Baja 4WD subsystem report

Tyler Trebilcock, Paolo Quattrociocchi, Preston Berchtold, Jehad Alqubaisi

Disclaimer

Executive Summary

Through this project design, Baja SAE is delivering a complete design of a four-wheel-drive system(4WD) of a small off-road vehicle. This device is created as a guidance reference for the capstone team to fulfill the 2020 new rulebook of the Baja SAE competition to have a 4WD system in their car. The team's client for this project was Dr. Sarah Omen and the spring 2020 mechanical engineering capstone team. The team target was to achieve all the clients' requirements within the best deliverables and budget. This report defines and examines the variety of potential engineering solutions developed by the Baja SAE Drivetrain design team. The four-wheel-drive system design provided contains the following: differentials, gearbox, driveshaft, and hubs/axles. The most important goal of this design was to create a system that is lighter, stronger, and more compact than the current models available. During the design process of the project, multiple solutions were considered to transfer power to the wheels: chain reduction, gearbox/differential reduction, and just gearbox reduction. The final design solution was selected to be reducing the gearbox rotating. This selection would allow the gearbox to have a larger center at the center distance, which will increase the clearance to ensure that it does not interfere with the operation of the CVT. The cost analysis of the design estimated a total of $3,000.

Acknowledgements

Baja team would like to give special thanks to:

- Dr. Sarah Oman
- Dr. David Willy
- NAU Machine Shop
- Society of Automotive Engineers
- 2019 and 2020 Baja SAE Capstone team

Table of Contents

[Use your word processor to delete the following Table of Contents and insert a new TOC. Include front matter (except for the cover page), body of the report, and all appendices. The Table should include four levels of headings, e.g., down to 2.2.1.3, as illustrated below.]

Table of Contents

Table of Figures

Table of Tables

Figure 1: Baja SAE Vehicle

1 Introduction

1.1 Introduction

Baja SAE is a collegiate design competition where engineering students design and manufacture a small off-road vehicle that fulfills requirements outlined by the competition rules. The cars closely resemble UTVs and often changes in the industry are developed through competitive innovations. Designing an entire vehicle is an extensive process so each system of the car is divided into teams within the group. The sub-teams include a drive train, front end, rear end, and frame team. The 2020 rule book states that a four-wheel-drive car will earn bonus points in each competitive dynamic event. The rules also state that a four-wheel drive vehicle is mandatory for the 2021 competition. With these new rules, the workload of the project has significantly increased so the capstone Baja team is asking for some help with the drivetrain subsystem. The system should be capable of in house 3 axis CNC machining.

1.2 Competition and Client Needs

The overall need that was defined by the competition is to design and manufacture a Baja car. The car would be handled to be designed by our team and a capstone team. One of the 2020 Baja requirements is to have our-wheel-drive transition system (4WD); therefore, the client tasked our group to design the 4WD, while the capstone team will handle the rest of the Baja car. We are to put in mind to design a 4WD system that can be adjusted and fits with the other parts of the vehicle that the capstone is working on. The competition requires all vehicles to be powered by Intek Model 19 engine with only a ten-horsepower that would be donated by Briggs and Stratton Corporation, so we are to recall that when designing. Our system must be inexpensive as the engine price suggested by the competition for Briggs and Stratton to be L'232-0054 engine with a price of $628.00

1.3 Goals and Objectives

The biggest goal is to design a system that can be lighter, stronger, and more compact. The primary objectives are to use engineering knowledge and analysis to optimize performance and simplicity in design. The goals will be met by communicating effectively with the client(s), and maintaining a motivated team committed to producing quality work. Producing an effective design holds the same priority as the satisfaction of the client(s). Specific tasks will be assigned to different group members to keep the project organized. By analyzing current benchmark products, the team will be able to identify design factors critical to success and be able to omit those that are not necessary for the application. A philosophy of "less is more" with respect to the design is critical in meeting the client's weight reduction goals.

1.4. Project Scope

This project will deliver a complete drive train system that will be adaptable to different chassis layouts while being lighter than the current models available. The system will include a gear reducer, front, and rear differential, and the necessary shafting to deliver power from the engine to all four wheels as per the new competition requirements. The design will comply with all SAE Mini Baja rules and regulations and will be constructed with safety in mind.

1.5 Project Description

The primary need is to create a "4-wheel drive" for the SAE 2020 Baja Team. Therefore, objectives should be set to maintain expectations of performance. This new design should be lighter and smaller than the current system. This system should be easy to manufacture while maintaining a price range between 1000-1500 dollars including material cost only. If the design goal of manufacturing in house is met, there will not be any labor costs. The 4WD system should also be designed with compatibility in mind, for easy serviceability. The client(s) expect(s) the new vehicle design to be robust for terrain benchmarks. Therefore, the new system will be reliable and durable to maintain are objectives.

1.6 Original System

The original system as designed by the current Baja SAE team consists of a purchased locked front and rear differentials with a 3.7:1 ratio. The system has a 2:1 spur gear reducer that is driven by a CVT.

1.6.1 Original System Performance

The original system performs well because it was designed for a vehicle that produces 9 times the horsepower of a Baja SAE car. However, since the system is over designed it makes it heavy and decreases performance for this application.

1.6.2 Original System Deficiencies

The original system is very heavy and lacks modularity. Since it is purchased component designed specifically for a Yamaha UTV it only functions properly with specific vehicles. From an engineering standpoint, this system is not optimized for the competitive and lightweight application required by the SAE Mini Baja competition.

2 Background

2.1 Literature Review

The understanding of previous work on 4WD systems is very important while designing. To understand differentials the team looked at resources that talked about the important design parameter that must be met while creating a gear train. This included making sure the alignment of the gears is held correctly as well as selecting gear geometry that will ensure proper functionality and durability of the system. Several forms of literature were reviewed so that the team could better understand how to properly design without running into unforeseen issues down the road.

2.2 Engineering Standards & Codes

Standards are important for this project to ensure that all components and materials are of known origins and meet the expectations for their desired application. The areas where standards are important to this project are those for materials, fasteners, and design.

The gears used both for the reduction and the differentials will be designed using methods shown by the American Gear Manufacturing Association (AGMA). These have been shown to reliably calculate the safe working limits of various gear forms. The gears will be manufactured from AISI 8620 nickel-chromium-molybdenum steel. It is widely accepted for automotive gearing applications due to its strength, hardenability, and low distortion during heat treatment. Any shafting used to transmit power will be manufactured from AISI 4340 nickel-chromium-molybdenum steel. This steel is recognized in the automotive industry as being a first choice for high-strength torque transmission.

AISI 8620 Chemical Composition and Material Properties

Chemistry	Percentage	
Carbon	.18 - .23	
Chromium	.40 - .60	
Manganese	.70 - .90	
Molybdenum	.15 - .25	
Nickel	.40 - .70	
Phosphorous	.40 max	
Silicon	.20 - .35	
Sulphur	.40 max	
Tensile Strength (as rolled)	97000	psi
Yield Strength (as rolled)	57000	psi
Tensile Strength (58 RC)	181250	psi
Yield Strength (58 RC)	134250	psi

AISI 4340 Chemical Composition and Material Properties

Chemistry	Percentage	
Carbon	.38 - .43	
Chromium	.70 - .90	
Manganese	.60 - .80	
Molybdenum	.20 - .30	
Nickel	1.65 - 2.00	
Phosphorous	.40 max	
Silicon	.20 - .35	
Sulphur	.40 max	
Tensile Strength (as rolled)	178000	psi
Yield Strength (as rolled)	100000	psi

Fig 2. Material properties and standards [1]

All fasteners will be SAE Grade 8 standard fasteners. This ensures consistent strength and material properties for each component. Additionally, due to the standard sizes and thread pitches, these fasteners can be found at any hardware store in the United States. Typically, coarse threaded fasteners will be used for ease of assembly however fine threaded fasteners can be utilized where increased strength is desired. All SAE Grade 8 fasteners have a tensile strength of 150,000 psi and are fitted with standard hex heads that fit standard SAE imperial sockets and wrenches. All Grade 8 hex heads are marked with six radial lines.

2.3 Existing Designs

An important research tool that will assist in developing an effective four-wheel drive system will be to use the material learned throughout coursework at NAU. This includes principles of machine design, mechanics of materials, as well as the management skills learned in the D4P program. In addition, techniques and methods can be combined by analyzing the construction of previous Baja vehicles and all-terrain vehicles for consumer applications.

2.3.1 Design Research

The gearbox or transmission in many high-performance off-road vehicles are typically designed for permanent four-wheel drive. Meaning torque is always delivered to all wheels. They are also equipped with a differential built into the transmission in order to allow the front and rear axles to rotate at different speeds which gives a tighter turning radius. All gears in the transmission are case hardened with a helical tooth profile for smooth and quiet operation.

The design standard for differentials has been the tried and true, ring and pinion design. This setup is very strong, reliable, and operated very smoothly. The gears are case hardened and have a helical tooth profile like the gears in the transmission. The gears are held in a housing that is sealed for lubricating oil to ensure smooth operation and long life. Additionally, many performance differentials are equipped with a selectable lock-up function. When engaged, both output shafts to the wheels are locked and must rotate at the same speed. This means that when one wheel has poor traction, the remaining drive is not wasted on driving that wheel. Instead it is always split evenly to keep the vehicle moving forward if one wheel is in contact with the ground. This also can put extra strain on the drivetrain which means that all axles and shafts must be strengthened to account for this.

2.3.2 System Level

2.3.2.1 Existing Design #1 Gearbox

Previous teams have used purchased gearboxes from UTV's as well as created custom gearboxes in house at the NAU Machine Shop. While the purchased system saves a significant amount of time from manufacturing, it is also not suitable for the needs of the competition. It is difficult to build the drivetrain around a component that is not meant for the specific application. Due to the weight and fact that the gear reduction is pre-determined, this is not an ideal option. The 2019 NAU team designed their own gearbox, which is like the goal for this upcoming competition, however improvements can be made to optimize the design. Overall, the design was reliable, but was heavy and difficult to assemble. It is likely that they used very conservative safety factors which resulted in large face widths for their gears.

2.3.2.2 Existing Design #2 Differential

There has been almost no work done by previous NAU Baja teams for differentials because it has never been required by competition to have a four-wheel drive system. Other than concept generation, there has not been a differential implemented in an NAU Baja vehicle.

2.3.2.3 Existing Design #3 Torque Transmission

Most teams utilize standard AISI 4130 or 4340 shafting due to its widely accepted reputation for automotive applications. Some schools have attempted constructing theses shafts out of hollow carbon fiber but have not had good results to the high shock nature of the competition. Alloy steel shafting tends to have exceptionally high strength characteristics as well as good ductility to absorb much of the shock loading on drivetrain components. Titanium has also been experimented with due to its outstanding strength-weight ratio however it is expensive in both material and machining time.

2.3.3 Subsystem Level

Subsystem breakdown consists of the following components: differential, gearbox, driveshafts, and hubs/axles.

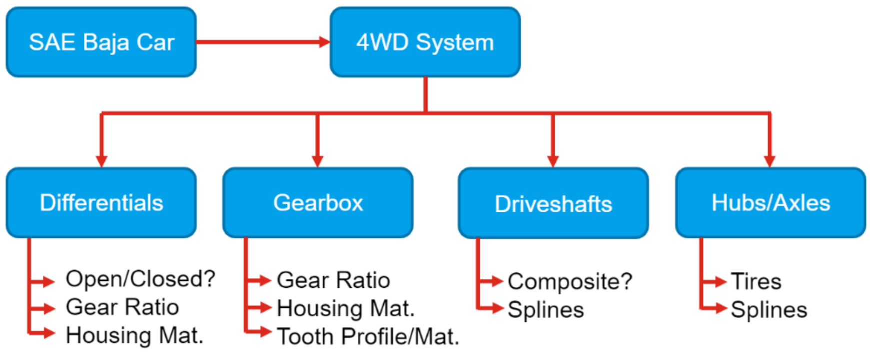

Fig 3. System Decomposition

2.3.3.1 Subsystem #1

Spur reduction gear box that transmits power from the CVT to the differentials.

2.3.3.1.1 Existing Design #1

A 2:1 spur gear reduction system manufactured in house. The reduction happens between the CVT and the differentials.

2.3.3.2 Subsystem #2

A differential system that can transmit power between two intersecting axes. This will be the final gear box within the drivetrain system.

2.3.3.2.1 Existing Design #1

The current system is a differential that is fully locked with a 3.7:1 gear ratio

2.3.3.3 Subsystem #3

Drive line shafts and half-shafts, these will transmit power from CVT to the spur gear reduction box. They will also transmit power from the gear reducer to the differentials.

2.3.3.3.1 Existing Design #1

The current system consists of a straight drive shaft that is flanged between the gear box and the differential. From the differential to the wheel hubs a constant velocity half shaft is used.

3 Design Requirements

The following table lists design requirements need and their respective basis of objectives to define if the requirement has been met.

Objectives	***Basis of Objectives***	***Units***
Light Weight	Lighter than previous system	Pounds [lbs]
Volume Consumed	Fit within chassis	Cubic Inches [in^3]
Strength	Gears should have infinite life	Yield Strength (KPSI)
Serviceability	10-minute removal time	Time (seconds)
Inexpensive	Unit manufacturing cost	Dollars [$]

Table 1: Design Requirements and metrics

3.1 Customer Requirements (CRs)

The following table lists the client requirements that will be introduced to the redesign of the 4WD system.

Client Criteria
Gear reduction to power four wheels
Light and durable
Easy mounting and integration
Meet all rule requirements

Table 2: Client needs

3.2 Engineering Requirements (ERs)

Table 3 lists the engineering requirements needed for the SAE Baja Car to perform within the competition, while also defining requirements needed for a redesign.

Engineering Requirement
Double gear reduction with shafts to transmit power to wheels
less than 15 pounds
Mounting holes
design covers to protect rotating parts

Table 3. Engineering requirements

3.3 Testing Procedures (TPs)

In order to ensure the design will meet all engineering requirements the design of our system will be modular. This way the system will have the ability to be mounted into several different chassis configurations. Once our system is manufactured it will be incorporated into the 2020 Baja car and tested over conditions like the ones seen in competition.

4 Designs Considered

Several designs were considered during the design stage of the project. To begin, three different designs were considered to deliver power to the wheels: chain reduction, gearbox/differential reduction, and just solely gearbox reduction. The final product chosen was to reduce power by the gearbox alone. The Pros and Cons of this design selection will be discussed, along with design criteria and benchmarking. It should be noted, all 4WD systems would be setup the same with two driveshafts (front and rear) that receive power from the gearbox or CCTV directly and would disperse power to the differentials to which disperses powers to the wheel.

4.1 Design #1: Chain Reduction

The use of chain reduction is widely known in use of bicycles and motor bikes and was a consideration within the project. The Baja Team discussed the alternative use of a chain to a gearbox for lighter weight, ease of manufacturing, and inexpensive costs. The cons of the design are its lack of reliability, strength, and ease of maintenance. Chains in this circumstance are prone to slipping teeth, link snapping, link cracking or chain derailing. A decision matrix was used to define the usability of the chain compared to a gearbox and to evaluate if the chain reduction was a valid alternative. The decision matrix concluded that the original gearbox method would be the most valid.

	Weight	Chain	Gear
Power Transmission to all 4 wheels	9	3	5
Maintain Turning Radius	3	3	3
Selectable Control	1	2	4
Lightweight	9	5	3
Easy Repair/Maintenance	3	2	4
Ease of Manufacturing	9	3	2
Reliability	3	2	5
Inexpensive	3	4	3
Balanced Speed to Torque Ratio	9	4	4
Machining Time	9	4	2
Strength	9	1	5
		215	238

Fig 4. Chain vs Gear decision matrix

4.2 Design #2: Gearbox and Differential Reduction

The Baja Team evaluated the chain reduction to not be valuable, therefore the team re-evaluated the original reduction method used by previous Capstone Baja Teams. This reduction method reduces gear ratios within the gearbox, but then reduces gear ratios again within the differential to gain optimal speed and torque. This design method was strong for previous Capstone Baja Teams due to only needing one differential in the rear; therefore, teams would divide the space needed for the gear reduction between both components to maximize volume available. With the new rule change, capstone teams continued the design to realize the same volume is not available in the front for the bigger differential. The pros of the design are the reliability and strength that come with two gear reductions. The cons of this design come with cost and time of manufacturing, large case volume, and the heavy weight. Optimizing this design for the Baja Team was an option by reducing case volume and weight with smaller gears, thinner case wall, and lighter materials with an increase to cost and manufacturing time.

4.3 Design #3: Gearbox Reduction

Lastly, the Baja Team considered the selected design, solely gearbox reduction. The design goals were to minimize case volume, weight, and machining time. By completing the full gear reduction in the gearbox, the spacing required to clear the CVT pulleys can be easily attained. Additionally, this allows for the differentials to utilize a 1:1 ratio, keeping them compact to avoid crowding in the front and rear of the vehicle where the braking system and driver’s feet are located. The gearbox is heavier and more expensive than a chain driven transmission but allows for an enclosed lubricating system to increase lifespan and reliability. Based on the analysis performed, this system is superior to both the chain and the combined gearbox and differential reduction.

5 Design Solution

5.1 Rationale for Design Selection

Based on the decision matrix and analysis, a gear driven full time 4WD system will be designed with a gearbox that contains the full reduction of 6.61:1 and a front and rear differential with no reduction. This will allow the gearbox to have a larger center to the center distance which will increase the amount of clearance to ensure that it does not interfere with the operation of the CVT. The gearbox and differentials will be machined out of aluminum at the NAU Engineering Fabrication Shop along with all necessary shafting. The spur gears will be EDM machined by a company in Phoenix, AZ. The motor will rotate a continuously variable transmission (CVT) that will be purchased off the shelf based on previous designs. A spur 6.61:1 gear reducer will be after the CVT. Once power is transmitted through the reducer, the 1:1 differential, located in front and rear of the vehicle, will then provide power to the wheels.

Final Design of Gearbox and Differential with Implemented Parameters

The design can be seen in appendix B. There is an isometric view as well as a sectioned view to see the internals of the box. There are also drawings in appendix C to give an idea of size of the system. Complete manufacturing drawing are not necessary since the machine shop will use the CAD files directly to CNC machine the housing.

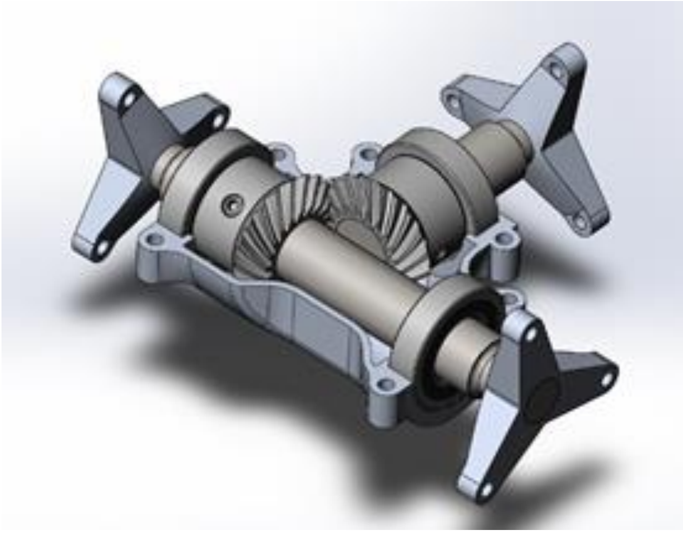

Fig 5. Final differential design using calculated parameters

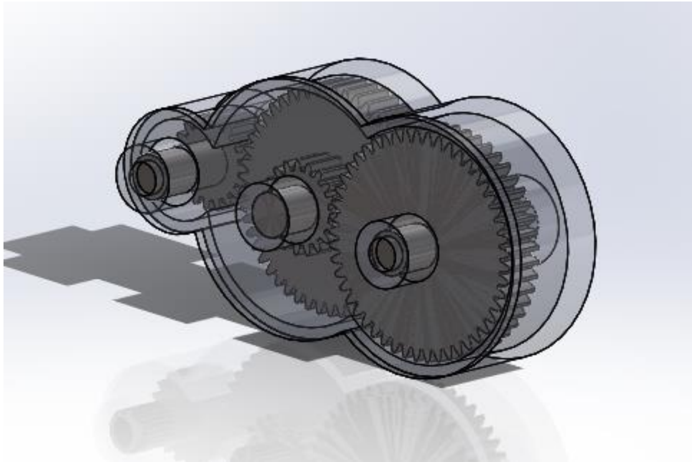

Fig 6. Gearbox CAD design

Preliminary calculations were done using Excel to get the basic variables needed to begin the design process.

Total Gear Reduction	6.611096	
ω(engine rpm)	3600	input
ω.(wheel rpm)	605.0434	
CVT Ratio Assumption*	0.9	input
Top Speed (mph) Assumption*	45	input
Wheel diameter (inches) Assumption*	25	input
Gearbox Ratio	6.61	
Final Drive Ratio	1	
Peak Hp (@ 3600 RPM)	10	
Peak Torque (ft*lb)	14.58889	
Torque After Reduction (ft*lb)	96.44854	
Torque @ wheel (ft.lb)	48.22427	
Wheel Force (lb)	46.2953	

Figure 7: Excel Calculations

Using the total gear reduction necessary for the design parameters and the minimum number of teeth allowable on the pinion gear without interference, the number of teeth on each gear was found as well as the pitch diameters which in turn yields the center to center distances.

In order to achieve the desired ratio, the driven gear would need to have 46 teeth. This led to an error in actual ratio of 1.2%. By changing the pinion to 19 teeth and thus, the driven gear to 49 teeth, an error of 0.7% was achieved.

5.2 Detailed Design Description

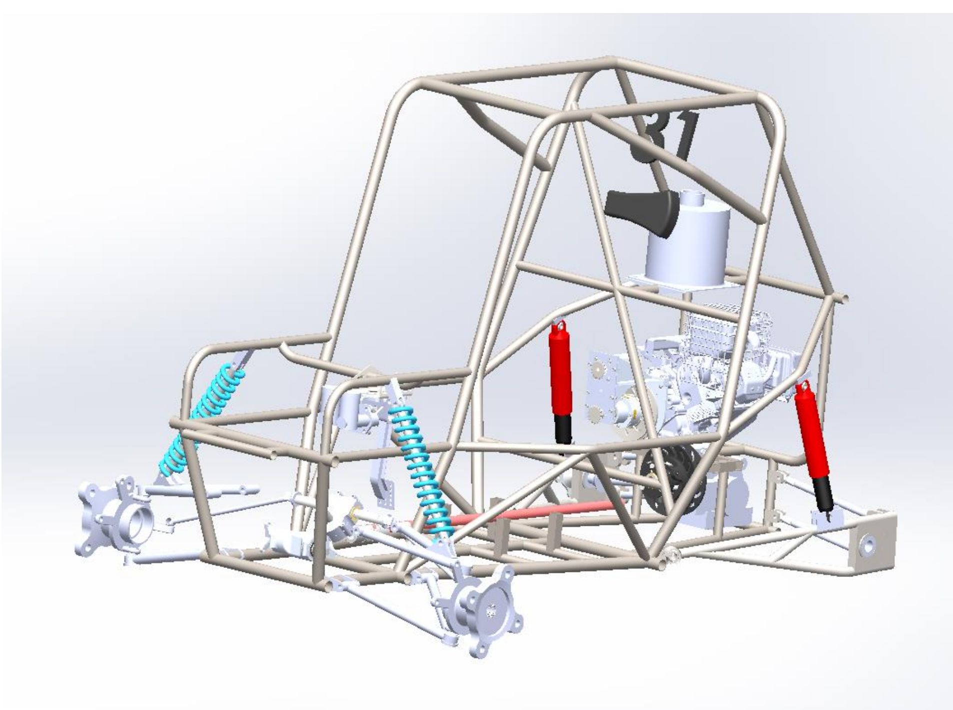

Fig 8. Cad model of drivetrain components with frame

6 Project Implementation

Project implementation will continue with the CAD models being implemented to other Capstone Baja Teams to adjust for fitment and alignment. Therefore, after CAD modeling fitment and adjustments have been made by Capstone Teams should continue with manufacturing. Fitment for the front differential should be focused on within teams to verify spacing meets requirement. The Gantt Chart (see appendix) visualizes the progress being made by the Baja Team along with the deliverables performed.

6.1 Deliverables

Major deliverables of this project included conducting extensive research on previous designs and investigate what has been accomplished through previous work. Another big deliverable was the development of CAD models. CAD helps engineers verify something will properly fit and function before investing money on a final design. The team created a full CAD package of the system and implemented it into a Baja chassis. Another major deliverable completed was the financial analysis. This deliverable helped the team identify how much the system will cost. The analysis also helped identify whether the design would be profitable for mass production.

6.2 Budget and Cost of Ownership

The result of the analysis shows the total cost of the component is $2698.39. The total manufacturing cost is $570. Some components can be manufactured at the NAU's engineering project workshop which significantly reduces costs and will save $500. The cost analysis of the system estimates a total of $2768,39. The estimated money value (TVM) analysis assuming to have a 10% interest rate is $3046.229 in one year. The budget provided by the client was between $2500 and $3000 which means this project meets the required budget.

Table 4. Bill of Materials

Component	Quantity	Cost ($)
CVT	1	1000.00
Gearbox	1	119.00
Steering rack	1	95.00
Hub	4	115.43
Knuckles	2	139.94
Brake caliper	4	215.96
Brake disk	4	71.08
Drive Shaft	2	31.99

Steering column	1	79.99
Tires	4	312.00
Miscellaneous	….	500.00
Total cost	….	2698.39

Table 5. Manufacturing costs

Process	Cost ($)
Welding	120
Machining	100
Tube bending	50
Composite Body Layup	200
Painting	100
Total	570

6.3 Team Qualifications (MUST HAVE)

The following sections will define and explain qualifications from Tyler Trebilcock, Paolo Quattrociocchi, Jehad Alqubaisi, and Preston Berchtold. This section will also define the role each member played along with attributes that were brought to the team.

6.3.1 Existing Team

Tyler Trebilcock is the analytical engineer of the team and overlooks progression within the project. Tyler has a strong background knowledge with the SAE Baja Competition rules, manufacturing, and overall Baja Car design. Tyler also plays a significant part in analyzing materials, parts and construction of the project to help foresee any problems or errors.

Paolo Quattrociocchi is the team's manufacturing engineer. Paolo has a strong background knowledge in heavy machining, material selection, and manufacturing standards. Therefore, Paolo's expertise in manufacturing helps the team reduce costs while keeping the same strength and durability. Lastly, Paolo's knowledge in manufacturing standards help the team pick materials to uphold ASME and SAE standards.

Jehad Alqubaisi is one of the two design engineers within the Baja Team. Jehad has a strong background in research, organization, and idea development. He is a strong activist for new ideas and suggests new practices that could be taken. Jehad's knowledge within organization and research helped the team discover new ideas that were applicable to the project and organize it into useful data.

Preston Berchtold is the second design engineer within the Baja Team. Preston has background knowledge in project management, general car mechanics, and organization. Preston's background helped the team format reports and presentations to professional standards. Preston also was helpful in organizing useful data into models or indices for the team to access later, while also communicating with the team to stay on track and within deadlines

6.3.2 Additional Desired Team Members

Inclusion of a true certified SAE engineer would be helpful in promoting SAE ideas and developments throughout the project. For this project within EGR386w, a fifth team member within the automotive industry would have provided good insight and an extra helping hand.

6.4 Conclusions and Future Work

Overall, the team created a functional 4WD system that can be incorporated into a Baja SAE vehicle. The design fulfilled all engineering requirements and after presenting the design to the client, Dr. Sarah Oman, she seemed impressed with the work that was completed. Moving forward the design is going to be implemented into a Baja car and used in competition. This will be the final step of this project.

References

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[2] SolidWorks 20018 installation manual SolidWorks Essentials Parts and Assemblies, 300 Baker Avenue, Concord, Massachusetts 01742 USA:SolidWorks Corporation.

Appendices

Appendix A

Design Requirements / Customer Requirements	Importance	Front & Rear Diff	Selectable 4WD/2WD	Lightweight	Small Case Volume	Minimize hardware	Machining Time	Gear Strength	Optimized Gear Ratio	Improvement Direction / Customer Competitive Assessment: 1 Worst (Spicer)	2 (Yamaha Rhino)	3 (UTV solutions GRB)	4 (TEAM)	5 Best
Power Transmission to all 4 wheels	9	9	3							9		9	9	
Maintain Turning Radius	3		9										9	
Selectable Control	1		9										3	
Lightweight	9	9		9	9	3						3		
Easy Repair/Maintenance	3	3			9	9				3		9		
Ease of Manufacturing	9	3				9	9	3				9	9	
Reliability	3		3					9		9				
Inexpensive	3		3	3	1	1	9							
Balanced Speed to Torque Ratio	9	9							9	9			9	
Technical Importance: Absolute		279	81	90	111	138	108	54	81					
Technical Importance: Relative		30%	9%	10%	12%	15%	11%	6%	9%					
Target Value		95%	Selectable 4WD/2WD	8	6Lx3Hx3W	5	8	1200	7.6:1					
USL		100%		12	8Lx5Hx4W	8	12	1600	8:01					
LSL		70%		6	5Lx3Hx2W	3	4	800	7:01					
Units		efficiency	on or off	lbf	in	# of bolts	hours	Wt=lbf	Ratio					
Design Competitive Assessment	Worst: 1	*					*	*						
	2	*	*				*	*						
	3	*			*	*		*						
	4	*	*				*	*						
	Best: 5	*		*	*	*			*					

Appendix B

Gear_calulator.m

```
S= input('Safe Material Stress (PSI): ')

F= input('Enter Face Width (in): ')

Y= input('Tooth form factor: ')

P= input('Diametral Pitch: ')

D= input('Pitch Diameter (in):  ')

RPM= input('RPM:   ')

V= .262 * D * RPM


W= ((S*F*Y)/(P))*(600/(600+V))*.75

T = (W * D)/2

fprintf('Acceptable Torque(ft*lbs): %0.0f\n',T/12);
```

Appendix C

TASK	START	END
Progress Report	8-Mar-20	13-Mar-20
Gear Ratio Analysis	8-Mar-20	13-Mar-20
Housing and Material Selection	13-Mar-20	20-Mar-20
Solid Works Models	20-Mar-20	30-Mar-20
Economic Analysis	30-Mar-20	6-Apr-20
Final Proposal	6-Apr-20	30-Apr-20