SAE MINI BAJA
FRAME & DRIVETRAIN

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Drivetrain: Tye Jorgenson
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SAE INTERNATIONAL®

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Project Description

General:

- Design and build a single-seat, all-terrain vehicle to compete in the SAE Baja Collegiate Competition
- Entire vehicle built within the limits of the official rulebook
- Performance measured by success in the static and dynamic events at competition in April
- Static Events: Cost Analysis/Product Marketing, Design Analysis, Technical Inspection
- Dynamic Events: Acceleration, Maneuverability, Hill Climb, S&T Evaluation, Endurance Race

Frame:

- Cage designed and fabricated to withstand impacts during normal operation, collision, or roll over
- Interfaces with all other sub-teams
- All welding done in-house

Drivetrain:

- Responsible for transmitting engine power to vehicle propulsion
- Up to 150 bonus points for operational 4WD/AWD system

Figure 1: 2018-19 NAU Baja

Prototype and CAD Package

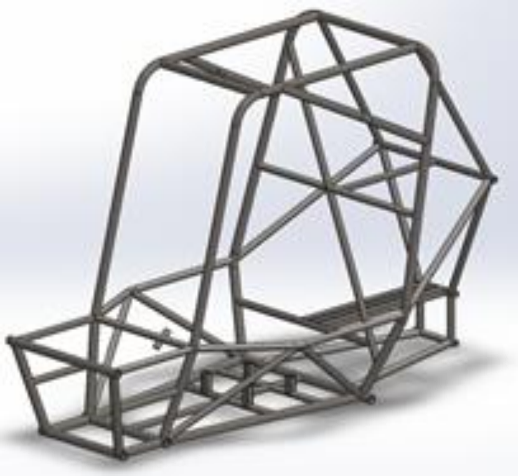


Figure 2: Frame Isometric View

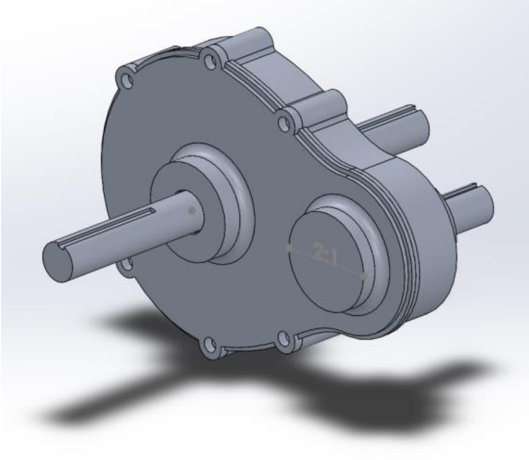


Figure 4: Gearbox Isometric View

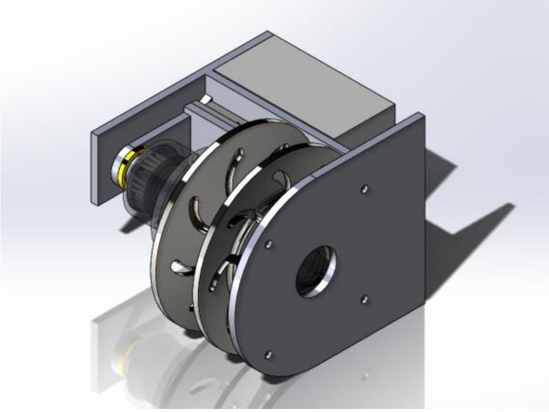


Figure 6: ECVT Isometric View

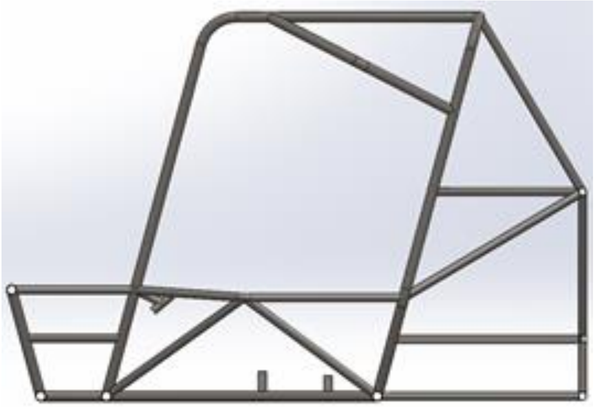


Figure 3: Frame Side View

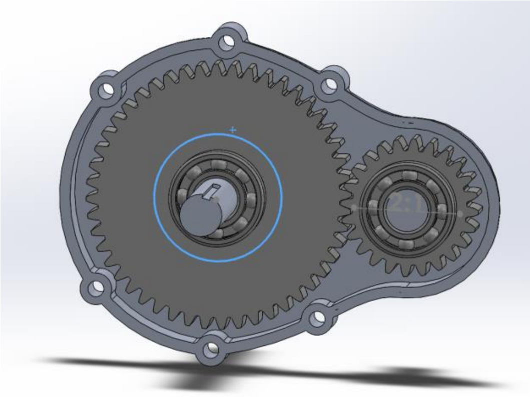


Figure 5: Gearbox Open View

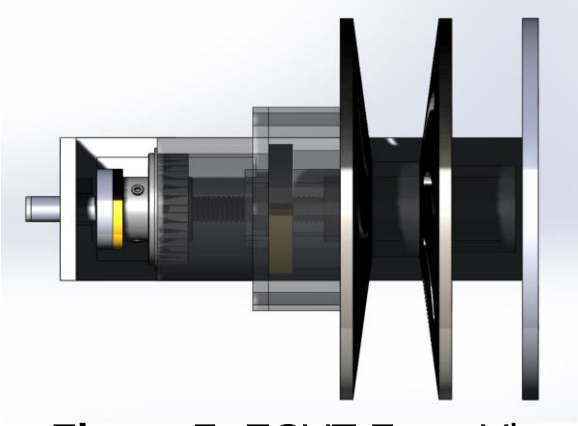


Figure 7: ECVT Front View

Overall Design CAD

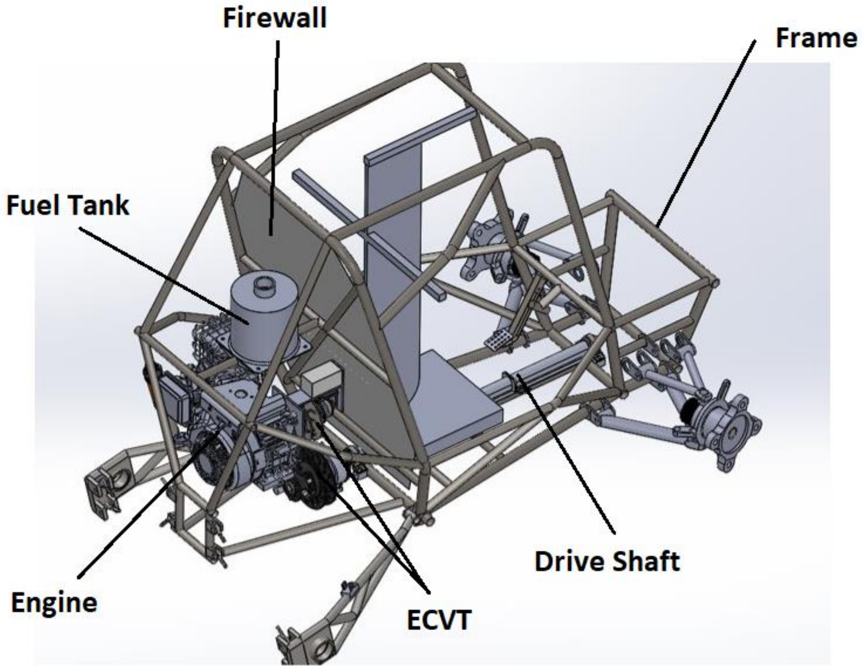


Figure 7: Assembly Isometric View

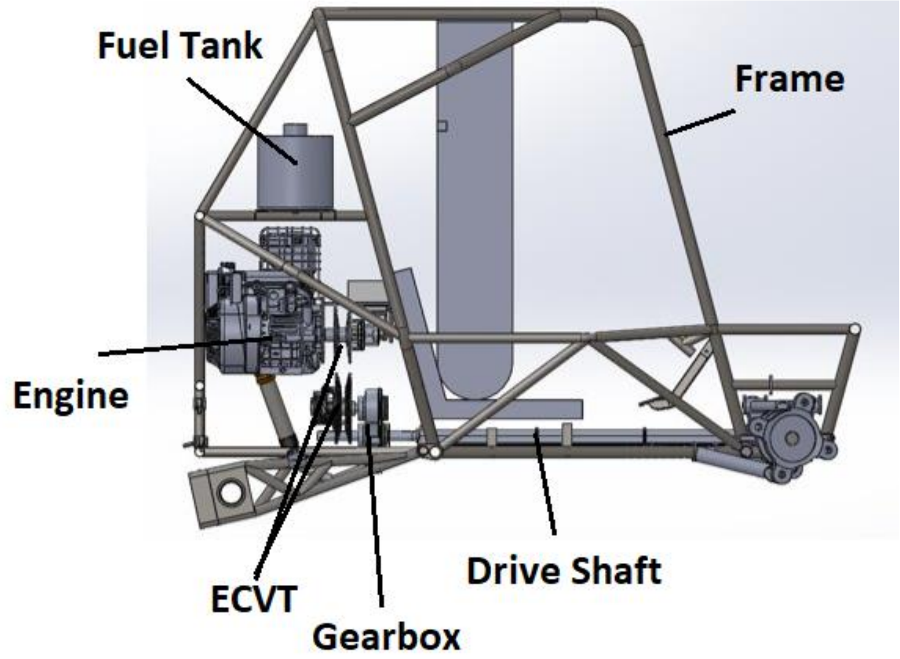


Figure 8: Assembly Side View

Drivetrain
- Engine > ECVT > Gearbox > Differential (Not Pictured)

Frame
- Support Driver, Front/Rear End Suspension, Drivetrain

Design Description: Drivetrain and Frame

ECVT
- Allows the vehicle to change gear ratios from a 4:1 to 1:1 manually and automatically
- Gear ratio controlled by stepper motor connected to a threaded rod
- User selectable modes for different events and automatic mode for ease of use

Gear Reducer
- Allows for a 2:1 gear reduction after the ECVT going to the front and rear differentials
- Allows for more torque to be transmitted with a lower power loss

Differentials
- Directs the power perpendicular to the driveshaft
- Final gear reduction of 3.67:1 giving the vehicle a final reduction of 7.34:1 to 29.36:1
- Allows for electronic control between 4wd and 2wd

Frame
- Supports all subcomponents of the buggy
- Protects driver in case of rollover or collision with another teams

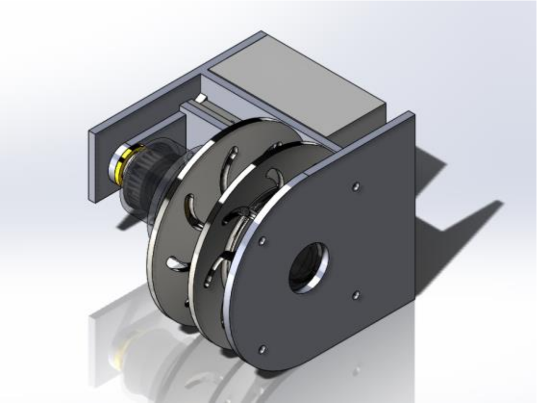


Figure 10: ECVT

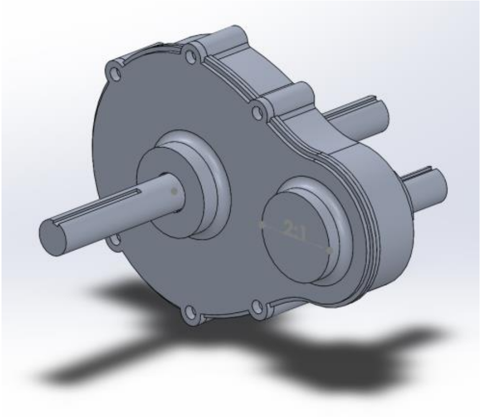


Figure 11: Transfer Case

Figure 12: Differential [1]

Current State: Drivetrain and Frame

ECVT

- Electrical Components have been ordered
- Hardware BOM is being finalized
- Currently validating material
- Machining will start before December

Gear Reducer

- 2:1 Gear Reducer final design concept
- Gear validation finalized
- Initial BOM built
- In progress of gear case validation

Differentials

- Front and Rear Differentials Selected
- 3.67:1 differential ratio selected
- Differentials just ordered (11/5)

Frame

- Finalized main structure
- Front and rear end adjustments will be necessary
- Initial vendor search for manufacturing

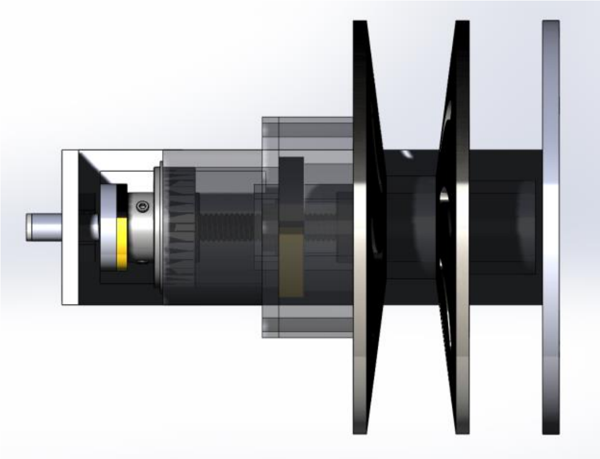


Figure 13: ECVT

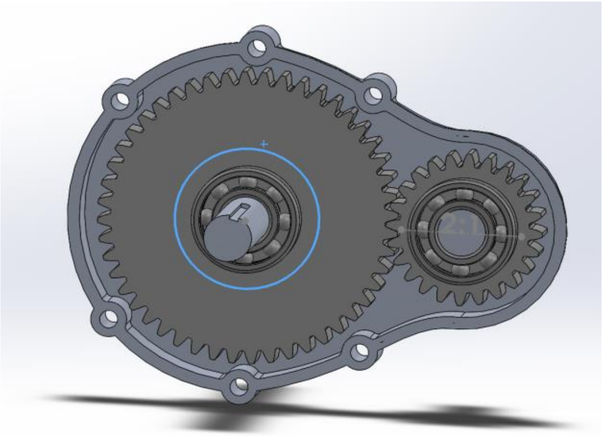


Figure 14: Transfer Case

Design Requirements (CRs)

Figure 15: 2019 California Competition Hill Climb

Customer Requirements

- Reliability
- Durability
- Low Weight
- Withstand Impact
- Ergonomic Cockpit
- High Torque Output
- High Power Output
- Operational Safety
- Low Center of Mass

Design Elements from CRs

- Factors of Safety; Strong Materials; FMEA *(Reliability; Durability; Withstand Impact; Operational Safety)*
- Minimal Factor of Safety (1.3-1.5) **[2]** *(Low Weight)*
- Inclined Firewall; Low SIMs; Design Geometry *(Ergonomic Cockpit; Low Center of Mass)*
- ECVT; Differential; Transfer Case *(High Torque Output; High Power Output)*

Design Requirements (Visual Representation)

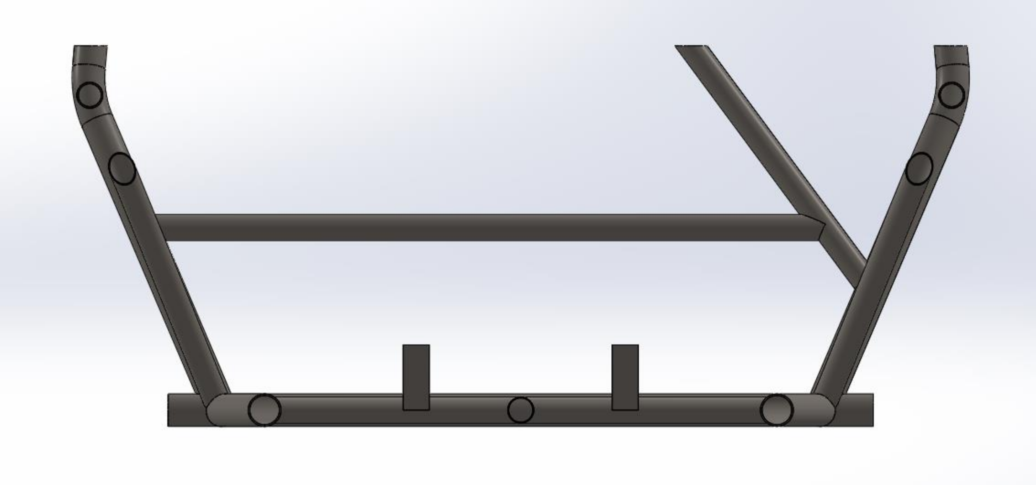


Figure 16: Section View of Frame

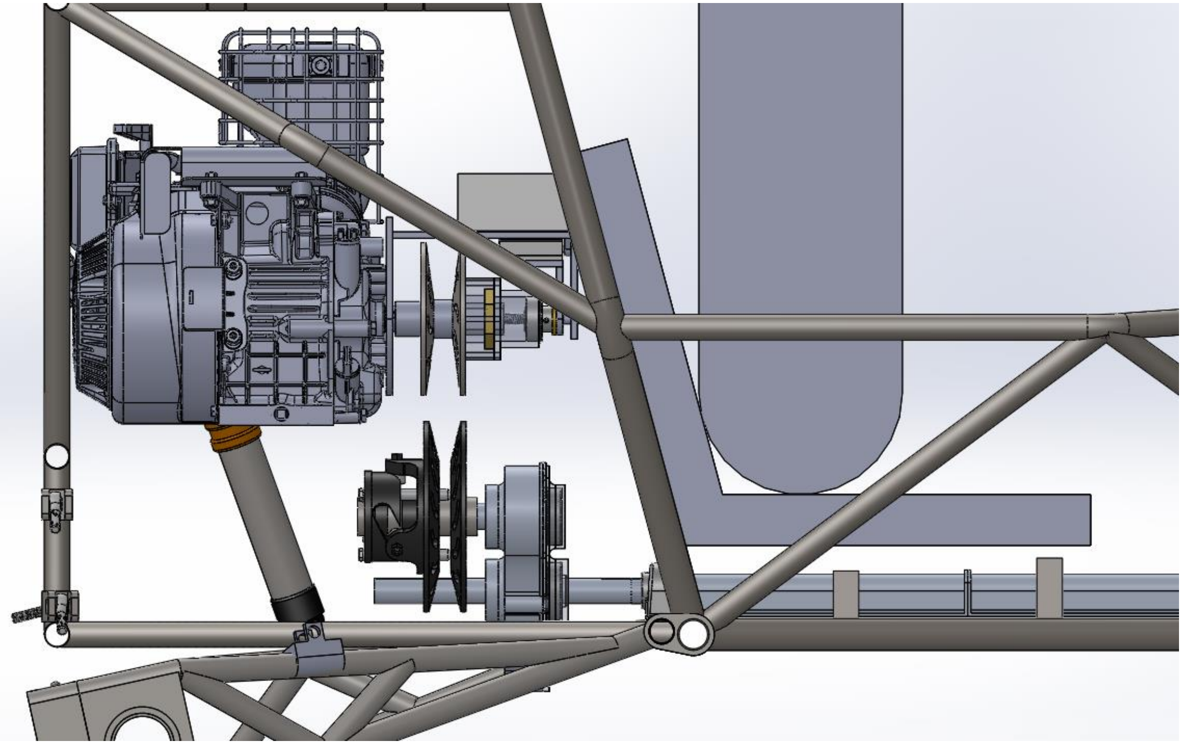


Figure 17: Spatial Location of Drive Train Components

Design Requirements (Analytical Analyses)

Table 1: Drive Shaft Torsion Analysis

Torque applied (lb*in)	2016
Major diameter (in)	1
Minor diameter (in)	0.93
Major radius (in)	0.5
Polar moment of inertia (in^4)	0.024735
Stress Experienced (lb/in^2)	40752.08
Yeild Stress (lb/in^2)	63100

Table 2: Frame Material Analysis

	Minimum Tubing	Primary Tubing	
material	1018 steel	4130 steel	
OD (in)	1	1.25	
Wall thickness (in)	0.12	0.065	
carbon content (%)	0.18	0.3	
E (kpsi)	29700	29700	
I (in^4)	0.032710765	0.042602298	
k_b (klb * in^2)	971.5097313	1265.288253	293.7785
S_y (kpsi)	52.9388	63.1	
c (in)	0.5	0.625	
S_b (klb*in)	3.463337331	4.301128015	0.837791
density (lb/in^3)	0.284	0.284	
weight per foot (lb)	1.130611444	0.824671841	-0.30594

Table 3: Gear Analysis

Bending factor of safety	SF	3.49	4.00
	(SH)^2	1.91	1.97
Wear factor of safety	SH	1.38	1.40

Circular pitch	p	0.393	in
tooth thickness	t	0.196	in
Length Check:			
Total Length	L	9	in
c-c	c	4.5	in
interference check:	We Good		
Pinion Teeth	24		
Equation Check	16.94181163		

Design Validation

Failure Mode and Effects Analysis

Frame
- Highest Risk Priority Number (RPN) is weld joint failure due to high stress concentration
- We decided to use an experienced welder that has done previous Baja welding

Drivetrain
- Highest RPN is ECVT failure due to electrical component failure
- We decided to use an Arduino for community support, modularity, and simplicity

Table 4: FMEA

Function	Potential Failure Mode	Potential Effect(s) of failure	Severity	Potential Cause(s)	Occurrence	Current design controls (prevention)	Current design controls (detection)	Detection	RPN
Frame Contain and protect driver while holding together all other subcomponents together	Weld Joint Fails	Members will become detached and frame will warp under normal loading. If any severe impact occurs, the frame will be severely damaged and endanger the driver or lead to accident.	9	Poor Welding	2	Quality control in the fabrication process, using a highly skilled welder	Visual inspection, test sample weld	2	36
				High Stress Concentration	6	Design to distribute loads evenly, strong materials and welds	Visual inspection	4	216
	Member Bends	Member becomes deformed leading to improper frame geometry. This could cause improper functioning of other components.	7	High Impact on Member	8	Build with strong materials and proper force distribution	Visual inspection	3	168
	Member Snaps	Member will become separate and frame will severely warp under normal loading. If any severe impact occurs, the frame will be severely damaged and endanger the driver or lead to accident.	10	High Tensile Stress on Member	1	Use strong materials and design proper load distribution	Visual inspection	6	60
Drive Train Provide propulsion for the Baja corresponding to driver input	ECVT fails	The Baja would not accelerate properly, it could lock up causing sudden braking and inoperability	7	Electrical Components Fail	4	Use quality electrical components and connections	System Testing	4	112
				Mechanical Parts Jam	3	Use of quality bearings and parts	System Testing and Visual Inspection	3	63
	Gear Reducer Fails	The Baja would not accelerate or could cause sudden braking and inoperability possibly leading to an accident	8	Gears Jam	4	Design and build quality casings and use of proper lubrication	System Testing	3	96
				Gears Break	2	Building with quality materials	System Testing	1	16
	Differentials Fail	The Baja would not accelerate or could cause sudden braking and inoperability possibly leading to an accident	8	Gears Jam	4	Design and build quality casings and use of proper lubrication	System Testing	3	96
				Gears Break	2	Building with quality materials	System Testing	1	16

Design Validation (Frame)

Torsional rigidity

- Widely used in the automotive industry
- Used FEA in SolidWorks to simulate a torsional rigidity test
- Deflection is less important in off road applications, but the stresses generated are very applicable

Design correction

- We were considering less side impact bracing to save weight
- This test demonstrated that we should keep the extra bracing

Physical Testing

- When we have the frame fabricated, we can physically test this to validate our FEA
- This can be done in the machine shop with some scrap metal

Procedure:

- Affix the rear end to a table or bench
- Slide a rod through the top nose member
- Support one end while hanging a weight off the other end

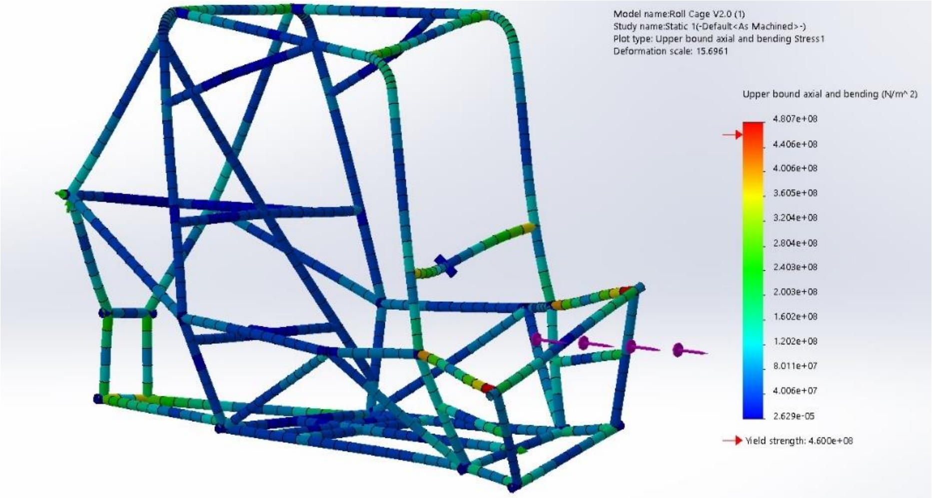


Figure 18: Torsional Rigidity FEA

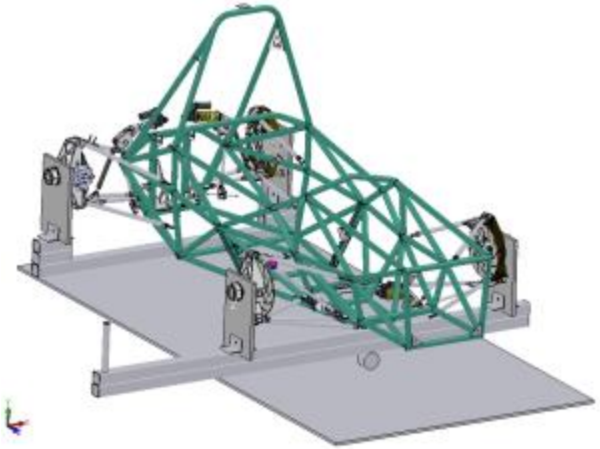


Figure 19: Physical Torsional Rigidity Test **[3]**

Design Validation (Drive Train)

Design correction

- Replace timing belt design
- Rationale: Volumetric Requirement, Similar Weight

Gear Reducer Calculations

- Utilized Excel sheet from Shigley's Machine Design
- Must satisfy required transmitted load

Physical Testing

- Once the gear reducer is assembled, test torque output
- Engine dynamometer

Procedure:

- With the engine and ECVT on the dynamometer, run a test to determine efficiency loss in transmitted torque

Table 5: Gear Calculations

		Pinion	Gear	
Number of Teeth		24	48	teeth
Diametral Pitch		10	10	TPI
Transmitted Load		200	200	lbf
Pitch-line velocity		3800	3800	ft/min
Material		Through-hardened G1	Through-hardened G1	
Brinell hardness		250	250	HB
User-specified bending stress		0	0	ksi
User-specified contact stress		0	0	ksi
Quality number		7	7	
Overload Power/driven		Uniform-uniform	Uniform-uniform	
Face width		1.25	1.25	in
Centered?		TRUE	TRUE	
Adjusted?		FALSE	FALSE	
Condition		Commercial	Commercial	
Fatigue model		250 HB	250 HB	
Load cycles		1.00E+09	5.00E+08	
Reliability		95	95	
Bending factor of safety	SF	3.49	4.00	
	(SH)^2	1.91	1.97	
Wear factor of safety	SH	1.38	1.40	

Budget

- Total FR-DT Budget
  - Low End: $4378.87
  - High End: $6003.17

- Team Budget: $6865.00
- Current Team Costs: $9228.96
- Deficit: **$2363.96**

- Deficit Solutions
  - Fundraising: GoFundMe, Car Shows, Food Nights
  - Sponsorship: Polaris, Fox, Ping

Team	Cost	
	Low	High
DR-FR	$ 4,378.87	$6,003.17
FE-RE	$ 2,222.49	$3,225.79
Total	$ 6,601.36	$9,228.96

Total:	$ 9,228.96
Current Budget	$ 6,865.00

Deficit:	$(2,363.96)

Table 6: Budget

Initial Bill of Materials: Drivetrain and Frame					
Item No.	**Description**	**Qty.**	**Vendor**	**Cost Range**	
1	B&S 10 HP Vanguard Engine	1	Briggs & Stratton	$546.30	$546.30
2	Fuel Tank	1	Pyrotect	$225.00	$225.00
3	Fuel Line	1	Napa Auto	$0.00	$0.00
4	Kill Switches	2	Parker SportsCenter	$51.00	$51.00
5	Primary ECVT Pulley	1	In-house	$0.00	$400.00
6	Linear Bearing for Splined Shaft	1	McMaster-Carr	$278.89	$278.89
7	Gaged Secondary CVT Pulley	1	Gaged Engineering	$0.00	$0.00
8	Nema 23 2.8A Stepper Motor	1	StepperOnline	$26.00	$26.00
9	US5881 Hall Effect Sensor	2	SainSmart	$7.98	$7.98
10	Arduino Components	TBD	Arduino	$0.00	$40.00
11	Spur Gears	2	TBD	$100.00	$400.00
	Gear Manufacturing	2	Ping	$0.00	$0.00
12	Case Material	1	SpeedyMetals	$0.00	$500.00
13	Case Manufacturing	2	Ping	$0.00	$0.00
14	5/8 Hollow Steel Tube	1	SpeedyMetals	$27.36	$27.36
15	Closed Cell High Density Foam	1	USAFoam	$22.36	$22.36
16	Safety Covers	2	SpeedyMetals	$54.32	$54.32
17	Misc. Hardware	TBD	Copper State	$20.00	$150.00
18	ECVT Electronic Components	N/A	N/A	$513.66	$567.96
	Yamaha Rhino 660 Rear Diff.	1	maXpeedingrods	$240.00	$240.00
	Yamaha Rhino 660 Front Diff.	1	maXpeedingrods	$266.00	$266.00
	Frame Material/Fabrication	N/A	VR# Engineering	$2,000.00	$2,000.00
19	Contingency Fund	N/A	Any	$0.00	$200.00
			Total:	**$4,378.87**	**$6,003.17**

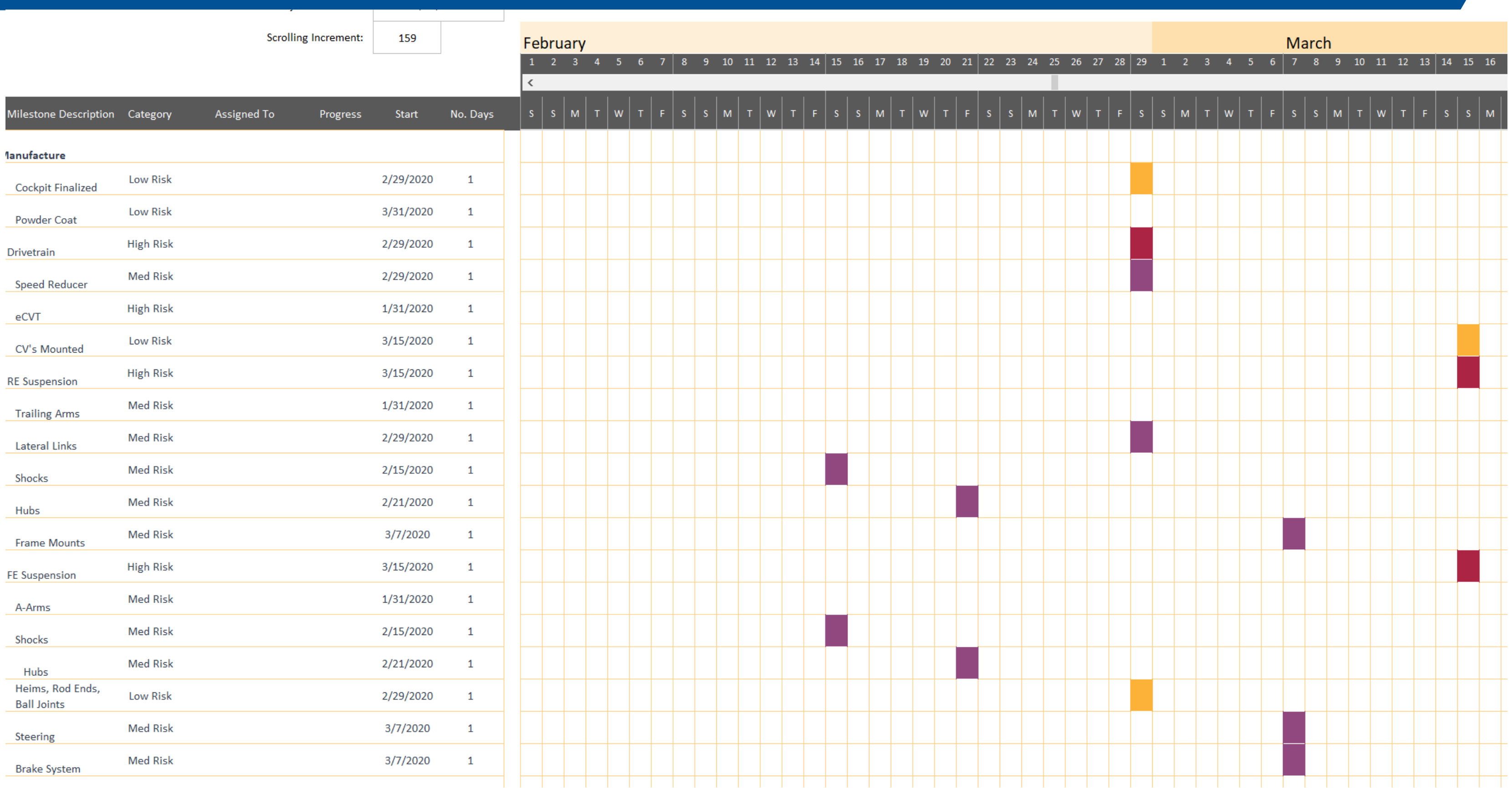
Timeline

- Timeline lengthened due to subsystem designs
- 1 Month Timeline

Frame moving to manufacture
Drivetrain is finalizing FEA simulation of sub-team components

- 4 Month Timeline

Manufacturing completed by March 15th



Milestone Description	Category	Assigned To	Progress	Start	No. Days
anufacture					
Cockpit Finalized	Low Risk			2/29/2020	1
Powder Coat	Low Risk			3/31/2020	1
Drivetrain	High Risk			2/29/2020	1
Speed Reducer	Med Risk			2/29/2020	1
eCVT	High Risk			1/31/2020	1
CV's Mounted	Low Risk			3/15/2020	1
RE Suspension	High Risk			3/15/2020	1
Trailing Arms	Med Risk			1/31/2020	1
Lateral Links	Med Risk			2/29/2020	1
Shocks	Med Risk			2/15/2020	1
Hubs	Med Risk			2/21/2020	1
Frame Mounts	Med Risk			3/7/2020	1
FE Suspension	High Risk			3/15/2020	1
A-Arms	Med Risk			1/31/2020	1
Shocks	Med Risk			2/15/2020	1
Hubs	Med Risk			2/21/2020	1
Heims, Rod Ends, Ball Joints	Low Risk			2/29/2020	1
Steering	Med Risk			3/7/2020	1
Brake System	Med Risk			3/7/2020	1

Figure 20: Timeline

Questions?

References

[1] Amazon.com. (2019). Rear Differential for Yamaha Rhino 700 2008-2013 660 2004-2007 450 2006-2007. [online] Available at: https://www.amazon.com/Differential-Yamaha-2008-2013-2004-2007-2006-2007/dp/B07K447FRL/ref=sr_1_6?keywords=yamaha+rhino+differential&qid=1572993653&sr=8-6 [Accessed 5 Nov. 2019].

[2] "Factors of Safety," *Engineering ToolBox*. [Online]. Available: https://www.engineeringtoolbox.com/factors-safety-fos-d_1624.html. [Accessed: 05-Nov-2019].

[3] - Finite Element Analysis. (2014). GUEST BLOG: RESULTS VALIDATION AT CURTIN MOTORSPORT. [online] Available at: https://www.finiteelementanalysis.com.au/featured/guest-blog-curtin-motorsport/ [Accessed 5 Nov. 2019].

Appendix A (Drive Shaft Calculations)

Torque applied (lb*in)	2016	[redacted]
Major diameter (in)	1	[redacted]
Minor diameter (in)	0.93	[redacted]
Major radius (in)	0.5	[redacted]
Polar moment of inertia (in^4)	0.024735	[redacted]
Stress Experienced (lb/in^2)	40752.08	[redacted]
Yeild Stress (lb/in^2)	63100	[redacted]
thickness	0.035	
Torque motor (lb*ft) (lb*in)	14	168
Reduction	12	
Torque applied (lb*in)	2016	
Factor of Safety	1.548387	
Weight/length (lb/1 in)	0.030028	
Density (4130 steel) (lb/in^3)	0.283	
cross sectional area (in^2)	0.106107	

Appendix B (Material Calculations)

	Minimum Tubing	Primary Tubing			Secondary Tubing
material	1018 steel	4130 steel			4130 steel
OD (in)	1	1.25			1
Wall thickness (in)	0.12	0.065			0.035
carbon content (%)	0.18	0.3			0.3
E (kpsi)	29700	29700			29700
I (in^4)	0.032710765	0.042602298			0.012367468
k_b ($klb * in^2$)	971.5097313	1265.288253	293.7785		367.3138007
S_y (kpsi)	52.9388	63.1			63.1
c (in)	0.5	0.625			0.5
S_b (klb*in)	3.463337331	4.301128015	0.837791		1.560774466
density (lb/in^3)	0.284	0.284			0.284
weight per foot (lb)	1.130611444	0.824671841	-0.30594		0.361613651

Appendix C (Gear Calculations: AGMA)

		Pinion	Gear		
Number of Teeth	N	24	48	teeth	
Diametral Pitch	P	8	8	TPI	
Transmitted Load	Wt	200	200	lbf	Eq. 13-35
Pitch-line velocity	V	3800	3800	ft/min	Eq. 13-34
Material		Through-hardened G1	Through-hardened G1		Fig. 14-2
Brinell hardness	HB	250	250	HB	
User-specified bending stress	St	0	0	ksi	
User-specified contact stress	Sc	0	0	ksi	
Quality number	Qv	7	7		
Overload Power/driven		Uniform-uniform	Uniform-uniform		Fig. 14-17
Face width	F	1.25	1.25	in	
Centered?		TRUE	TRUE		Eq. 14-33
Adjusted?		FALSE	FALSE		Eq. 14-35
Condition		Commercial	Commercial		Table 14.9
Fatigue model		250 HB	250 HB		Fig. 14-14
Load cycles		1.00E+09	5.00E+08		
Reliability		95	95		
Diameter	d	3	6	in	Eq. 13-1
Addendum	a	0.125	0.125	in	
Deddendum	b	0.15625	0.15625	in	
Bending stress slope		77.3	77.3	psi/HB	
Bending stress intercept		12800	12800	psi	
Contact stress slope		322	322	psi/HB	
Contact stress intercept		29100	29100	psi	
Bending stress	St	32.125	32.125	ksi	Figure 14-2
Contact stress	Sc	109.6	109.6	ksi	Figure 14-5
Geometry factor	J	0.354	0.399		Figure 14-6
Speed ratio	mG	2.0000	2.0000		Eq. 14-22

		Pinion	Gear		
Bending factor of safety	SF	4.32	4.95		Eq. 14-41
	(SH)^2	2.37	2.43		Eq. 14-43
Wear factor of safety	SH	1.54	1.56		Eq. 14-42

Circular pitch	p	0.393	in
tooth thickness	t	0.196	in
Length Check:			
Total Length	L	9	in
c-c	c	4.5	in
interference check:	We Good		
Pinion Teeth	24		
Equation Check	16.94181163		