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R/C Mini Baja Car: Drive train and Steering

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R/C Mini Baja Car: Drivetrain and Steering

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Abstract

The purpose of the Baja R/C Car is to compete in the ASME eFX competition in a series of events to prove the functionality of the vehicle. This series of events includes the Slalom, Drag, and Baja race, The Slalom is a test in the steering capability of the vehicle, the Drag is a test in the acceleration of the vehicle in a straight line, and the Baja puts all factors together in a race to test every component of the vehicle. This project is about building an R/C car that not only functions, but also has maximum performance capabilities to win the competition.

This report describes the analysis, construction, and testing evaluation of the drivetrain and steering systems of the R/C Baja Car. Collin McKenzie was responsible for the chassis and suspension portion, together the car is a complete system. The drivetrain was built with a two-gear reduction system, one at the motor to the driveshaft, and one from the drive shaft to the rear differential. The steering system was built with a high ratio servo, adjustable tie rods, and camber arms to ensure proper alignment. Lightweight material was used such as 6061 Aluminum and ABS plastic to keep weight low. An enclosed differential casing was used to allow a lubricated system.

Testing focused on the acceleration of the vehicle and the turning radius of the steering system. The testing requirements of the Baja car were to exceed a speed of 20 mph, acceleration of 17.2 ft/s^2, and turning radius of 60 degrees.

Keywords: Baja, R/C, Drivetrain

Introduction

The R/C Mini Baja Car can be used in contests/sport or recreation. The goal would be to compete in the ASME Baja race, after finishing a developed product. The R/C Mini Baja Drivetrain would be applied in the system of the R/C Mini Baja Car, to provide power to the wheels to project forward motion.

Motivation:
This project was motivated by a need for a device, that would convert the power and torque from the brush or brushless motor to the rear wheels, to induce forward motion.

Function Statement:
The RC Mini Baja Car's drivetrain will provide the power necessary to drive the vehicle in two directions. The steering assembly will change the direction of the vehicle while in motion.

Requirements:
The Baja Car must meet the ASME RC Baja Race requirements.

- The cost of parts for the Baja car should be limited to $400.
- Drivetrain must be no higher than 2 inches from the chassis plate.
- Drivetrain must be powered by a 7.2 voltage battery.
- The RC motor must be ROAR Racing compliant.
- Driveshaft must withstand torque produced by motor.
- The R/C Baja Car must meet/exceed a final velocity of 20 mph.
- The R/C Baja Car must accelerate to max speed at a rate of 17.2 ft/s^2.
- The R/C Baja Car must have a steering angle of at least 60 degrees.

Engineering Merit:
During this project, a gear analysis while be conducted on the rear differential. Stress, strain, and bending moment analysis will be done on the driveshaft while converting torque and power to the rear differential. Stress and strain analysis on the steering mechanism to determine max amount of force allowed to be applied.

Scope of this effort:
This portion of the project will only cover the drivetrain system and the steering assembly of the RC Mini Baja Car. The remainder of the project will be developed by Collin McKenzie.

Benchmark:
The model that will be referenced is the Losi 1/10 Ford Raptor Baja Rey R/C Car. The model number for this car is LOS03020T1.

Success of the project:
The success of this project depends on the performance of the RC Mini Baja Car in testing and in competition. In competition, success will be determined by placing at least Top 5.

Design & Analysis

The approach for this design was to start with set gear ratio for the drive gears and rear differential, these were based off a true full-scale Trophy Truck. Also known was the max rpm of the motor chosen. The rest was how to figure out the transfer of power from the motor to the rear axles. The differential casing that holds the rear differential gears would then be connected to the chassis with supporting parts.

The design of the drivetrain for the R/C Mini Baja car was designed to power only the rear axles in a rear wheel drive action, and a servo in the front to steer the front axles. The design of the drivetrain can be broken into two parts, the transmission and the differential. There was a gear reduction in both parts to allow the proper power and torque to be transmitted to the rear axles and wheels of the R/C Mini Baja. The rear differential gears will be enclosed in a differential housing and connected to the chassis in a four-link suspension set up.

While designing the drivetrain for the R/C Mini Baja Car the requirements needed to be met, using the R.A.D.D format to satisfy these needs. The main requirement of the drivetrain is the maximum speed requirement, which is written as the max speed of the car must not be less than 20 mph. However, knowing that the chassis was going to be above and beyond that to hopefully win the competition portion of the ASME Baja Competition. With research on competition-based trophy trucks, the gear ratio for maximum acceleration but with allowable torque for jumps and acceleration was found.

The analysis for this was done by first calculating the maximum RPM that the motor could produce at the pinion drive gear. Knowing the max RPM from the motor, using the gear ratio from the drive gears to find the RPM of the driveshaft. This is then incorporated into another gear reduction at the differential gears. The determined ratio allowed the analysis of the final RPM to the axles. After finding the travel distance of one tire, using width and overall diameter, the final max speed could be calculated. (Appendix A.1).

With the found max speed, exceeding the requirement, the ratio was then used to find the number of teeth on the drive gears, and the required dimensions were found for those gears (Appendix A.4&5). The main drive gear will be 64T and the pinion drive gear will be 26T.

In Appendix 7, an analysis was done on the maximum allowable torque for the rear axles. Since the torque of the axle was already found (Appendix 3), it was important compare the maximum allowable torque to the torque produced, to make sure the limit is not exceeded which would result in failure of the axle.

The analysis was done by first choosing a material that best fit. Since keeping weight to a minimum is the priority of the project, Aluminum 6061-T6 was chosen. A safety factor was chosen based on the material being used, 2.5 was the chosen factor. Once these properties were established, using Sy divided by the safety factor, gave the value of, $\boldsymbol{\tau}$. Using these values, then solve for torque max using (Equation 3-7). Comparing the max torque to the applied torque, the conclusion was that the material Aluminum 6061-T6 would be acceptable for rear axle application. This would allow low weight and still meet the requirements for strength.

<u>Predicted Performance:</u>

Based on the current gear ratios in both the drive gears and differential gears, the max speed of the R/C Mini Baja will reach about 60 mph, neglecting losses in the system, friction loss, and weight of the vehicle.

Methods & Construction

The idea for this project was conceived by two group members involved in the MET program on the CWU campus. The analysis, design, manufacturing, and testing are completed within the restraints of the CWU Hogue building capabilities and the ASME Radio-Controlled Baja Car Contest Rules.

Drivetrain:

The parts for this project have been purchased and manufactured. Some parts are easily available for purchase and due to time constraints were more efficiently purchased than manufactured in house. Other parts have been manufactured due to the required parameters of dimensions needed.

The parts required for this system are as listed and can be seen in Appendix C:

1. Hobby wing EZN RUN Electric Motor (x1).
2. Hobby wing ESC MAX10 (x1).
3. 26T Spur Pinion Gear (x1).
4. 64T Spur Main Gear (x1).
5. Main Gear Locker. – Appendix B.10
6. 13T Bevel Pinion Gear (x1).
7. 43T Bevel Ring Gear (x1).
8. M2 Set Screws (x6).
9. Drive Shaft - 5mm Rod (x1). - Appendix B.2
10. Traxxas Adjustable Drive Shaft (x1).
11. 5mm I.D. Ball Bearings (x8).
12. Motor Mounts (x2). - Appendix B.7-8
13. Differential Housing (x1). - Appendix B.5-6
14. Rear Axle – 5mm Rod (x1). - Appendix B.4
15. Rear Axle Locker (x1). – Appendix B.3
16. Rear Wheel Hub (x2).
17. M3 and M4 Fasteners.
18. 7.2 Volt 5400 mAh Battery (x1)

Steering:

The parts for the steering system have been purchased, and 3D printed out of ABS material. The parts required for this system are as listed and can be seen in Appendix C.

1. Futaba S3003 Steering Servo (x1).
2. Steering ratio correction joint (x1).
3. Tie Rods - M3 x 0.7 Threaded Rod (300mm).
4. SSD Tie Rod Ends (x4).
5. M3 bolt & nuts (x2).
6. Front Wheel Hubs with radial bearing (x2).
7. Servo Mount – Appendix B.9

Drawing Tree and Drawing Numbers:

In Appendix B1, a drawing tree is available showing the process from full assembly to preliminary parts.

Device Operation:

The drivetrain of the R/C Baja Car is a system of parts, starting from the power supply, a 5400-kV sensor less brushless electric motor. The motor produces power and a max RPM which has a gear reduction at the drive gear. The pinion drive gear is attached to the shaft on the motor and the main drive gear is attached to the driveshaft. This gear reduction is a 2.46:1 reduction. Through the drive shaft there is two U-joints that allow the driveshaft to produce power to the differential at an angle and allow travel of the rear end four-link suspension. The power to the rear axles has a gear reduction of 3.3:1 decreasing the overall RPM but increasing the torque to the wheels.

The steering system of the R/C Baja Car is powered by a steering servo, engaged to a steering ratio correction joint. This joint fixed the offset of the servo pin and makes sure the wheels travel equally from left to right. Attached to the joint, are two tie rods that are threaded to tie rod ends attached to the knuckle holding the wheel. The threaded extensions allow the adjustability of toe alignment for the front wheels so it can be made sure the car turns correctly and drives straight.

Manufacturing Parts:

The parts pictured in the Appendix include the Servo Mount, Axle Locker, and Motor Mount Top/Bottom. These parts were designed in SolidWorks, then 3D printed using a Creality Printer. The manufacturing process for 3D printing these parts is simple - upload the STL file to program, level printing board, pre-heat the filament, then let the printer do its job. Some issues occurred when printing these parts, the printer was having issues with applying the ABS filament properly to the printing board, therefore the part would end up failing. After a few trial and errors, the parts were successfully printed.

The rest of the parts manufactured were the Driveshaft, Rear Axle, Differential Casing, Axle Tubes, Main Gear Locker, Tie Rods, and Camber Arms. Some of these parts were 3D printed, then drilled and tapped for mounting points. The differential casing was put together with the axle tubes to create a sealed rear differential casing that will house a lubricated gear system. High strength glue was used to keep the parts together. The axle tubes were easily broken, so Acetone was used on the outer surface to harden the material and increase the shear strength. The driveshaft and rear axle were manufactured out of 5mm aluminum rod. Set screw holes were drilled out for mounting the main gear locker and adjustable drive shaft to the solid shaft. The ends of the rear axle were threaded with a M5x0.8 die thread to hold a nylon locking nut on the wheels.

One of the issues with manufacturing parts was the set back of the brittleness of the axle tubes. The part broken when assembling the rear end, so the parts had to be glued together and acetone applied to strengthen the material. After finishing these parts, a secondary design was created to try and improve the strength of the tubes. These parts will be printed and used as a back in case of failure.

Testing Methods

The main test for the Mini R/C Baja Drivetrain will be the testing of speed and acceleration of the Baja car. This test will be done on off-road and smooth surfaces. Testing the speed and acceleration will allow the ability to see accuracy of the previously done analysis.

Method/Procedure/Requirements:
The speed of the vehicle can be calculated by recording the following data:

- Total distance traveled, **x**
- Amount of time for the vehicle to reach total distance, **t**

Using these factors will give the information of how fast the car will accelerate, and what velocity it will reach in that distance. To calculate the max speed of the vehicle, a constant speed is required. The vehicle will have to be accelerated to the max possible RPM (38,000) and held constant for an x-amount of distance. Using the constant max RPM, set distance, and time it took to travel that distance, the max velocity can be calculated using this equation:

$$\textbf{velocity} = \frac{distance}{time}$$

Referring to acceleration, after recording the values, the known factors would be:

- Initial Velocity, $\mathbf{v_o}$
- Final Velocity, $\mathbf{v_f}$
- Time, **t**
- Distance, **x**

Using these values, the kinematic equations will play a role in the final value of acceleration, a:

$$v_f = v_o + at$$

$$v_f^2 = v_o^2 + 2ax$$

$$\Delta x = v_o t + 1/2at^2$$

These equations will allow the ability to solve for the acceleration of the vehicle under different surface conditions and different weight transfer methods due to ride height adjustments. The equipment required for this test will be a tape measure, stopwatch, and tape to mark the set distance.

Space will be required to be able to test the vehicle properly. Since various types of surfaces will affect the friction to the wheels, which will impact the results of acceleration, testing will take place on three different surfaces. The test will require the surfaces of smooth concrete, unfinished concrete, and off-road. All testing will be done on the Central Washington University campus. The smooth concrete surface will be tested in an open and safe area in Hogue Hall. The unfinished surface will be tested on the concrete walkway outside of Hogue Hall. The off-road surface will be tested on a dirt surface on campus. Each testing surface will require a minimum of three trial runs with the vehicle. If more distance is needed, the location of testing is subjected to change.

Important factors to consider:

- Battery voltage must be maintained at the same voltage for each run, this will reduce the factor of lacking power in the trial runs.
- Vehicle must travel in a straight line to be considered an applicable trial run.
- Weather may affect the outcome of testing, so a dry day will be used.

A more detailed testing procedure can be found in Appendix G.

Additional Factors during Testing:

When testing the final design of the R/C Baja Car, additional information will be recorded. While focusing on speed and acceleration, the behavior of the suspension components and steering will be noted. One of the important factors of the competition will be in the steering and the ability for the car to withstand jumps.

While running the acceleration test, the compression of the suspension or “squat” of the vehicle will be watched. When the vehicle is pursuing high speeds and maximum torque when leaving the starting line, the squat must be minimalized and not allow the vehicle to bottom out on the ground.

If the chassis plate contacts the ground, suspension modifications will have to be made. Some of the ways to fix this problem consist of adding bump stops to the suspension, increasing spring stiffness, adjust damping in shocks, or raise ride heights. All of these components will keep the vehicle from dragging on the floor and slowing the vehicles speed.

Issues during Testing:

Some design issues were found prior to getting to do any test runs. The first test to be done on the R/C Baja Car was the velocity test. The issues that occurred were in the drive gear system. The first gear used was a 26T drive gear that was made of casted steel. However, the amount of torque that is applied from the motor, shredded off the gear teeth of the drive gear. After figuring out the material issue, the old drive gear was replaced with a machined steel gear of the same tooth count. The machined gear is stronger and will hold up to the torque applied in the drive gear system.

After the drive gear was replaced, a test run was done to make sure there was proper gear alignment in the system. The gears did not skip or chatter, resulting in the only issue being the material the gear was made from. During this test run, the Main Gear Locker (Appendix B.10) sheared. This was another result of the piece being too weak for the torque from the drive gear system. The piece was also 3D printed hollow and not solid, causing a weakness in the part. The Main Gear Locker, was then redesigned with a greater collar thickness, adding 2mm, and reprinted solid to prevent the issue happening again. Testing Report can be referred to in Appendix G.

Budget

The final budget of this project was estimated to be around $250 for the parts that need to be purchased for the drivetrain. The budget of this project was meant to be kept small and affordable. Some of the costs may change due to the availability of some parts, in which these parts would not have to be purchased.

One of the main costs of this project was the purchase of a new power source for the drivetrain. The previous motor set up that is available for use, did not allow the design to meet the requirements set for this project. The new motor setup allows a higher max RPM and an increase of torque to the rear wheels to increase acceleration. This made it vital to be purchased to increase the performance of the vehicle. A risk of trying to keep a lower budget on a project was the issue with the material required to make alterations to designed parts. All the parts on the Mini R/C Baja Car Drivetrain will be 3-D printed. 3-D printing was chosen due to the complexity and size of the parts within the drivetrain. If machining was chosen, time would have to sacrificed and the time restraints of this project do not allow it. Since these parts will be 3-D printed, when alterations need to be made, a whole new part must be printed. This could increase the cost of the project as the construction portion is under way. This project is going to be funded by personal funds initially. A table of the total part cost can be found in Appendix D.

During the manufacturing of the assembly, all parts and material have been ordered. The current budget includes the items listed in Appendix D. The project stayed on budget, expect when ordering the new motor for the R/C Baja Car. The motor had to be sourced from a new supplier, and this price was increased. The motor put the project over budget by $17. The final budget for this project was $271.39. This price includes shipping and handling of the parts ordered. Other than having to find a new source for the motor, there have been no issues in ordering parts or material. All parts were ordered in a timely manner as the assembly began. The parts were ordered step by step, following the manufactured parts, as these parts tend to incorporate mounting points for the purchased parts.

The parts were ordered as following:

- 6061 Aluminum Rod (3 feet).
- M3 threaded rod.
- Main drive gear/pinion.
- Ball bearings (11mm O.D x 5mm I.D.).
- 2 batteries (7.2 volt).
- Metric bolt/nut kit.
- Motor
- ESC
- M5x0.7 thread die.
- M5x0.7 Nylon locking nuts.

These parts all arrived on time, and kept the project making forward progression matching the scheduled time periods. There was no change in design that required purchasing different parts. No parts need to be ordered to complete the project.

During the testing of the R/C Baja Car, there were some failures of parts that added expense to the budget, this included the drive gear, main gear locker, and rear axle. More parts had to be 3-D printed to fix these issues, and the cost of printing had to be accounted for. Another issue was when the axle sheered at the wheel hub pin. This required the purchase of more material to make another axle, which added an additional $10.17 to the final cost. The project’s final cost was $281.56. This final cost kept the total project cost under $400, meeting the budget requirement.

Schedule

The schedule for this project was estimated during the design phase, prior to the start of any construction or ordering of necessary parts. Within the design portion of the project, the deadlines were met at a weekly basis. The time involved with the design was estimated accurately and ended up being an overestimate of time needed. During the construction of the project, sometime restraints considered are the amount of time it takes to get various parts shipped to the location needed. A more detailed Gantt Chart is available in Appendix E.

While creating the schedule it was important to consider the major deadlines. During the course of the MET capstone class, the workload is divided into three sections. Fall 2019 quarter will pertain to all the design phase and proposal writing. Winter 2020 quarter will be used to manufacture and construct the project. Finally, Spring 2020 quarter will be used to test and modify the project. Knowing the split of the work per quarter, it was important to make sure the correct deadline was met within the parameters of the appropriate quarter. Some of these milestones are:

Milestones	**Deliverable**
December 2019	Proposal completed
January 2020	Analysis completed; Parts documented
February 2020	Modifications made; Parts Manufactured
March 2020	Project assembled
April 2020	Project evaluated
May 2020	Testing
June 2020	Project completed

(Table 1: Project Milestones.)

During the manufacturing process of the R/C Baja Car, some issues occurred that affected the timing of the schedule. When 3D printing the parts needed, some parts failed to print in one attempt. The time required for the printed parts increased and pushed back the construction of the final assembly. To compensate for this time loss, while the printing was being done, the purchased parts were ordered earlier and fitted, to ensure that once the manufactured parts were done the construction could proceed in a timely manner. Once the construction could begin, the parts were put together with little to no issues and allowed the schedule to remain on time. The total time for construction resulted in 60.5 hours to complete the final assembly and working drivetrain system.

While testing the R/C Baja Car, some failures in the drivetrain system occurred that delayed the time of testing. The first issue was with the drive gear, in which the gear teeth sheared which required ordering a new part. The second issue was in the main gear locker, the part sheared from the driveshaft and had to be redesigned and reprinted. The last issue was with the axle. The axle sheared at the push pin hole but was then rebuilt to continue testing. Once all issues were fixed, the testing went as planned and took 30.25 hours to complete on time.

To complete the project the following sections were required; design/analysis, construction, and testing. Upon completing the project, the total hours concluded to be 182.75 hours.

Project Management

Some risks that may occur during this project are the chances of going over the predicted budget costs. Due to possibly having to reprint or incorporate additional unseen parts into the build, may require more 3-D printing than expected. This could cause the increase of the needed budget, however with already being below the requirement for budget, it would be hard to exceed the limit. Another risk of the project is due to scheduling. Since most of the parts will be ordered, the lack of measurements prior may require some modifications to the prior drawings, which may cause more time being taken in fixing any issues with the current drawings before manufacturing. The schedule may also be affected since some parts cannot be designed until these parts are ordered.

This project was successful due to the availability of the appropriate technical expertise and resources at Central Washington University. Test equipment was available to use for the testing needs of the Mini R/C Baja Car, when testing velocity and acceleration. The other portion of the testing of the chassis also had the available testing equipment to ensure the accuracy of the testing methods. The principle engineer has provided expertise in the drivetrain and steering portion of this project and resume is shown in Appendix H of the proposal.

Discussion

The goal of the Mini R/C Baja drivetrain was to find a way to transfer power from the motor to the rear wheels in the most efficient way, while still allowing maximum power and torque output. During the design process it was essential to make sure all the components worked together in an assembly. Basing the design to a modern trophy truck, the first idea for power transmittal was a rear wheel drive function. Since the gear reduction would be placed at the back of the Baja chassis, implementing a four-link suspension system would give advantages to the performance of the vehicle compared to previous years.

Four-link suspension allows the differential gears to be enclosed, in a differential housing. Being that this system is sealed, lubrication can be used to increase the efficiency of the gears used in the reduction. Another advantage of the four-link suspension design is the way that the components allow travel of the rear axles to accommodate for rough terrain. Since the suspension is tied into a solid axle casing, the shocks and struts will react together but still allows various travel heights on each side. Using this design, created spacing for the drivetrain components on the chassis, and created more equal weight distribution throughout the car. This gave the opportunity to reduce size of the chassis plate and ultimately reduce the total weight of the vehicle.

A main factor in designing the drivetrain for the Mini R/C Baja Car was determining the proper gearing ratios between the motor, driveshaft, and rear axle. When starting the design, an assumption was made that the gear reduction at the transmission portion of the gears (motor to driveshaft) would be around 2.5:1. Another assumption was made with the gear reduction at the differential portion (driveshaft to rear axles). Basing this assumption off a modern trophy truck, the assumed gear ratio was around 4.1:1. After analyzing the sizing of the gears for the differential, it was found that the ring gear needed for that sort of ratio would be too large for the differential casing. Being restricted to the gears that could be found available for purchase online, a reduction in the gear ratio size was made to accommodate for the size of the differential casing. The final design gear ratio was 3.3:1 in the differential portion. This gave a greater final drive speed of roughly 60 mph (neglecting all losses), but a lower amount of torque to the rear axle.

Another important aspect to the design of the drivetrain, was the type of material being used for the driveshaft and rear axles. Initially, a choice was made to use stainless steel. After modeling the drivetrain completely and doing a mass properties evaluation, it was apparent that the weight was too much for the design requirement of keeping the whole vehicle under 7 pounds. Unable to modify the weight of the gears, u-joints, differential casing, and bearings, the only modification made was to the material of the driveshaft and axles. After research of online material sources, 6061 Aluminum rods were found in the correct dimensions for these parts. To be certain of this change, an analysis was done on the shafts. After finding the allowable torque of the material and the actual torque from the motor transmitted to the shafts, it was safe to change the material to the 6061 Aluminum reducing the weight of the shafts by over 30%.

The design of the steering setup for the Mini R/C Baja Car was done to allow the car to turn while under high velocity without causing understeer. Using the Ackerman's Angle steering principle allowed the ability to find the proper angles for the steering arms, in which the truck could turn at a proper radius to be competitive in the slalom event portion of the ASME Baja Competition.

During the manufacturing process, many parts required 3D printing. The parts that have been 3D printed are the axle locker, motor mount top, motor mount bottom, and the servo mount. While the manufacturing of these parts occurred, some failures in printing happened. This was due to the ABS filament not sticking to the platform surface. In order to correct these issues, the temperatures of both the platform and nozzle were adjusted. After a few corrections of temperature, the printer got a solid base layer on the platform and the pieces printed without failure. The tolerances of the 3D printer were not perfect, some modification had to be made on the pieces. The holes had to be reamed out, and the outer surface of the axle locker had to be sanded to fit the bevel gear.

The manufacturing of the differential case took an extended amount of time than what was predicted. The first iteration of the differential casing was one whole piece that would be printed all together. The first print failed, and the axle tubing lifted from the rafting, causing the tubes to not be straight. There was also a weak point in the design, so the tubes broke off from the casing without much force. A second iteration of the differential casing was to use the existing center piece and reprint the axle tubes, press the bearings than glue the pieces together. The axle tubes were printed, and the differential case was assembled. However, after one incident during manufacturing the axle tube fractured. The ease of the fracture was concerning, and this was due to the orientation of the 3D printing process. The third iteration was a redesign process. The axle tubes were created in a D-shape, allowing the axle to sit on the rafting when printed and change the orientation of the printing lengthwise. This change made the axle tubes much stronger and this final assembly of the differential case will be used.

During the testing of the R/C Baja Car, some issues regarding the drivetrain system occurred. Once the vehicle's construction was complete precautionary test runs were done prior to data testing to ensure the proper functionality of the vehicle. The first issue occurred in the pinion drive gear of the transmission. The material used for this gear was casted steel and was too weak for the amount of torque from the motor and sheared the gear teeth, this also could be due to manufacturing imperfections. To improve the system, a machined hardened steel gear was used in replacement and the issue was concluded. The following issue was in the 3D printed gear locker for the main drive gear in the transmission. The torque sheared this part from the driveshaft; however, the main issue was the part being printed hollow causing it to be weaker. The part was then reprinted solid and with a greater hub diameter to give more strength and the problem was concluded. The final issue of the system was in the rear axle. Upon turning the vehicle at a higher speed, the axle sheared at the set pin hole location. During manufacturing this hole was drilled slightly over size, leaving less material then needed. So, new material was ordered going from aluminum rod to steel rod for greater strength and decreasing the diameter of the set pin hole which fixed the issue.

Once the issues with the drivetrain were fixed, the testing was completed. The final velocity test resulted on a final velocity of 15.56 mph. This result was under the requirement speed of 20 mph. The system's predicted speed was done considering a 100% efficiency, so a lower result was expected. However, some improvements towards performance could be made. One aspect to consider in increasing the speed of the vehicle would be the overall weight. Reducing the chassis plate thickness would lower the weight significantly and help gain a faster overall speed. This would also increase the acceleration of the vehicle, which resulted in 10.57 ft/s^2.

The final test done on the R/C Baja Car was on the steering angle of the steering system. The requirement was to have a 60-degree steering angle to allow quick turns around the course without understeer from the speed of the vehicle. The results of this test ended up being an average angle of 54.3 degrees. The result was under the requirement, but the relationship between both wheels was nearly identical which gives the car the maximum steering capability and handling. The car was then tested to see how well it could turn when speed was involved, and the car had no understeer and handled a sharp turn radius without any issues. This gave the car a pass on the test as it would be competitive in the Slalom or Baja event of the ASME Baja Competition.

Conclusion

The Mini R/C Baja Car drivetrain has been conceived, analyzed, and designed to meet the function requirements presented. The drivetrain will allow the car to exceed 20 mph, remains under the $400 budget set for parts and manufacturing, is under 2 inches high from the chassis plate, and is complaint with ROAR Racing rules. The steering portion of the project also meets the requirement of allowing the vehicle to have a 60-degree turning radius, due to the geometry of the steering arms. All the parts for these systems have been specified and budgeted for acquisition. With all the information provided and analyzed data, the Mini R/C Baja car drivetrain and steering system are ready to be created.

This project meets all requirements to be a successful senior project, including:

1. Having engineering merit in mechanical design (gearing ratios, torque specs, and required forces.)
2. Size and cost of the project are within budget and resource parameters.
3. Fulfills all requirements under the rules of the ASME Baja Car competition.
4. Functions as a working system, with other parts made by co-engineer, Collin McKenzie.

Construction was completed for the design of the R/C Baja Car drivetrain, and with a working device. Testing will be done to make sure the requirements are met for the system.

After the construction was completed, testing was done on the final R/C Baja Car assembly. The requirements were that the car must reach a max speed of 20 mph, acceleration of 17.2 ft/s^2, and a steering angle of 60 degrees. The predicted performance of the vehicle from the analysis (Appendix A) was that the vehicle would obtain a max speed of 60 mph, acceleration of 67ft/s^2, and a steering angle of 60 degrees. The predicted values for speed and acceleration were set on a system that would endure zero losses or imperfections. Knowing this the requirements were the focus of comparison for the results of testing.

Tested Aspect	**Results**	**Requirements**	**Error Percentage**
Max Speed, Asphalt	15.56 mph	20 mph	22.2%
Max Speed, Gravel	13.07 mph	20 mph	34.62%
Max Accel, Asphalt	10.57 ft/s^2	17.2 ft/s^2	38.56%
Max Accel, Gravel	7.35 ft/s^2	17.2 ft/s^2	57.3%
Max Steering Angle	54.83 degrees	60 degrees	8.6%

(Table 2: Comparison of Results to Requirements)

In comparison to the requirements, the results fell short. Seeing that the results were below the requirement, further research into the problems was done. It was found out that the ESC (Electrical System Control) of the power train, had a low voltage cut-off that was tuned in as a stock tune. Once tuning was done on the ESC to fix this issue, the R/C Baja Car was noticeably faster, unfortunately there was no more time to test because of the required timeline. However, it was expected to see lower results in the gravel testing since the vehicle would have significantly less grip when attempting to accelerate as fast as possible. Slippage in the tires occurred, which could pertain to further research in this project of how to get more grip on alternate terrain.

Improvements that could be made to increase the performance of the vehicle are as listed:

- Lowering weight of chassis plate (thinner material, lighter material).
- Different gear ratio to increase final drive speed or torque to increase acceleration.
- Shorter control arms to increase throw of servo.
- Higher ratio servo, allowing more rotation in the steering system.
- Higher output battery (recreational use, not allowed in ASME competition.).

After some of these modifications are made, the R/C Baja car would reach maximum performance and meet all requirements provided. The following check list shows the requirements the project did or did not meet.

Requirement	**Pass or Fail**
The cost of parts for the Baja car should be limited to $400.	Pass
Drivetrain must be no higher than 2 inches from the chassis plate.	Pass
Drivetrain must be powered by a 7.2 voltage battery.	Pass
The RC motor must be ROAR racing compliant.	Pass
Driveshaft must withstand torque produced by motor.	Pass
The R/C Baja Car must meet/exceed a final velocity of 20 mph.	Fail
The R/C Baja Car must accelerate to max speed at a rate of 17.2 ft/s^2.	Fail
The R/C Baja Car must have a steering angle of at least 60 degrees.	Fail

(Table 3: Pass/Fail of Requirements.)

Overall, the R/C Baja Car met most of the requirements for this project. In success, the vehicle is completely functional and could have competed in the ASME Baja Race and done well. The final speed was lower than expected but the vehicle did obtain an impressive speed and acceleration. The vehicle also provided the proper steering and handling capabilities for sharp and accurate turns, which is needed for the Slalom and Baja events, deeming the overall project a success.

Acknowledgements

Mentors of this senior project:
Charles Pringle – CWU
Craig Johnson – CWU
John Choi – CWU
Tedman Bramble – CWU
Matt Burvee - CWU

References

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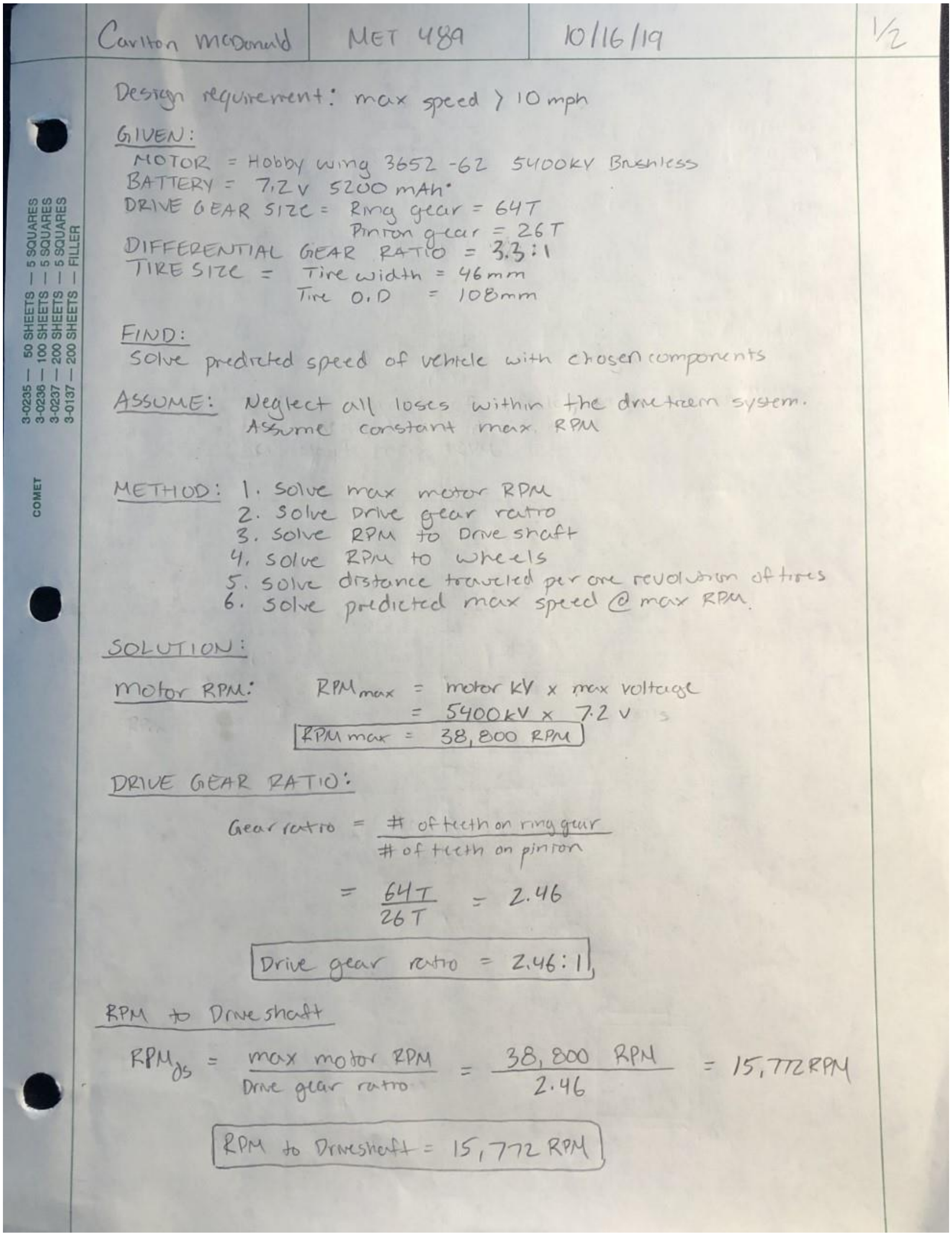
Appendix A – Green Sheet Analysis

Appendix A.1-1



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Design requirement: max speed > 10 mph

GIVEN:

MOTOR = Hobby wing 3652-6Z 5400KV Brushless
BATTERY = 7.2V 5200 mAh
DRIVE GEAR SIZE = Ring gear = 64T
Pinion gear = 26T
DIFFERENTIAL GEAR RATIO = 3.3:1
TIRE SIZE = Tire width = 46mm
Tire O.D = 108mm

FIND:

Solve predicted speed of vehicle with chosen components

ASSUME: Neglect all loses within the drivetrain system.
Assume constant max RPM

METHOD:
1. Solve max motor RPM
2. Solve Drive gear ratio
3. Solve RPM to Drive shaft
4. Solve RPM to wheels
5. Solve distance traveled per one revolution of tires
6. Solve predicted max speed @ max RPM

SOLUTION:

Motor RPM: RPM_{max} = motor KV x max voltage
= 5400kV x 7.2 V
RPM max = 38,800 RPM

DRIVE GEAR RATIO:

$$\text{Gear ratio} = \frac{\#\text{ of teeth on ring gear}}{\#\text{ of teeth on pinion}}$$

$$= \frac{64T}{26T} = 2.46$$

Drive gear ratio = 2.46:1

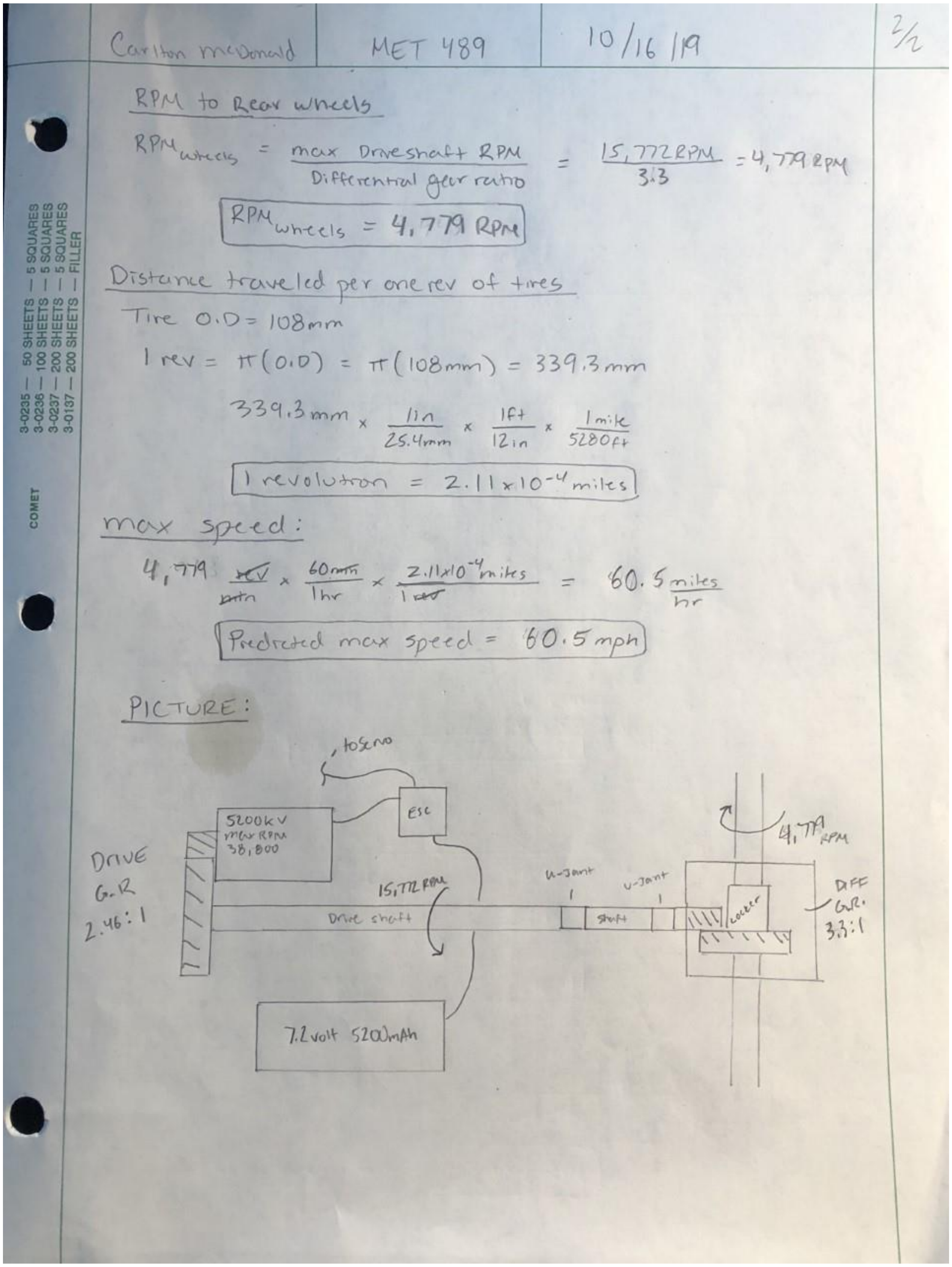
RPM to Driveshaft

$$RPM_{DS} = \frac{\text{max motor RPM}}{\text{Drive gear ratio}} = \frac{38,800\text{ RPM}}{2.46} = 15,772\text{ RPM}$$

RPM to Driveshaft = 15,772 RPM

(Figure A-1: Max speed calculation, page one.)

Appendix A.1-2



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RPM to Rear wheels

$$RPM_{wheels} = \frac{\text{max Driveshaft RPM}}{\text{Differential gear ratio}} = \frac{15{,}772\,RPM}{3.3} = 4{,}779\,RPM$$

$$\boxed{RPM_{wheels} = 4{,}779\ RPM}$$

Distance traveled per one rev of tires

Tire O.D = 108mm

$$1\ rev = \pi(O.D) = \pi(108mm) = 339.3mm$$

$$339.3mm \times \frac{1in}{25.4mm} \times \frac{1ft}{12in} \times \frac{1mile}{5280ft}$$

$$\boxed{1\ revolution = 2.11 \times 10^{-4}\ miles}$$

max speed:

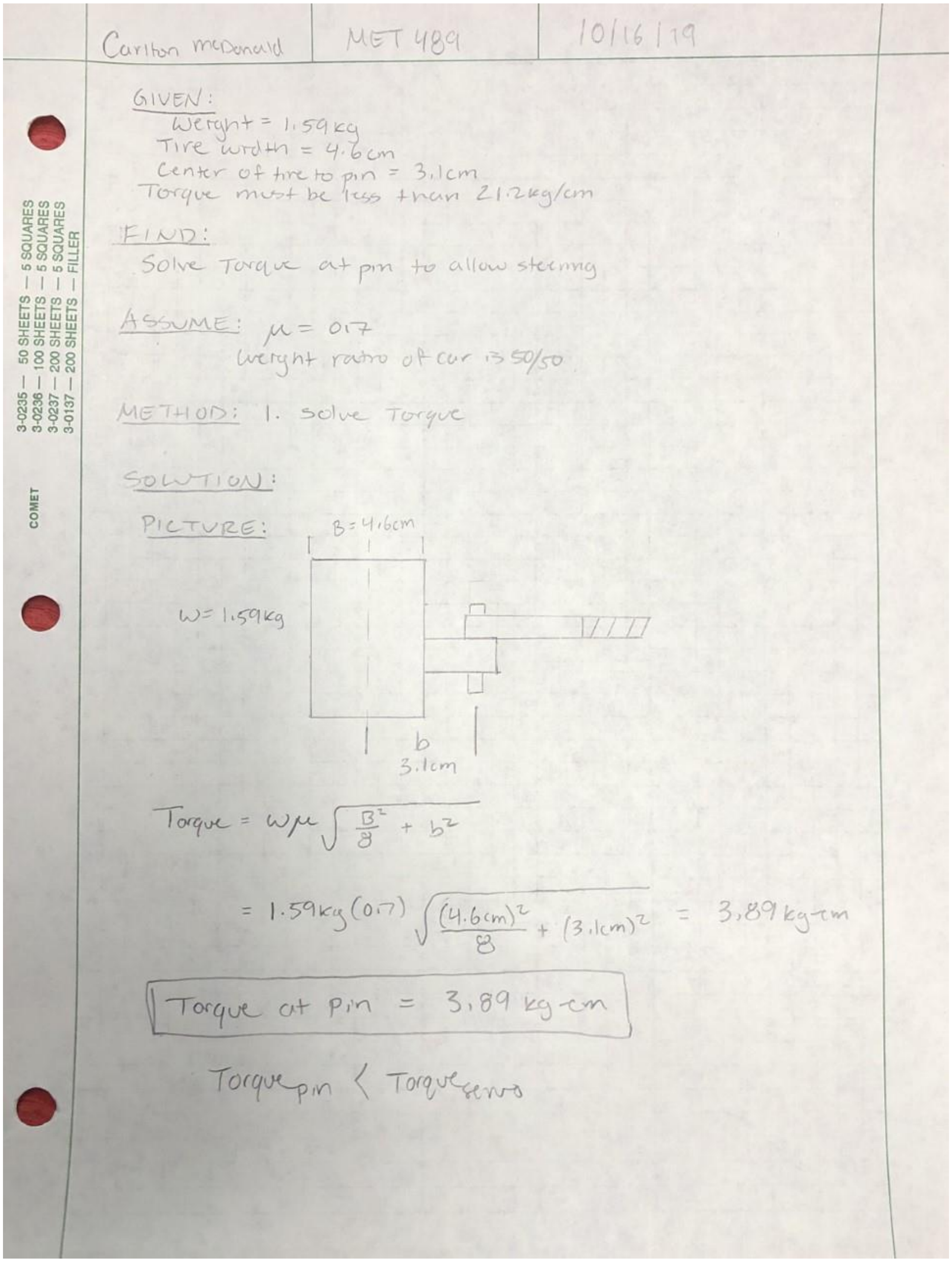
$$4{,}779\ \frac{rev}{min} \times \frac{60min}{1hr} \times \frac{2.11\times10^{-4}miles}{1rev} = 60.5\ \frac{miles}{hr}$$

$$\boxed{\text{Predicted max speed} = 60.5\ mph}$$

PICTURE:

(Figure A-2: Max speed calculation, page two.)

Appendix A.2



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GIVEN:
Weight = 1.59 kg
Tire width = 4.6 cm
Center of tire to pin = 3.1 cm
Torque must be less than 21.2 kg/cm

FIND:
Solve Torque at pin to allow steering

ASSUME: $\mu = 0.7$
Weight ratio of car is 50/50

METHOD: 1. Solve Torque

SOLUTION:

PICTURE: B = 4.6 cm

W = 1.59 kg

b
3.1 cm

$$\text{Torque} = W\mu\sqrt{\frac{B^2}{8} + b^2}$$

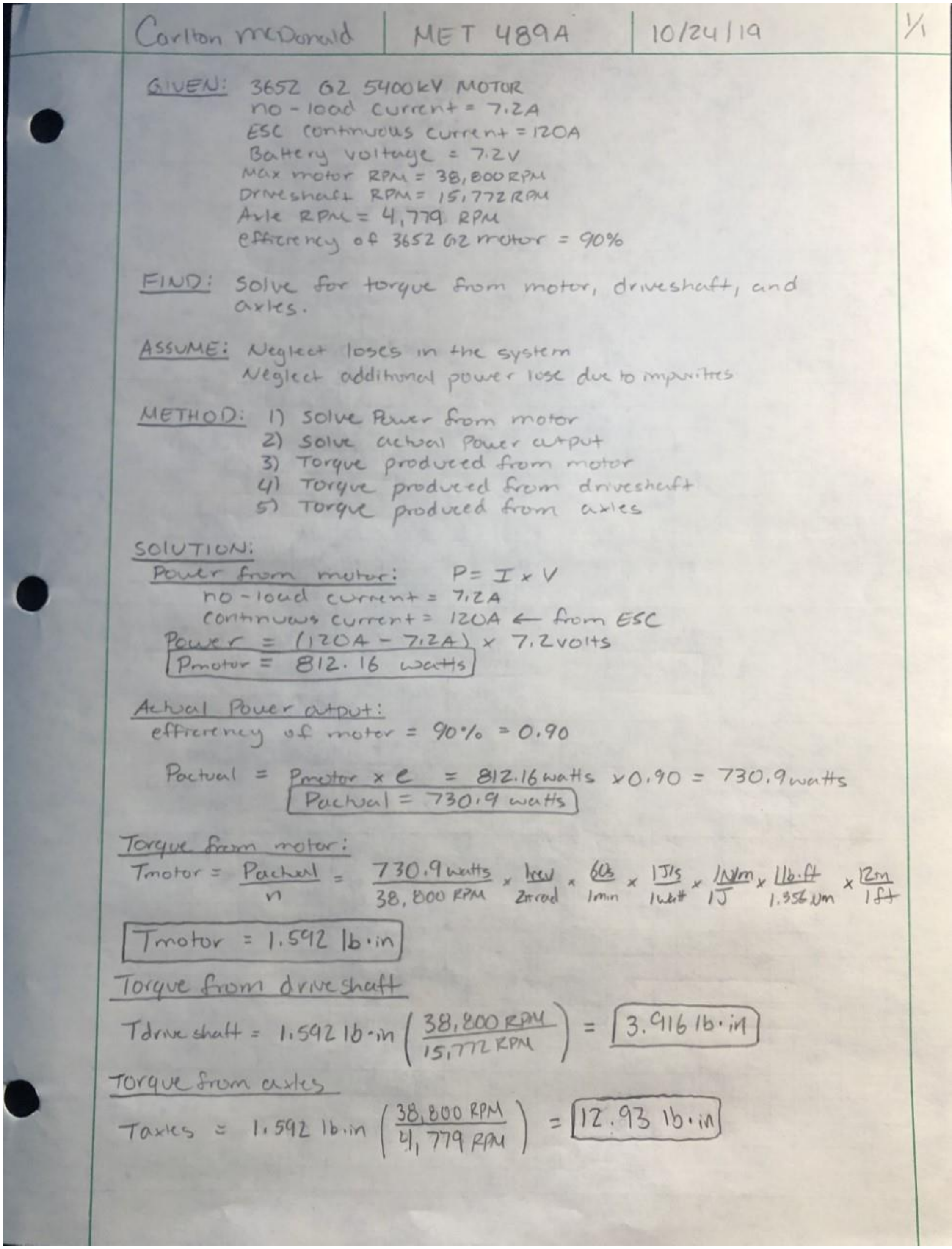
$$= 1.59\,\text{kg}\,(0.7)\sqrt{\frac{(4.6\,\text{cm})^2}{8} + (3.1\,\text{cm})^2} = 3.89\,\text{kg-cm}$$

Torque at Pin = 3.89 kg-cm

$\text{Torque}_{pin} < \text{Torque}_{servo}$

(Figure A-2: Torque at front steering pin calculation.)

Appendix A.3



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GIVEN: 3652 G2 5400kV MOTOR
no-load current = 7.2A
ESC continuous current = 120A
Battery voltage = 7.2V
Max motor RPM = 38,800 RPM
Driveshaft RPM = 15,772 RPM
Axle RPM = 4,779 RPM
efficiency of 3652 G2 motor = 90%

FIND: Solve for torque from motor, driveshaft, and axles.

ASSUME: Neglect loses in the system
Neglect additional power lose due to impurities

METHOD: 1) Solve Power from motor
2) Solve actual Power output
3) Torque produced from motor
4) Torque produced from driveshaft
5) Torque produced from axles

SOLUTION:

Power from motor: $P = I \times V$
no-load current = 7.2A
continuous current = 120A ← from ESC
Power = (120A − 7.2A) × 7.2volts
P_{motor} = 812.16 watts

Actual Power output:
efficiency of motor = 90% = 0.90

$P_{actual} = P_{motor} \times e = 812.16\text{ watts} \times 0.90 = 730.9\text{ watts}$
P_{actual} = 730.9 watts

Torque from motor:

$$T_{motor} = \frac{P_{actual}}{n} = \frac{730.9\text{ watts}}{38,800\text{ RPM}} \times \frac{1\text{rev}}{2\pi\text{rad}} \times \frac{60\text{s}}{1\text{min}} \times \frac{1\text{J/s}}{1\text{watt}} \times \frac{1\text{N}\cdot\text{m}}{1\text{J}} \times \frac{1\text{lb}\cdot\text{ft}}{1.356\text{ N}\cdot\text{m}} \times \frac{12\text{in}}{1\text{ft}}$$

T_{motor} = 1.592 lb·in

Torque from driveshaft

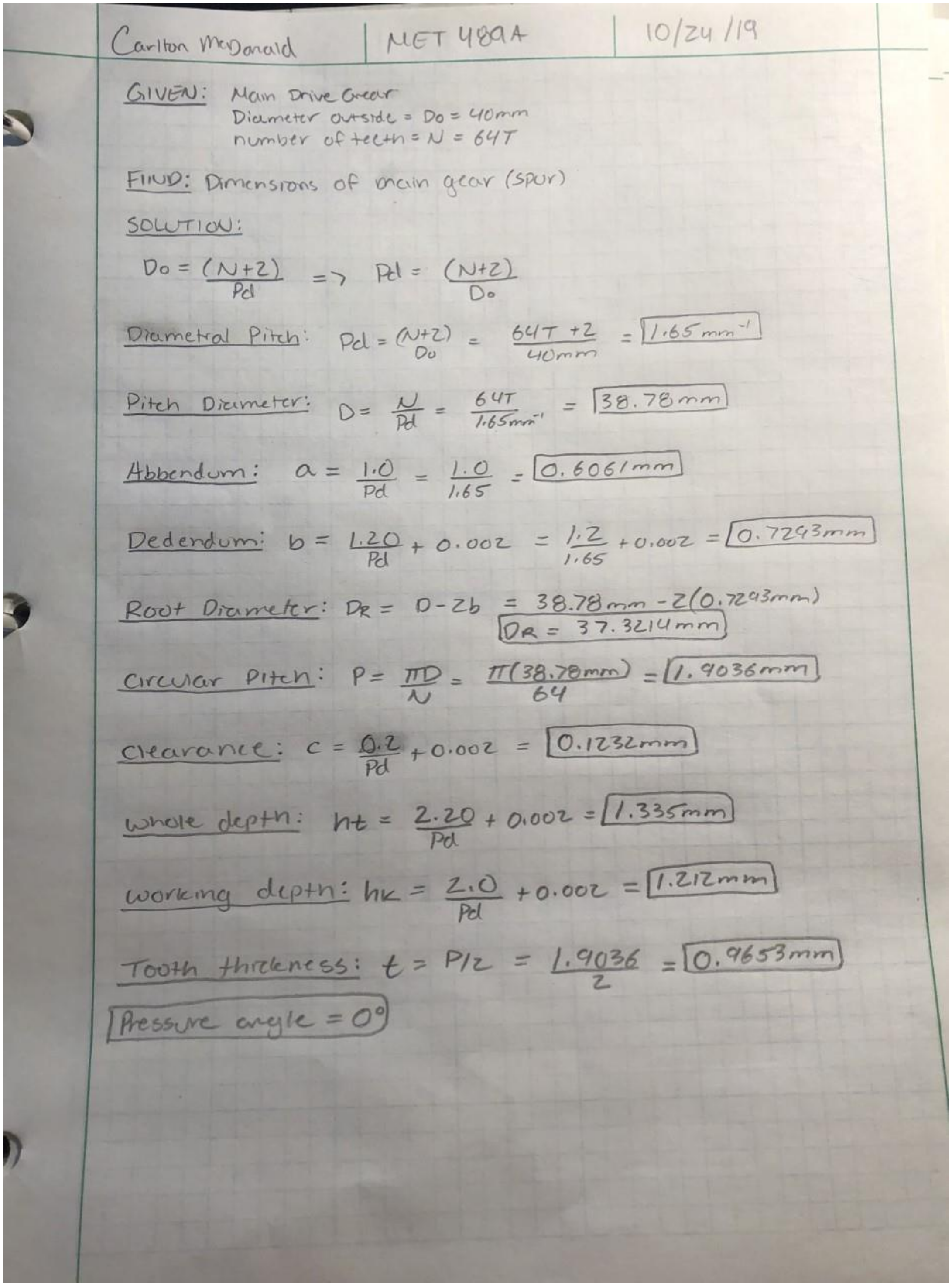
$$T_{driveshaft} = 1.592\text{ lb}\cdot\text{in}\left(\frac{38,800\text{ RPM}}{15,772\text{ RPM}}\right) = 3.916\text{ lb}\cdot\text{in}$$

Torque from axles

$$T_{axles} = 1.592\text{ lb}\cdot\text{in}\left(\frac{38,800\text{ RPM}}{4,779\text{ RPM}}\right) = 12.93\text{ lb}\cdot\text{in}$$

(Figure A-3: Torque produced by motor, driveshaft, and axles.)

Appendix A.4



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GIVEN: Main Drive Gear
Diameter outside = D_o = 40mm
number of teeth = N = 64T

FIND: Dimensions of main gear (spur)

SOLUTION:

$$D_o = \frac{(N+2)}{P_d} \Rightarrow P_d = \frac{(N+2)}{D_o}$$

Diametral Pitch: $P_d = \frac{(N+2)}{D_o} = \frac{64T+2}{40mm} = \boxed{1.65\,mm^{-1}}$

Pitch Diameter: $D = \frac{N}{P_d} = \frac{64T}{1.65mm^{-1}} = \boxed{38.78\,mm}$

Abbendum: $a = \frac{1.0}{P_d} = \frac{1.0}{1.65} = \boxed{0.6061\,mm}$

Dedendum: $b = \frac{1.20}{P_d} + 0.002 = \frac{1.2}{1.65} + 0.002 = \boxed{0.7293\,mm}$

Root Diameter: $D_R = D - 2b = 38.78mm - 2(0.7293mm)$
$\boxed{D_R = 37.3214\,mm}$

Circular Pitch: $P = \frac{\pi D}{N} = \frac{\pi(38.78mm)}{64} = \boxed{1.9036\,mm}$

Clearance: $c = \frac{0.2}{P_d} + 0.002 = \boxed{0.1232\,mm}$

whole depth: $h_t = \frac{2.20}{P_d} + 0.002 = \boxed{1.335\,mm}$

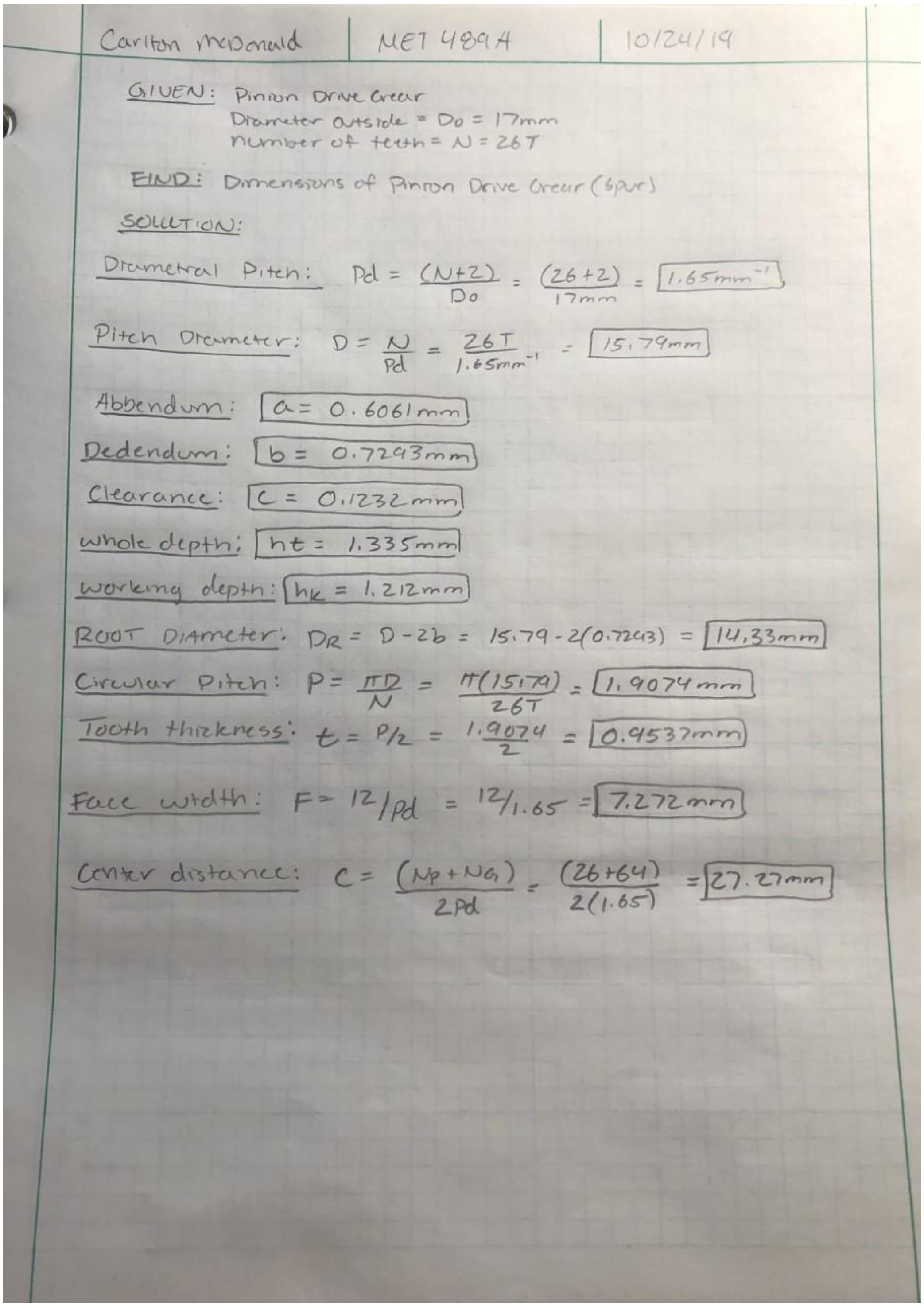
working depth: $h_k = \frac{2.0}{P_d} + 0.002 = \boxed{1.212\,mm}$

Tooth thickness: $t = P/2 = \frac{1.9036}{2} = \boxed{0.9653\,mm}$

$\boxed{\text{Pressure angle} = 0°}$

(Figure A-4: Dimension analysis for Main Drive Gear (Spur))

Appendix A.5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GIVEN: Pinion Drive Gear
Diameter outside = D_o = 17mm
number of teeth = N = 26T

FIND: Dimensions of Pinion Drive Gear (Spur)

SOLUTION:

Diametral Pitch: $P_d = \frac{(N+2)}{D_o} = \frac{(26+2)}{17mm} = 1.65mm^{-1}$

Pitch Diameter: $D = \frac{N}{P_d} = \frac{26T}{1.65mm^{-1}} = 15.79mm$

Abbendum: $a = 0.6061mm$

Dedendum: $b = 0.7243mm$

Clearance: $c = 0.1232mm$

whole depth: $h_t = 1.335mm$

working depth: $h_k = 1.212mm$

Root Diameter: $D_R = D - 2b = 15.79 - 2(0.7243) = 14.33mm$

Circular Pitch: $P = \frac{\pi D}{N} = \frac{\pi(15.79)}{26T} = 1.9074mm$

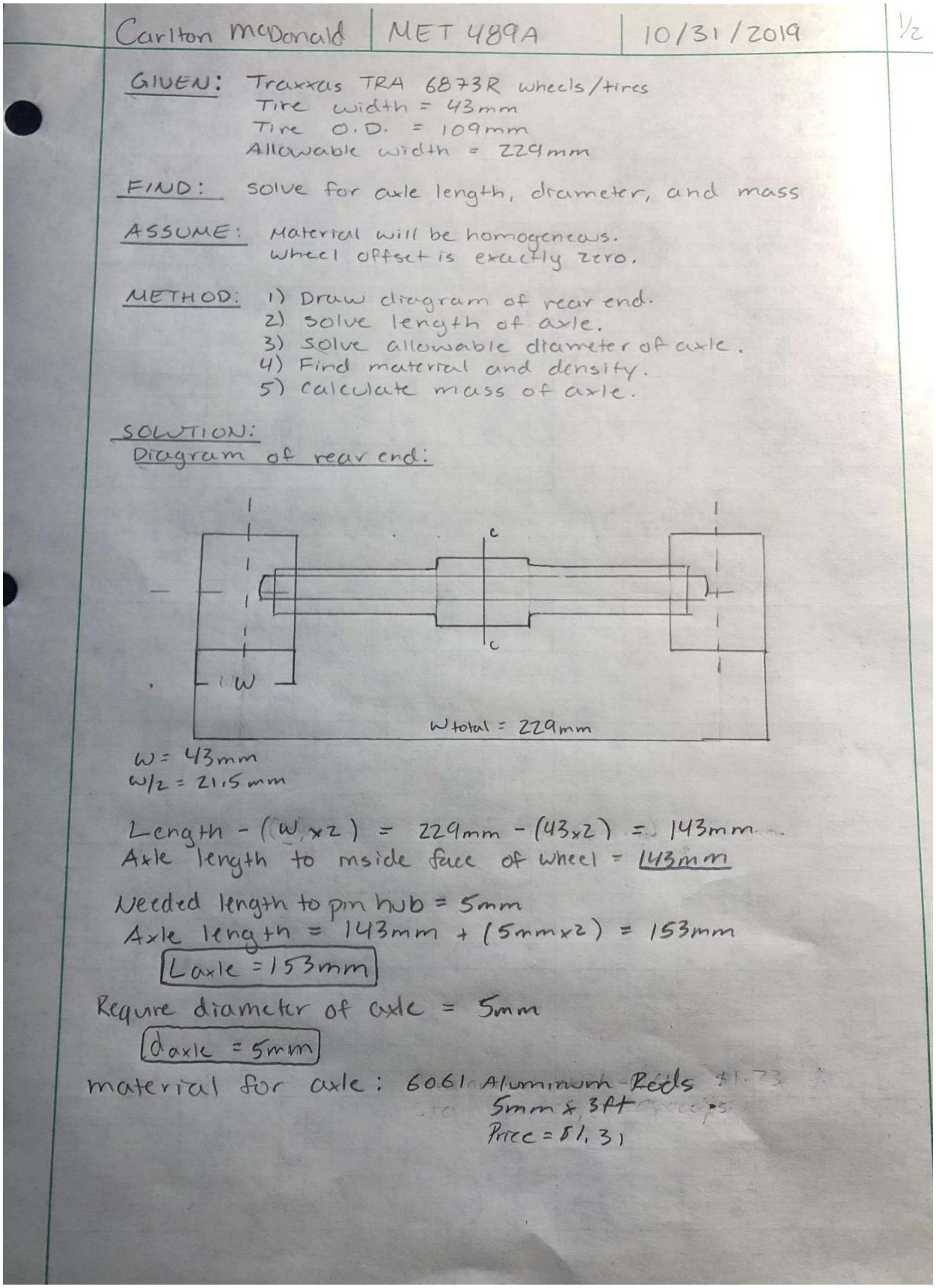
Tooth thickness: $t = P/2 = \frac{1.9074}{2} = 0.9537mm$

Face width: $F = 12/P_d = 12/1.65 = 7.272mm$

Center distance: $C = \frac{(N_P + N_G)}{2P_d} = \frac{(26+64)}{2(1.65)} = 27.27mm$

(Figure A-5: Dimension analysis for Pinion Drive Gear)

Appendix A.6-1



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GIVEN: Traxxas TRA 6873R wheels/tires
Tire width = 43mm
Tire O.D. = 109mm
Allowable width = 229mm

FIND: solve for axle length, diameter, and mass

ASSUME: Material will be homogeneous.
Wheel offset is exactly zero.

METHOD: 1) Draw diagram of rear end.
2) solve length of axle.
3) solve allowable diameter of axle.
4) Find material and density.
5) calculate mass of axle.

SOLUTION:
Diagram of rear end:

w = 43mm
w/2 = 21.5mm

Length − ((W x2) = 229mm − (43x2) = 143mm
Axle length to inside face of wheel = 143mm

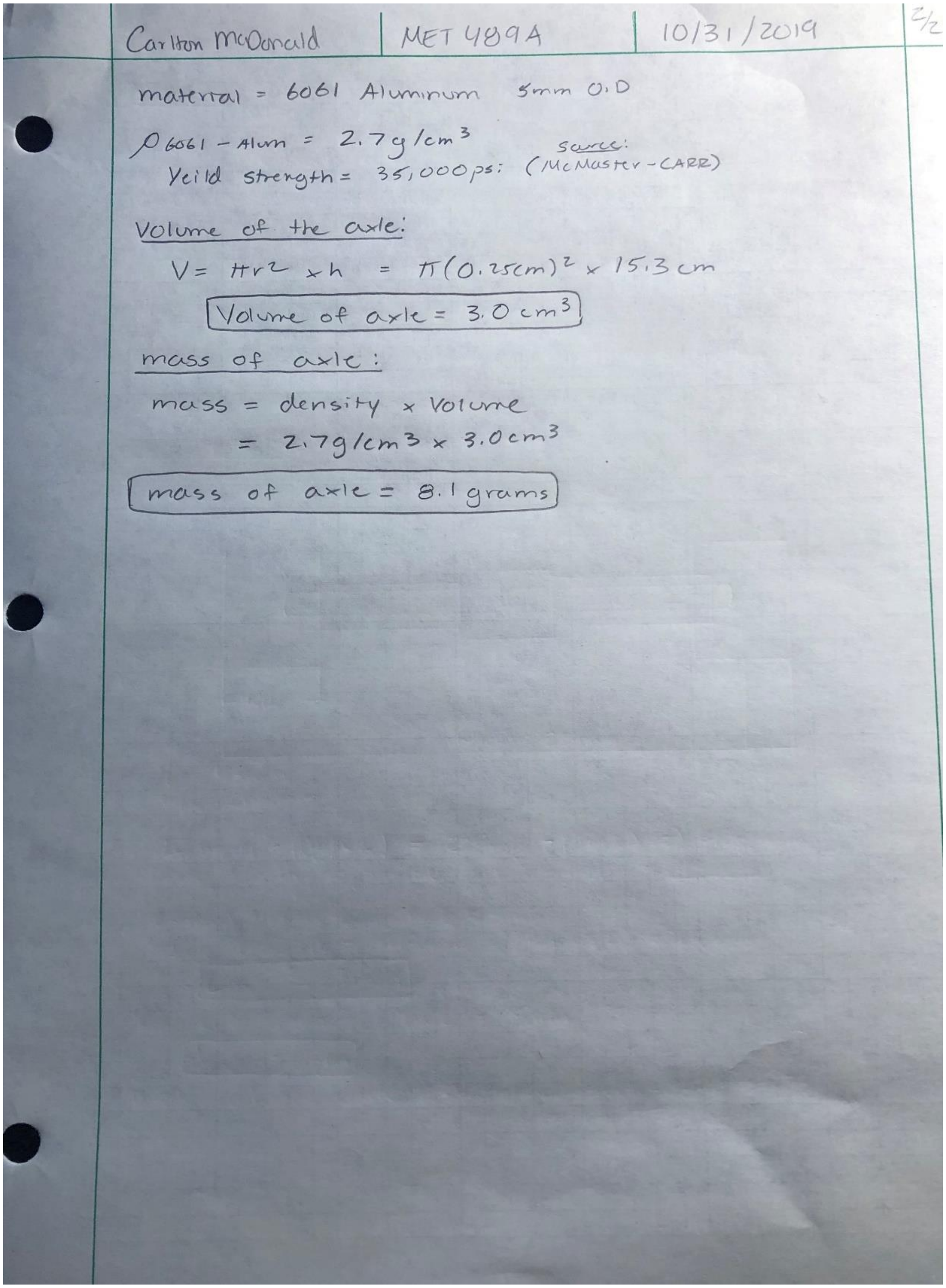
Needed length to pin hub = 5mm
Axle length = 143mm + (5mmx2) = 153mm
L axle = 153mm

Require diameter of axle = 5mm
d axle = 5mm

material for axle: 6061 Aluminum Rods
5mm & 3ft
Price = $1.31

(Figure A-6.1: Axle length, diameter, and mass.)

Appendix A.6-2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material = 6061 Aluminum 5mm O.D

$\rho_{6061-Alum} = 2.7 g/cm^3$

Yeild strength = 35,000psi

Source: (McMaster-CARR)

Volume of the axle:

$V = \pi r^2 \times h = \pi (0.25cm)^2 \times 15.3 cm$

Volume of axle = $3.0 cm^3$

mass of axle:

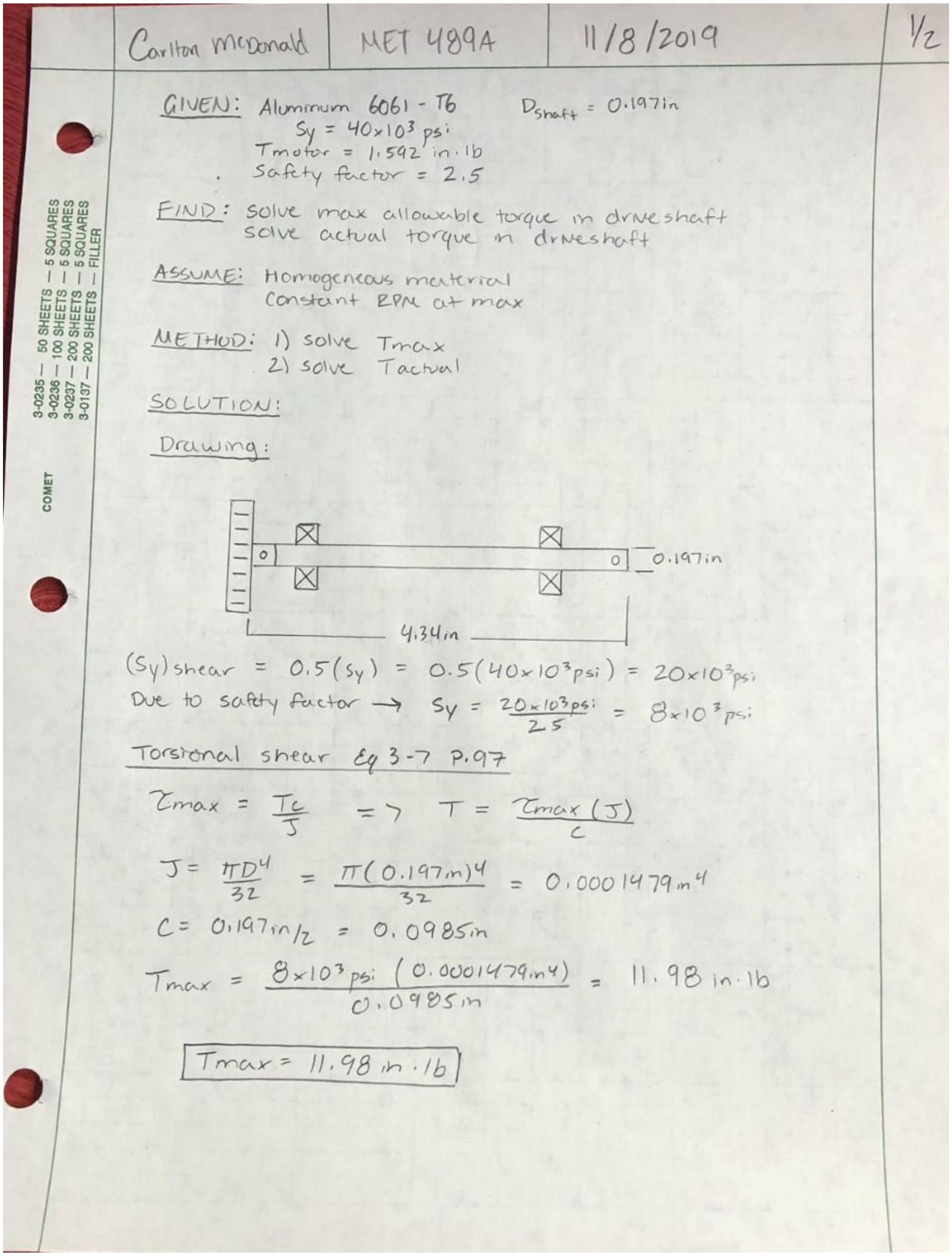
mass = density × Volume

$= 2.7 g/cm^3 \times 3.0 cm^3$

mass of axle = 8.1 grams

(Figure A-6.2: Axle length, diameter, and mass.)

Appendix A.7-1



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GIVEN: Aluminum 6061 - T6 $D_{shaft} = 0.197in$

$S_y = 40\times10^3$ psi

$T_{motor} = 1.592$ in·lb

Safety factor = 2.5

FIND: solve max allowable torque in driveshaft

solve actual torque in driveshaft

ASSUME: Homogeneous material

Constant RPM at max

METHOD: 1) solve Tmax

2) solve Tactual

SOLUTION:

Drawing:

$(S_y)_{shear} = 0.5(S_y) = 0.5(40\times10^3 psi) = 20\times10^3 psi$

Due to safety factor $\rightarrow$ $S_y = \frac{20\times10^3 psi}{2.5} = 8\times10^3 psi$

Torsional shear Eq 3-7 P.97

$\tau_{max} = \frac{Tc}{J} \Rightarrow T = \frac{\tau_{max}(J)}{c}$

$J = \frac{\pi D^4}{32} = \frac{\pi(0.197in)^4}{32} = 0.0001479 in^4$

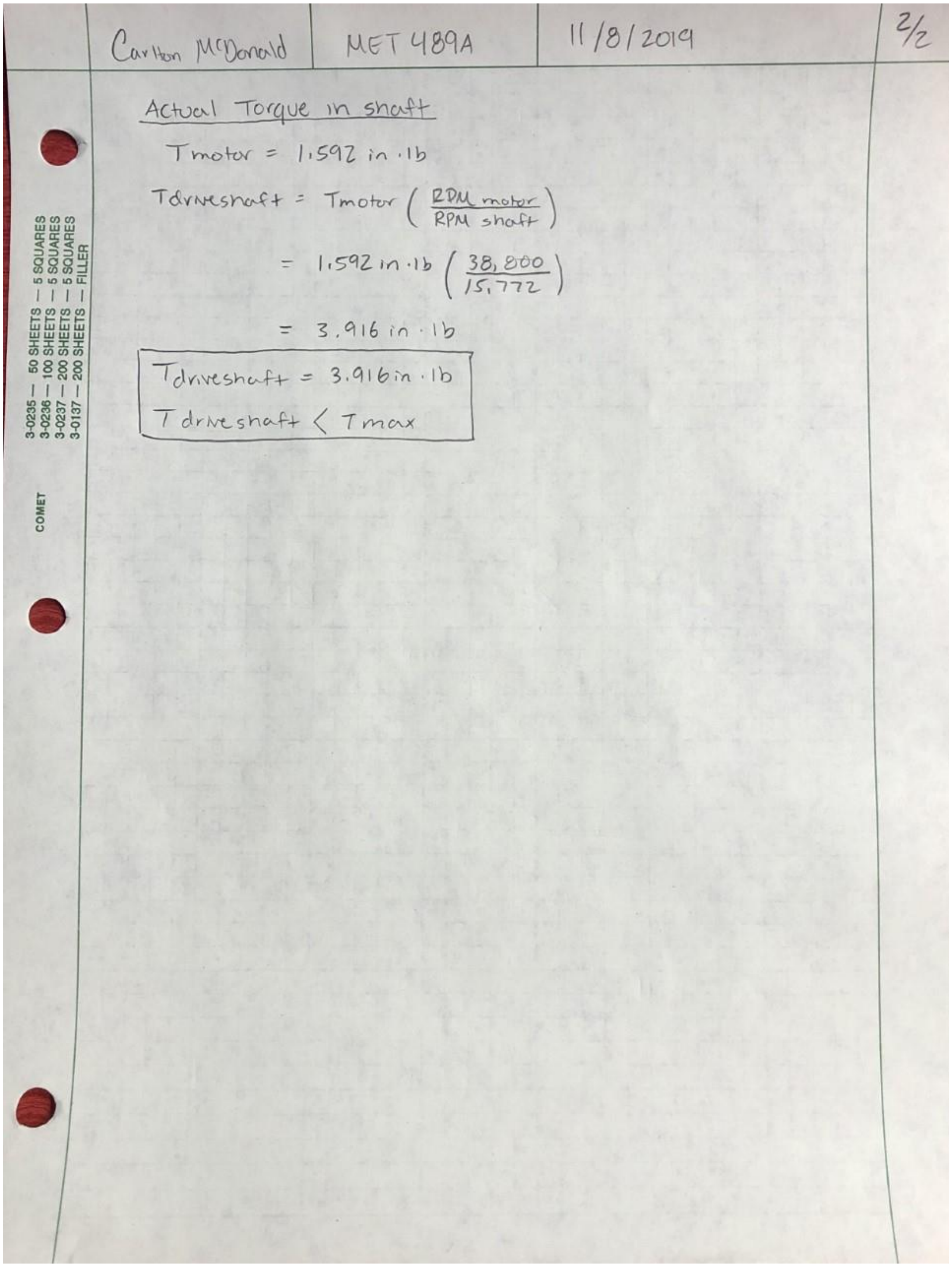
$C = 0.197in/2 = 0.0985in$

$T_{max} = \frac{8\times10^3 psi\ (0.0001479 in^4)}{0.0985in} = 11.98$ in·lb

$T_{max} = 11.98$ in·lb

(Figure A-7.1: Max Allowable Torque on Driveshaft.)

Appendix A.7-2



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Actual Torque in shaft

$T_{motor} = 1.592 \text{ in}\cdot\text{lb}$

$T_{driveshaft} = T_{motor}\left(\frac{RPM_{motor}}{RPM_{shaft}}\right)$

$= 1.592 \text{ in}\cdot\text{lb}\left(\frac{38,800}{15,772}\right)$

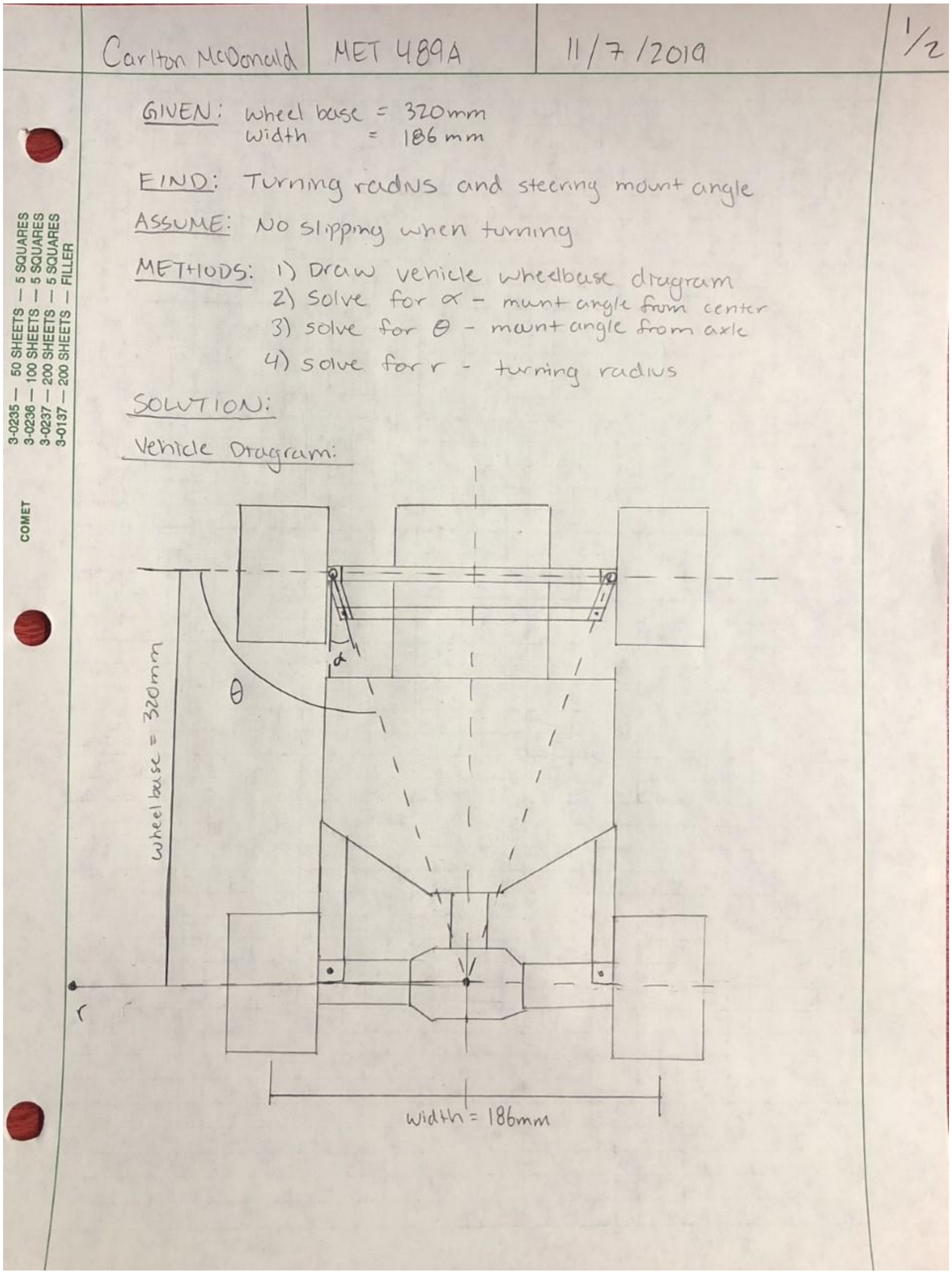
$= 3.916 \text{ in}\cdot\text{lb}$

$T_{driveshaft} = 3.916 \text{ in}\cdot\text{lb}$

$T_{driveshaft} < T_{max}$

(Figure A-7.2: Max Allowable Torque on Driveshaft.)

Appendix A.8-1



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GIVEN: wheel base = 320mm
width = 186 mm

FIND: Turning radius and steering mount angle

ASSUME: No slipping when turning

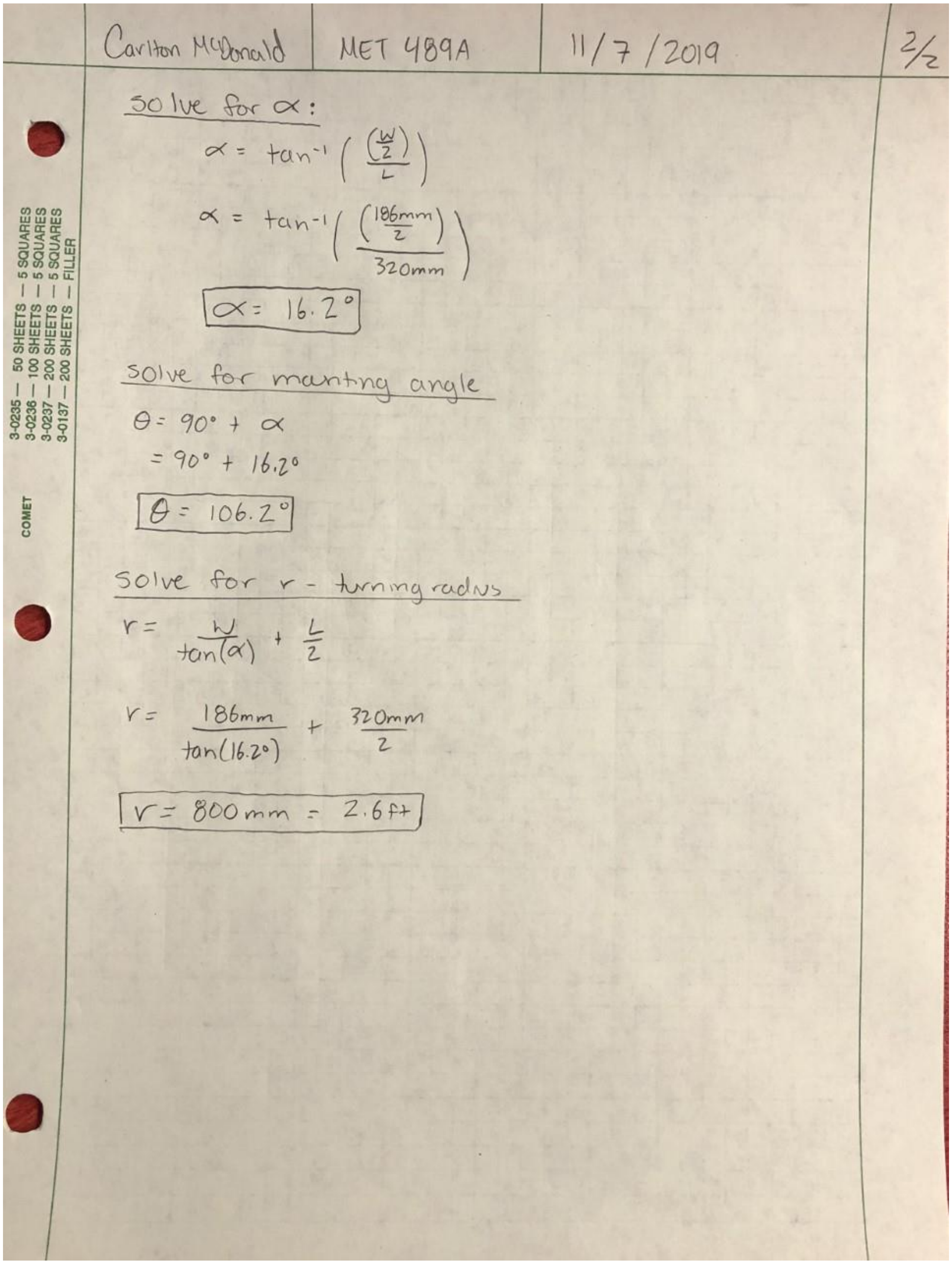
METHODS: 1) Draw vehicle wheelbase diagram
2) Solve for α - mount angle from center
3) solve for θ - mount angle from axle
4) solve for r - turning radius

SOLUTION:

Vehicle Diagram:

(Figure A-8.1: Ackerman's Angle for Turn Radius.)

Appendix A.8-2



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Solve for α:

$$\alpha = \tan^{-1}\left(\frac{\left(\frac{W}{2}\right)}{L}\right)$$

$$\alpha = \tan^{-1}\left(\frac{\left(\frac{186mm}{2}\right)}{320mm}\right)$$

$$\boxed{\alpha = 16.2^\circ}$$

Solve for mounting angle

$$\theta = 90^\circ + \alpha$$

$$= 90^\circ + 16.2^\circ$$

$$\boxed{\theta = 106.2^\circ}$$

Solve for r - turning radius

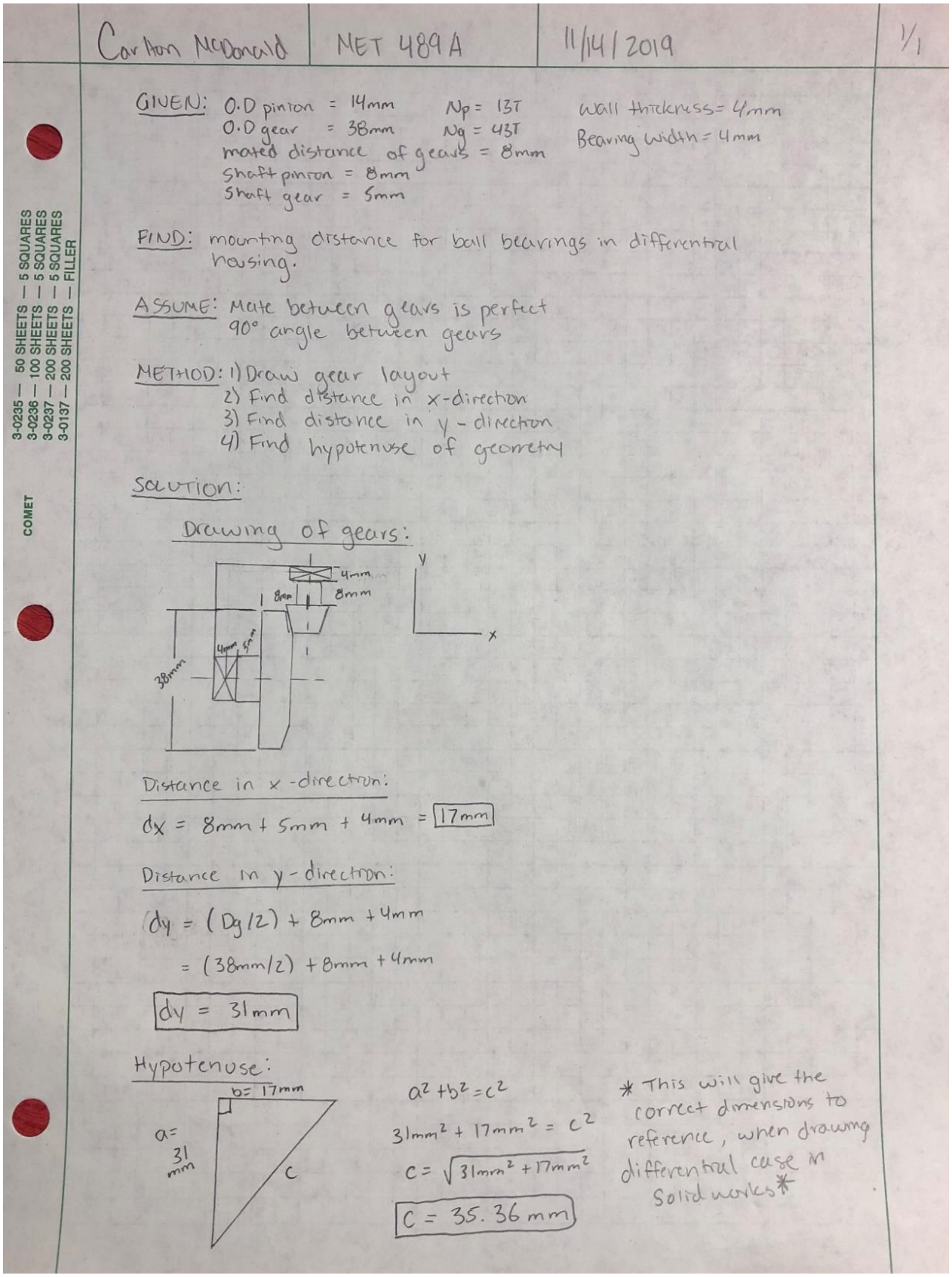
$$r = \frac{W}{\tan(\alpha)} + \frac{L}{2}$$

$$r = \frac{186mm}{\tan(16.2^\circ)} + \frac{320mm}{2}$$

$$\boxed{r = 800mm = 2.6ft}$$

(Figure A-8.2: Ackerman's Angle for Turn Radius.)

Appendix A.9



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GIVEN: O.D pinion = 14mm N_p = 13T wall thickness = 4mm
O.D gear = 38mm N_g = 43T Bearing width = 4mm
mated distance of gears = 8mm
Shaft pinion = 8mm
Shaft gear = 5mm

FIND: mounting distance for ball bearings in differential housing.

ASSUME: Mate between gears is perfect
90° angle between gears

METHOD: 1) Draw gear layout
2) Find distance in x-direction
3) Find distance in y-direction
4) Find hypotenuse of geometry

SOLUTION:

Drawing of gears:

Distance in x-direction:

$dx = 8mm + 5mm + 4mm = \boxed{17mm}$

Distance in y-direction:

$dy = (D_g/2) + 8mm + 4mm$

$= (38mm/2) + 8mm + 4mm$

$\boxed{dy = 31mm}$

Hypotenuse:

$a^2 + b^2 = c^2$

$31mm^2 + 17mm^2 = c^2$

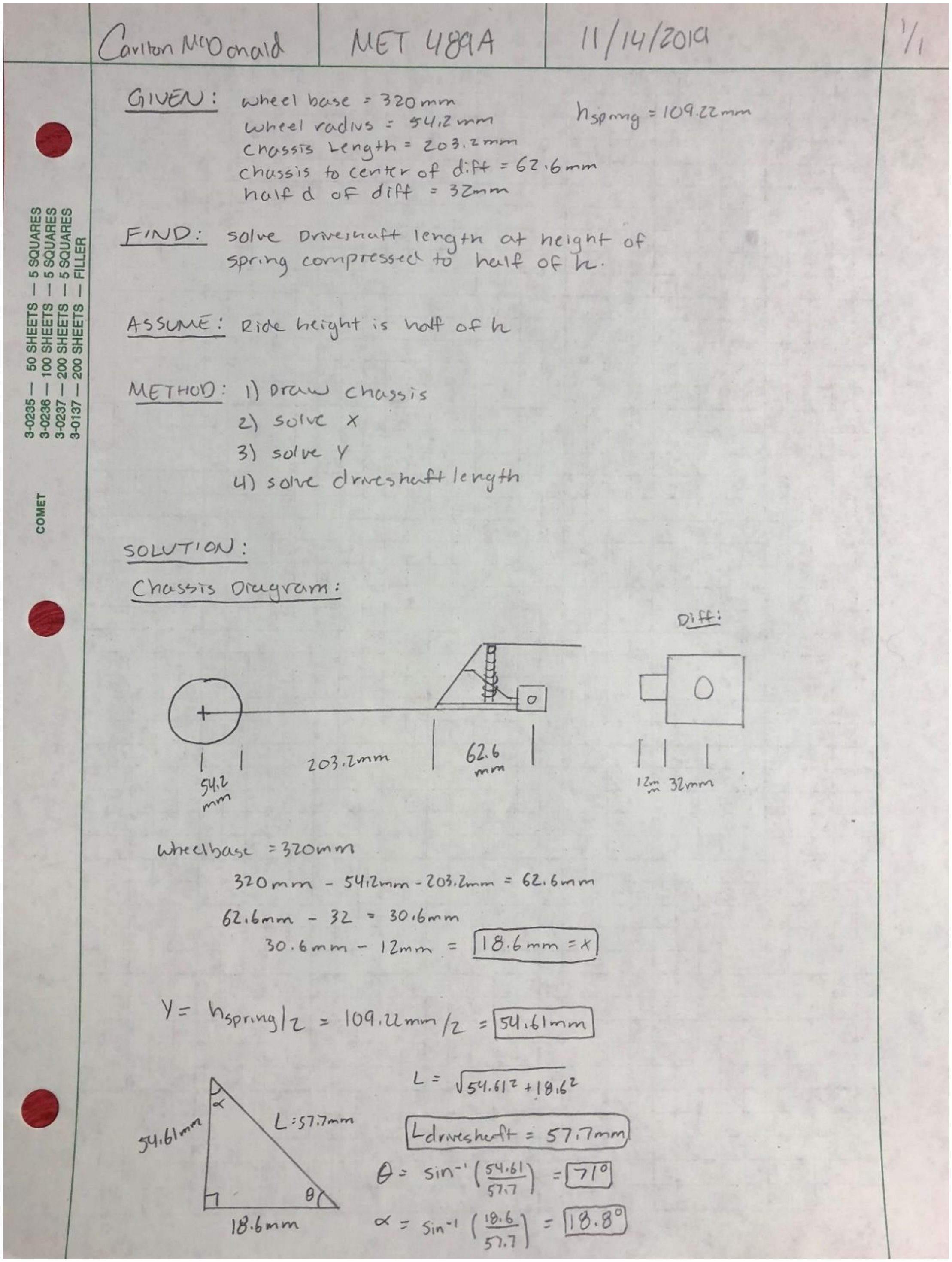
$c = \sqrt{31mm^2 + 17mm^2}$

$\boxed{c = 35.36\ mm}$

* This will give the correct dimensions to reference, when drawing differential case in Solidworks *

(Figure A-9: Differential bearing mount points.)

Appendix A.10



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3-0235 — 50 SHEETS — 5 SQUARES
3-0236 — 100 SHEETS — 5 SQUARES
3-0237 — 200 SHEETS — 5 SQUARES
3-0137 — 200 SHEETS — FILLER
COMET

GIVEN: wheel base = 320 mm
wheel radius = 54.2 mm
chassis Length = 203.2 mm
chassis to center of diff = 62.6 mm
half d of diff = 32 mm
$h_{spring} = 109.22$ mm

FIND: solve Driveshaft length at height of spring compressed to half of h.

ASSUME: Ride height is half of h

METHOD: 1) Draw chassis
2) solve X
3) solve Y
4) solve driveshaft length

SOLUTION:

Chassis Diagram:

Wheelbase = 320mm

320 mm − 54.2mm − 203.2mm = 62.6 mm

62.6mm − 32 = 30.6mm

30.6 mm − 12mm = 18.6 mm = X

$Y = h_{spring}/2 = 109.22\text{mm}/2 = 54.61\text{mm}$

$L = \sqrt{54.61^2 + 18.6^2}$

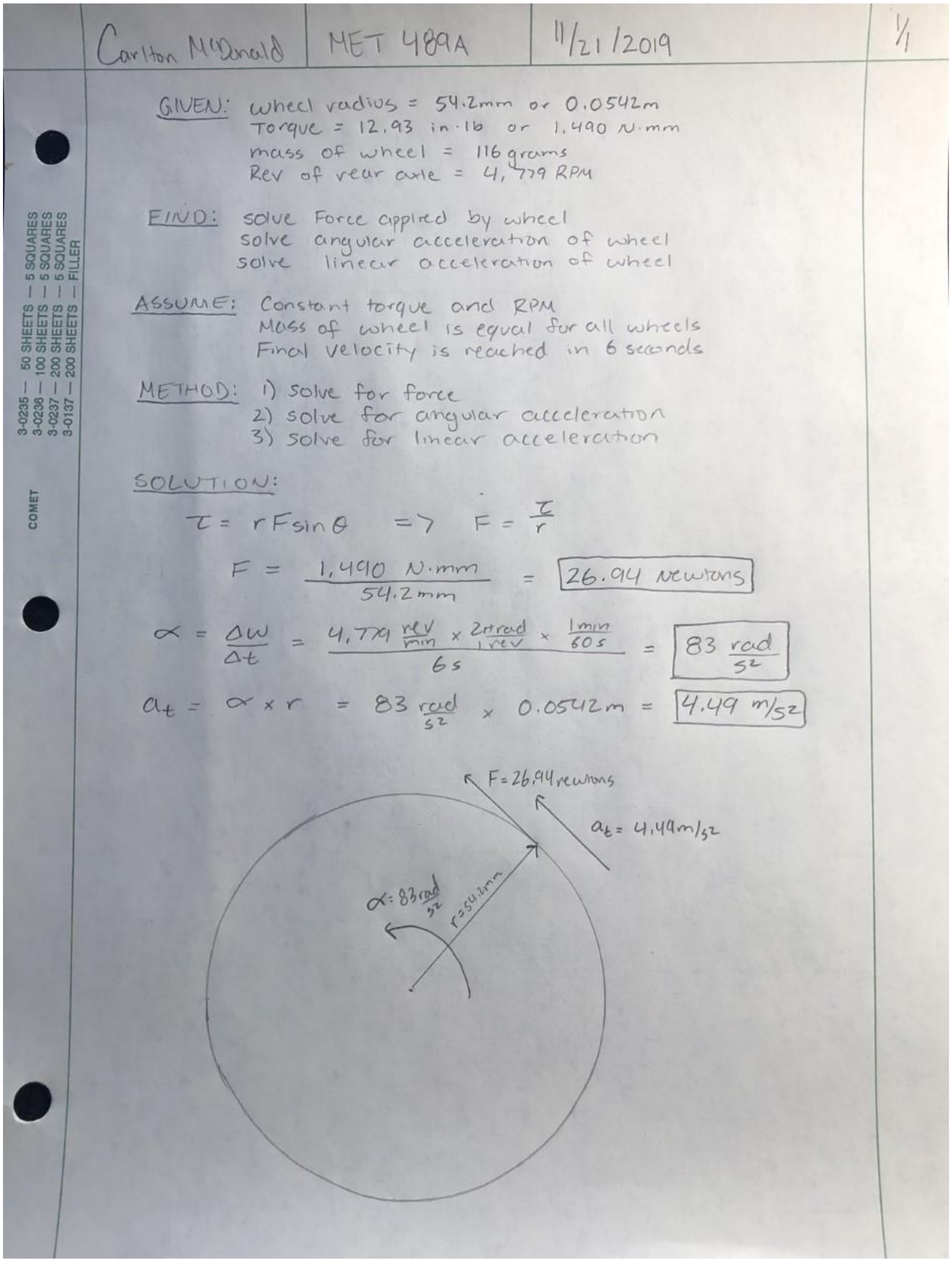
$L_{driveshaft} = 57.7\text{mm}$

$\theta = \sin^{-1}\left(\frac{54.61}{57.7}\right) = 71°$

$\alpha = \sin^{-1}\left(\frac{18.6}{57.7}\right) = 18.8°$

(Figure A-10: Secondary Driveshaft length.)

Appendix A.11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GIVEN: wheel radius = 54.2mm or 0.0542m
Torque = 12.93 in·lb or 1,490 N·mm
mass of wheel = 116 grams
Rev of rear axle = 4,779 RPM

FIND: solve Force applied by wheel
solve angular acceleration of wheel
solve linear acceleration of wheel

ASSUME: Constant torque and RPM
Mass of wheel is equal for all wheels
Final velocity is reached in 6 seconds

METHOD: 1) solve for force
2) solve for angular acceleration
3) solve for linear acceleration

SOLUTION:

$$\tau = rF\sin\theta \Rightarrow F = \frac{\tau}{r}$$

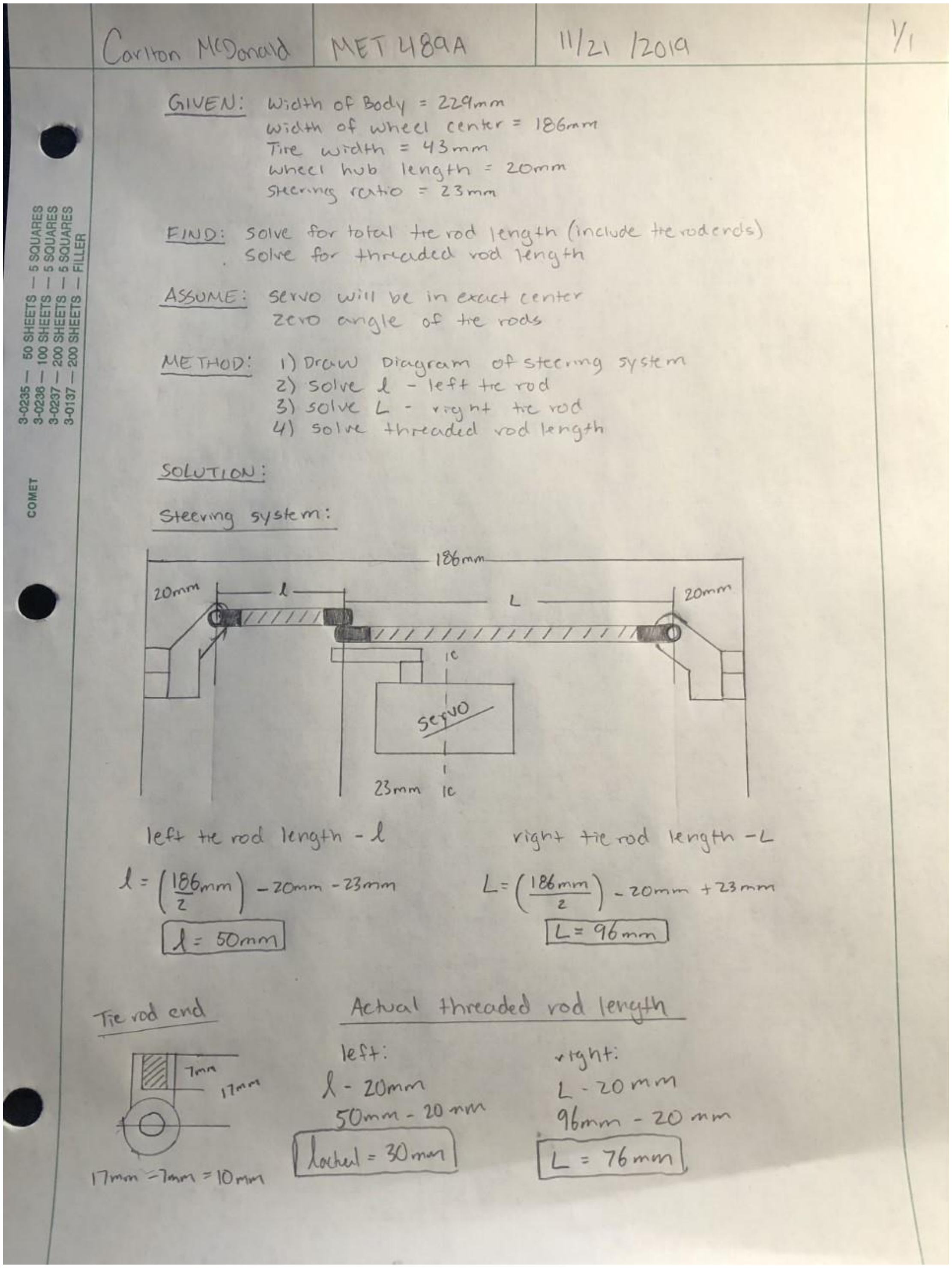
$$F = \frac{1,490\ N\cdot mm}{54.2mm} = \boxed{26.94\ newtons}$$

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{4,779\ \frac{rev}{min} \times \frac{2\pi\ rad}{1\ rev} \times \frac{1\ min}{60\ s}}{6\ s} = \boxed{83\ \frac{rad}{s^2}}$$

$$a_t = \alpha \times r = 83\ \frac{rad}{s^2} \times 0.0542m = \boxed{4.49\ m/s^2}$$

(Figure A-11: Force, angular acceleration, linear acceleration of rear wheels.)

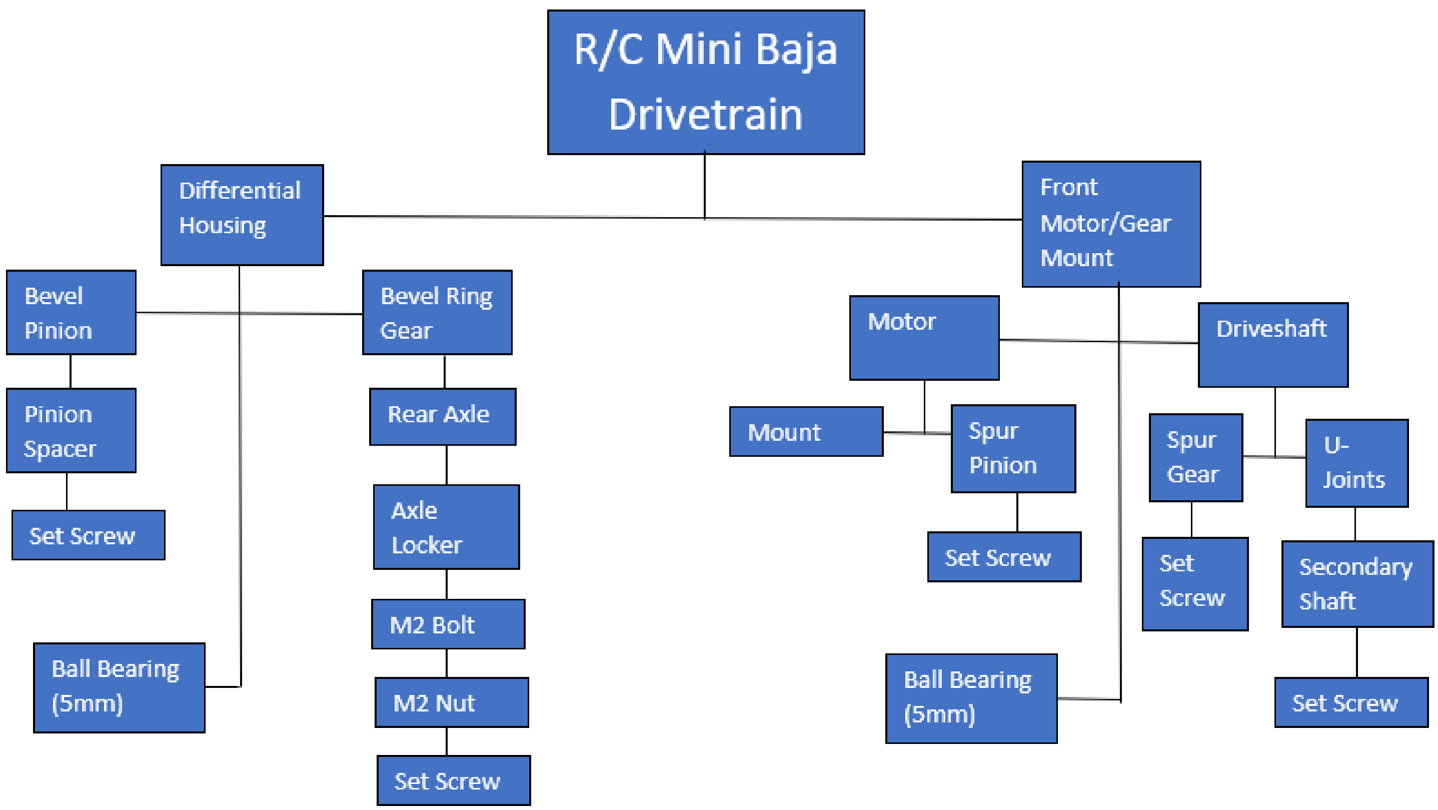
Appendix A.12



(Figure A-12: Steering tie rod lengths.)

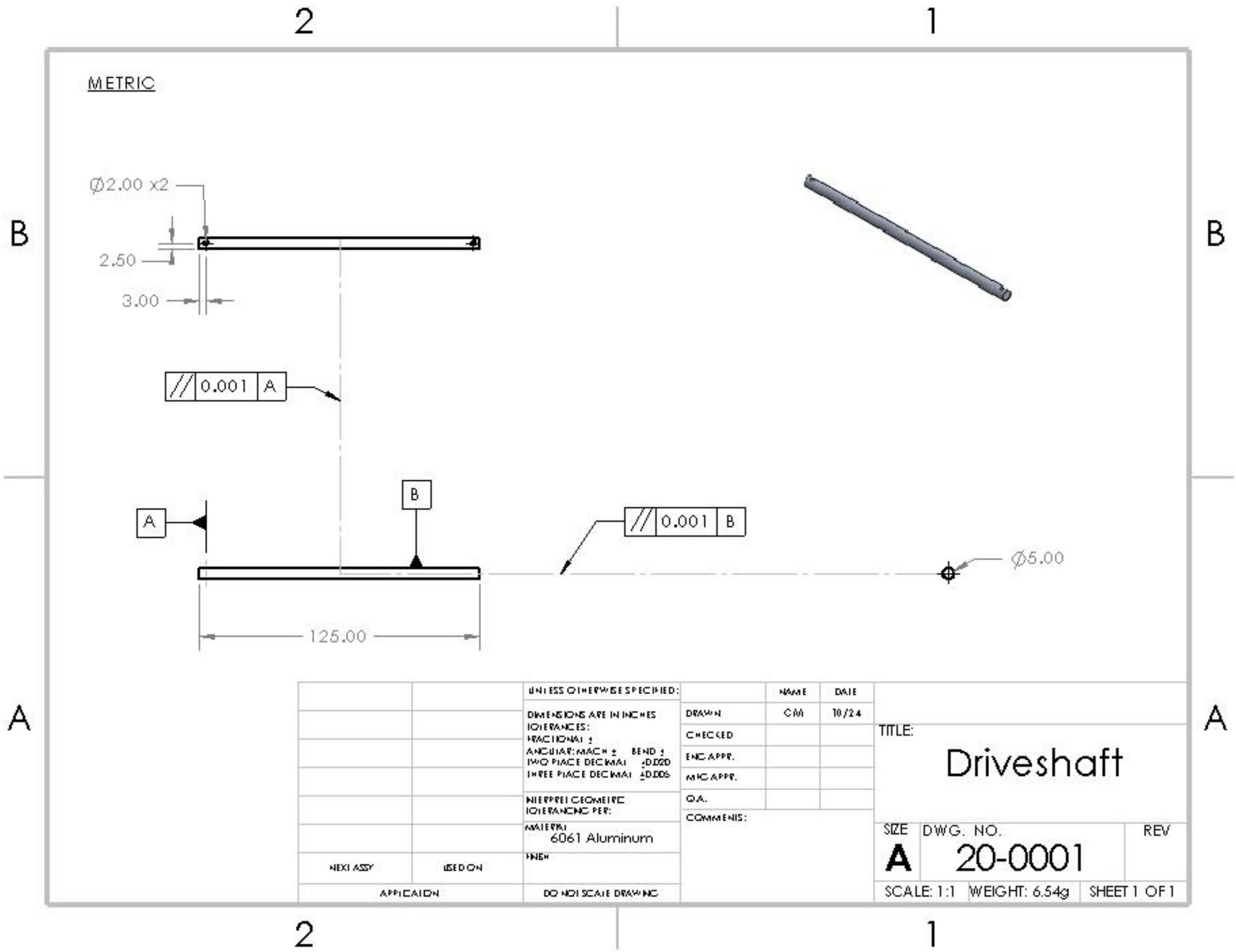
Appendix B – Engineering Drawings

Appendix B.1



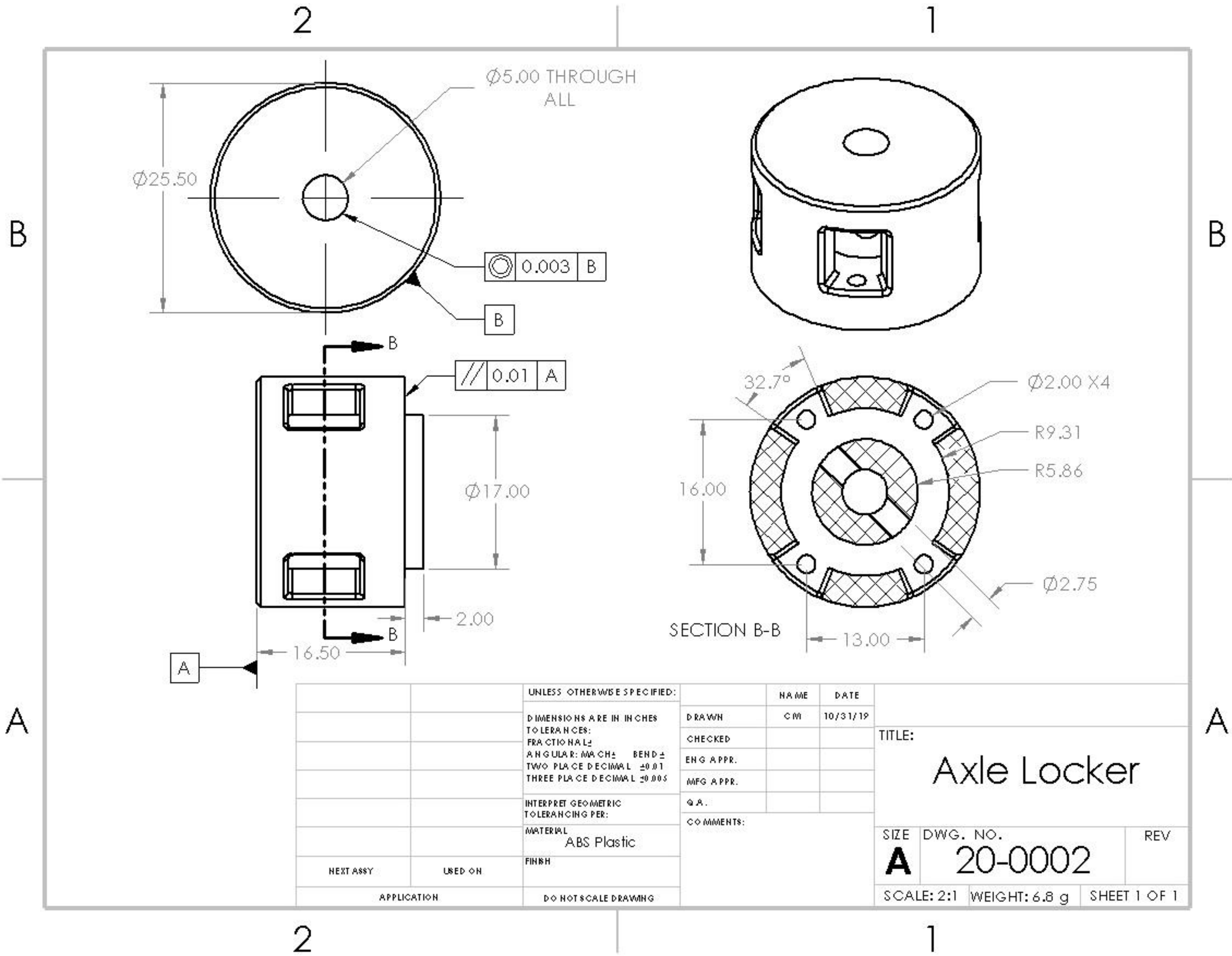
(Figure B-1: Drawing tree of Drivetrain Parts.)

Appendix B.2



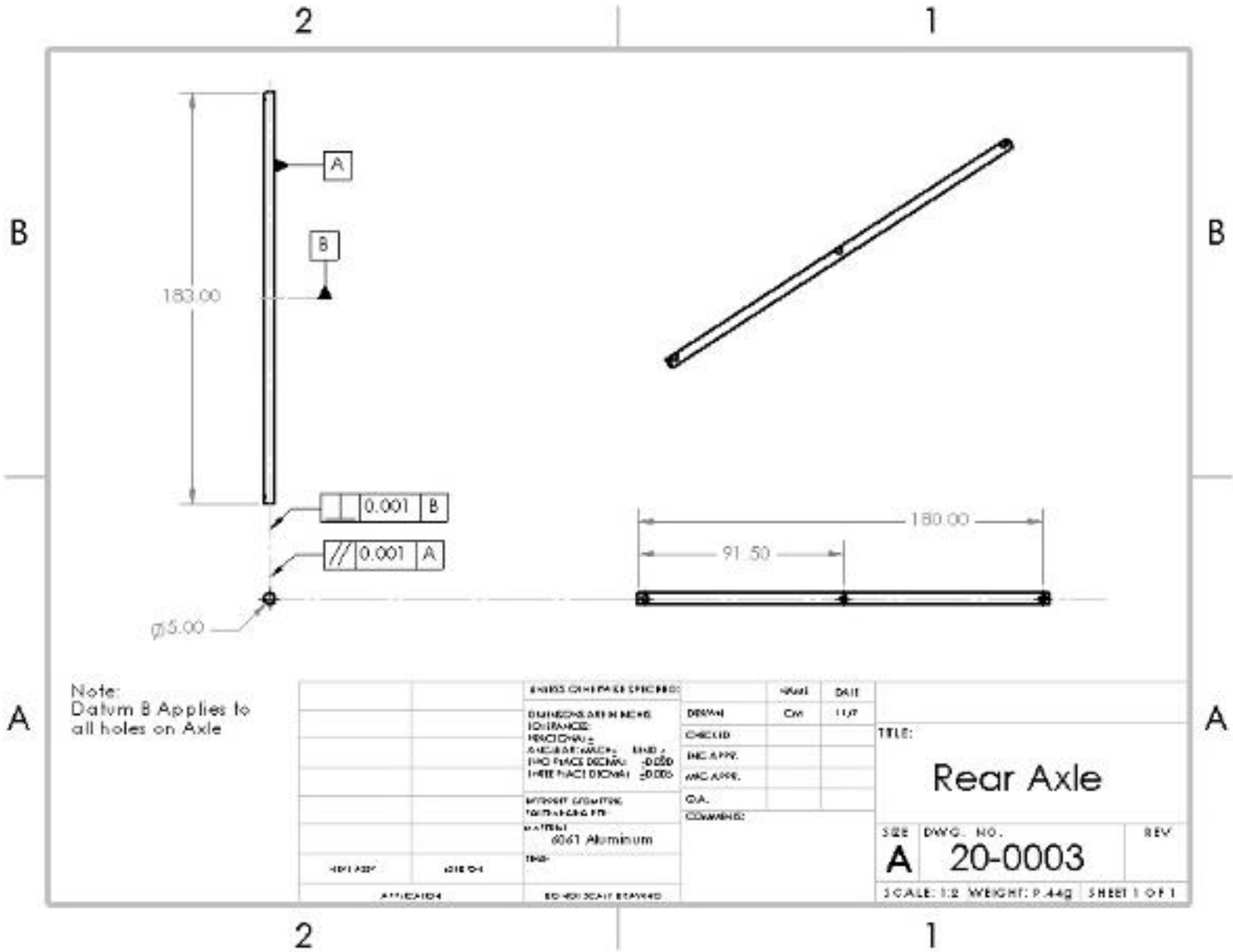
(Figure B-2: Primary Driveshaft Drawing.)

Appendix B.3



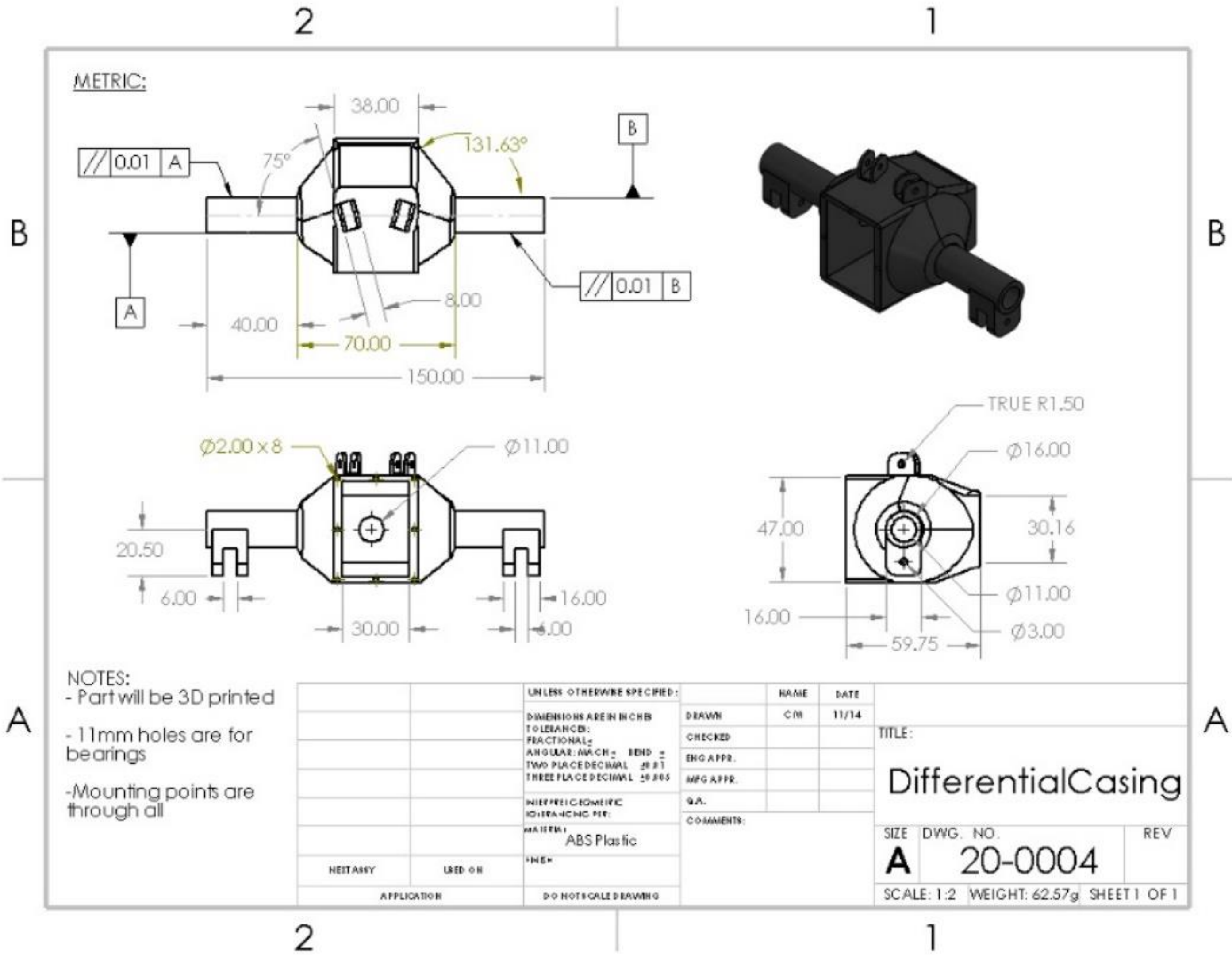
(Figure B-3: Axle Locker Drawing.)

Appendix B.4



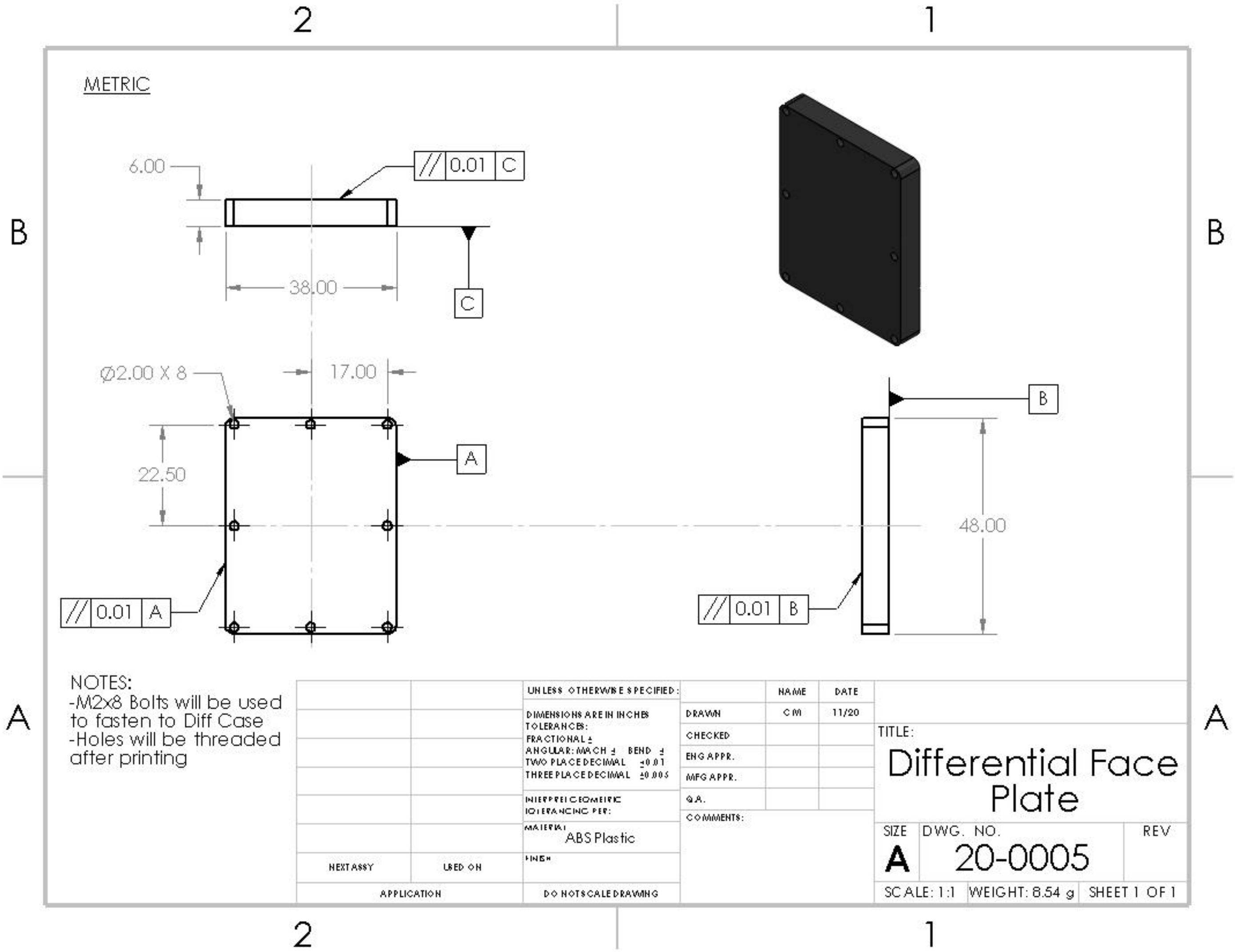
(Figure B-4: Rear Axle Drawing.)

Appendix B.5



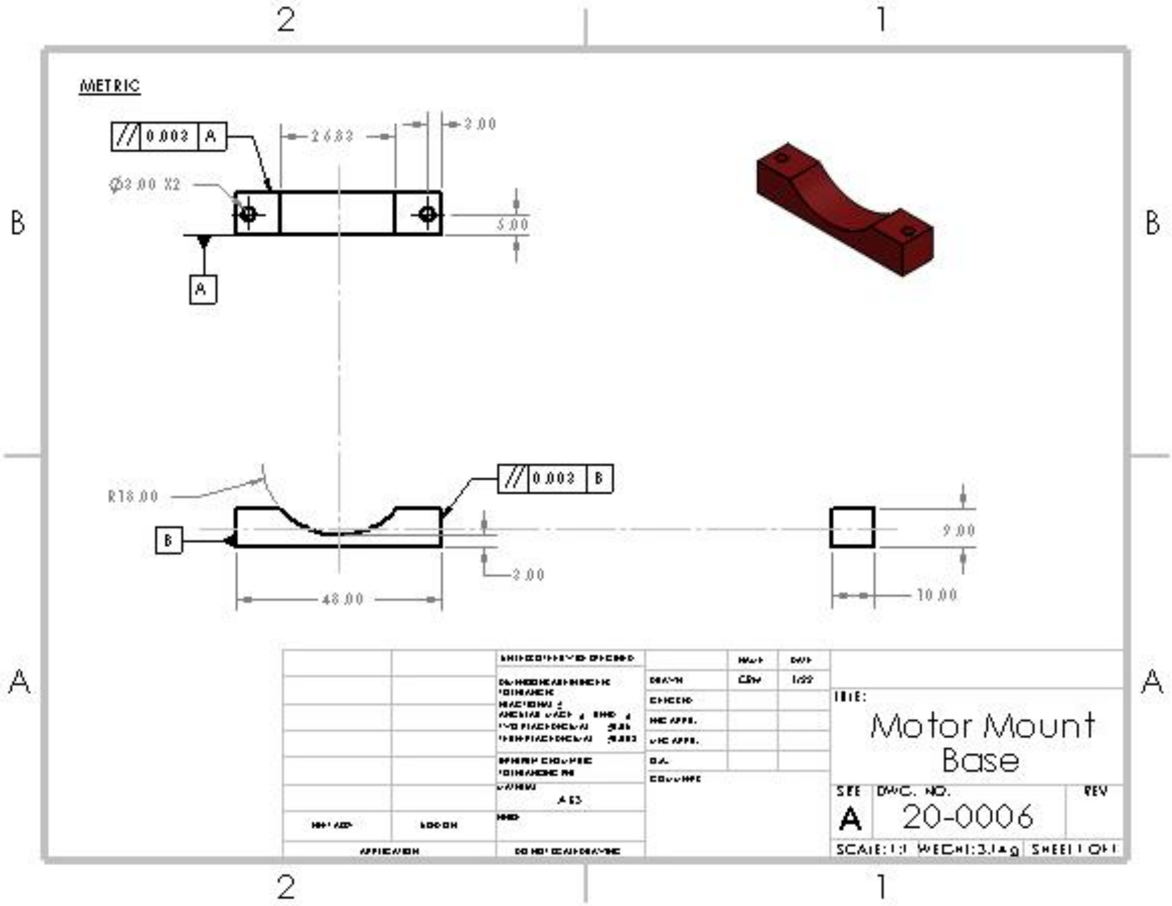
(Figure B-5: Differential Casing.)

Appendix B.6



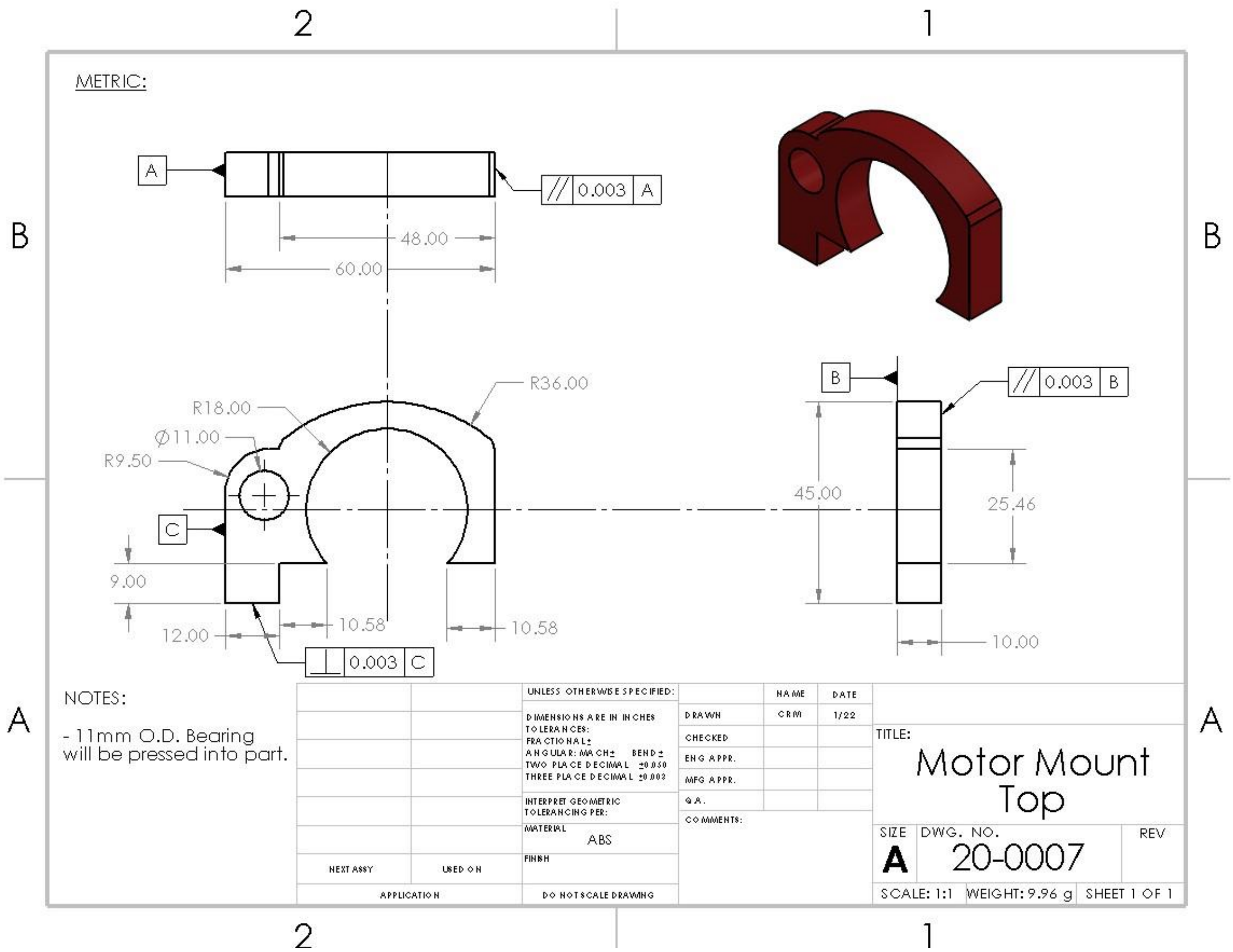
(Figure B-6: Differential Faceplate.)

Appendix B.7



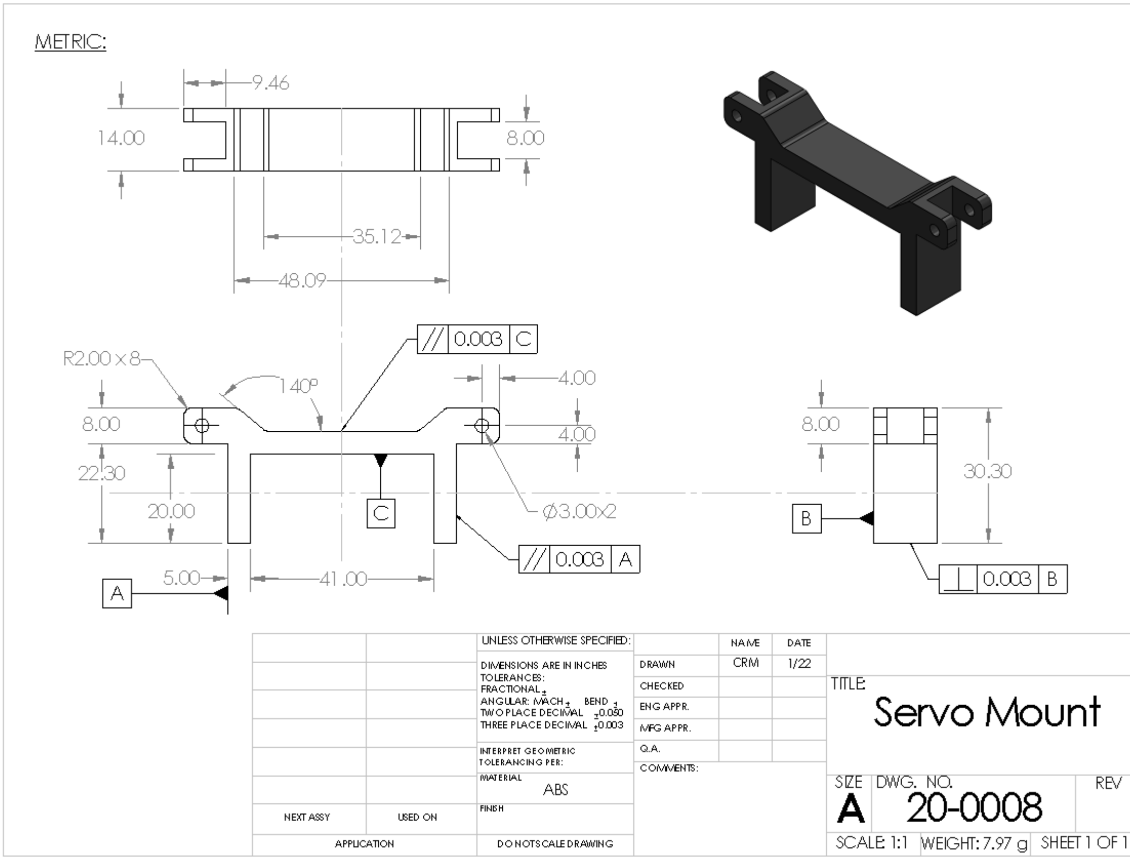
(Figure B-7: Motor Mount Base.)

Appendix B.8



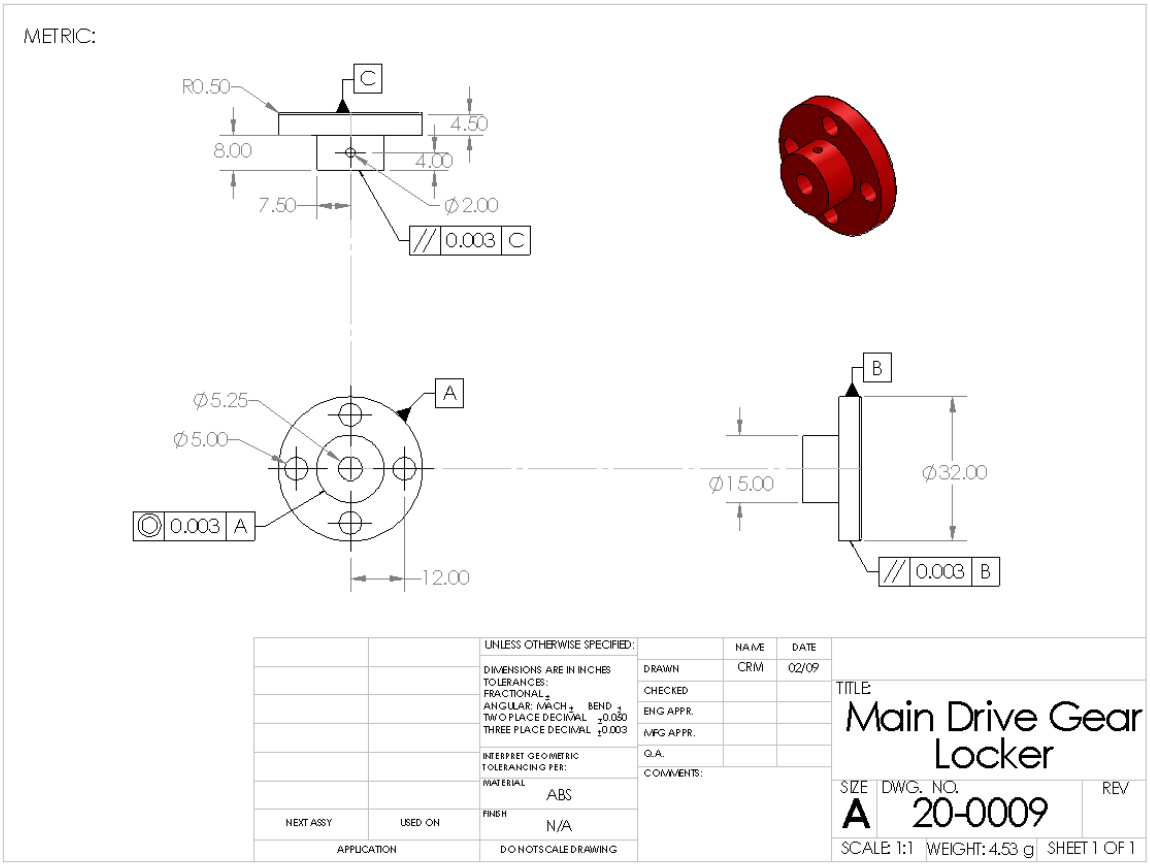
(Figure B-8: Motor Mount Top.)

Appendix B.9



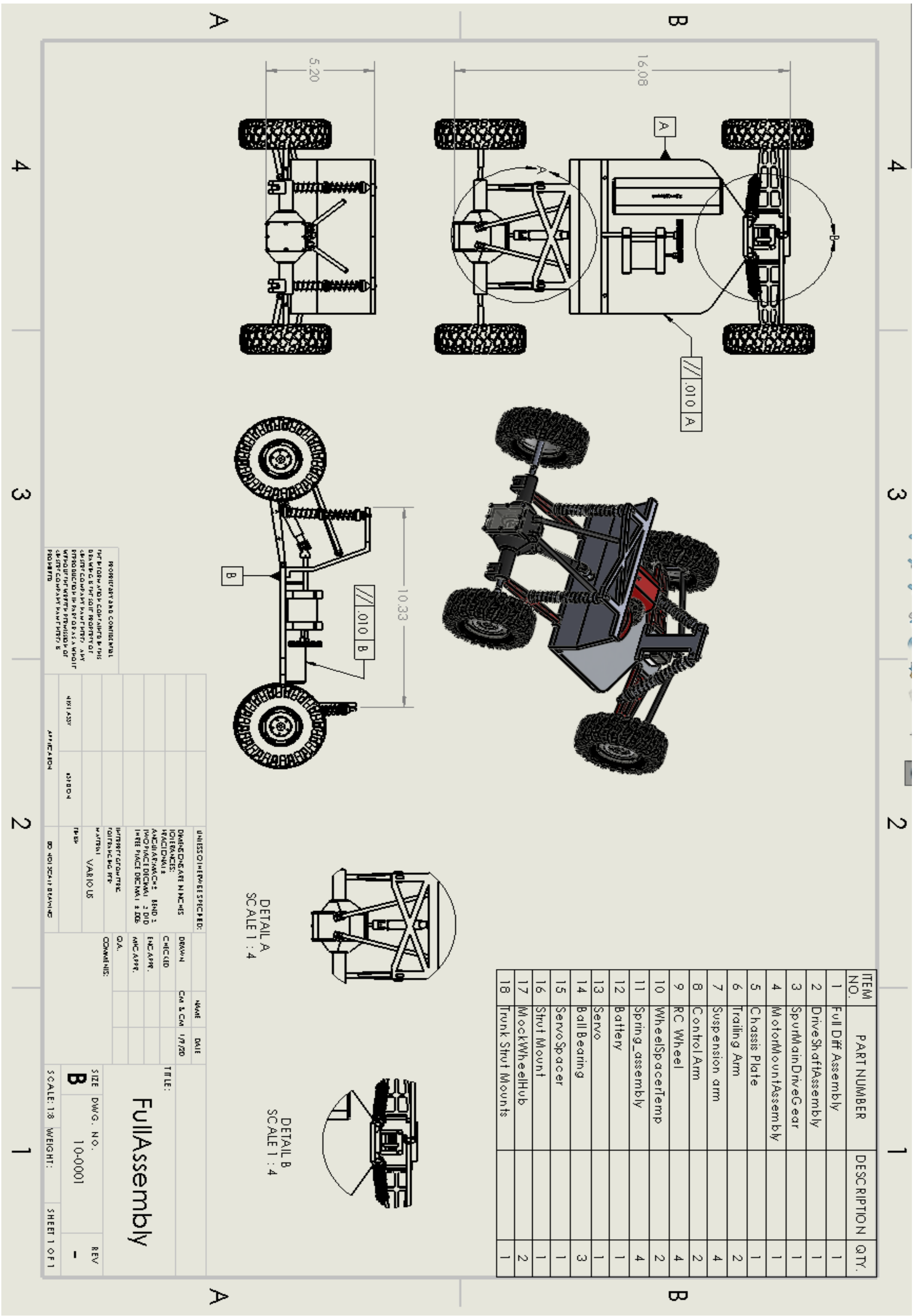
(Figure B-9: Servo Mount.)

Appendix B.10



(Figure B-10: Main Gear Locker.)

Appendix B.11



(Figure B-11: Full R/C Assembly)

Appendix B.12

(Figure B-12: 3D Model of R/C Baja Car Completed.)

Appendix C – Parts List

Part ID#	Part Description	Quantity	Buy or Mfg
1	Hobbywing Motor	1	Buy
2	Hobbywing ESC	1	Buy
3	26T Spur Pinion Gear	1	Buy
4	64T Spur Main Gear	1	Buy
5	Main Gear Locker	1	Mfg
6	13T Bevel Pinion Gear	1	Buy
7	43T Bevel Ring Gear	1	Buy
8	M2 Set Screws	6	Buy
9	Drive Shaft -5mm Rod	1	Mfg
10	Traxxas Adjustable DS	1	Buy
11	5mm I.D. Ball Bearings	8	Buy
12	Motor Mounts	2	Mfg
13	Differential Housing	1	Mfg
14	Rear Axle - 5mm Rod	1	Mfg
15	Rear Axle Locker	1	Mfg
16	Rear Wheel Hub	2	Buy
17	M3 Bolt/Nut	17	Buy
18	7.2V 5400 mAh Battery	2	Buy
19	Futaba Steering Servo	1	Buy
20	Steering Ratio Joint	1	Buy
21	Tie Rods - M3x0.7 Rod	2	Mfg
22	SSD Tie Rod Ends	4	Buy
23	Front Wheel Hubs	2	Buy
24	Servo Mount	1	Mfg

(Figure C-1: Parts List.)

Appendix D – Budget

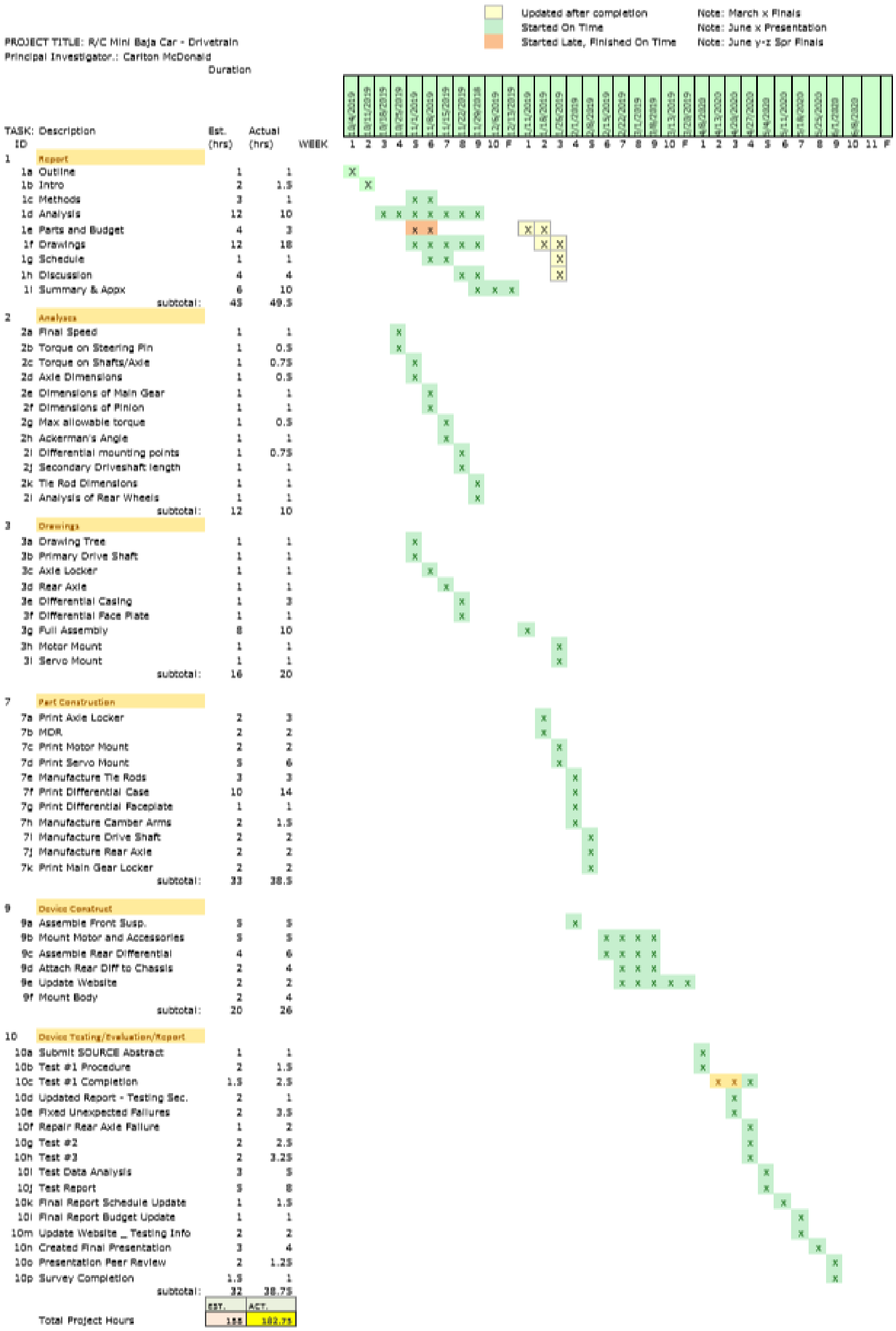
PARTS LIST AND BUDGET

R/C Baja Car Drivetrain

ITEM ID	ITEM Description	Item Source	Brand Info	Model/SN	Price/Cost	Quantity	Subtotals
					(US Dollars)		
					($ / hour)		
1	Motor/ESC/Fan Kit	rcMart.com	Hobbywing	EZRUN-3652-G2	$ 129.00	1	$ 129.00
2	Drive Gear Set	Amazon	ShareGoo	11184/11176	$ 8.89	1	$ 8.89
3	Ball Bearings	Amazon	Traxxas	MR115-2RSBU	$ 10.48	1	$ 10.48
4	6061 Aluminum Rod	McMaster-Carr	-------	4634T31	$ 1.31	1	$ 1.31
5	7.2v 5000mAh Battery	Amazon	Tamiya	B01DHK7O76	$ 39.99	1	$ 39.99
6	SSD RC M4/M3 Rod Ends	Amainhobbies	-------	SSD00116	$ 3.99	1	$ 3.99
7	Stainless Threaded Rod M4	McMaster-Carr	-------	90024A221	$ 3.01	1	$ 3.01
8	M3 set screw	McMaster-Carr	-------	91390A105	$ 13.71	1	$ 13.71
9	M2x8 Bolt	McMaster-Carr	-------	92942A807	$ 9.40	1	$ 9.40
10	M2x10 Bolt	McMaster-Carr	-------	93070A277	$ 8.21	1	$ 8.21
11	3D printing costs	CWU MET	ABS	-------	$ 6.00	4.4	$ 26.40
						SubTotal	$ 254.39
	Additional Budget Costs				**Increase**		
	New Motor Source	rcplanet.com	Hobbywing	EZRUN-3652-G2	$ 17.00		$ 271.39
	Additional Axle Material	Amazon	-------	--------	$ 10.17		$ 281.56

(Figure D-1: Budget List.)

Appendix E – Schedule



(Figure E-1: Gantt Chart.)

Appendix F – Expertise/Resources

Expertise/Resources	Description
Central Washington University	Allows access to Hogue building amenities, such as the CAD Lab, Machine Shop, Hydraulics Lab and other resources.
CWU – Dr. Craig Johnson	Provided guidance throughout the project.
CWU – Charles Pringle	Provided guidance throughout the project.
CWU – Jeunghwan Choi	Provided guidance throughout the project.
CWU – Tedman Bramble	Provided guidance throughout the manufacturing/construction portion of the project.
CWU – Matt Burvee	Provided guidance throughout the manufacturing/construction portion of the project.

Appendix G – Testing Report

Introduction:

During the testing of the R/C Baja Car drivetrain and steering, the max velocity, acceleration, and steering angle will be found. The requirements for this project are as followed:

Requirements:

- The R/C Baja Car must meet/exceed a final velocity of 20 mph.
- The R/C Baja Car must accelerate to max speed at a rate of 17.2 ft/s^2.
- The R/C Baja Car must have a steering angle of at least 60 degrees.

In the analysis process, the final drive speed was found without the factor of friction due to the type of surface the car will be performing on, this could deviate the results found. The deviation allowed will be plus/minus 5 mph of the final drive speed and 5 ft/s^2 of acceleration. If the results do not obtain the correct speed, redesign work will be done to increase the performance of the vehicle.

Predicted Performance:

The predicted performance of the final velocity of the vehicle is 54 mph. this value was found at 100% efficiency in the system, neglecting the weight of the vehicle, subsequent power loss, or any friction between the tires and ground. More calculations were made, and another predicted value was found, this value was 40 mph in consideration of having a 75% efficient system.

The predicted performance of the vehicle's acceleration was based off the 40-mph predicted velocity; the predicted acceleration was calculated to be 67 ft/s^2.

The predicted performance of the steering angle was 60 degrees.

Data Acquisition:

Data during this test will be collected by using a tape measure and stopwatch, to have a known distance and time of the R/C Baja Car to pass through said distance. This data collecting method will be used for both velocity and acceleration. Data for the steering angle test will use a protractor and metal rod in which will record the degree of turn per movement of the remote control.

Schedule:

The schedule for this testing is related to the due dates of the Spring Senior Project course. The testing was completed during the allotted time period of the beginning of the quarter to the due date of the testing report. Some complications occurred during the testing that altered planned test dates, more details can be found on the Gantt chart included in Appendix G5.

Method/Approach:

Resources:

During the testing process some resources were needed to complete the test. Each test had a requirement for a team of two people. One person was required to operate the R/C car, while another was required for taking time measurements or angle measurements and recording the data on the tables. All other resources were used from acquired equipment that was common in the household such as measuring equipment and timing equipment (iPhone).

Data capture/doc/processing:

Data capture was done by human. The data capture only required the start and stop of a time watch and by eye measurements of turning angle. The data was then recorded on the printed-out Excel sheets to later store on the actual Excel program.

Test procedure overview:

The testing procedures that can be found in the following pages of the report consist of three different tests, final velocity, acceleration, and turning angle. Final velocity test is done by timing the vehicle at a constant speed for a set distance. The acceleration test is done by timing the amount of time it took for the R/C car to reach its final velocity. Both tests are done on two different surfaces to compare the effect of the terrain on the results. The steering angle test consist of taking measurement of wheel angle at different increments of turning the remote control. This test is done for both left- and right-hand turns.

Operational limitations:

Limitations in the testing come from the ability to accurately measure the time and angle of the wheel. More precise equipment would be recommended to get a more accurate result of data. There are no limitations to the device itself, other than needing two people to operate and record data.

Precision and accuracy discussion:

During the testing, the precision and accuracy of timing the R/C car can vary. To narrow down the possibility of error, a test was done to see how fast a human thumb can start/stop the stopwatch on an iPhone. This resulted in a precision of around +/- 0.1 seconds. The precision of the steering angle measurements remained around +/- 2.0 degrees of deviation per measurement.

Data storage, analysis, and presentation:

Data was stored into an Excel sheet in different tables per test once the test were completed. The data was then used to find the final calculation for each trial. These calculations were then used to find the average final giving the result of the test. The results of the test will be presented as tables and graphs. These will be used to compare the results of different terrains and the comparison of passenger side wheel and driver side wheel in steering angle.

Test Procedures:

Test # 1 – R/C Baja Car Final Velocity

Summary:

During this test, the final velocity of the R/C Baja Car will be found. The speed of the vehicle can be calculated by recording total distance travel and the amount of time for the vehicle to travel the total distance. Using these factors will give the information of how fast the car will go at max speed. To calculate the max speed of the vehicle, a constant speed is required. The vehicle will have to be accelerated to the max possible RPM and held constant for an x-amount of distance. Using the constant max RPM, set distance, and time it took to travel that distance, the max velocity can be calculated using this equation:

$$\textbf{Max velocity} = \frac{distance}{time}$$

When setting up the testing area, the Baja car will be given a run up distance of 25 feet to reach maximum RPM in the motor. At 25 feet, tape will be indicated when the timer should start the stopwatch. As soon as the front wheels of the vehicle cross the tape the time of the trial starts, and when the back wheels cross the tape at the end of the run the time stops. The total travelled distance will be measured out to be 20 feet. This data will then be recorded and used for max velocity calculations.

Scheduled date/time of testing: April 15th, 2020 at 12:30 PM

Duration of testing: Approx. 1 hour.

Location of testing: Ellensburg, WA

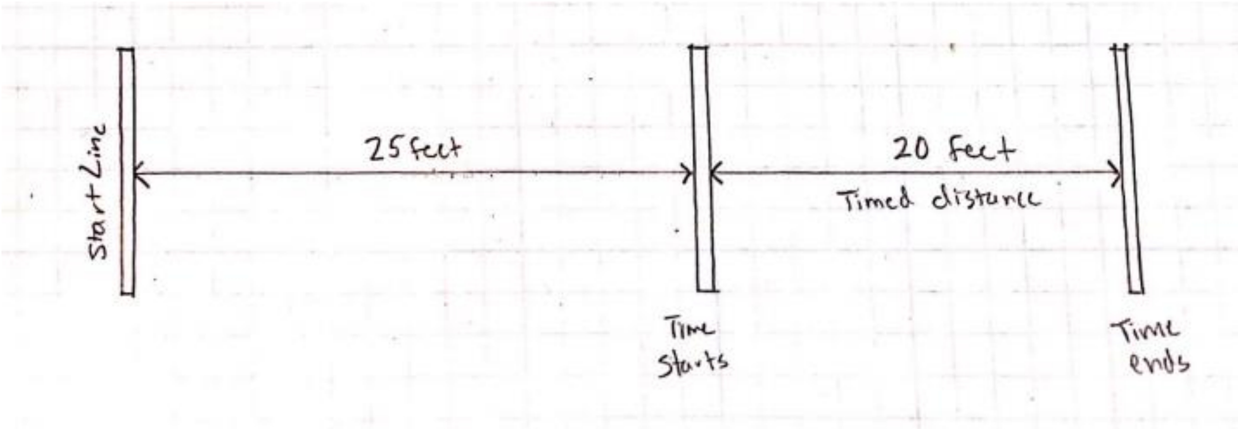
Required resources to complete test: Tape measure, stopwatch, tape or spray paint, and 60 feet of runway. 2 persons, one for stopwatch duty and one for driving duty.

Procedure of test: (*Diagram of setup can be found on page 6.*)

1. Find location for testing (Asphalt, dirt, gravel, etc.). Three locations will be required.
2. Indicate starting position for R/C car. Mark with tape/spray paint.
3. Measure straight out 25 feet using tape measure. Mark with tape/spray paint.
4. From the 25-foot location, measure 20 more feet straight out, this will be the 45-foot mark. Mark with tape/spray paint.
5. Place R/C car at starting point.
6. Run R/C car through each indication point.
7. Record time from 25-foot mark to 45-foot mark. Repeat this step 5 times.
8. Record data.
9. Repeat steps 1-8, for two total locations of different terrain.
10. Using data found, calculate the average time it took for R/C car to travel 20 feet.
11. Use the average time to find max velocity of the R/C car.

Safety/Risk requirements of test: Proper safety eye wear is required for this test. Unexpected failure of the vehicle could eject parts or rocks/particles could be launched.

Diagram of Test Setup:



Discussion:

During the testing some issues occurred. The first issue was the failure of the 3-D printed locker attached to the main gear of the transmission. This part failed and had to be reprinted and installed. After fixing that issue, a failure in the rear axle occurred, causing another delay in testing. Once repaired the testing took place and was completed without issue. The original test date was April 15th, but after finding some issues with the system the testing occurred on May 3rd. The test progressed as planned and the data was able to be recorded for later analysis.

Test # 2 – R/C Baja Car Acceleration
Summary:

During this test, the acceleration of the R/C Baja Car will be found. The acceleration of the vehicle can be calculated by finding the time it takes the car to reach max velocity. The results of Test #1 will be used for final velocity. The time will be recorded between the start point of an initial velocity of 0 ft/s^2 and the car traveling 25 feet. Using the distance, time, final velocity, and initial velocity the acceleration can be calculated using the following equation:

$$\text{Final Velocity} = dS/dt$$

$$\text{Acceleration} = dV/dt$$

When setting up the testing area, the R/C car will be given an acceleration distance of 25 feet. The time will be recorded from the start line to the 25-foot distance then recorded. As soon as the front wheels of the vehicle cross the tape the time of the trial stops, the total travelled distance will be measured out to be 25 feet. This data will then be recorded and used for acceleration calculations.

Scheduled date/time of testing: May 3rd, 2020 at 1:30 PM

Duration of testing: Approx. 1 hour.

Location of testing: Ellensburg, WA

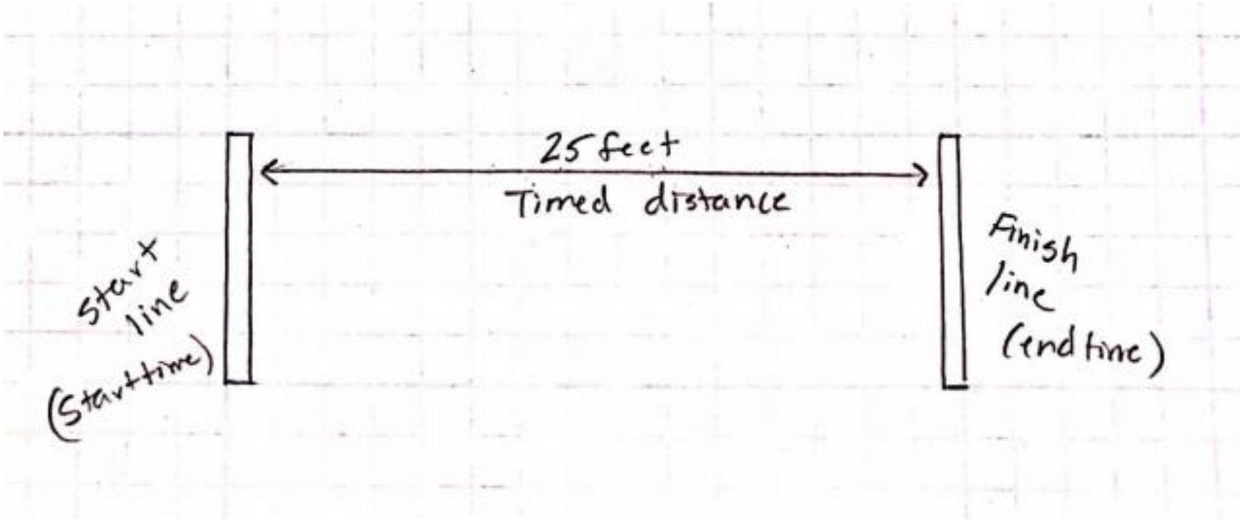
Required resources to complete test: Tape measure, stopwatch, tape or spray paint, and 60 feet of runway. 2 persons, one for stopwatch duty and one for driving duty.

Procedure of test: (*Diagram of setup can be found on page 8.*)

1. Find location for testing (Asphalt, dirt, gravel, etc.). Three locations will be required.
2. Indicate starting position for R/C car. Mark with tape/spray paint.
3. Measure straight out 25 feet using tape measure. Mark with tape/spray paint.
4. Place R/C car at starting point.
5. Run R/C car through each indication point.
6. Record time from start line to 25-foot mark. Repeat this step 5 times.
7. Record data.
8. Repeat steps 1-8, for two total locations of different terrain (Asphalt &Gravel).
9. Using data found, calculate the acceleration of the R/C for each trial.
10. Use the calculated acceleration to find average acceleration for each terrain.
11. Compare both terrains to predicted value.

Safety/Risk requirements of test: Proper safety eye wear is required for this test. Unexpected failure of the vehicle could eject parts or rocks/particles could be launched.

Diagram of Test Setup:



Discussion:

The delays in testing also occurred for this test. After resolved issues the testing went as planned and was completed on time. The data was record and later analyzed in Excel.

Test # 3 – R/C Baja Car Steering Angle
Summary:

During this test the steering angle of the R/C Baja car will be found. The setup of the test is the most important part of the test. The wheels need to be zeroed to the protractor before starting. After setting up and the measurements have been taken for each type of turn and compression, the data will be put into an excel worksheet. This data will show the average steering angle, and the behavior between the driver side and passenger side wheels.

Scheduled date/time of testing: May 3rd, 2020 at 2:30 PM

Duration of testing: Approx. 1 hour.

Location of testing: Ellensburg, WA

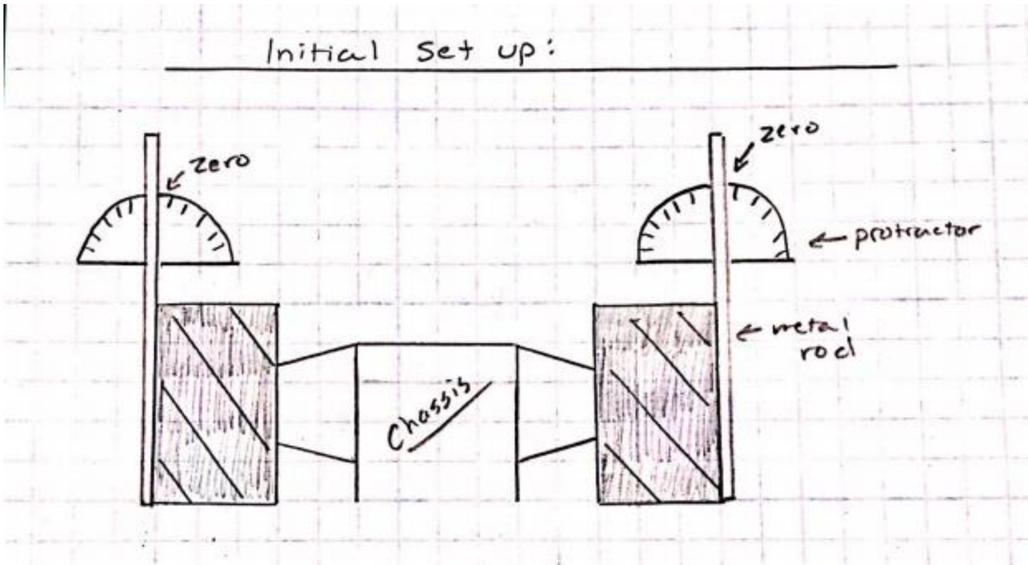
Required resources to complete test: Two protractors, 2 metal rod (2mm), tape, 2 persons; one to measure and one to operate the remote, item tall enough to stand R/C car on with wheels barely touching, and 5 lbs. weight.

Procedure of test: (*Diagram of setup can be found on page 2.*)

1. Find flat table to set car on.
2. Place R/C car on stand where wheels are barely touching table (uncompressed).
3. Line zero (90 degrees) on protractor to outside of wheels both left and right.
4. Tape metal rod to the outside of wheel, centered to the lug nut.
5. Measure angle degree when the wheels are straight, record.
6. Take measures at ¼, ½, ¾, and full lock for both right- and left-hand turn.
7. Record data.
8. Take car off stand and allow weight of chassis to compress suspension.
9. Repeat steps 5-7, record data.
10. Place 5lbs weight on front of car to fully compress suspension.
11. Repeat steps 5-7, record data.

Safety/Risk requirements of test: Proper safety eye wear is required for this test. Unexpected failure of the vehicle could eject parts.

Diagram of Test Setup:



Discussion:

An issue with this testing was getting the zero-set perfect to ensure accurate measurements. This issue was only time consuming and increased the time it took to complete the test. Once the data was record it was then put into an Excel worksheet and analyzed.

Deliverables

Once the testing was completed the data was entered in Excel worksheets to be able to compare the collected data and calculate the results of the test. All testing data can be found in Appendix G3. The calculated results were under the expected results, showing that improvement is needed to be made to the drivetrain and steering system. In the final velocity test, the average final velocity for gravel was 13.02 mph and the for asphalt 15.56 mph. This was under the requirement for final speed. Reasons for this result may be due to the losses within the system, such as, vehicle weight, friction between the tires and ground, any friction in the bearings, and the possibility that the ESC of the system may be lacking power. Tracing through the results, this reports that the motor was only turning at 10,000 rpms. The calculate rpm of the motor was to be near 38,000 rpm. Further research was put into the system, and the battery requirement for the ASME Baja Race, may not be efficient enough for this ESC. This could have caused the lack of power giving a much lower motor rpm and final velocity.

The acceleration of the vehicle resulted in 7.35 ft/s2 for gravel and 10.57 ft/s2 on asphalt. This was expected due to the lower final velocity and could be directly related to the losses in the system that effect the final speed. For the difference in the terrains it was expected to see a lower acceleration in the gravel. The R/C car tended to spin the rear tires and lack the capability of getting grip as instantly as on the asphalt. The asphalt result was used to come the error percentage to the requirement, the error percentage was 38.8%. Further research will go into the system to try and improve the vehicles performance.

During the steering angle test, the results were within a 9.5% error percentage. The result for average steering angle was 54.3 degrees both left and right. The results were still under the requirement, but the steering system was still functional and allowed the vehicle to turn swiftly and handle turns without understeer. While looking at the graphs that showed the comparison of both wheels, it was found that under compression the wheels will react almost identically. This shows that the steering system, will react the same whether turning right or left, giving a success in the design, the calculated results and graphs can be seen in Appendix G4.

After finishing the tests of the R/C Baja car it is apparent that more improvement to the drivetrain system and steering system could be made. Performance improvements that could be made would be in the velocity and acceleration. To improve the performance, the power to the motor would need to be checked and made sure the system was receiving the correct power. Beyond the power of the motor, gear ratios could be changed to reduce the torque and improve the final drive speed. Vehicle weight reduction would be the biggest target to start with, reducing the chassis plate thickness would help the vehicles final velocity and acceleration greatly. However, in success the vehicle is completely functional and could have competed in the ASME Baja Race. The final speed was lower than expected but the vehicle did obtain an impressive speed and acceleration. The vehicle also provided the proper steering and handling capability needed for the Slalom and Baja events.

Test Resources and Set-Up Check List

Carlton McDonald | MET 489c Test | 05/03/2020 | 1/1

Test #1

Materials needed:

- [X] Tape measure
- [X] Stop watch (Iphone)
- [X] Tape
- [X] Spray paint
- [X] R/C car
- [X] Remote Control

Set Up Process

- [X] clear any debris
- [X] mark start point
- [X] measure 25 feet / mark point
- [X] measure 20 feet / mark point
- [X] Set car on start
- [X] Test

→ [X] Asphalt [X] Gravel

Test #2

Materials needed:

- [X] same as test #1

Setup Process:

- [X] use test #1 setup → [X] Asphalt [X] Gravel

Test #3

Materials needed

- [X] Two Protractors
- [X] Two Metal rods
- [X] Tape
- [X] R/C car
- [X] Remote

Set up process

- [X] Set Protractors to outside of wheels
- [X] Tape rods to each wheel

→ [X] No load [X] Chassis [X] Full load

(Figure 1: Test Resources and Set-Up Check List.)

Appendix G2 – Blank Data Sheets

Test #1: Final Velocity after max RPM is reached.

	Terrain:	Gravel			
Btry Volt	Trial	Distance (feet)	Time (S)	Initial Velocity	Final Velocity
7.2	Requirement	20	0.68	0 ft/s	29.33
	Trial 1	20		0 ft/s	
	Trial 2	20		0 ft/s	
	Trial 3	20		0 ft/s	
	Trial 4	20		0 ft/s	
	Trial 5	20		0 ft/s	
				AVG Final	

	Terrain:	Asphalt			
Btry Volt	Trial	Distance (feet)	Time (S)	Initial Velocity	Final Velocity
7.2	Requirement	20	0.68	0 ft/s	29.33
	Trial 1	20		0 ft/s	
	Trial 2	20		0 ft/s	
	Trial 3	20		0 ft/s	
	Trial 4	20		0 ft/s	
	Trial 5	20		0 ft/s	
				AVG Final	

(Figure 2: Test #1 Blank Data Sheet.)

Test #2: Find Acceleration of R/C Car

		Terrain:	Gravel			
Bttry Volt	Trial	Initial V (ft/s)	Distance (ft)	Time (s)	Final V ((ft/s)	Acceleration (ft/s^2)
7.2	Requirement	0	25	1.71	29.33	17.2
	1	0	25			
	2	0	25			
	3	0	25			
					AVG Acceleration	

		Terrain:	Asphalt			
Bttry Volt	Trial	Initial V (ft/s)	Distance (ft)	Time (s)	Final V ((ft/s)	Acceleration (ft/s^2)
7.2	Requirement	0	25	1.71	29.33	17.2
	1		25			
	2		25			
	3		25			
					AVG Acceleration	

Use Average of Final Velocity found in Test # 1	
Assume constant acceleration due to electric turn motor	

(Figure 3: Test #2 Blank Data Sheet.)

Test #3: Turning Angle of R/C Baja Car Steering System

Predicted Steering Angle of Lead Wheel: 60 degrees		All units in degrees
Under No Load : Wheels barely making contact to surface		

Left Turn	*Lead Wheel*	*Follow Wheel*	Right Turn	*Follow Wheel*	*Lead Wheel*
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight			Straight		
1/4 Turn			1/4 Turn		
1/2 Turn			1/2 Turn		
3/4 Turn			3/4 Turn		
Full Lock			Full Lock		

Under Chassis Load : Weight of Chassis on Suspension

Left Turn	*Lead Wheel*	*Follow Wheel*	Right Turn	*Follow Wheel*	*Lead Wheel*
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight			Straight		
1/4 Turn			1/4 Turn		
1/2 Turn			1/2 Turn		
3/4 Turn			3/4 Turn		
Full Lock			Full Lock		

Under Full Load: Chassis Suspension is compressed

Left Turn	*Lead Wheel*	*Follow Wheel*	Right Turn	*Follow Wheel*	*Lead Wheel*
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight			Straight		
1/4 Turn			1/4 Turn		
1/2 Turn			1/2 Turn		
3/4 Turn			3/4 Turn		
Full Lock			Full Lock		

(Figure 4: Test #3 Blank Data Sheet.)

Appendix G3 – Raw Testing Data

Test #1: Final Velocity after max RPM is reached.

Terrain: Gravel

Btry Volt	Trial	Distance (feet)	Time (S)	Initial Velocity	Final Velocity
7.2	Requirement	20	0.68	0 ft/s	29.33
7.8	Trial 1	20	1.13	0 ft/s	17.70
7.8	Trial 2	20	0.99	0 ft/s	20.20
7.8	Trial 3	20	1.02	0 ft/s	19.61
7.8	Trial 4	20	1.15	0 ft/s	17.39
7.8	Trial 5	20	0.99	0 ft/s	20.20
				AVG Final	19.17

Terrain: Asphalt

Btry Volt	Trial	Distance (feet)	Time (S)	Initial Velocity	Final Velocity
7.2	Requirement	20	0.68	0 ft/s	29.33
8.32	Trial 1	20	0.85	0 ft/s	23.53
8.32	Trial 2	20	0.9	0 ft/s	22.22
8.32	Trial 3	20	0.88	0 ft/s	22.73
8.32	Trial 4	20	0.93	0 ft/s	21.51
8.32	Trial 5	20	0.83	0 ft/s	24.10
8.32	Trial 6	20	0.98	0 ft/s	20.41
				AVG Final	22.83

Equation used for Velocity: V = ds/dt

Conversions:
1 ft/s = 0.681818 mph

Terrain	Avg Final Velocity	
Requirement	20	*mph*
Gravel	13.07	*mph*
Asphalt	15.56	*mph*

Drivetrain System Efficiency

Terrain	MPH	100% Efficiency	Efficiency %
Gravel	13.07021887	54	24.20
Asphalt	15.56338374	54	28.82

(Figure 5: Test #1 Raw Data Sheet.)

Test #2: Find Acceleration of R/C Car

Terrain: Gravel

Btry Volt	Trial	Initial V (ft/s)	Distance (ft)	Time (s)	Final V ((ft/s)	Acceleration (ft/s^2)
7.2	Requirement	0	25	1.71	29.33	17.2
7.4	1	0	25	2.61	19.17	7.34
7.4	2	0	25	2.54	19.17	7.55
7.4	3	0	25	2.68	19.17	7.15
					AVG Acceleration	7.35

Terrain: Asphalt

Btry Volt	Trial	Initial V (ft/s)	Distance (ft)	Time (s)	Final V ((ft/s)	Acceleration (ft/s^2)
7.2	Requirement	0	25	1.71	29.33	17.2
8.32	1	0	25	2.19	22.83	10.42
8.32	2	0	25	2.05	22.83	11.13
8.32	3	0	25	2.25	22.83	10.15
					AVG Acceleration	10.57

Use Average of Final Velocity found in Test # 1
Assume constant acceleration due to electric turn motor

Terrain	Avg Accel
Predicted	17.2
Gravel	7.35
Asphalt	10.57

(Figure 6: Test #2 Raw Data Sheet.)

Test #3: Turning Angle of R/C Baja Car Steering System

Predicted Steering Angle of Lead Wheel: 60 degrees		All units in degrees
Under No Load : Wheels barely making contact to surface		

Left Turn	Lead Wheel	Follow Wheel	Right Turn	Follow Wheel	Lead Wheel
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight	-2	2	Straight	2	-2
1/4 Turn	17	27	1/4 Turn	26	21
1/2 Turn	30	50	1/2 Turn	37	34
3/4 Turn	40	55	3/4 Turn	47	44
Full Lock	44	57	Full Lock	60	62

Under Chassis Load : Weight of Chassis on Suspension

Left Turn	Lead Wheel	Follow Wheel	Right Turn	Follow Wheel	Lead Wheel
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight	2	-2	Straight	-2	2
1/4 Turn	18	19	1/4 Turn	20	22
1/2 Turn	27	40	1/2 Turn	39	38
3/4 Turn	40	55	3/4 Turn	49	44
Full Lock	48	62	Full Lock	58	50

Under Full Load: Chassis Suspension is compressed

Left Turn	Lead Wheel	Follow Wheel	Right Turn	Follow Wheel	Lead Wheel
Remote Turn	DS Wheel Angle	PS Wheel Angle	Remote Turn	DS Wheel Angle	PS Wheel Angle
Straight	4	-4	Straight	-4	4
1/4 Turn	12	5	1/4 Turn	10	15
1/2 Turn	25	20	1/2 Turn	31	32
3/4 Turn	40	39	3/4 Turn	43	41
Full Lock	55	64	Full Lock	50	48

	Average	Average	Average	Average	
Load Type	DS Wheel Angle	PS Wheel Angle	Left Turn	Right Turn	Avg Per Loading
No Load	52	59.5	50.5	61	55.75
Chassis Load	53	56	55	54	54.5
Full Load	52.5	56	59.5	49	54.25
				Total Avg Angle	54.83333333

(Figure 7: Test #3 Raw Data Sheet.)

Appendix G4 – Testing Results

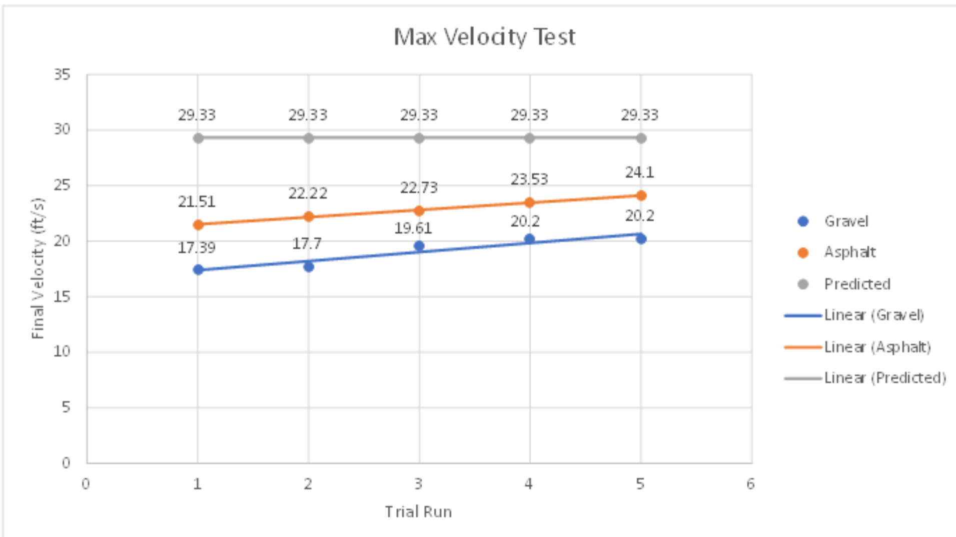
Equation used for Velocity: V = ds/dt

Conversions:
1 ft/s = 0.681818 mph

Drivetrain System Efficiency

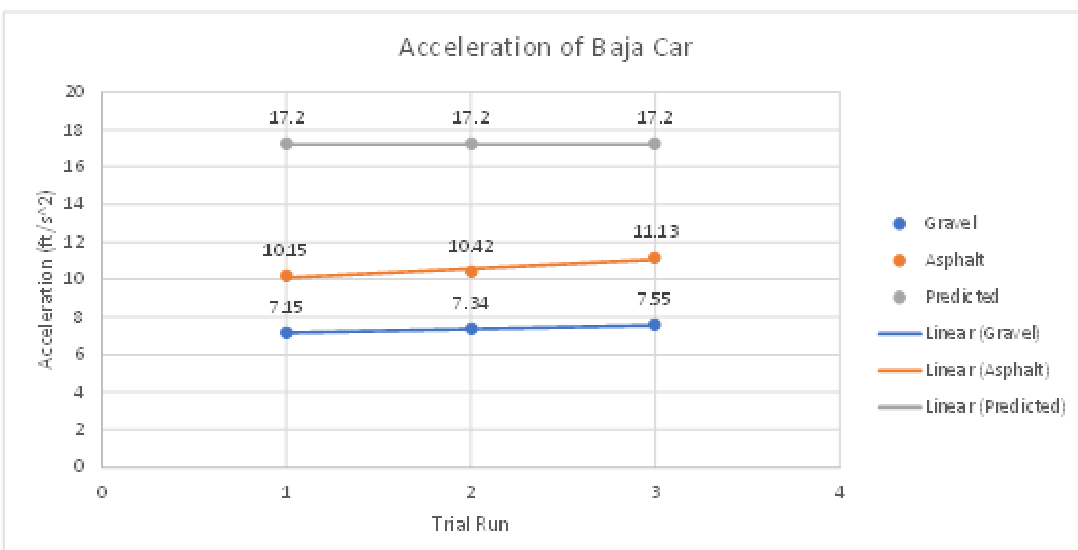
Terrain	Avg Final Velocity	
Requirement	20	*mph*
Gravel	13.07	*mph*
Asphalt	15.56	*mph*

Terrain	MPH	100% Efficiency	Efficiency %
Gravel	13.07021887	54	24.20
Asphalt	15.56338374	54	28.82



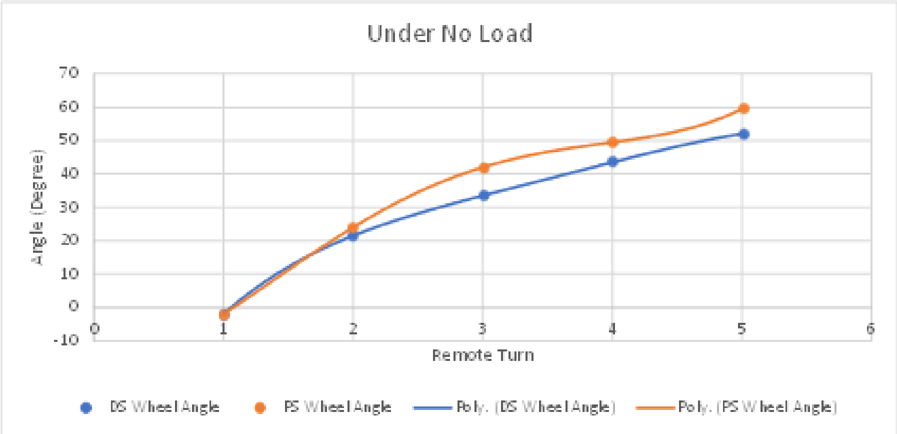
(Figure 8: Test #1 Results and Graph.)

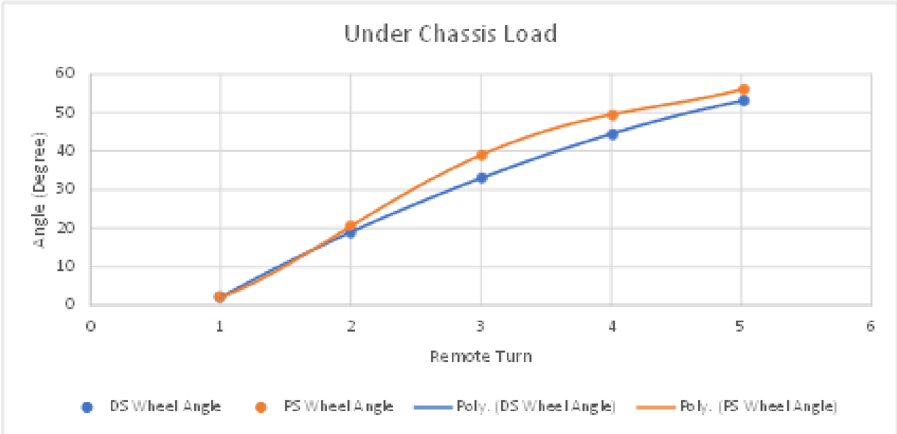
Terrain	Avg Accel
Predicted	17.2
Gravel	7.35
Asphalt	10.57

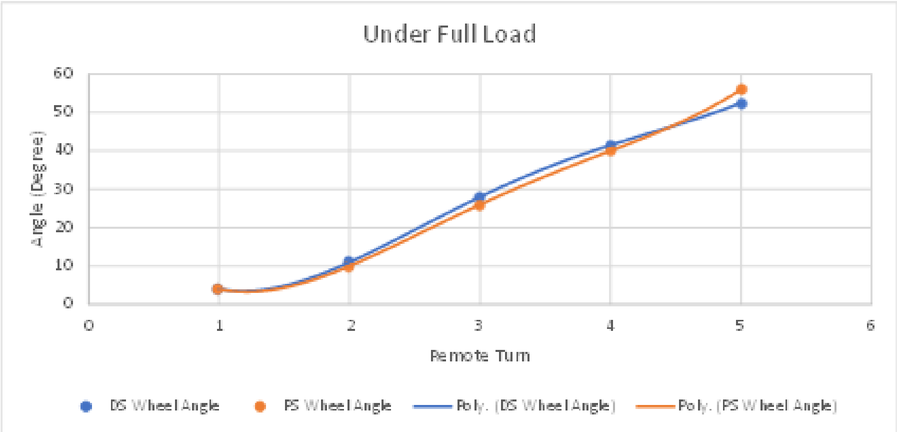


(Figure 9: Test #2 Results and Graph.)

Load Type	Average DS Wheel Angle	Average PS Wheel Angle	Average Left Turn	Average Right Turn	Avg Per Loading
No Load	52	59.5	50.5	61	55.75
Chassis Load	53	56	55	54	54.5
Full Load	52.5	56	59.5	49	54.25
				Total Avg Angle	54.83333333







(Figure 10: Test #3 Results and Graph.)

Appendix H - Resume

Carlton McDonald

2017 Meadowview Pl
Camano Island, Washington 98282
360-610-6990 Carltonmcd8@yahoo.com

OBJECTIVE: Design Engineer

EDUCATION: Bachelor's degree in mechanical engineering
Emphasis: Design/Three-Dimensional Modelling
Central Washington University Graduate
Cumulative GPA: 3.341

Related Courses:

- Metallurgy: Studied ferrous and nonferrous metals and alloys; polymeric, ceramic, and cellular materials; use of phase diagrams, cooling curves, stress-strain diagrams, and metallography.
- Three-Dimensional Modeling: Studied the design of parts, assemblies, and working drawings using 3-D solid modeling software, basic theory of threaded fasteners and gears, wielding representation, geometric dimensioning, and tolerancing.
- Basic Machining: Studied the basic operations and technical information concerning common metal working machines and metal machining processes.

EXPERIENCE:

Camano Island Masonry — Arlington, Washington
Mason Hot Carrier — June 2018 – Present

- Provide/Replenish the Mason with stone, mud, and needed supplies for the job at a quick pace.
- Set-up scaffolding and large set-ups for jobs.
- Use problem solving skills to help Mason finish job/make finished work look good.

NASCAR Late Model Team — Monroe, Washington
Mechanic/Tire Guy — June 2016 – Sept 2018

- Worked in fast pace environment with strong emphasis on quick decision making and use of knowledge.
- Worked on suspension tuning, engine maintenance, rear end maintenance, and tire set-up.
- Developed aluminum building skills, when building parts or replacing parts during post-race maintenance.

OTHER ACTIVITIES:

- Hands on experience in modifying vehicles with aftermarket parts.
- Restoration of old classic vehicles back to spec/factory state.

Appendix J – Hazard/Safety

OPERATION/MANUFACTURING HAZARD ANALYSIS
R/C Mini Baja Car

Prepared by: Carlton McDonald	Reviewed by:

Location of Task:	R/C Mini Baja Car Drivetrain and Steering
Required Equipment / Training for Task:	Ability to operate a miniature moving vehicle. Understanding of DC power supply. Understanding of mechanical procedures. Knowledge of basic machining skills.
Reference Materials as appropriate:	ETSC Safety Policy: https://www.cwu.edu/engineering/department-engineering-technologies-safety-and-construction-etsc-safety-committee https://ehs.berkeley.edu/job-safety-analysis-jsas-listed-topic

Personal Protective Equipment (PPE) Required (Check the box for required PPE and list any additional/specific PPE to be used in “Controls” section)						
Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
☒	☐	☒	☐	☒	☐	☐
Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.						

TASK DESCRIPTION	HAZARDS	CONTROLS
Operation:		
Operation/handling of power supply and wiring.	Electrical Shock	1. Before unplugging wires, make sure the power switch is set to off. 2. Do not connect the negative (black) and positive (red) wires of the battery together.
Operate in appropriate weather.	Corrosion/Failure of R/C Car.	1. Failure to keep dry, may cause the explosion of the lithium battery. 2. Corrosion may occur if water remains on the chassis components.

Handling/removal of the drive or differential gears.	Injury to self. (Hands, toes and other body parts.)	1. Make sure the car's power is disconnected, to prevent the possibility of the gears rotating. 2. DO NOT place your fingers or other body parts near the gears while motor is operating.
Manufacturing:		
Band Saw.	.	
1. Check condition of blade. 2. Align materials flat on table. 3. Adjust guard to no more than ¼ inch above top of material. **4.** Start blower and saw.	Cutting fingers and hands. Pinching fingers or hands. Pinching fingers or hands. Cutting fingers and hands. Injuries from flying sawdust.	Avoid contact with the blade teeth. Keep fingers and hands away from pinch points. Avoid pinch points between guard and housing and between guard and material. Keep fingers and hands away from blade. Use push bar for smaller material. Wear safety glasses or face shield.
Required Training: 1. Proper operation of band saw.		**Required Personal Protective Equipment (PPE):** 1. Safety glasses or face shield.
Drill Press Operation		
1. Clean the table. 2. Load the vise. 3. Lock the table in place. 4. Load the bit. 5. Start the drill. 6. Feed the drill with the feed.	Eye injury from metal debris. Foot injury if the vise falls. Finger pinching while sliding the vise. Back strain. Hand injury from the bit. None foreseen. Injury caused by breaking the bit. Eye or skin damage from cutting oil. Hand injury from the exposed pulley near the feed handle.	Wear eye protection. Do not use compressed air. Don't let your fingers get under the vise, unless you are lifting it from table. Keep your eyes on task. Don't lean over the table to twist lock handle. Wear gloves. Don't hold on the end of the bit. Feed with the appropriate pressure. Use the appropriate bit for the type of metal. Wear eye protection. Wear long sleeved shirt. Use lowest RPM. Make sure pulley guard is in place.

7. Unload the vise.	Foot injury is the vise falls. Finger pinching while sliding vise.	Leave the vise secure on the table with T-pins until unloaded. Keep eyes on your task.
Required Training: 1. Operation of drill press. 2. First aid.		**Required Personal Protective Equipment (PPE):** 1. Gloves. 2. Eye protection.
3D Printing		
1. During Printing. 2. Removal of printed part.	Injury due to touching of nozzle tip temperature. Injury due to poor removal of part from platform bed. Cut or eye damage due to sharp/rough edges and small plastic pieces while removing support material on part. Injury due to platform bed temperatures.	Wear leather gloves and stay away from nozzle head as the printer prints. Use proper tooling removal of part following the tutorial training. Wear safety glasses and avoid handling rough edges.
Required Training: 1. Operation of 3D-printer		**Required Personal Protective Equipment (PPE):** 1. Leather gloves. 2. Safety glasses.