SAE Baja '24 Capstone Team

Presentation 2

Abraham Plis, Evan Kamp, Bryce Fennell
Joey Barta, Lars Jensen, Seth Deluca
Cooper Williams, Gabriel Rabanal, Antonio Sagaral
Henry Van Zuyle, Donovan Parker, Ryan Fitzpatrick, Jarett Berger

Front Team

Abraham Plis, Evan Kamp, Bryce Fennell

Project Description

NAU SAE Baja 2020-2021

What is SAE Baja?

The Society of Automotive Engineers (SAE) Baja Collegiate Design Series is an engineering challenge for students to design and build a single-seat, all-terrain vehicle.

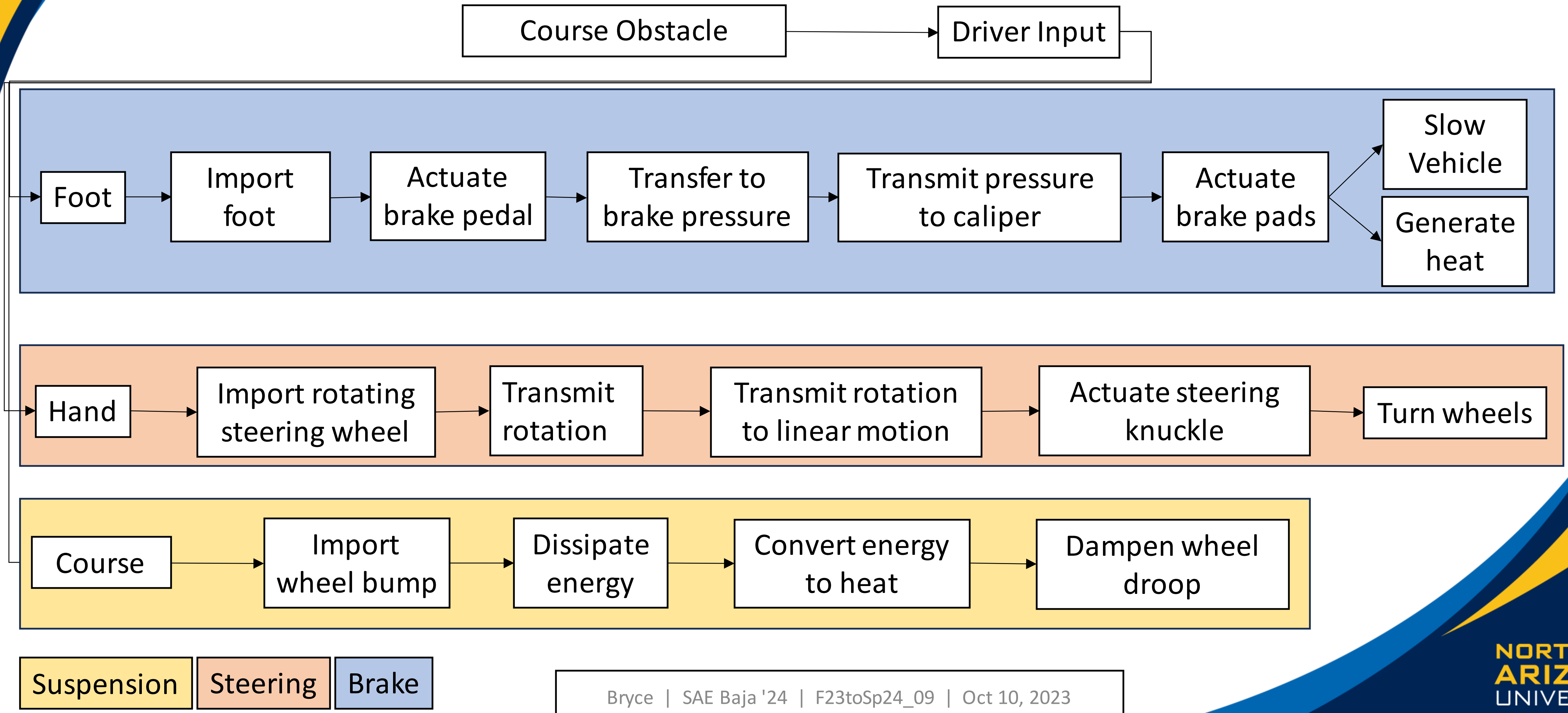
- Compete against other universities
- 13 members total, 4 sub-teams
  - Front End, Rear End, Frame, Drivetrain
- Sponsors: WL GORE, Monster Energy
- Successful performance puts NAU on the map, strengthens internal Baja knowledge, and grows NAU Baja industry sponsorship connections

NORTHERN ARIZONA UNIVERSITY

Black Box Model

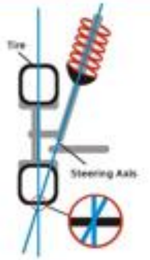
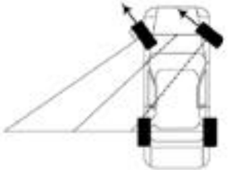
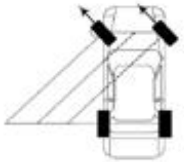
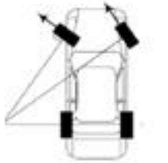
NORTHERN ARIZONA UNIVERSITY

Functional Model



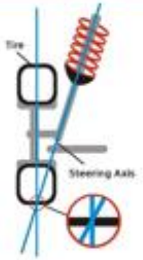
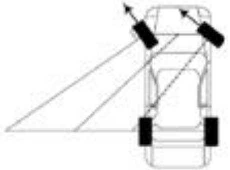
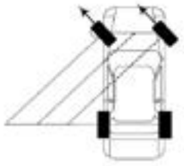
NORTHERN ARIZONA UNIVERSITY

Concept Generation

	Variants		
Subsystem	1	2	3
Scrub Radius	 Positive	 Negative	 Zero
Control Arm Geometry	 A Arm	 J Arm	 Wishbone
Control Arm Construction	 CNC	 Welded	 Carbon
Steering Arrangement	 Anti-Ackerman	 Parallel	 Pro-Ackerman

- **Sub-systems** were generated by researching the required attributes of a functioning SAE Baja vehicle
- **Variants** were generated based off prior literature reviews and calculations performed in Presentation 1

Concept Generation

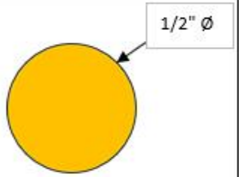
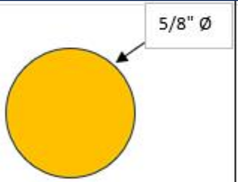
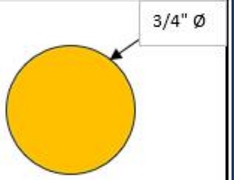
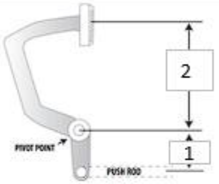
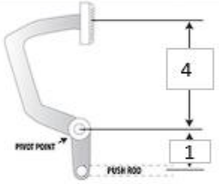
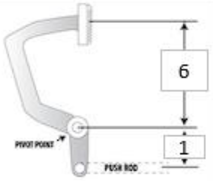
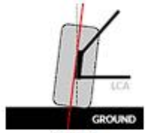
	Variants		
Subsystem	1	2	3
Scrub Radius	 Positive	 Negative	 Zero
Control Arm Geometry	 A Arm	 J Arm	 Wishbone
Control Arm Construction	 CNC	 Welded	 Carbon
Steering Arrangement	 Anti-Ackerman	 Parallel	 Pro-Ackerman

Sub-System Influence

- Steering control under hard braking/acceleration
- Stresses seen by the arm during dynamic operation
- Ease of Fabrication and Cost
- Turning Radius of Vehicle

NORTHERN ARIZONA UNIVERSITY

Concept Generation

	Variants		
Subsystem	1	2	3
Master Cylinder Bore Size			
Brake Pedal Ratio	 2	 4	 6
Camber During Suspension Bump	POSITIVE CAMBER  Loss	NEGATIVE CAMBER  Gain	NEUTRAL CAMBER  No-Change
Shock Mount Location	 UCA	 LCA	

Sub-System Influence

Clamping Force and Caliper Size

Mechanical Advantage On Brake Pedal

Roll Performance/Stability

Geometry of 4WD Axle Path in Front

Engineering Calculations – Front 1

Equations, Tools, & Examples

Side view swing arm height given percentage anti dive Formula

Side View Swing Arm Height = Percentage Anti Dive Front/((Percentage front braking)*(1/Side View Swing Arm Length)/(Height of CG above road/Wheelbase of Vehicle))

$svsa_{height} = \%antidive_{front}/((\%Braking_{front})*(1/svsa_{length})/(h/b))$

Percentage Anti Dive Front [$\%antidive_{front}$]	20	
Percentage front braking [$\%Braking_{front}$]	60	
Side View Swing Arm Length [$svsa_{length}$]	37.2	Inch
Height of CG above road [h]	22	Inch
Wheelbase of Vehicle [b]	62	Inch
Side view swing arm height given percentage anti dive [$svsa_{height}$]	4.4	Inch

+10% / -10% · Copy

Equation/online platform used to calculate anti-dive characteristics based on a variety of predetermined vehicle dimensions [90]

General range of the values

Parameters	Front	Rear
Camber @Jounce 5"	-2deg – 3deg	0 - 4 deg
Caster	10-12 deg	0
KPI	7-10 deg	0
Toe in and Toe out	0 – 2deg (in or out)	0 – 2deg (in or out)
Scrub radius	2 – 5in	0
Roll center height	11in – 15in	7in – 12in
C.G of vehicle	23 – 28 in	

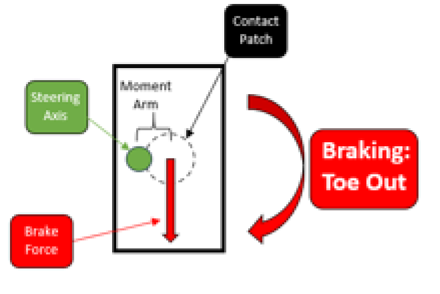
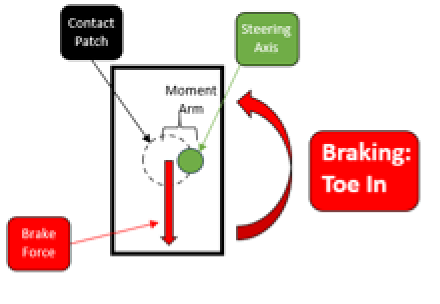
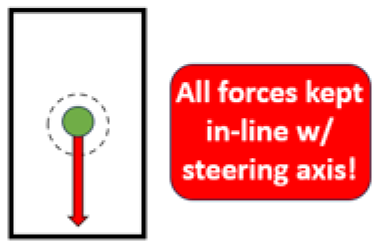
Example of ideal spec ranges for SAE Baja vehicles to guide this year's suspension design [91]

ADAMS Suspension software provides a "free" alternative to Lotus Shark (should the need arise), application for comp. package [92]

NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Front 2

Scrub Radius

Scrub Radius - Wheel Torque Under Braking		
Variant	**Diagram**	**Result**
1 - Positive		64 lbf*ft
2 - Negative		64 lbf*ft
3 - Zero		0 lbf*ft

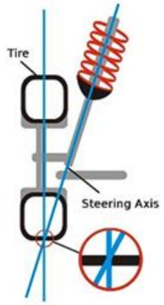
To calculate the influence of scrub radius on toe characteristics, we can use the following governing equations & assumptions:

$$F_{braking} = \frac{Weight\ of\ Car}{2} * (Coeff.Friction\ Tire\ to\ Asphalt)$$

$$T_{wheel} = F_{braking} * D_{MomentArm}$$

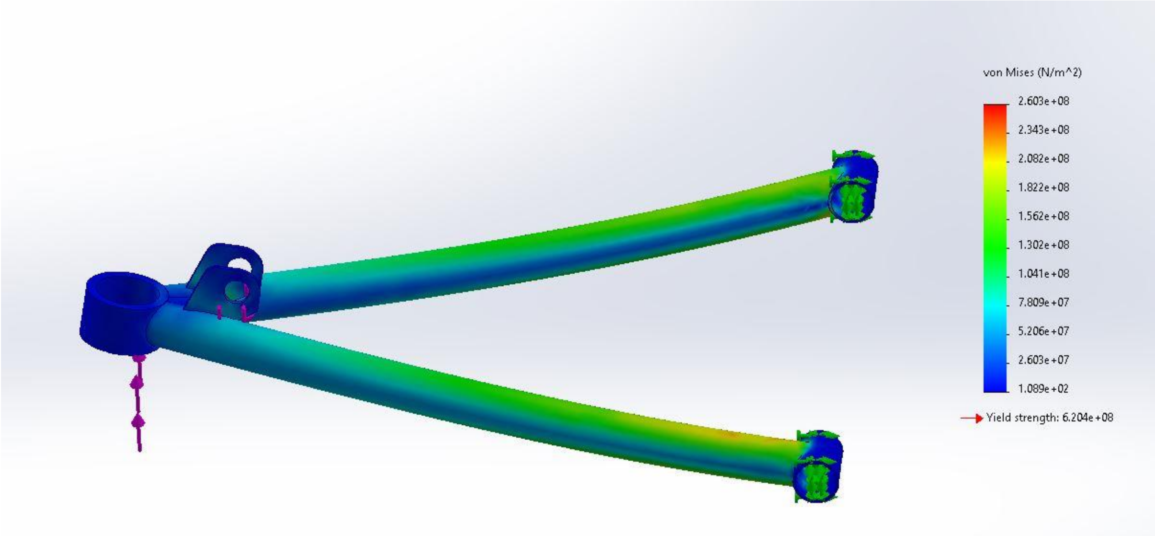
Wight of Car = 550 lbs. (with driver)
Coeff. = 0.7 (worst case)
Moment Arm = 4 in.

Zero Scrub Has Least Steering Influence!

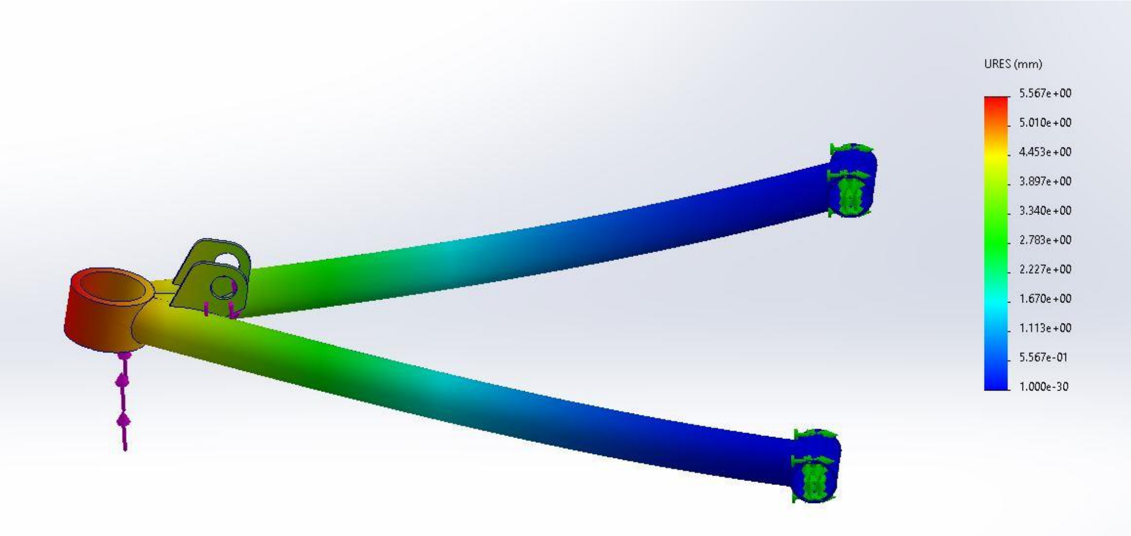


Engineering Calculations – Front 3

Control Arm Geometry – A Arm Minimized Complication



Developed stress on front upper control arm



Displacement on front upper control arm

Assumptions: 550lb vehicle enduring full weight on a single w wheel falling from ~3 feet
Importance: Of all geometries simulated, A-Arm has least complicated stress interaction

SolidWorks analysis of stresses on the **Upper Control Arm** during a maximum force event. Resulting FOS of 2.38 meaning the **Design Passes!**

Engineering Calculations – Front 4

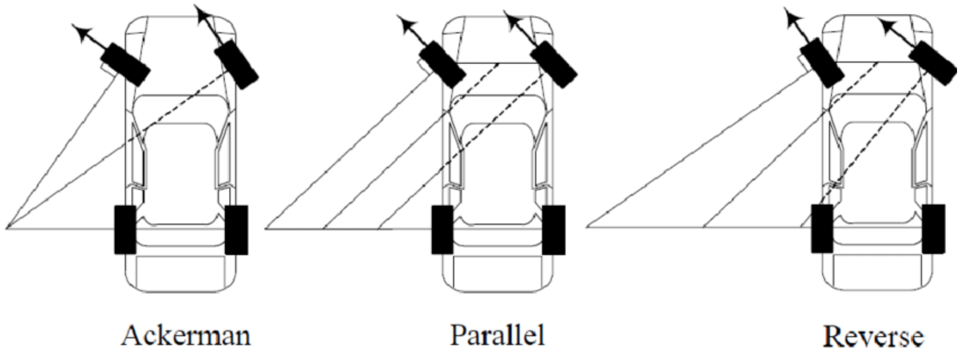
Control Arm Construction

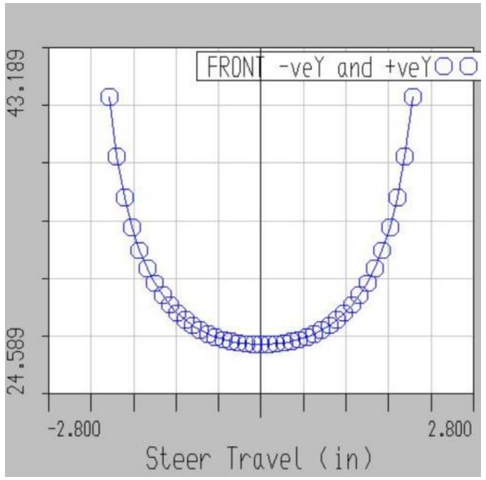
Type of Control Arm	Material Cost	Design Time	Manufacturing Time	Other Benefits
Welded 	4'x4 control arms 1"OD with 1/16" ID Using 4130 Steel **$40x4 = $160**	1 hour CAD for both the upper and lower control arm. 10 minutes to mirror to passenger side **TOTAL 2hr 10min**	1 hour of jigging with 45 minutes of welding **TOTAL 1hr 45min**	Additional Adjustability with welded
CNC Aluminum 	2'x1'x2" billet for each Control Arm **$600x4 = $2400**	4 hour CAD for both upper and lower control arm. 10 minutes to mirror to passenger side **TOTAL 8hr 10min**	2 hours of Programming 2 hours of Machining **TOTAL 4hr**	If done correctly could be Lightweight

NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Front 5

Steering Arrangement





Preliminary Measurements Using Lotus Shark

Inner wheel angle (δi)	50°
Outer wheel angle (δo)	28.4°
δavg	39.2°
Rear wheel to center of gravity (a2)	32

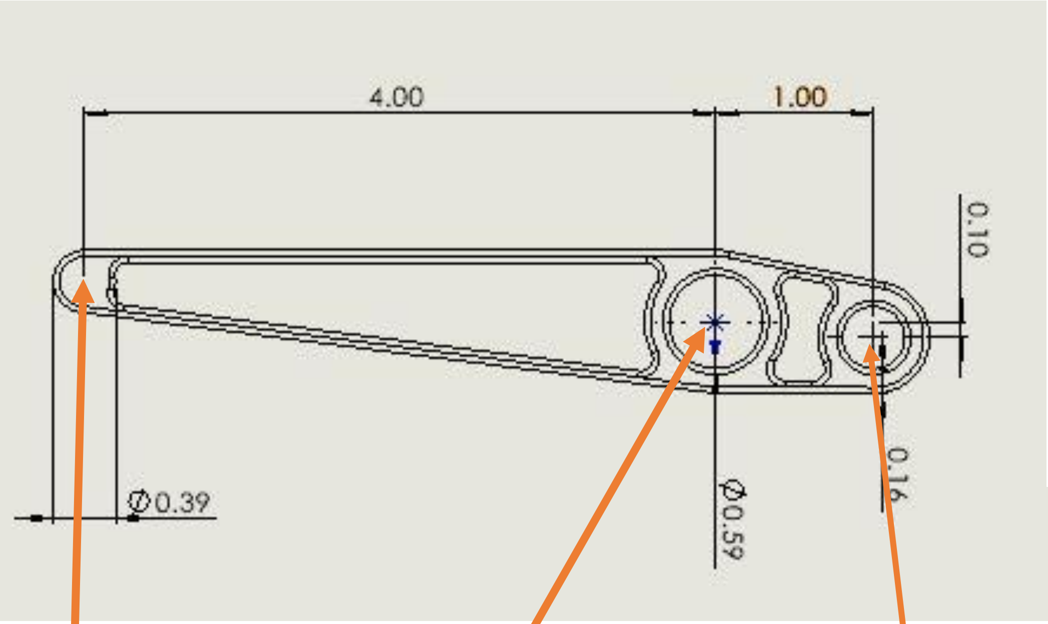
Results

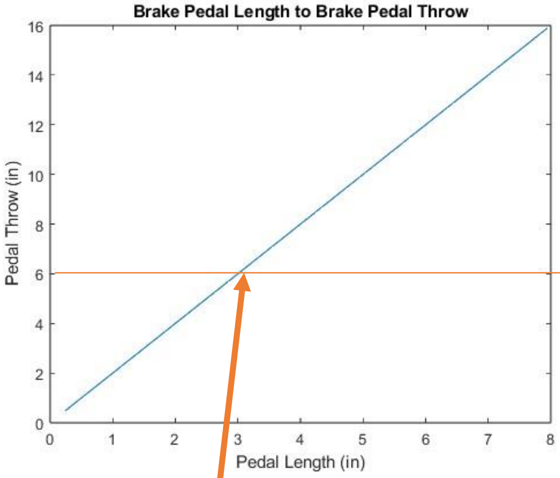
Percent Ackerman Used	43.189%
Projected Turning Radius (R)	6.93ft

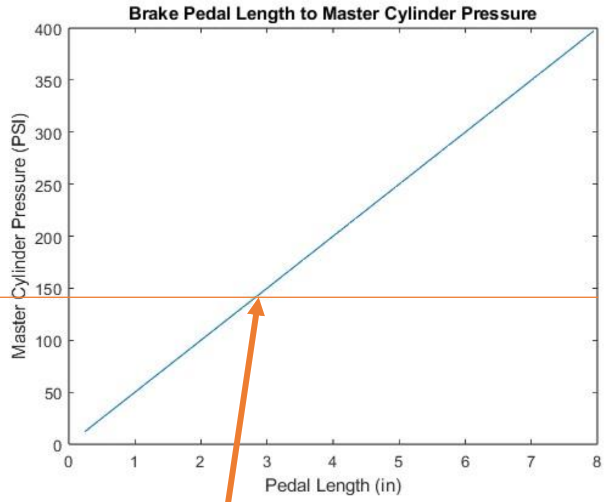
NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Front 6

Brake Pedal Length







Brake Pedal Center Mount

Pivot Point

Master Cylinder Mount

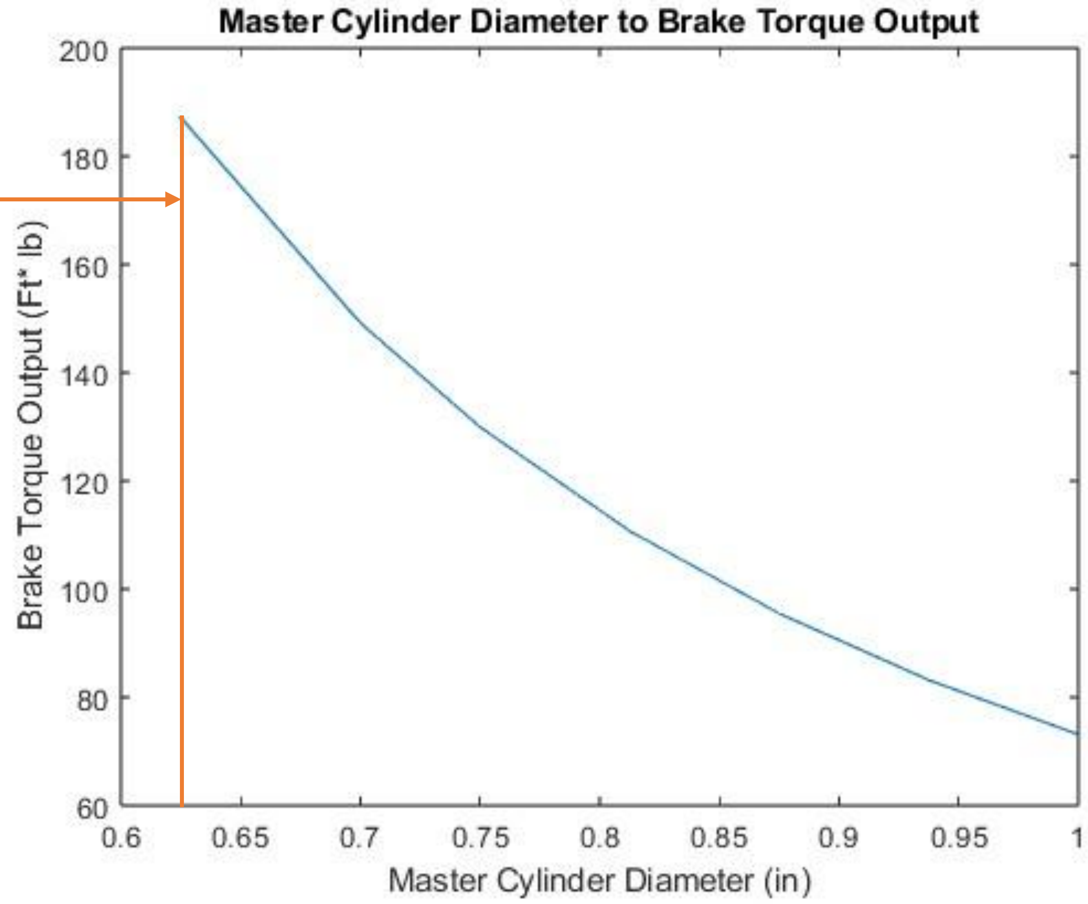
Optimal pedal throw per driver requirements, Resulting master cylinder hydraulic pressures

A brake pedal throw to master cylinder throw ratio of 4:1 will provide **maximum** power transfer with **minimal** pedal motion

Engineering Calculations – Front 7

Master Cylinder Bore Size

Maximum brake torque (5/8” bore) at ~190 ft*lb.



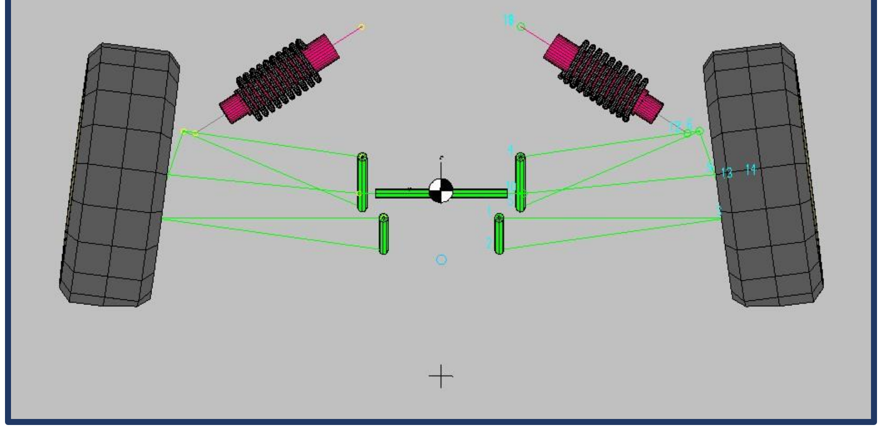
Optimizing for the maximum braking output for master cylinder ID compared to **maximum** braking force

Tilton Brake Master Cylinder, 5/8” Bore

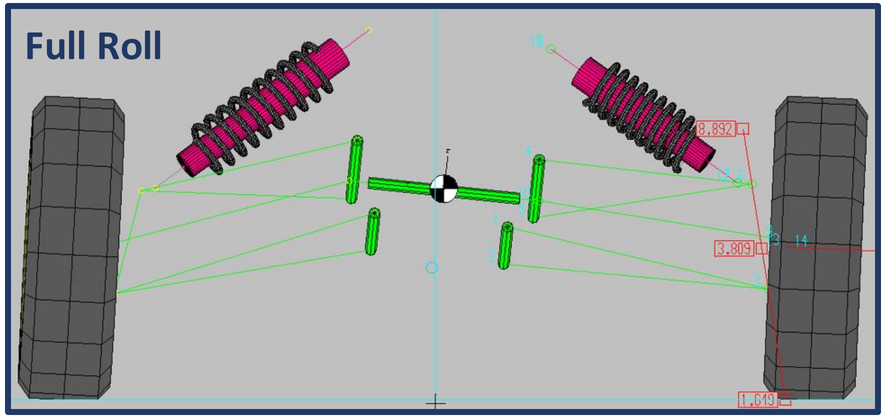
Engineering Calculations – Front 8

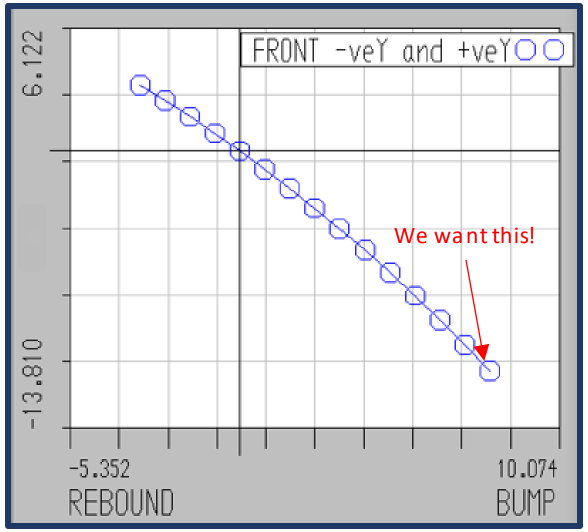
Camber During Suspension Bump

Full Bump



Full Roll

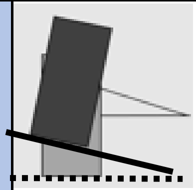
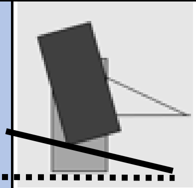
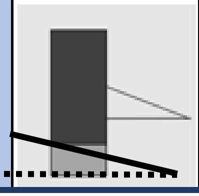




More **negative camber gained** during compression helps maintain tire contact and prevent wheels from tipping over during roll

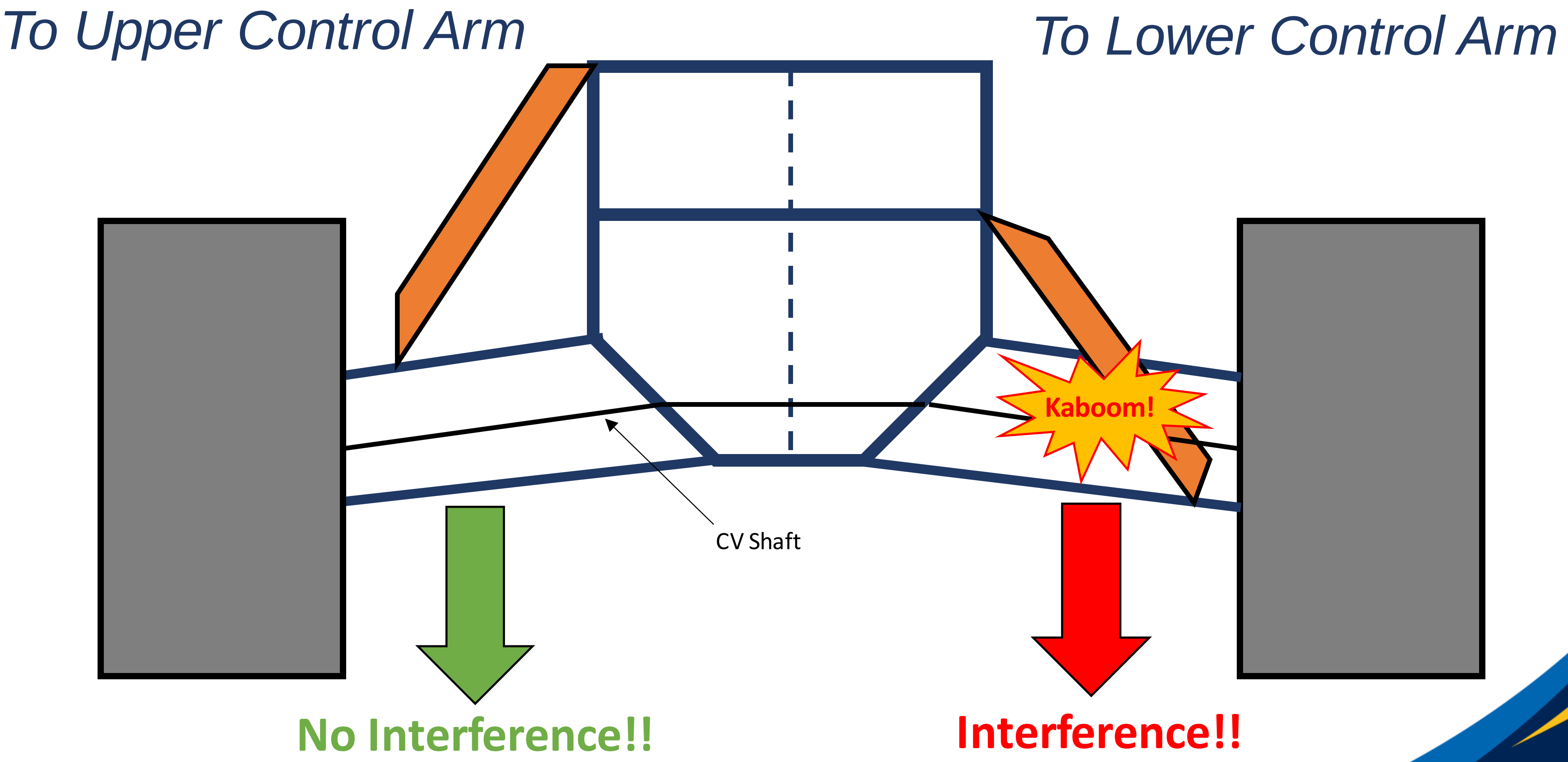
Camber gain refers to how much negative camber the wheels gain during compression (bump)

Camber During Bump

Variant	Diagram	Result
1 - Gain		Better Roll Performance
2 - Loss		Worse Roll Performance
3 - No Change		Subpar Roll Performance

Engineering Calculations – Front 9

Shock Mount Location



NORTHERN ARIZONA UNIVERSITY

Concept Evaluation

	Variants					
Subsystem	*1*	*Rating*	*2*	*Rating*	*3*	*Rating*
Scrub Radius	Positive	X	Negative	X	Zero	✓
Control Arm Geometry	A Arm	✓	J Arm	X	Wishbone	X
Control Arm Construction	CNC	X	Welded	✓	Carbon	X
Steering Arrangement	Anti-Ackerman	X	Parallel	X	Ackerman	✓
Master Cylinder Bore	1/2”	X	5/8”	✓	3/4”	X
Brake Pedal Ratio	2	X	4	✓	6	X
Camber During Suspension Bump	Loss	X	Gain	✓	No-Change	X
Shock Mount Location	UCA	✓	LCA	X		

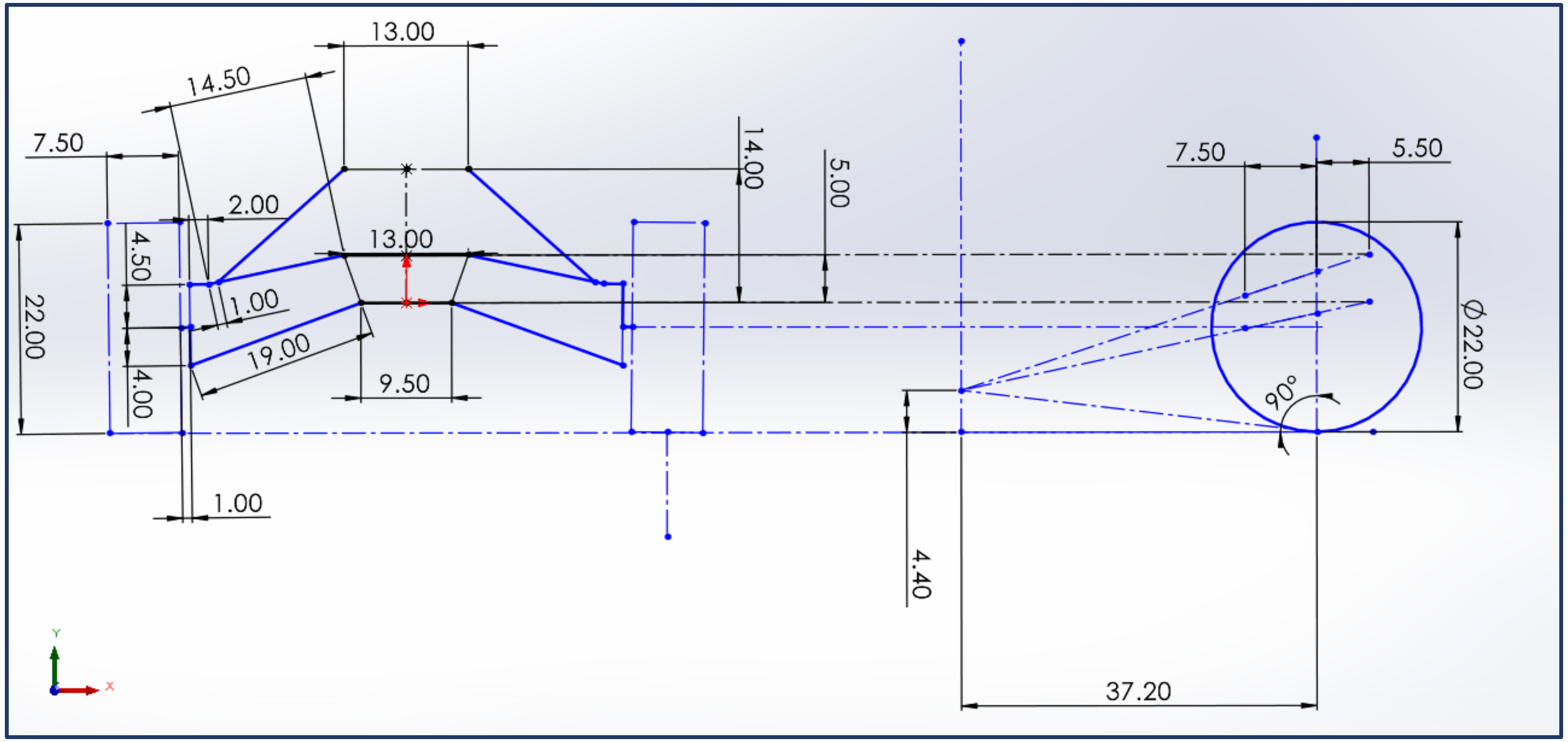
Final Design Discussion

	Variants					
Subsystem	*1*	*Rating*	*2*	*Rating*	*3*	*Rating*
Scrub Radius	Positive	X	Negative	X	Zero	✓
Control Arm Geometry	A Arm	✓	J Arm	X	Wishbone	X
Control Arm Construction	CNC	X	Welded	✓	Carbon	X
Steering Arrangement	Anti-Ackerman	X	Parallel	X	Ackerman	✓
Master Cylinder Bore	1/2"	X	5/8"	✓	3/4"	X
Brake Pedal Ratio	2	X	4	✓	6	X
Camber During Suspension Bump	Loss	X	Gain	✓	No-Change	X
Shock Mount Location	UCA	✓	LCA	X		

NORTHERN ARIZONA UNIVERSITY

Final Design Visualization

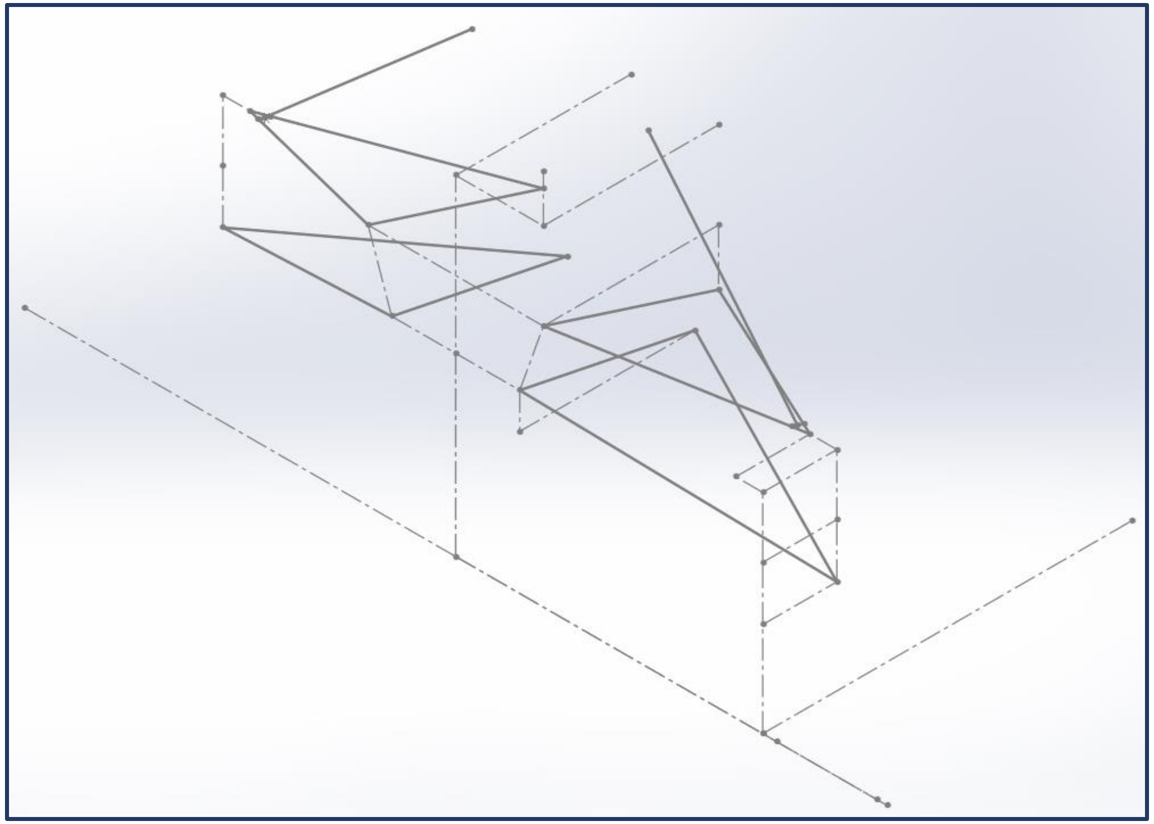
Initial Steering Geometry Calculations



- 2D geometry calculations performed in accordance with *Race Car Vehicle Dynamics* and other sources [93, 94]
- Convert to 3D points for Shark Processing…

Final Design Visualization

Initial Steering Geometry Calculations



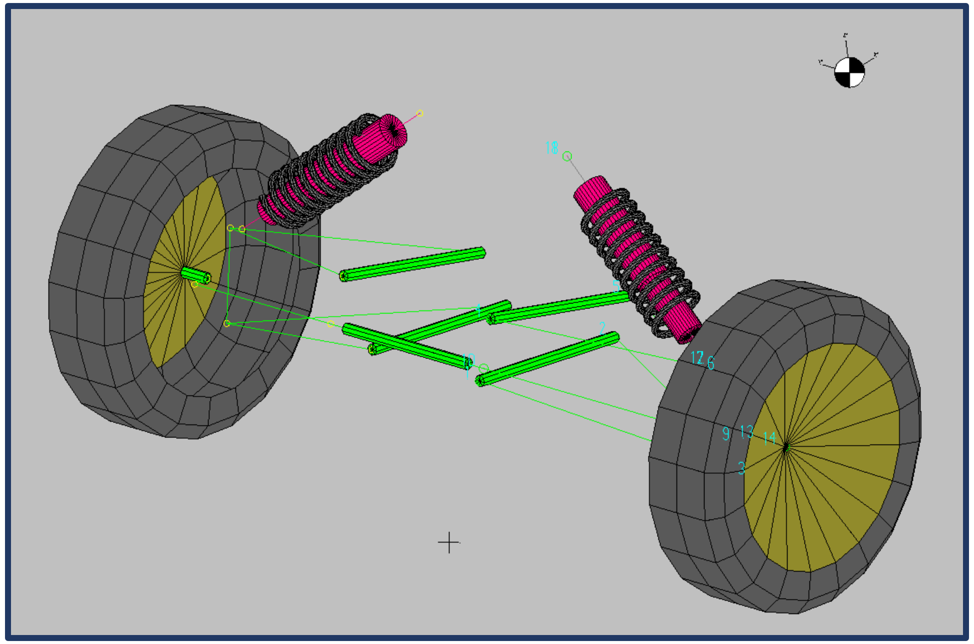
	SolidWorks			
	Coordinate Description	X (Driver + Passenger -)	Y(Up + Down -)	Z(Towards Front + Towards Rear -)
Drivers Side	UCA Front Pivot	6.5	18.06	0
	UCA Rear Pivot	6.5	13.9	-13
	LCA Front Pivot	4.75	13.06	0
	LCA Rear Pivot	4.75	10.42	-13
	UCA Ball Joint	20.77	15.51	-5.5
	LCA Ball Joint	22.77	7.01	-5.5
	UCA Shock Mount	19.77	15.54	-5.57
	Frame Shock Mount	6.54	26.77	-7.75
Passenger Side	UCA Front Pivot	-6.5	18.06	0
	UCA Rear Pivot	-6.5	13.9	-13
	LCA Front Pivot	-4.75	13.06	0
	LCA Rear Pivot	-4.75	10.42	-13
	UCA Ball Joint	-20.77	15.51	-5.5
	LCA Ball Joint	-22.77	7.01	-5.5
	UCA Shock Mount	-19.77	15.54	-5.57
	Frame Shock Mount	-6.54	26.77	-7.75

- 2D calculations transferred to 3D sketch
- Initial hardpoints tabulated for easier import into Shark
- Iteration, iteration, iteration…

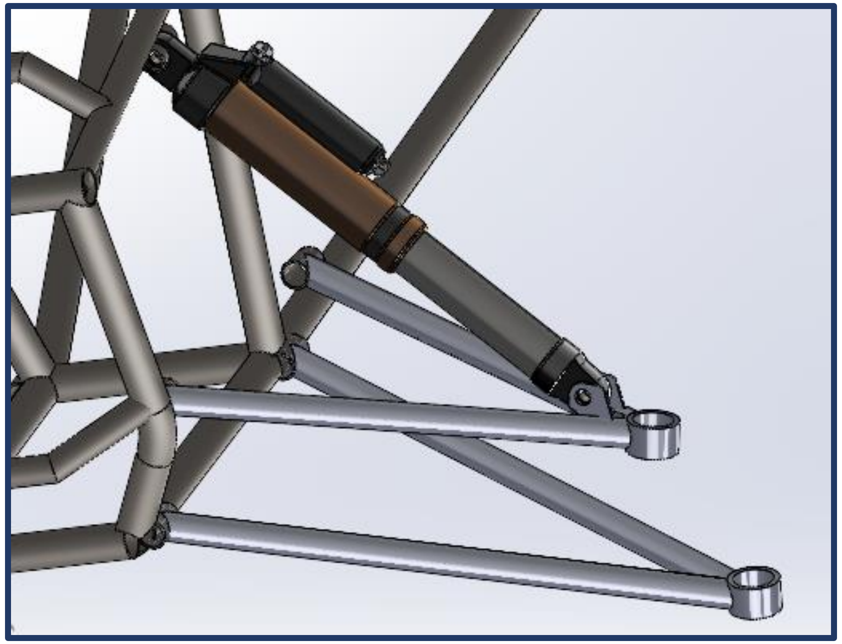
NORTHERN ARIZONA UNIVERSITY

Final Design Visualization

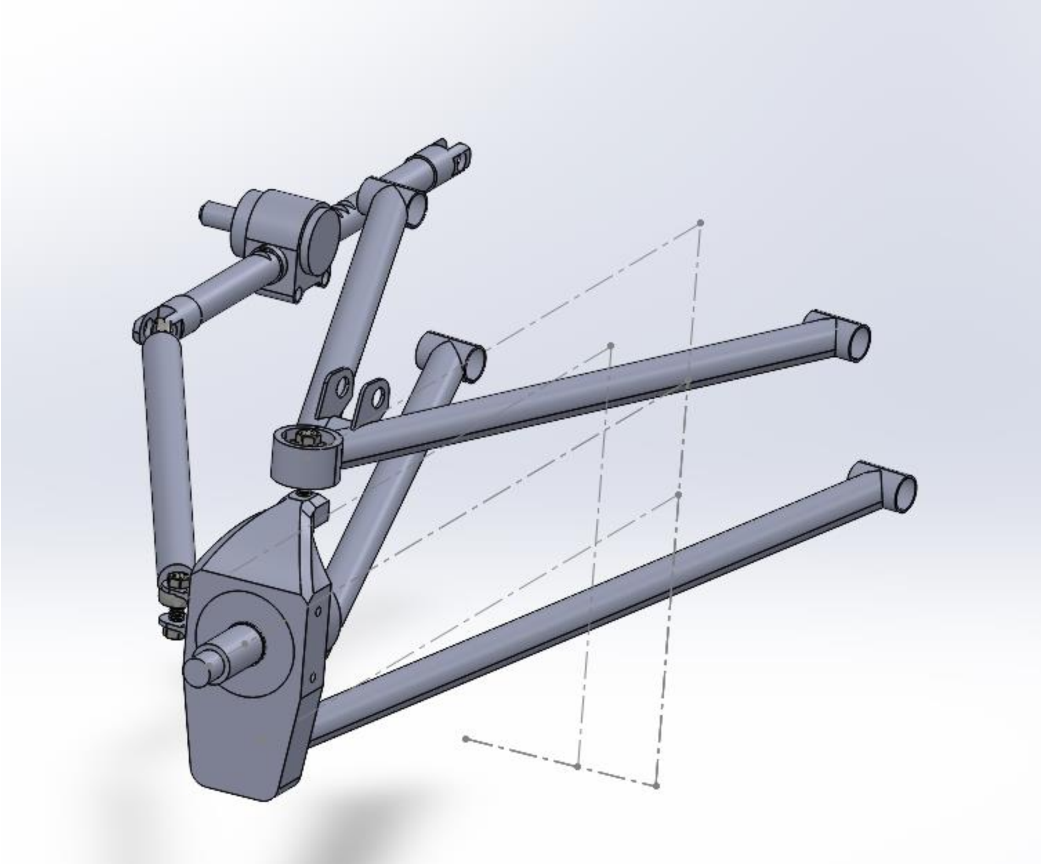
Finalized Front End Geometry from *Shark*

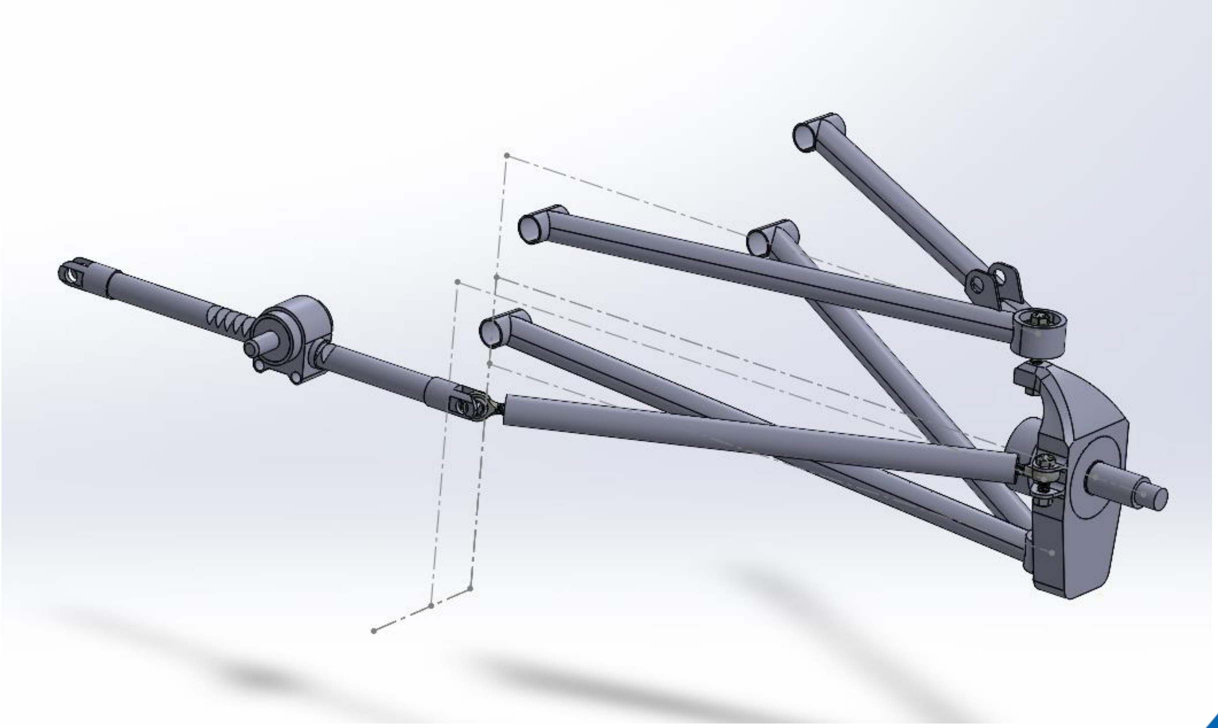


Upper & Lower Control Arms w/ Shock On Frame



Final Design Visualization





Isometric view of current SolidWorks model for SAE Baja '24 front end

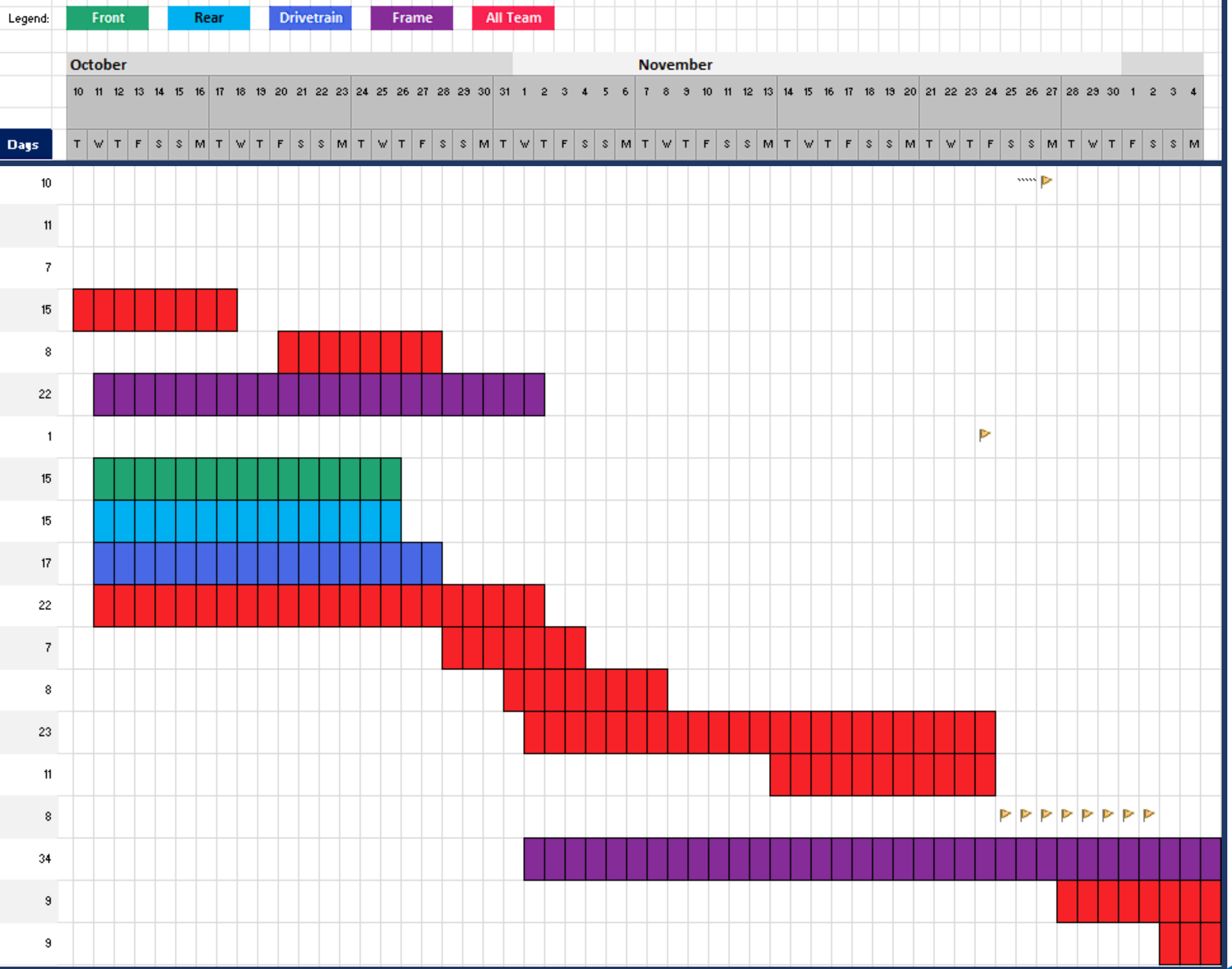
Project Schedule

PROJECT: SAE Baja 24

NAU A.Y. 2023-2024
Project Manager: Abe Plis

Project start date: 10/9/2023
Scrolling increment: 1

Milestone description	Responsible Sub-Team	Assigned To	Progress	Start	Days
Measure Hailey & Design Rollcage	Frame	Cooper Lead	100%	9/18/2023	10
Concept Generation & Selection	All Team	Team Leads	100%	9/26/2023	11
Presentation 2	All Team	N/A	100%	10/3/2023	7
Packaging Integration (Wheelbase, car length, etc.)	All Team	Cooper & Henry Lead	90%	10/3/2023	15
Report 1 & Webiste 1	All Team	Seth	30%	10/20/2023	8
Finalize Frame (footbox, lower rear triangle, rollcage)	Frame	Cooper Lead	40%	10/11/2023	22
Subsystem Designs	Milestone			11/23/2023	1
UCA, LCA, Knuckle, Rack, Brakes, Hubs	Front	Bryce Lead	25%	10/11/2023	15
Trailing Arm, Camber Links	Rear	Seth Lead	20%	10/11/2023	15
eCVT, Front/Rear Gear Box, Belt Power Transfer, Brakes	Drivetrain	Henry Lead	30%	10/11/2023	17
Rough Designs Fully in CAD	All Team	All Team	0%	10/11/2023	22
Analysis Memo	All Team	All Team	0%	10/28/2023	7
Pres 3 & 1st Demo	All Team	All Team	0%	10/31/2023	8
Refined Designs in CAD	All Team	All Team	0%	11/1/2023	23
Report 2	All Team	All Team	0%	11/13/2023	11
Full CAD Assembly Completed & BOM	Milestone	All Team	0%	11/24/2023	8
Frame Construction (Tac then Full Weld)	Frame	Cooper Leads	0%	11/1/2023	34
2nd Demo	All Team	All Team	0%	11/27/2023	9
Website 2	All Team	Seth	0%	12/2/2023	9



Project Schedule

Next Steps:

- ***Front:*** UCA, LCA, Knuckle, and Steering in CAD
- ***Rear:*** Trailing Arm & Camber Links in CAD
- ***Frame:*** Finalize Frame by Halloween (Tabs & All Members)
- ***Drive:*** Front/Rear Gearboxes & 4WD Belt in CAD, continue work on eCVT

Deadline(s): Rough CAD by 10/31

Project Status: **On-Track ✓**

Bill of Materials – Front

Steering	Quantity	Costing	Total	Suspension	Quantity	Costing	Total
steering column	1	50	$ 50.00	upper arm	2	33	$ 66.00
steering rack	1	200	$200.00	lower arm	2	27	$ 54.00
bearing for steering column	2	20	$ 40.00	ball joints	4	25	$ 100.00
rod ends	4	15	$ 60.00	delrin bushing	4	3	$ 12.00
tie rods	2	45	$ 90.00	shocks	2	Owned	$ -
		Total:	$440.00			Total:	$ 232.00

Brake	Quantity	Costing	Total	Drive	Quantity	Costing	Total
caliper	2	180	$180.00	cv axle	2	Owned	$ -
master cylinder	1	280	$280.00	cv bearing	2	15	$ 30.00
rotor	2	40	$ 80.00	knuckle	2	300	$ 600.00
brake lines	10ft	150	$150.00	hub	2	180	$ 360.00
brake line fittings	From Kit (~10)	90	$ 90.00	rim*	2	Owned	$ -
brake pressure sensor	1	15	$ 1.00	tire	2	Owned	$ -
dot 5.1 fluid	32oz	20	$ 20.00	stud	8	6	$ 48.00
brake pads	4	Included	$ -	lugnut	2	12	$ 24.00
brake pedal	1	110	$110.00	cotter pin	2	2	$ 4.00
		Total:	$911.00			Total:	$ 1,066.00

Total Cost Per Unit: $2649

BOM for SAE Baja '24 Front Team

NORTHERN ARIZONA UNIVERSITY

Front End Budget

	Category	Relevant Items	Approximated Cost
1	**Vehicle Expenses**	Brake System Control Arm Materials Rod-ends/Ball Joints Shock Rebuild Knuckle Material/Manufacturing **Estimated Total**	$1,000 $120 $50 $126 $1600 **$2649**
2	**Spare Parts**	Rod-ends, Bushings, Welding supplies, Hardware	$500
3	**Competition Expenses** Front Sub-team	Registration, travel (hotel rooms, vehicle rentals, gas, etc.)	$1,125
4	**Contingency (5%)**	Unpredicted Expenses	$400
		Total	**$4,674**

NORTHERN ARIZONA UNIVERSITY

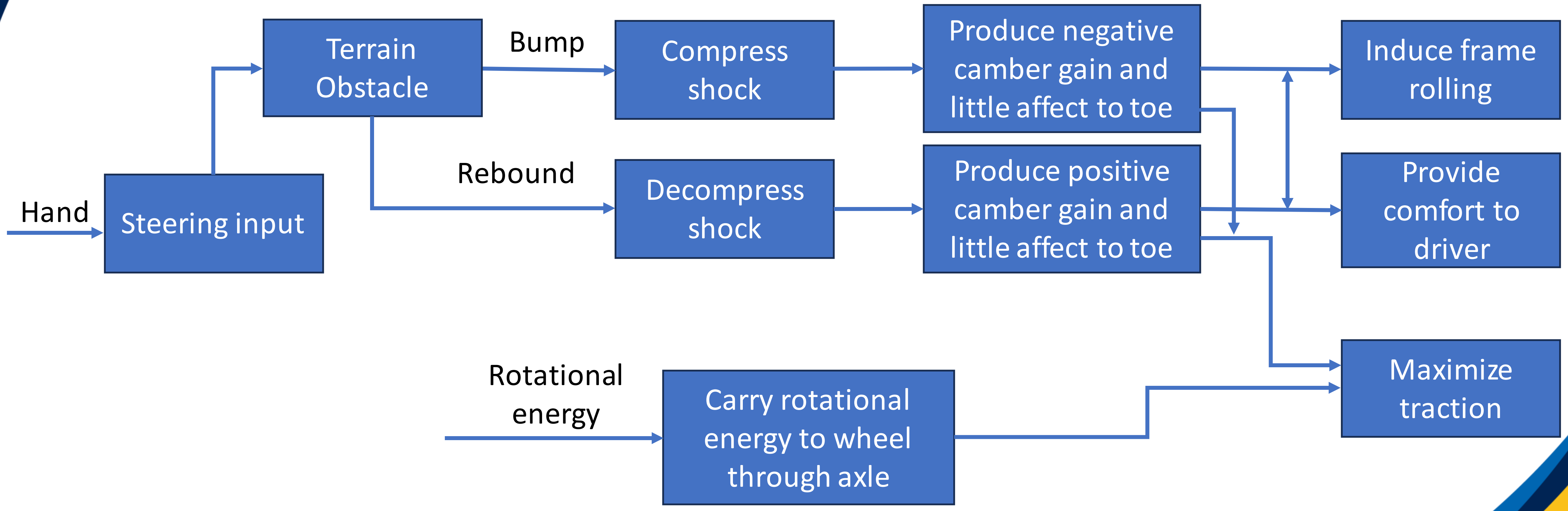
Rear Team

Seth DeLuca, Joey Barta, Lars Jensen

Black Box Model - Rear

Input	Flow	Function	Flow	Output
Feet, compressed air	Material In	Maintain traction and driver comfort over off-road terrain	Material Out	Feet
Human, Mechanical, Vibration	Energy In		Energy Out	Thermal, Kinetic, Rotational
Compression, Rebound	Signal In		Signal Out	Compression, Rebound, Chatter

Functional Model



Concept Generation

	Variants		
Subsystem	**1**	**2**	**3**
Camber	POSITIVE CAMBER  positive	NEGATIVE CAMBER  negative	NEUTRAL CAMBER  neutral
Toe	TOE-IN  in	TOE-OUT  out	NEUTRAL TOE  neutral
Camber Link Material	 Carbon Fiber	 Steel	 Alumminum
Axle types	 CV Axle	 Dogbone	 U-Joint axle

Concepts generated by researching successful baja teams and the subsystems they use.

Sub-System Influence

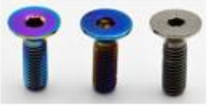
Cornering performance and traction

Steering characteristics and handling

Weight and strength

Reliability/strength

Concept Generation

	Variants		
Subsystem	1	2	3
Knuckle Design	 CNC Machined Aluminum	 Steel	 Attach knuckle to trailing arm
Hub	 Aluminum (machined)	 Cast	
hardware	 SS	 Steel	 Ti
Trailing Link Design	 Boxed Sheet Metal	 Steel Tubing	 CNC Machined Aluminum
Wheel dish	 Dish out	 Dish in	

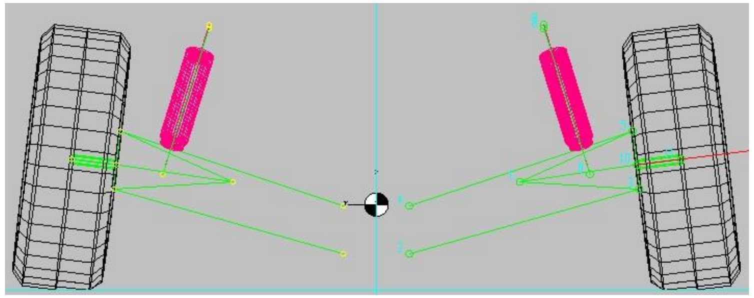
Sub-System Influence

- Production, tunability, weight, and strength
- Weight, production, and strength
- Weight and strength at joints
- EVERYTHING
- Geometry of 4WD Axle Path in Front

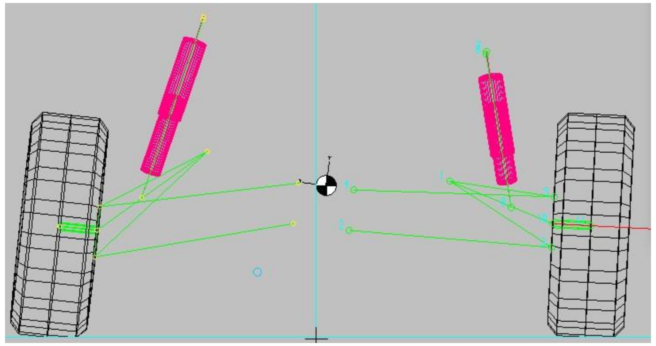
Engineering Calculations – Rear 1

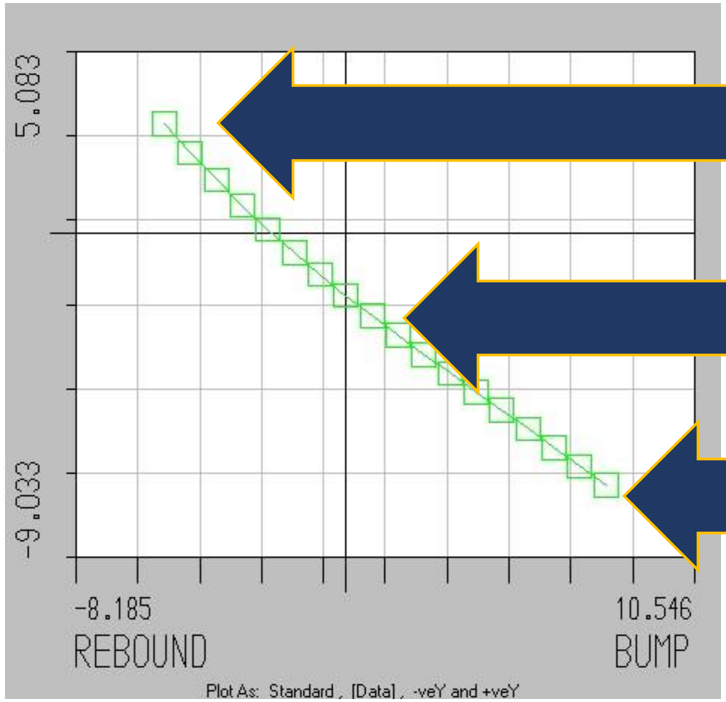
Camber

Full Compression



Full Roll





Positive camber at full droop

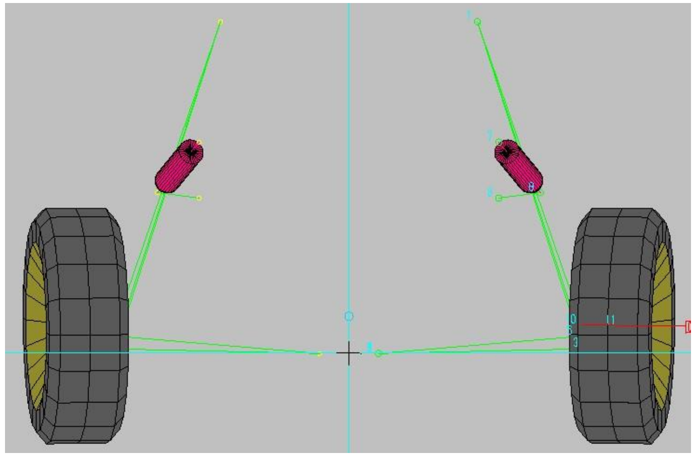
Negative camber at ride height

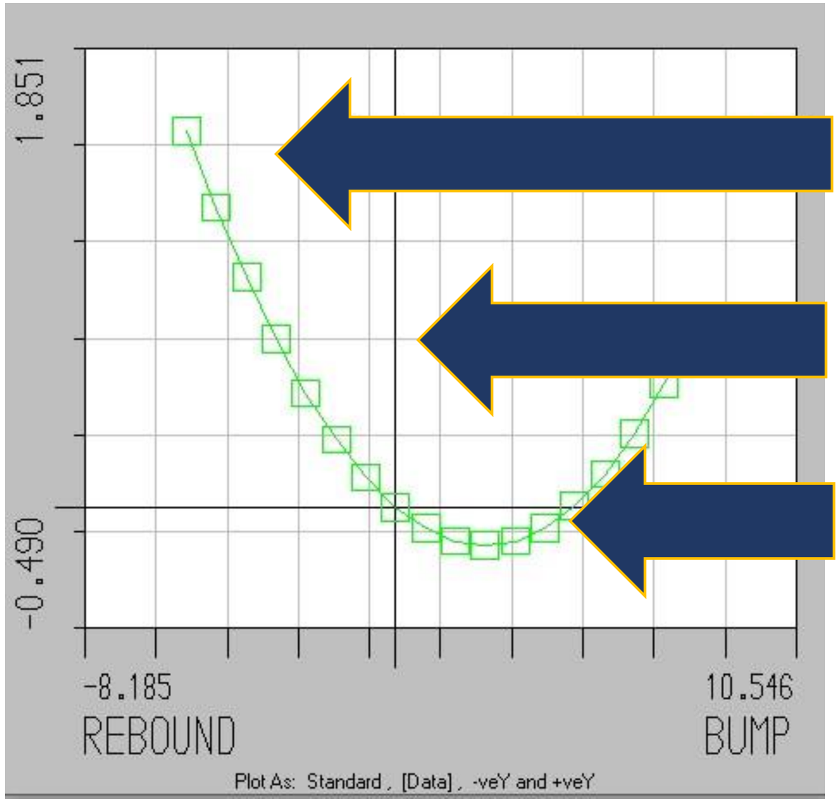
Negative camber gain

Engineering Calculations – Rear 2

Toe

Top view full compression





Minor toe out at droop

Zero at ride height

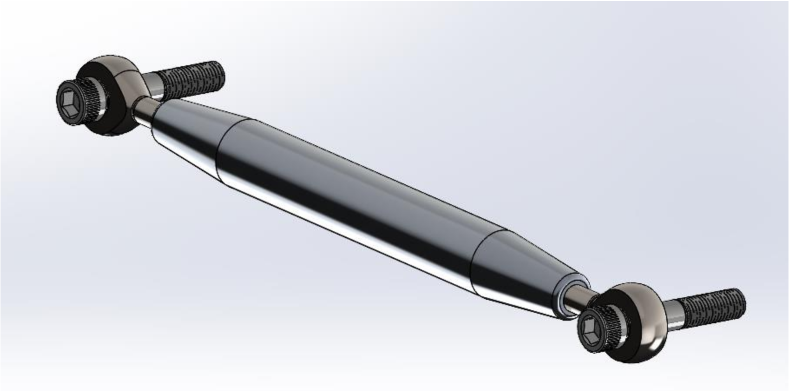
As close to zero as possible

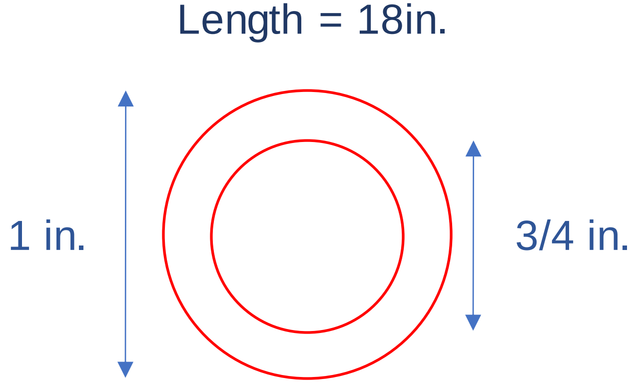
NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Rear 3

Camber link material

Aluminum Camber Link – tapered tube





Assumptions

- Uniform Cross-Section
- Analysis under load (compression)
- No affect from ball joints and screw connections

$$Q_{max} = \frac{2}{3}(r_o^3 - r_i^3) \qquad \tau_{max} = \frac{4V}{3A}\left(\frac{r_o^2 + r_o r_i + r_i^2}{r_o^2 + r_i^2}\right) = \frac{4 \times 45lbf}{3 \times 0.3436in^2}(1.48in^2) \gg 258.44psi$$

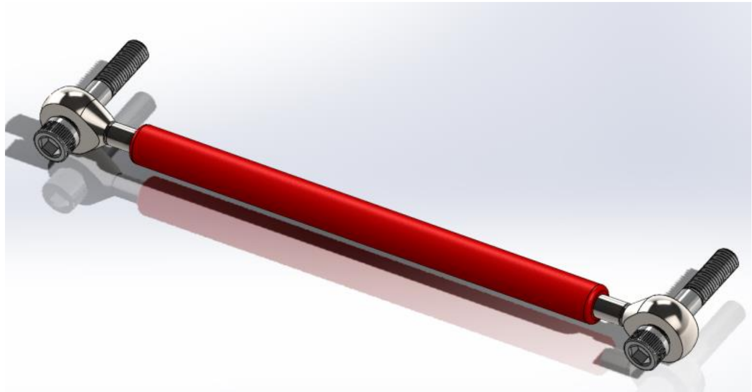
$$S_Y for\ 6063 - T6\ Aluminum = 31{,}118\ psi \qquad FoS = \frac{31{,}118}{258.44} = 120.4$$

NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Rear 3

Camber link material

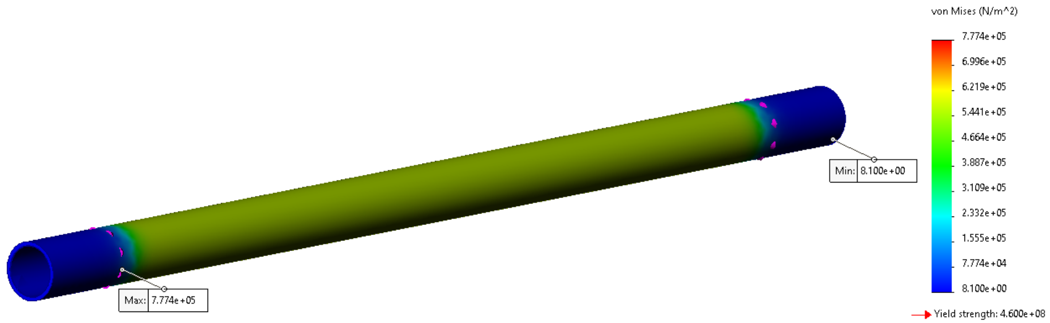
Other Possible options:



Carbon Fiber Camber Link – Hollow uniform cross-section tube with 7075 T6 machined aluminum insert

$$S_{Ut} for\ Carbon\ Fiber = 650{,}000\ psi$$

Note: Carbon Fiber has varying strength in different axis' making it difficult to analyze/compare



Steel Camber Link –uniform cross-section tube

$$S_Y for\ 4130\ Steel = 66{,}717\ psi$$

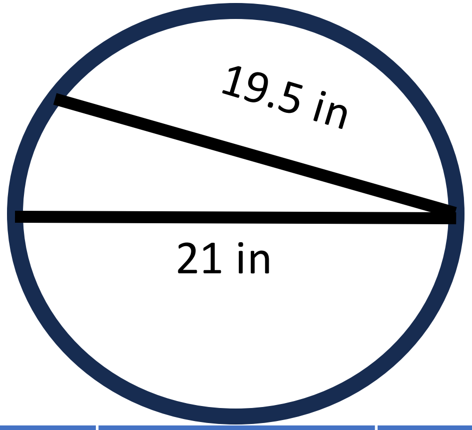
NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Rear 4

Axle types [95]

Axle type	Pro	Con
Universal Joint (U-Joint)	-Easy to replace -Allows angle change	-Acts as a suspension member -More stress on drivetrain's subsystems -Rougher ride -Spline- Very expensive to buy and can't manufacture at machine shop.
Constant-Velocity axle (CV)	-Allows angle change -Changes length at different points in travel (plunges) -Cheaper	-Hard to replace

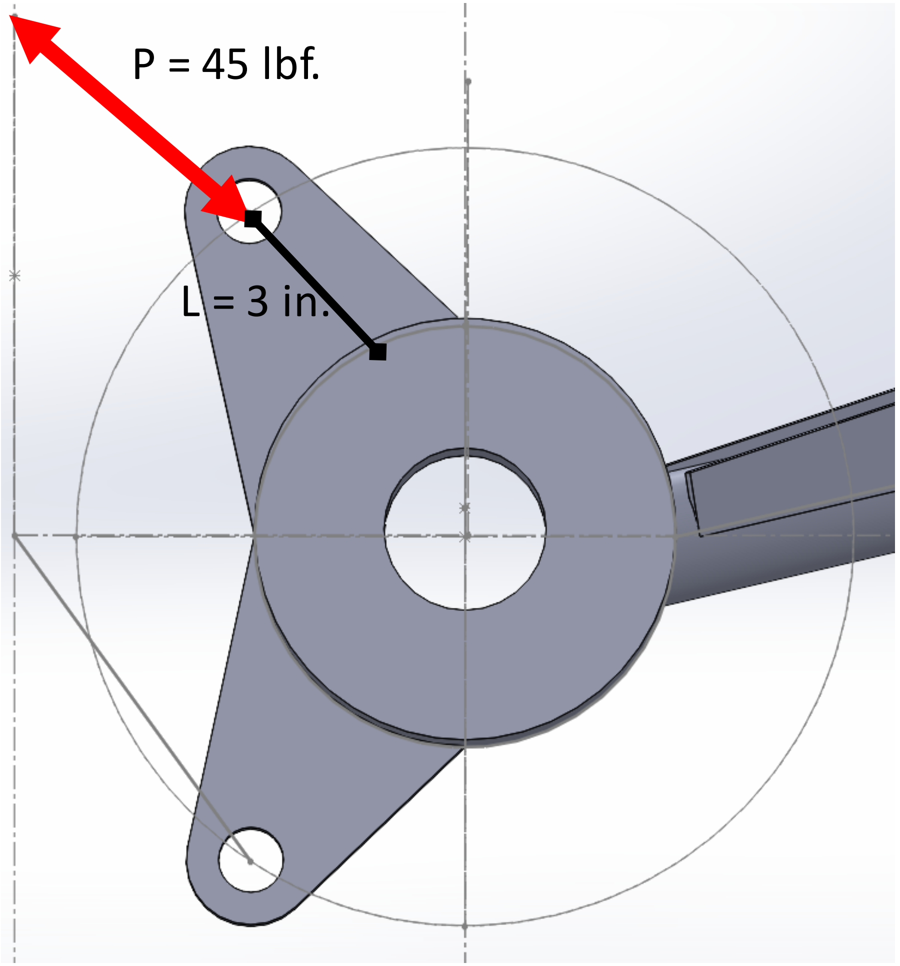
CV – Axle max/min length



Change in length needed for suspension geometry	Change in length of CV Axle	Change in U-joint (Non–spline)
1.5 in	1-3 in	0 in

Engineering Calculations – Rear 5

Knuckle Design [97]



$$\sigma = Normal\ Stress, psi$$
$$\tau = Shear\ Stress, psi$$
$$P = External\ Applied\ Load, lbf$$
$$L = Linear\ Distance, in$$
$$h = Size\ of\ Weld, in$$
$$l = length\ of\ Weld, in$$

$$\sigma_b = \frac{6PL}{lh^2} = \mathbf{1,270.59\ psi}$$

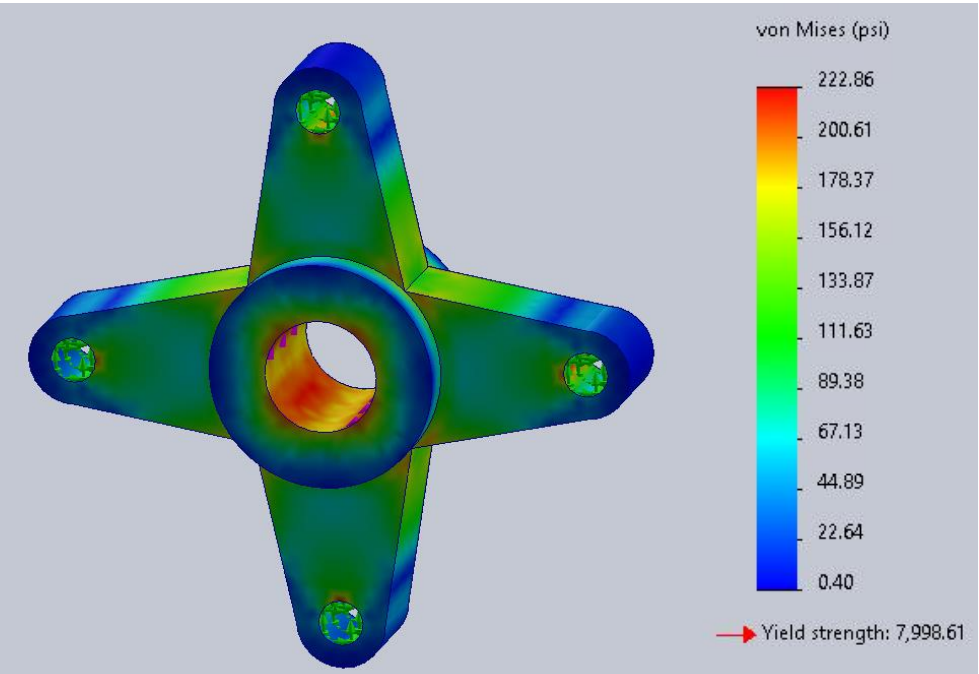
$$\tau = \frac{P}{lh} = \mathbf{35.29\ psi}$$

NORTHERN ARIZONA UNIVERSITY

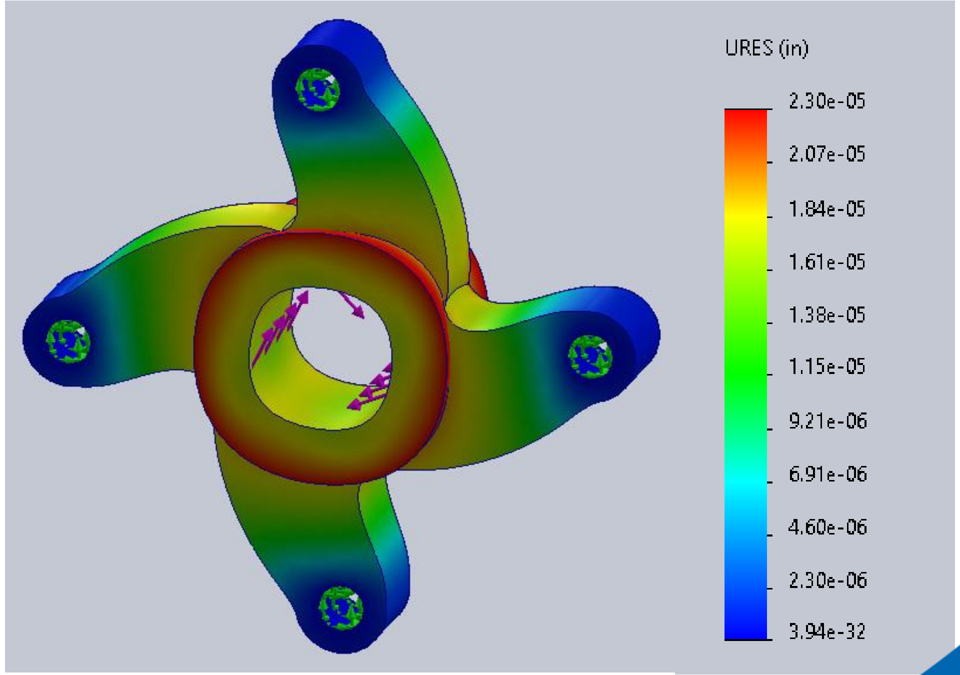
Engineering Calculations – Rear 6

Hub Design

Stress Analysis



Displacement Analysis



Engineering Calculations – Rear 7

Hardware

Black-Oxide Alloy Steel

- $S_{UT} = 90,000\ psi$
- Tensile = 170,000 psi
- Mass density = 0.2782 lb/in^3
- Cheap!
- $1.82 per screw
- Many size options

18-8 Stainless Steel

- $S_Y = 31,200\ psi$
- $S_{UT} = 73,200\ psi$
- $\rho = 0.2890\ lb/in^3$
- $7.58 per screw
- Corrosion Resistant

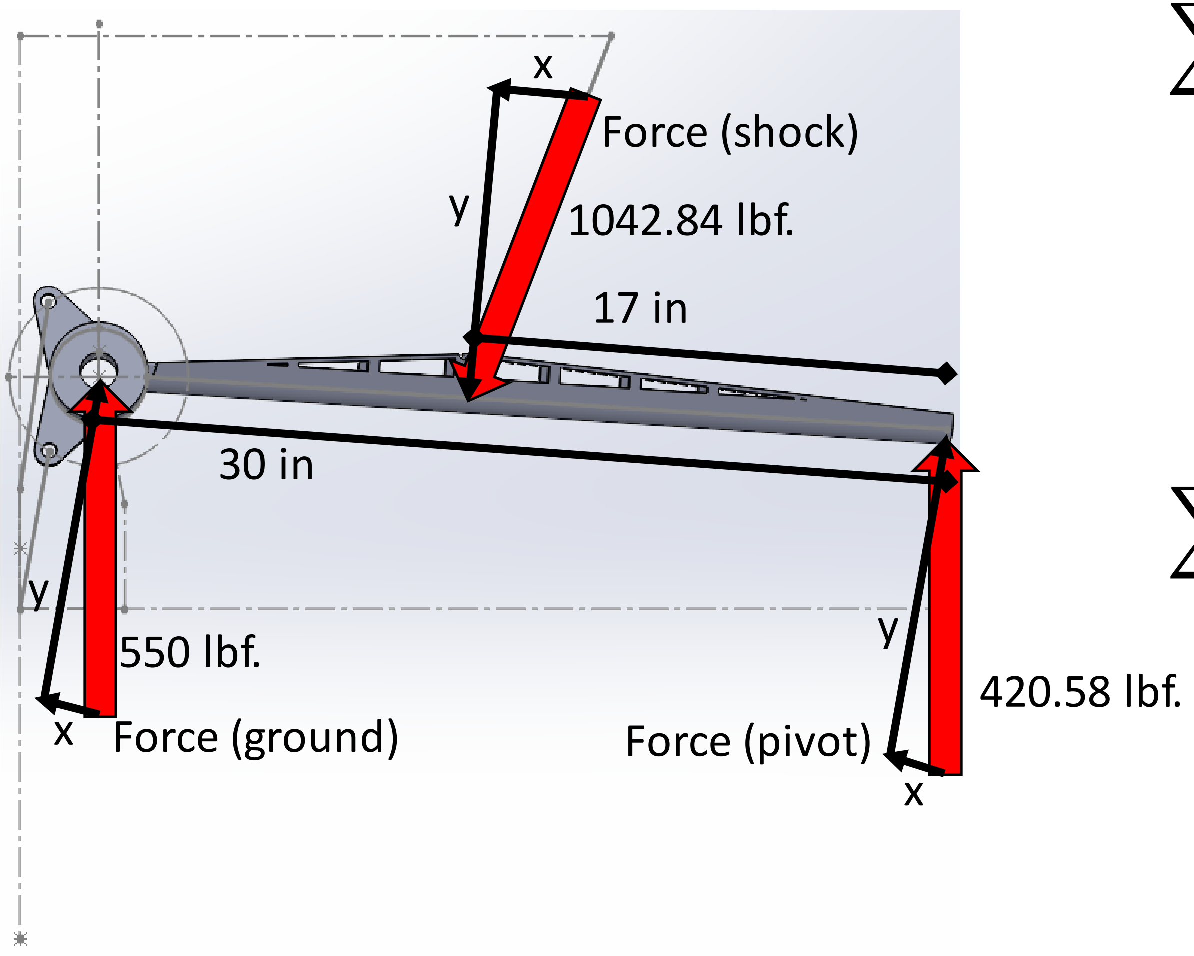
Grade 2 Titanium

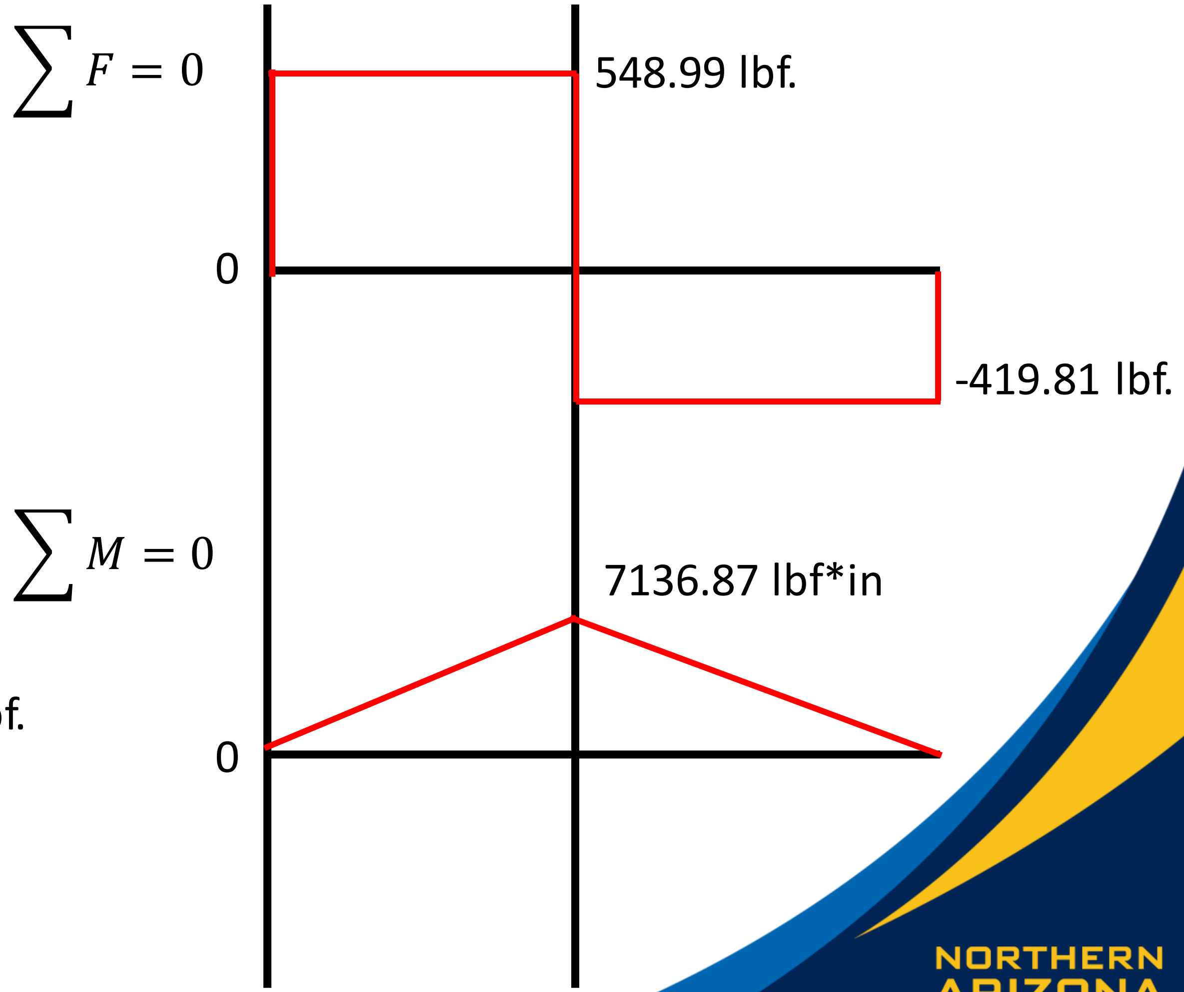
- $S_Y = 39,900 - 59,500\ psi$
- $S_{UT} = 49,900 psi$
- 40% Lighter than Carbon Steel
- $\rho = 0.1629\ lb/in^3$
- Expensive!
- $54.54 per screw

NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Rear 8

Trailing Link Design



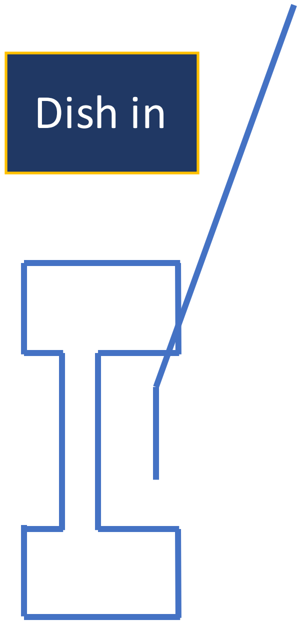


NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Rear 9

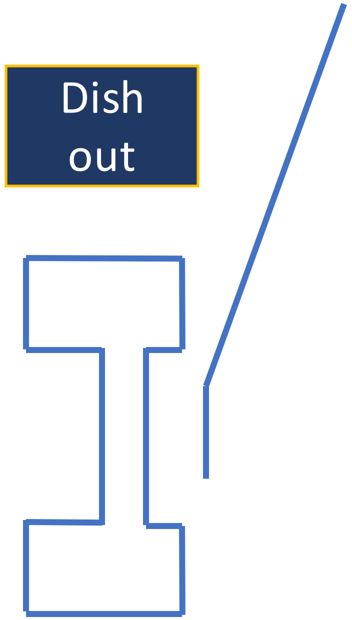
Wheel Dish Design

Dish in



Dish in will cause interference issues with side wall of tire and the trailing arm

Dish out



Dish out makes sense for rear since the brakes are being ran onboard

Concept Evaluation

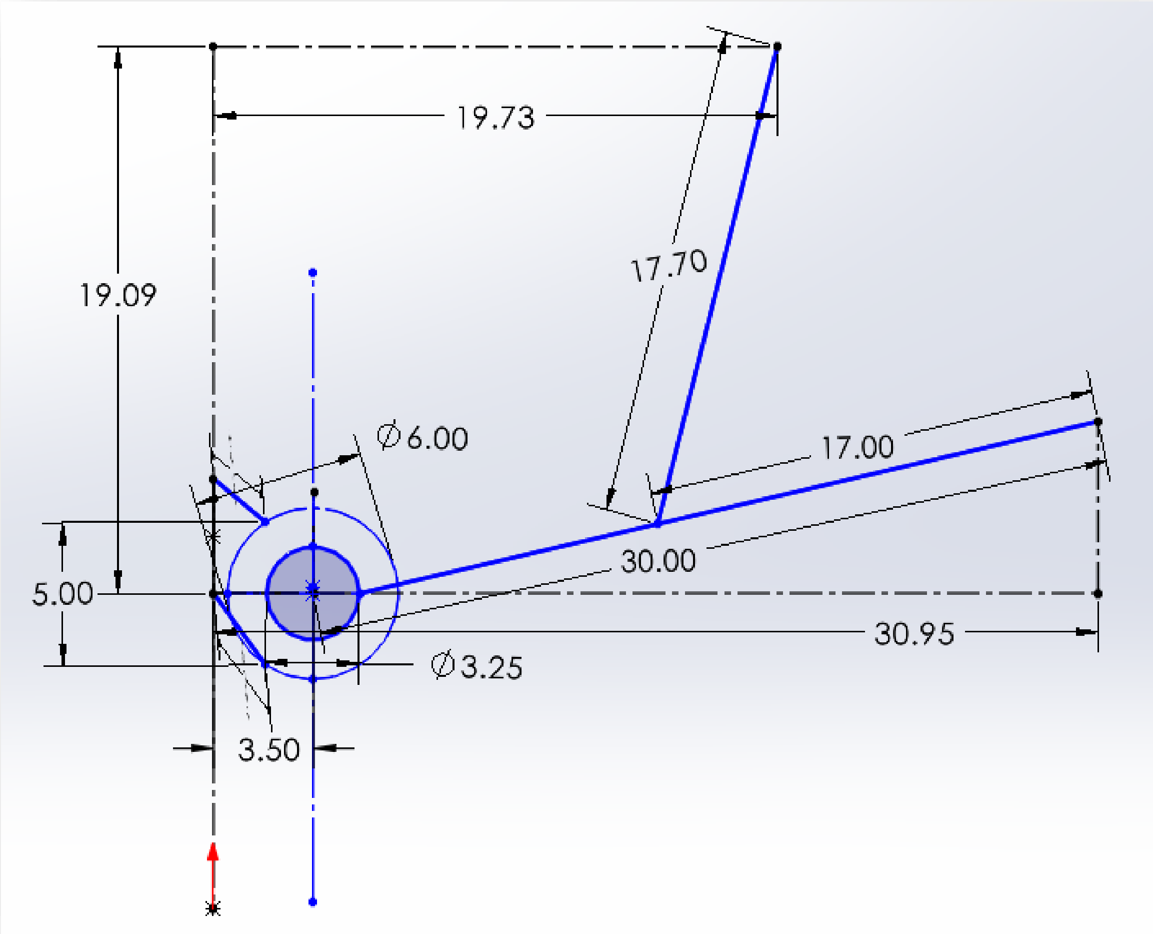
	Variants					
Subsystem	**1**	**Results**	**2**	**Results**	**3**	**Results**
Camber	Positive	✓	Negative	✓	Neutral	✓
Toe	In	✗	Out	✗	Neutral	✓
Camber Link Material	Carbon Fiber	✗	Steel	✓	Alumminum	✓
Axle types	CV Axle	✓	Dogbone	✗	U-Joint axle	✗
Knuckle Design	CNC Machined Aluminum	✗	Steel	✓	Attach knuckle to trailing arm	✓
Hub	Aluminum (machined)	✓	Cast	✗	NA	
Hardware	Stainless Steel	✗	Steel	✓	Titanium	✗
Trailing Link Design	Boxed Sheet Metal	✓	Steel Tubing	✓	CNC Machined Aluminum	✗
Wheel dish	Dish out	✓	Dish in	✗	NA	

Concept Evaluation

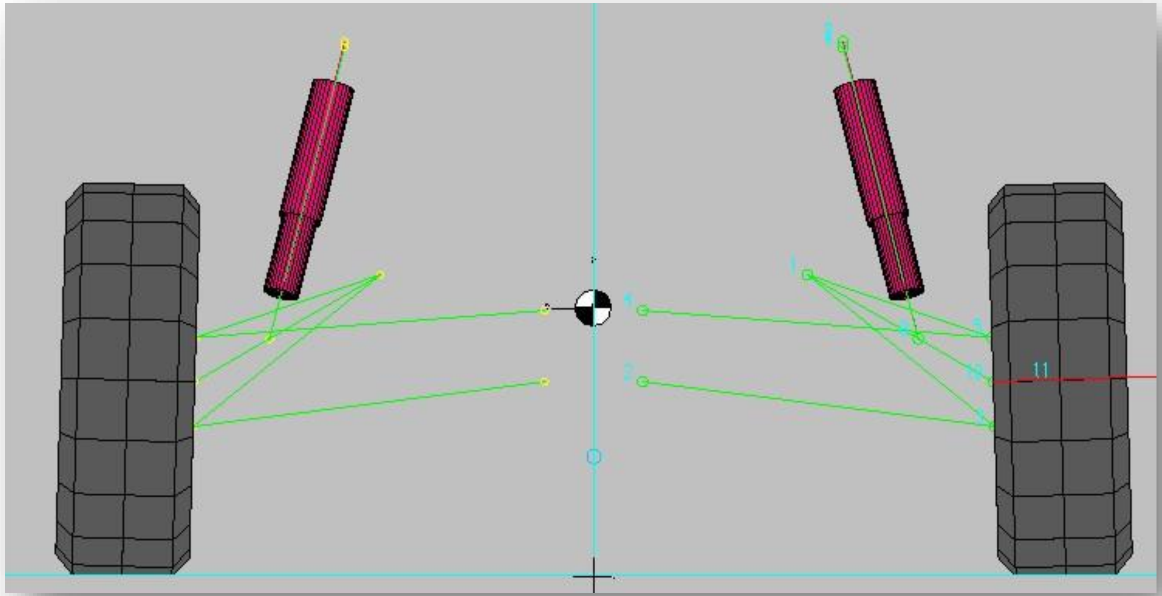
	Variants					
Subsystem	**1**	**Results**	**2**	**Results**	**3**	**Results**
Camber	Positive	✓	**Negative**	✓	Neutral	✓
Toe	In	✗	Out	✗	**Neutral**	✓
Camber Link Material	Carbon Fiber	✗	Steel	✓	**Alumminum**	✓
Axle types	**CV Axle**	✓	Dogbone	✗	U-Joint axle	✗
Knuckle Design	CNC Machined Aluminum	✗	**Steel**	✓	**Attach knuckle to trailing arm**	✓
Hub	**Aluminum (machined)**	✓	Cast	✗	NA	
Hardware	Stainless Steel	✗	**Steel**	✓	Titanium	✗
Trailing Link Design	**Boxed Sheet Metal**	✓	**Steel Tubing**	✓	CNC Machined Aluminum	✗
Wheel dish	**Dish out**	✓	Dish in	✗	NA	

NORTHERN ARIZONA UNIVERSITY

Final Design Discussion

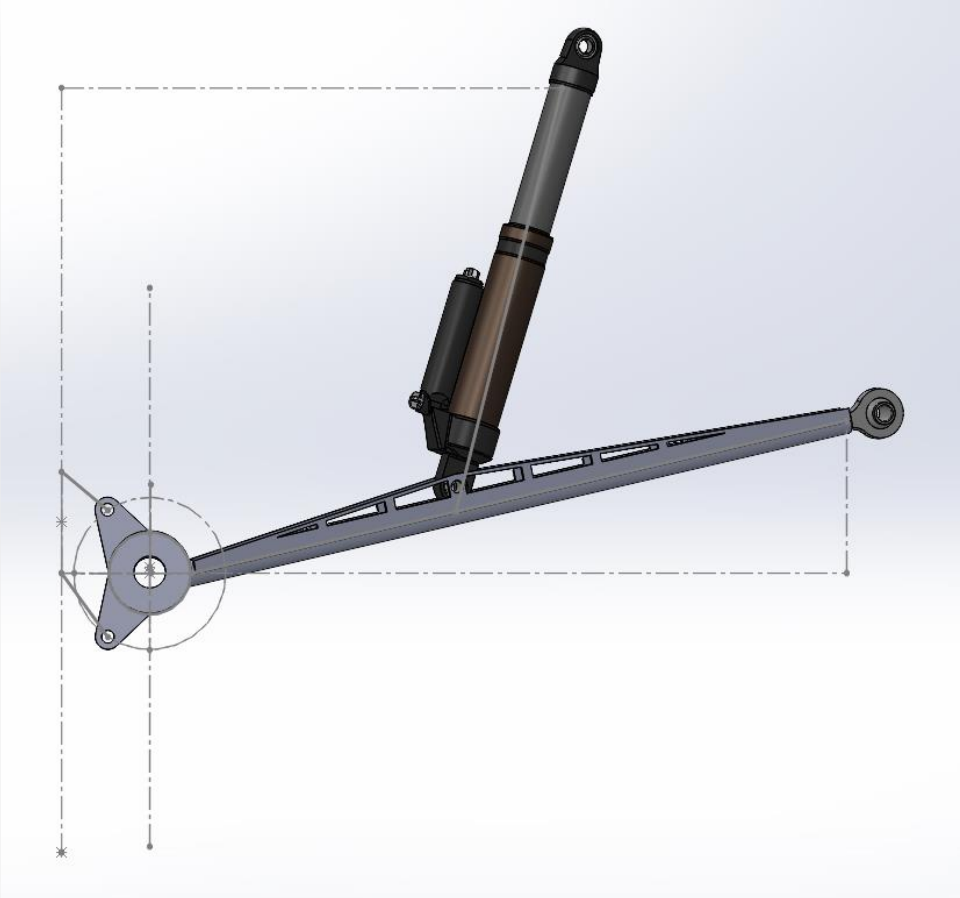


Right view wire frame dimensions

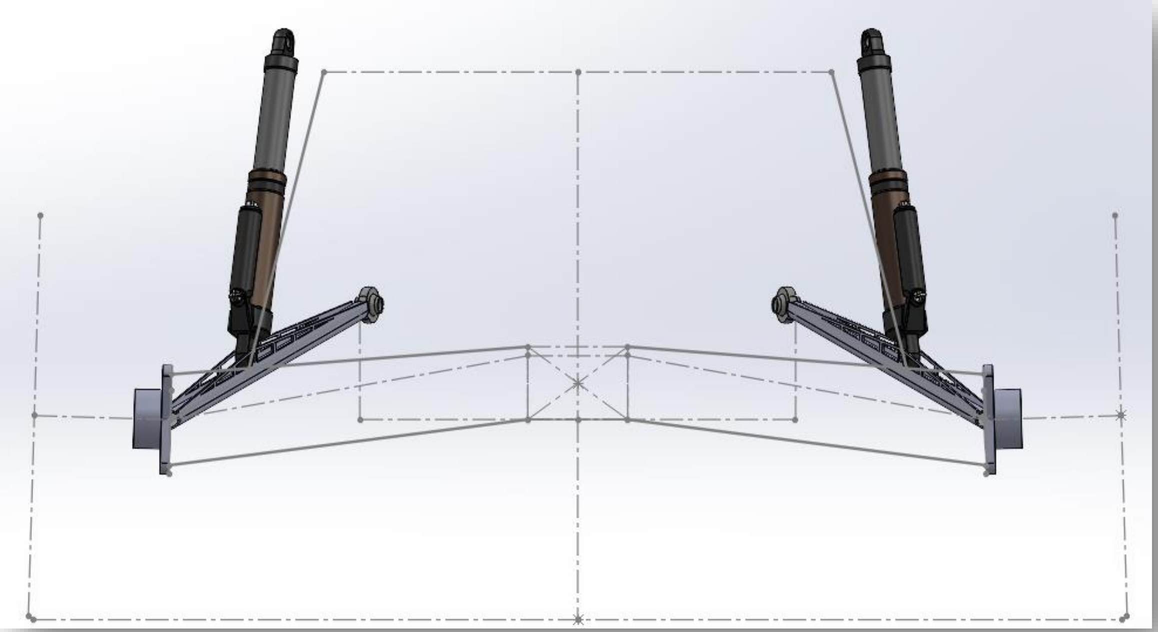


Rear view suspension geometry in Shark

Final Design Discussion



Right view of trailing link assembly



Rear view of trailing link assembly

NORTHERN ARIZONA UNIVERSITY

Bill of Materials – Rear

Suspension	Quantity	Cost	Drive	Quantity2	Cost2	Overall Total:
Trailing link	2	$70.00	CV axles	2	$110.00	
Camber link	4	$50.00	Knuckles	2	$120.00	
Shocks	2	$0.00	CV bearings	2	$0.00	
Rod ends	10	$80.00	Hubs	2	$400.00	
Pivot hardware	28	$50.00	Wheels	2	$0.00	
Frame mounts	8	$30.00	Tires	2	$0.00	
PVC	1	$10.00	Wheel nuts	8	$20.00	
Spares	4	$120.00	CV hardware	2	$0.00	
			Spares	3	$200.00	
Total:	59	$410.00	**Total:**	25	$850.00	**$1,260.00**

NORTHERN ARIZONA UNIVERSITY

Rear End Budget

	Category	Relevant Items	Approximated Cost
1	**Vehicle Expenses**	Suspension System Drive System **Estimated Total**	\$410 \$850 **\$1,260**
2	**Spare Parts**	Camber links, rod ends, cv axles, hubs	\$320
3	**Competition Expenses** Rear Sub-team	Registration, travel (hotel rooms, vehicle rentals, gas, etc.)	\$1,125
4	**Contingency (5%)**	Unpredicted Expenses	\$135
		Total	**\$2,840**

NORTHERN ARIZONA UNIVERSITY

Drivetrain Team

Henry Van Zuyle, Donovan Parker, Ryan Fitzpatrick, Jarett Berger

NORTHERN ARIZONA UNIVERSITY

Black Box Model - Drivetrain

Material In: Gas, Air

Energy In: None

Signal In: Throttle Position, Brake Position, Selector Position

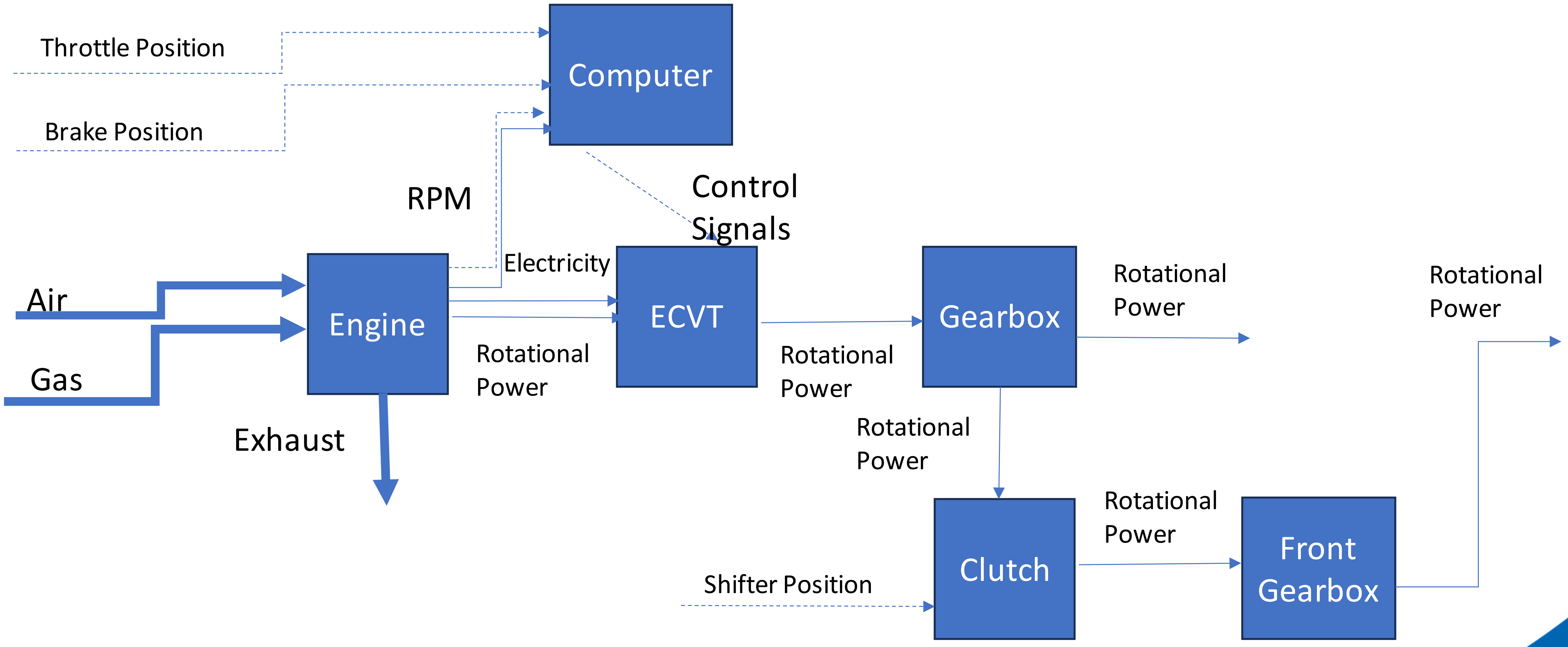
Selectable 4WD Power Transmission

Material Out: Exhaust

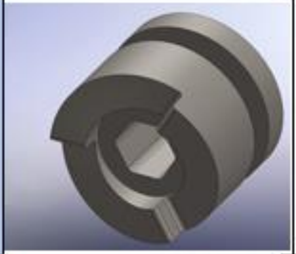
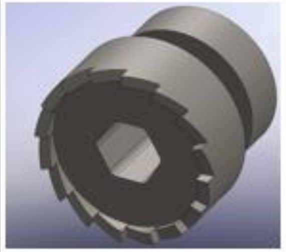
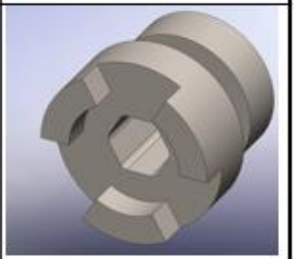
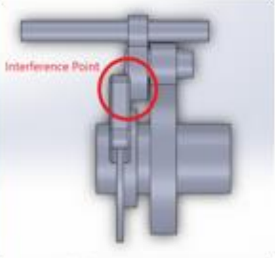
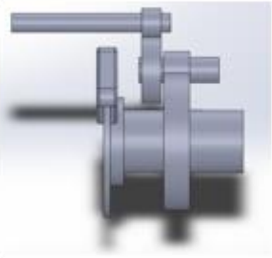
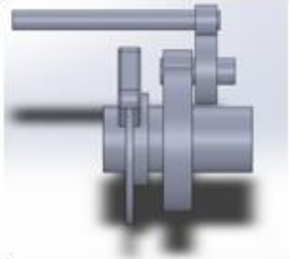
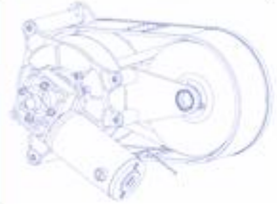
Energy Out: Rotation At The Wheels

Signal Out: None

Functional Model - Drivetrain



Concept Generation - Drivetrain

Concept Generation	Variants		
Subsystem	*1*	*2*	*3*
CV Joint Integration			
Dog Clutch Choice			
Rear Brake Integration			
CVT System Choice			

Sub-System Influence

Compact Front End and Reduce Weight

Selectable 4-Wheel Drive

Optimize Rear End Geometry Reduce Weight

Change Gears and Allow a High Total Ratio

Engineering Calculations – Drivetrain 1

Equations, Tools, & Examples

Equations:

- $\Delta r = r_o - r_i$, $\Delta d = 2 \times \Delta r$
- $F = \frac{T}{r_i/12} = 1742.0 \text{ lbs}$
- $\sigma = \frac{F}{A} = 11{,}531 \frac{lb}{in^2}$
- $n = \frac{\pi S \Delta d^2}{4F} = 28.84$
- $a = \frac{F}{m} = 553.35 \frac{ft}{s^2}$

Where:

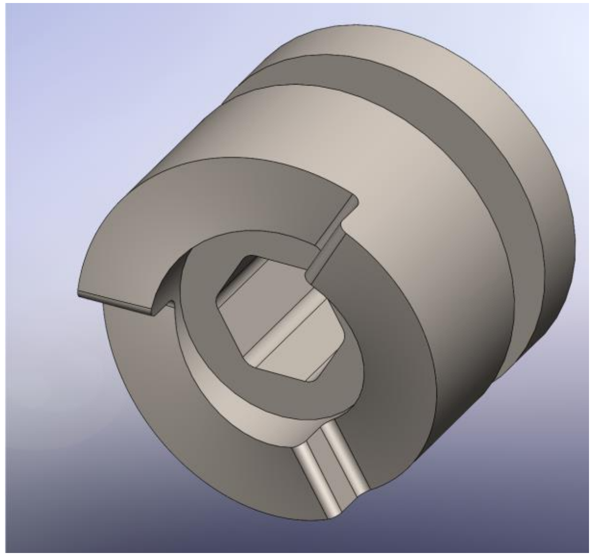
T = Torque
F = Force
σ = Normal Stress on Teeth
A = Planar Surface Area on Teeth
a = Acceleration
r = Radius, d = Diameter
m = mass
S = Material Strength
n = Factor of Safety

Analysis Tool: MATLAB

```
clc; clear; close all;
% All units are IPS
% Material: 4130 Steel Annealed at 865C (Non Heat Treated)
%Knowns
%{
Torque, Material Strength, Outer Radius, Inner Radius, Tooth Surface
Area, Mass
%}
T=126.66; S=81221.13; r_o=1.5; r_i=0.872516; A=0.151073; m=3.148067;
%Calculations
% Radius Difference
dr=r_o-r_i; % inches
% Force
F=T/(r_i/12); %pounds
% Normal Stress on teeth on contact
sigma_t=F/A; %psi
% Factor of Safety
n=((pi*S*(2*dr^2))/(4*F)); %unitless
% Engage Acceleration
a=F/m; %ft/sec^2
```

Spiral Jaw Dog Clutch

- Forces
- Tooth Normal Stress
- Factor of Safety
- Acceleration

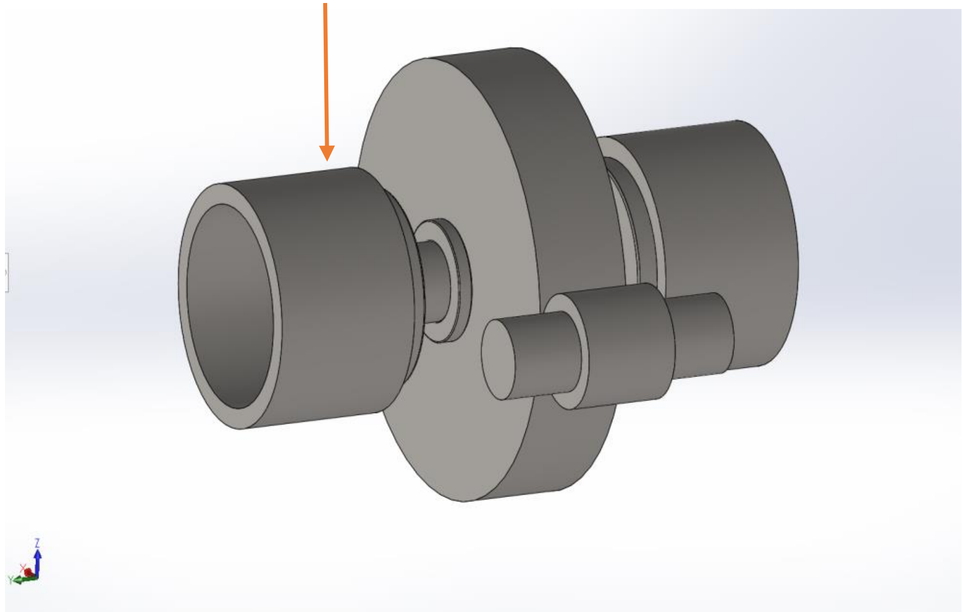


Modeling Material: 4130 Steel Annealed at 865C

Engineering Calculations – Drivetrain 2

CV Joint Integration

Radial Load



Analysis

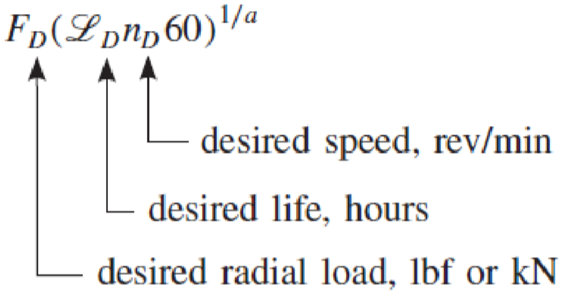
```
H = 11.45; % Horsepower (HP)
N = 3600; % Desired speed (rev/min)
G1 = 17; % Number of teeth
G2 = 65; % Number of teeth
D = 12; % Diametral Pitch (teeth/in)
p = 20; % Pressure Angle
DP1 = G1/D; % Diametral Pitch for Gear 1
DP2 = G2/D; % Diametral Pitch for Gear 2
Ti = (550*H*60)/(N*2*pi)*12; % Input Torque (lb*in)

Rx = Ti/(DP2/2); % Reaction force in x direction
Ry = Rx*tan(p); % Reaction force in y direction
R = sqrt(Rx^2+Ry^2); % Resultant Bearing Reaction Force
disp(R) % Displays Bearing Reaction Force

Fr = 39.3822; % Bearing Reaction Force
a = 1/3; % Bearing load life
LD = 1000; % Desired design life (hours)
LR = 10^6; % Rating life (hours)

L = LD*N*60; % Desing life
C = Fr(L/(LR)^a); % Catalog Load Rating Equation
disp(C) % Displays Catalog Load Rating
```

Equations



$$C_{10} = F_R = F_D \left(\frac{L_D}{L_R}\right)^{1/a} = F_D \left(\frac{\mathcal{L}_D n_D 60}{\mathcal{L}_R n_R 60}\right)^{1/a}$$

Results

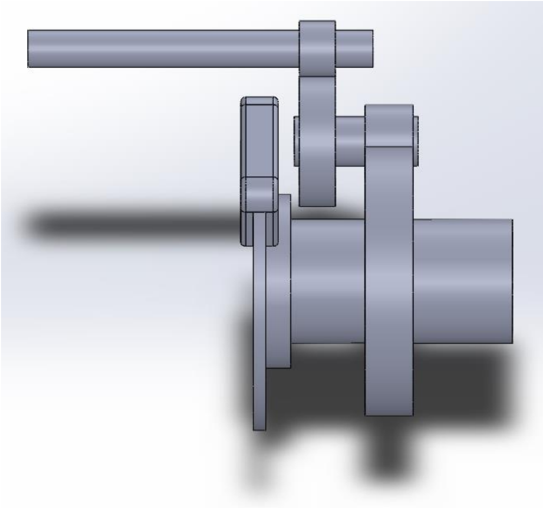
Sprag nominal torque = **75lbf**

Bearing reaction force = **39.7lb**

Catalog load rating = **8506.56lbf** or **37.8kN**

Engineering Calculations – Drivetrain 3

Equations, Tools, & Examples



Option 2 : Optimal Gearbox Geometry

```
d_gearbox = gear5_pitch_diameter ; % Depth of gearbox casing at point of
 interest (in)
t_gearbox = 0.125 ; % Thickness of gearbox casing
L_reduction = (0.5*gear4_pitch_diameter + gear5_pitch_diameter) -
 (0.5*gear3_pitch_diameter) ; % Length of casing material reduction (in)
w_reduction = gear_width_23 + 0.1 ; % Width of casing material reduction (in)
V_reduction =
 (2*(L_reduction*w_reduction*t_gearbox))+(w_reduction*d_gearbox*t_gearbox) ; %
 Volume of reduced material (in^3)
density_Al = 0.0975 ; % Density of 6061 T6 Aluminum (lb/in^3)
Weight_reduction_lbs = V_reduction*density_Al % Weight of gearbox casing
 removed (lbs)
density_St = 0.284 ; % Density of 4140 Steel (lb/in^3)
Weight_shaftA_increase_lbs = (1.0667*((pi/4)*0.75^2))*density_St % Weight of
 Shaft A material increase (lbs)
Weight_Frontshaft_increase_lbs = (1.0667*((pi/4)*1^2))*density_St % Weight of
 Front Shaft material increase (lbs)
net_Weight_reduction_lbs = Weight_reduction_lbs - Weight_shaftA_increase_lbs -
 Weight_Frontshaft_increase_lbs % Net weight reduction of Option 3 compared to
 Option 2.


Weight_reduction_lbs =

    0.1512


Weight_shaftA_increase_lbs =

    0.1338


Weight_Frontshaft_increase_lbs =

    0.2379


net_Weight_reduction_lbs =

   -0.2205
```

MATLAB Script for Calculations

Results of Calculations:

Net Weight Reduction of Option 3 = -0.2205 lbs

This means that Option 3 (flipping stage 1 to passenger side of vehicle) results in a weight GAIN of 0.2205 pounds. Option 2 eliminates the brake caliper interference from Option 1 and weighs less than Option 3 with less design alterations than Option 3.

Equations:

$$Weight = V_{component} * \rho_{material}$$

Where... $V = Volume\ (in^3)$

$$\rho = density\ (\frac{lb}{in^3})$$

$$\rho_{steel,4140} = 0.285\ \frac{lb}{in^3}$$

$$\rho_{aluminium,6061\ T6} = 0.0975\ \frac{lb}{in^3}$$

NORTHERN ARIZONA UNIVERSITY

Engineering Calculations – Drivetrain 4

ECVT Motor Specs

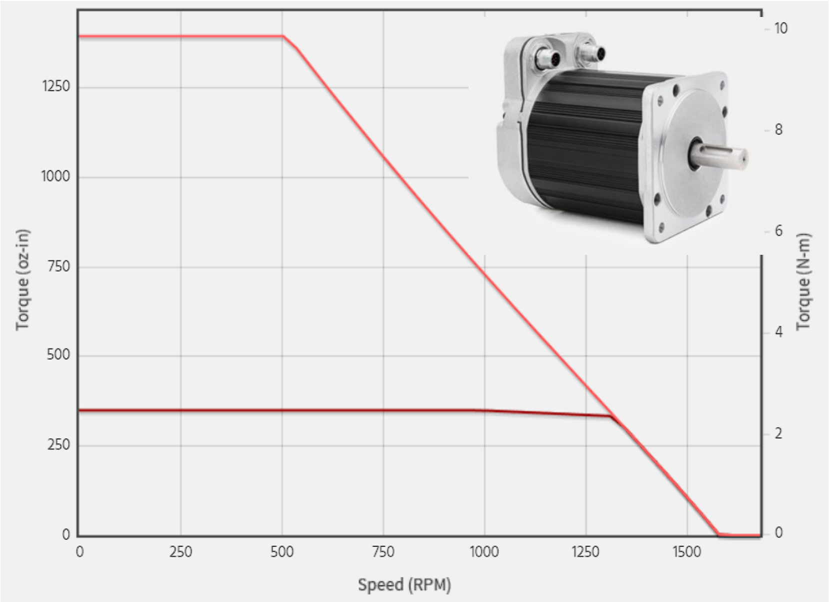
$$T_R = \frac{F d_m}{2}\left(\frac{l + \pi f d_m}{\pi d_m - f l}\right)$$

- Force = 429.7 Lbf
- ½-10 lead screw
- Coef. Friction = .2

Max torque required from motor is 448 oz in

These equations calculate what torque output the ECVT Control motor needs to generate.

Hudson M-3432F-LS-08D



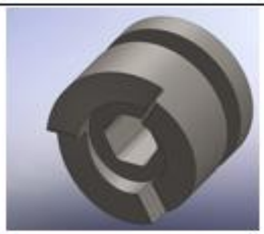
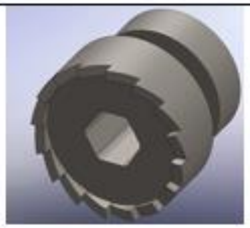
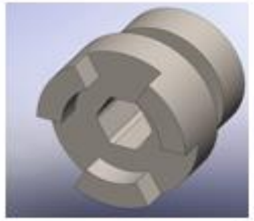
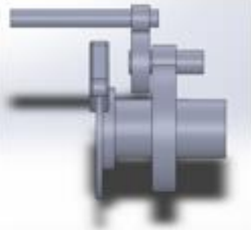
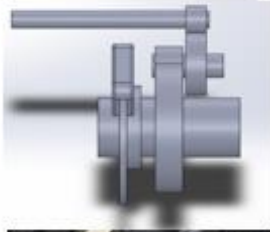
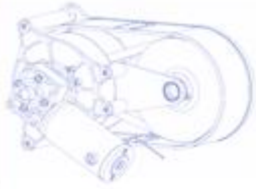
- P=IV

- I = 12A
- V = 48V

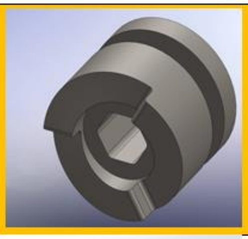
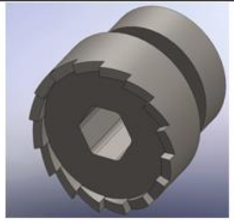
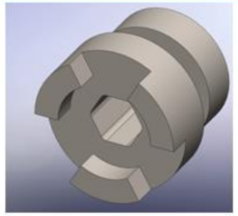
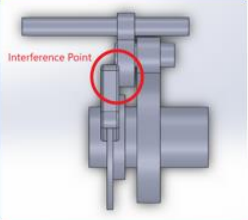
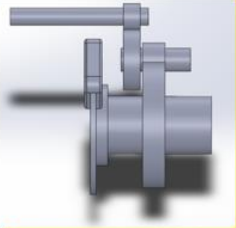
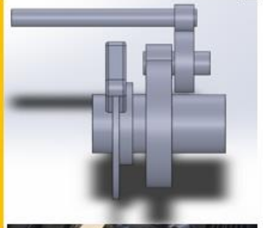
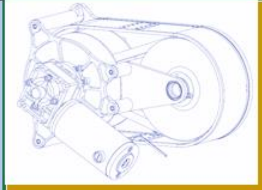
- Max motor power is 576 watts

NORTHERN ARIZONA UNIVERSITY

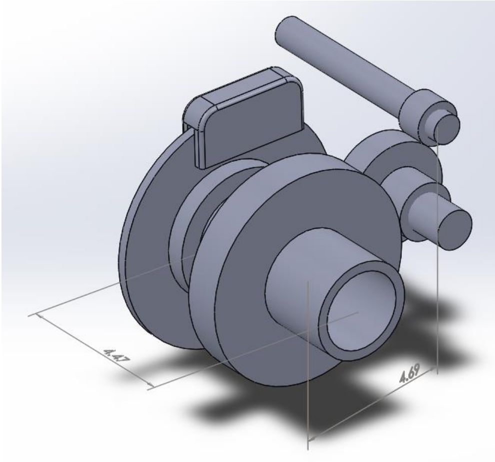
Concept Evaluation - Drivetrain

Concept Evaluation	Variants					
Subsystem	*1*	*Rating*	*2*	*Rating*	*3*	*Rating*
CV Joint Integration		✗		✗		✓
Dog Clutch Choice		✓		✗		✗
Rear Brake Integration		✗		✓		✗
CVT System Choice		✓		✗		✗

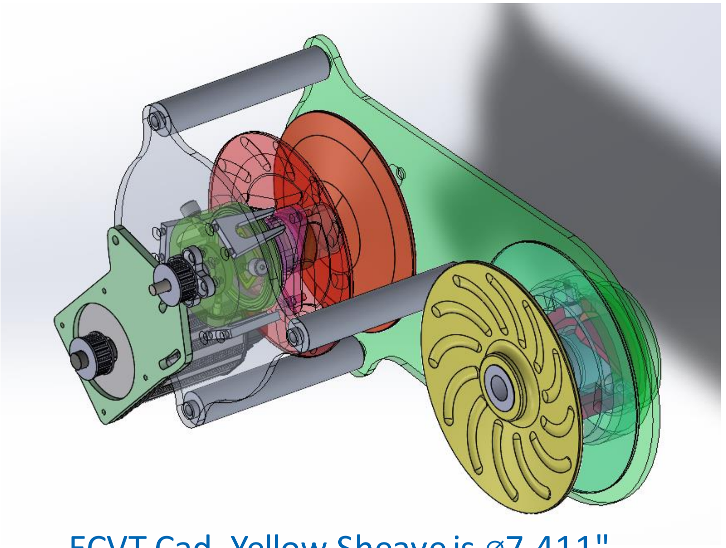
Final Design Discussion - Drivetrain

Concept Evaluation	Variants					
Subsystem	*1*	*Rating*	*2*	*Rating*	*3*	*Rating*
CV Joint Integration		✗		✗		✓
Dog Clutch Choice		✓		✗		✗
Rear Brake Integration		✗		✓		✗
CVT System Choice		✓		✗		✗

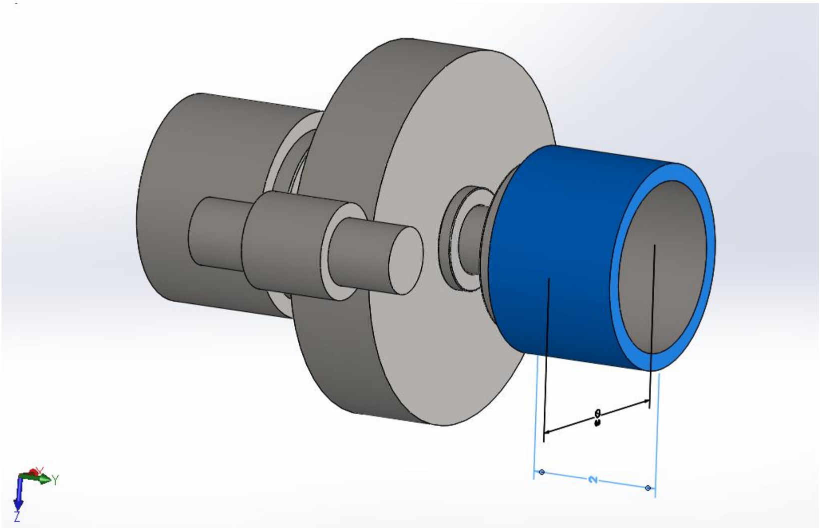
Final Design Visualization - Drivetrain



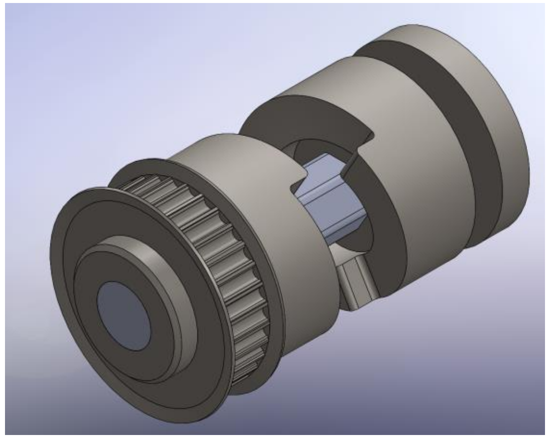
Rear Gearbox CAD, Approximate Dimensions Are: 6"x8"x4.5"



ECVT Cad, Yellow Sheave is ⌀7.411"



Front Gearbox CAD, CV Cup Width is 2"



Four-Wheel Drive Integration, 3” Diameter Belt Pulley

NORTHERN ARIZONA UNIVERSITY

Bill of Materials – Drivetrain

Clutch System			
Part	Quantity	Cost ($)	Total $
Driven Side Clutch	1	59.00	59.00
Driving Side Clutch	1	59.00	59.00
Shift Fork	1	21.49	21.49
High Strength HTD Timing Belt	2	99.00	198.00
3in Belt Pulley	1	5.35	5.35
4.5in Belt Pulley	1	10.92	10.92
Idler Pulleys	11	52.25	574.75
Housing	1	25.43	25.43
Shifter	1	32.99	32.99
Linkage Cables	1	78.74	78.74
Cable Tabs	10	27.09	270.90

ECVT			
Part	Quantity	Cost $	Total $
ECVT Primary Shaft	1	25.00	25
Ecvt Primary Fixed Sheave	1	70.00	70
ECVT Primary Mobile Sheave	1	70.00	70
ECVT Primary Square Bushing	1	25.00	25
ECVT Primary Sliding Shaft	1	40.00	40
ECVT Primary Lead Screw Flange	1	50.00	50
ECVT Primary Lead Screw nut	1	75.00	75
ECVT Primary Lead SCrew	1	25.00	25
ECVT Primary Mobile Sheave Bushing	1	10.00	10
ECVT Secondary Shaft	1	50.00	50
ECVT secondary Fixed Sheave	1	75.00	75

ECVT			
Part	Quantity	Cost $	Total $
ECVT Secondary Moving Sheave	1	75	75.00
ECVT Secondary Cam	1	50	50.00
ECVT Secondary Cam Nut	1	15	15.00
ECVT Backplate	1	60	60.00
ECVT Main Mounting Plate	1	30	30.00
ECVT Main Mount Standoff	3	20	60.00
ECVT Lead Screw Bearing Mount	1	4	4.00
ECVT Motor Mount PLate	1	15	15.00
ECVT Controll Pulley	2	5	10.00
ECVT Lead Screw Nut Flange Fork	3	2	6.00
Engine	1	900	900.00

Summary	
Sub-System	Total ($)
Clutch System	1336.57
ECVT	3210.00
Front Gearbox	794.00
Rear Gearbox	1018.55
Total	6359.12

Front Gearbox			
Part	Quantity	Cost ($)	Total $
Bearings, SKF 210-ZNR	4	80	320
Sprag, GMN FK6205-2RS	2	80	160
Circlips	2	2	4
Gear 1	1	30	30
Gear 2	1	50	50
Housing	2	75	150
Shaft	2	30	60
Hardware	1	20	20

Rear Gearbox			
Part	Quantity	Cost $	Total $
Bearings, SKF 210-ZNR	2	80	160
Bearings, 6206	2	35	70
Bearings, 6208	1	80	80
Bearings, 6212	1	175	175
Gears 2-4	1	74.56	74.56
Gear 5	1	290	290
Gearbox Casing (6061 Aluminum)	1	108.99	108.99
Shaft (4140 Steel)	2	30	60

ECVT			
Part	Quantity	Cost $	Total $
Control Motor	1	500.00	500
Control Motor Cables	2	90.00	180
Arduino	1	70.00	70
Motor Controller	1	220.00	220
Boost converter	1	60.00	60
Buck Converters	2	10.00	20
Sensors	1	50.00	50
Hardware	1	20.00	20
Bearings	1	170.00	170
Belts	2	90.00	180

Drivetrain Budget

	Category	Relevant Items	Approximated Cost
1	**Vehicle Expenses**	Motor Front Gearbox Rear Gearbox ECVT 4WD **Estimated Total**	\$900 \$794 \$1018.55 \$2310 \$1336.57 **\$6359.12**
2	**Spare Parts**	Hardware, Gears, CV axles	\$500
3	**Competition Expenses** Drivetrain Sub-team	Registration, travel (hotel rooms, vehicle rentals, gas, etc.)	\$1,125
4	**Contingency (5%)**	Unpredicted Expenses	\$300
		Total	**\$8284.12**

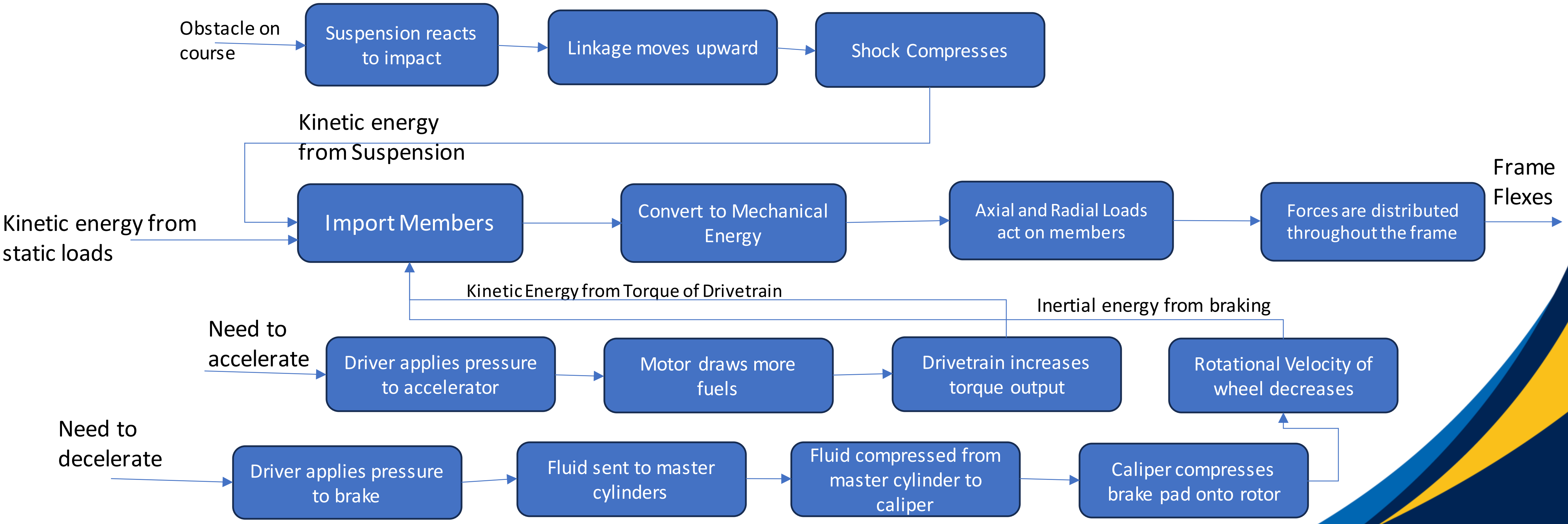
NORTHERN ARIZONA UNIVERSITY

Frame Team

Cooper Williams, Gabriel Rabanal, Antonio Sagaral

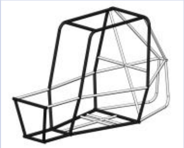
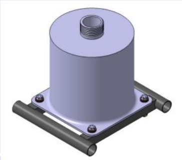
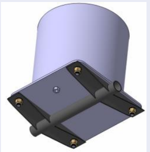
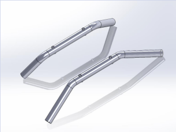
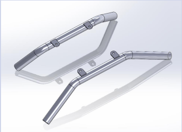
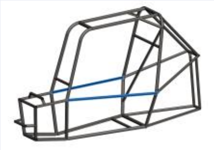
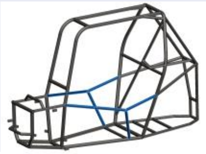
Black Box Model

Functional Model



NORTHERN ARIZONA UNIVERSITY

Concept Generation

Subsystem	Variant 1	Variant 2
Frame Type		
Fuel Tank Mounting		
Seat Design		
Side Impact Member		
Tube Material	AISI 4130	AISI 1018

Engineering Calculations – SIM

Equations, Tools, & Examples

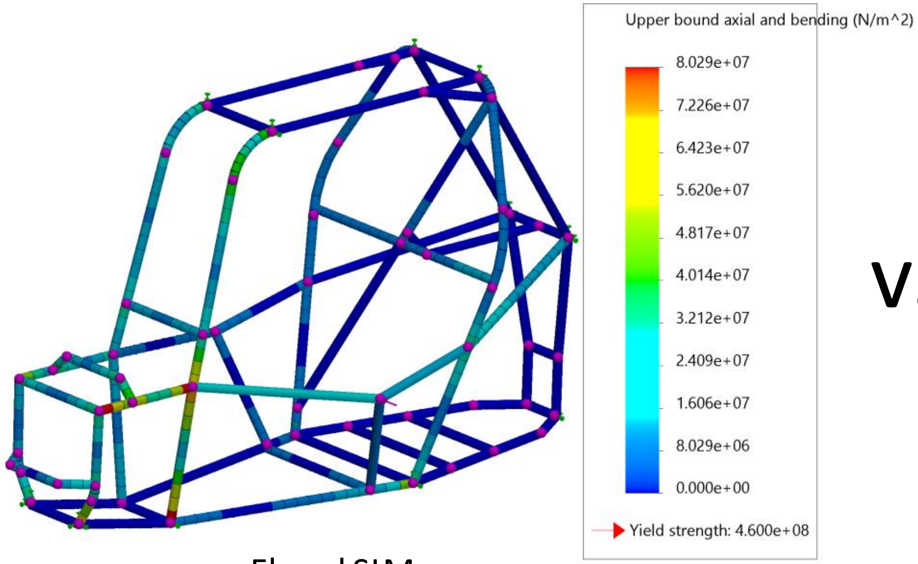
Flared SIM's
- Fewer members in parallel
- Overall vehicle length shortened
- Lower Egress time

	Variants	
Engineering Recs	*Flared SIM*	*Straight SIM*
Maximum Width (in)	32	28
Total Primary Tubing (ft)	45	48
Total Secondary Tubing (ft)	45	49
Overall Vehicle Length (in)	67	75

Governing Equations:

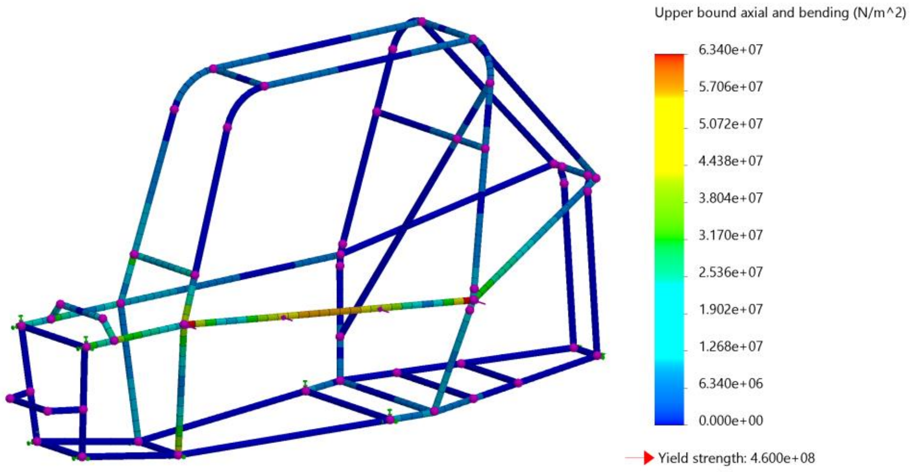
$$I = \frac{\pi}{4}\left(R^4 - R_i^4\right)$$

$$P = \frac{F}{A}$$



Flared SIM

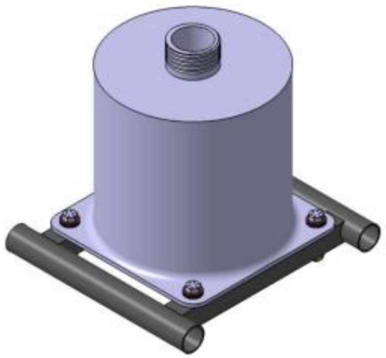
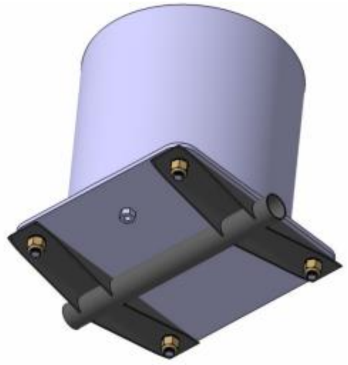
vs.



Straight SIM

Engineering Calculations

Equations, Tools, & Examples

	Variants	
Engineering Recs	*Rectangular Tubing*	*C-Brackets*
Figure		
Material Volume (in^3)	6.9492	6.289
Weight (lb)	1.97357	1.78608
# of Weld Jigs	2-3	1-2
Types of alternative materials	1	0

$$Volume = (\pi {r_o}^2 - \pi {r_i}^2) * L$$

Rectangular tubing substituted for circular tubing for simplicity

C-Bracket volume calculated using Solidworks tools

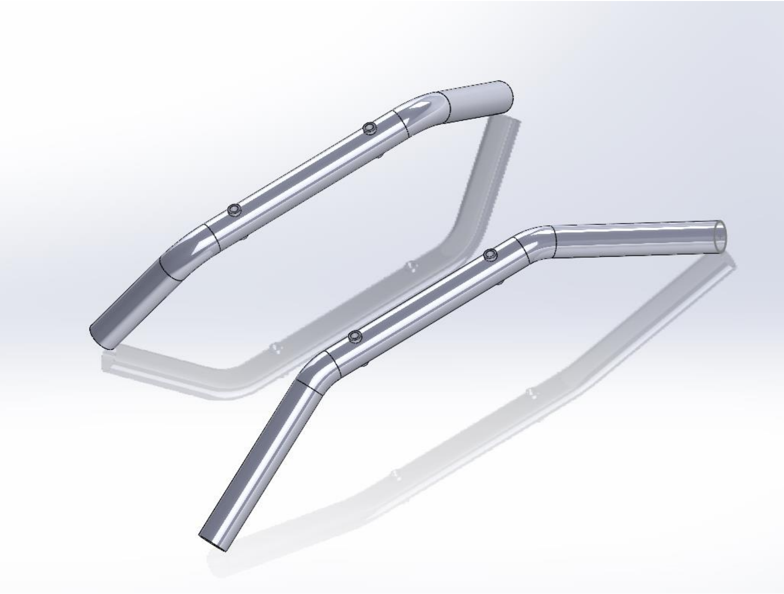
$$Weight = \frac{\rho}{V}$$

Engineering Calculations – Lower Seat Mount

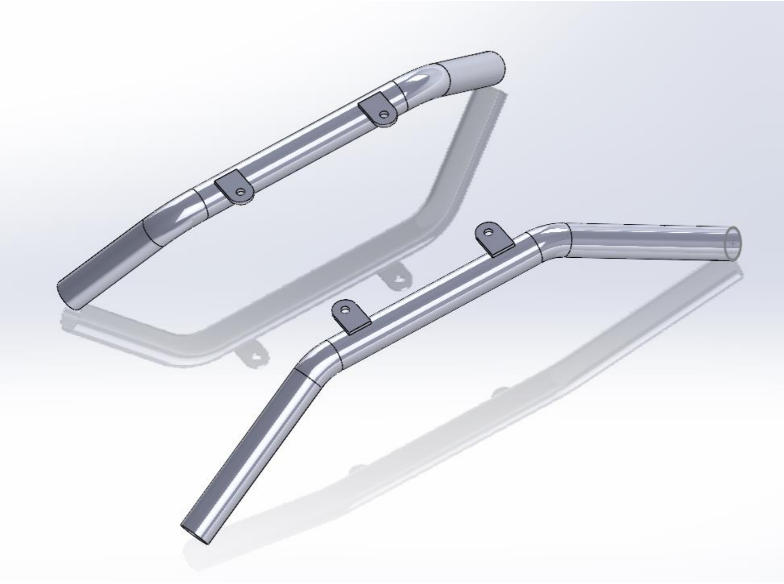
Equations, Tools, & Examples

	Variant 1	Variant 2
Total Material volume (in³)	4.27	4.35
Ease of manufacturing	+	-

Variant 1



Variant 2



Concept Evaluation

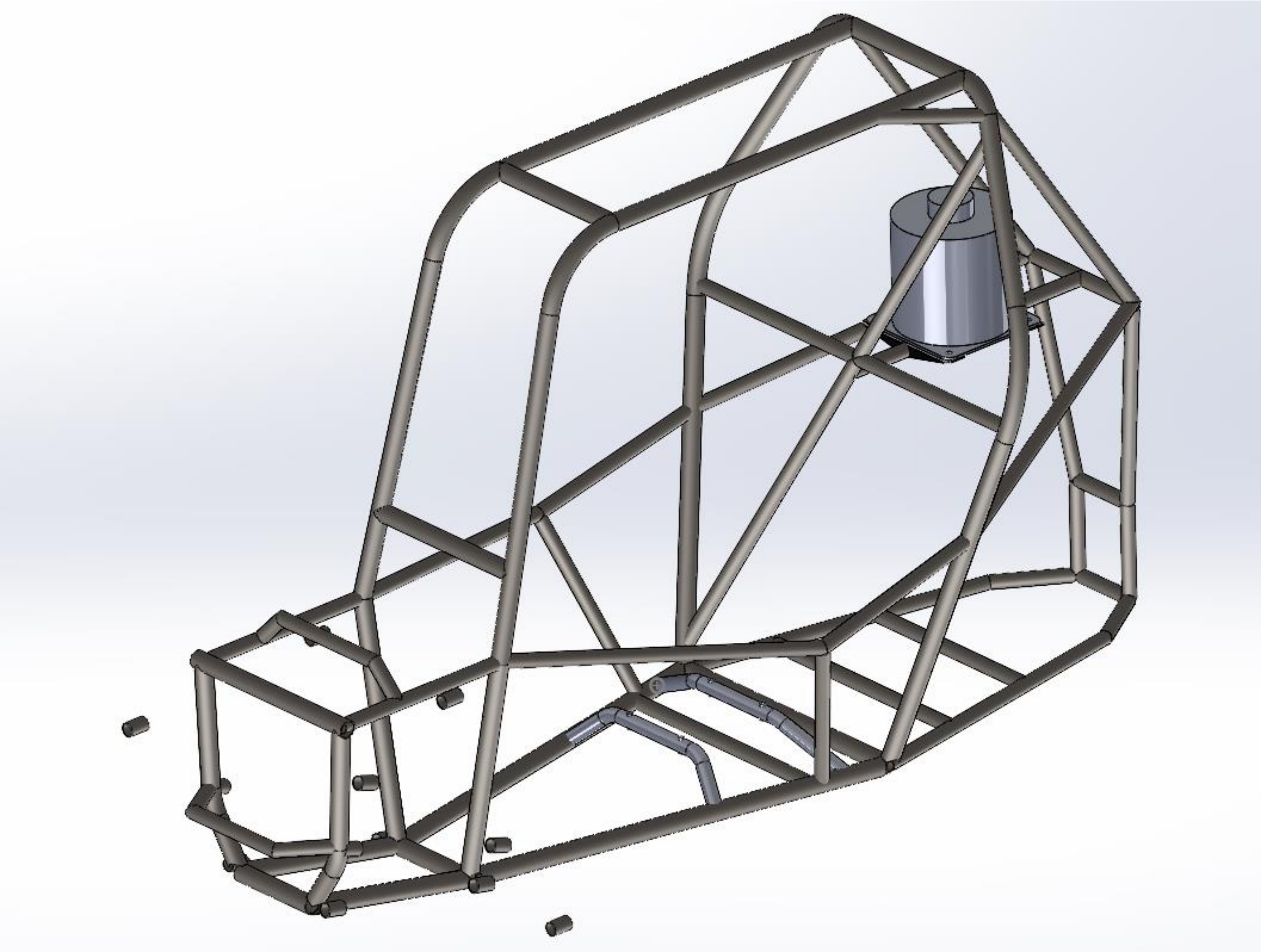
	Variants			
Subsystem	*1*	*Rating*	*2*	*Rating*
Frame Type	Front Brace	X	Rear Brace	✓
Fuel Tank Mount	Square Brackets	X	C-Brackets	✓
Seat Design	Slotts	✓	Tabs	X
Side Impact Members	Straight	X	Flared	✓
Tube Material	AISI 4130	✓	AISI 1018	X

NORTHERN ARIZONA UNIVERSITY

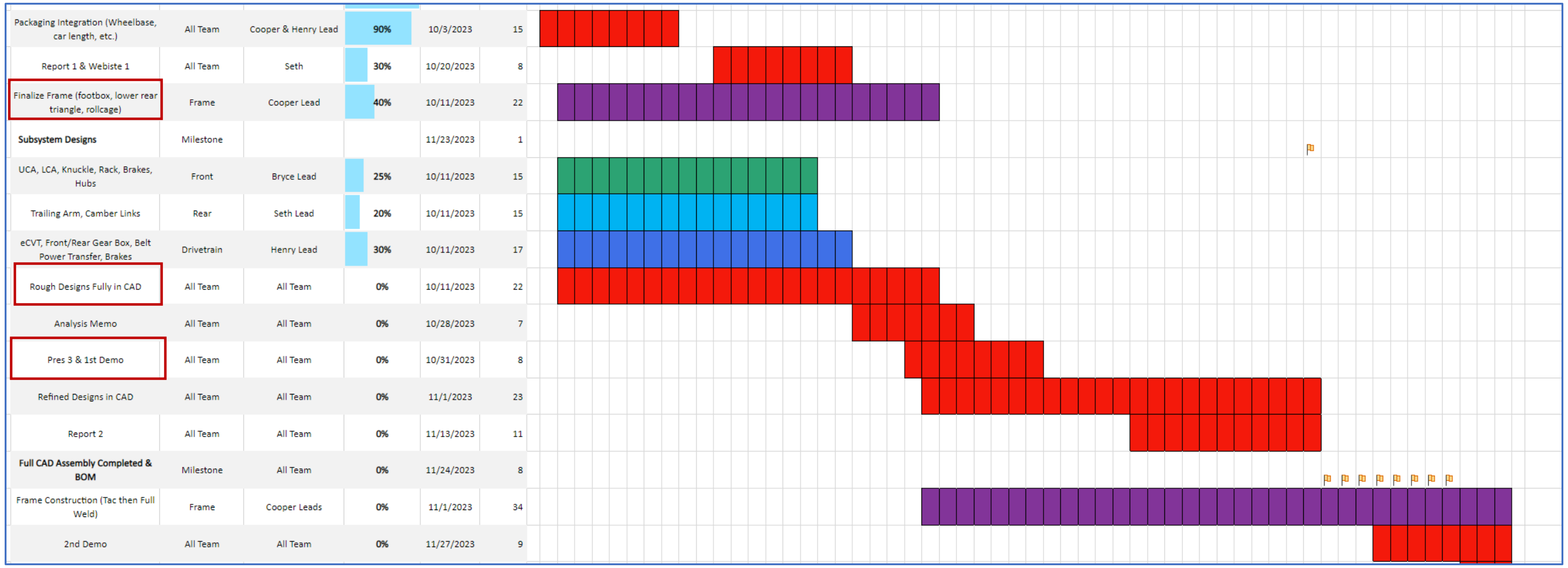
Final Design Discussion

	Variants			
Subsystem	*1*	*Rating*	*2*	*Rating*
Frame Type	Front Brace	X	Rear Brace	✓
Fuel Tank Mount	Square Brackets	X	C-Brackets	✓
Seat Design	Slots	✓	Tabs	X
Side Impact Members	Straight	X	Flared	✓
Tube Material	AISI 4130	✓	AISI 1018	X

Final Design Visualization



Project Schedule



Packaging Integration (Wheelbase, car length, etc.)	All Team	Cooper & Henry Lead	90%	10/3/2023	15
Report 1 & Webiste 1	All Team	Seth	30%	10/20/2023	8
Finalize Frame (footbox, lower rear triangle, rollcage)	Frame	Cooper Lead	40%	10/11/2023	22
Subsystem Designs	Milestone			11/23/2023	1
UCA, LCA, Knuckle, Rack, Brakes, Hubs	Front	Bryce Lead	25%	10/11/2023	15
Trailing Arm, Camber Links	Rear	Seth Lead	20%	10/11/2023	15
eCVT, Front/Rear Gear Box, Belt Power Transfer, Brakes	Drivetrain	Henry Lead	30%	10/11/2023	17
Rough Designs Fully in CAD	All Team	All Team	0%	10/11/2023	22
Analysis Memo	All Team	All Team	0%	10/28/2023	7
Pres 3 & 1st Demo	All Team	All Team	0%	10/31/2023	8
Refined Designs in CAD	All Team	All Team	0%	11/1/2023	23
Report 2	All Team	All Team	0%	11/13/2023	11
Full CAD Assembly Completed & BOM	Milestone	All Team	0%	11/24/2023	8
Frame Construction (Tac then Full Weld)	Frame	Cooper Leads	0%	11/1/2023	34
2nd Demo	All Team	All Team	0%	11/27/2023	9

Frame	
Purchase Material	10/13/2023
Complete Integration	10/27/2023
Prototype	11/10/2023

Bill of Materials

SAE Baja Frame						
Part	**Description**	**Qty**	**Units**	**Unit Cost**	**Cost**	**Obtained**
Primary Members	4130 1.25x.065" tubing	45	ft	7.00	315.00	N
Secondary Members	4130 1x.035"tubing	45	ft	6.00	270.00	N
Tabs	4130 0.1"sheet	100	in^2	0.28	27.78	N
Side Panneling	Carbon Weave	20	ft^2	6.00	120.00	N
Seat	Carbon Weave	4	ft^2	6.00	24.00	N
Epoxy	Carbon resin epoxy	1	gallon	85.00	85.00	N
Harness	Standardized	1	unit	100.00	100.00	Y
Submarine Straps	Standardized	2	unit	23.00	46.00	N
Fire Extinguisher	5BC Standard	1	unit	25.00	25.00	Y
Extinguisher Mount Bracket	Drake FIREX-MNT-DAG	1	unit	75.00	75.00	Y
Fuel Tank Mounting Washers	McMaster Carr 94733A723	8	50	14.00	2.24	Y
Mounting Hardware	Misc. nuts, bolts, washers needed	1	unit	50.00	50.00	N
Skid Plate	.06"HDPE	6	ft^2	5.00	30.00	N
Firewall	.02" sheet metal	9.5	ft^2	7.75	73.63	N
				Total Costs	**1243.64**	**1041.40**

Frame Team Materials Cost: $1041

Does not include materials sponsor discounts

Frame Budget

	Category	Relevant Items	Approximated Cost
1	**Vehicle Expenses**	Frame Material Paneling and Carbon Layup Safety Equipment Hardware **Estimated Total**	$716 $229 $46 $50 **$1041**
2	**Spare Parts**	Welding supplies, Hardware, Tab Materials, Tubing	$200
3	**Competition Expenses** Frame Sub-team	Registration, travel (hotel rooms, vehicle rentals, gas, etc.)	$1,125
4	**Contingency (5%)**	Unpredicted Expenses	$100
		Total	**$2466**

NORTHERN ARIZONA UNIVERSITY

Bibliography

[90] "Side View Swing Arm Height given Percentage Anti Dive Calculator," Calculate Side View Swing Arm Height given Percentage Anti Dive, https://www.calculatoratoz.com/en/side-view-swing-arm-height-given-percentage-anti-dive-calculator/Calc-32332#FormulaPanel (accessed Oct. 2, 2023).

[91] "Baja Virtual Presentation Series Day 6: - suspension calculations slide (baja virtuals 2020)," YouTube, https://youtu.be/iRHNzfvKpNQ?si=ms6VxcSwpj-PEc1O (accessed Oct. 2, 2023).

[92] "Introduction to adams/car for FSAE," YouTube, https://m.youtube.com/watch?v=L_vFjUI25r8 (accessed Oct. 2, 2023).

[93] W. F. Milliken and D. L. Milliken, *Race Car Vehicle Dynamics*. Warrendale, Pa, 1995.

[94] "Double wishbone suspension geometry: Designing: Calculation: Hard points: Camber vs wheel travel," YouTube, https://youtu.be/JDKgwjwIyT4?si=2ObxDxfgtZL5KZiQ (accessed Oct. 2, 2023).

[95] CV joints vs U-joints - CJ pony parts, https://www.cjponyparts.com/resources/u-vs-cv-joints (accessed Oct. 9, 2023).

Bibliography

[96] D. Colgrove, "Steering system for SAE baja," thesis, BYU Scholars Archive, Provo, 2019

[97] Jazar, R.N. (2008). Steering Dynamics. In: Vehicle Dynamics: Theory and Application. Springer, Boston, MA.

[98] LLC. Engineers Edge, "Tee section load full penetration weld perpendicular loading applied stress calculator," Engineers Edge - Engineering and Manufacturing Solutions, https://www.engineersedge.com/weld/weld-calc5.htm (accessed Oct. 10, 2023).

[99] APSEd, "Deflection and Slope in Simply Supported Beams | Beam Deflection Table, Formula," APSEd, Jan. 17, 2021. https://www.apsed.in/post/deflection-and-slope-in-simply-supported-beams-beam-deflection-table-formula

[100] "SolidWorks Education SAE Frame Analysis," YouTube. Jul. 30, 2012. Accessed: Jan. 10, 2020. [YouTube Video]. Available: https://www.youtube.com/watch?v=Pk4JRCyOTMc

NORTHERN ARIZONA UNIVERSITY