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# BAJA SAE CAPSTONE

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# Abstract


The goal of this project was to design, build, and test a vehicle to compete in the 2023 Oregon Baja SAE competition. The vehicle was designed from scratch aside from various parts purchased by previous LMU Baja teams. The preliminary design phase consisted of research and testing to create design requirements and goals for improving vehicle design. Vehicle performance was evaluated according to performance in top speed, acceleration, traction, maneuverability, braking, and suspension dynamic tests.

The vehicle drivetrain was modeled in MATLAB to determine vehicle’s top speed and 150 ft acceleration time. The model was then refined after gathering CVT revolution data via hall sensors. Available CVT parameters were tuned to optimize vehicle torque and power, and the chain reduction was chosen to optimize vehicle acceleration. The traction, maneuverability, and braking performance of the vehicle were designed and dynamically tested to meet design requirements. The vehicle suspension underwent a series of dynamic tests to gather acceleration and gyroscopic data to tune available suspension parameters. The suspension parameters were tuned to optimize driver comfort and low-speed and high-speed obstacle impacts. An ideal rear suspension spring rate was found to improve vehicle handling. The new spring was then compared to the original settings in a controlled test. The chassis underwent finite element modeling to determine member stress and deflection. A torsional rigidity test was also conducted on the model.

The vehicle was redesigned and tuned according to the results of dynamic testing. The vehicle met all requirements specified by the 2023 Baja SAE Rulebook. The team will participate in all static and dynamic events at the 2023 Baja SAE Oregon competition.

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# Introduction

The goal of this capstone project is to design, build, test, and complete a race ready vehicle for the 2023 Baja SAE competition. The team will develop a single seater, 4WD, off-road race vehicle capable of meeting SAE requirements by the end of March 2023. Baja SAE divides competition events into static and dynamic categories. Static events include Design, Cost, and Business presentations, while dynamic events include Acceleration, Hill Climb (Traction), Maneuverability, Suspension or Rock Crawl, and Endurance events. Acceleration, top speed, maneuverability, handling, and suspension impact tests will provide insight into dynamic event performance. The team will individually tune drivetrain, suspension, and steering variables to optimize driving performance for each dynamic event.

The capstone team will generate the overall vehicle design, and the Baja Lions Racing Club will carry out fabrication with the capstone team. The Baja Lions Racing club is divided into four sub-teams: Drivetrain, Chassis, Suspension, and Ergonomics. The capstone team will manage all sub-team efforts ensuring proper system integration. The vehicle currently exhibits fully functional 4WD and independent suspension articulation. Improvement of all sub team capabilities depends on vehicle performance during dynamic testing. Test results will drive future design needs and changes allowing for vehicle optimization. The Baja Lions Racing Team plans to compete in the 2023 Baja SAE Oregon competition in Summer 2023 with a fully functioning and race-legal vehicle.

# Problem Statement

An off-road vehicle is to be produced that must satisfy SAE requirements and meet performance criteria to be competitive in Baja SAE dynamic events. An existing vehicle will be analyzed, modified, and tested to improve vehicle dynamic performance. A well performing vehicle will reliably exhibit superb handling, acceleration, and suspension characteristics.

# Background

**Baja SAE Competition:**

The Baja SAE competition is a part of SAE International’s Collegiate Design Series (CDS) designed to prepare engineering students for real-world engineering challenges. The Baja SAE challenges students to design, engineer, and build a vehicle suitable for a recreational user market. The vehicle design, cost, and performance will be analyzed by a fictitious manufacturing firm according to the vehicle’s performance in static and dynamic events.

Static events consist of a Design Evaluation, Cost Evaluation, and Business Presentation. The objective of the engineering Design Evaluation is to evaluate the design of the vehicle and compatibility with the intended recreational market. The goal of the Cost Evaluation is to show the cost/benefit analysis for design decisions. The Business Evaluation event evaluates the team’s business, logistical, production, and technical capability that will convince outside parties to invest in the team’s concept.

Dynamic events consist of an Acceleration, Hill Climb or Traction, Maneuverability, Suspension or Rock Crawl, and Endurance event. Specialty dynamic events depend on the competition location and may include rock crawl and mud bog events. The endurance event comprises the largest part of the dynamic events and tests the vehicle’s ability to race over rough terrain for four hours.

**Previous Work:**

The 2019 LMU capstone team registered for the Baja SAE competition but failed to complete building the vehicle. The design for a 2WD vehicle was made along with a full CAD model and cost report. In 2020, a senior capstone team designed a new 4WD drivetrain, but failed to manufacture it. The current vehicle utilizes various components purchased and built by the 2019 and 2020 teams; however, the overall vehicle design is entirely new.

During Summer 2022, the majority of the vehicle was designed and built. The 2019 chassis was modified to fit a new 4WD drivetrain along with double-A arm suspension for each wheel. The vehicle's suspension system and 4WD drivetrain were in operation by the start of the Fall 2022 semester. The vehicle did not meet Baja SAE safety and regulatory requirements. The 2023 rules require the 14 hp Kohler engine, which replaces the 10 hp Briggs & Stratton engine.

## System Requirements

**Table 1.** System requirements per SAE rules and desired performance parameters.

| Rule Number | Category | Parameter | Requirement | Capability | Margin | Basis |
|---|---|---|---|---|---|---|
| D.3 | Dynamic Events | Top Speed | Reach a top speed of 25 mph on a dirt straightaway | 23 mph | 3 mph | By Testing |
| D.3 | Dynamic Events | Acceleration | Run a 100-foot course from standstill in 5.5 seconds and 150 ft course in 6.5 seconds | 150 ft in 7 seconds | 0.25 seconds | By Testing |
| D.4 | Dynamic Events | Traction | Climb 40° incline | | | SAE Recommendation |
| D.5 | Dynamic Events | Maneuverability | Turning radius of 10 ft | 12 ft | 2 ft | By Testing |
| D.6 | Dynamic Events | Suspension/ Maneuverability | Increase lateral acceleration and decrease body roll | Improved | | By Testing and Analysis |
| D.6 | Dynamic Events | Suspension | Wheel travel of 10 inches | 12.6 inches | 3 inches | By Testing |
| D.6 | Dynamic Events | Suspension | Achieve driver desired low-speed and high-speed vibrational characteristics | Comply | | By Analysis Testing |
| D.6 | Dynamic Events | Suspension | Ride height of at least 10 inches | 12 inches | 2 inches | By Design |
| B.1.1-1.2 | Design Requirements | General | Capable of carrying 6'3 250 lb person | Comply | | By Design |
| B.1.4-1.5 | Design Requirements | General | 4WD capability | Comply | | By Design |

| | | | | | | |
|---|---|---|---|---|---|---|
| B.3.1-3.7 | Design Requirements | General | Roll cage meets SAE safety and size requirements | Comply | | By Design |
| B.4.1-4.5 | Design Requirements | General | Driver restraint meets SAE safety requirements | Comply | | By design |
| B.7.1-7.2 | Design Requirements | Controls | Braking system meets SAE safety requirements | Comply | | By Testing |
| B.10.1-10. 7 | Design Requirements | Electrical System | Electrical systems meets SAE safety requirements | Comply | | By design |

The design must satisfy all SAE rules and guidelines and meet additional vehicle performance requirements deemed necessary for success in dynamic events. Requirements to perform successfully in the acceleration event include the 100 ft and 150 ft timed acceleration tests. The CVT, gear ratios, and tire size will be optimized to increase acceleration times in the acceleration tests. The top speed requirement will impact acceleration times as the gear ratios will need to achieve both a high top speed and the necessary torque to accelerate quickly. The traction event is closely related to acceleration as the gear ratio must also deliver enough torque to climb a 40 degree incline.

The maneuverability requirements are set to ensure the vehicle can complete the maneuverability event which tests handling and turning radius. Handling and turning radius depends on the suspension design and steering system. These requirements will be tested using accelerometers to measure lateral acceleration and reduce body roll when turning. Turning radius will be reduced with the design and implementation of a secondary steering input system.

The suspension system requirements will ensure proper vibrational characteristics and performance. The low speed and high speed suspension travel movements will be tested, and the available parameters will be tuned according to data analysis and driver preference. Ride height and wheel travel ensure proper clearance over obstacles and will be directly measured.

The vehicle must meet all rules and regulations specified by SAE. The general requirements of the chassis, safety equipment, braking performance, and electrical systems must satisfy SAE Baja rules. These requirements will be determined by design and testing.

## Design Alternatives Creation and Evaluation:

### DAQ - CVT/Powertrain RPM sensors

The drivetrain data capture DAQ system is designed to gather CVT and engine RPM data to optimally tune and modify the powertrain. This allows for the vehicle to be tailored for speed, torque and acceleration needed in the competition setting.

The laser tachometer is accurate and reliable, as it is the most used tool in industry for measuring revolutions per minute. However, it is expensive and the measurements from the tachometer cannot be easily recorded and stored using a DAQ unit, making the RPM data difficult to analyze.

Both the Hall effect sensor and the Hall effect gear tooth sensor can be used in conjunction with an Arduino microcontroller. The Hall effect sensor is the most cost-effective option but will require a mount to be made to ensure proper data collection. The Hall effect gear tooth sensor can be more easily mounted (and does not require the use of a magnet) and can measure RPMs with a high degree of accuracy. However, the gear tooth Hall effect sensor is significantly more expensive. Therefore, with cost and the ability to upload data to an Arduino unit being the deciding factors, the team decided to use a standard Hall effect sensor for RPM vs. time tests on the CVT and wheels.

**Table 2.** CVT/Powertrain RPM sensor selection matrix for capturing engine, CVT, wheel speed.

| RPM Sensor Design Alternatives | | Laser Tachometer | | Hall Effect Sensor | | Hall Effect Gear Tooth Sensor | |
|---|---|---|---|---|---|---|---|
| Selection Criteria | Weight | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating |
| Ease of Use | 20% | 5 | 1 | 3 | 0.6 | 4 | 0.8 |
| Complexity of Analysis | 25% | 1 | 0.25 | 4 | 1 | 4 | 1 |
| Accuracy | 25% | 4 | 1 | 4 | 1 | 4 | 1 |
| Reliability | 10% | 4 | 0.4 | 4 | 0.4 | 4 | 0.4 |
| Cost | 20% | 3 | 0.6 | 5 | 1 | 1 | 0.2 |
| | Total Score | | 3.25 | | 4 | | 3.4 |

### DAQ - Suspension Sensors

The goal of the suspension data capture DAQ unit is to optimize suspension tuning characteristics for improved vehicle handling. To achieve this goal, several different sensors were compared to create a viable data capture solution. A 3-axis accelerometer, 6-axis accelerometer, and suspension travel sensors were compared based on criteria objectives (**Table 3**). These sensors need to measure linear acceleration and angular acceleration while providing ease of analysis and low cost.

The 3-axis accelerometer is extremely cost efficient and provides vital linear acceleration data in 3 axes. However, this sensor does not easily allow for angular acceleration data collection, which is needed to show vehicle body roll and pitch characteristics. Additionally, the sensor requires complex analysis to give insightful information to the team for suspension tuning.

The 6-axis accelerometer costs the same as the 3-axis variant while also providing angular acceleration data. This sensor will allow the team to measure all important vehicle suspension characteristics including acceleration, body roll and pitch characteristics and low/high speed disturbance performance. The sensor requires relatively simple analysis and is a reliable option.

Suspension travel sensors can be used at all four shock absorbers to individually measure shock travel with linear potentiometers. This would be the most accurate and reliable as the wheel/shock displacements are measured directly. However, the sensors cost much more than the previous options and pose issues when measuring angular acceleration and data analysis.

**Table 3**. Suspension sensor selection matrix for characterizing suspension vibrational data

| Suspension Design Alternatives | | 3-Axis Accelerometer | | 6-Axis Accelerometer | | Suspension Travel Sensors | |
|---|---|---|---|---|---|---|---|
| Selection Criteria | Weight | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating |
| Acceleration | 15% | 4 | 0.6 | 4 | 0.6 | 5 | 0.75 |
| Angular Acceleration | 15% | 1 | 0.15 | 4 | 0.6 | 1 | 0.15 |
| Analysis Complexity | 30% | 2 | 0.6 | 3 | 0.9 | 1 | 0.3 |
| Reliability | 20% | 3 | 0.6 | 4 | 0.8 | 5 | 1 |
| Cost | 20% | 5 | 1 | 5 | 1 | 1 | 0.2 |
| | Total Score | | 2.95 | | 3.9 | | 2.4 |

### Steering System - Design Alternatives

The steering systems goals are focused on creating a reliable design to reduce the vehicle's steering radius. Various design alternatives pose a viable solution which can be implemented to the vehicle. These designs include a brake bias cutting brake and passive/active 4-wheel steering.

An active 4-wheel steer implementation will provide the best steering radius improvement. The complex hydraulic design will steer the rear wheels at a different rate compared to the front. The negatives of this design are the low reliability, high cost, and increased system complexity.

The passive 4-wheel steer design will give the vehicle significant improvements in steering radius, while using a less complex system when compared to active 4-wheel steer. The rear and front wheels will steer at the same steering rate, thus having fewer steering benefits when compared to passive.

The cutting brake design is composed of reliable components and is minimally complex. The design also poses cost benefits compared to 4-wheel steer alternatives. However, the cutting brake will provide less steering radius benefits. This system will be implemented to the vehicle to reduce steering radius due to its ease of design and application.

**Table 4.** Steering design alternative matrix to decrease the steering radius of the vehicle

| Steering Design Alternatives | | Cutting Brake | | 4-Wheel Steer Active | | 4-Wheel Steer Passive | |
|---|---|---|---|---|---|---|---|
| Selection Criteria | Weight | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating |
| Min Steering Radius | 25% | 3 | 0.75 | 5 | 1.25 | 4 | 1 |
| Complexity | 20% | 3 | 0.6 | 1 | 0.2 | 2 | 0.4 |
| Weight | 20% | 4 | 0.8 | 2 | 0.4 | 2 | 0.4 |
| Reliability | 25% | 4 | 1 | 2 | 0.5 | 3 | 0.75 |
| Cost | 10% | 3 | 0.3 | 1 | 0.1 | 2 | 0.2 |
| | Total Score | | 3.45 | | 2.45 | | 2.75 |

## Description of Project

### Drivetrain

The main goals of the drivetrain team are to implement a gear reduction that optimizes vehicle acceleration and to tune the CVT to optimize torque and power and to. From preliminary calculations for gear ratios, as the overall gear reduction of the drivetrain increases, the theoretical acceleration will increase while the theoretical top speed will decrease. Inversely, as the tire size increases (assuming the overall gear ratio stays the same), the theoretical acceleration decreases while the top speed increases. After attending the SAE Baja event in Arizona and seeing teams struggle with their vehicles' acceleration and traction on a rugged dirt course (particularly during the acceleration and suspension events), the team collectively made the decision to prioritize torque over top speed. Moreover, most teams, even in the 4-hour endurance event, never reached their vehicle's theoretical top speed. The goal will be to engineer a drivetrain system that optimizes gear ratios to meet the team's 6.5-second requirement for the 150-foot acceleration test while adjusting tire size and CVT characteristics to ensure the vehicle comes close to the 25-mph top speed target.

The iterative design cycle for the drivetrain team will be twofold. First, theoretical calculations for top speed and acceleration based on several factors (e.g., sprocket size, tire size, CVT high/low end, etc.) will determine the design's current capacity and will be used as a basis for addressing how changing each parameter will impact performance. Second, dynamic testing will be conducted in the form of 150-foot acceleration tests to validate theoretical acceleration data and determine how the CVT should be tuned for optimal performance. Capturing CVT and wheel RPMs will allow the team to correct and improve upon the initial theoretical calculations.

The theoretical calculations are composed in a working spreadsheet (A2) and a MATLAB drivetrain model (A3) and will be used for optimizing values obtained through analytical and dynamic drivetrain testing. Additionally, the theoretical calculations will allow the team to make a selection for the chain based on chosen sprocket ratios and the resulting gear reduction. At current capabilities (12-tooth sprocket to a 22-tooth sprocket), the current ANSI 50 chain will suffice. However, if there is a decision in the future to change the sprocket ratio for the chain drive, the driving sprocket speed and design power (calculated in the spreadsheet) can be applied to the design horsepower chain selection chart shown in the appendix (A4).

**Suspension**

The goal of optimizing the suspension system is to balance speed, control, and comfort through a variety of obstacles by tuning suspension variables according to DAQ data and driver feedback. Acceleration and gyroscope data collected by the DAQ provide key insights into handling and suspension characteristics. Analysis of the data combined with driver feedback allow for complete tuning and optimization of the suspension system. A series of maneuverability, low speed impact, and high-speed impact tests will be conducted to determine the performance of the suspension system. The DAQ unit will record the acceleration and gyroscope data during the tests and three available tuning parameters will be changed for each test. The tuning parameters include adjusting the low-speed compression ratio of the front shocks, adjusting spring preload, and testing various springs. The tuning parameters are to be optimized for the maneuverability, suspension, and endurance events.

A 6-axis MPU-6050 accelerometer will be used to capture 3-axis acceleration and 3-axis gyroscope data as discussed in the design alternatives section. The primary sensor will be placed on the vehicle's base plate below the vehicle's center of gravity. Placement below the center of gravity will provide the best estimate for the vehicle's global acceleration and rotational movements. Additional sensors may be placed at the front and rear of the vehicle, or the vehicle's four corners, to validate the readings of the primary sensor and provide insight into local accelerations of the vehicle. A sampling rate of at least 200 Hz is recommended and a low pass filter between 5Hz and 256Hz will be applied to smooth out the data [4]. High frequency vibrational analysis is not required as the low frequency acceleration and angular data provide enough information to determine global vehicle acceleration and vibrational responses.

The accelerometer sensor is used in conjunction with an Arduino Uno microcontroller and SD card output. The Arduino code was written to gather gyroscope or acceleration data with respect to microseconds. The selected data is then printed in real time to the on-board SD card allowing for complete standalone data collection with an external power supply. The functional test bench breadboard suspension DAQ unit is shown in **Fig. 2**. Data collection occurs every 20 milliseconds, with the ability to adjust the time. Current real-world testing shows the ability to record 4-minute data cycles at a file size of 400kb. Engine vibrations and chassis excitations do not halt or stop data recording. This is vital for vehicle testing and reliability of the suspension DAQ unit.

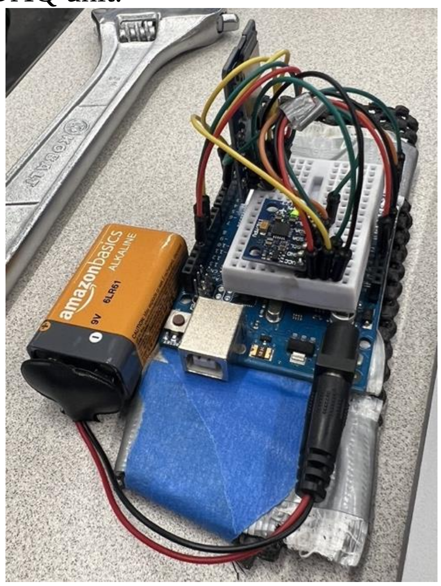


**Fig. 1.** Prototype Suspension DAQ Unit

The suspension DAQ unit was then housed in an airtight enclosure mounted to a 3D printed polymer pipe mount. This will allow for the DAQ unit to be mounted to the vehicles main frame tubes. The housing and DAQ unit are shown in **Fig. 2.**

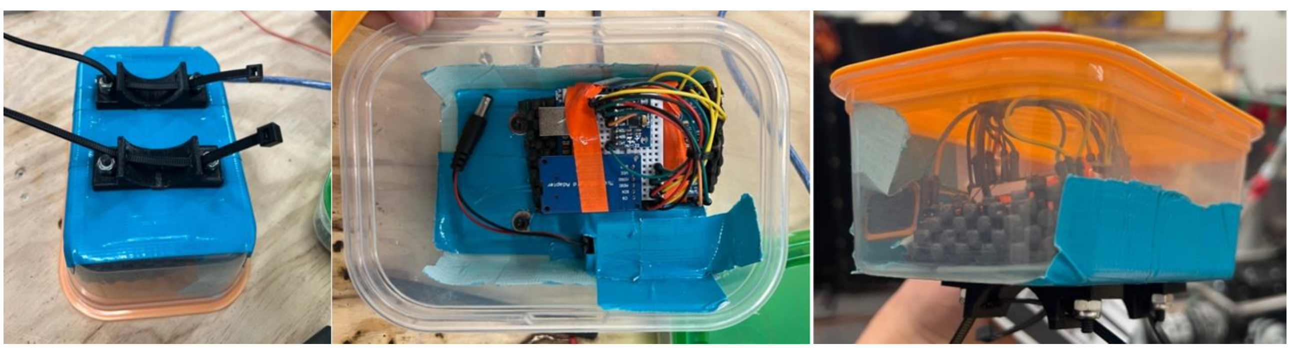

**Fig. 2.** Enclosed Suspension DAQ Unit

Four variables may be manipulated during testing to determine the optimal suspension system set-up (**Table 6**). The variables must be manipulated to perform well in separate maneuverability, suspension, and endurance events. The spring may be swapped out for one with a smaller or larger spring rate which will impact suspension compression and rebound rates. The spring-preload adjusts the vehicle's ride height and initial spring load. The low speed (front) compression dial adjusts the damping compression rate. The suspension geometry may be adjusted to change handling, ride height, and suspension travel. This variable impacts the whole of the suspension system and will not be tuned unless deemed necessary after testing. Tuning of the variables must also conform to the requirements laid out in the system requirements table (**Table 1**). Current suspension tuning variables and suspension requirements are found in **Table 7**.

**Table 6**. Available suspension tuning variables

| Variable | Parameter(s) | Margin | Impact |
|---|---|---|---|
| Spring | Spring | +-200 lb/in | Spring Rate |
| Spring Pre-load | Retaining Rings | +-2 in | Ride Height, Spring Load |
| Low Speed Compression (Front) | Low Speed Compression Dial | 1-10 | Compression Rate |
| Suspension Geometry | Shock + Control Arm Mounting Point | N/A | Wheel Rate, Ride Height, Suspension Travel |

**Table 7**. Current suspension tuning set-up and suspension requirement measurements

| | Pre-load | Spring Stiffness | Low Speed Compression | Ride Height | Wheel Travel |
|---|---|---|---|---|---|
| **Front** | 11/16" | 100lb/in | 3 | 12 1/8" | 12 5/8" |
| **Rear** | 1 7/16" | 100lb/in | N/A | 13 5/8" | 12 3/4" |

Optimization of the suspension system depends on the event types including maneuverability, suspension, and endurance. The maneuverability event requires high speed, stability, and control throughout a tight course. Our maneuverability suspension test will mimic the types of speed and turns experienced during the event. Analysis of the DAQ unit data will focus on transverse linear acceleration and pitch and roll. To maintain speed and control through corners a large transverse linear acceleration is desirable. To maintain stability and control a small pitch and roll is desirable. The most impactful variables are suspected to be spring rate and low speed compression.

The suspension event requires the vehicle to maintain stability and control through a large variety of obstacles. These obstacles will produce both low speed compression responses and high-speed compression responses. Thus, low suspension speed and high suspension disturbance tests must be run. Optimization of stability and control is preferred for low-speed disturbances while maintaining speed and driver comfort is preferred for high-speed obstacles. Through low suspension obstacles, a soft suspension with large amounts of travel and clearance is desirable. Through high-speed suspension obstacles, a quick rebound to standard ride height and driver comfort is desirable. While the suspension event will produce both low and high-speed suspension movements, optimization should focus on low-speed movements as the low-speed features tend to be more difficult such as the rock garden. Analysis of the DAQ unit data will focus on vertical acceleration, lateral acceleration, pitch, and roll. All suspension variables, except geometry, will need to be tuned.

The endurance event includes aspects from both the maneuverability event and suspension event. The suspension tuning set-up must therefore combine the positive aspects of maneuverability and low speed and high-speed suspension disturbances. Optimization for the endurance event will heavily depend upon the course and will likely be tuned on site at the SAE Baja event.

Based on analysis shown in the suspension analysis section, the calculated optimal spring stiffness values are 100 lb/in for the front and 150 lb/in for the rear. These theoretical values will be dynamically tested and compared using the DAQ data plots for vehicle performance.

**Steering**

The goal of steering is to direct the vehicle into a desired direction. For competition, minimizing steering radius angle and maximizing stability at speed is paramount. The vehicle's dynamic events, DAQ data, and driver feedback will be used to balance these characteristics. In conjunction with suspension tuning and field testing, the DAQ vehicle maneuverability data is necessary to characterize the stability of the steering system. To reduce the steering angle of the vehicle, a bias cutting brake will be implemented. A standardized driving behavior testing track will be utilized during all tests to compare and analyze performance of designs. Optimization of the cutting brake ergonomics is vital for positive driver feedback, allowing for easy access of the bias brake and positive reduction in steering radius.

In depth testing of the brake bias system is vital to the success of the goal. Low and high-speed tests through "standardized" testing tracks such as slalom and hairpin corners will be used to quantify the vehicle's steering performance. The tests will be base lined by steering the vehicle at its sharpest angle at low and high speed and have the radii of those turns be recorded.

The terrain of the Baja SAE courses is rough and unforgiving. This intense course coupled with a 4-hour endurance race calls for minimal driver fatigue and road feedback to the driver. The scrub radius of the car will be calculated, tested, calibrated by driver feedback and adjusted. The goal is ½" of positive scrub radius. This can be adjusted through wheel spacers, tire psi, tire-sidewall length, and wheel centerline offset. The tires currently have a 33% positive centerline offset, which means the centerline is closer to the outside of the vehicle than in. Reducing scrub radius will reduce road feedback and sudden steering wheel jerks, but maintaining some scrub radius will allow the driver to understand how his vehicle is gripping and reacting to the ground.

**Chassis**

The goal of the chassis team is to create a CAD model of the existing frame for theoretical testing along with making modifications to various characteristics in order to meet SAE requirements. A model of the chassis enables the team to identify any weak points before field testing with strain gauges.

Stress and strain tests will be conducted on the model of the chassis to determine how much force it can withstand. To get a rough idea of how the vehicle may behave during the dynamic events, a drop and fatigue study will be conducted on the axles to simulate turns, jumps, and obstacles. These tests will help determine where strain gauges are placed for field tests and if any improvements can be made to help dissipate forces.

Field testing with strain gauges and a DAQ will be conducted to verify the simulation data. These tests will be designed to replicate competition scenarios. Ideally, the chassis will be able to experience large forces with minimal stress through its members.

## Analysis

**Drivetrain Analysis**

A MATLAB model of the drivetrain system was generated to determine drivetrain performance.

After inputting current vehicle parameters (i.e., gear ratios, tire size, rolling resistance, drag, etc.), the program computed the 150 ft acceleration time to be 7.26 seconds. Acceleration time was determined through analysis of engine speed versus wheel speed (**Fig. 3**). The initial analysis required finding the engine and wheel speeds at the CVT low and high gears. An engine speed of 3,000 RPM was determined to be optimal for CVT cut-in speed since engine power is maximum at that RPM (A1). The wheel speed at the CVT cut-in and cut-out speeds was then determined. The acceleration values were determined via engine torque and wheel torque. The amount of power to the wheels was determined to be 25% less than the engine power due to drivetrain losses, so a drivetrain efficiency of 75% was assumed. Also factored into the acceleration values were vehicle rolling resistance, drag force, and moment of inertia.

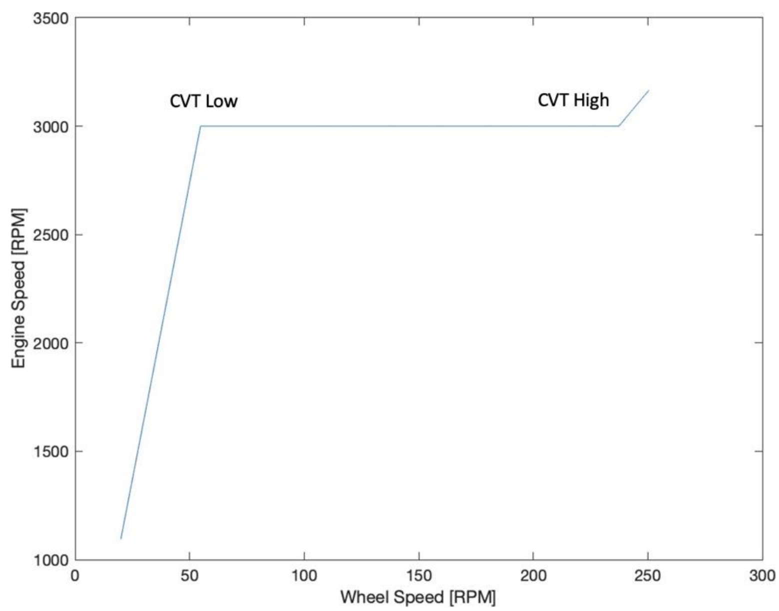


**Fig. 3.** Engine speed vs. wheel speed indicating CVT cut-in and cut-out speeds

Vehicle rolling resistance was calculated based on the coefficient of rolling resistance for loose dirt, drag force was calculated based on the frontal area of the vehicle, and the moment of inertia was assumed to be one-half the total rotating mass. The 150 ft acceleration time was then calculated for future comparison and optimization. The full MATLAB script can be found in Appendix A3.

After theoretical analysis, the next step of the drivetrain team's design process is dynamic testing of the engine and CVT. The test will involve using an RPM measuring device with an Arduino DAQ unit that records the rotational speed of the engine or CVT with respect to time. One option for measuring RPM is a standard laser tachometer, which works by reflecting a beam of light off a rotating surface. Another option is the Hall effect sensor. A Hall effect sensor device works by outputting an electrical current from the presence of a magnetic field. The Hall effect sensor would be placed normal to a magnet that is attached to the surface of a rotating object (e.g., engine, CVT, or wheel). As the test is running, the Hall effect sensor records each full revolution and the Arduino DAQ unit records the RPM values with respect to time. In addition to a standard hall sensor, there is also a single channel Hall effect gear tooth sensor which works in the same way, but can more easily be fixed normal to a rotating surface but is significantly more expensive. The set-up for the Hall effect sensor Arduino

DAQ unit is shown in **Fig. 4**.

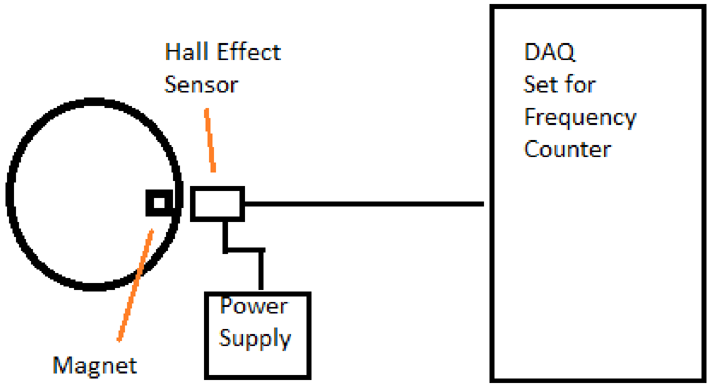


**Fig. 4.** Hall Effect Sensor set-up for data acquisition [2]

Two Hall effect sensors attached to an Arduino DAQ unit will run simultaneously, one fixed normal to the driving pulley of the CVT (the same RPM as the engine), and the other facing the driveshaft. After obtaining RPM vs. time measurements for both the engine and the driveshaft in the DAQ unit, the team will be able to make decisions about what parameters of the CVT must be changed to improve performance of the drivetrain.

**Spring/Suspension Analysis**

Analysis through measured vehicle data mass and measurements were used to find the optimal spring rate for the current vehicle design. Weight of all unsprung members of the vehicle were measured (ie. control arm / hub assembly, wheels/tires, and brakes). Current spring settings and preload measurements were recorded. Control arm dimensions and spring angles were measured. The spring preload force and vehicle weight compression force were used to find spring force.

The motion ratio of the current suspension design was found from the control arm measurements and shock angle as shown in **Fig. 5.** The effective wheel rate was calculated using the spring rate and motion ratio values. The calculated effective spring stiffness was found using the previous values and a spring frequency value. The equations used for these calculations are shown in **Fig. 6.**

$$F_{preload} = k_s * Spring\ Preload$$
$$F_{preload} = Preload\ force\ [lb]$$
$$k_s = Spring\ stiffness\ \left[\frac{lb}{in}\right]$$

$$F_{compressed} = k_s * Compressed\ Spring\ Length$$
$$F_{compressed} = Compressed\ force\ due\ to\ vehicle\ weight\ [lb]$$

$$F_{spring} = F_{preload} + F_{compressed}$$
$$F_{spring} = Force\ of\ spring\ [lb]$$

$$MR = \frac{Dimension\ A}{Dimension\ B} * Sin(\theta_{spring})$$
$$MR = Motion\ Ratio$$
$$\theta_{spring} = Spring\ Angle\ [°]$$

$$W_s = F_{spring} * MR$$
$$W_s = Sprung\ Weight\ [lb]$$

$$Desired\ Spring\ Stiffness = W_s * \omega^2 * (2\pi)^2$$
$$\omega = Spring\ frequency\ [Hz]$$

$$Wheel\ Rate = k_s * MR^2$$
$$Wheel\ rate = Effective\ stiffness\ at\ wheel\ \left[\frac{lb}{in}\right]$$

**Fig. 5.** Equations and units for desired spring stiffness calculation.

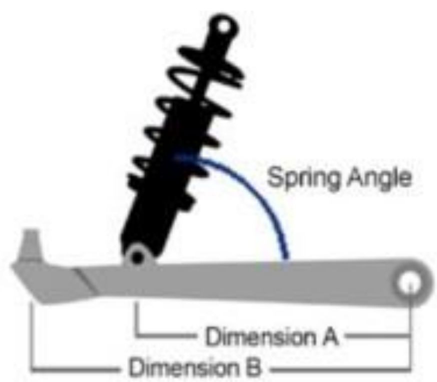


**Fig. 6.** Suspension Design Measurements for Motion Ratio

The spring frequency value was set to a range of 2-3.2 Hz based on prior experiments regarding similar mini baja sized vehicles [8]. This yields a range of spring stiffness values, as shown in **Fig. 7.**

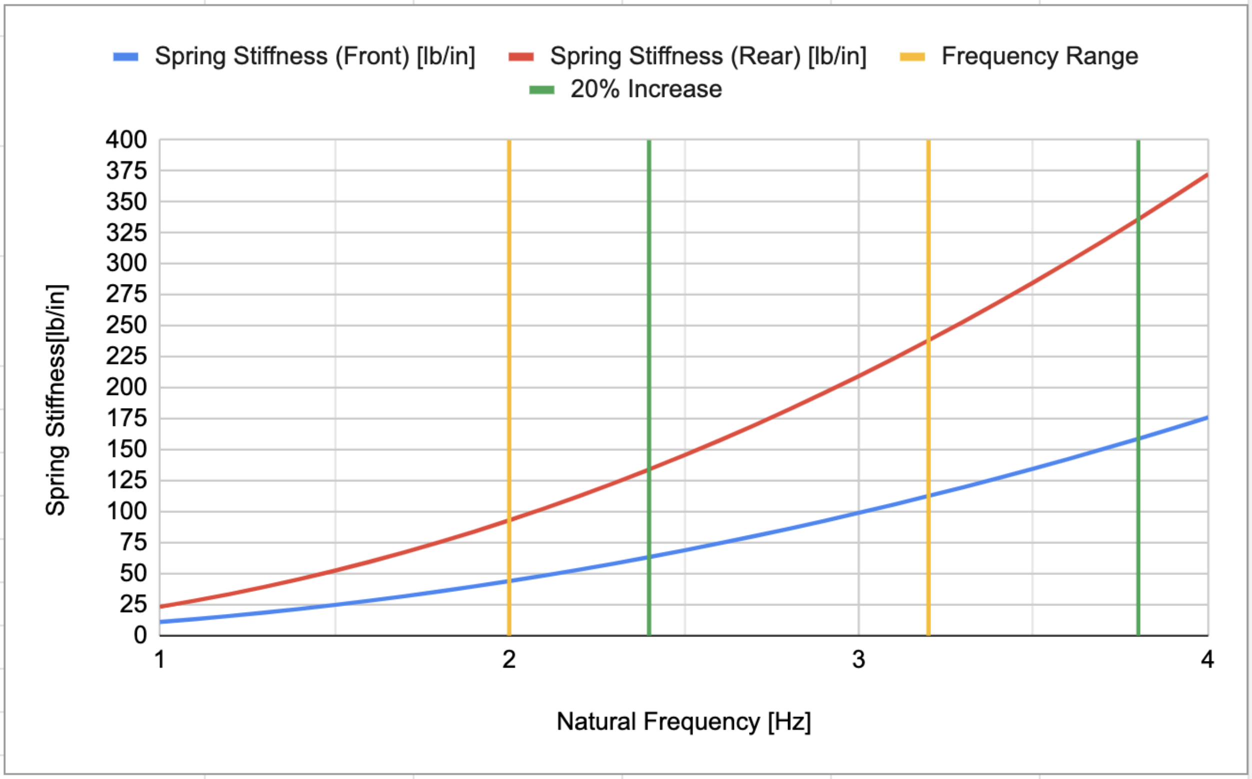


**Fig. 7.** Spring Stiffness in Relation to Natural Frequency for Front and Rear

The frequency range of 2-3.2 Hz is plotted (in yellow) along with a 20% increase for additional skid-plate and component weight for the vehicle (in green). A lower value of spring frequency should be chosen to achieve a softer and more compliant vehicle dynamic. However, a stiffer and more direct characteristic will be found with the use of a higher frequency spring.

With the ability to tune low speed compression, the front coils will benefit from a lower spring weight, allowing for a wider tuning spectrum with the low-speed compression dial. The optimal selection for the front spring will be 100 lb/in. This shows a relatively high natural spring frequency of 3 Hz. This high value will be compensated with the ratio of damped natural frequency between the front and rear of the vehicle. The rear weight of the vehicle and analysis shows the need for a heavier spring rate. The optimal selection for the rear will be 150 lb/in. The increased spring weight of 50 lb/in compared to the initial setup will increase the wheel rate by 23%. This increased spring weight value yields an optimal spring frequency of 2.55 Hz. To offset the lower natural frequency of the rear, the front damping will need to be adjusted to a lower compression setting to balance the damped natural frequency. The total measured and calculated weights and spring stiffness values are shown in **Table 8.** and the appendix (A4). The analytically chosen spring weights will be dynamically tested using the DAQ unit and driver feedback.

**Table 8**. Vehicle weight and desired spring stiffness calculations

| | | | |
|---|---|---|---|
| **Weights:** | F(spring) | **1316.875** | **lb** |
| | Weight(sprung) | **691.67** | **lb** |
| | Weight(unsprung) | **319.90** | **lb** |
| | Weight(car)+driver | **1011.57** | **lb** |
| | Weight(car) | **847.87** | **lb** |
| **Springs:** | Spring Stiffness (front) | **99** | **lb/in** |
| | Spring Stiffness (rear) | **151** | **lb/in** |

**Chassis Analysis**

Finite Element Analysis (FEA) was conducted on the chassis. The weight of the chassis and various components such as the engine and CVT were measured and incorporated into the analysis. In order to simulate dropping off a ledge, a total force of 1700 pounds was inflicted on the front control arm mounting tabs, and a total of 900 pounds was put on the rear control arm mounting tabs. This equates to about 2G's of force on the front of the vehicle and about 1G on the rear. A single fixed member, indicated by green arrows, was implemented. Conducting analysis in this manner produced exaggerated values to create an upper limit of values we should expect.

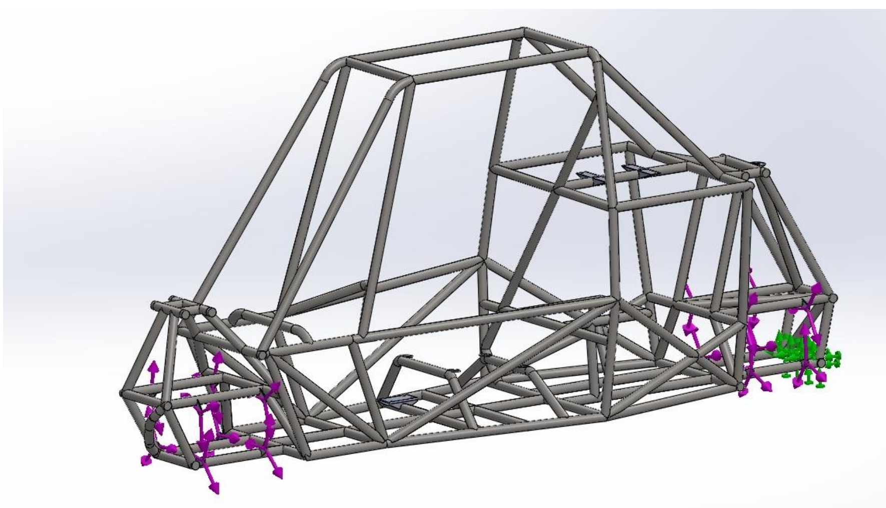

**Fig. 8.** Force and fixed member locations for FEA

A number of assumptions were made while conducting the FEA in order to simplify the analysis. The forces applied to each tab was placed on the inside of the hole cutout. Small displacements of forces in alternate directions were neglected in doing so. The figure above depicts pink arrows representing each force inflicted on the chassis and a fixation member indicated by green arrows.

Further analysis was done on the chassis to verify the integrity of the frame. In the following simulations, it was assumed the total weight of the vehicle and driver is 1000 pounds (about 450 kilograms), it will have a velocity of 20 miles per hour (8.94 m/s), and an impact time of 0.25

seconds to represent the instantaneous nature of a crash. Newton's second law of motion was utilized to calculate the force values for the analysis. Through calculation, it was determined that 16.09 kN of force would be inflicted on the surface of impact given the assumed parameters. The yield strength of our pipes is 3.516*10^8 N/m^2. Conducting front impact analysis on the front suspension tower with the calculated force shows that the chassis will experience a maximum stress of 1.253*10^9 N/m^2 at the 90° mounting points as shown in **Figure 9.**

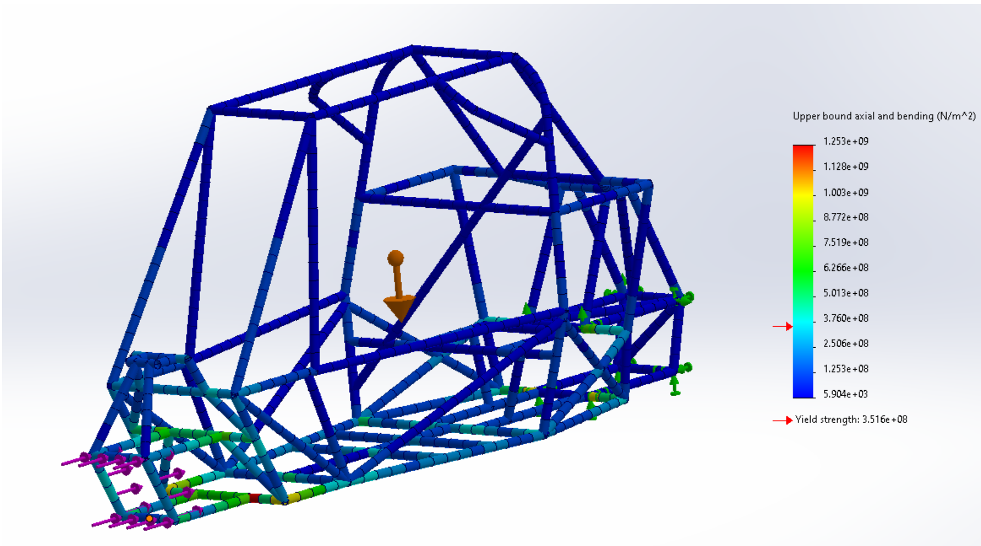


**Fig. 9.** Front Impact FEA

It was important to analyze the structural integrity of the 'roof' of the vehicle given the case that the car rolls over and rests upside down. With the entire weight of the vehicle on the top members, it was assumed the force the top members would experience is about a quarter of the impact force or 4023 N of force. This would equate to about 9 G's of force. Through simulation, it was determined that the members would only experience stresses below the yield strength, with the maximum upper bound axial and bending stress being 2.994*10^8 N/m^2.

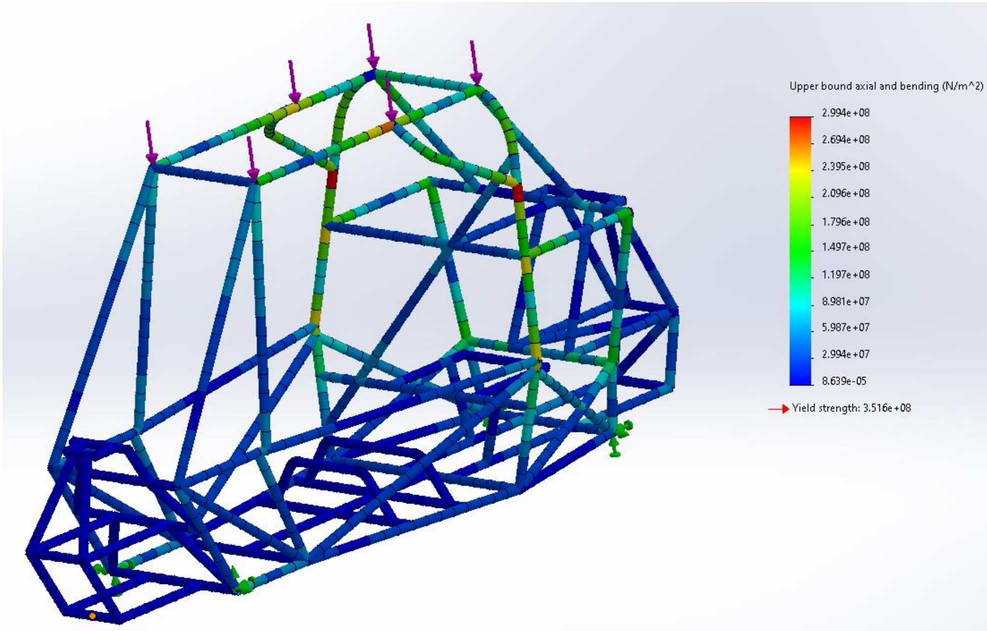


**Fig. 10.** Roll-over FEA

When creating a torsion simulation, it is believed that the car will be going over alternating bumps while driving through the competition course. To replicate the forces that the car would experience, the members below the driver's seat are fixed and a 2250N (5 G) force is enforced on the front left and back right suspension mounting members. As a result, it is shown in **Fig. 11** that the members below the driver's seat experience the most stress with a maximum upper bound axial and bending stress of 9.439*10^8 N/m^2. This information will be important to be cognizant of while racing to ensure the structural integrity of the chassis throughout the entirety of the competition.

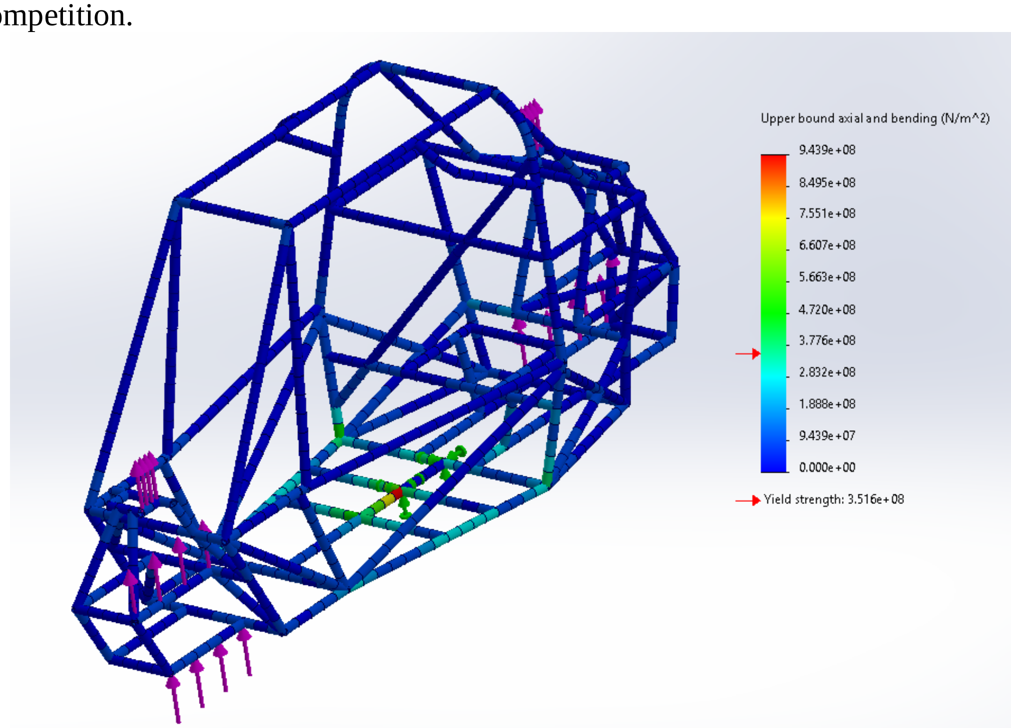


**Fig. 11**. Torsion FEA

To simulate the vehicle going over a bump similar to a speed bump, a force of 2250 N (5 G's) was inflicted on the suspension mounting points as shown in **Fig. 12**. The simulation shows that the greatest stress concentration is at the 90° attachment points where the suspension tower is welded to the main chassis. From the simulation, the maximum upper bound axial and bending stress resulted in 1.602*10^8 N/m^2 which is about half of the yield strength. Therefore, the driver will be able to navigate bumpy terrain to his liking.

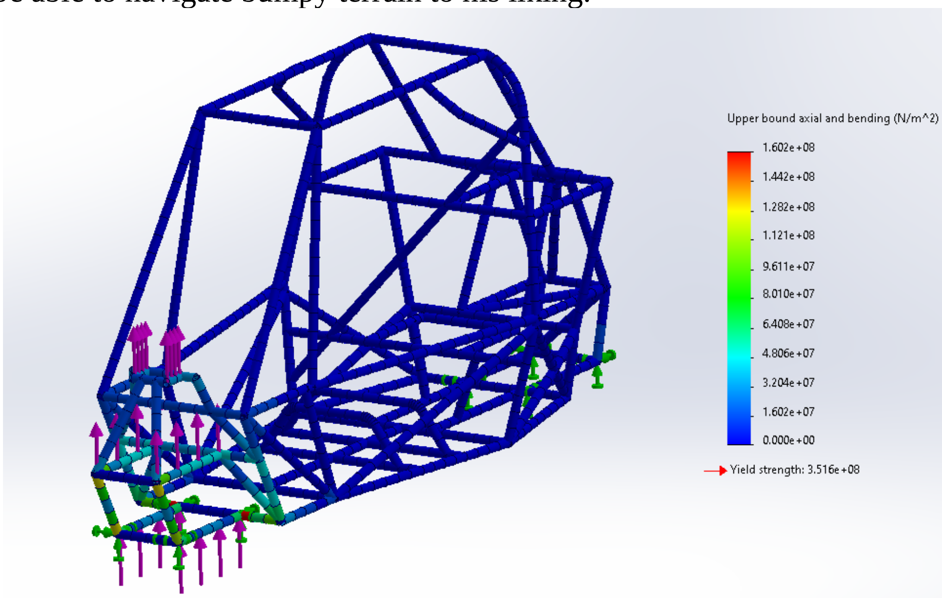


**Fig. 12.** Front bump FEA

## Manufacturing

### Data Acquisition Units

The CVT Drivetrain DAQ requires manufacturing of a stable and solid hall sensor mount assembly. This assembly can be constructed from sheet metal and purchased hardware to mount to the frame. The Arduino connections will need to be soldered with stranded wire to prevent failure during testing and high vibrations. The Arduino unit will be enclosed with a 3D printed case to prevent dirt and debris from affecting the unit.

The Suspension DAQ will be enclosed with a PLA 3D printed clamshell to prevent damage from potential driver contact, mishandling and debris. The circuit will be constructed using stranded wire and solderable breadboard PCBs. The SD card slot will additionally have 3D printed covers to prevent the SD card from becoming dislodged from testing. (Appendix E4).

### Test/Performance Readiness Components

Several vehicle parameters and components must be manufactured to be able to reliably test and operate the vehicle prior to competition. These include the engine mount, cutting brake assembly, baseplate components of the vehicle and a variety of other rule specification modifications. Refer to Appendix B for subsequent figures and information.

The **engine mount** plate will be manufactured via electrical discharge machining (EDM). This engine mount will then be welded onto the frame tubes. The engine can then be mounted with necessary hardware, followed by the CVT assembly. The rear left of the engine mount tube and center of the engine mount will be cut halfway horizontally and have a 1/16 inch metal plate welded to the bottom of it.

The **rear brakes** and **cutting brake** assembly will be installed and manufactured. The brake hose will be routed from the brake pedal reservoirs down to the car's baseplate. Brake lines will be installed on the right side of the vehicle cabin to the cutting brake. A t-intersection will be installed where the brake pressure sensor is attached. Wiring will be sent up to the Roll Hoop (RRH) and will attach to the brake light. The cutting brake lines will be routed down to the rear of the vehicle secured with p-clamps. The brake hose will attach to the brake line on the corresponding side of the differential, and then be routed to the brake caliper and secured using cable ties. [10]

The **brake light** and **reverse light** will be mounted off of two tabs (one for each side) from the RRH. These tabs will be EDM machined from sheet steel and welded on to the frame members. nominal hole diameter of 7/16 in. (D), edge distance of 1.5*D, base width of 3*D, in double shear, and with one sided weld. (B3) [10]

The vehicle will be painted with polyurethane aerosol Steel-It 1002b steel gray. First, any parts that will not be painted will need to be removed from the vehicle. Next, the chassis metal will be sanded to remove the surface rust. Metal surfaces will be wiped and cleaned with brake cleaner. The chassis will be painted in multiple layers.

The **firewall panel**, **body side panels**, **baseplate**, and **splash shield** will be made from .025" aluminum sheet. All these panels will be fastened with Dzus nuts. The firewall metal will be mounted on the front of the RRH. The aluminum will be bent around the slight protrusion of the engine air intake tower through the RRH plane. The firewall panel will be a single sheet with multiple grommeted holes for routing of the brake line, throttle cable, and wiring. A cutout for the driveshaft and intake tube clearance will be made. The splash shield will be made out of two overlapping panels with a hole cut out of it and grommeted to allow the fuel line to go through. The body panels will overlap to ensure a gap free construction.

The **skid plates** will be made from 0.125" and 0.032" aluminum sheets. The panels below the differentials and the rear driveshaft pillow block bearings will be made of 0.125" aluminum sheet secured with ¼ inch grade 8 bolts. The rest of the belly of the car will be plated with 0.032" aluminum sheet. The 0.032" sheet will be cut into two pieces with the front portion overlaid on top of the rear. In front of the front differential, 0.032" aluminum sheet will be fastened via ¼ inch grade 8 bolts. [10]

The **powertrain guard** will be made out of 0.125" aluminum sheet. Some of the materials will be welded but mainly fastened together. An inlet hole will be cut out on the left side of the guard next to the driven pulley and an outlet will be made on the top of the powertrain guard near driving clutch. The holes will be 3" in diameter and have 3" diameter flexible PVC tubing connecting the intake to the firewall cutout. [10]

The **rear gussets for the Roll Hoop Overhead Members (RHO)** will be made out of 1", 1020 DOM, 0.065" thick steel tubing. They will be 2' in length with a 15 degree bend. They will be fabricated and welded to the chassis on both sides. They will attach 6” below the top of the RRH, and 15” forward of the RRH top corner. The tubes will be cut with an angle grinder and coped with a notching tool. [10]

BR (B4), and no further than 180 mm (7.0 inches), dimension “Z”, below named point BR, and shall be mounted on a tab connected directly to the RRH. The external kill switch shall not be recessed more than 51 mm (2.0 inches) from the outside edge of the RRH tube. The switch will be mounted on 1/16 inch aluminum that will be fastened to mounts on the rear gusset. The cockpit kill switch will be mounted inside and to the left of the drive along the SIM that is within reach of the driver when belted in. The mount for the switch will be made out of 1/16 inch steel plate that is bent and coped to fit onto the SIM. The kill switches will be wired in series with the sparkplug power circuitry. [10]

The throttle pedal will have a **throttle return hoop** fastened to it to allow the driver to bring the engine to idle and 100% throttle. The hoop will be made out of 0.125” aluminum sheet cut with electric metal cutting shears. The pieces will be bent twice to make a C channel for the toe of the driver’s shoe to rest via the sheet metal bender. The hoop will be fastened with two ¼ inch bolts. [10]

The **drive shaft cover** will be made out of 0.025” aluminum sheet that will be cut with electric metal cutting shears and bent with the sheet metal bender. The mounting holes will align with the mounting along the USM. [10]

The rear shock tower end caps will be welded on the ends of the parallel tubes of the rear shock tower with MIG welding with 75% argon gas.

# Testing

## Drivetrain Tests and CVT Tuning

For the final step in the team’s drivetrain design process, the team will affirm theoretical and analytical calculations through dynamic testing. Using the Hall effect sensor DAQ unit, the team will run several 150-foot acceleration tests, collecting rpm versus time data for the driven pulley and driveshaft. The data will be used to plot the engine speed against the vehicle speed, allowing the team to qualitatively examine various characteristics of the CVT, such as belt squeezing force, belt engagement speed, and CVT back shifting/upshifting. These characteristics can then be changed by tuning certain parameters within the CVT system, which can be summarized in the table below.

**Table 9.** Possible CVT Adjustments and Their Impact on CVT Performance [6]

| TUNING OBJECTIVE | PRIMARY CLUTCH | | SECONDARY CLUTCH | |
|---|---|---|---|---|
| | PRESSURE SPRING | FLYWEIGHT | TORSION SPRING | HELIX CAM |
| Increase Shift Speed | Same Rate<br>Higher Engagement Load<br>Higher Full Shift Load | Lighter Flyweights | Same Rate<br>More Pretension | Less Cam Angle |
| Decrease Shift Speed | Same Rate<br>Less Engagement Load<br>Less Full Shift Load | Heavier Flyweights | Same Rate<br>Less Pretension | Larger Cam Angle |
| More RPM on Top End | More Rate<br>Same Engagement Load | Less Aggressive Curvature | More Rate<br>Same Pretension | Less Angle at End of Shift |
| Less RPM on Top End | Less Rate<br>Same Engagement Load | More Aggressive Curvature | Less Rate<br>Same Pretension | More Angle at End of Shift |
| More Aggressive Acceleration Less RPM at Beginning of Shift | More Rate<br>Less Engagement Load<br>Same Full Shift Load | More Aggressive Curvature | More Rate<br>Less Pretension | More Angle at Start of Shift |
| Less Aggressive Acceleration. More RPM at Beginning of Shift | Less Rate<br>More Engagement Load<br>Same Full Shift Load. | Less Aggressive Curvature<br>Grind Flat and Extend it Into Shift Curve | Same Rate<br>Higher Pretension | Less Angle at Start of Shift |
| Increase Engagement Speed | Less Rate, Add Shim<br>More Engagement Load<br>Same Full Shift Load | Grind Flat or Notch | No Change | No Change |

The process will be repeated in multiple iterations, changing individual or multiple CVT parameters at a time, with each plot being compared against the plot generated by the MATLAB acceleration code. Doing so will allow the team to determine various characteristics of the current CVT setup, such as belt engagement speed and shift-out speed and will be the basis for adjusting parameters like spring pretension, spring rates, and flyweight ramp aggressiveness. Throughout dynamic testing, the team will consistently reference the plot from MATLAB code, as this serves as the ideal case with a straight shift at 3000 RPM and shift out at around 18 mph.

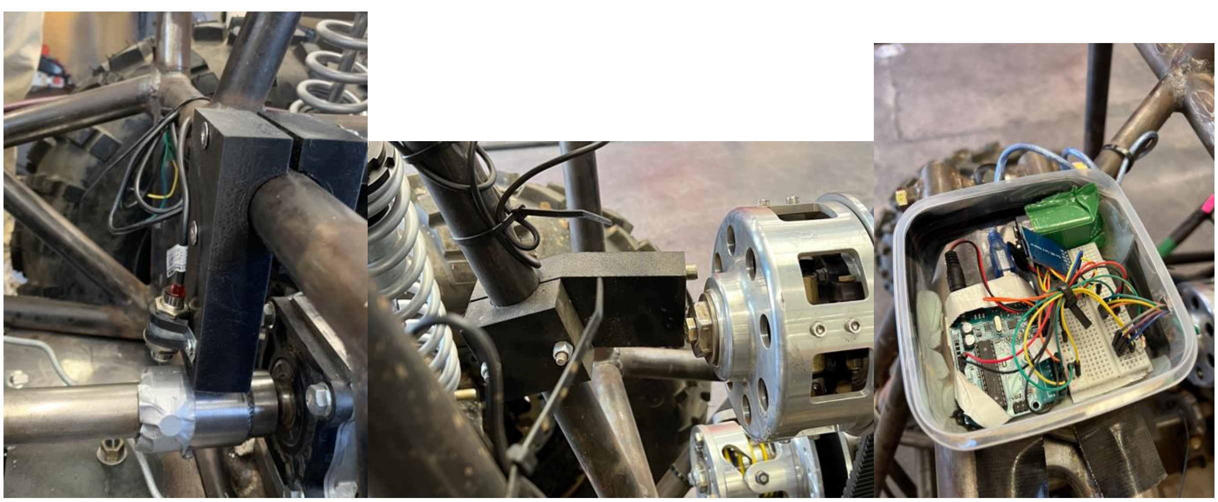

**Fig. 13.** Hall Effect sensor mounts for driveshaft (left) and CVT (middle), and the Arduino DAQ unit (right)

A Continuously Variable Transmission (CVT) has three major components which can be modified to alter performance: the primary (driving) pulley, the secondary (driven) pulley, and the belt. In addition, there are four operating phases of the CVT: the clutching phase, low ratio acceleration, shift out, and high ratio acceleration.

The clutching phase occurs while the engine is idling. Initially, the flyweights of the driving pulley do not produce sufficient force to overcome the tension of the spring, causing the belt to slip. As the engine RPM increases, the clamping force will build up in the sheaves until the belt is fully engaged and the vehicle begins to move forward. The RPM where this occurs is called the engagement speed. Ideally, the belt engagement should occur during peak torque, which according to the engine dyno curve (A1), happens around 2400 RPM. The rule of thumb for CVTs for ICE systems is to aim for about 20-30% of the overall clamping force required for belt engagement [6]. Larger weights will increase the belt squeezing force while lower weights will decrease the squeezing force.

After belt engagement, the power is now transferred from the primary to the secondary pulley, and the vehicle will begin to accelerate at the low-end ratio (3.9 : 1). During this phase, the flyweights of the driving pulley have overcome the tension of the spring but have not created more clamping force than the driven pulley, and so the sheaves remain stationary.

As the vehicle continues to accelerate in low gear ratio, the CVT reaches a critical point called shift out, where the driving pulley tension overcomes the clamping force of the driven pulley, causing the sheaves to start closing. During shift out, the balance of the two pulley tensions changes continuously. As the sheaves of the driving pulley begin closing, the sheaves of the driven pulley start to open. After shifting out, once both sheaves stop moving (and the spring forces achieve maximum compression), the vehicle will continue accelerating at the high gear ratio (0.9 : 1) until it reaches top speed. The process of balancing the forces during shift out is complicated and is affected by several CVT parameters, but the overall objective is to have the belt's transition from low to high ratio occur during peak engine power, which is around 3000 RPM. This can be achieved by adjusting the spring rate and ramp aggressiveness of the driving clutch depending on the measured RPM range(s) where shifting occurs.

From **Table 9, i**ncreasing spring rate and ramp aggressiveness will create less RPM at the beginning of shifts and yield higher vehicle acceleration. Another way to improve acceleration would be to change out the helix and alter the helix angle, which determines the number of torsional forces that are converted to clamping force. A larger helix angle results in a faster upshift and slower backshift, while a smaller helix angle results in a slower upshift and faster backshift. However, the team has decided that for the CVT tuning process, we will first tune basic parameters (initial pretension, spring rates, and ramp aggressiveness) to optimize vehicle acceleration and shifting speed, before switching out components like helixes and weights.

### Drivetrain and CVT Tuning Test Results

The first CVT parameter that was tested was the pretension of the driven pulley's pressure spring – a process known as "clocking". The team clocked the pulley 45 degrees (Fig. 14), which compressed the spring by about 1/5 of an inch. In this way, more pretension adds additional initial spring force, slowing down how quickly the sheaves open which keeps the

CVT operating in low gear ratio for longer duration. The team decided to begin the CVT tuning process by clocking the driven unit because it is an easily adjustable parameter, and the team wanted to see the ways it affected performance before implementing more involved CVT changes.


**Fig. 14.** 45-degree clocking of driven pulley of CVT

Before clocking, the Hall effect sensor DAQ unit was used to plot the speed of the engine against vehicle speed (Fig. 15). The same process was repeated with the driven pulley clocked at 45 degrees. The two-speed curves for before and after clocking were then compared in the same plot (Fig. 16). From plotting the comparison, it was determined that clocking the driven pulley did in fact increase the amount of time the CVT operated in low gear ratio. However, while this did increase the duration of the low-end torque, clocking did not yield any change to overall vehicle acceleration. On the other hand, clocking did increase the engine speed at shifts. This meant shifting occurs sooner with more pretension, which might become useful in competition events if there is a straightaway that leads into an incline. This way, the driver would benefit from the longer torque duration and the quicker shift to high gear ratio.

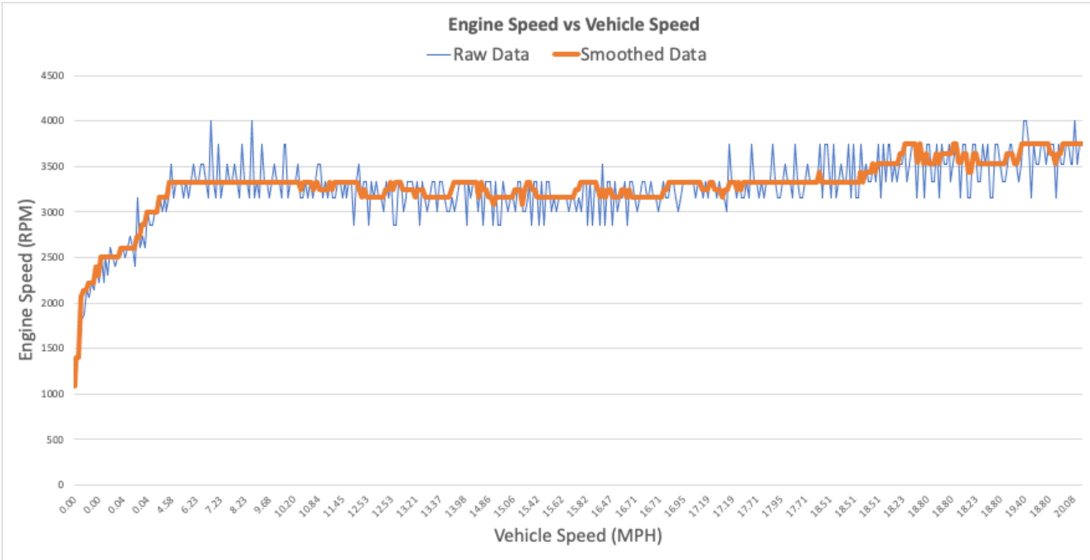


**Fig. 15** Engine versus wheel speed curve (before clocking)

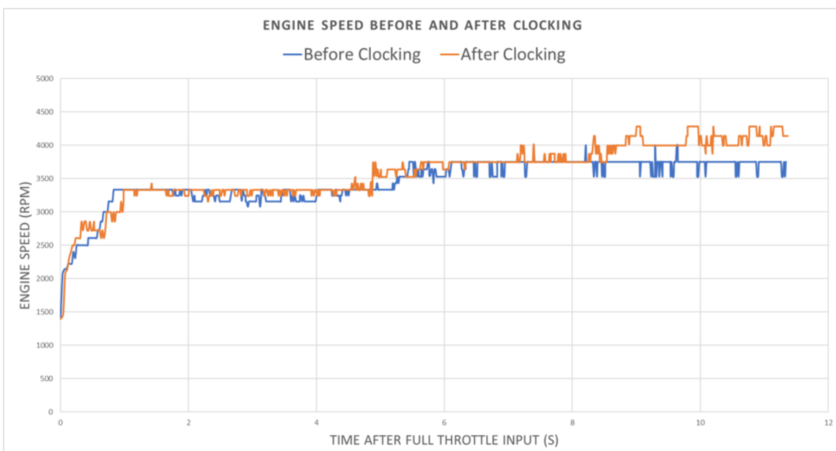


**Fig. 16** Engine speed before and after clocking driven pulley

From the clocking results, the team concluded that the added pretension to the driven unit provided little in the way of improved performance, but it would be a quick and easy way to offset possible shift speed decreases resulting from changing other CVT parameters in the future. For this reason, it might be useful to test clocking the driven pulley again after implementing higher stiffness springs and more aggressive ramps to the CVT. This is because in preparation for competition, the team will iterate Hall effect sensor tests with two new driving pulley springs, one new driven pulley spring, and a new ramp set (Fig. 17). According to Aaen's Clutch Tuning Handbook [6], higher spring rates for the driving and driven unit as well as more aggressively angled ramps for the flyweight system increases overall vehicle acceleration.

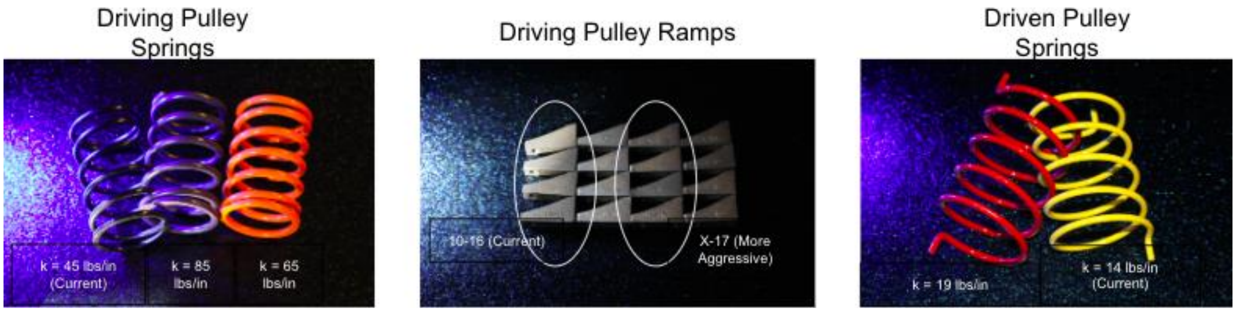

**Fig. 17** CVT springs and ramps acquired from Gaged Engineering

While modifying our CVT with these new components and then conducting further tests, the drivetrain team will adhere to an overall strategy that will ensure our changes bring us closer to our goal of improving vehicle acceleration. Firstly, full belt engagement should remain at peak torque (2400 RPM), as this makes for optimal vehicle acceleration from a stop, especially as it becomes necessary during an event to traverse inclines and rough terrain. Secondly, as the CVT pulleys are moving from a low to high gear ratio, the engine should remain operating at peak power (3000 RPM). Ideally, the engine-vehicle speed curve will be straight throughout the entire shift, allowing power to be transferred to the wheels as efficiently as possible. If a single parameter change negatively affects the vehicle’s ability to meet one of these goals, another parameter may be implemented to offset this. For example, the team intends to replace the current 45 lb/in spring with a 65 lb/in spring. Doing so may decrease RPM too much during shifting. To counterbalance this, as we found when we clocked the driven unit by 45 degrees, adding more pretension to the spring should raise the shifting RPM back to an acceptable level.

**Suspension Tests**

Initial suspension tests were held to confirm suspension DAQ readiness. The initial DAQ prototype experienced issues due to engine vibrations and chassis excitations when placed on the vehicle’s base plate near the vehicles center of gravity. To combat this issue, the DAQ unit was mounted at the frontal section of the vehicle with foam and adhesive tape. After these adjustments, gyroscopic data in the yaw, pitch, and roll directions and acceleration in the x and y axes were successfully measured during an S-turn test.

Simple low speed tests will be held to measure data, such tests include S-turns at 20 feet intervals and braking tests to measure body pitch and roll. Additional tests planned include low and high-speed excitation tests and undulating excitations at a constant velocity. Test results of gyroscopic and acceleration plots will be compared to confirm performance impacts of parameter changes. Off-campus tests are planned to be held in Gorman, CA. The ATV testing center and parks allow for the Baja buggy to be tested with proper license and permits.

S-turn sinusoidal testing were planned to measure the vehicle's body roll and acceleration through the test course. The test compared the two different rear spring rates (100lb, 150lb), front compression damping, and spring preload. Various trials for the sinusoidal tests resulted in noisy and inconclusive data. Stringent testing layouts and control variables were implemented to reduce errors. Tests were held on flat asphalt using the cone layout shown below in Fig 18. Vehicle tire pressure, surface conditions, surface slope, vehicle velocity and cone layout were kept constant during all tests. Each testing trial was saved on a new SD card to prevent human errors and large data files. The DAQ unit was moved towards the rear of the vehicle to increase the measurement sensitivity of the system.

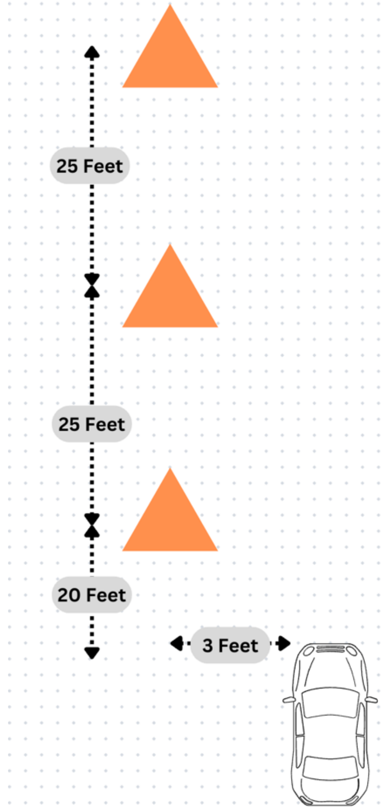


**Fig.** 18. S-turn Testing Layout

Table XX. Shows the testing constants and variables altered during sinusoidal s-turns. The vehicle rear preload was altered between springs to provide the same ride height. The 4 different trials compared 0-4 compression settings and 100-150lb rear spring rates.

**Table XX.** S-turn Testing Constants and Variables

| Testing Constants | | | | |
|---|---|---|---|---|
| Tire PSI | 7 PSI | | | |
| Surface Condition | Asphalt | | | |
| Surface Slope | 0 degrees | | | |
| Cone distance | 25 ft | | | |
| Runup distance | 20 ft | | | |
| | | | | |
| Variables | Trial 1 | Trial 2 | Trial 3 | Trial 4 |
| Front Compression | 0 | 4 | 0 | 4 |
| Rear Spring lb/in | 100 | 100 | 150 | 150 |
| Rear Preload in | 12 3/4 | 12 3/4 | 13 | 13 |
| Front Preload in | 10 1/4 | 10 1/4 | 10 1/4 | 10 1/4 |

**Suspension Testing Results**

The collected suspension data was filtered by removing flyer values to reduce roll and acceleration noise. The plots were then adjusted vertically to ensure the same starting points for sake of trial comparison. The plots derived from the gyroscopic roll/pitch and acceleration data are shown in Figure XX1 and XX2. Figure XX1 shows the vehicle roll data gathered from the S-turn cone tests. It is seen that the maximum angle of the 100lb and 150lb spring tests are similar. However, the 150lb spring curves are shown to recover from the max angle faster than the 100lb spring. This recovery rate (shown in red boxes) could be attributed to a faster shock rebound due to the increased spring rate. This was shown to provide a measurable improvement for driver handling during maneuverability tests.

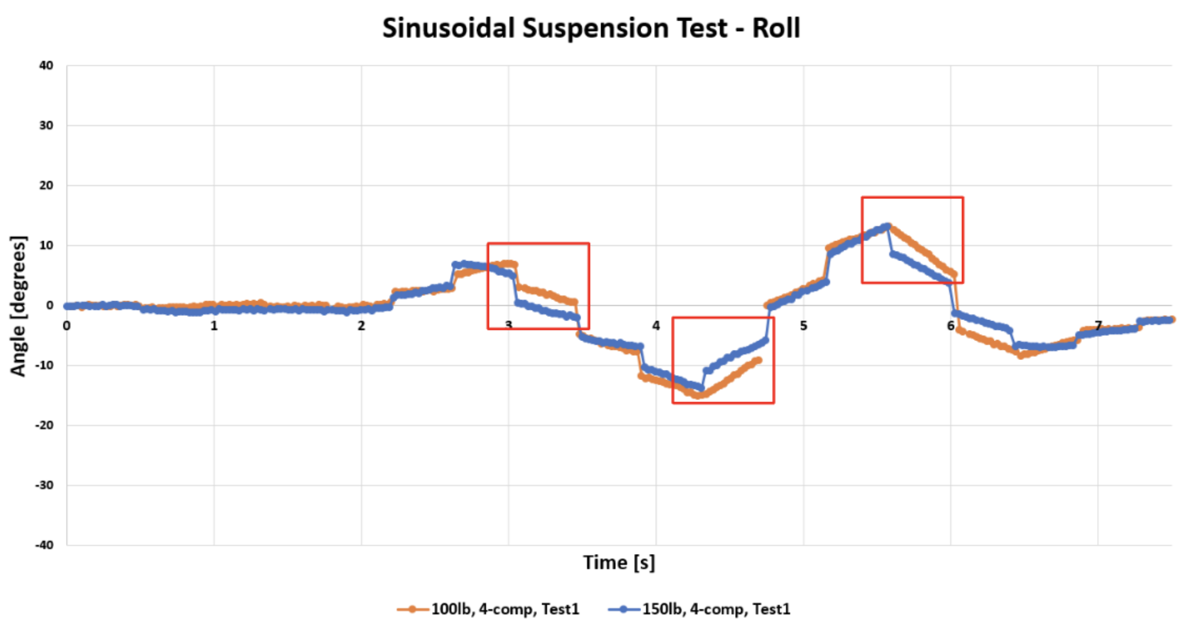


**Fig. 19** S-Turn Roll Data Plot

The acceleration plot shown below in figure 19. compares the vehicles X axis (lateral) acceleration throughout the S-turn tests. The graph shows that the 100lb spring and 150lb spring tests resulted in similar peak acceleration values.

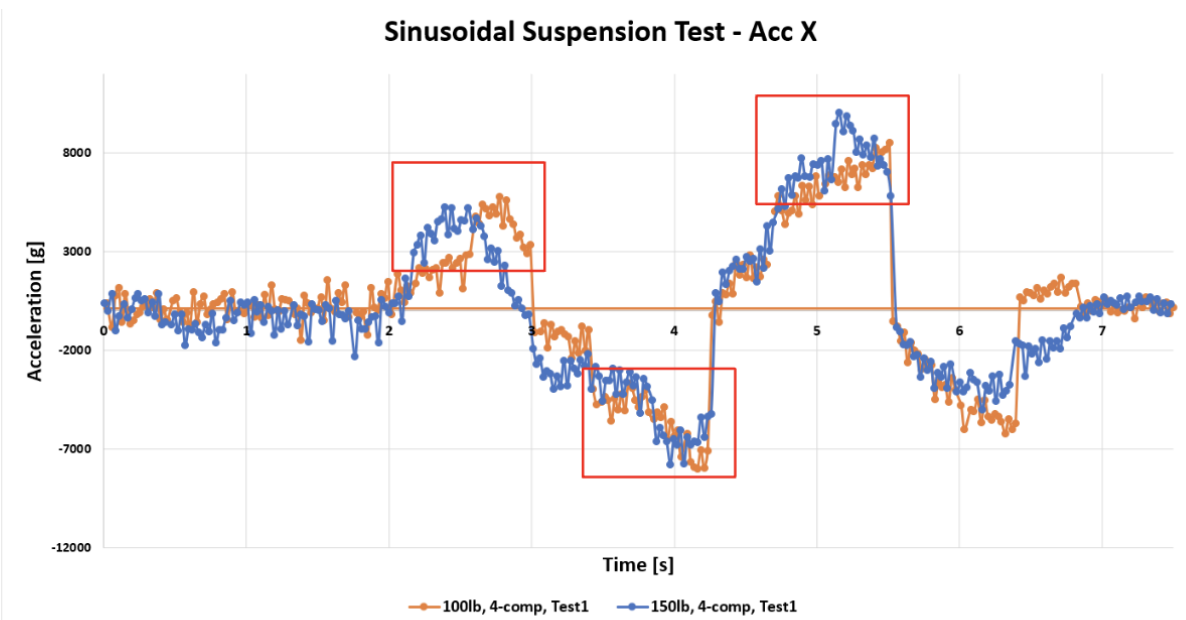

**Fig. 20** S-Turn X Acceleration Data Plot

The similar roll and acceleration peak values of the 100lb and 150lb spring tests initially was thought to prove a lack of improvement between the spring options. However, benefits of the 150lb spring were shown through analysis of testing video footage and driver feedback. While the two different variables exhibited the same acceleration, the 150lb spring was found to reduce lateral load transfer. This allowed for the vehicle to handle better with higher driver confidence. Figure 20 shows this difference in lateral load transfer. The 100lb spring test shows the inside wheel lifting in the air, whereas the 150lb spring allows for all wheels to remain on the ground while maintaining similar roll and acceleration. This improvement in lateral load transfer was shown to increase vehicle driver handling and control. Additional tests in front suspension damping did not yield any measurable differences based on the S-turn tests.

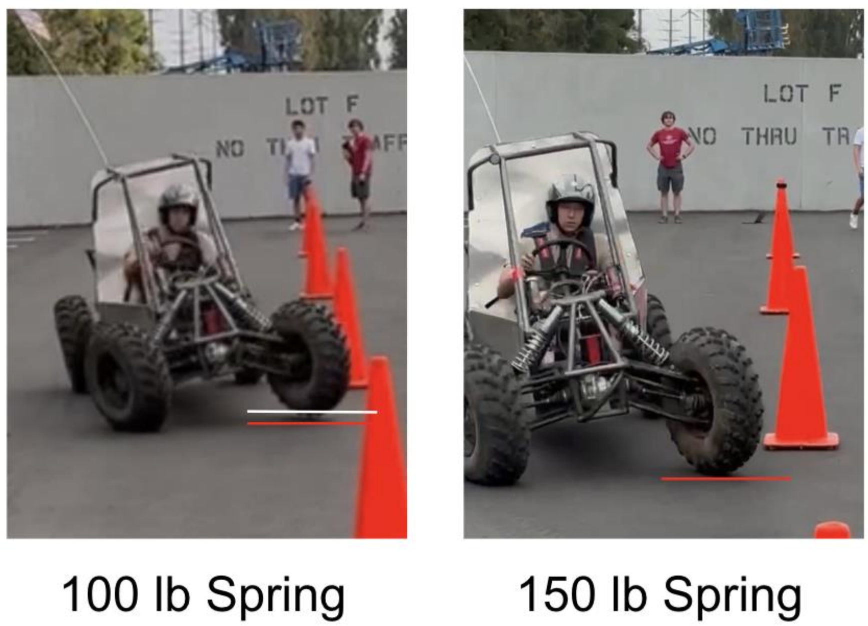


**Fig. 21** Visual Comparison of S-Turn Vehicle 100-150lb Springs

Further testing such as impact and undulation tests were not successful due to the lack of sensitivity of the accelerometer. For further testing a linear potentiometer connected to the shock is recommended to obtain a direct measurement of vehicle suspension travel. This combined with an overall vehicle acceleration as seen from the accelerometer will provide greater insight into suspension and dynamics.

### Steering Tests

The steering tests will be done at Gorman, CA and at LMU. The test will consist of the vehicle moving at 10 mph. The vehicle will approach a cone and immediately turn left once the rear left wheel is immediately next to it. This test will be performed 5 times. This test will be mirrored for the right turn testing and performed 5 times. Speed will be confirmed by the Apple Store application, Speedometer Simple. If it is a right turn test. The rear left wheel will be the measuring point and vice versa for a left turn. An average of the turning radius at speed will be calculated for right, left and combined. The test in Gorman will be on hard packed dirt, and the LMU one will be on asphalt.

A second steering test will be two parts. The first part will consist of removing the front right tire of the vehicle and temporarily putting the front of the vehicle on jack stands, and straightening the steering to center. The front shocks and coilover springs will then be removed from the car so as to not cause any opposing force on the movement of the assembly. After that, the bottom of the farthest outside point of the front right lower control arm will be placed on a 4”x4”x12” block of wood. Next, attach a 1’x2’ piece of smooth sheet metal with the hole pattern of the hub lug bolt pattern cut out of it. Next, put a dial indicator on that piece of metal. This dial indicator will run along the surface of the metal and read out how much the movement occurs during cycling. The car will then be cycled through its suspension to see if the wheel toes in or out. Although, zero change in toe (zero bump steer) is ideal, one inch of bump steer is acceptable. If it is greater than 1”, then adjust the tie rods in or out until it is not. If the wheel toes in on both compression and droop, decrease the tie rod length. If the wheel toes out on both compression and droop, increase the tie rod length. If the wheel toes in on compression and out on droop, lower the outer tie rod (add shims) or, if possible, raise inner (remove shims). If the wheel toes out on compression and in on droop, raise the outer tie rod (remove shims) or, if possible, lower inner (add shims). Then repeat this process for the remaining three corners. The second part of this test will be conducted in Gorman, CA. Moving at a speed of 10 mph over a 6 inch rock, the driver will measure how many degrees the steering wheel moved. 15 degrees is acceptable but this is up to the driver’s feel. Perform this test 5 times on each side. Adjust the tie rods if necessary using the same logic found in part 1. If adjustments are made. Repeat part 1 of this test and record that data.

**Chassis Tests**

The FEA conducted on the chassis produced exaggerated results due to the moderately large force applied, the simplification of forces, and the use of one fixed member. The test resulted in a theoretical maximum stress of 50,000 N/m^2 on members of the rear control arm box along with below the firewall as shown in **Fig. 22**.

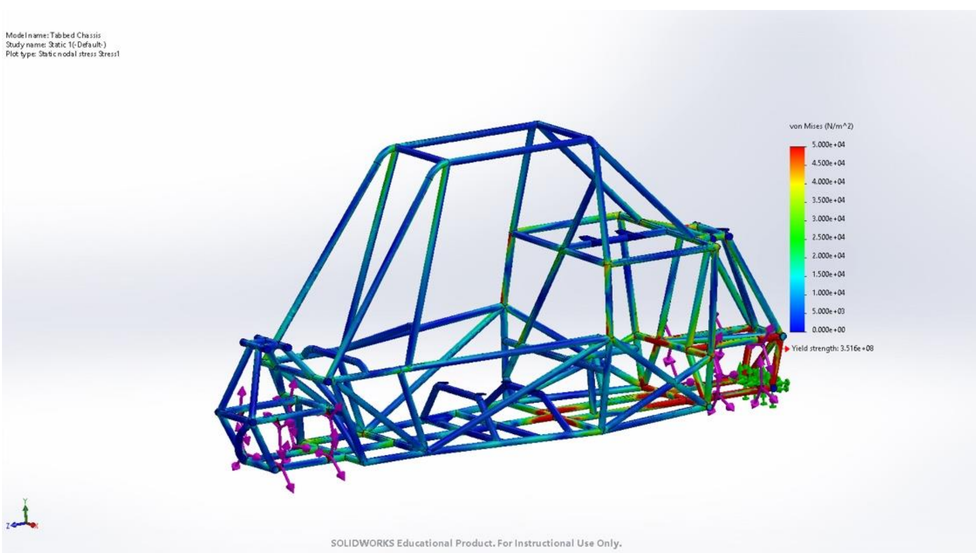


**Fig. 22.** FEA Stress results

To be able to verify the finite element analysis done on the chassis, we conduced experimental tests. The first test was a torsional rigidity test. We applied about 900 pounds of bodyweight to the chassis. We then applied a vertical load to the various members and measured the subsequent deflection. The load was applied to the left Side Impact Member (left SIM), GLC, E Lateral Cross Member (ELC), Rear Lateral Cross Member (RLC), Aft Lateral Cross Member (ALC), Upper Lateral Cross Member (CLC), Overhead Lateral Cross Member (BLC), right Side Impact Member (right SIM), left Lower Frame Side Member (left LFS), right Lower Frame Side Member (right LFS), right Roll Hoop Overhead Member (right RHO), and left Roll Hoop Overhead Member (left RHO). See Appendix B for visuals of where these members are located on the chassis. After testing, it was determined that the observed deflection was below the threshold required for accurate deformation measurements of the frame. Based on this, we can conclude that the chassis can maintain its structural integrity when subjected to various loads.

### Welding Test

Two welding samples will be made with the same materials and processes used in the roll cage element welds. This means it will be done with the same tube material, diameter, and thickness. The Date of construction, welder name, and LMU initials shall be engraved, etched, or stamped on the sample. Sample 1 will be a 90-degree joint with an unrestricted leg length (See Appendix B). This joint will be destructively tested, which will cause the joint to fail in the base material and not the weld metal. This test will have the peak stress located at the weld by inducing tensile or bending failure. In the case of bending failure, make sure that the largest bending moment is located at the weld. For sample 2, two tubes joined at a 30-degree with a length of at least 5.9 inches from the center of the joint (See Appendix B). The sample must be sectioned along the length of the tube to reveal adequate and uniform weld penetration.

### Fuel Economy Test

In Gorman, CA, the car's fuel tank will be drained of all gasoline and then refilled with exactly half a gallon. The car will then run around in a 100 yard diameter circle until it completely is out of gas. The number of laps will be recorded to know the exact distance traveled. The tank will then be drained, and if there is any remaining fuel, that will be calculated. From the information learned in the first fuel economy test, the car will go on a trail to better simulate competition conditions. The amount of fuel put into the tank will be dictated by the estimated miles per gallon (mpg) and the distance to a recoverable spot of the course where a chase truck can easily access the vehicle in case the initial calculations were off. Once the vehicle runs out of fuel, any remaining fuel will be drained and measured. We will then have a good estimate of the vehicle's mpg.

## Safety and Ethics

The SAE Baja competition states one of the goals is to design the vehicle for a viable market item for public purchase and use. The product must be safe, reliable, and dependable to provide customers an enjoyable and desirable experience. Design considerations were held to keep safety the highest priority, with repairability and serviceability additionally in mind. The main goal for the baja vehicle is to compete at the SAE events. The team and race driver have responsibilities during competition and rule keeping. Insuring the fairness of competition and legitimacy of the team and design. Sponsors, manufacturers, providers, and teams must be made sure to compete fairly. The rules and regulations as stated by the SAE Baja competition will be followed to insure fairness for all of those who are involved. This is vital to show respect and support to other teams and the SAE organization. The environmental impact must also be kept in consideration during testing and evaluation of the design. The vehicle's operating fluids, emissions, and other factors will be closely monitored to not negatively damage the environment.

## Conclusions

The final vehicle design successfully met the majority of the system requirements. For the dynamic event requirements, the vehicle was able to reach a top speed of 23 mph, which was within our acceptable margin of error. The vehicle was able to complete a 150 ft acceleration test in 7.0 seconds, falling short of our 6.5-second goal. Further testing will be conducted on CVT parameters (i.e., driving/driven pulley springs, flyweight ramps, etc.) and then implemented before the competition to improve vehicle acceleration. The vehicle's handling and maneuverability were drastically improved by reducing the lateral load transfer. Further tuning of front compression settings will be held to achieve ideal impact-damping characteristics. Completed finite element analysis of the vehicle frame shows no concerns for the frame's structure.

~~The current phase of the project has successfully planned and outlined the route for completed vehicle race readiness, testing, and optimization. The suspension of the vehicle is ready to be tested for performance using theoretically chosen spring stiffness values and the data acquisition system. Matlab analysis of the vehicle's transmission and the optimized data gathering unit will allow for future tuning and evaluation of cvt/vehicle parameters. Initial finite element analysis was completed, however further efforts will need to be held to gather useful frame construction information. Future manufacturing and construction of vehicle components is vital to bring the vehicle to test and race specifications. Thorough dynamic testing will be necessary to find potential issues and confirm theoretical calculations.~~

Acceleration 150 6.5s, 150 7s
Improved vehicle handling and maneuverability from reduced lateral load transfer.

-add suspension testing conclusion
-add FEA conclusion
-add drivetrain testing conclusion

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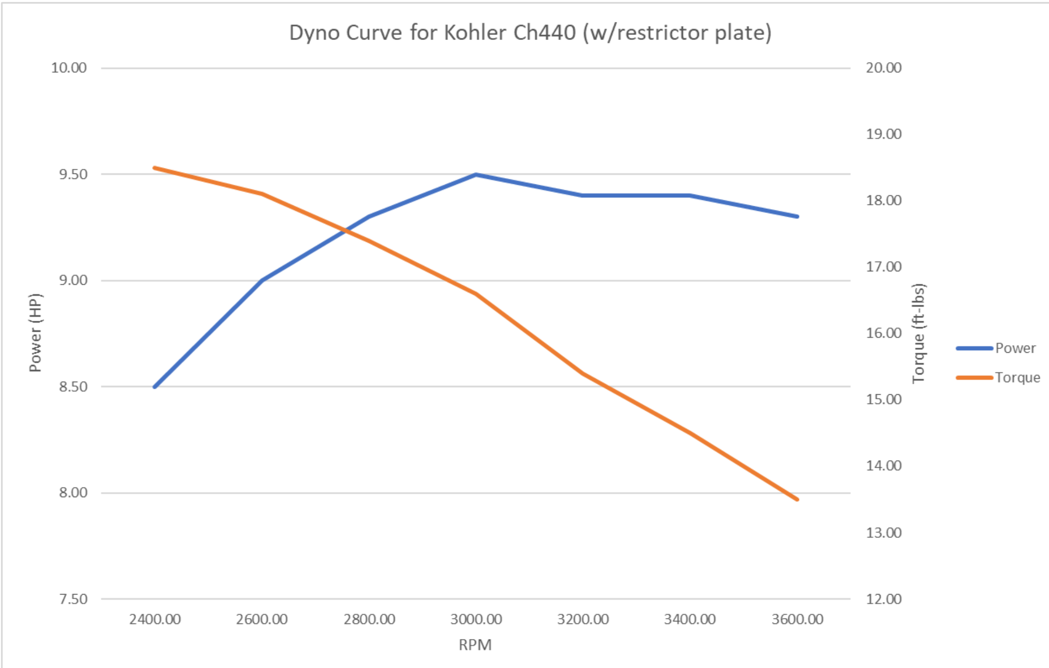
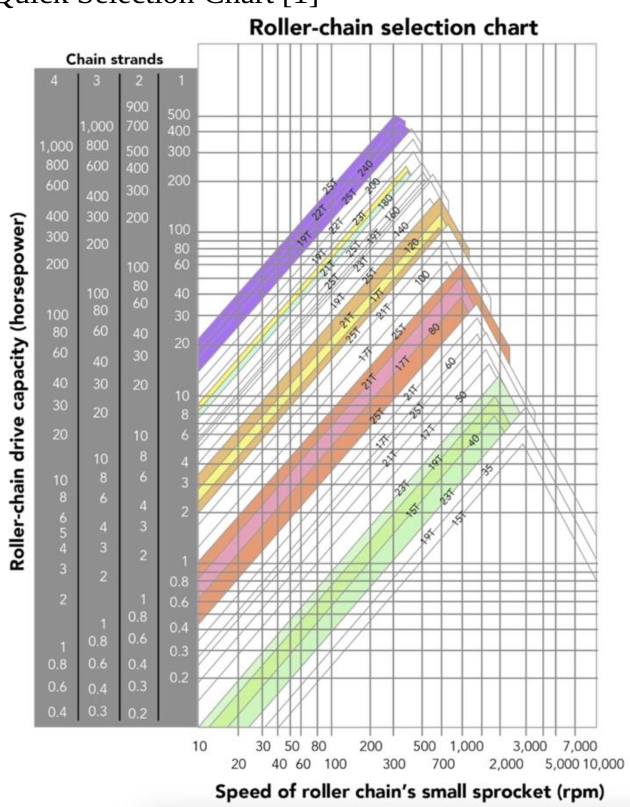
# Appendices

## Appendix A. Reference Diagrams

1. Dyno Curve Kohler CH440 Engine [10]




2. Design Horsepower Quick Selection Chart [1]



## Appendix B. Analysis

### 1. Drivetrain Acceleration Equations

| | | | | |
|---|---|---|---|---|
| **Driving Sprocket Speeds:** | High End Driving Sprocket Speed: | n1 = (Engine RPM) / [(FNR Gearbox ) x (CVT High End)] | | |
| | | n1 = | 461.54 | RPM |
| | Low End Driving Sprocket Speed: | n1 = (Engine RPM) / [(FNR Gearbox ) x (CVT Low End)] | | |
| | | n1 = | 2000.00 | RPM |

| | |
|---|---|
| Driven Sprocket Speed: | n2 = (Engine RPM) / [(FNR Gearbox) x (CVT [high/low end]) x (Sprocket)] |
| Wheel Speed: | n3 = (Engine RPM) / [(FNR Gearbox) x (CVT [high/low end]) x (Sprocket) x (Rear Differential)] |
| Torque to Wheels = | tau = (5250 * Input Power) / (Wheel Speed) |
| Wheel Force: | F = (Wheel Torque) / (Wheel Radius) |
| Acceleration (friction ignored): | a = (Wheel Force) / (Mass of Vehicle) x (Acceleration due to Gravity) |
| 150 ft Accel. Time (friction ignored): | t = SQRT(2 x 150 ft / Acceleration) |
| Top Speed = | v = (Tire Radius) (Max Engine RPM / Low End Gear Ratio) (2π rad / rev) (mile / 63,360 in) (60 min / hr) |

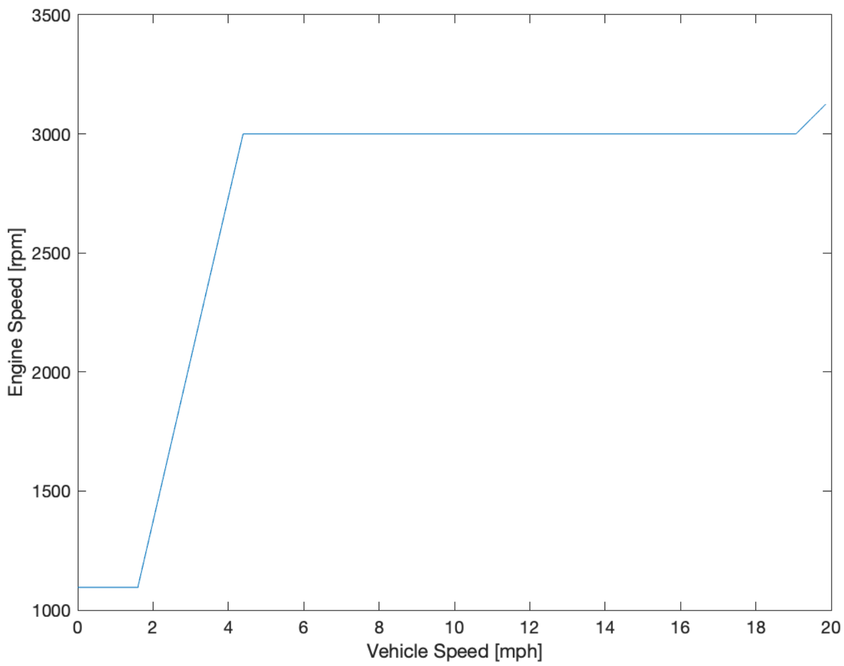
Drag Force = 0.5 x Coeff. of Drag x Air Density x (Top Speed)^2 x Frontal Area

Rolling Resistance Force = Coeff. Of Rolling Resistance x Vehicle Weight

### 2. MATLAB Drivetrain Acceleration Model

```
%% Engine, CVT, and Wheel Speed RPM

% time parameters
dt=1/1000;
t=0;

% kinematic parameters
x_desired=150; %ft
x=0;
wheel_radius=(27/12)/2; %ft
v=20*(2*pi)*(1/60)*wheel_radius; %ft/s
a=0; %ft/s^2

% Engine Parameters
idle_RPM=1300;
max_RPM=3800;
drivetrain_efficiency=0.75;
engine_torque=15.4495;
RPM_sweet_spot=3000;

% RPM Parameters
engine_RPM=idle_RPM;
CVT_driven_RPM = 0;
wheel_RPM=20;

% Wheel Parameters
vehicle_rotating_weight=120; %lb
wheel_torque=0;
wheel_force=0;

% Gear_Ratio
fixed_GR=2*(22/12)*3.83;
CVT_high=3.9;
CVT_low=0.9;
CVT_GR=CVT_high;
```

```
% Vehicle Properties
vehicle_weight=1000-40; %lbf
vehicle_mass=vehicle_weight/32.2; %slugs
coef_roll_resist=0.03;
force_roll_resist=coef_roll_resist*vehicle_weight; %lbf

% Drag Properties
density_air=2.33*10^(-3); %lb/ft^3
area_firewall=11; %ft^2
coeff_drag=1.9;

%Vehicle Speed
vehicle_speed = 0;
i=1;
while x(i)<x_desired
if wheel_RPM(i) <= 54.75
engine_RPM(i) = wheel_RPM(i)*fixed_GR*CVT_high;
elseif wheel_RPM(i) <= 237.36
engine_RPM(i) = RPM_sweet_spot;
elseif wheel_RPM(i) <= 284.83*(3800/3600)
engine_RPM(i) = wheel_RPM(i)*fixed_GR*CVT_low;
else
engine_RPM(i)=max_RPM;
wheel_RPM(i)=284.83*(3800/3600);
end
engine_torque(i)=(-3*10^(-6)*(engine_RPM(i)^2))+0.0109*engine_RPM(i)+6.3495;
wheel_torque(i)=engine_torque(i)*fixed_GR*CVT_GR(i)*drivetrain_efficiency;
wheel_force(i)=(wheel_torque(i))/wheel_radius;
a(i) = (wheel_force(i)-(coef_roll_resist*vehicle_weight)-(.5*coeff_drag*density_air*...
area_firewall*v(i)^2))/(vehicle_mass+(vehicle_rotating_weight/32.2));
v(i+1) = v(i) + a(i)*dt;
if engine_RPM(i)==max_RPM
v(i+1)=v(i);
a(i)=0;
end
x(i+1)= x(i) + v(i)*dt;
wheel_RPM(i+1) = v(i)*(1/(2*pi))*60/wheel_radius;
vehicle_speed(i+1) = wheel_RPM(i)*2*pi*wheel_radius*(12*60/63360);
CVT_GR(i+1) = engine_RPM(i)/(wheel_RPM(i)*fixed_GR);
t(i+1)=t(i)+dt;
i = i+1;
end
t(i)
plot(wheel_RPM(1:i-1),engine_RPM(1:i-1))
plot(vehicle_speed(1:i-1), engine_RPM(1:i-1))
```

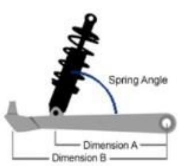



The MATLAB script takes in inputs such as gear ratio, wheel size, vehicle properties, and drag, and calculates the overall vehicle acceleration using iterative computations for the engine and wheel RPM. The code also produces a plot of engine RPM versus vehicle speed in mph, including the theoretical “sweet spot” of 3000 RPM for the Kohler engine. This plot will be critical during the CVT tuning process, as the team will be able to reference the diagram when changing CVT parameters to alter the belt engagement, shifting, and power transfer along the belt.

3. Spring Selection Analysis

## Givens

| | | | |
|---|---|---|---|
| **Tire Weights:** | Front Left | **38.2** | **lb** |
| | Front Right | **44.2** | **lb** |
| | Rear Left | **43.2** | **lb** |
| | Rear Right | **41.5** | **lb** |
| **Unsprung Weights:** | Control Arms, Half Shaft, Hubs | **33** | **lb** |
| | Shock + Spring | **10.4** | **lb** |
| | **Unsprung Weight** | **319.9** | **lb** |
| **Spring Settings:** | Spring Stiffness (front) | **100** | **lb/in** |
| | Spring Stiffness (rear) | **130** | **lb/in** |
| | Spring Frequency (front) | **3** | **Hz** |
| | Spring Frequency (rear) | **2.55** | **Hz** |
| | Preload (front) | **0.75** | **in** |
| | Preload (rear) | **1** | **in** |
| | Compressed Spring Length (front) | **1.8125** | **in** |
| | Compressed Spring Length (rear) | **2.0937** | **in** |
| **Front Suspension Geometry** | | | |
| | Dimension A | **8.5** | **in** |
| | Dimension B | **13** | **in** |
| | Spring Angle | **40** | **degrees** |
| **Rear Suspension Geometry** | | | |
| | Dimension A | **8.5** | **in** |
| | Dimension B | **13** | **in** |
| | Spring Angle | **60** | **degrees** |




## Calculations

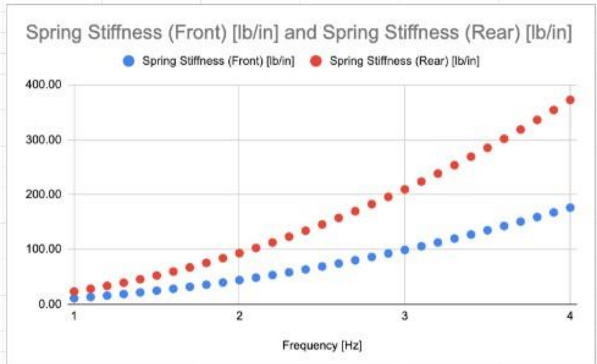
| | | | | |
|---|---|---|---|---|
| **Front:** | F(spring)=kx [lb] | Pre-load Force | 75.00 | lb |
| | | Compressed Force Due to Vehicle Weight | 181.25 | lb |
| | | **F(spring)** | **256.25** | **lb** |
| | Motion Ratio=(Dim A/Dim B)*sin(spring angle | | | |
| | | **Motion Ratio** | **0.42** | **[]** |
| | Weight(sprung)=F(spring)*Motion Ratio | | | |
| | | **Weight(sprung)** | **107.70** | **lb** |
| | Wheel Rate=Spring Stiffness*(Motion Ratio)^2 | | | |
| | | **Wheel Rate** | **17.66** | **lb/in** |
| | Desired Spring Stiffness formula | | | |
| | | **Desired Spring Stiffness** | 99.11102597 | **lb/in** |
| **Rear:** | F(spring)=kx [lb] | Pre-load Force | 130.00 | lb |
| | | Compressed Force Due to Vehicle Weight | 272.19 | lb |
| | | **F(spring)** | **402.19** | **lb** |
| | Motion Ratio=(Dim A/Dim B)*sin(spring angle | | | |
| | | **Motion Ratio** | **0.57** | **[]** |
| | Weight(sprung)=F(spring)*Motion Ratio | | | |
| | | **Weight(sprung)** | **227.74** | **lb** |
| | Wheel Rate=Spring Stiffness*(Motion Ratio)^2 | | | |
| | | **Wheel Rate** | **41.68** | **lb/in** |
| | | **Desired Spring Stiffness** | 151.4215379 | **lb/in** |

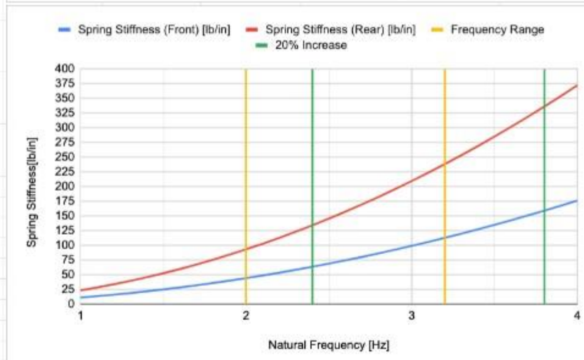
## Results

| | | | |
|---|---|---|---|
| **Weights:** | F(spring) | **1316.875** | **lb** |
| | Weight(sprung) | **691.67** | **lb** |
| | Weight(unsprung) | **319.90** | **lb** |
| | Weight(car)+driver | **1011.57** | **lb** |
| | Weight(car) | **847.87** | **lb** |
| **Springs:** | Spring Stiffness (front) | **99** | **lb/in** |
| | Spring Stiffness (rear) | **151** | **lb/in** |
| | | 527.67 | |

**Additional Calculations/Results**

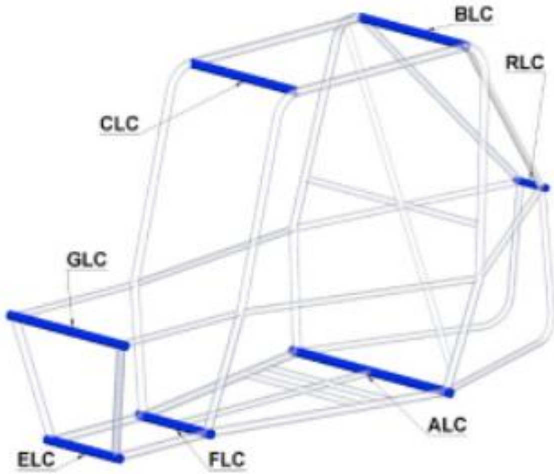
| Frequency [Hz] | Spring Stiffness (Front) [lb/in] | Spring Stiffness (Rear) [lb/in] |
|---|---|---|
| 1 | 11.01 | 23.29 |
| 1.1 | 13.32 | 28.18 |
| 1.2 | 15.86 | 33.53 |
| 1.3 | 18.61 | 39.35 |
| 1.4 | 21.58 | 45.64 |
| 1.5 | 24.78 | 52.39 |
| 1.6 | 28.19 | 59.61 |
| 1.7 | 31.83 | 67.30 |
| 1.8 | 35.68 | 75.45 |
| 1.9 | 39.75 | 84.06 |
| 2 | 44.05 | 93.15 |
| 2.1 | 48.56 | 102.69 |
| 2.2 | 53.30 | 112.71 |
| 2.3 | 58.26 | 123.19 |
| 2.4 | 63.43 | 134.13 |
| 2.5 | 68.83 | 145.54 |
| 2.6 | 74.44 | 157.42 |
| 2.7 | 80.28 | 169.76 |
| 2.8 | 86.34 | 182.57 |
| 2.9 | 92.61 | 195.84 |
| 3 | 99.11 | 209.58 |
| 3.1 | 105.83 | 223.78 |
| 3.2 | 112.77 | 238.46 |
| 3.3 | 119.92 | 253.59 |
| 3.4 | 127.30 | 269.19 |
| 3.5 | 134.90 | 285.26 |
| 3.6 | 142.72 | 301.80 |
| 3.7 | 150.76 | 318.79 |
| 3.8 | 159.02 | 336.26 |
| 3.9 | 167.50 | 354.19 |
| 4 | 176.20 | 372.59 |



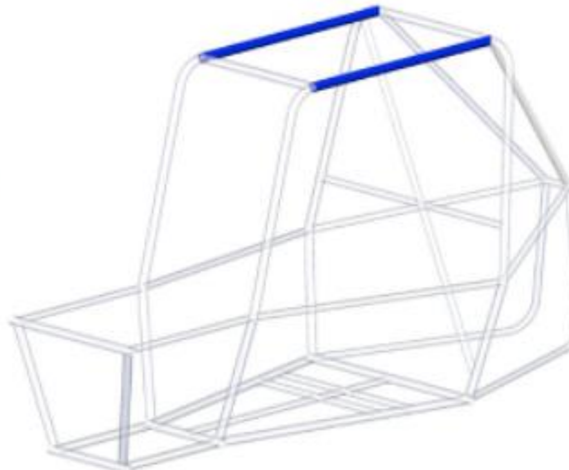




## Appendix C. Manufacturing Plan

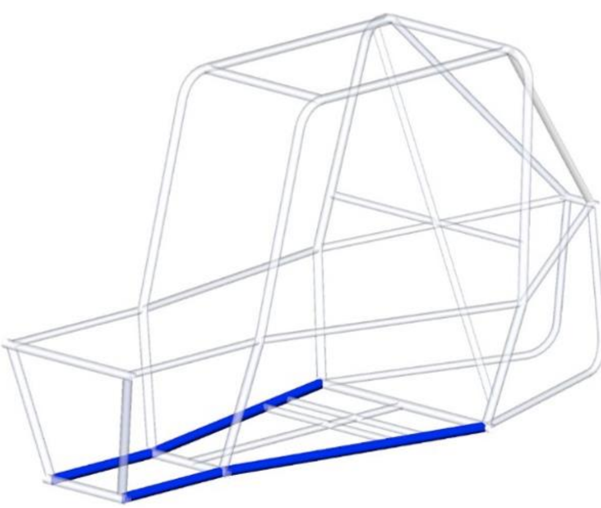
1. Chassis Members



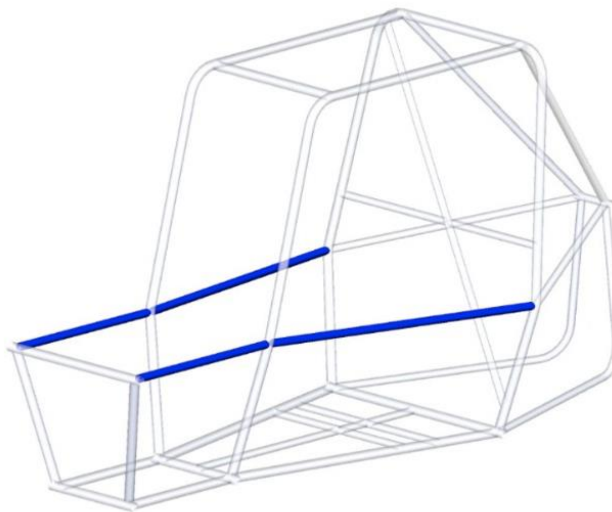

Roll Cage, LC



Roll Cage, RHO

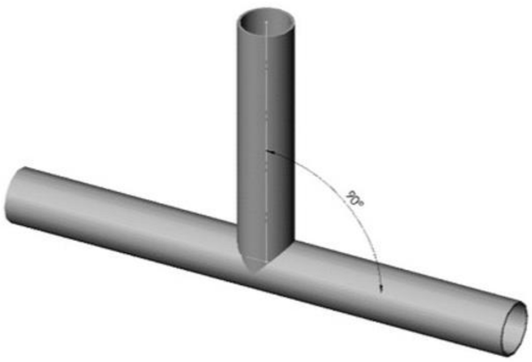


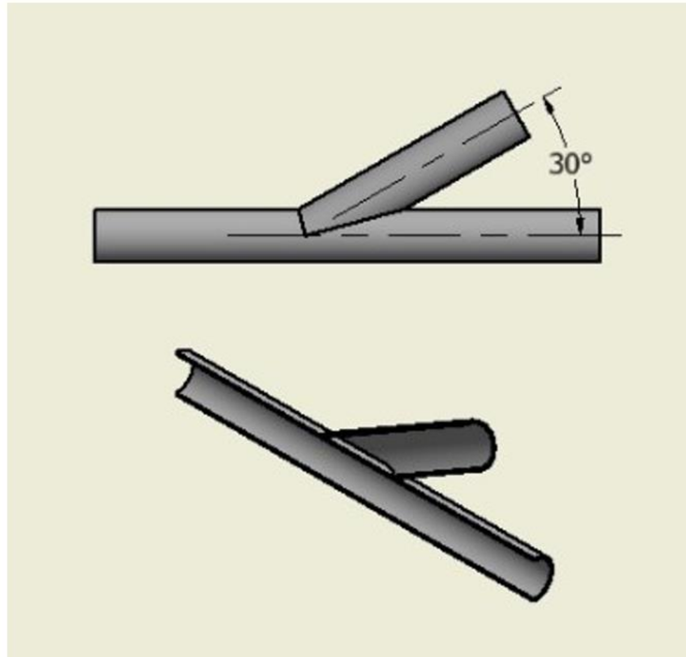
Roll Cage, LFS



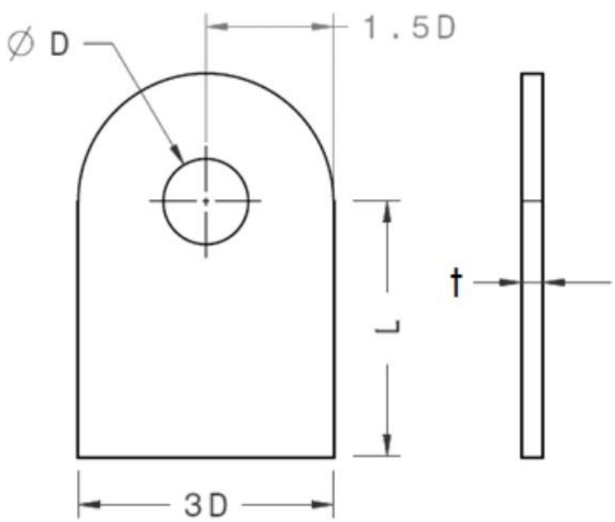
Roll Cage, SIM

2. Weld and Tube Standard/Test

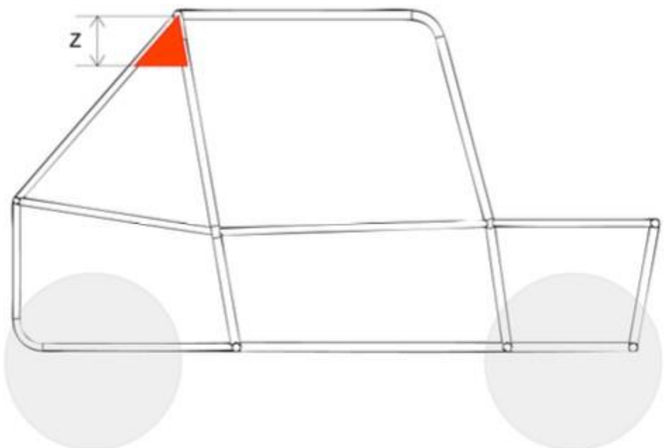


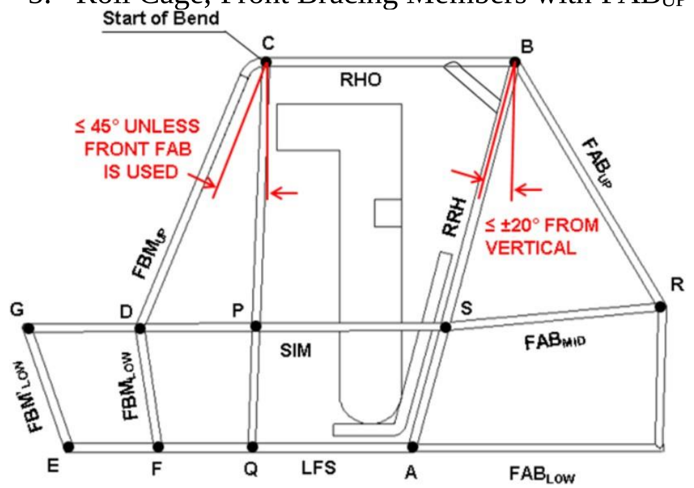

3. Required Tab Drawing



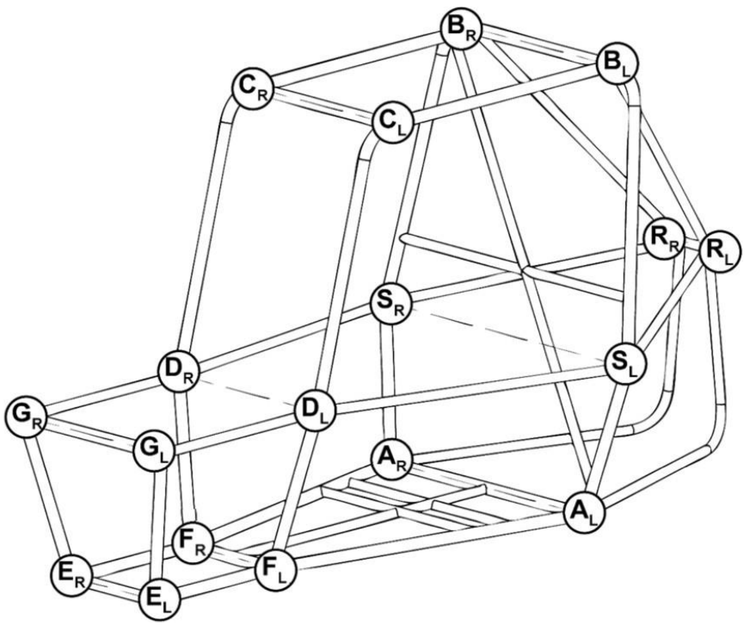
4. Engine Kill Switch Mounting Location




5. Roll Cage, Front Bracing Members with $FAB_{UP}$




6. Roll Cage Named Points, Car with Rear Bracing

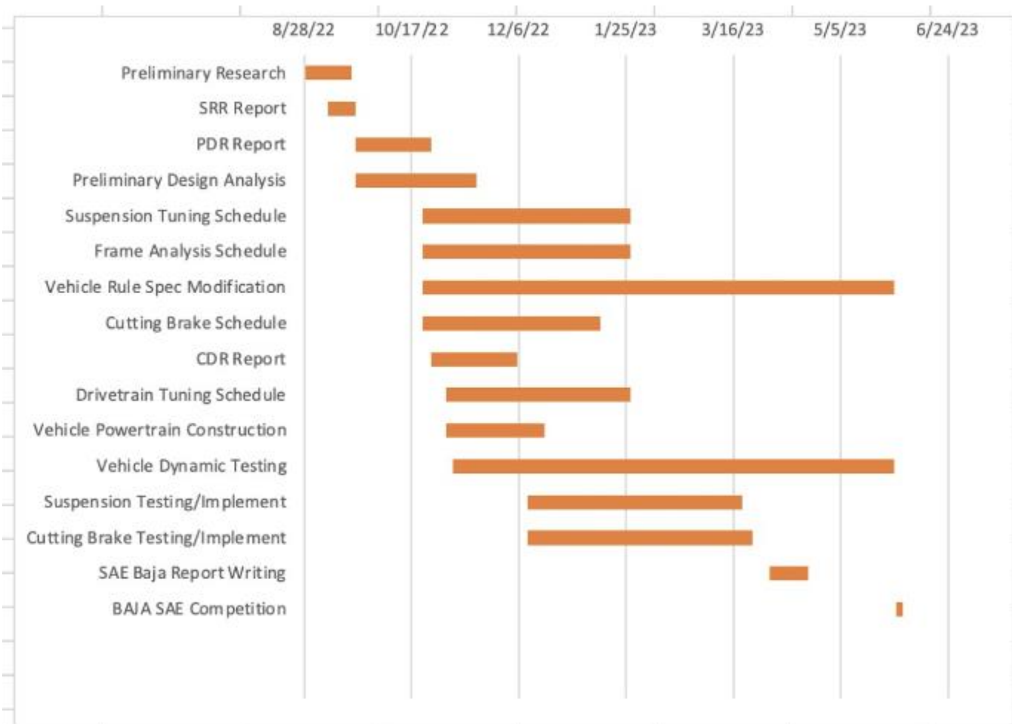



# Appendix D. Project Schedule

## 1. Suspension Schedule

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Suspension Schedule | | | | | | | | |
| **Task:** | **Measure and record current setup** | **Complete prototype suspension DAQ unit** | **Complete vehicle test readiness** | **Complete standard for testing track** | **Begin vehicle testing - spring preload** | **vehicle testing - front damper compression** | **vehicle testing - heavier spring rate** | **vehicle testing - suspension layout** |
| **Due Date:** | 10/22/22 | 11/10/22 | 12/8/22 | 12/6/22 | 01/13/23 | 01/13/23 | 1/20/23 | 1/27/23 |
| **Status:** | Completed - 10/20/22 | completed - 11/02/22 | Initiated - 10/23/22 | Initiated - 10/22/22 | pending | pending | pending | pending |
| Drivetrain Schedule | | | | | | | | |
| **Task:** | **Measure and record current setup** | **Complete prototype CVT/ENGINE DAQ unit** | **Complete vehicle test readiness and new powertrain install** | **Complete standard for testing track** | **Drivetrain testing - spring preload** | **Drivetrain testing - spring rate** | **Drivetrain testing - CVT weights** | |
| **Due Date:** | 10/22/22 | 12/6/22 | 12/8/22 | 12/6/22 | 01/13/23 | 1/20/23 | 1/27/23 | |
| **Status:** | Initiated - 10/22/22 | Initiated - 10/05/22 | Initiated - 10/23/22 | Initiated - 10/22/22 | pending | pending | pending | |
| Cutting Brake Schedule | | | | | | | | |
| **Task:** | **Preliminary design and analysis** | **Complete cutting brake design and part order** | **Complete vehicle test readiness and cutting brake installation** | **Complete standard for testing track** | **Brake bias testing** | | | |
| **Due Date:** | 10/22/22 | 12/4/22 | 12/8/22 | 12/6/22 | 01/13/23 | | | |
| **Status:** | Initiated - 10/22/22 | Completed - 12/2/22 | Initiated - 10/23/22 | Initiated - 10/22/22 | pending | | | |
| Frame Analysis Schedule | | | | | | | | |
| **Task:** | **Preliminary design and analysis** | **Complete strain gauge DAQ unit** | **Complete frame CAD/FEA** | **Complete vehicle test readiness** | **Complete standard for testing track** | **Strain gauge testing, data analysis** | | |
| **Due Date:** | 10/22/22 | 01/13/23 | 12/4/22 | 12/8/22 | 12/6/22 | 1/27/23 | | |
| **Status:** | Initiated - 10/22/22 | Initiated - 10/05/22 | Initiated - 10/10/22 | Initiated - 10/23/22 | nitiated - 10/22/2 | pending | | |

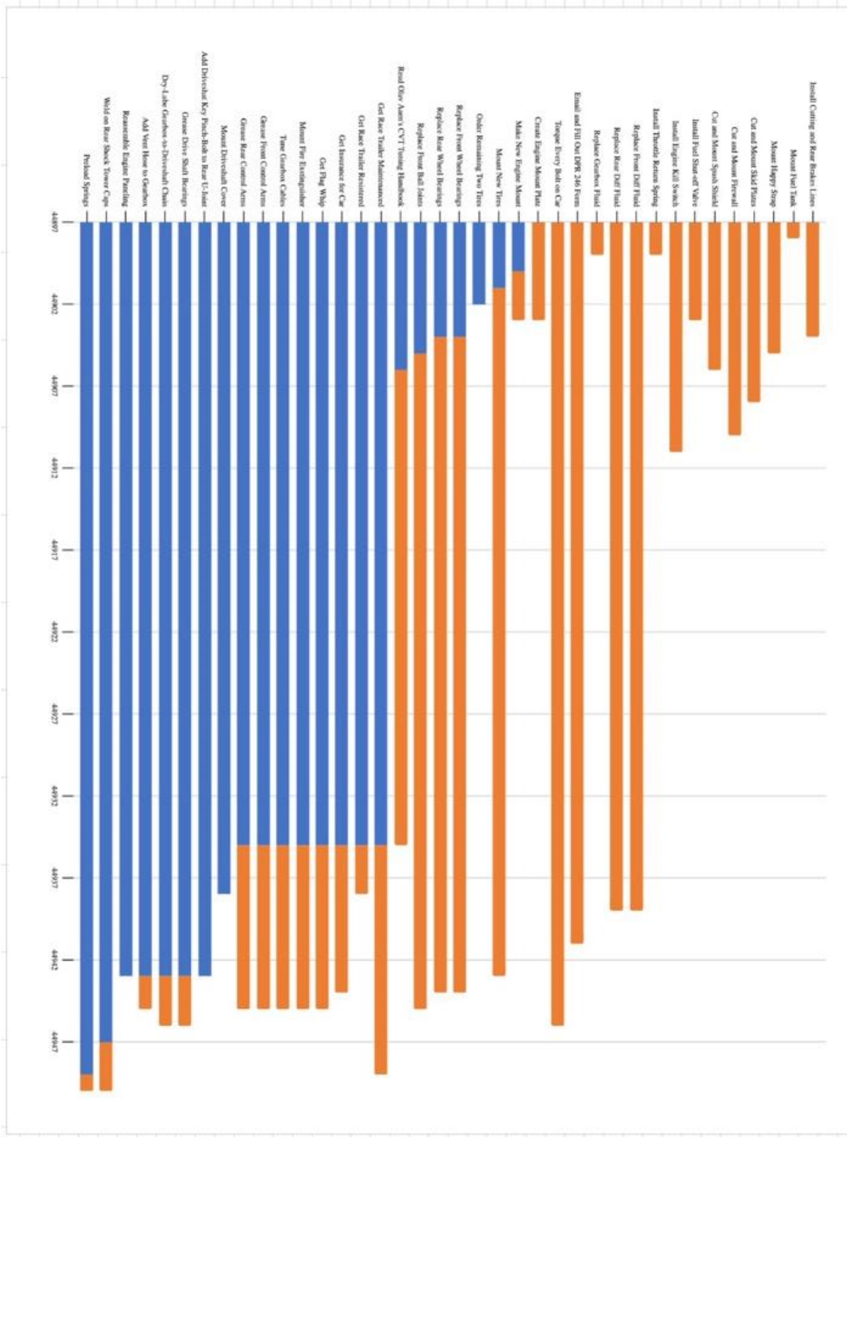
2. Capstone High-Level Schedule




**SAE BAJA CAPSTONE TIMELINE**

| Task | Begin Dat | Duration | Completion Date |
|---|---|---|---|
| Preliminary Research | 8/28/22 | 22 | 9/19/22 |
| SRR Report | 9/8/22 | 13 | 9/21/22 |
| PDR Report | 9/21/22 | 35 | 10/26/22 |
| Preliminary Design Analysis | 9/21/22 | 56 | 11/16/22 |
| Suspension Tuning Schedule | 10/22/22 | 97 | 1/27/23 |
| Frame Analysis Schedule | 10/22/22 | 97 | 1/27/23 |
| Vehicle Rule Spec Modification | 10/22/22 | 220 | 5/30/23 |
| Cutting Brake Schedule | 10/22/22 | 83 | 1/13/23 |
| CDR Report | 10/26/22 | 40 | 12/5/22 |
| Drivetrain Tuning Schedule | 11/2/22 | 86 | 1/27/23 |
| Vehicle Powertrain Construction | 11/2/22 | 46 | 12/18/22 |
| Vehicle Dynamic Testing | 11/5/22 | 206 | 5/30/23 |
| Suspension Testing/Implement | 12/10/22 | 100 | 3/20/23 |
| Cutting Brake Testing/Implement | 12/10/22 | 105 | 3/25/23 |
| SAE Baja Report Writing | 4/2/23 | 18 | 4/20/23 |
| BAJA SAE Competition | 5/31/23 | 3 | 6/3/23 |

| Tasks | Start Date | End Date | Duration |
|---|---|---|---|
| Install Cutting and Rear Brakes Lines | 12/2/2022 | 12/9/2022 | 7 |
| Mount Fuel Tank | 12/2/2022 | 12/3/2022 | 1 |
| Mount Happy Strap | 12/2/2022 | 12/10/2022 | 8 |
| Cut and Mount Skid Plates | 12/2/2022 | 12/13/2022 | 11 |
| Cut and Mount Firewall | 12/2/2022 | 12/15/2022 | 13 |
| Cut and Mount Spash Shield | 12/2/2022 | 12/11/2022 | 9 |
| Install Fuel Shut-off Valve | 12/2/2022 | 12/8/2022 | 6 |
| Install Engine Kill Switch | 12/2/2022 | 12/16/2022 | 14 |
| Install Throttle Return Spring | 12/2/2022 | 12/4/2022 | 2 |
| Replace Front Diff Fluid | 12/2/2022 | 1/13/2023 | 42 |
| Replace Rear Diff Fluid | 12/2/2022 | 1/13/2023 | 42 |
| Replace Gearbox Fluid | 12/2/2022 | 12/4/2022 | 2 |
| Email and Fill Out DPR 246 Form | 12/2/2022 | 1/15/2023 | 44 |
| Torque Every Bolt on Car | 12/2/2022 | 1/20/2023 | 49 |
| Create Engine Mount Plate | 12/2/2022 | 12/8/2022 | 6 |
| Make New Engine Mount | 12/5/2022 | 12/8/2022 | 3 |
| Mount New Tires | 12/6/2022 | 1/17/2023 | 42 |
| Order Remaining Two Tires | 12/7/2022 | 12/7/2022 | 0 |
| Replace Front Wheel Bearings | 12/9/2022 | 1/18/2023 | 40 |
| Replace Rear Wheel Bearings | 12/9/2022 | 1/18/2023 | 40 |
| Replace Front Ball Joints | 12/10/2022 | 1/19/2023 | 40 |
| Read Olav Aaen's CVT Tuning Handbook | 12/11/2022 | 1/9/2023 | 29 |
| Get Race Trailer Maintenanced | 1/9/2023 | 1/23/2023 | 14 |
| Get Race Trailer Resistered | 1/9/2023 | 1/12/2023 | 3 |
| Get Insurance for Car | 1/9/2023 | 1/18/2023 | 9 |
| Get Flag Whip | 1/9/2023 | 1/19/2023 | 10 |
| Mount Fire Exstinguisher | 1/9/2023 | 1/19/2023 | 10 |
| Tune Gearbox Cables | 1/9/2023 | 1/19/2023 | 10 |
| Grease Front Control Arms | 1/9/2023 | 1/19/2023 | 10 |
| Grease Rear Control Arms | 1/9/2023 | 1/19/2023 | 10 |
| Mount Driveshaft Cover | 1/12/2023 | 12/12/2022 | -31 |
| Add Driveshat Key Pinch-Bolt to Rear U-Joint | 1/17/2023 | 1/13/2023 | -4 |
| Grease Drive Shaft Bearings | 1/17/2023 | 1/20/2023 | 3 |
| Dry-Lube Gearbox-to-Driveshaft Chain | 1/17/2023 | 1/20/2023 | 3 |
| Add Vent Hose to Gearbox | 1/17/2023 | 1/19/2023 | 2 |
| Reassemble Engine Paneling | 1/17/2023 | 1/11/2023 | -6 |
| Weld on Rear Shock Tower Caps | 1/21/2023 | 1/24/2023 | 3 |
| Preload Springs | 1/23/2023 | 1/24/2023 | 1 |




3. First Test Gantt Chart

# Appendix E. Purchased Parts List

| Date | Company | Parts | Product Number | Quantity | Unit Price | Subtotal | Total | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 5/19/2022 | Very & Lewis Welding Supply, INC. | Tig Welding Class | 86-GTAWTRAINING | 3 hr | $75.00 | $225.00 | $225.00 | 10041.181 |
| 5/28/2022 | Personal Connection: Tyler Carpenter | 14" Wheel | | 4 | $12.50 | $50.00 | $200.00 | |
| | | 29" Tire | | 4 | $12.50 | $50.00 | | |
| | | Prop Shaft | | 1 | $50.00 | $50.00 | | |
| | | Lower steering Shaft | 744A110613 | 1 | $10.00 | $10.00 | | |
| | | Steering Rack | 20180202 | 1 | $30.00 | $30.00 | | |
| | | Slip Yoke | | 1 | $10.00 | $10.00 | | |
| 6/3/2022 | Foddrill Motorsports | Large Gusset | 7019 | 4 | $3.40 | $13.60 | $53.75 | |
| | | Medium Gusset | 7018 | 4 | $2.33 | $9.32 | | |
| | | 3/16" Tab | 381010 | 4 | $2.12 | $8.48 | | |
| | | Tab 3/16 | 3820 | 4 | $2.12 | $8.48 | | |
| | | 3/16 Tab | 381020 | 4 | $2.46 | $9.84 | | |
| 5/30/2022 | Facebook Group: Casey Cochran | Control Arm Left Front Lower | - | 1 | - | - | $250.00 | |
| | | Control Arm Right Front Lower | - | 1 | - | - | | |
| | | Control Arm Left Front Upper | - | 1 | - | - | | |
| | | Control Arm Right Front Upper | - | 1 | - | - | | |
| | | Front Half Shaft Left | - | 1 | - | - | | |
| | | Front Half Shaft Right | - | 1 | - | - | | |
| 6/2/2022 | Facebook Group: KB ATV | Brake Caliper Left | 191186 | 1 | - | - | $320.00 | |
| | | Brake Caliper Right | 191187 | 1 | - | - | | |
| | | Control Arm Left Front Upper | 1015453-458 | 1 | - | - | | |
| | | Control Arm Left Front Lower | 1018205-458 | 1 | - | - | | |
| | | Control Arm Right Front Upper | 1018204-458 | 1 | - | - | | |
| | | Control Arm Right Front Lower | 1018206-458 | 1 | - | - | | |
| | | Knuckel Right | 5135443 | 1 | - | - | | |
| | | Knuckel Left | 5135442 | 1 | - | - | | |
| | | Both Hubs | 5135409 | ? | - | - | | |
| | | 40mm Hubs | 5137659-067 | ? | - | - | | |
| | | Wheel Bearings 40mm | 72-1066 | 1 | - | - | | |
| | | Wheel Bearings 44mm | 72-1064 | 1 | - | - | | |
| 6/3/2022 | Industrial Metal Supply Co. | 1020/1026 DOM Steel Tube R/L 1-1/4 | RDT12509DOM | 42 lf | $3.46 | $145.32 | $157.82 | |
| 6/6/2022 | Foddrill Motorsports | 1/8 Tab (10 Pack) | 371008-BULK | 2 | $17.00 | $34.00 | $37.85 | |
| | | | | | | $0.00 | | |
| 6/6/2022 | Ace Hardware | Ace Carpenter's Pencil | 2198562 | 1 | $1.39 | $1.39 | $50.55 | |
| | | Chalk White 12 Sticks | 91206 | 1 | $1.59 | $1.59 | | |
| | | Black Silicone ADHSV 30Z | 85377 | 1 | $6.59 | $6.59 | | |
| | | Saw Hole 1-1/4" W/ARB ACE | 24310 | 1 | $13.99 | $13.99 | | |
| | | ROD Threaded SS 3/8x36" | 78923 | 1 | $22.99 | $22.99 | | |
| 6/7/2022 | Ace Hardware | SPRYPNT 2X Matte Clear | 1395839 | 1 | $7.99 | $7.99 | $15.18 | |
| | | Painters Tape 0.94"X60YD | 1010339 | 1 | $5.99 | $5.99 | | |
| 6/9/2022 | Ebay: Pirate MX | Front Driver Left Lower A-Arm | 1018205-458 | 1 | $59.95 | $59.95 | $59.95 | |
| | | | | | | | | |
| 6/9/2022 | Industrial Metal Supply Co. | 1020/1026 DOM Steel Tube R/L 1-1/4 | RDT12509DOM | 21.3333 lf | $3.56 | $75.95 | $135.92 | |
| | | 1020/1026 DOM Steel Tube R/L 1-1/4 | RDT12506DOM | 21.5833 lf | $2.28 | $49.21 | | |
| 6/9/2022 | Industrial Metal Supply Co. | Hr Sheet Pre-Cut Hr Sheet Pre-Cut | HRPRESHT | 10 lb | $1.59 | $15.90 | $22.69 | |
| | | Brite Mark White Marker Pen Valve Ti | BRITEWHITE | 1 | $4.99 | $4.99 | | |
| 6/10/2022 | Foddrill Motorsports | 3/16" Tab | 381010 | 16 | $2.13 | $36.84 | $36.84 | |
| | | | | | | | | |
| 6/11/2022 | Foddrill Motorsports | 7/16 ROD END | CM7 | 2 | $4.22 | $8.44 | $495.82 | |
| | | 1/2 ROD END | CM8 | 2 | $5.24 | $10.48 | | |
| | | 1/2 X 3/8 .342 TALL Misalinment(PR) | 8-6HB | 2 | $8.99 | $17.98 | | |
| | | 1-1/8 DIA STEEL TUBE W/BEARING | FOD4135 | 1 | $44.00 | $44.00 | | |
| | | 5/8-36 X 3/4 SMOOTH U-Joint | 06X07 | 1 | $60.00 | $60.00 | | |
| | | 06 X 06 U-JOINT | 06X06 | 1 | $60.00 | $60.00 | | |
| | | BLACK SWEET 6 BOLT QUICK RELE | 1121 | 1 | $130.00 | $130.00 | | |
| | | 3/4 X .120 4130 TUBING {PER FT} N | 3/4X.120TUBING | 5 | $7.45 | $37.25 | | |
| | | 1-1/4" TUBE CLAMP | ALL14481 | 1 | $13.17 | $13.17 | | |
| | | RETAINING RING: WIRE 0.078 CS X | 038-01-007-A | 4 | $1.70 | $6.80 | | |
| | | SEALS:O-RING (-031) .070 C.S. X 1. | 029-00-031 | 4 | $1.70 | $6.80 | | |
| | | SPRING HARDWARE: (T) SPRING R | 234-03-203-A | 3 | $21.25 | $63.75 | | |
| 6/11/2022 | Ace Hardware | CUTTING KIT 11PC DREMEL | 2331262 | 1 | $24.99 | $24.99 | $47.31 | |
| | | GRIND-STONE9/32CARB83142 | 22885 | 1 | $3.59 | $3.59 | | |
| | | SA-43 1/8 CYL SHANK | KT58480 | 1 | $14.99 | $14.99 | | |
| 5/11/23 | U-Haul | UV- 4' x 8' Utility Van | UV3866B | 1 | $233.00 | $233.00 | $253.81 | |
| 5/26/22 | Blast LED INC | 40 SERIES GO KART FORWARD RE | BL-40S-FRG | 1 | $259.99 | 259.99 | $310.57 | |
| 7/10/22 | Home Depot | MKE M18 4-1/2 IN GRINDER (TOOL | 45242158799 M18 G | 1 | $129.00 | $129.00 | $168.09 | |
| | | MILWAUKEE 1-1/4" BI-METAL HOLE | 45242198375 | 1 | $23.94 | $23.94 | | |
| 7/11/22 | Foddrill Motorsports | EYELET PARTS: SPACER 0/506 ID X | 213-18-005-C | 10 | $1.70 | $17.00 | $34.48 | |
| | | 3/4 X .120 4130 TUBING {PER FT} N | 3/4 X .120 TUBING | 2 | $7.45 | $14.90 | | |
| 7/18/22 | Foddrill Motorsports | SPRING HARDWARE: (T) SPRING R | 234-03-203-A | 1 | $21.25 | $21.25 | $22.97 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7/19/22 | Staples | TR STND DUALPRF LT | 718103391436 | 1 | $6.49 | $6.49 | $36.44 |
| | | STPLS EXP FLE 7PKT | 718103349321 | 1 | $9.49 | $9.49 | |
| | | TR FLX PU JRNL M 1 | 718103318860 | 1 | $14.49 | $14.49 | |
| | | SHARPIE FINE METAL | 071641054905 | 1 | $1.99 | $1.99 | |
| | | SHARPIE FINE METAL | 071641390133 | 1 | $1.99 | $1.99 | |
| | | SHARPIE FINE METAL | 071641300514 | 1 | $1.99 | $1.99 | |
| 7/23/22 | Caltric | FRONT REAR PROPELLER SHAFT | KJ1076DB106HH | 1 | $40.98 | $40.98 | $43.99 |
| 7/23/22 | McMaster-Carr | Wear-Resistant Sprocket for ANSI 50 | 2500T682 | 1 | $40.12 | $40.12 | $52.90 |
| 7/25/22 | Mace Offroad | Front A Arm Lower Bushing Kit with S | AA-190007-002-AE | 1 | $19.72 | $19.72 | $21.42 |
| 7/26/22 | Phoenix Pumps | Rexnord/Falk 10057514 Hub, 5R, 0.7 | 10057514 | 2 | $37.04 | $74.08 | $136.71 |
| | | Rexnord/Falk 10057440 Element, 5R | 10057440 | 1 | $26.75 | $26.75 | |
| | | Rexnord/Falk 10042529 Nylon Cover, | 10042529 | 1 | $13.89 | $13.89 | |
| 7/30/22 | Ace Hardware | All THRD PLT 10MM-1,50X1M | H11079 | 1 | $9.29 | $9.29 | $24.90 |
| | | FASTENERS | 56 | 6 | $0.79 | $4.74 | |
| | | FASTENERS | 56 | 10 | $0.89 | $8.90 | |
| 8/1/22 | Iron City Polaris | BOLT-M10X1.5X270 | 7518458 | 1 | $12.90 | $12.90 | $14.01 |
| 8/5/22 | Foddrill Motorsports | STEEL-IT GRAY 14OZ AEROSOL | 1002B | 10 | $30.00 | $300.00 | $324.00 |
| 8/11/22 | Foddrill Motorsports | STEEL-IT GRAY 140Z AEROSOL | 1002B | -10 | $30.00 | ($300.00) | -$324.30 |
| 8/11/22 | Foddrill Motorsports | STEEL-IT GRAY 140Z AEROSOL | 1002B | 5 | $30.00 | $150.00 | $162.15 |
| 8/11/22 | Foddrill Motorsports | 7/16 JAMNUT | SJNR7 | 4 | $0.34 | $1.36 | $215.27 |
| | | 1/2 JAMNUT | SJNR8 | 4 | $0.43 | $1.72 | |
| | | 1/2 ROD END | JMX8T | 4 | $21.68 | $86.72 | |
| | | MOUNTING HARDWARE: WELD ON | 026-01-003-A | 3 | $3.40 | $10.20 | |
| | | 1/2 X 3/8 .342 TALL MISALINMENT(F | 8-6HB | 2 | $8.99 | $17.98 | |
| | | GAS PEDAL | 16-2158-0 | 1 | $37.36 | $37.36 | |
| | | 3/4 X .120 4130 TUBING {PER FT} N | 3/4 X .120 TUBING | 5 | $8.76 | $43.80 | |
| 8/14/22 | RideNow Powersports | OIL-FRONT DEMAND DRIVE | 2877922 | 1 | $20.99 | $20.99 | $22.84 |
| 8/18/22 | Foddrill Motorsports | 7' H/D THROTTLE CABLE | 100-3333-84 | 1 | $45.86 | $45.86 | $86.13 |
| | | 3/4-48 WELD COUPLER | 670 | 1 | $19.00 | $19.00 | |
| | | 3/16 TAB | 381020 | 6 | $2.47 | $14.82 | |
| 8/19/22 | Ace Hardware | ROD END- FML RIGTH 10-32 | V883513 | 1 | $10.99 | $10.99 | $28.70 |
| | | BALL JNT-MLE RIGTH 10-32 | V883529 | 1 | $10.99 | $10.99 | |
| | | FASTENERS | 56 | 5 | $0.89 | $4.45 | |
| 8/19/22 | Bearings-Belt & Chain, Inc. | RIM ONLY | MAR 50JA15 | 1 | $38.48 | $38.48 | $100.81 |
| | | JA QD BUSHING | MAU JA10018 | 1 | $12.32 | $12.32 | |
| | | 1 1/8 X 36 KEYED SHAFTING 144-18 | G&G 1 1/8 X 36 KEY | 1 | $39.78 | $39.78 | |
| | | 1/4 SQ KEY 65-120 | MAK 1/4 SQ KEY | 1 | $2.25 | $2.25 | |
| 8/19/22 | Bearings-Belt & Chain, Inc. | SS Pillow Block | BRO VPS-218 | 2 | $90.46 | $180.92 | 196.48 |
| 8/20/22 | Foddrill Motorsports | #3 X 3/8-24 I.F. BRAKE ADAPTER - S | 650302 | 2 | $6.62 | $13.24 | $99.56 |
| | | #3 BULKHEAD TEE - STEEL | 583403 | 1 | $10.60 | $10.60 | |
| | | #3 BULKHEAD NUT - STEEL 3/8-24 | 592403 | 1 | $0.50 | $0.50 | |
| | | 10MM X 1.0 BANJO BOLT-STEEL | 650155 | 1 | $5.76 | $5.76 | |
| | | MORSE CABLE END | MORSEBALLEND | 1 | $5.91 | $5.91 | |
| | | #3 HOSE ASSEMBLY STR X STR 30 | 310030 | 1 | $19.47 | $19.47 | |
| | | #3 HOSE ASSEMBLY STR X STR 90 | 320012 | 1 | $23.50 | $23.50 | |
| | | #3 CAP BLACK | 492903-BL | 1 | $2.30 | $2.30 | |
| | | #3 X 3/8 BANJO ADAPTER - STEEL | 650103 | 1 | $9.12 | $9.12 | |
| | | TAB: 1652 THIN, 13 GAUGE | 1652-13GA | 1 | $1.70 | $1.70 | |
| 8/20/22 | Ace Hardware | FASTENERS | 56 | 5 | $0.99 | $4.95 | $5.38 |
| 8/20/22 | Lowes | HXHDBLT 1/2-13X6 GR8 CT-1 | 136334 | 4 | $4.25 | $17.00 | $18.87 |
| 8/20/22 | X-Power Auto | ATV 3/8"-24 Lug Nuts | N050P-16 | 1 | $22.99 | $22.99 | $24.97 |
| 8/22/22 | Bearing-Belt & Chain, Inc. | RIM ONLY | MAR 50SDS21 | 1 | $58.09 | $58.09 | $96.42 |
| | | Q.D. BUSHING | MAR SDS 1 1/8 | 1 | $30.69 | $30.69 | |
| 8/25/22 | Arizona Driveshaft & Differential | RETUBE | 1310-1410 | 1 | $138.72 | $138.72 | $237.38 |
| | | INSTALL 2 U-JOINTS | BB2 | 1 | $82.61 | $82.61 | |
| 8/27/22 | U-Haul | RV - 6' X 12' Van Trailer | RV2968G | 1 | $189.00 | $189.00 | $214.70 |
| 9/9/22 | Tractor Suppply | Kohler Command Pro 14 HP Engine 1 | 1433590 | 1 | $899.99 | $899.99 | $1,006.48 |
| 9/9/22 | Pyrotect | Baja SAE Fuel Tank | SFC1000 | 1 | $360.99 | $360.99 | $415.25 |
| 9/28/22 | Home Depot | SAE 10-30W Full Synthetic motor oil ( | | 1 | $25.97 | $25.97 | $28.44 |
| 9/30/22 | O'Reilley Auto Parts | Prime Line Wheel Bearing 40MM- 72- | 721066 | 2 | $30.99 | $61.98 | $141.96 |
| | | Prime Line Wheel Bearing 44MM- 72- | 721064 | 2 | $39.99 | $79.98 | |
| 9/30/22 | Kohler | SPRING, GOVERNOR | 17 089 64-S | 1 | $4.89 | $4.89 | $10.14 |
| Oct | | | | | | | |
| Nov | | | | | | | |
| Dec | | | | | | | |
| Jan | | | | | | | |
| 1/17/23 | Summit Racing Equipment | Race Main Spring | EIB-14002500150S | 2 | $79.00 | $158.00 | $173.01 |
| 1/17/23 | Harbor Freight Tools | 3PC UNIV IMP JOINT SKT ADAPTER | 67986 | 1 | $11.99 | $11.99 | $33.25 |
| | | 3PC 1/2IN IMP WOBBLE SKT EXT | 67066 | 1 | $11.99 | $11.99 | |
| 1/17/23 | Speedway Motors | 1/4 TURN FASTENER PLATE | 910-07101 | 4 | $13.59 | $54.36 | $133.33 |
| | | ALUM 1/4 TURN .500 OVAL | 910-07151 | 4 | $13.19 | $52.76 | |

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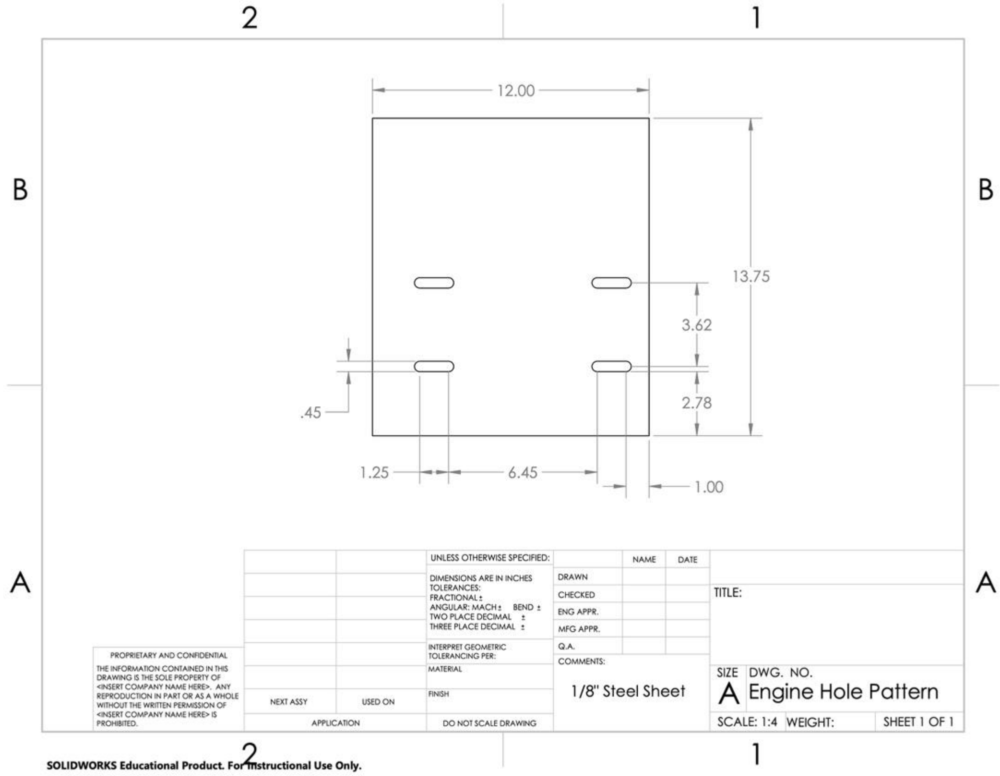
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1/30/23 | Autozone | Slime 4 Way Tire Valve Stem Core Re | 2044-A | 1 | $1.99 | $1.99 | $13.44 |
| | | 80W 90 Conventional Gear Oil 1 Quai | STPGO80W90QTST | 1 | $8.49 | $8.49 | |
| | | Slime Tire Valve Stem Core 4 Pack | 22042 | 1 | $1.79 | $1.79 | |
| TRUE | Partzilla | NUT | 7547337 | | 2 | $2.99 | $16.34 |
| TRUE | Grainger | Natural Rubber Sheet: Std, 12 in x 24 in, 0.25 in Thick, 40A, Plain Backing, Tan, Smooth | 1XWD8 | | 1 | $30.42 | $42.67 |
| TRUE | MFG Supply | Ski-Doo Kill Switch | 01-171 | | 1 | $32.49 | $42.73 |
| TRUE | Kartek | Fragola 22" Long AN -3 Female Straight To 3/8" Straight Banjo Stainless Steel Brake Lines / Hoses | FRA330022 | | 2 | $21.99 | $24.19 |
| TRUE | Kartek | Fragola 26" Long AN -3 Female Straight To AN -3 Female Straight Stainless Steel Brake Lines / Hoses | FRA310026 | | 1 | $17.49 | $19.24 |
| TRUE | Kartek | An Bolt For Banjo Fittings 10Mm X 1.00 Metric Thread | an-bolt-10mm | | 2 | $4.00 | $15.00 |
| TRUE | Pacific Customs | An 10Mm Or 3/8 Inch Copper Crush Washer For Banjo Bolt Fittings | an-w10mm | | 8 | $1.35 | $13.00 |
| TRUE | Pacific Customs | Brake Light Switch with 3/8 Inch IFM Adapter Fitting | | | 1 | $26.60 | $37.65 |
| | Walmart | | | | | | |
| TRUE | Ebay | Flush Mount LED Light Pods 2Pcs 7 | | | 1 | $19.99 | $21.99 |
| TRUE | Joes Racing | XRP Aluminum AN Hose Plugs - #3 | XRP980603BB | | 3 | $2.95 | $12.34 |
| TRUE | Joes Racing | XRP Aluminum AN Hose Caps - #3 | XRP992903BB | | 3 | $3.95 | $15.64 |
| TRUE | Ebay | Polaris Ranger Sportsman RZR 325 500 570 12x6 Wheel Front (Black) 1520263-067 | | | 4 | $43.94 | $193.34 |
| Cancelled | ~~Discount Tire~~ | ~~CARLISLE ATV AT489 X/L 27 X9.00 D 12 52F 3S BSW~~ | ~~14809~~ | | ~~4~~ | ~~$153.47~~ | ~~$0.00~~ |
| TRUE | Kartek | EMPI 16-2540 - 3/4" Bore Single Upright Handle Steering Brake | MRB162540 | | 1 | $125.99 | $143.59 |
| TRUE | Industrial Metal Supply | 5052-H32 Alum Sheet .025 AMS QQA-250/8, ASTM-B209 | 52SH025412 | | 1 | $92.67 | $101.94 |
| TRUE | Industrial Metal Supply | 6061-T6 Alum Sheet, Import .190 AMS-4027 | 61SH190412IM | | 2 | $220.00 | $484.00 |
| TRUE | Industrial Metal Supply | 1020/1026 DOM Steel Tube R/L 1 OD X .065 ASTM-A-513 STRESS RELIEVED/ANN | RDT10006DOM | | 1 | $47.04 | $51.74 |
| TRUE | Industrial Metal Supply | 1020/1026 DOM Steel Tube R/L 1-1/4 OD X .065 ASTM-A-513 STRESS RELIEVED/ANN | RDT12506DOM | | 1 | $56.16 | $61.78 |
| TRUE | Industrial Metal Supply | 6061-T6 Import Alum Mill Finish Sheet .125 AMS-4027 | 61SH125412IM | | 1 | $172.00 | $189.20 |
| TRUE | Pyrotect | Standard SFI 5-Point 3" Harness With 2" Latch & Link | B180020 (Pull Down) | | 1 | $99.00 | $95.77 |
| FALSE | Ebay | 1/4" Inline Straight Gas Fuel Cut Shut Off Valve For Briggs & Stratton Outdoor S | | | 1 | $2.84 | $3.08 |
| TRUE | Pete's Tire Store | AT27x9-12 Carlisle AT489 X/L ATV Tire | 560470 | | 2 | $164.39 | $367.69 |
| FALSE | Baja SAE | Kohler CH440-3302 Horizontal OHV Command PRO Engine | SKU A-CH440-3302 BAJA | | 1 | $476.91 | $749.60 |
| TRUE | Walmart | Prestone DOT 3 Brake Fluid 1 gal Synthetic, High Grade, 50,000 Mile | AS402 | | 1 | $24.88 | $27.37 |
| TRUE | Walmart | Hyper Tough 8inch Cable Tie Uv Black 250Pcs | XLS-8-75-0-TF | | 1 | $9.72 | $10.69 |
| TRUE | Walmart | Super Tech CA Compliant Brake Cleaner, 14.5 oz. | SP-500930 | | 3 | $3.04 | $10.03 |
| TRUE | Walmart | SLIME 1034-A Tire Plug Kit for Car & Truck Tires-8 piece Rubber Cement Plug Kit | 1034-A | | 1 | $10.99 | $12.09 |
| TRUE | Ebay | TZ400 LTZ50 King Quad LT80 Quadsport Ozark 2 Part 7' Whip Flag Can-am USA | A9012US | | 1 | $15.00 | $19.50 |
| TRUE | Walmart | Carlisle AT489 II ATV/UTV Tire - 27X9.00-12 LRC 6PLY Rated | 6P0371 | | 2 | $127.14 | $283.25 |
| TRUE | Home Depot | 1-Handed Swivel Riveter Kit | RT187SHK | | 1 | $31.97 | $35.17 |
| TRUE | The OEM Parts Store | Kohler EX22-17146-0027 OEM BAJA | EX22-17146-0027 | | 1 | $6.11 | $17.06 |
| TRUE | Ebay | Ball Joint for Polaris 7061220 RZR XF | | | 2 | $31.50 | $69.46 |
| FALSE | Autozone | Mr. Gasket 0-30 PSI Tire Pressure Ga | 72101MRG | | 1 | $26.99 | $34.54 |
| FALSE | Kartek | Fragola AN -3 Male T | FRA482303 | | 3 | $7.69 | $27.88 |
| FALSE | Kartek | Fragola AN -3 Male T | FRA481503 | | 3 | $3.29 | $13.36 |
| FALSE | Kartek | Fragola AN -3 Fitting | FRA492903 | | 4 | $2.52 | $13.59 |
| FALSE | Kartek | Fragola AN -3 Fitting | FRA480603 | | 4 | $1.82 | $10.51 |
| FALSE | Kartek | Fragola 26" Long AN | FRA310026 | | 3 | $17.59 | $60.55 |

## 2. On-Vehicle Parts Inventory List

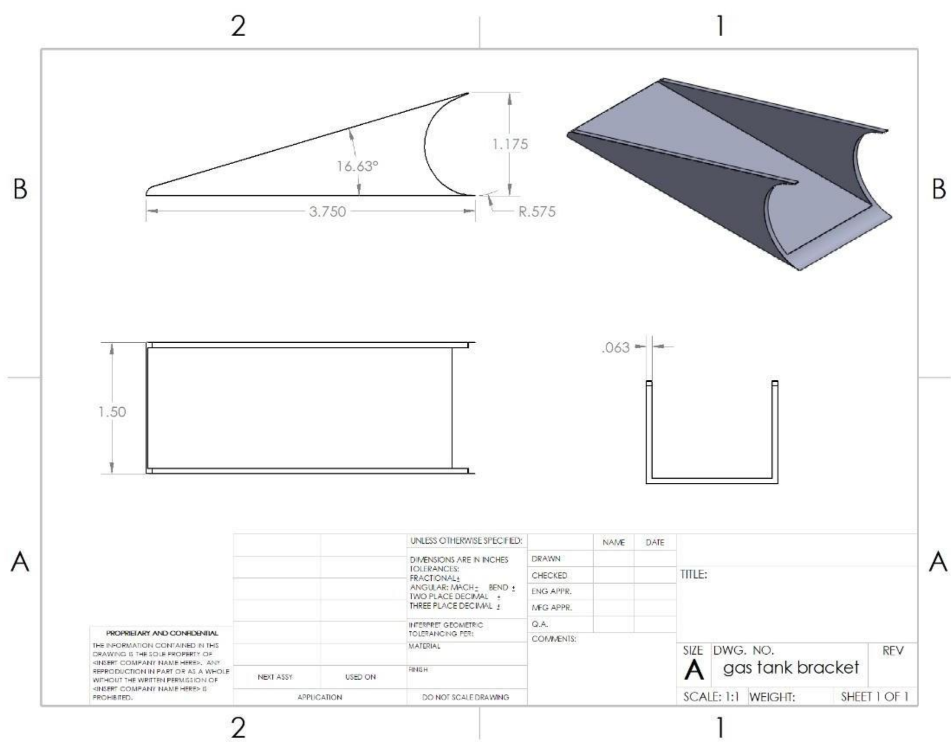
| Part Name | Quantity on Car |
|---|---|
| Upper Control Arm | 4 |
| Lower Control Arm | 4 |
| Ball Joint | 8 |
| Tire | 4 |
| Wheel | 4 |
| Seat | 1 |
| Driven Clutch | 1 |
| Driving Clutch | 1 |
| CVT Belt | 1 |
| Engine | 1 |
| Gearbox | 1 |
| Electronic Differential | 1 |
| Differential | 1 |
| Half-Shaft | 4 |
| Wheel Bearing Carrier | 4 |
| Wheel Hub | 4 |
| Tie Rod | 4 |
| Hollow Drive Shaft | 1 |
| Solid Drive Shaft | 1 |
| Sprocket | 2 |
| Chain | 1 |
| Brake Pedal | 1 |
| Cutting Brake | 1 |
| Brake Caliper | 4 |
| Brake Rotor | 4 |
| Brake Pad | 8 |
| Steering Rack | 1 |
| Vent Tube | 3 |
| Fuel Line | 1 |
| Throttle Cable | 1 |
| Gear Shifter Cable | 2 |
| Throttle Pedal | 1 |
| 5 Point Seat Belt | 1 |
| Pillow Block Bearing | 2 |
| Keys | 4 |
| Fuel Tank | 1 |
| Steering Wheel | 1 |
| Steering Column Shaft | 1 |
| Springs | 4 |
| Shocks | 4 |
| Gear Shifter | 1 |

**Appendix F. Engineering Drawings**

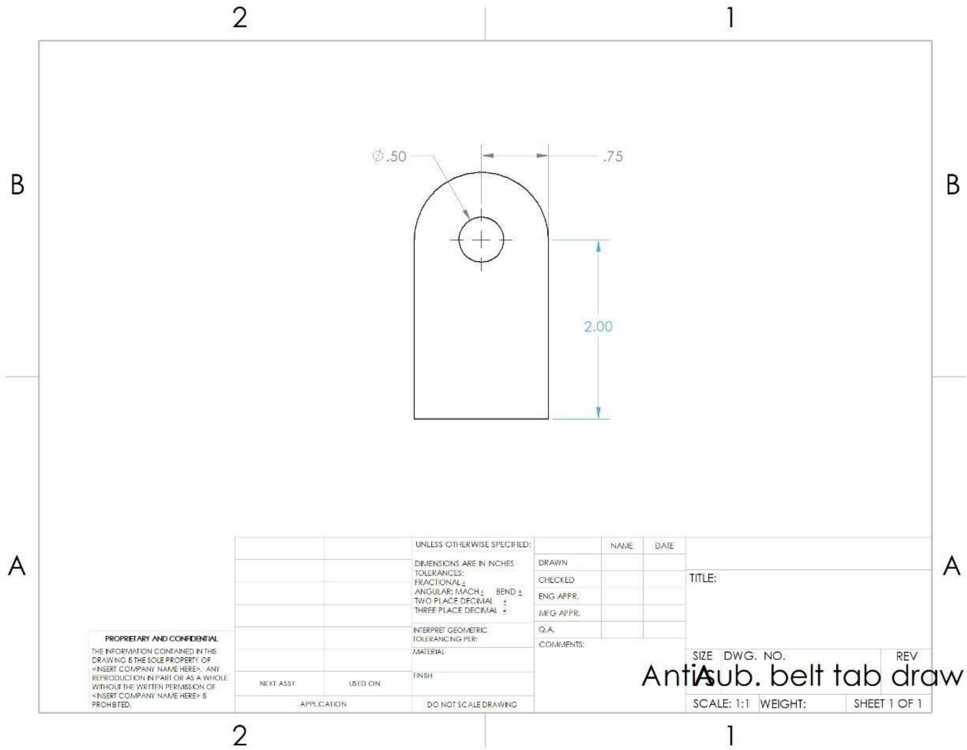
1. Engine Mount Hole Pattern

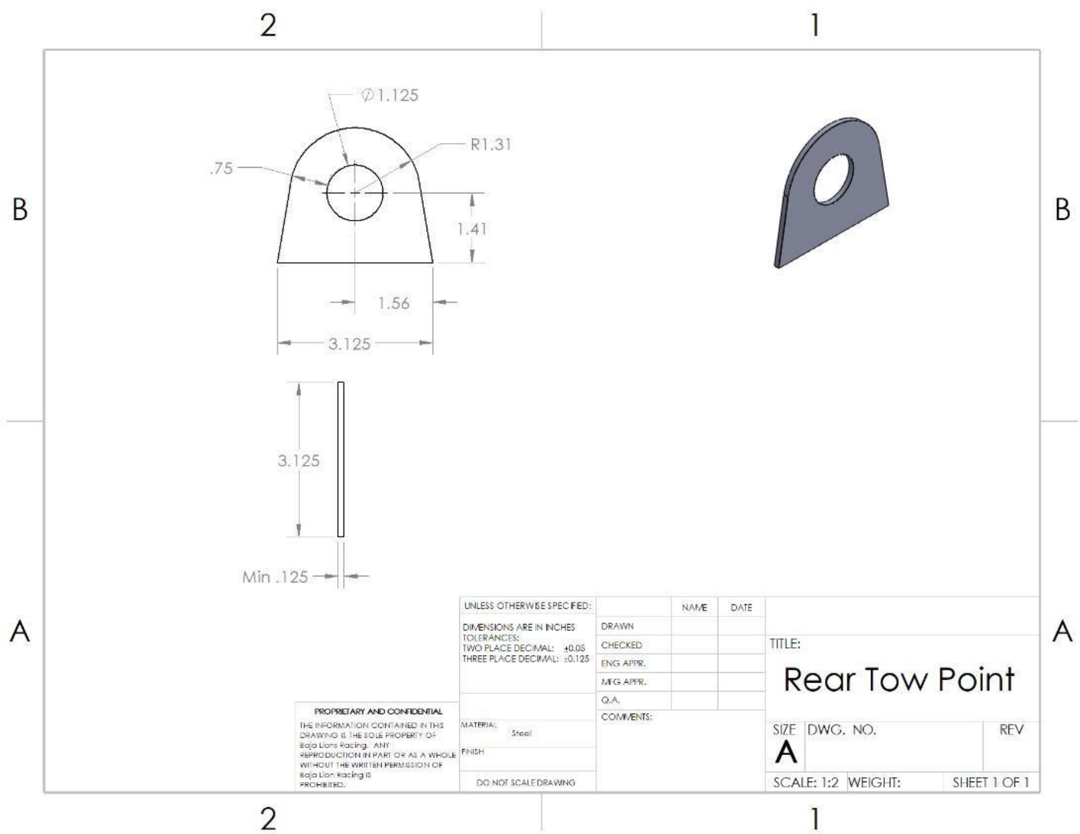



2.Gas Tank Installation Bracket

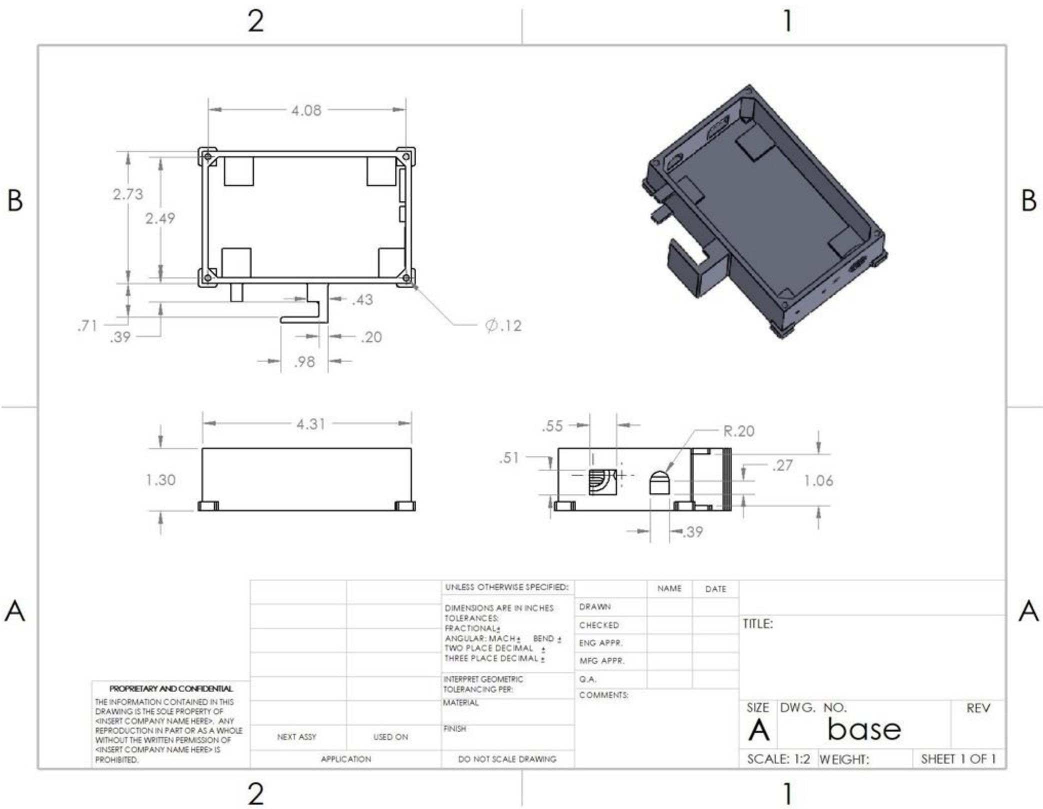


3. Belt Tab and Tow Point

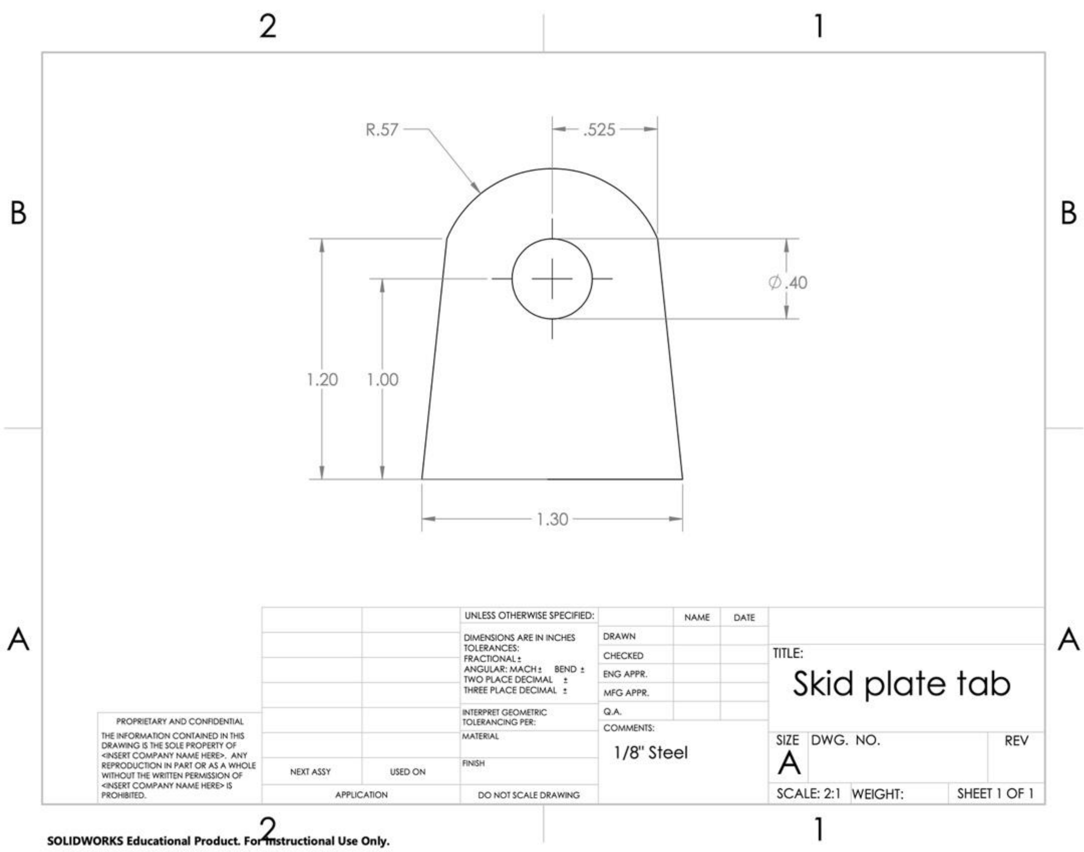


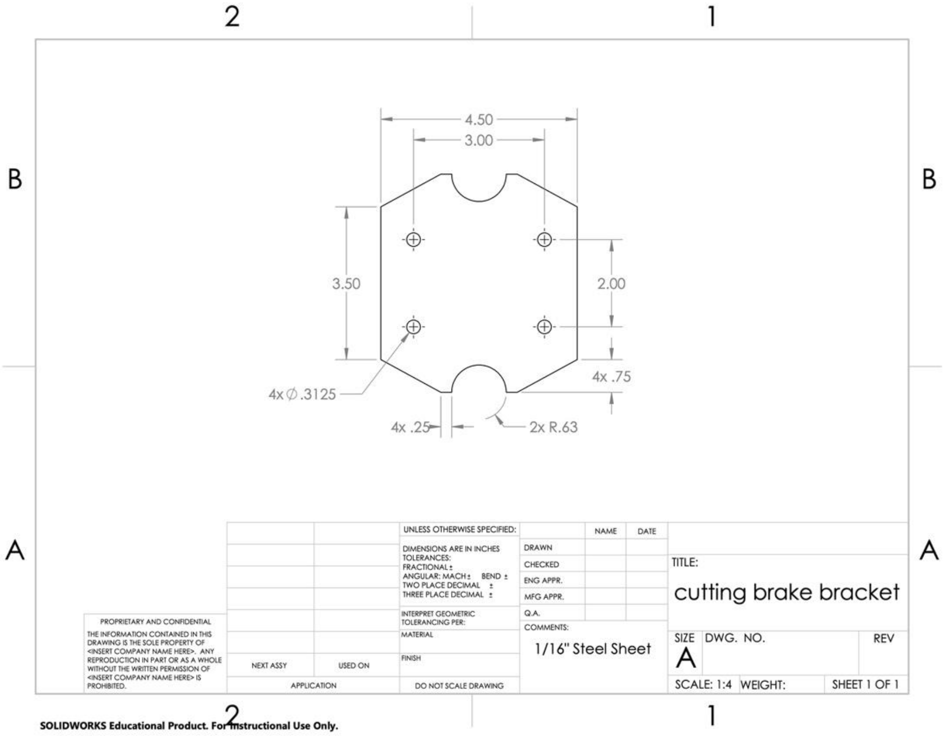
4. Suspension Arduino/SD DAQ Unit Enclosure



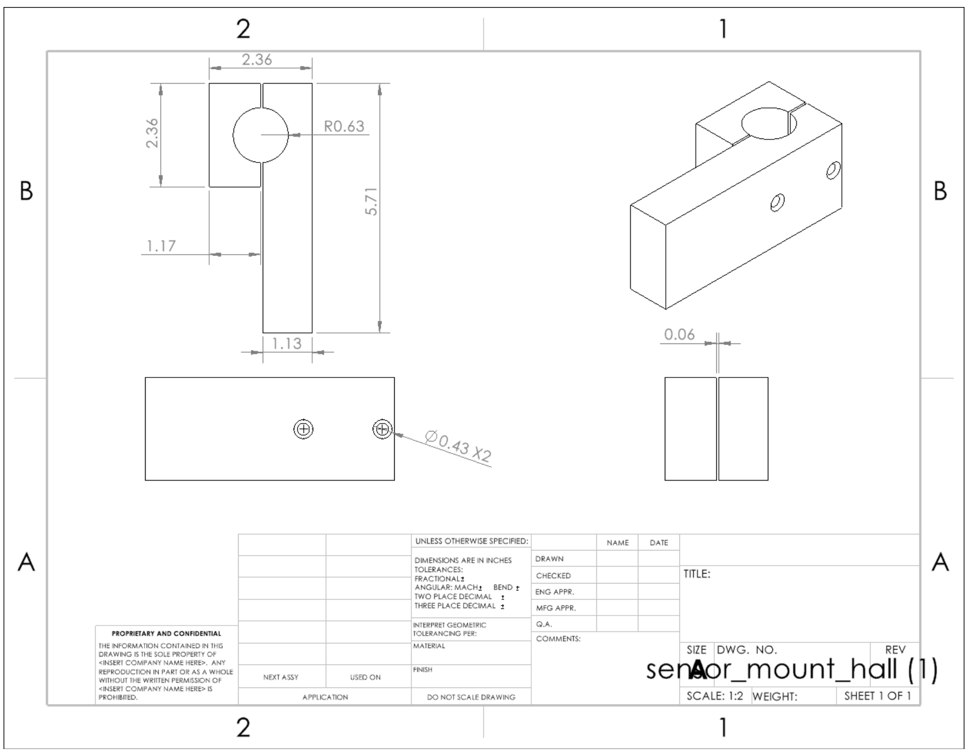

5. Skid Plate Tab



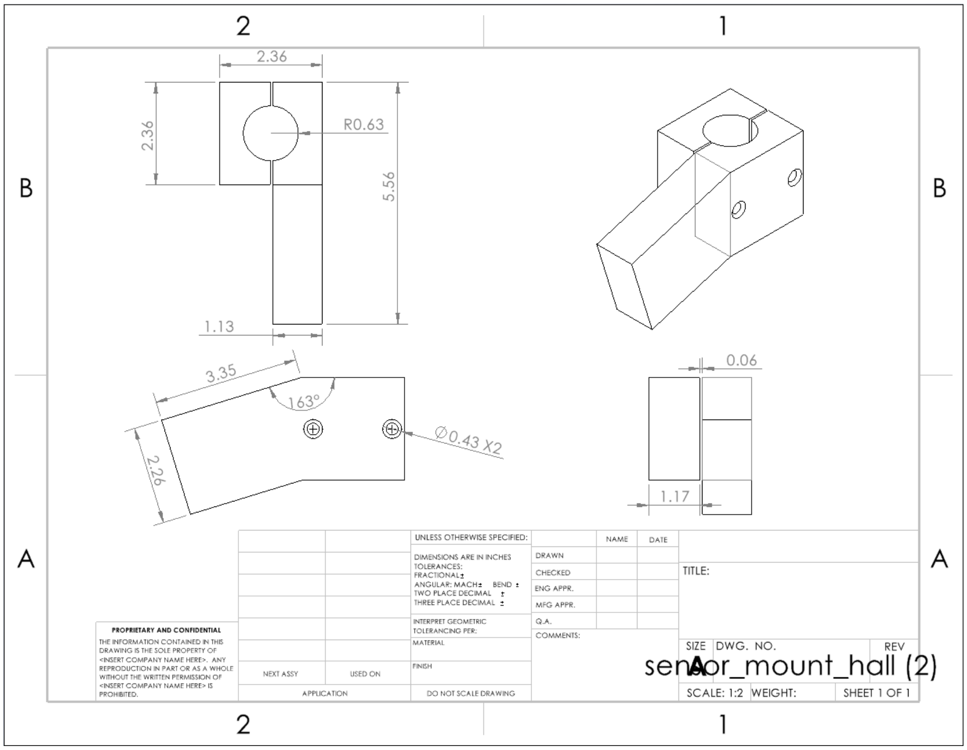
6. Cutting Brake Bracket



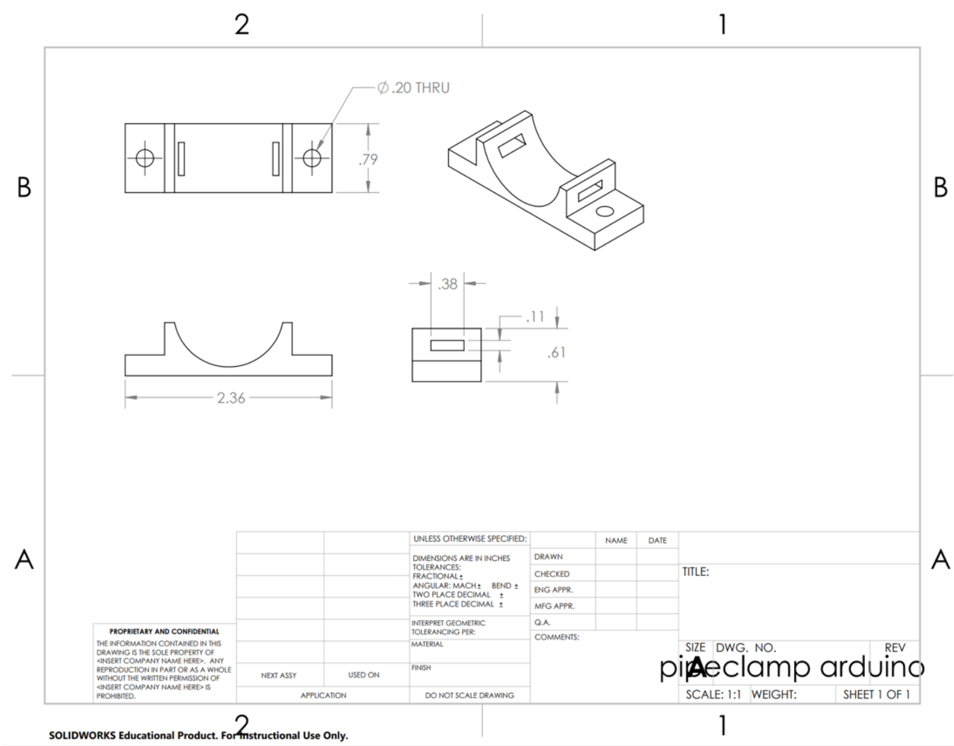

7. Hall Effect Sensor Mount (Rear Differential)



8. Hall Effect Sensor Mount (Driving Pulley CVT)




9.




## Appendix G. Project Budget

| 7.98381.06 | Part/Material | Item # | Quantity | Unit Price | Subtotal | Total before tax | Tax = 10% | Total after Tax | Shipping | Total with Ship | Grand Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ace Hardware | Zipties | 3004692 | 3 | $15.99 | $47.97 | $136.88 | $13.69 | $150.57 | $12.00 | $162.57 | $7,732.45 | 7066.46 |
| | Speed Square | e2994 | 1 | $12.97 | $12.97 | | | | | | | |
| | 1" Hole Saw | 24306 | 5 | $11.99 | $59.95 | | | | | | | |
| | 4-3/4 in. L X 4-3/4 in. W Angle Finder Yellow | 25865 | 1 | $15.99 | $15.99 | | | | | | | |
| Autozone | Dot 4 Brake Fluid | | 1 | $27.99 | $27.99 | $137.95 | $13.80 | $151.75 | $12.00 | $163.75 | | |
| | Multipurpose Grease | 101 | 2 | $9.99 | $19.98 | | | | | | | |
| | Nitrile Disposable Gloves 100 piece | D0109009100 | 2 | $34.99 | $69.98 | | | | | | | |
| | Lugnuts | | 1 | $20.00 | $20.00 | | | | | | | |
| MFG Supply | Engine Kill Switch | 01-171 | 1 | $32.49 | $32.49 | $32.49 | $3.25 | $35.74 | $6.99 | $42.73 | | |
| McMaster-Carr | Wear-Resistant Sprockets for ANSI Roller Chain 24 Tooth | 2500T672 | 1 | $90.52 | $90.52 | $334.20 | $33.42 | $367.62 | $41.26 | $408.88 | | |
| | Wear-Resistant Sprockets for ANSI Roller Chain 23 Tooth | 2500T682 | 1 | $87.12 | $87.12 | | | | | | | |
| | Wear-Resistant Sprockets for ANSI Roller Chain 21 Tooth | 2500T692 | 1 | $72.90 | $72.90 | | | | | | | |
| | Wear-Resistant Sprockets for ANSI Roller Chain 20 Tooth | 2500T109 | 1 | $63.06 | $63.06 | | | | | | | |
| | Machinable-Bore Sprockets for ANSI Roller Chain 9 Tooth | 6793K209 | 1 | $20.60 | $20.60 | | | | | | | |
| Foddrill Motorsp | 1/2 X 3/8 .342 TALL Misalignment(PR) | 8-6HB | 12 | $8.99 | $107.88 | $107.88 | $10.79 | $118.67 | $35.00 | $153.67 | | |
| Ebay | 8-12 Wheels | | 4 | $120.00 | $480.00 | $1,235.54 | $123.55 | $1,359.09 | $100.00 | $1,459.09 | | |
| | 27" Tires | | 4 | $153.00 | $612.00 | | | | | | | |
| | Lower Control Arms 2 pack | | 0 | $83.70 | $0.00 | | | | | | | |
| | Upper Left Control Arm | | 0 | $140.99 | $0.00 | | | | | | | |
| | Upper Right Control Arm | | 0 | $140.99 | $0.00 | | | | | | | |
| | Demand Drive Front Gearcase Oil | 2877922 | 1 | $23.94 | $23.94 | | | | | | | |
| | Floor Jack | | 0 | $142.84 | $0.00 | | | | | | | |
| | Battery Adapter for Milwaukee 12V Power Connector | | 1 | $11.98 | $11.98 | | | | | | | |
| | Non-Chlorinated Brake Cleaner 12 Pack | | 1 | $66.99 | $66.99 | | | | | | | |
| | Reverse Light | | 1 | $16.99 | $16.99 | | | | | | | |
| | Champion Power Equipment 100519 6250-Watt Open Frame Inv | 100519 | 0 | $902.74 | $0.00 | | | | | | | |
| | Ball Joint | 7081505 | 0 | $71.49 | $0.00 | | | | | | | |
| | M10x1.0 Banjo Bolt and Crush Washers | | 1 | $12.99 | $12.99 | | | | | | | |
| | Rubber Brake Line Band Clamps | | 1 | $10.65 | $10.65 | | | | | | | |
| | Front Upper and Lower A-Arm Bushing, Shaft | | 0 | $79.88 | $0.00 | | | | | | | |
| | Duct Tape | | 0 | $30.24 | $0.00 | | | | | | | |
| Industrial Metal | Firewall/Splash Shield Material | | 1 | $200.00 | $200.00 | $939.20 | $93.92 | $1,033.12 | $50.00 | $1,083.12 | | |
| | Skid Plate/Body Panel Material | | 1 | $340.00 | $340.00 | | | | | | | |
| | Powertrain Guard Material | | 1 | $200.00 | $200.00 | | | | | | | |
| | 1020/1026 DOM Steel Tube R/L 1" OD X .060 20' length | | 2 | $31.80 | $63.60 | | | | | | | |
| | 1020/1026 DOM Steel Tube R/L 1.25" OD X .060 20' length | | 2 | $67.80 | $135.60 | | | | | | | |
| 76 | Transportation for Testing | | 0 | $1,000 | $0.00 | $0 | $100 | $0 | 0 | $0 | | |
| Kohler | Kohler Command Pro 14 HP Engine 1 in. Crankshaft Diameter, F | 1433590 | 0 | $500.00 | $0.00 | $899.99 | $85.50 | 0 | $20.99 | $0.00 | | |
| PCI Race Radio | SENA 50S MESH HEADSET | 4061 | 0 | $359.99 | $0.00 | $507.95 | $50.80 | $558.75 | $50.00 | 0 | | |
| | NX-1300 UHF KENWOOD HANDHELD | 3877 | 0 | $399.99 | $0.00 | | | | | | | |
| | Male External Racing Catheter Kit | 71 | 4 | $16.99 | $67.96 | | | | | | | |
| | 2 Layer Driving Suit | 2359 | 1 | $439.99 | $439.99 | | | | | | | |
| Rugged Radios | XStack Tear Offs for Simpson Matrix, SX, Jr. Shark, HJC Auto, | HJC-TEAROFFS | 2 | $30.00 | $60.00 | $60.00 | $6.00 | $66.00 | $15.00 | $81.00 | | |
| Partzilla | Castle Nut | 7547337 | 4 | $2.99 | $11.96 | $45.92 | $4.59 | $50.51 | $8 | $58.51 | | |
| | RZR 570 Front Half Shaft | 1332440 | 0 | $262.49 | $0.00 | | | | | | | |
| | Retaining Ring | 7710780 | 4 | $8.49 | $33.96 | | | | | | | |
| | Front Wheel Hub | 5137659-067 | 0 | $110.49 | $0.00 | | | | | | | |
| | Wheel Bearing Carrier LH | 5135442 | 0 | $215.99 | $0.00 | | | | | | | |
| | Wheel Bearing Carrier RH | 5135443 | 0 | $131.49 | $0.00 | | | | | | | |
| Home Depot | Milwaukee M12 Volt 3.0Ah Lithium Ion Battery | | 3 | $129.99 | $389.97 | $542.84 | $54.28 | $597.12 | $12 | $609 | | |
| | Milwaukee 12 Volt Battery Charger | | 0 | $55.00 | $0.00 | | | | | | | |
| | 5/16 in. Keystone-Tip Flat Head Demolition Driver with 6 in. Rou | | 2 | $19.49 | $38.98 | | | | | | | |
| | 5-B:C Fire Extinguisher | KD57 | 2 | $19.97 | $39.94 | | | | | | | |
| | Ratchet Tie-Down Straps with S-Hook | | 1 | $19.98 | $19.98 | | | | | | | |
| | Rivet Gun with 40 Rivets | | 1 | $14.00 | $14.00 | | | | | | | |
| | Pistol Lever Grease Gun | | 1 | $39.97 | $39.97 | | | | | | | |
| | M18 Fuel 18V 1/2 in. Impact Wrench w/ 2 Batteries, Charger, an | | 0 | $479.00 | $0.00 | | | | | | | |
| Pyrotect | Safety Restraints | | 1 | $189.99 | $189.99 | $189.99 | $19.00 | $208.99 | $16.57 | $225.56 | | |
| Poly Perfromanc | Nitrogen Shock Recharge Kit | PARENT_ITEM | 0 | $535.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0 | $0.00 | | |
| Eibach | Eibach Silver Coilover Spring - 2.50" I.D. | 1200.250.0150S | 4 | $76.00 | $304.00 | $304.00 | $30.40 | $334.40 | $25.00 | $359.40 | | |
| Speedway Moto | Black Aluminum 1/4 Turn Panel Fasteners, .500 Inch Grip, Pack | 91007153 | 4 | $19.99 | $79.96 | $130.93 | $13.09 | $144.02 | $15.31 | $159.33 | | |
| | Quarter Turn Fastener Spring Plate, Flat Spring and Rivet Sets F | 91007101 | 3 | $16.99 | $50.97 | | | | | | | |
| Wholesale Indus | Stainless Steel Hose Clamp (10 per Bag) | SSC6716 | 3 | $16.20 | $48.60 | $48.60 | $4.86 | $53.46 | $15.37 | $68.83 | | |
| Gaged Engineer | 10" Enduro Belt | | 1 | $68.50 | $68.50 | $518.50 | $51.85 | $570.35 | $40 | $610 | | |
| | CVT Spring | | 2 | $75.00 | $150.00 | | | | | | | |
| | CVT Enduro 100 Weights | | 4 | $75.00 | $300.00 | | | | | | | |
| Fasteners | Bulk Fasteners | | 0 | $1,000 | $0.00 | $0.00 | $0.00 | $0.00 | $300 | $300 | | |
| Fox | V3 RS Ryaktr Helmet | 29641-172-L | 0 | $549.95 | $0.00 | $0.00 | $0.00 | $0.00 | $8.99 | $8.99 | | |
| Custom Ink | Apparel | | 0 | $700 | $0.00 | $0.00 | $0.00 | $0.00 | $50 | $50 | | |
| Willwood | Hand Cutting Brake Assembly | 340-14744 | 1 | $346.42 | $346.42 | $346.42 | $34.64 | $381.06 | $45 | $426.06 | | |
| O'Reilly Auto Pa | Prime Line Wheel Bearing | 72-1064 | 4 | $39.99 | $159.96 | $235.91 | $23.59 | $259.50 | 0 | $259.50 | | |
| | Medium Thread Locker | 24300 | 2 | $13.99 | $27.98 | | | | | | | |
| | High Thread Locker | 27200 | 3 | $15.99 | $47.97 | | | | | | | |
| Kartek | Brake Hose 22" Female to Banjo | FRA330022 | 2 | $21.99 | $43.98 | $160.45 | $16.05 | $176.50 | $12 | $188 | | |
| | Brake Hose 22" Female to Female | FRA310022 | 1 | $16.49 | $16.49 | | | | | | | |
| | Push Pull Cable | IDI322280 | 2 | $49.99 | $99.98 | | | | | | | |
| Jegs | AN Fitting Plug -6AN | 580606 | 3 | $4.81 | $14.43 | $37.44 | $3.74 | $41.18 | $14.99 | $56.17 | | |
| | AN Fitting Cap -6AN | 592906 | 3 | $7.67 | $23.01 | | | | | | | |
| Motosport | Leatt Velocity 5.5 Iriz Goggles | | 0 | $99.99 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | | |
| Pegasus Auto R | AiM Brake Pressure Sensor | MC-327 | 1 | $138.99 | $138.99 | $178.48 | $17.85 | $196.33 | $11.00 | $207.33 | | |
| | Brake Pressure T-Fitting, Female | | 1 | $39.49 | $39.49 | | | | | | | |
| Grainger | Natural Rubber Sheet 1/4" Plain Backing | 1XWD8 | 1 | $30.42 | $30.42 | $30.42 | $3.04 | $33.46 | $12.25 | $45.71 | | |
| Quad Logic | RZR 570 Front and Rear Wheel Bearing Install/Removal Press T | 100-4261-1 | 1 | $79.95 | $79.95 | $154.90 | $15.49 | $170.39 | $0.00 | $170.39 | | |
| | Sportsman 570 Front Ball Joint Puller | | 1 | $74.95 | $74.95 | | | | | | | |
| Harbor Freight | Transfer Punch Set | | 0 | $11.99 | $0.00 | $0.00 | $0.00 | $0.00 | $11.00 | $11.00 | | |
| | Cold Chisel and Punch Set | | 0 | $16.99 | $0.00 | | | | | | | |
| | Spring-Loaded Center Punch | | 0 | $3.99 | $0.00 | | | | | | | |
| | Storage System Modular Organizer | | 0 | $34.99 | $0.00 | | | | | | | |
| | Large Modular Toolbox | | 0 | $39.99 | $0.00 | | | | | | | |
| | 18in. Organizer Case | | 0 | $39.99 | $0.00 | | | | | | | |
| | Dual Head Air Chuck Inflator with Dial Gauge | | 0 | $14.99 | $0.00 | | | | | | | |
| | 12V 150 PSI Compact Air Compressor | | 0 | $74.99 | $0.00 | | | | | | | |
| Walmart | Slime 11-Piece Tire Plug Kit | | 1 | $7.17 | $7.17 | $7.17 | $0.72 | $7.89 | $5.00 | $12.89 | | |
| Misc | Misc | | 0 | $2,000 | $0.00 | $0.00 | $0.00 | $0.00 | $350 | $350.00 | | |

Q