse power the wheels.

Experiment 4 – FEA Accelerometer Confirmation:

- Tested ER/CR: All DRs
- Impacted ERs/CRs: All DRs
- Comments: This impacts every single component on the vehicle.

Experiment 5 – Shock Setup Testing:

- Tested ER/CR: All DRs
- Impacted ERs/CRs: All DRs
- Comments: This impacts all DRs because every component plays a role in this testing.

Drivetrain

After developing the customer and engineering requirements, it can then be analyzed in the QFD seen below. The drivetrain QFD helps quantify the relative importance between the two requirements and can be further used to gauge how the drivetrain subsystems can be optimized.

Table 12: Drivetrain QFD

		top speed	drivetrain efficiency	torque to the wheels	service life	total system weight (w/out engine)	total transmission range	Meets HROE Guard specifications
1	top speed							
2	drivetrain efficiency							
3	torque to the wheels	6						
4	service life							
5	total system weight (w/out engine)		3					
6	total transmission range		6					
7	Meets HROE Guard specifications					-9		

Legend
A Cornell 2023
B NAU 2021 #21
C NAU 2023 #74

	Customer Needs	Customer Weights	Technical Requirements: top speed	drivetrain efficiency	torque to the wheels	service life	total system weight (w/out engine)	total transmission range	Meets HROE Guard specifications	Customer Opinion Survey: 1 Poor	2	3 Acceptable	4	5 Good
1	fast	5	9	6	6	3	6	6	1	C			B	A
2	High effeciency	3	9	9	6	6	3	6	3	C		B		A
3	fast acceleration	5	3	6	9	3	9	9	1	C		B		A
4	durable	1	1	6	1	9	1	4	9			AC		B
5	can crawl and go fast	4	9	6	9	3	3	9	1	C			B	A
6	NEEDS TO BE SAFE	5	1	1	1	6	1	1	9			C	B	A
7	Aesthetically Pleasing	3	9	1	9	3	9	9	3		C		A	B
8														
9														
10														
11														
	Technical Requirement Units		MPH	Unitles	Lbf/Ft	hours	lbs	Unitless	N/A					
	Technical Requirement Targets		40	80	400	1000	60	01:04.5	N/A					
	Absolute Technical Importance		156	125	162	108	129	165	86					
	Relative Technical Importance		4	6	3	7	5	2	1					

Based on the results, the team has determined that there are certain characteristics that the team must follow to have an effective drivetrain. The customer requirements and engineering requirements were evaluated immensely so that it would reduce any design flaws later in the design process.

Experiment 1 – 4WD Test

- Tested ER/CR: CR2, CR3, ER2, ER3
- Impacted ERs/CRs: CR2, CR3, ER2, ER3
- Comments: The operation of the 4WD system is critical because it must be functional, or the team will not pass tech inspection. Therefore, ensuring that all engineering requirements are met will guarantee a functioning four-wheel drive system.

Experiment 2 – Weigh Components

- Tested ER/CR: CR5, ER5
- Impacted ERs/CRs: CR5, ER5
- Comments: The performance of the vehicle relatively relies on the weight of the drivetrain components. Therefore, optimizing all parts are necessary to improve performance at competition.

Experiment 3 – Top Speed / Acceleration Test

- Tested ER/CR: CR1, CR4, ER1, ER4
- Impacted ERs/CRs: CR1, CR4, ER1, ER4
- Comments: Both CR1 and ER1 are necessary in determining the performance of the drivetrain. Achieving a high-top speed will also correlate to acceleration testing of the vehicle.

Experiment 4 – Dyno Test

- Tested ER/CR: CR3, CR4, CR6, ER3, ER4, ER6
- Impacted ERs/CRs: CR3, ER3
- Comments: This crucial in determining the output power from the wheels and relates critically to the engineering requirements of achieving high torque.

Frame

With both the CR and ER being important to the design and manufacturing of the frame, the requirements are compared in a QFD to find similarities between requirements and identify the most important requirements to focus on in production and testing. The completed QFD is shown below.

Table 13: Frame QFD

System QFD

Project: Baja 24 Frame
Date: 9/14/23

	Decrease weight	Decrease length of body	Decrease width of body	Decrease Cost	increase aerodynamics	Increase strength of frame
Decrease weight						
Decrease length of body	6					
Decrease width of body	3	-9				
Decrease Cost	-9	3	3			
increase aerodynamics	-3	-6	3	-3		
Increase strength of frame	6	-3	-9	-6		

Legend

A	ETS Baja
B	SAE Beaver racing
C	Cornell Baja Racing

		Technical Requirements						Customer Opinion Survey				
Customer Needs	**Customer Weights**	Decrease weight	Decrease length of body	Decrease width of body	Decrease Cost	increase aerodynamics	Increase strength of frame	*1 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*
Rigid	3	1	6	3	3	1	9				ÀBC	
Easy to manufacture	3	3	3	1	3	6	3			B	AC	
Maneuverable	2	3	9	9	1	1	3					ABC
Aesthetics	1	3	1	3	3	9	1			C	B	A
Durable	2	3	1	3	3	3	9			AC	B	
Satisfy SAE Baja Frame Guidlines	4	3	1	6	3	1	6					ABC
Stable	3	1	3	9	1	3	6				C	AB
Fast	3	6	3	3	9	9	3				BC	A
Lightweight	4	9	6	3	9	3	6				ABC	
Affordable	3	9	6	3	9	6	6			ABC		
Technical Requirement Units		lbs	in	in	$	lbf	psi					
Technical Requirement Targets			64	64								
Absolute Technical Importance		123	112	120	134	108	154					
Relative Technical Importance		3	5	4	2	6	1					

The QFD reveals that several of the CRs and ERs work towards the same goal (ratings of 6 and 9) while others tend to work weakly or inversely with each other (ratings of 3 or -3, not considered relevant at this point). These interaction effects are addressed based on engineering requirements and the associated experimental test plans below:

Experiment 1 – Technical Inspection:

- <u>Tested ER/CR:</u> CR 1, CR 3, ER 3, ER 5
- <u>Impacted ERs/CRs:</u> CR 1, CR 3, ER 3, ER, 5
- <u>Comments:</u> This is the single most important testing plan for the frame. Passing technical inspection at the competition is the base requirement for competition and must be met. Most impacted ERs are ER3 and ER5, which directly correlate to specific SAE technical inspection rules.

Experiment 2 – Ergonomic Assessment:

- Tested ER/CR: CR 1, CR 9
- Impacted ERs/CRs: CR 1
- Comments: Technical inspection at competition dictates driver ergonomics and egress times for a vehicle to pass. These rules must be met. In addition, if ergonomics perform well, the driver will be more prepared to perform better in all events.

Experiment 3 – Suspension Inspection and Evaluation:

- Tested ER/CR: ER 3, ER 6
- Impacted ERs/CRs: CR 1, CR 2, CR, 5, CR 9, ER 6
- Comments: Properly performing suspension components will contribute to a higher performing vehicle. Propper installation of these components are key to performing well in race events.

Experiment 4 – Drivetrain Compatibility:

- Tested ER/CR: ER 7
- Impacted ERs/CRs: CR 1, CR 2, CR 8, ER 7
- Comments: Proper installation of the drivetrain components is key to an efficient and fast vehicle. Limiting problem area in the drivetrain during competition will lead to better results.

Experiment 5 – Member Deflection and Deformation:

- Tested ER/CR: CR 1, CR 3, CR 7, ER 5
- Impacted ERs/CRs: CR 1, CR 3, CR 4, CR 7, CR 10, ER 1, ER 5
- Comments: One of the most important parts of the frame design is minimizing weight while maximizing strength. Propper testing of the frame structure will ensure that real life use correlates properly to simulations and calculations performed during the design stage.