SAE Baja ‘24 Capstone Team

Presentation 1

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

NORTHERN ARIZONA UNIVERSITY

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: Stay tuned!
- Successful performance puts NAU on the map, strengthens internal Baja knowledge, and grows NAU Baja industry sponsorship connections

Background

Baja ETS SOTA Vehicle

"State-of-the-Art" University Teams

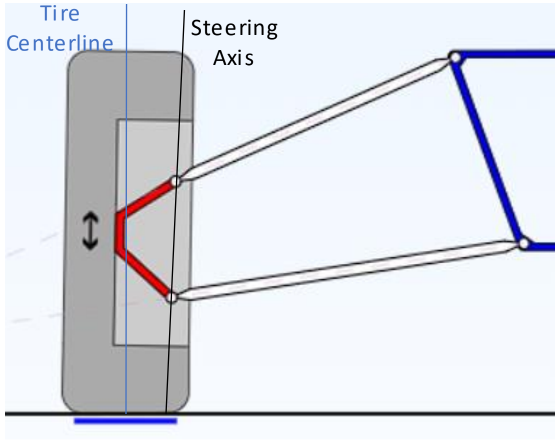
Creative innovation without rule violations is the goal. Some teams do this better than others due to funding & legacy knowledge:

- Baja ETS
  - #1 Overall (Oregon 2023), Placed Top 3 in 8/10 Events
- Beaver Racing
  - #2 Overall (Oregon 2023), Place Top 3 in 4/10 Events
- Cornell Baja Racing
  - #3 Overall (Oregon 2023), Place Top 3 in 5/10 Events

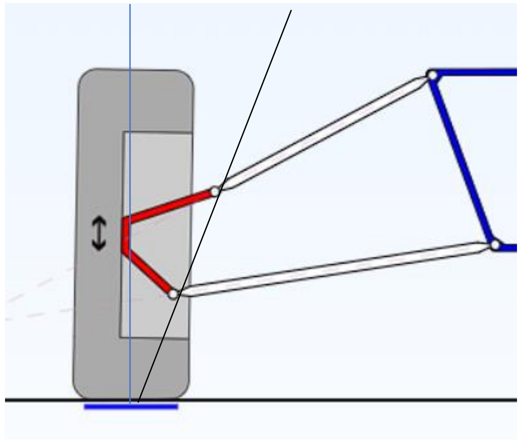
NORTHERN ARIZONA UNIVERSITY

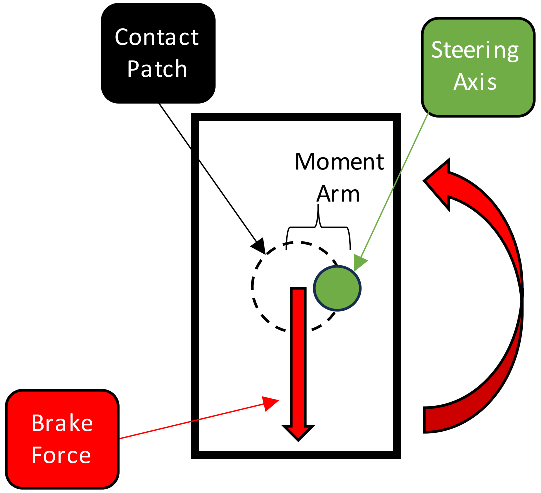
Benchmarking #1 – Front

Positive Scrub Radius

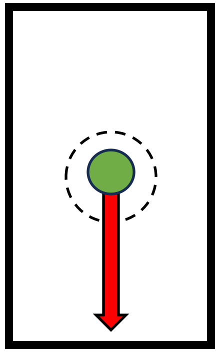


Zero Scrub Radius





Braking: Toe In



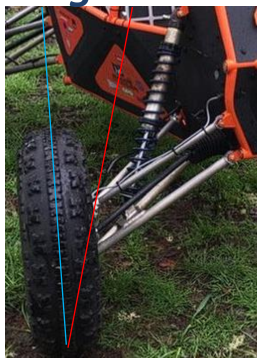
All forces kept in-line w/ steering axis!

Knuckle Design - Scrub Radius

Many top teams go with a **zero (or near zero) scrub radius** when designing their front suspension. This minimizes scrub radius influence on steering and toe characteristics under braking/acceleration.

Cornell

Oregon State



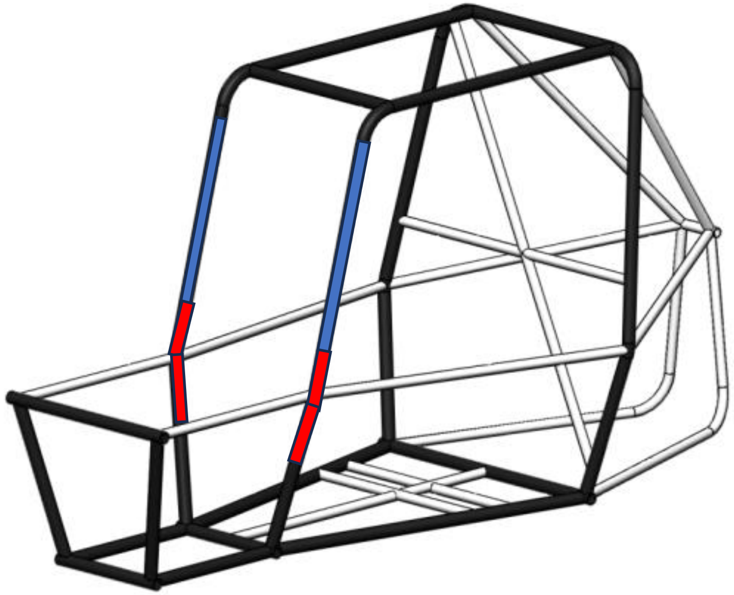
NORTHERN ARIZONA UNIVERSITY

Benchmarking #2 - Front

Front Shock Placement

3 front shock lower mounting locations can be:

- Upper A arm mounted to the upper front brace member
- Upper A arm mounted to the lower front brace member
- Lower J arm mounted to the lower front brace member



Upper Front Brace Members highlighted in blue

Lower Front Brace Member highlighted in red

- First Place 2023 Oregon: ETS – Lower front brace mounted
- First Place 2023 Ohio: CWRU – Lower front brace mounted
- First Place 2017 Oshkosh: UM Ann Arbor – Side impact/lower brace junction mounted

NORTHERN ARIZONA UNIVERSITY

Benchmarking #3 - Front

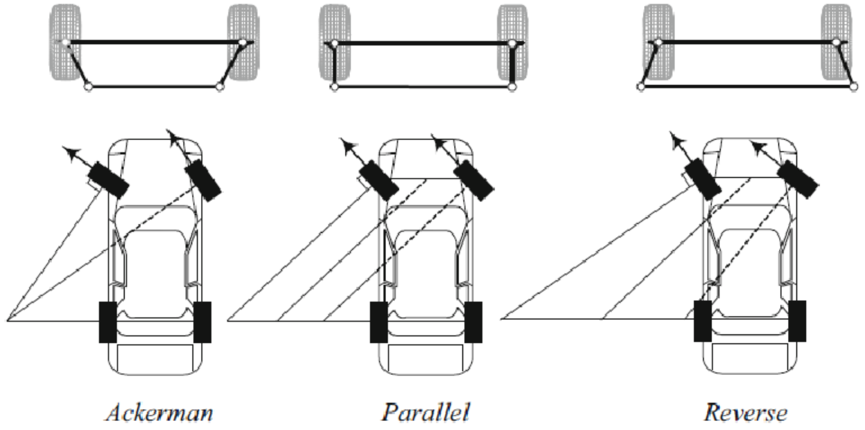


Diagram showing Ackermann, parallel, and Anti-Ackermann steering geometries. [24]

Cornell Ackermann Steering on Display

Steering Design

Ackermann is most useful at very low speeds and tight turns because that is when you have the least wheel slip and load transfer side to side. (Gillespie, 1992) (Team, BYU Baja, 2017)

- Baja ETS - Ackermann
  - #1 Maneuverability (Oregon 2023)
- Cornell Baja Racing – 50% Ackermann
  - #2 Maneuverability (Oregon 2023)
- Beaver Racing - Ackermann
  - #3 Maneuverability (Oregon 2023)

Customer & Engineering Requirements - Front

Customer Requirements

- Vehicle must comply with the dimensions of SAE Baja courses
- Vehicle must have adequate ground clearance
- Vehicle must have adequate traction across all terrains
- Vehicle must be capable of safe operation over rough land terrain
- Vehicle must have agile maneuverability
- Front suspension must be robust in design (control arms, hubs, knuckles, tie rods, etc.)

Engineering Requirements

- Decrease Vehicle Width
  - *Max Vehicle Width = 64”*
- Increase Ride Height
  - *Front Ride Height Minimum = 10”*
- Increase Tire Traction
  - *Scrub Radius = ~0 degrees*
- Increase Capability in Rough Terrain
  - *Wheel Travel = ~12” total (3:1 bump to droop)*
- Increase Turn-In Angle
  - *Pro-Ackerman = 40%-100%*
- Increase Crash Durability
  - *Target 40mph collision*

NORTHERN ARIZONA UNIVERSITY

QFD Discussion - Front

Customer Needs	Customer Weights	Decrease Vehicle Width	Increase Ride Height	Increase Tire Traction	Increase Capability in Rough Terrain	Increase Turn-In Angle	Increase Crash Durability	Customer Opinion Survey: 1 Poor	2	3 Acceptable	4	5 Excellent
Comply with track dimensions	4	9									A	BC
Adequate ground clearance	2		9	6	9		3			A	C	B
Adequate traction	3	3	3	9	6	3	3			A		BC
Safe operation over rough terrain	3	6	6	3	9		9				ABC	
Agile manuverability	4	6	3	6	3	9					A	BC
Robust design	3		3		3		9			BC	A	
Technical Requirement Units		Inches	Inches	Degrees (Scrub Rad)	Inches (Wheel Travel)	Degrees	mph					
Technical Requirement Targets		64	10	0	12	40-100	40					
Absolute Technical Importance		87	66	72	84	45	69					
Relative Technical Importance		1	5	3	2	6	4					

Legend	
A	NAU #74
B	Baja ETS
C	Cornell Racing

CR & ETSR Correlation

Many of the requirements from the rulebook work together with each other, leading to a more direct design path. The top 3 technical focuses for front end are as follows:

- **Modulating vehicle width** (track compliance)
- **Increasing rough terrain capability** (wheel travel)
- **Increasing tire traction** (scrub radius mitigation)

Other considerations include durability, ride height, and steering angle

NORTHERN ARIZONA UNIVERSITY

Literature Review

-Abraham Plis-

Textbooks

- ***Suspension Geometry and Computation* [3]**
  - Ch 12: Double Arm Suspensions
- ***The Automotive Chassis: Engineering Principles* [4]**
  - Ch 1: Types of Suspension and Drive

Papers

- ***Analysis of Steering Knuckle of All Terrain Vehicles (ATV) Using Finite Element Analysis* [5]**
  - Knuckle Design/FEA
- ***Design and Development of Front Suspension System for an Off-Road Vehicle* [6]**
  - A-Arm FEA & Anti-Dive Geometry
- ***Design Review of Suspension Assembly of a BAJA ATV* [7]**
  - Lotus Shark Suspension Analysis

Online

- ***Suspension & Steering Geometry (Front) | Double Wishbone | Anti-Ackerman | SAE BAJA | Solidworks* [8]**
  - CAD Tutorial, A-Arm Geometry
- ***Steering Knuckle | Solidworks | 3D - Modelling | BAJA ATV* [9]**
  - CAD Tutorial, Knuckle Design

NORTHERN ARIZONA UNIVERSITY

Literature Review

-Evan Kamp-

Textbooks

- **Vehicle Dynamics: Theory and Application [23]**
  - Chapter 7: Steering Dynamics
  - Calculations for Turning Radius and Viable Steering Angles
- **The Science of Vehicle Dynamics Handling, Braking, and Ride of Road and Race Cars [77]**
  - Chapter 5: The Kinematics of Cornering

Papers

- **Analysis of Ackermann Steering Geometry [74]**
- **Steering system for SAE Baja [46]**
  - Ackermann vs Parallel Steering Design
- **Design and Optimization of Steering Assembly for Baja ATV Vehicle [12]**
  - Design of Ackerman Steering Arms

Online

- **Tech Explained: Ackermann Steering Geometry [59]**
  - Viable Steering Angles as a function of Slip Angle and Lateral Force
- ***Baja Virtual Presentation Series [79]***
  - *Day 8 - Steering Calculations*

NORTHERN ARIZONA UNIVERSITY

Literature Review

-Bryce Fennell-

Papers

Optimal Design of Suspension System of Four-Wheel Drive Baja Racing [34]

- Suspension kinematics, shock mounting positional data

Fine-Tuning Of the Suspension System of Baja ATV [33]

- Camber angle, wheel axle path

Redesigning the Cooper Union SAE Mini-Baja Front Suspension and Steering [35]

- Steering angle, double a-arm suspension system, calculations

Online

Baja SAE, SAE International, 2023. [32]

- Competition rules and guidelines for frame/suspension integration

TUTORIAL ON LOTUS SUSPENSION SOFTWARE [31]

- How to recover suspension data from the program

Lotus Shark Suspension | Tutorial [30]

- Basic overview of Lotus Shark software
- Suspension system input into program

Textbooks

Suspension Geometry and Computation [36]

- Chapter 7, Camber and scrub
- Chapter 12, double-Arm Suspension

Road and Offroad Vehicle Dynamics [58]

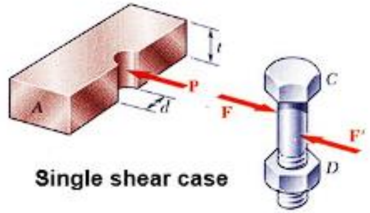
- Suspension characteristics pg: 379-422

NORTHERN ARIZONA UNIVERSITY

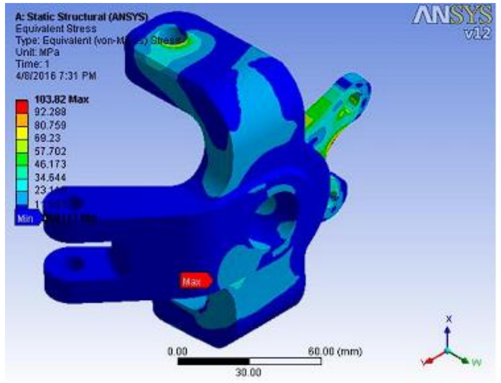
Mathematical Modeling #1 - Front

Equations, Tools, and Examples

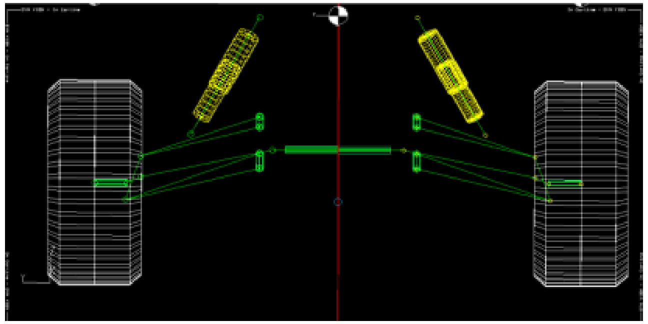
$$\sigma_b = \frac{P}{A_b} = \frac{P}{td}$$



Hole bearing stress equation for bolted connections to design against tear-out and deform [10]



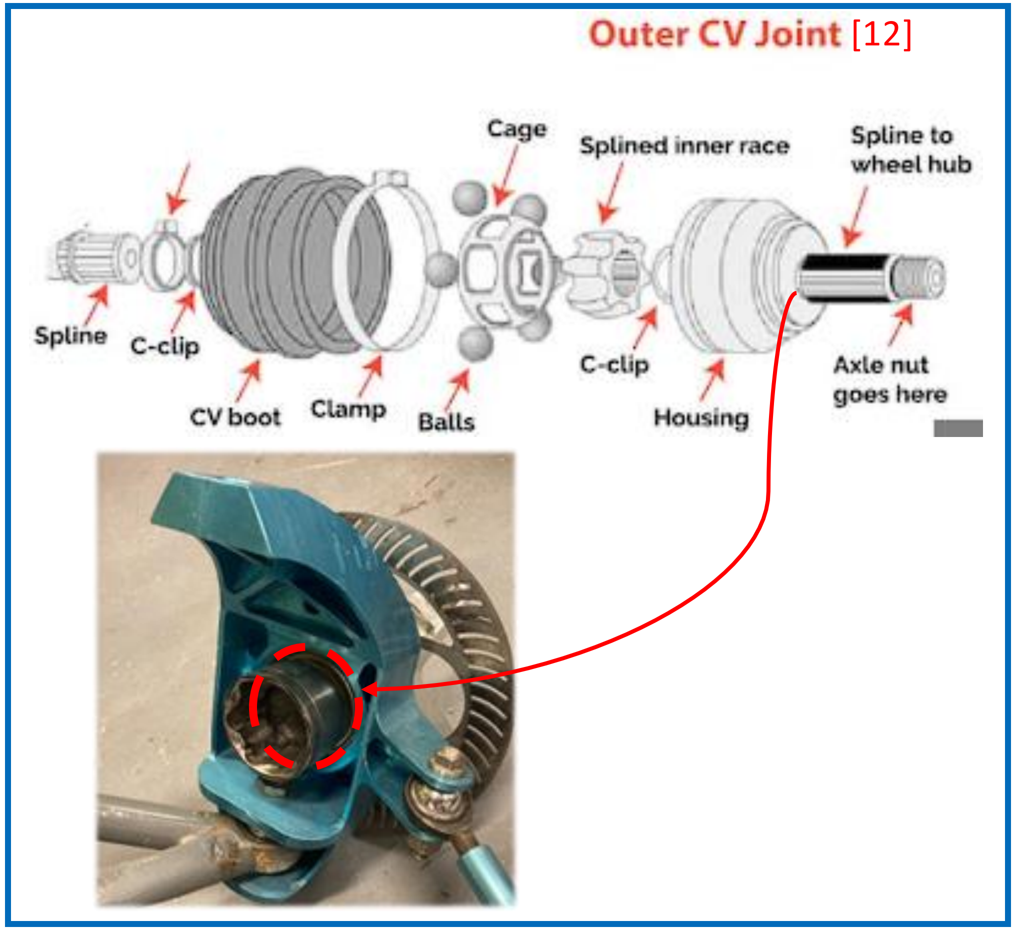
Excellent example of how to perform FEA analysis on a steering knuckle to optimize design characteristics



Lotus *Shark* software will help define and optimize suspension geometry, allowing hardpoints to be established [7]

Mathematical Modeling #1 - Front

How much bearing stress will the central knuckle hole see from the outboard cv spline during a jump?



Standard Baja Weight (with driver): 500 lb.
Max Acceleration During Scenario: 3*g
Drop Height: ~6 ft.
Duration of Impact: 0.1 seconds
Diameter of Spline: ~1”
Thickness of Contact Surface: ~2”

$$F = \frac{m * \sqrt{g * h}}{t}$$ [11]

÷

$$A_b = d * t$$

→

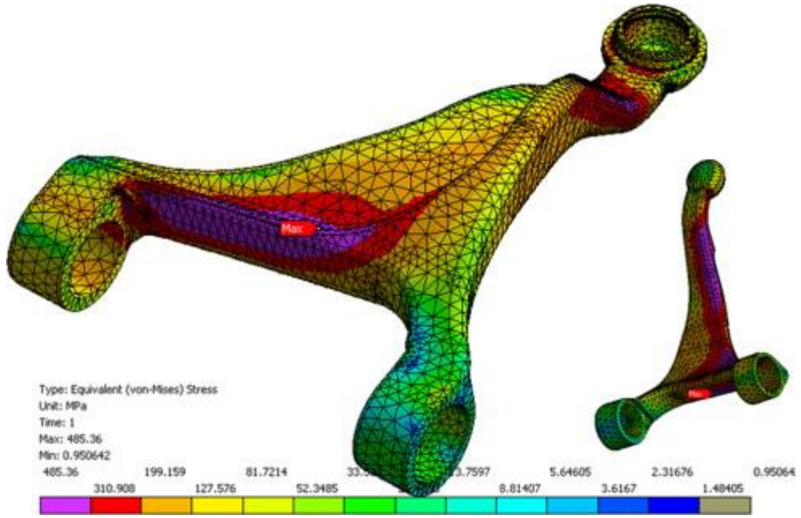
$$\sigma_b = 1080psi$$

Answer can be validated by comparing to **yield strength** of billet aluminum (26,107 psi, meaning σ_b is 4% of that [13]). This tells us that **skeletonization** of the steering knuckle around the **inner contact surfaces is possible!**

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #2 - Front

A-Arm Design, Forces, and Inputs

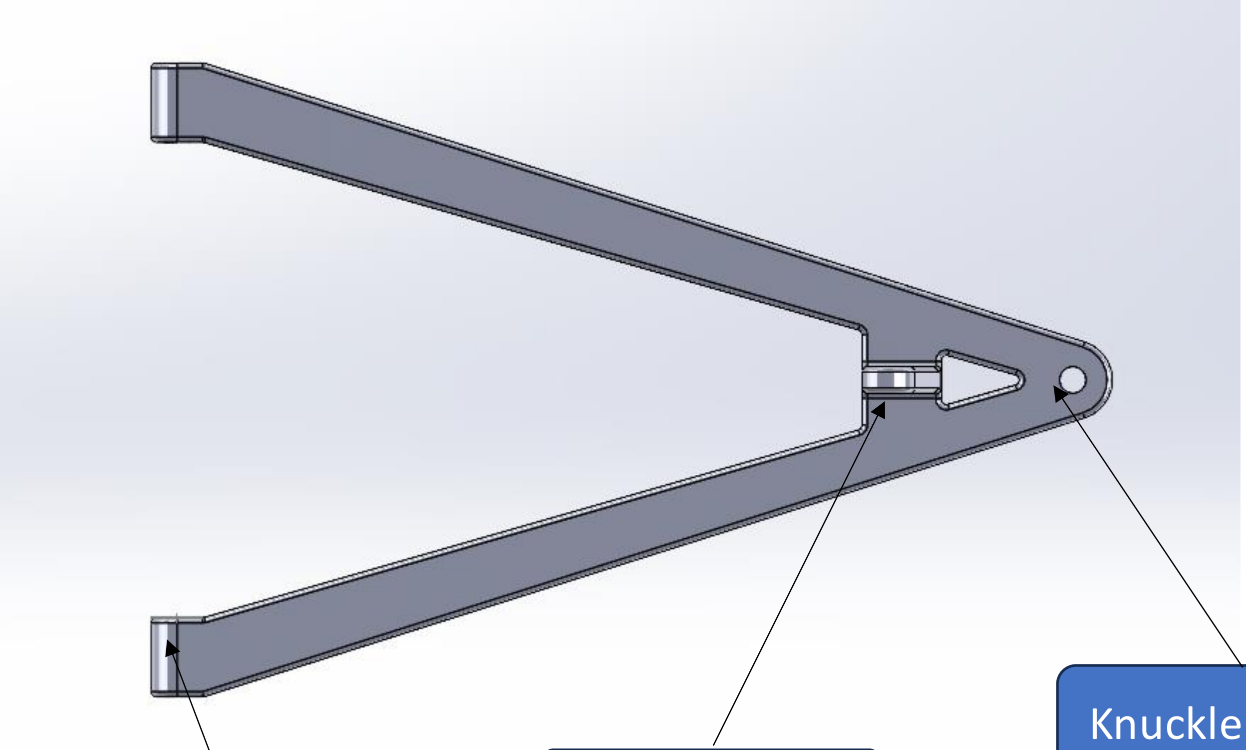


FEA of a modeled A-arm showing stresses developing under a compressive load

2023 ETS SAE Baja vehicle using lower front brace mounted front suspension

Mathematical Modeling #2 - Front

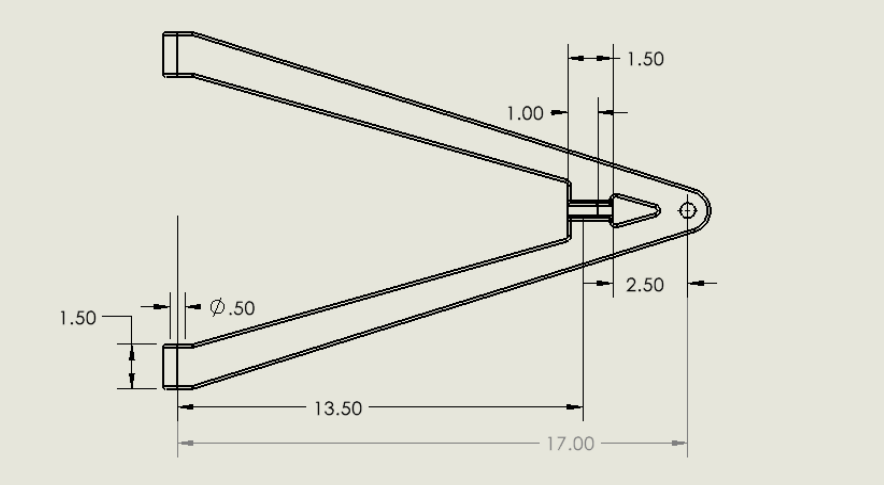
A-Arm Design, Forces, and Inputs



Chassis Mount location

Shock Mount

Knuckle Mount



Dimensioned model of upper A Control arm. Dimensions are in Inches

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #2 - Front

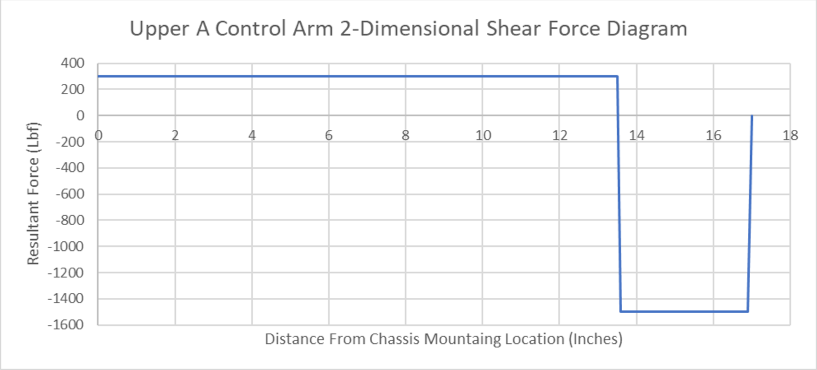
2-Dimensional shear force and bending moment diagrams on the upper A-arm during a max force compression

Instantaneous Shear force equation:

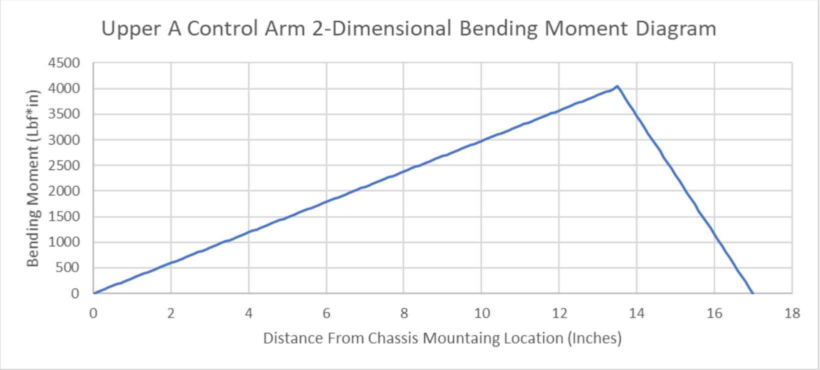
$$\tau = \frac{F}{A}$$

Bending Moment equation:

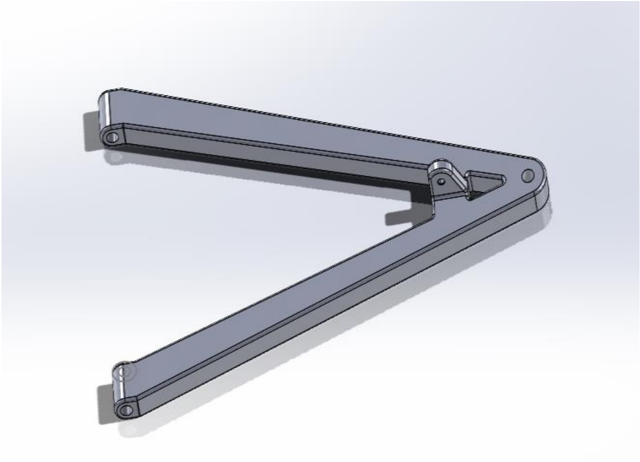
$$M = \int Sfd$$



Upper A Control Arm 2-Dimensional Shear Force Diagram in the Vertical Direction



Upper A Control Arm 2-Dimensional Bending Moment Diagram in the Vertical Direction



SolidWorks Isometric view of upper A control arm with shock mounting uprights

The upper A control arm must be designed to withstand a maximum bending moment of 4050 lbf*in at 13.56 in from the chassis pivot point

Mathematical Modeling #3 - Front

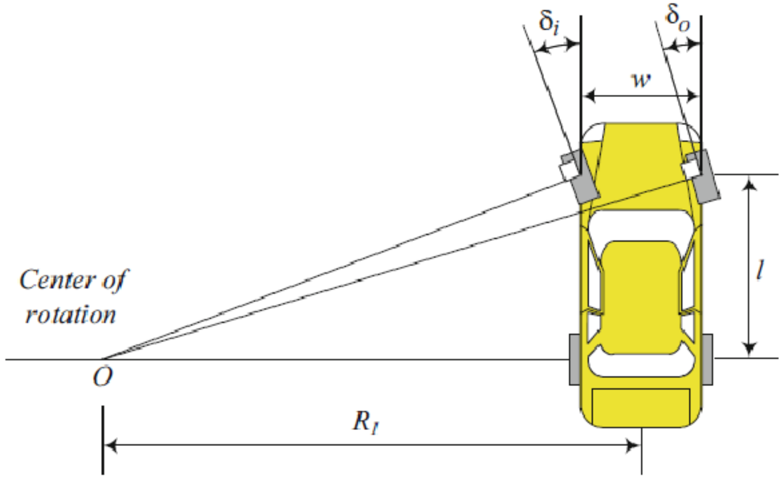
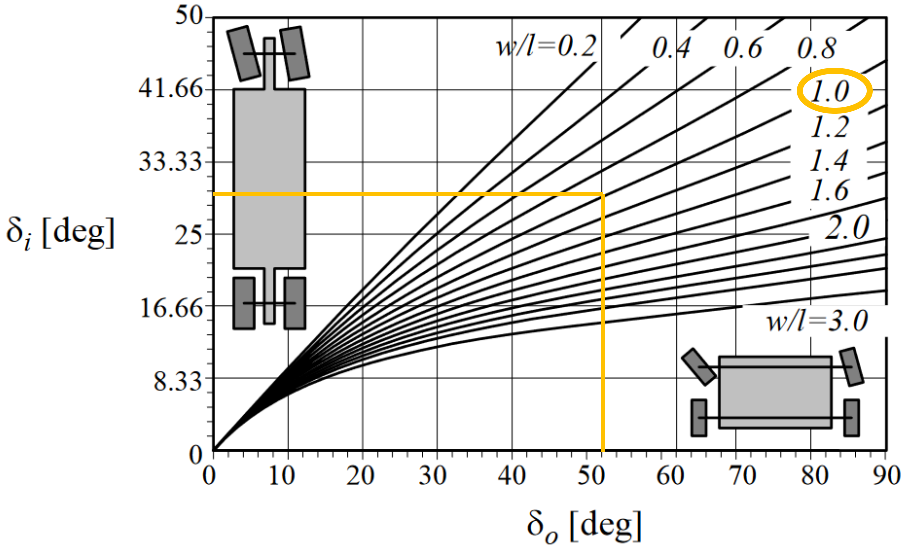


Diagram of Steering Radius correlated to Inner and Outer Steering Angles [24]

The above diagram and following equations used are under the assumption that the slip angles are close to or are 0º during a slow turn. To meet this condition, the chart on the right must be used to determine viable angles.



Effect of Width and Length on Viable Outer and Inner Steering Angles. These angles are calculated as a function of Lateral Force and Slip Angle [24]

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #3 - Front

Calculating the average Steering Angle

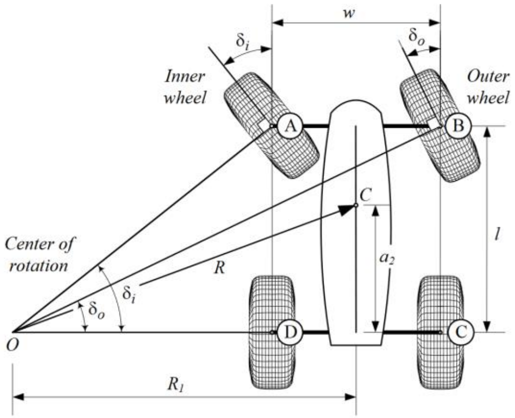
$$\cot\delta = (\cot\delta_o + \cot\delta_i)\frac{1}{2}$$

Steering Radius being calculated using center of Mass (a)

$$R = \sqrt{a_2^2 + l^2\cot^2\delta}.$$

Calculating the Percent Ackerman Used

$$\%Ackermann = \frac{\delta_i - \delta_o}{\delta_i} * 100\%$$



Preliminary Measurements

Wheel Center Length (l)	64in
Wheel Center Width (w)	64in
Inner wheel angle (δi)	50°
Outer wheel angle (δo)	30°
δavg	40°
Rear wheel to center of gravity (a2)	32in

Results

Percent Ackerman Used	40%
Hypothetical Turning Radius (R)	6.89ft

Project Schedule

PROJECT: SAE Baja 24

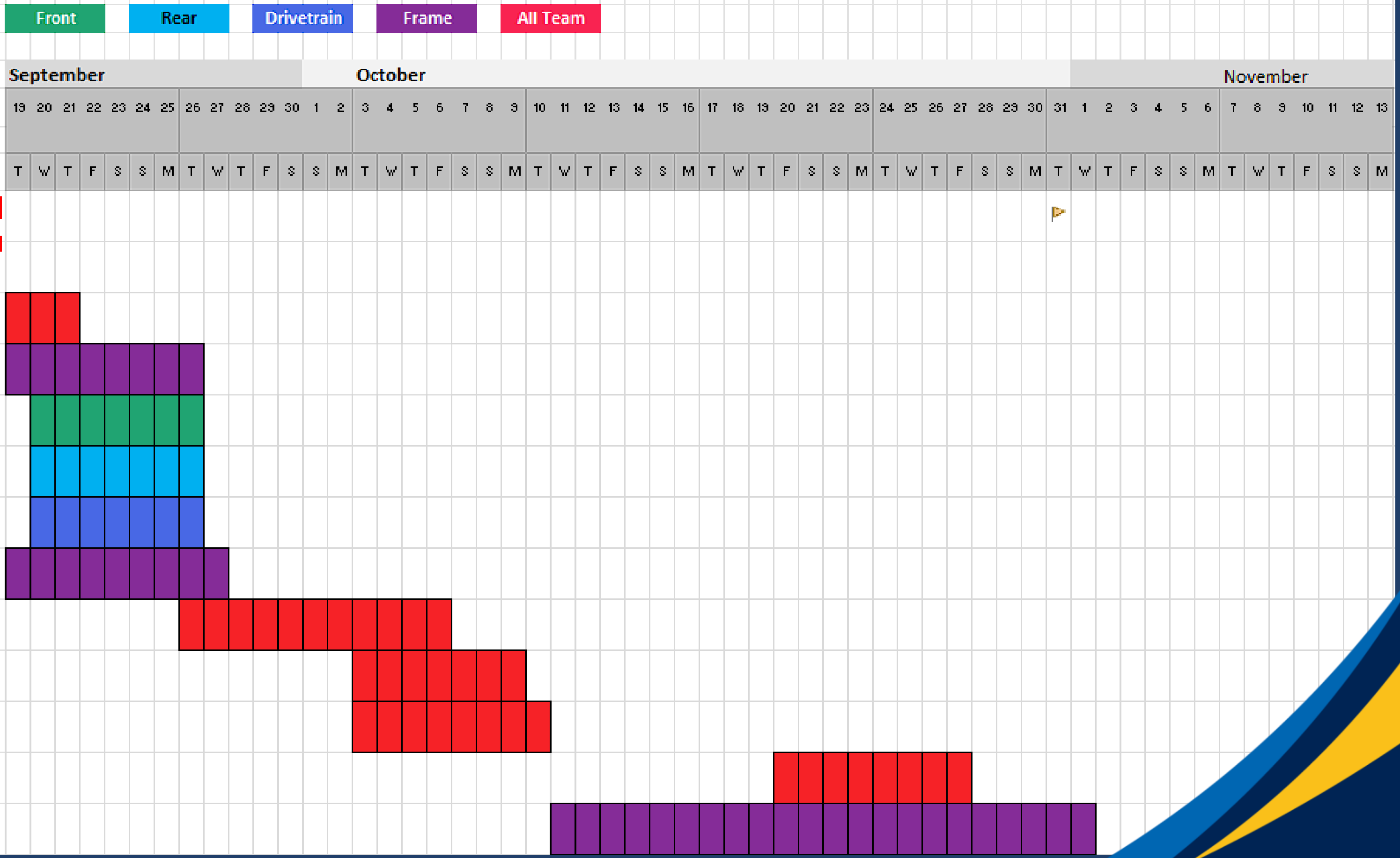
NAU A.Y. 2023-2024

Project Manager: Abe Plis

Project start date: 9/14/2023

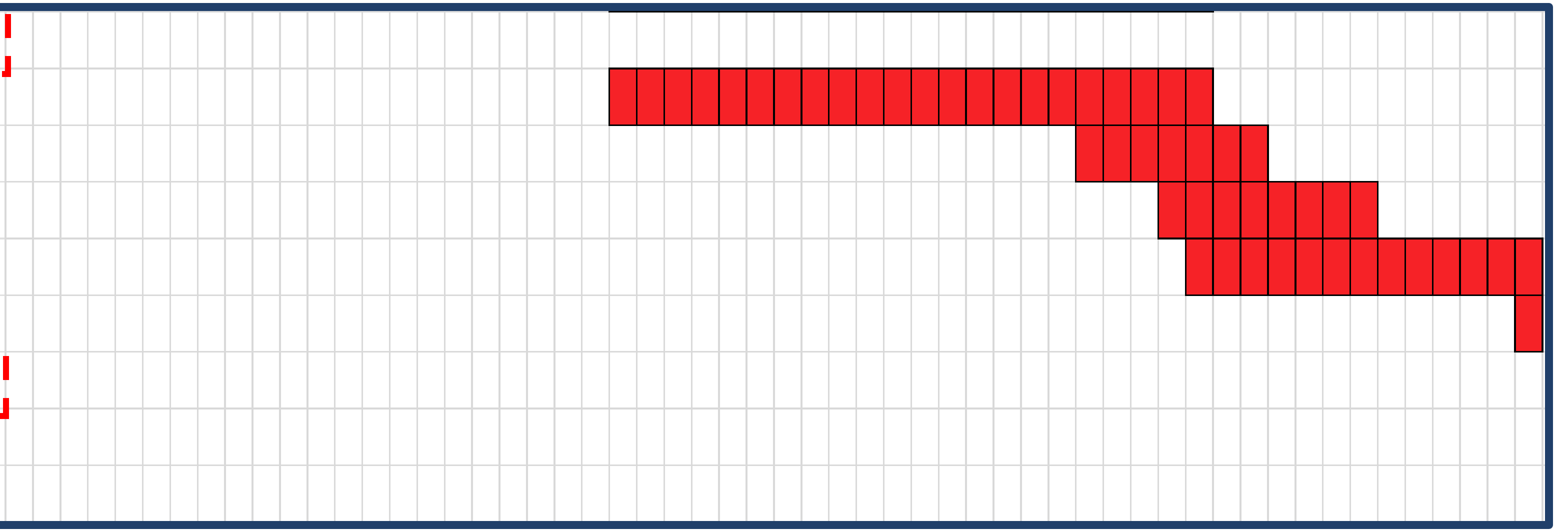
Scrolling increment: 5

Milestone description	Responsible Sub-Team	Assigned To	Progress	Start	Days
Frame Completion in CAD	Milestone			10/31/2023	1
Presentation 1	All Team	N/A	0%	9/12/2023	7
Major Sub-System Decisions	All Team	Team Leads	0%	9/15/2023	7
Wire Frame	Frame	Cooper Lead	0%	9/12/2023	15
Define Front Suspension Points & Begin CAD	Front	Bryce Lead	0%	9/20/2023	7
Define Rear Suspension Points & Begin CAD	Rear	Seth	0%	9/20/2023	7
Define Drivetrain Points & Begin CAD	Drivetrain	Henry Lead	0%	9/20/2023	7
Measure Hailey & Design Rollcage	Frame	Cooper Lead	0%	9/18/2023	10
Concept Generation & Selection	All Team	Team Leads	0%	9/26/2023	11
Presentation 2	All Team	N/A	0%	10/3/2023	7
Packaging Integration (Wheelbase, car length, etc.)	All Team	Cooper & Henry Lead	0%	10/3/2023	8
Report 1 & Webiste 1	All Team	Seth	0%	10/20/2023	8
Finalize Frame (footbox, lower rear triangle, rollcage)	Frame	Names	0%	10/11/2023	22



Project Schedule

Subsystem Designs	Milestone			11/23/2023	1
Rough Designs in CAD	All Team	Names	0%	10/11/2023	22
Analysis Memo	All Team	Names	0%	10/28/2023	7
Pres 3 & 1st Demo	All Team	Names	0%	10/31/2023	8
Refined Designs in CAD	All Team	Names	0%	11/1/2023	23
Report 2	All Team	Names	0%	11/13/2023	11
Full CAD Assembly Completed & BOM	Milestone	Names	0%	11/24/2023	8
2nd Demo	All Team	Names	0%	11/27/2023	9
Website 2	All Team	Seth	0%	12/2/2023	9



Progress: On-Track…but need to be more aggressive!

Next Steps (~1-1.5 Week(s) Out): wireframe, front/rear hardpoints & geometry, initial powertrain calcs & geometry

Project Budget

	Category	Relevant Items	Approximated Cost
1	**Vehicle Expenses**	Raw materials, hardware, engine & drivetrain components, tooling, harness & safety equipment, labor (if out-sourced manufacturing)	$15,000
2	**Spare Parts**	Raw materials, labor (if out-sourced manufacturing), hardware	$7,500
3	**Competition Expenses**	Registration, travel (hotel rooms, vehicle rentals, gas, etc.)	$4,500
4	**Contingency (5%)**	Unpredicted Expenses	$1,350
		Total	**$28,350**

Fundraising Plan

This is a steep budget that won't be covered by grants or singular donations…turn to sponsors!

Potential Sponsors:

Copper State, Mother Road, Findley Toyota, Home Depot, ETM, Gore, HASS, N.A.P.A., etc.

Sponsor Methodology:

Request funding in return for representation at competition via customized livery

Rear Suspension Team

Joey Barta, Lars Jensen, Seth Deluca

NORTHERN ARIZONA UNIVERSITY

Benchmarking #1 – Rear Trailing Link

RIOT Racing

1st in suspension
(4th overall)

LSU Baja Bengals

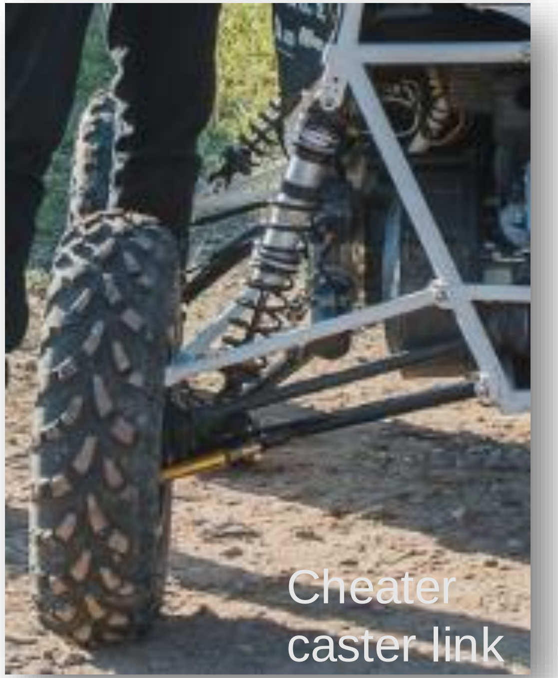
6th in suspension
(21st overall)

Blue Jays Racing

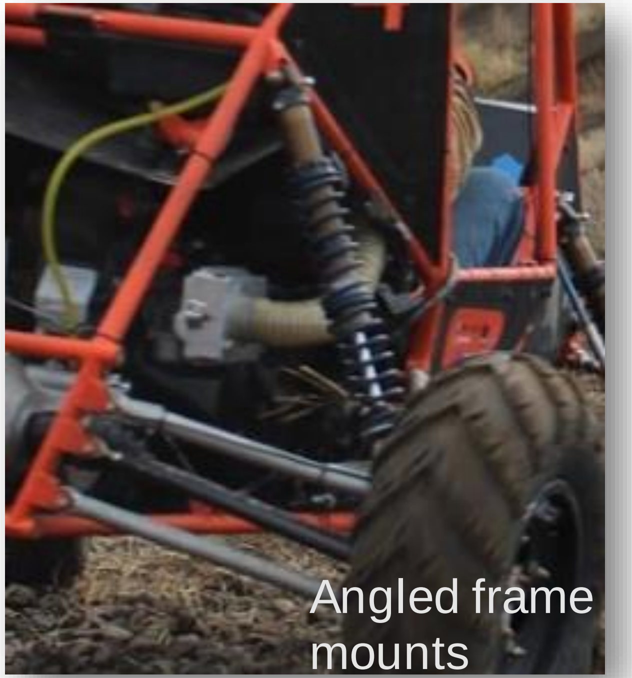
43rd in suspension
(30th overall)

NORTHERN ARIZONA UNIVERSITY

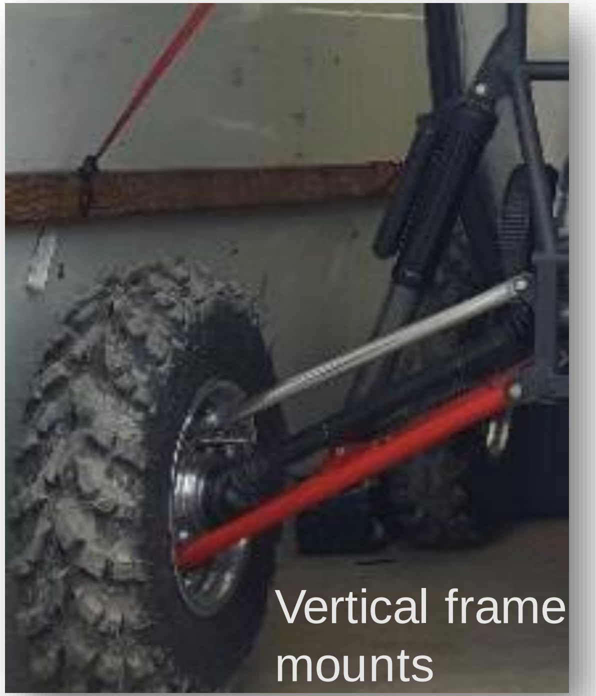
Benchmarking #2 – Rear Double A-Arm



ETS – 3rd in suspension (5th overall)



Oregon State University – 3rd in maneuverability (2nd overall)



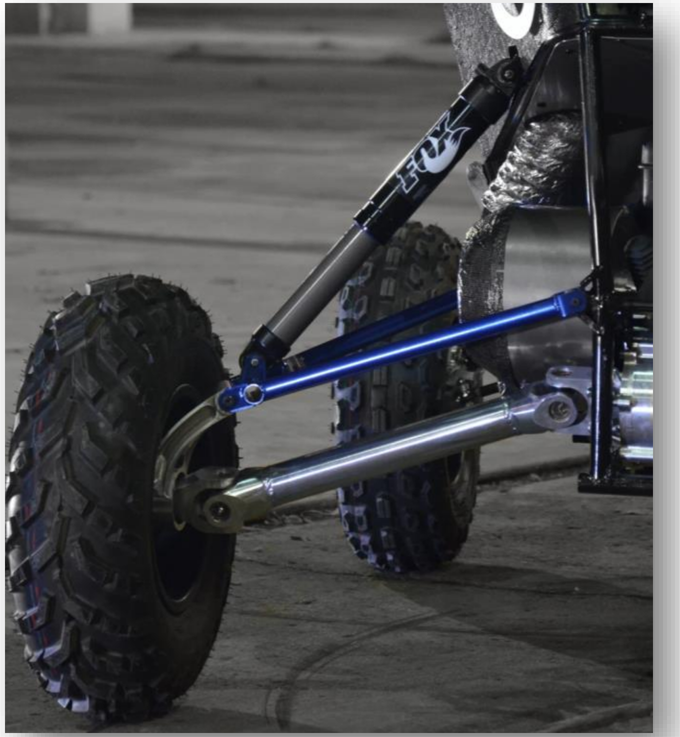
Cornell University – 2nd in maneuverability (3rd overall)

NORTHERN ARIZONA UNIVERSITY

Benchmarking #3 – Rear Single H-Arm

Northern Arizona University (2nd in suspension, 5th overall)

University of Michigan (4th overall)



Case Western Reserve University (6th overall)

NORTHERN ARIZONA UNIVERSITY

Customer & Engineering Requirements - Rear

Customer Requirements

- Tunability
- Serviceability
- Reliability
- Ease of manufacturing
- Low cost
- Maximum Traction
- Maneuverability

Engineering Requirements

- Decrease weight (lb.)
  - Rear suspension under 50 lbs.
- Increase strength (psi)
- Increase rearward axle path (in.)
  - 1 in. of rearward movement
- Increase linkage radii (in.)
  - 22 in. camber links
- Increase ground clearance(in)
  - 8 in. of ground clearance
- Vehicle width (in.)
  - Maximum vehicle width of 64 in.
- Decrease CV axle angle (degrees)
  - 180 degrees

NORTHERN ARIZONA UNIVERSITY

QFD Discussion - Rear

System QFD

Project:	Lumberjack Motorsports SAE Baja Rear Suspension
Date:	9/19/23
	Input areas are in yellow

Legend	
A	CWRUM
B	RIOT Baja
C	TS BAJA

	Decrease weight	Increase strength	increase rearward axle path	Increase linkage radii	Increase ground clearance	Vehicle width
Decrease weight						
Increase strength	-3					
increase rearward axle path						
Increase linkage radii	-1					
Increase ground clearance	-6	3	1			
Vehicle width	1	3		6	2	
Decrease CV axle angle		3	-2	1		

Customer Requirements	Customer Weights	Decrease weight	Increase strength	increase rearward axle path	Increase linkage radii	Increase ground clearance	Vehicle width	Decrease CV axle angle	1 Poor	2	3 Acceptable	4	5 Excellent
		Technical Requirements							**Customer Opinion Survey**				
Tunability	2	2	3	8	7	3	2	7	C	A			B
Servicability	2	2	6						A		BC		
Reliability	5	3	9	3	2			7			A	B	C
Ease of manufacturing	3	6	7	1	1		1	1		C	A		B
Low cost	5	9	9	3	3		1	3			A	C	B
Maximum Traction	2	7		8	8		3	1				B	AC
Maneuverability	4	5	1	8	6	5	7	1				AB	C
Technical Requirement Units		lb	Psi	in	in	in	in	degrees					
Technical Requirement Units		<50	NA	<1	22	>8	<64	180					
Absolute Technical Importance		120	133	97	82	26	46	73					
Relative Technical Importance		2	1	3	4	7	6	5					

NORTHERN ARIZONA UNIVERSITY

Literature Review

-Joey Barta-

Textbooks

- ***W. F. Milliken and D. L. Milliken, Race Car Vehicle Dynamics [48]***
  - Highly regarded as the "bible" of suspension engineering. Authors developed many of the vehicle dynamics theories in the book
- ***R. G. Budynas, Shigley's Mechanical Engineering Design [22]***
  - Useful source for failure prevention as well as design for mechanical elements
- ***J. C. Dixon, Tires, Suspension and Handling [49]***
  - Detailed coverage of the theory and practice of vehicle cornering and handling

Papers

- ***Suspension Types – SUSPROG [50]***
  - illustrates potential rear suspensions with downloadable excel files pertaining to each.
- ***J. Isaac-Lowry, "Suspension Design: Types of Suspensions," [51]***
  - short list of applicable designs to reference in the early stages of design
- ***SLASIM: Suspension Analysis Program [52]***
  - software through MATLAB that analyzes functionality of suspension kinematics

Online

- ***Setup Suspension 101 [79]***
  - Article expands on preload, compression, rebound, ride-height, and crossover spacers tuning.
- ***Suspension Geometry Calculator [65]***
  - Provides an intuitive, simple suspension geometry calculator

Literature Review

-Seth DeLuca-

Textbooks

- ***Vehicle Suspension System Technology and Design*** **[60]**
  - *Chapter 4: Analysis and Design of Suspension Mechanisms*
- ***Geometric Design of Independent Suspension Linkages*** **[61]**
  - Chapter 2.2: different mounting systems and joints

Papers

- ***Fine-Tuning of the Suspension System*** **[62]**
  - Includes information regarding things to look out for when tuning suspension
- ***Design Analysis of 3 Link Trailing Arm*** **[63]**
  - In depth to 3-Link Trailing Arm
- ***Design Analysis of H-arm with Camber Link*** **[64]**
  - Looks into H-arm Suspension

Online

- ***Racing Aspirations suspension Geometry*** **[65]**
  - Quick suspension software analysis
- **Spring rate and wheel rate calculator [66]**
  - Calculates shock angle when given different parameters based on a simple geometry

NORTHERN ARIZONA UNIVERSITY

Literature Review

-Lars Jensen-

Textbooks

- ***Performance Vehicle Dynamics: Engineering and Applications [67]***
  - *Chapter 7 – Suspension Kinematics, Chapter 8 – Dynamic Modelling of Vehicle Suspension*
- ***The Multibody Systems Approach to Vehicle Dynamics [68]***
  - *Chapter 4 – Modelling and Analysis of Suspensions Systems*

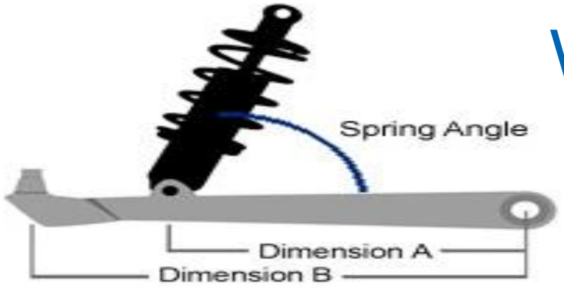
Papers

- ***Suspension Design and testing of an All-Terrain Vehicle using Multi-body dynamics Approach [69]***
  - *Flow of design calculations for suspension parameters*
- ***Optimal Design of Suspension System of Four-wheel Drive Baja Racing [70]***
  - *Geometric design of rear suspension*
- ***Design and Optimization of Rear Wheel Assembly for All-Terrain Vehicle [71]***
  - *FEA analysis of rear knuckle and hub*

Online

- ***Float 3 EVOL RC2 Factory Series Owner's Manual [72]***
  - Shock service and tuning
- ***A Square C & D "BAJA ATV Videos" Playlist [73]***
  - *SolidWorks modeling of suspension systems and knuckles*

Mathematical Modeling #1 - Rear



What angle should the shock be to the suspension system?

Assumptions:
Corner weight ≅ 150 lbs
Unsprung weight ≅ 45 lbs
Dimension A ≅ 16 in
Dimension B ≅ 20 in
Spring angle ≅ 80 degrees
Shock ride height = 2.27 in

Spring angle ≅ 60,70,80,90 degrees

Formulas [66]

$$Sprung\ height = Corner\ weight - Unsprung\ weight$$

$$\text{Motion ratio} = \left(\frac{Dimension\ A}{Dimension\ B}\right) * \sin(Spring\ angle)$$

$$Static\ load = \frac{Sprung\ weight}{Motion\ ratio}$$

$$Spring\ rate = \frac{Static\ load}{Shock\ ride\ height}$$

$$Effective\ wheel\ rate = Spring\ rate * Motion\ ratio^2$$

$$Spring\ rate = \frac{(Corner\ weight - Unsprung\ weight)}{\frac{Dimension\ A}{Dimension\ B} * \sin(Spring\ angle)} \div Shock\ ride\ height$$

90 degrees
$Spring\ rate =$ 57.76 lb / in
$Effective\ wheel\ ratio =$ 36.96 lb / in

80 degrees
$Spring\ rate =$ 58.65 lb / in
$Effective\ wheel\ ratio =$ 36.40 lb / in

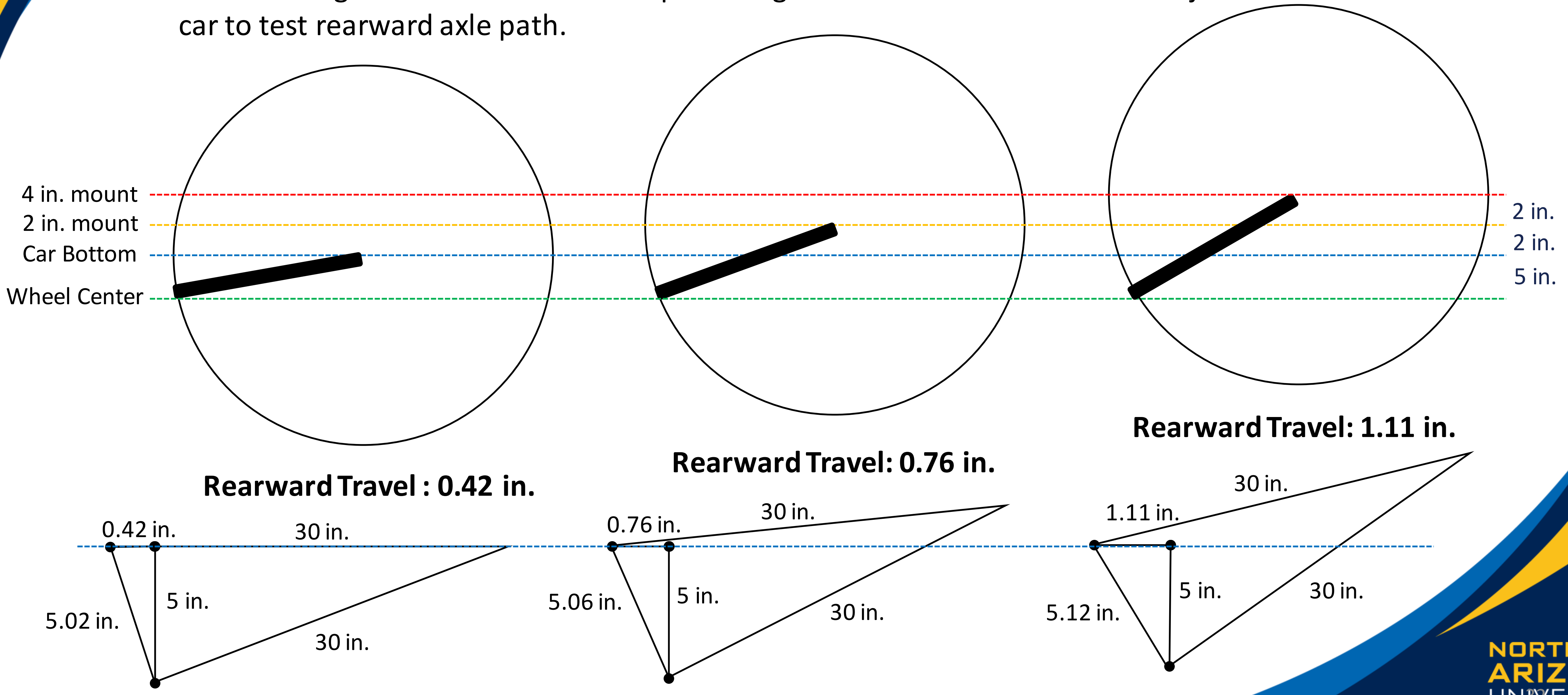
70 degrees
$Spring\ rate =$ 61.46 lb / in
$Effective\ wheel\ ratio =$ 34.73 lb / in

60 degrees
$Spring\ rate =$ 66.69
$Effective\ wheel\ ratio =$ 32.01

NORTHERN ARIZONA UNIVERSITY

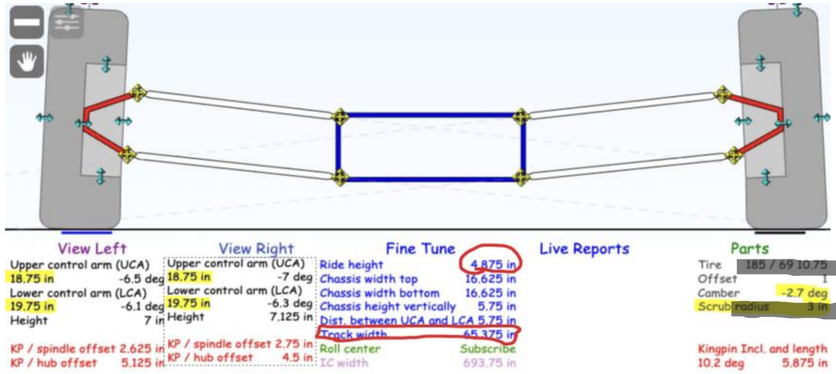
Mathematical Modeling #2 - Rear

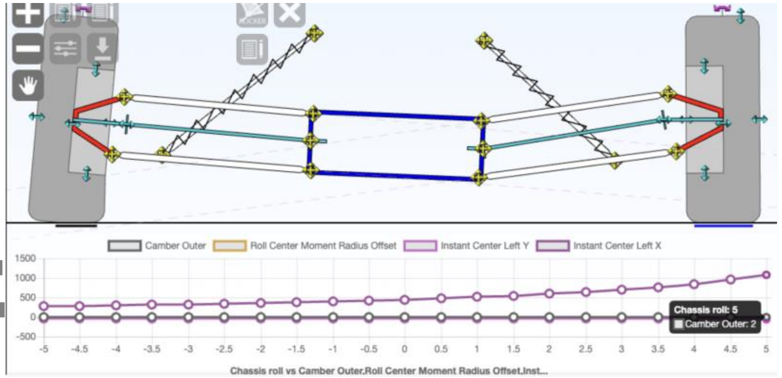
30 in. trailing link with different front pivot heights relative to the bottom of baja car to test rearward axle path.

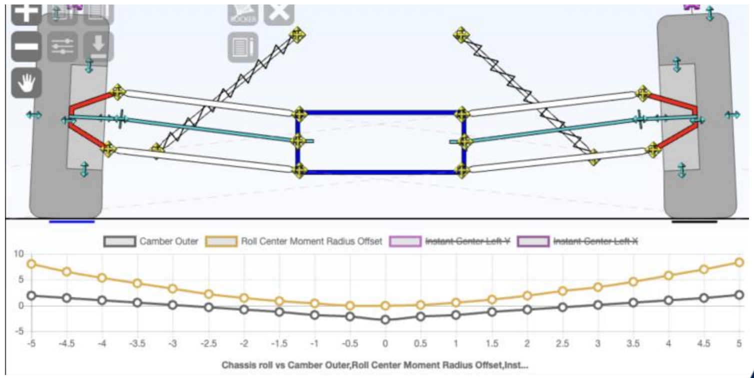


Mathematical Modeling #3 - Rear

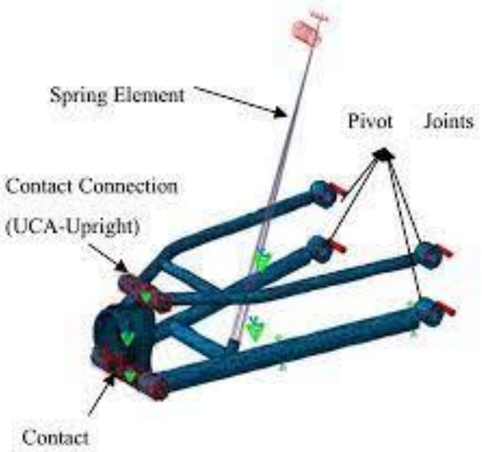
How does change in upper a-arm position/length affect camber gain?







Rear double h-arm



Goal: design a rear suspension with 90° camber at unsprung weight and negative camber (around 3-6°) under hard cornering.

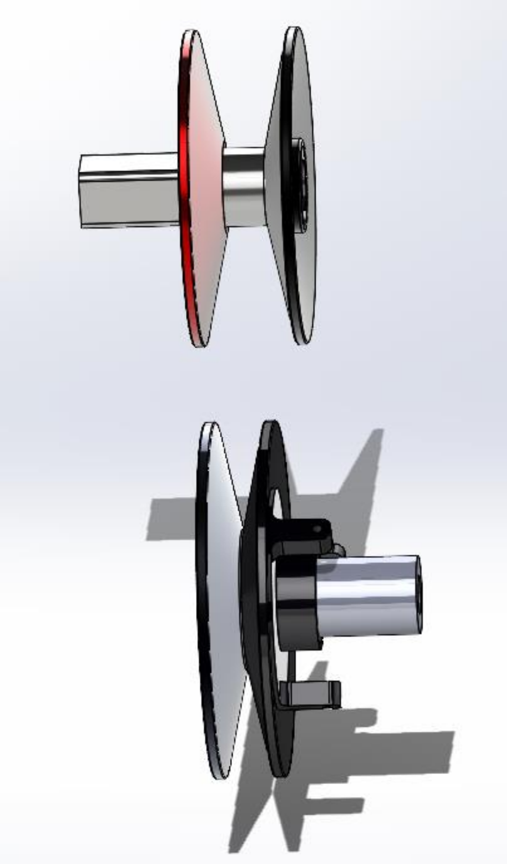
[79]

NORTHERN ARIZONA UNIVERSITY

Drivetrain Team

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

Benchmarking #1 – Drive



New CVT Sheave Geometry with Appropriate Total Range

Total gear ratio change

Researched other transmissions to find out what is a good total transmission ratio change

- Michigan 4.0:1 to .75:1 total range 5.333
- Cornell 2.23:1 to .5:1 total range 4.46
- Gaged 3.9:1 to .9:1 total range 4.333
- New ECVT 2.66:1 to .588:1 total range 4.53

Benchmarking #2 - Drive

Purdue University

Cornell University

Rear End Optimization

Integrated CV Cups

Northern Arizona University

Benchmarking #3 - Drive

CV joint

U-joint

CV joint and U-joint Comparison

Front End Optimization

Use CV joint rather than U-joint

- No binding with CV joint
- Increased range of angle
- Load is equally distributed

ETS Baja CV Axles

Michigan Baja Front End

Customer & Engineering Requirements - Drive

Customer Requirements

- High top speed
- Maximum efficiency
- High torque
- High service life
- Low weight
- High transmission range

Engineering Requirements

- 40mph top speed
- 80% drivetrain efficiency
- 400lb-ft of torque to the wheels
- 1000-hour service life
- Total drivetrain weight (w/out engine) 60lbs
- 1:4.5 total transmission range

NORTHERN ARIZONA UNIVERSITY

QFD Discussion - Drive

Input areas are in yellow

		1	2	3	4	5	6	7
1	top speed							
2	drivetrain efficiency							
3	torque to the wheels	6						
4	service life							
5	total system weight (w/out engine)		3					
6	total transmission range		6					
7	Meets HROE Guard specifications					-9		

Legend

A	Cornell 2023
B	NAU 2021 #21
C	NAU 2023 #74

	Customer Needs	Customer Weights	top speed	drivetrain efficiency	torque to the wheels	service life	total system weight (w/out engine)	total transmission range	Meets HROE Guard specifications	1 Poor	2	3 Acceptable	4	5 Good
			Technical Requirements							**Customer Opinion Survey**				
1	fast	5	9	6	6	3	6	6	1	C			B	A
2	High effeciency	3	9	9	6	6	3	6	3	C		B		A
3	fast acceleration	5	3	6	9	3	9	9	1	C		B		A
4	durable	1	1	6	1	9	1	4	9			AC		B
5	can crawl and go fast	4	9	6	9	3	3	9	1	C			B	A
6	NEEDS TO BE SAFE	5	1	1	1	6	1	1	9			C	B	A
7	Aesthetically Pleasing	3	9	1	9	3	9	9	3		C		A	B
8														
9														
10														
11														
	Technical Requirement Units		MPH	Unitles	Lbf/Ft	hours	lbs	Unitless	N/A					
	Technical Requirement Targets		40	80	400	1000	60	01:04.5	N/A					
	Absolute Technical Importance		156	125	162	108	129	165	86					
	Relative Technical Importance		4	6	3	7	5	2	1					

Drivetrain QFD

Literature Review

-Henry Van Zuyle-

Textbooks

- **Shigley's Mechanical Engineering Design [22]**
  - Chapter 17, Flexible Mechanical Elements
- **Machinery's Handbook [25]**
  - Chapter, Gearing

Papers

- **US Patent US20180172150A1, Electromechanically actuated continuously variable transmission system and method of controlling thereof [37]**
  - ETS ECVT patent
- **An Experimentally-Validated V-Belt Model for Axial Force and Efficiency in a Continuously Variable Transmission [38]**
  - Factors that effect CVT efficiency
- **Modeling and Tuning of CVT Systems for SAE® Baja Vehicles [40]**

Online

- **Shaft Splines & Serrations [42]**
  - Spline strength and geometry
- **Altair Motion View: CVT Model [43]**
  - Helped me develop my CVT design software

Literature Review

-Ryan Fitzpatrick-

Textbooks

- **Shigley's Mechanical Engineering Design [22]**
  - Chapters 13 & 14, Gears – General & Spur and Helical Gears
- **Machinery's Handbook [25]**
  - Chapter 12, Gearing

Papers

- **Methodology for Designing a Gearbox and its Analysis – IJERT [56]**
  - Gearbox Design General
- **Design and Analysis of Gearbox for SAE Baja Competition – IJERT [55]**
  - Gearbox Design for SAE
- **Lightweight Design of Gearbox Housing of Baja Racing Car Based on Topology Optimization – Journal of Physics [81]**
  - Gearbox Housing Design for optimization

Online

- **Gear Design by AGMA Theory – The Engineering Blog [82]**
  - AGMA theory source that includes lube factor
- **A Look at Belt, Chain and Gear Drive Technology – Power Transmission Engineering [83]**
  - Power Transmission Options Discussion
- **Chain Sprocket Calculator [84]**
  - Used to calculate the chain drive option

Literature Review

-Donovan Parker

Textbooks

- **Shigley's Mechanical Engineering Design [22]**
  - Chapter 17, Flexible Mechanical Elements
- **Machinery's Handbook [25]**
  - Machine Elements -> Flexible Belts and Sheaves/ Transmission Chains

Papers

- **Design Analysis and Fabrication of the Powertrain System for All-Terrain Vehicle – IJERT [80]**
  - Calculations
- **SAE Baja '24 Rule Book [89]**
  - Belt, Gear, and Chain Drives
- **Design of a Drivetrain for SAE Baja Racing Off-Road Vehicle – IJAEMS [85]**
  - Powertrain

Online

- **Belts and Chains Play to Their Strengths – Power Transmission Engineering [88]**
- **Belts/ Other Drives – Baja SAE Forums [87]**
- **Belt and Chain CVT: Dynamics and Control – Mechanism and Machine Theory [86]**

Literature Review

-Jarett Berger

Textbooks

- **Shigley's Mechanical Engineering Design [22]**
  - Chapter 14, Spur and Helical Gears, Chapter 18, Power Transmission
- **Machinery's Handbook [25]**
  - Gears, Splines, and Cams

Papers

- **Spur Gear Designing and Weight Optimization – IJERT [45]**
  - Designing spur gear
- **Design, Analysis, and Simulation of a Four-Wheel-Drive Transmission for an All-Terrain Vehicle – SAE [54]**
  - 4WD analysis
- **Design and Analysis of Gearbox for SAE Baja Competition – IJERT [55]**
  - Gearbox analysis

Online

- **Methodology for Designing a Gearbox and its Analysis - IJERT [56]**
  - Design approach for gearbox
- **Design and Analysis of Gearbox with Integrated CV Joints – Blog [57]**
  - CV joints integrated with output shaft

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #1 - Drive

$$\Phi_d = \pi - 2sin^{-1}\frac{D-d}{2C} = 2.282\text{rads} = 130.757°$$

$$\Phi_D = \pi + 2sin^{-1}\frac{D-d}{2C} = 4.001\text{rads} = 229.243°$$

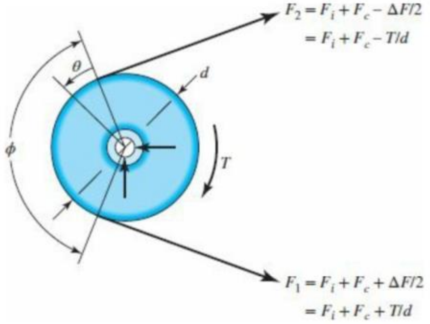
$$L = \sqrt{4C^2 - (D-d)^2} + \frac{1}{2}(D\Phi_D + d\Phi_d) = 110.92\ in. = 9.24\ ft$$

$$F_1 = \frac{T \times 12}{r} = 1048\ lbf\ (Tension\ Side\ Force)$$

$$F_2 = F_1 - \frac{2T}{d} = 0\ lbf\ (Slack\ Side\ Force)$$

Where:

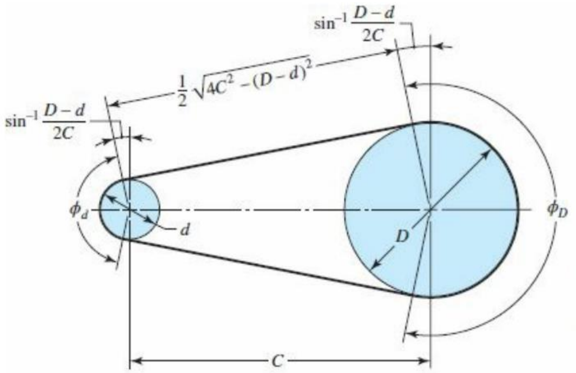
Φ_d = Smaller pulley wrap angle
Φ_D = Larger pulley wrap angle
L = Belt length
F_1 = Tension side force
F_2 = Slack side force



Wrap angle and Centrifugal Force

Creep prevention and Maximum power output and efficiency for 4WD integration

- Wrap angle calculation
- Belt Length calculation
- Centrifugal force calculation



Mathematical Modeling #2 - Drive

If $\beta \geq \pi$

$$T_0(lbf) = \frac{2\sin\left(\frac{\beta}{2}\right) * \left[2F_{Clamp}\tan\left(\frac{\phi}{2}\right) + \frac{1}{12}M_{Belt} * R^2 * \omega^2\right]}{cos\left(\frac{1}{2}(\beta - \pi)\right) * (e^{\mu_e \beta} + 1)}$$

If $\beta \leq \pi$

$$T_0(lbf) = \frac{2\sin\left(\frac{\beta}{2}\right) * \left[2F_{Clamp}\tan\left(\frac{\phi}{2}\right) + \frac{1}{12}M_{Belt} * R^2 * \omega^2\right]}{cos\left(\frac{1}{2}(\pi - \beta)\right) * (e^{\mu_e \beta} + 1)}$$

$$\tau_{Max_{Secondary}}(ft.* lbf) = \left(T_{Taught\_Secondary} - T_{Slack\_Secondary}\right) * \frac{Radius_{Secondary}}{12}$$

$$T_1 = T_0 e^{\mu_e \beta}$$

$$T_{1\_Primary}(lbf) = T_{1\_Secondary}$$

Governing Equations for CVT Geometry and Forces

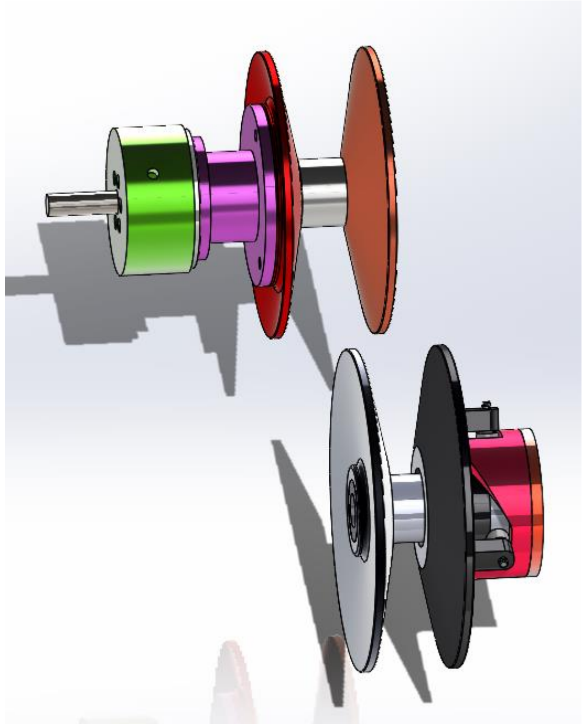
CVT Geometry and actuation force requirements

Utilized a matlab script to iterate through

- CVT sheave geometry to ensure large enough total ratio change
- Secondary cam geometry to generate sufficient clamping force

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #2 - Drive



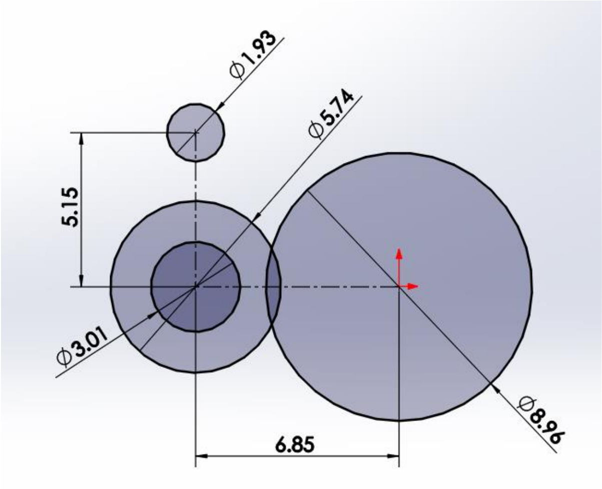
CVT design with non-optimized components

Results

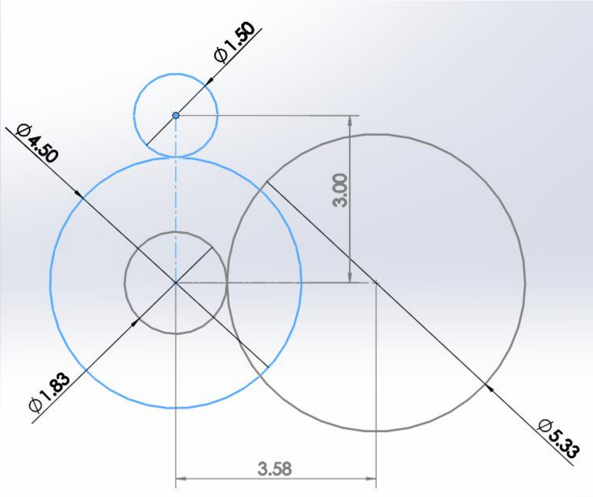
- Center to center is 9.5 inches
- Sheave angle is 12.77 degrees
- Sheave diameters clear each other and the motor
- CVT has a competitive range of 4.533
- Max actuation force from primary is 301 LbF

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #3 - Drive



Chain Drive Basic Sizing



Gearbox Basic Sizing

By taking the torques and angular velocity on each stage the minimum ANSI Chain Number of #50 was determined. These values were input into an online sprocket calculator [84] and the above dimensions were determined for a chain drive.

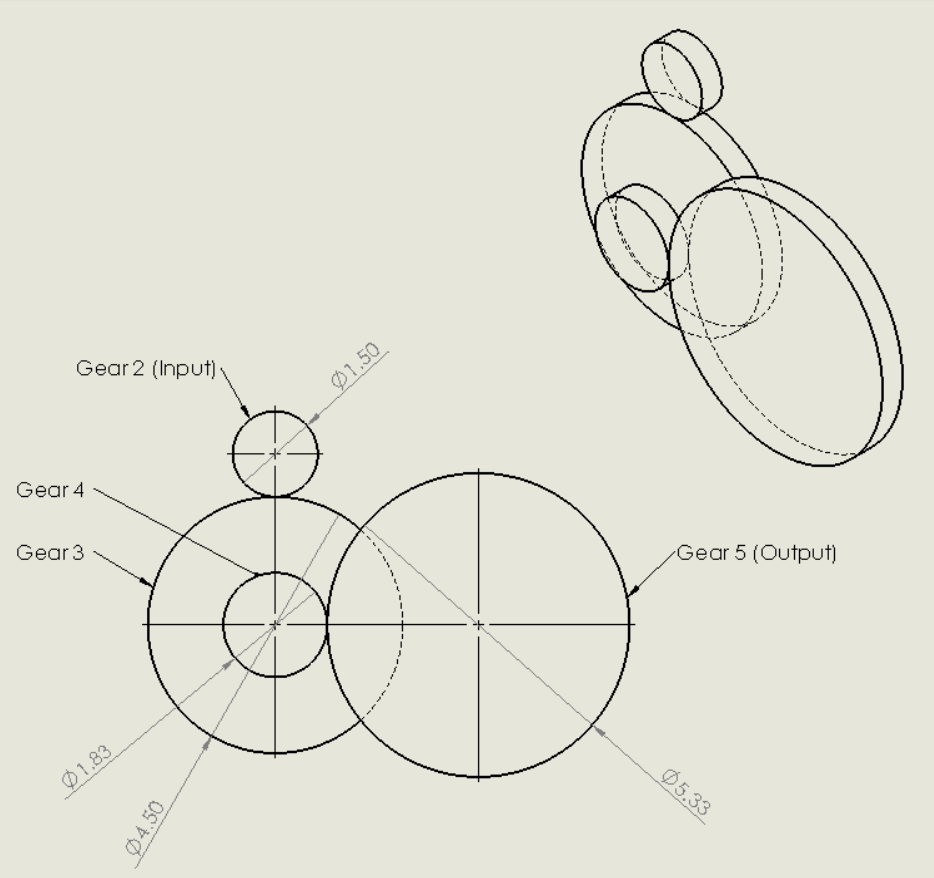
Rear Power Transmission

Did research and basic calculations to determine if power should be transmitted via chain or gear drive.

- Gearbox is slightly more efficient (Chain drives have efficiencies "up to about 98%" [83] versus gearboxes efficiencies of "less than 2%" [22]).
- Gearbox takes up 60% less space (see modeling to the left)
- Gearbox requires less maintenance [83]
- The top teams run gearboxes

From these calculations, we have decided to move forward with a gearbox as opposed to a chain drive.

Mathematical Modeling #4 - Drive



Preliminary Gearbox Design

Rear Gearbox Design

Looking to achieve a reduction of ~9.2 via a two-stage compound gear train while minimizing the space occupied by the gearbox to allow for better rear suspension geometry.

Diametral Pitch : $P = \frac{N}{d}$; $P\ (1st\ Stage) = 16\ \frac{teeth}{in}$; $P\ (2nd\ Stage) = 12\ \frac{teeth}{in}$

Train Value : $e = \frac{product\ of\ driving\ tooth\ numbers}{product\ of\ driven\ tooth\ numbers}$; $e_{target} = \frac{1}{9.2}$

Minimum Pinion Teeth : $N_{P,min} = \frac{2k}{(1+2m)sin^2(\Phi)}\left(m + \sqrt{m^2 + (1+2m)sin^2(\Phi)}\right)$

where… k = 1 (for full-depth teeth)

Φ = 20deg (standard pressure angle)

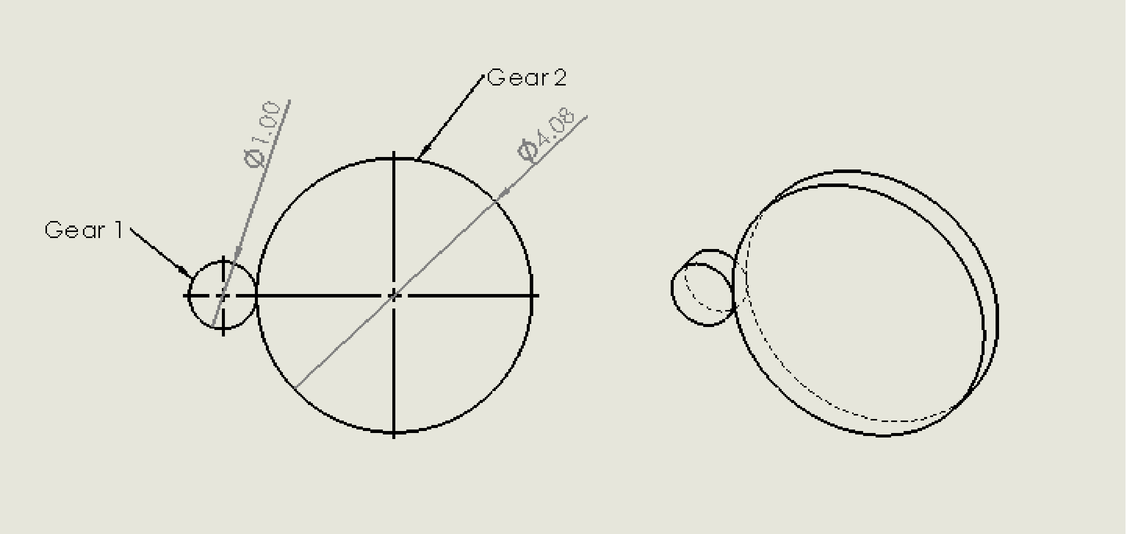
Input RPM = 1200

Output RPM = 120-140

Gear	d (diameter, in)	N (number of teeth)
2	1.5	24
3	4.5	72
4	1.83	22
5	5.33	64

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #5 - Drive



Preliminary Gear Design

	Gear 1	Gear 2
Teeth	12	49
Pitch Dia. (in)	1	4.08333
Dia Pitch (teeth/in)	12	12

Gear Calculations

Front Gearbox Design

- 1 stage gear reduction to achieve more torque and steering traction
- Size of gear teeth will minimize front end space so that suspension and steering designs are optimized

Table 13-2 **Tooth Sizes in General Uses**

Diametral Pitch *P* (teeth/in)	
Coarse	2, $2\frac{1}{4}$, $2\frac{1}{2}$, 3, 4, 6, 8, 10, 12, 16

Minimum Teeth for Pinion: $N_P = \frac{2k}{3sin^2\phi}(1 + \sqrt{3sin^2\phi})$

Maximum Teeth for Gear: $N_G = \frac{N_P sin^2(\phi) - 4k^2}{4k - 2N_P * sin^2(\phi)}$

K (Full-Depth) = 1

Pressure angle Φ = 20deg

NORTHERN ARIZONA UNIVERSITY

Frame Team

Cooper Williams, Gabriel Rabanal, Antonio Sagaral

NORTHERN ARIZONA UNIVERSITY

Benchmarking – Frame

ETS
Rear Brace
1st overall in Oregon 2023

University of Michigan
Rear Brace
4th overall in Oregon 2023

Cornell University
Front Brace
4th overall in NY 2020

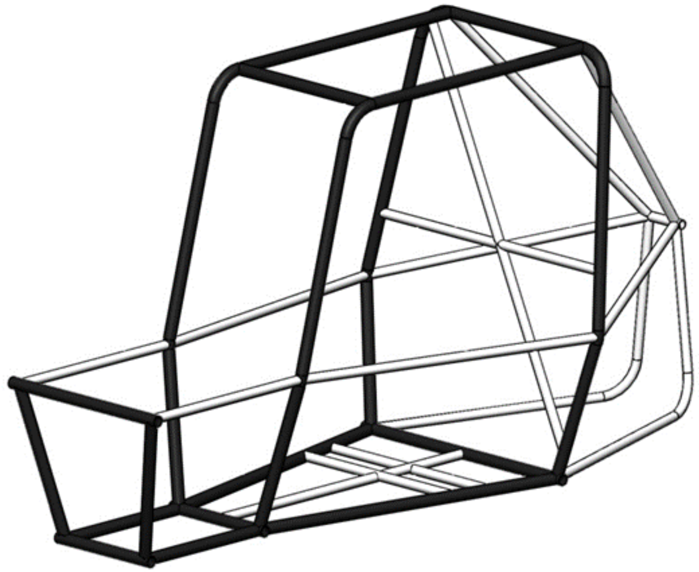
Customer & Engineering Requirements - Frame

Customer Requirements

- Lightweight
- Durable
- Easy to manufacture
- Satisfy SAE Baja frame guidelines
- Affordable
- Maneuverable
- Rigid
- Fast

Engineering Requirements

- Steel carbon content greater than 18%
- RRH angle between 0 and 20 deg
- Primary members minimum specs: 0.984in O.D. and 0.062in wall thickness
- Secondary members minimum specs: 1.0in O.D. and 0.035in wall thickness



Roll Cage, Primary Members (filled in black), Rear Braced Frame

NORTHERN ARIZONA UNIVERSITY

QFD Discussion - Frame

System QFD

Project:	Baja 24 Frame
Date:	9/14/23

#	Technical Requirement	Decrease weight	Decrease length of body	Decrease width of body	Decrease Cost	increase aerodynamics
2	Decrease weight					
3	Decrease length of body	6				
4	Decrease width of body	3	-9			
5	Decrease Cost	-9	3	3		
6	increase aerodynamics	-3	-6	3	-3	
7	Increase strength of frame	6	-3	-9	-6	

Legend
- A [illegible]
- B [illegible]
- C [illegible]

#	Customer Needs	Customer Weights	Decrease weight	Decrease length of body	Decrease width of body	Decrease Cost	increase aerodynamics	Increase strength of frame	1 Poor	2	3 Acceptable	4	5 Excellent
			Technical Requirements						**Customer Opinion Survey**				
1	Rigid	3	1	6	3	3	1	9				ÀBC	
2	Easy to manufacture	3	3	3	1	3	6	3			B	AC	
3	Maneuverable	2	3	9	9	1	1	3					ABC
4	Aesthetics	1	3	1	3	3	9	1			C	B	A
5	Durable	2	3	1	3	3	3	9			AC	B	
6	Satisfy SAE Baja Frame Guidlines	4	3	1	6	3	1	6					ABC
7	Stable	3	1	3	9	1	3	6				C	AB
8	Fast	3	6	3	3	9	9	3				BC	A
9	Lightweight	4	9	6	3	9	3	6				ABC	
10	Affordable	3	9	6	3	9	6	6			ABC		
	Technical Requirement Units		lbs	in	in	$	lbf	psi					
	Technical Requirement Targets			64	64								
	Absolute Technical Importance		123	112	120	134	108	154					
	Relative Technical Importance		3	5	4	2	6	1					

Main Customer Needs

- Satisfies SAE Rules
- Lightweight
- Affordable
- Easy to manufacture

Main Engineering Requirements

- Increased frame strength
- Decrease cost
- Decrease weight
- Decrease body width

Literature Review

-Gabriel Rabanal-

Textbooks

- ***Materials selection in mechanical design* [18]**
  - Ch 5-6: material selection process
- ***The Automotive Chassis: Engineering Principles* [14]**
  - Ch 6: loading effects on chassis types, braking behaviors

Papers

- ***A novel approach for design and analysis of an all-terrain vehicle roll cage* [15]**
  - Impact analysis for rear braced frame design
- **Computational analysis for improved design of an SAE Baja frame structure [16]**
  - Rear braced frame analysis and materials discussion
- **Design and FE analysis of chassis for solar powered vehicle [17]**
  - Frame material comparison

Online

- **Mini Baja Vehicle Design Optimization [19]**
  - Bracing analysis/failure testing
- **SolidWorks BAJA SAE Tutorials - How to Model a Frame (Revised) [20]**
  - CAD Tutorial, Design of SAE Baja frame in SolidWorks

Literature Review

-Antonio Sagaral-

Textbooks

- ***Shigley's Mechanical Engineering Design* [22]**
  - Ch 2-22: Materials selection
- ***Fundamentals of Machine Component Design [29]***
  - Ch 11: Rivets, Welding, and Bonding

Papers

- ***Design, Analysis and Optimization of a BAJA-SAE Frame [39]***
  - FEA Analysis and Material options
- ***Design and Construction of a Space-frame Chassis [41]***
  - Suspension forces and FEA Analysis
- ***DESIGN AND STRUCTURAL ANALYSIS OF BAJA FRAME WITH CONVENTIONAL AND COMPOSITE MATERIALS [44]***
  - Impact analysis and stress calculations

Online

- ***[Front Impact Test & Meshing] BAJA SAE Roll Cage/Frame Design in ANSYS Workbench Static Structural [53]***
  - Impact testing points and strategies
- ***Baja SAE Frame Investigations [47]***
  - Investigation of rear vs front brace frames

Literature Review

-Cooper Williams

Textbooks

- ***Shigley's Mechanical Engineering Design* [22]**
  - Chapter 9: Welding, Bonding, and the Design of Permanent Joints
- ***The Automotive Chassis: Engineering Principles* [14]**
  - Ch 6.1: Vehicle and body center of gravity

Papers

- ***Design and Analysis of Chassis for SAE BAJA Vehicle* [19]**
  - Member Stress Analysis
- ***Mathematical Model for Prediction and Optimization of Weld Bead Geometry in All-Position Automatic Welding of Pipes* [25]**
  - Strength of Welds given several factors
- ***Design, analysis and optimization of all-terrain vehicle chassis ensuring structural rigidity* [21]**
  - Provides analysis for different frame impacts

Online

- ***Design Judging Discussion* [28]**
  - Discusses how some judges approach scoring vehicles
- ***Getting Started with weldments in SOLIDWORKS* [27]**
  - Introduction to Weldments, Manufacturing

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #1-Frame

Densities of Suitable Steels

Material	Density (lb/in^3)
1018 LC, CD Steel	0.284
1020 LC, CD Steel	0.284
4130 MC, CD Steel	0.284

Table: Density Comparison

Material/Cost Comparison

- ***Each year, about 80 feet is purchased for frame manufacturing***
- ***Only use about 90% of the 80ft***

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

ρ: density, lb/in^3

m: mass, lbm

V: volume, in^3

NORTHERN ARIZONA UNIVERSITY

Mathematical Modeling #2 - Frame

Steel Type (AISI)	1018	4130	1020	1020
O.D. (in)	1	1	1	1.125
Wall thickness (in)	.12	.12	.12	.12
S_b(klb*in)	3.513	4.128	3.323	4.381
A_s (in^2)	.3317	.3317	.3317	.3789

Equations

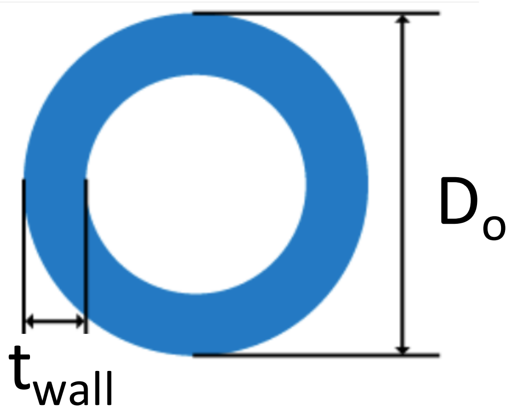
- $S_b = \frac{S_y I}{c}$
- $A_s = \pi(\frac{D_o}{2})^2 - \pi(\frac{D_o}{2} - t_{wall})^2$

Frame Material Comparison

Calculations performed for primary members

SAE Specifications:

- Minimum OD of 1”
- Standard minimum thickness of .12”



Mathematical Modeling #3 - Frame

Primary Member Tube Specs

Equations

- $S_b = \frac{S_y I}{c}$
- $K_b = EI$

	Base 1018 requirements	4130	4130	4130
O.D. (in)	0.984	1	1.125	1.25
I.D. (in)	0.748	0.76	0.959	1.12
Wall thickness (in)	0.118	0.12	0.083	0.065
K_b(klb*in)	**948.6**	**948.6**	**1076.2**	**1235.5**
S_b(klb*in)	**3.513**	**4.128**	**4.163**	**4.301**

Thank you!

NORTHERN ARIZONA UNIVERSITY

Bibliography

[1] "Nau Sae Baja team on Instagram: 'so excited to see where our team members end up in the next few years...and that's a wrap!,'" Instagram, https://www.instagram.com/p/COd0nAALO0O/?utm_source=ig_web_copy_link&igshid=MzRlODBiNWFlZA (accessed Sep. 12, 2023).

[2] "Baja ETS on Instagram: 'Rencontre d'infromation le 21 septembre au local D-2027! il n'est pas trop tard pour joindre l'équipe de baja ets. tous les programes sont les bienvenues. Au Plaisir de vous rencontrer'" Instagram, https://www.instagram.com/p/Ciu68AvuA_X/?utm_source=ig_web_copy_link&igshid=MzRlODBiNWFlZA (accessed Sep. 12, 2023).

[3] J. C. Dixon, "12 - Double Arm Suspensions," in *Suspension geometry and computation*, Chichester, U.K.: Wiley, 2009

[4] J. Reimpell, H. Stoll, and J. W. Betzler, "1 - Types of Suspension and Drive," in *The Automotive Chassis: Engineering principles*, Warrendale: SAE International, 2001

[5] S. V. Dusane, M. K. Dipke, and M. A. Kumbhalkar, "Analysis of steering knuckle of all terrain vehicles (ATV) using finite element analysis," IOP Conference Series: Materials Science and Engineering, vol. 149, p. 012133, 2016. doi:10.1088/1757-899x/149/1/012133

NORTHERN ARIZONA UNIVERSITY

Bibliography

[6] I. Hiremath, A. Nalawade, and J. Patil, "Design and development of front suspension system for an off-road vehicle," International Journal of Research in Engineering, Science and Management, https://journal.ijresm.com/index.php/ijresm/article/view/79 (accessed Sep. 14, 2023).

[7] S. Sharma, Design Review of Suspension Assembly of a Baja ATV - IRJET, https://www.irjet.net/archives/V7/i5/IRJET-V7I51227.pdf (accessed Sep. 15, 2023).

[8] "Suspension & Steering Geometry (front) | double wishbone | anti-ackerman | SAE baja | solidworks," YouTube, https://www.youtube.com/watch?v=KuSQnUwzi-c (accessed Sep. 14, 2023).

[9] "Steering knuckle | Solidworks | 3D - modelling | Baja ATV," YouTube, https://www.youtube.com/watch?v=sCCMHqDhjmw (accessed Sep. 14, 2023).

[10] "Bearing stresses (contact stresses)," Bearing Stresses | Engineering Library, https://engineeringlibrary.org/reference/bearing-stress-air-force-stress-manual (accessed Sep. 15, 2023).

[11] SAE Mini Baja Frame Analysis, https://ceias.nau.edu/capstone/projects/ME/2014/SAE-MiniBaja/team_01/team_01-engineering-analysis-report.pdf.

NORTHERN ARIZONA UNIVERSITY

Bibliography

[12] "CV Joints," CV joints, https://www.aa1car.com/library/cvjoint1.htm (accessed Sep. 15, 2023).

[13] H. V. Heer, "Billet aluminium - composition, properties, uses," ThePipingMart Blog, https://blog.thepipingmart.com/metals/billet-aluminium-composition-properties-uses/#:~:text=Billet%20Aluminium%20Mechanical%20Properties,(up%20to%20180%20MPa). (accessed Sep. 15, 2023).

[14] J. Reimpell, H. Stoll, and J. W. Betzler, "6 – Chassis and vehicle overall," in The automotive chassis : engineering principles, 2nd ed. Oxford: Butterworth-Heinemann, 2001.

[15] R. Soundararajan, R. Ajith, C. Mahesh kumar, U. Sabarivasan, and J. Sonu Mourya, "A novel approach for design and analysis of an all-terrain vehicle roll cage," in Materials today : proceedings, 2021, vol. 45, pp. 2239–2247. doi: 10.1016/j.matpr.2020.10.224.

[16] N. Noorbhasha, "Computational analysis for improved design of an SAE Baja frame structure," ProQuest Dissertations Publishing, 2010.

[17] D. Patel, V. Jasani, D. Shah, and A. Lakdawala, "Design and FE analysis of chassis for solar powered vehicle," in Materials today : proceedings, 2022, vol. 62, pp. 1626–1631. doi: 10.1016/j.matpr.2022.04.137.

NORTHERN ARIZONA UNIVERSITY

Bibliography

[18] M. F. Ashby, Materials selection in mechanical design, 4th ed. Amsterdam ; Butterworth-Heinemann, 2010.

[19] J. Hastie, "Mini Baja vehicle design optimization," Northeastern University, https://repository.library.northeastern.edu/downloads/neu:376750?datastream_id=content (accessed Sep. 18, 2023).

[20] SOLIDWORKS. "SolidWorks BAJA SAE Tutorials - How to Model a Frame (Revised)" YouTube, Sept. 26, 2010 [Video file]. Available: https://www.youtube.com/watch?v=7ZTIFgUZ1cY [Accessed: Sept. 18 2023].

[21] S. Jacob, V. Thiruvarasan, S. Surendhar, and R. Senthamizh, "Design, analysis and optimization of all terrain vehicle chassis ensuring structural rigidity," Science Direct, https://www-sciencedirect-com.libproxy.nau.edu/science/article/pii/S221478532101083X (accessed Sep. 18, 2023).

[22] Budynas, R.G. and Nisbett, J.K. (no date) Loose Leaf for Shigley's Mechanical Engineering Design 11th. Available at: https://www.directtextbook.com/isbn/9781260407648 (Accessed: 19 September 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

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

[24] E. Oberg *et al.*, *Machinery's Handbook*. South Norwalk, CT: Industrial Press, Inc., 2020.

[25] C. Sommitsch and C. Sommitsch, Numerical Modelling and Simulation of Metal Processing. Basel, Switzerland: MDPI - Multidisciplinary Digital Publishing Institute, 2021. 020.

[26] C. Bennett, E. Lockwood, A. Mcclinton, R. Mcree, and C. Team, "SAE Mini Baja Frame Analysis Analysis of the Baja Frame Document." Accessed: Sep. 19, 2023. [Online]. Available: https://ceias.nau.edu/capstone/projects/ME/2014/SAE-MiniBaja/team_01/team_01-engineering-analysis-report.pdf

[27] Hawk Ridge Systems. "Get Started with Weldments in SOLIDWORKS," *www.youtube.com*. https://www.youtube.com/watch?v=mruur6CUrQ0 (accessed Sep. 19, 2023).

[28] "Design Judging Discussion," *Official Baja SAE Forums*. http://forums.bajasae.net/forum/design-judging-discussion_topic2106.html (accessed Sep. 19, 2023).

[29] R. C. Juvinall and K. M. Marshek, Fundamentals of machine component design. Hoboken, Nj: Wiley, 2020.

NORTHERN ARIZONA UNIVERSITY

Bibliography

[30] S. Patil, "Lotus Shark Suspension | Tutorial," Youtube, 4 1 2022. [Online]. Available: https://www.youtube.com/watch?v=lJdWphDkFtY. [Accessed 17 9 2023].

[31] A. CALCULATIONS, "LIVE TUTORIAL ON LOTUS SUSPENSION SOFTWARE," Youtube, 22 8 2020. [Online]. Available: https://www.youtube.com/watch?v=9RPZkpUpUm8. [Accessed 17 9 2023].

[32] S. Baja, "Baja SAE," SAE International, 2023. [Online]. Available: https://www.bajasae.net/cdsweb/gen/DocumentResources.aspx. [Accessed 17 9 2023].

[33] P. A. Nitish Malik, "Fine-Tuning Of the Suspension System of Baja ATV," *Journal of Engineering Research and Application,* vol. 7, no. 8, pp. 1-5, 2017.

[34] J. C. X. S. Aoqi Wang, "Optimal Design of Suspension System of Four-Wheel Drive Baja Racing," *Journal of Physics: Conference Series,* vol. 1, no. 1, pp. 3-9, 2021.

[35] R. W. L. Barkovitz, "Redesigning the Cooper Union SAE Mini-Baja Front Suspension and Steering," The Cooper Union Albert Nerken School of Engineering, 2006.

Bibliography

[36] J. C. Dixon, Suspension Geometry and Computation, West Sussex: Wiley, 2009

[37] Anglehart Et Al, Ecole de Technologie Superieure, "Electromechanically actuated continuously variable transmission system and method of controlling thereof", US20180172150A1, July 14, 2020

[38] Matthew James Messick, An Experimentally-Validated V-Belt Model for Axial Force and Efficiency in a Continuously Variable Transmission, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2018

[39] Y. Chandra, "International Journal of Science and Research (IJSR)," Design, Analysis and Optimization of a BAJA-SAE Frame, vol. 9, no. 2, pp. 617–626, Feb. 2020, Accessed: Sep. 18, 2023. [Online]. Available: https://www.ijsr.net/archive/v9i2/SR20208233756.pdf

[40] Skinner, Sean Sebastian, "Modeling and Tuning of CVT Systems for SAE® Baja Vehicles" (2020). Graduate Theses, Dissertations, and Problem Reports. 7590.

[41] Brendan. J. W. Waterman , "Design and Construction of a Space-frame Chassis," Nov. 2011.

NORTHERN ARIZONA UNIVERSITY

Bibliography

[42] "CVT Model". Altair.com. https://2022.help.altair.com/2022.1/hwdesktop/mv/topics/motionview/cvt_scooter_cvt_model_r.htm

[43] Shaft Splines & Serrations. Engineeringproductdesign.com. https://engineeringproductdesign.com/knowledge-base/splines-serrations/

[44] P. D. RAJA RAO, CH. NARESH, and B. S. S. PHANISANKAR, "INTERNATIONAL JOURNAL OF ADVANCE SCIENTIFIC RESEARCH AND ENGINEERING TRENDS," DESIGN AND STRUCTURAL ANALYSIS OF BAJA FRAME WITH CONVENTIONAL AND COMPOSITE MATERIALS, vol. 5, no. 7, pp. 23–31, Jun. 2020, Accessed: Sep. 18, 2023. [Online]. Available: http://ijasret.com/VolumeArticles/FullTextPDF/475_5.DESIGN_AND_STRUCTURAL_ANALYSIS_OF_BAJA_FRAME_WITH_CONVENTIONAL_AND_COMPOSITE_MATERIALS.pdf

[45] Kumar, N., Chittoria, V., & Upadhyay, U. (2020). Spur Gear Designing and Weight Optimization - International Journal of Engineering Research and Technology

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

[47] "Baja SAE Frame Investigations," Portfolio and projects, Dec. 13, 2019. https://travisforhireblog.wordpress.com/2019/12/12/baja-sae-frame-investigations/ (accessed Sep. 19, 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

[48] W. F. Milliken and D. L. Milliken, Race Car Vehicle Dynamics. Warrendale,, PA, 1995.

[49] J. C. Dixon, Tires, Suspension and Handling, 2nd ed. Warrendale, PA: Society of Automotive Engineering, SAE, 1996.

[50] "Suspension Types," Suspension design software susp types, http://www.susprog.com/susptype.htm (accessed Sep. 17, 2023).

[51] J. Isaac-Lowry, "Suspension Design: Types of Suspensions," Automotive Articles, http://www.automotivearticles.com/Suspension_Design_Types_of_Suspensions.shtml (accessed Sep. 17, 2023).

[52] S. Wolfe, "PDF." Ohio state University, Spring. 2010

[53] "[Front Impact Test & Meshing] BAJA SAE Roll Cage/Frame Design in ANSYS Workbench Static Structural," www.youtube.com. https://www.youtube.com/watch?v=CJ7S6JnruJk&ab_channel=DeltaAcademy (accessed Sep. 19, 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

[54] C. Kanna, Design, Analysis, and Simulation of a Four-Wheel-Drive Transmission for an All-Terrain Vehicle, 2022

[55] Anjali Mukeshkumar Sah , Naved Anwar Husain Farooqui, Design and Analysis of Gearbox for SAE BAJA Competition, 2020

[56] Neeraj Patel, Tarun Gupta, Methodology for Designing a Gearbox and its Analysis, Vol. 5 Issue 01, January-2016

[57] Mrinal Gupta, Mayank Pant and Akshit Khandelwal, Design and Analysis of Gearbox with Integrated CV Joints, Volume 8, Issue 8, August 2017

[58] Z. E.-S. Moustafa El-Gindy, Road and Off-Road Vehicle Dynamics, Springer, 2023.

[59] J. Vogel, “Tech Explained: Ackermann Steering Geometry,” *Racecar Engineering*.

NORTHERN ARIZONA UNIVERSITY

Bibliography

[60] A. Goodarzi and A. Khajepour, *Vehicle Suspension System Technology and Design*. San Rafael, CA: Morgan & Claypool Publishers, 2017.

[61] D. E. Kline, *Geometric Design of Independent Suspension Linkages*. David E Kline, 2018.

[62] N. Malik and P. Agarwal, "Fine-Tuning Of the Suspension System of Baja ATV." Aug. 2017

[63] A. Thosar, "Design, Analysis and Fabrication of Rear Suspension System for an All-Terrain Vehicle." Nov. 2014

[64] M. Poojari, A. Raj, B. S. Babu, R. Muddaiah, and B. S. Shreyas, "Design, analysis of H-arm camber link rear suspension system along with design of custom coil springs for an electric all-terrain vehicle," *Materials Today: Proceedings*, vol. 46, pp. 2858–2867, 2021. doi:10.1016/j.matpr.2021.03.131

[65] "Suspension geometry calculator," RACING ASPIRATIONS, https://www.racingaspirations.com/apps/suspension-geometry-calculator/ (accessed Sep. 16, 2023).

[66] "Spring Rate Calculator: Wheel rate calculator: Automotive," Hyperco, https://www.hypercoils.com/spring-rate-calculator (accessed Sep. 17, 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

[67] J. Balkwill, Performance vehicle dynamics : engineering and applications. Oxford, England: Butterworth-Heinemann, 2018.

[68] M. Blundell and D. Harty, The multibody systems approach to vehicle dynamics, 2nd ed. Oxford, England ;: Butterworth-Heinemann, 2015.

[69] S. S. Sankar, “Suspension Design and testing of an All-Terrain Vehicle using Multi-body dynamics Approach,” IOP conference series. Materials Science and Engineering, vol. 376, no. 1, p. 12094–, 2018, doi: 10.1088/1757-899X/376/1/012094.

[70] A. Wang, J. Chen, and X. Shen, “Optimal Design of Suspension System of Four-wheel Drive Baja Racing,” Journal of physics. Conference series, vol. 2235, no. 1, p. 12086–, 2022, doi: 10.1088/1742-6596/2235/1/012086.

[71] M. Anthony Bala Paul Raj, R. Pala Raviramachandran, N. Prakash, B. Chirudeep Reddy, and V. Gopi Krishna, “Design and Optimization of Rear Wheel Assembly for All-Terrain Vehicle,” International journal of vehicle structures and systems, vol. 13, no. 3, pp. 285–288, 2021, doi: 10.4273/ijvss.13.3.07.

[72] “2.5 PODIUM-X AFTERMARKET SHOCK OWNER’S MANUAL FLOAT 3 EVOL RC2 FACTORY SERIES OWNER’S MANUAL.” Accessed: Sep. 19, 2023. [Online]. https://www.ridefox.com/fox17/dl/atv/605-00-114_Rev_B.pdf

[73] “Semi-Trailing Arm Suspension Geometry | Solidworks | SAE BAJA | ATV,” *www.youtube.com*. https://www.youtube.com/watch?v=Xuoic1KMWB0&list=PLWfMzLgRVSS8bc2TjSl0h-Mj1xyGP9civ&index=3 (accessed Sep. 19, 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

[74] W. C. Michell, A. Staniforth, and I. Scott, "Analysis of Ackermann Steering Geometry," SAE International, 2006.

[75] V. Bhardwaj, O. Chauhan, and R. Arora, "Design and Optimization of Steering Assembly for Baja ATV Vehicle," SAE Technical Paper 2023-01-0161, 2023.

[76]

[77] M. Guiggiani, *The Science of Vehicle Dynamics Handling, Braking, and Ride of Road and Race Cars*. Cham: Springer International Publishing, 2023.

[78] *Baja Virtual Presentation Series Day 8: - Steering Calculations Slide (Baja Virtuals 2020)*. Youtube, 2019.

[79] A. Knowles, “Set Up Suspension 101,” ATV Rider, https://www.atvrider.com/set-suspension-101/ (accessed Sep. 19, 2023).

[80] V. Waladkar, P. Vitthaldas, S. Karle, and N. Ingale, “Design, Analysis & Fabrication of the Powertrain System for All-Terrain Vehicle,” International Journal of Engineering Research & Technology, https://www.ijert.org/design-analysis-fabrication-of-the-powertrain-system-for-all-terrain-vehicle (accessed Sep. 19, 2023).

NORTHERN ARIZONA UNIVERSITY

Bibliography

[81] "A Look at Belt, Chain and Gear Drive Technology," Power Transmission Engineering Magazine RSS, https://www.powertransmission.com/blogs/4-editors-choice/post/105-a-look-at-belt-chain-and-gear-drive-technology#:~:text=Gear%20drives%20are%20mechanically%20strong,drives%20have%20high%20transmission%20efficiency (Accessed Sep. 19, 2023).

[82] "Gear Design by AGMA Theory: Online Calculator," The Engineering Blog, https://theengineeringblog.com/gear-design-by-agma-theory/ (Accessed Sep. 19, 2023).

[83] Z. Zeng, Y. Zhang, and D. Tang, "Lightweight Design of Gearbox Housing of Baja Racing Car Based on Topology Optimization," *Journal of Physics: Conference Series*, vol. 2235, no. 1, p. 012084, 2022. doi:10.1088/1742-6596/2235/1/012084

[84] "Chain and Sprocket Calculator: RPM and Chain Speeds," Chain and Sprocket Calculator | RPM and Chain Speeds, https://www.blocklayer.com/chain-sprocket (Accessed Sep. 19, 2023).

[85] 6 IJAEMS-JUL-2015-11-Design of a Drivetrain for Sae Baja Racing Off ..., https://ijaems.com/upload_images/issue_files/1452664386-6%20IJAEMS-JUL-2015-11-Design%20of%20a%20Drivetrain%20for%20Sae%20Baja%20Racing%20Off-Road%20Vehicle.pdf (accessed Sep. 19, 2023).

[86] Author links open overlay panel Nilabh Srivastava a, a, b, and A. the last two decades, "A review on belt and chain continuously variable transmissions (CVT): Dynamics and control," Mechanism and Machine Theory, https://www.sciencedirect.com/science/article/pii/S0094114X08001432

NORTHERN ARIZONA UNIVERSITY

Bibliography

[87] "Belt/Other Drives," Official Baja SAE Forums, http://forums.bajasae.net/forum/belt-other-drives_topic168.html (accessed Sep. 19, 2023).

[88] "Chains and Belts Play to Their Strengths," Power Transmission Engineering Magazine RSS, https://www.powertransmission.com/articles/808-chains-and-belts-play-to-their-strengths#:~:text=Tooth%20belts%20simply%20do%20not,transmitted%20in%20smaller%20envelope%20dimensions.%E2%80%9D (accessed Sep. 19, 2023).

[89] 2024 Baja SAE Rules, https://www.bajasae.net/cdsweb/app/NewsItem.aspx?NewsItemID=fca69591-edf2-46fc-aac2-0b7ed04f88a9 (accessed Sep. 19, 2023).

NORTHERN ARIZONA UNIVERSITY