

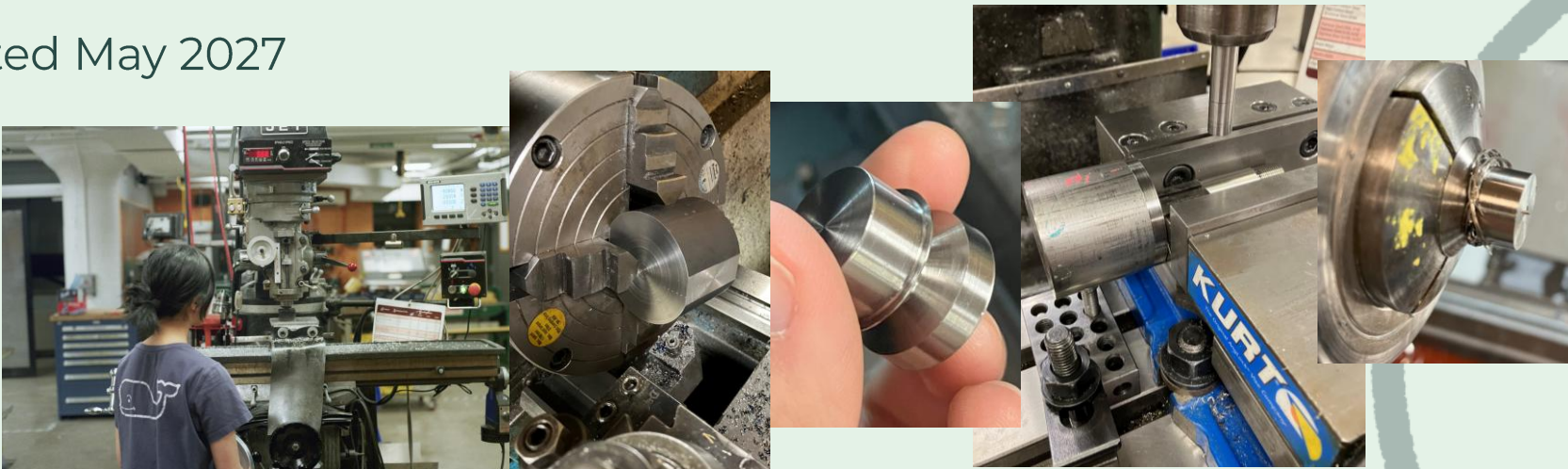
baja-ing art-ing
traveling music-ing organizing
notion-ing metal-cutting

Shelley Wei

B.S.E. Mechanical Engineering

Case Western Reserve University

Expected May 2027





Baja SAE:

Continuously Variable Transmission

Shelley Wei
August 2025

Baja SAE (Society of Automotive Engineers)

- Student-led teams who design and build cool off-road race cars

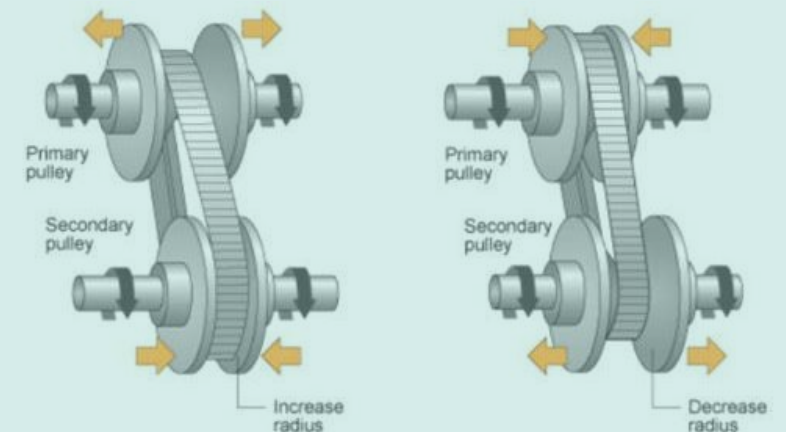
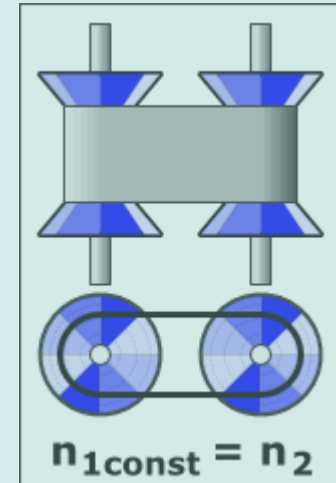
Events

- Dynamic
 - Acceleration, Hill Climb/Sled Pull, Maneuverability, Suspension & Traction
 - Points based on relative placement
- Static
 - Design Presentation, Business Presentation, Cost
 - Points based on judging
- Endurance (4-hour wheel-to-wheel race)
 - Points based on number of laps completed



What's a continuously variable transmission (CVT)?

- Used in some road cars, ATVs, and snowmobiles (and Baja SAE cars)
- Consists of input pulley, output pulley, belt
- No discrete gearings
- Purpose: accelerate vehicle at engine peak power ($P = mav$)



Setting Requirements

Vehicle Requirements

3.8-second acceleration time over 100 feet

Top speed of 38 MPH within 300 feet

Ability to clear endurance obstacles at a minimum of 75% of top speed

Lap times to increase no more than 6% after 4 hours of continuous runtime

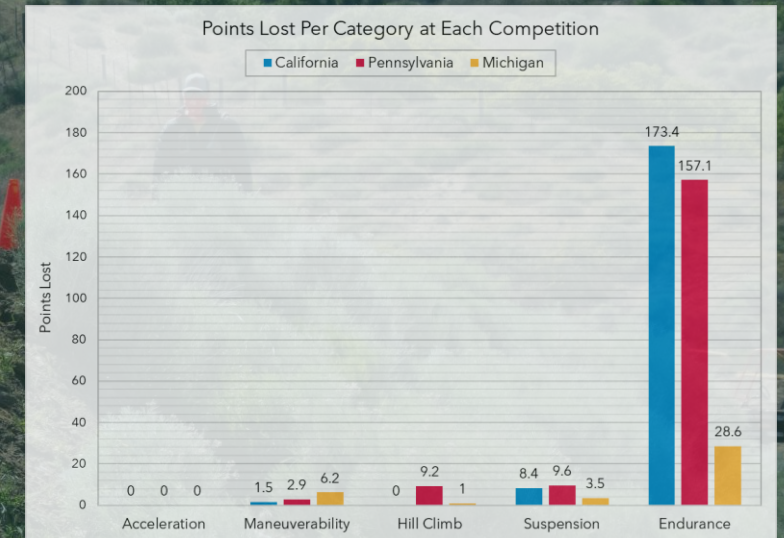
Cascaded Requirements

CVT must shift at engine peak power (3000 RPM)

Shift to max CVT ratio (0.639:1) within 300 feet

CVT must backshift from ratio at 20 MPH to low ratio in 0.5 seconds

CVT acceleration times don't increase more than 5% after 4 hours of runtime



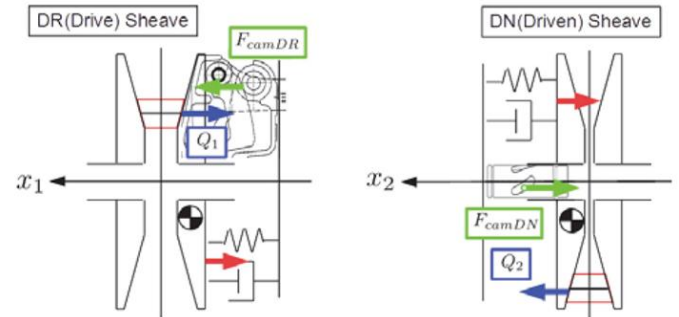
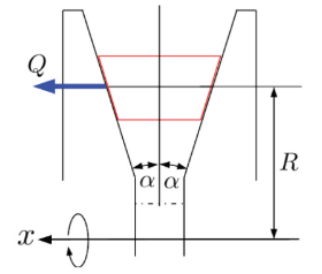
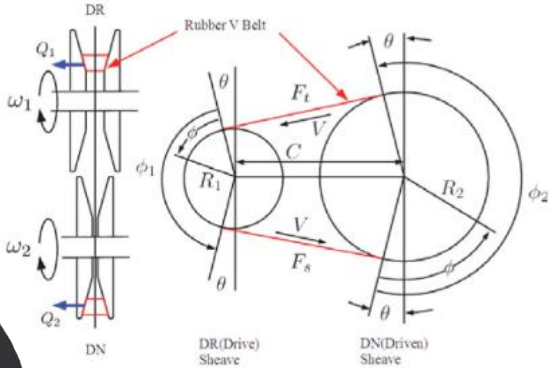
Decision Matrix



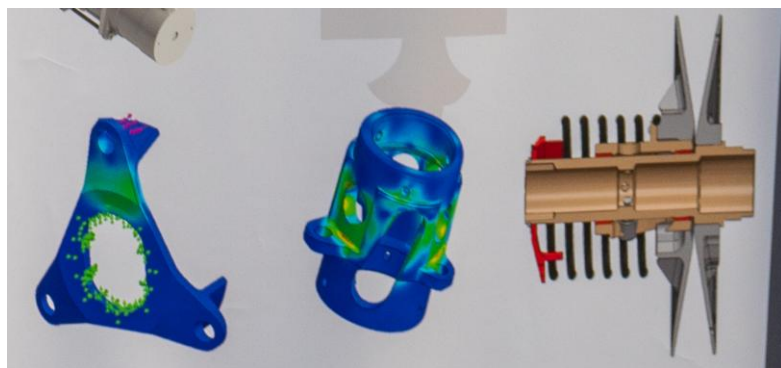
Rating	Value
Unsatisfactory	0
Just Tolerable	1
Average	2
Good	3
Very Good	4

Criteria	Importance Weight	Custom Secondary Pulley		Modified Gaged Secondary Pulley		Gaged Secondary Pulley	
		Rating	Weighted Value	Rating	Weighted Value	Rating	Weighted Value
Cost	0.125	4	0.5	2	0.25	1	0.125
Weight	0.1	4	0.4	2	0.2	1	0.1
Manufacturability	0.05	2	0.1	3	0.15	4	0.2
Reliability	0.2	3	0.6	2	0.4	1	0.2
Integration	0.125	3	0.375	4	0.5	4	0.5
Serviceability	0.05	3	0.15	2	0.1	1	0.05
Complexity	0.05	2	0.1	3	0.15	3	0.15
Risk	0.15	2	0.3	3	0.45	4	0.6
Performance	0.15	4	0.6	3	0.45	2	0.3
Weight Total	1	Regular Value	Weighted Value	Regular Value	Weighted Value	Regular Value	Weighted Value
Total		27	3.125	24	2.65	21	2.225

Research + Inspiration



Acceleration Performance Analysis for Rubber V-Belt CVT with Belt Tension Clutching, SAE International Journal of Engines, Vol. 9, No. 1 (April 2016), pp. 417-422

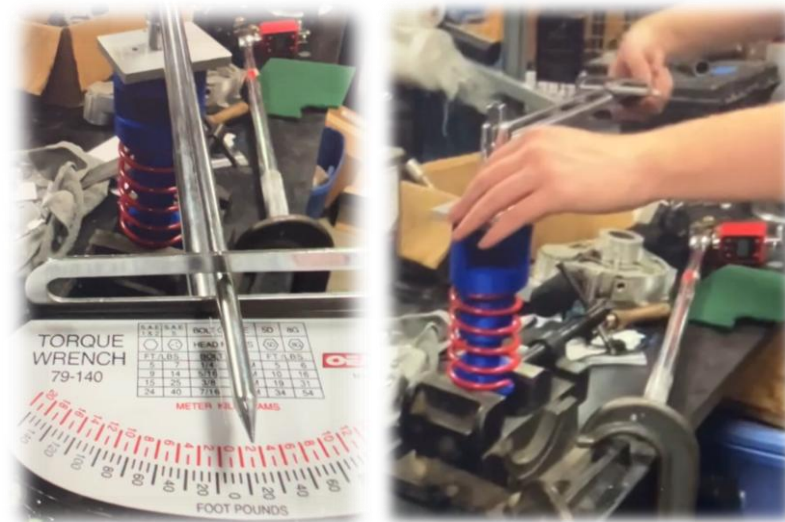
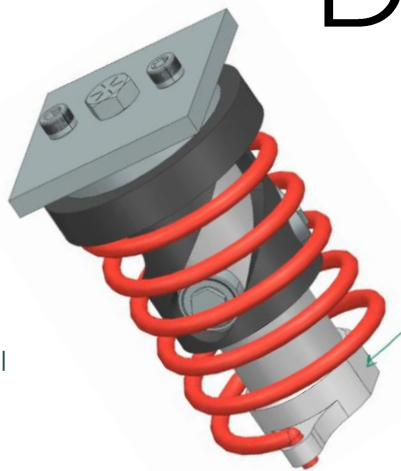
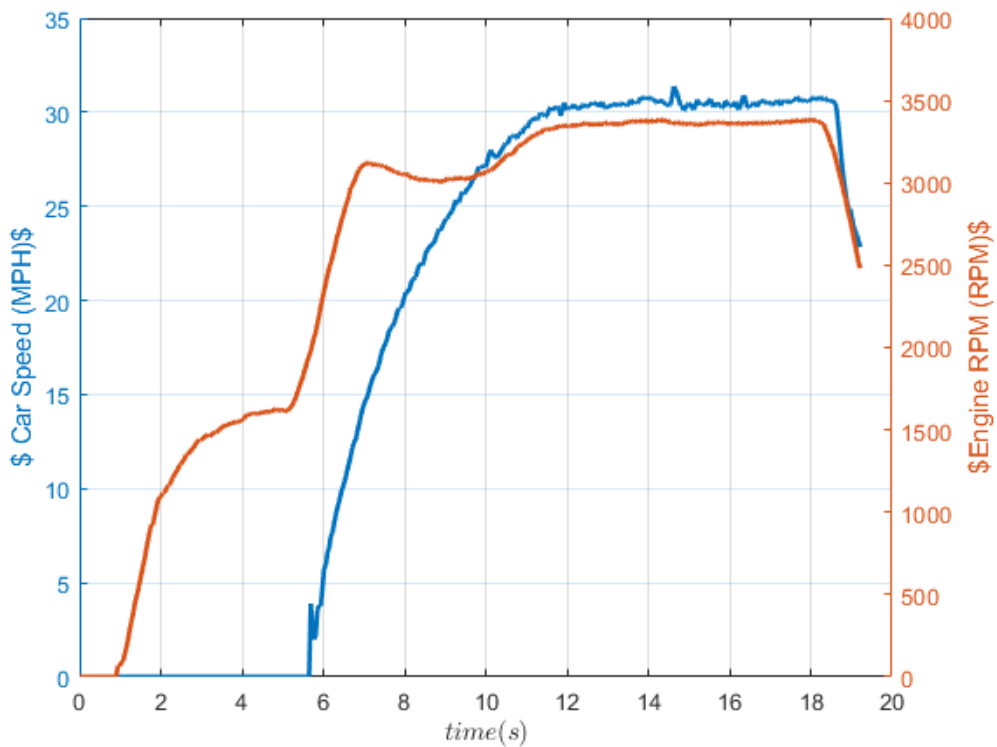


Early July 2024

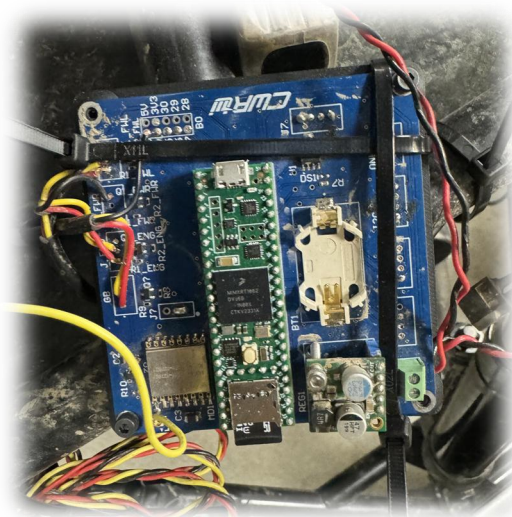
Data Collection

Engine RPM vs Wheel Speed: SR24 Data

Data used as reference for ideal shifting conditions for SR25, measured with hall sensor



Torsion Testing of Secondary Spring



Hall Monitor Unit PCB



Free-Body Diagrams

START

Griped
 $F_s \sin 40^\circ = 140 \text{ lbs}$
 $F_s = \frac{140 \text{ lbs}}{\sin 40^\circ} = 217.8 \text{ lbs}$

Speed down X
 $F_s \sin 40^\circ = 51.5 \text{ lbs} = F_{eq}$
 $F_s = \frac{51.5 \text{ lbs}}{\sin 40^\circ} = 80.12 \text{ lbs}$

END

$F_e =$
 $F_{eq} = 60 \text{ lbs} = F_e \sin 25^\circ$
 $F_e = \frac{60 \text{ lbs}}{\sin 25^\circ} = 142 \text{ lbs}$

Let's figure this out for speed control

assuming force is evenly distributed along roller width

$\frac{0.5625}{2} = 0.28125$

$0.719 \cdot 0.10$	0.1565
-0.5625	$+0.28125$
0.1565	0.43775

$\tau = Fr$
 $\tau_c = F_s r = 80.12 (0.43775) = 35.07 \text{ lb-in}$
 $\tau_e = F_e r = 142 (0.43775) = 62.16 \text{ lb-in}$

$2.12 \Rightarrow 0 \text{ lbs}$
 1.25°
 75 lbs
 $F = 120$
 $50 = 2.12 \text{ k}$
 $75 = 1.25 \text{ k}$

- horizontal forces cause sheave to rotate about post
- vertical forces provide resistance from belt force to control shift speed over time (assists spring in resistance to immediate constant-acceleration shift)

sheave

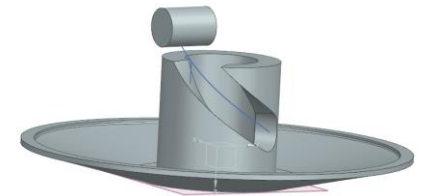
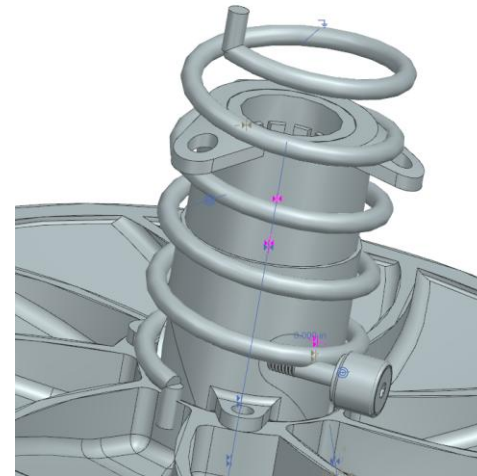
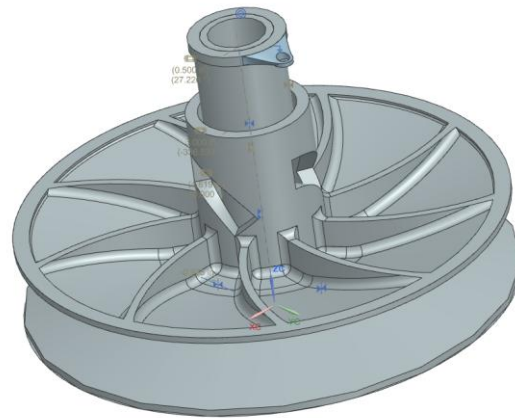
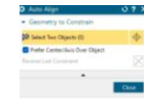
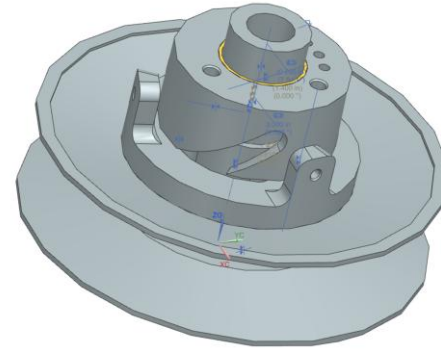
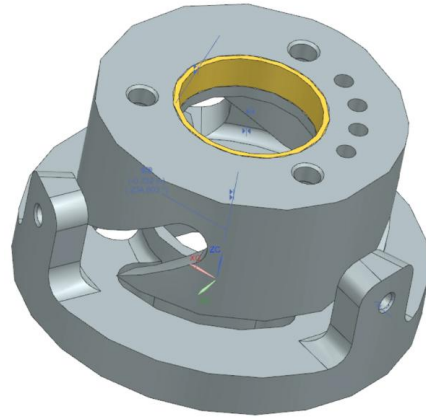
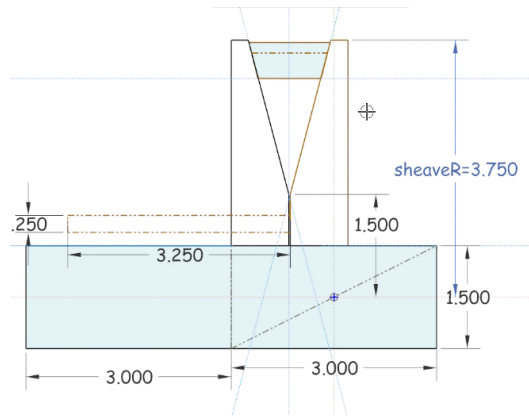
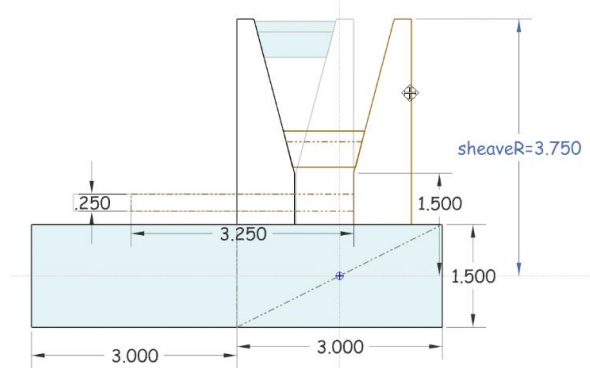
↑ F_{spring}

up

As the secondary pulley shifts, the vertical component of bearing reaction force decreases, allowing for quicker shifting toward the end of the ratio.

As it backshifts (i.e. during tight turns in narrow/endurance events), the spring

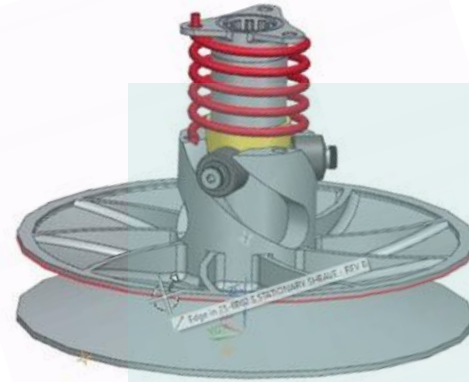
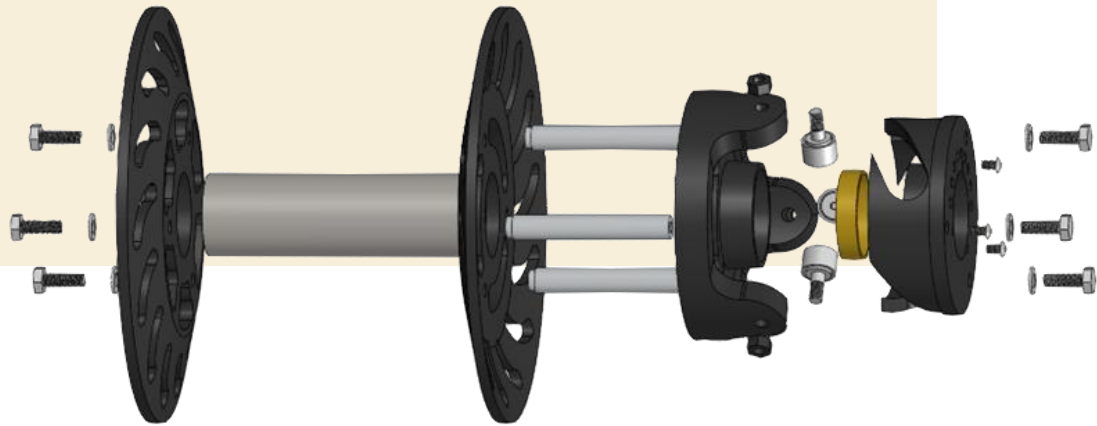
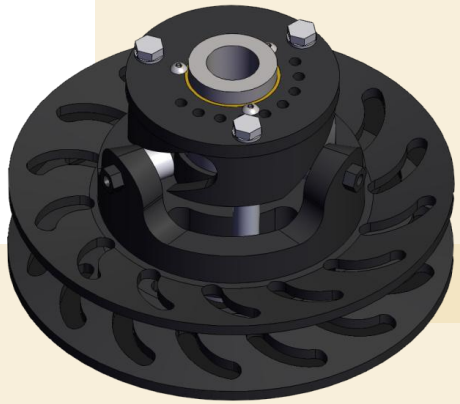
Generating Concepts



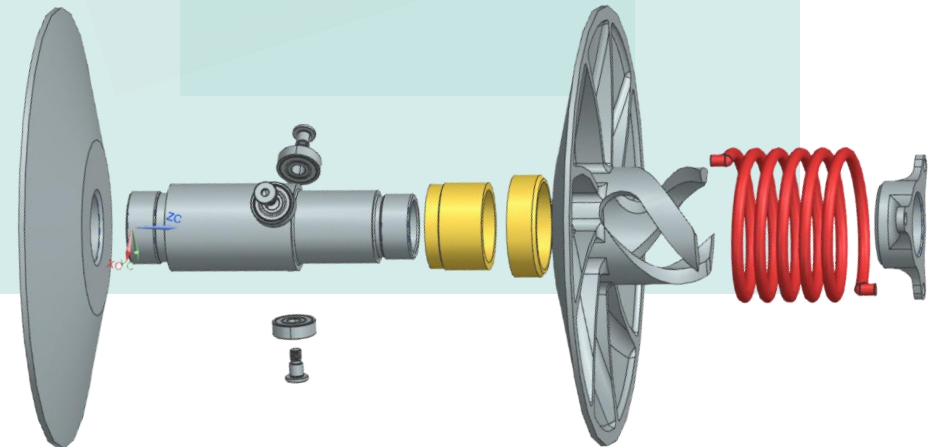
Early July to August 2024

SR24 vs SR25

Gaged
Secondary
(OEM)

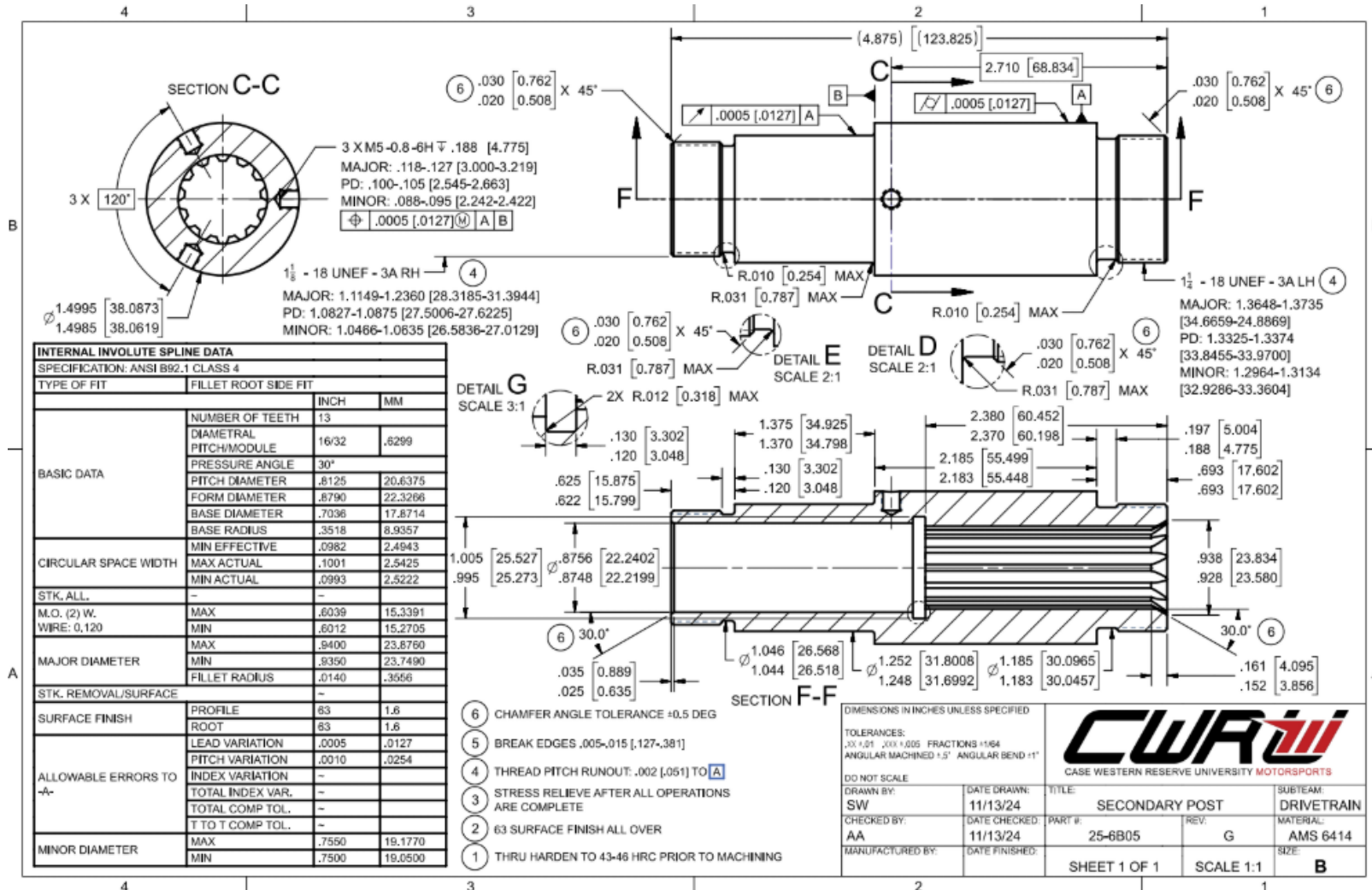


Early Versions of
Custom Secondary



August to October 2024

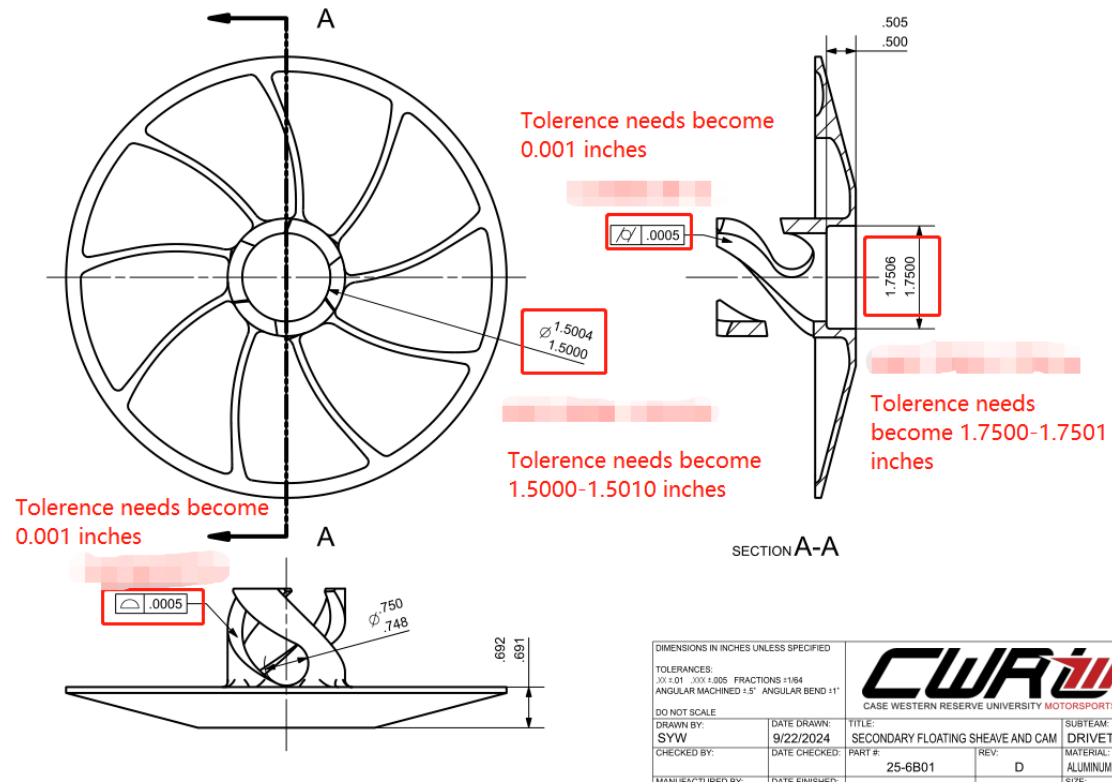
Spline Drawing for Sponsor



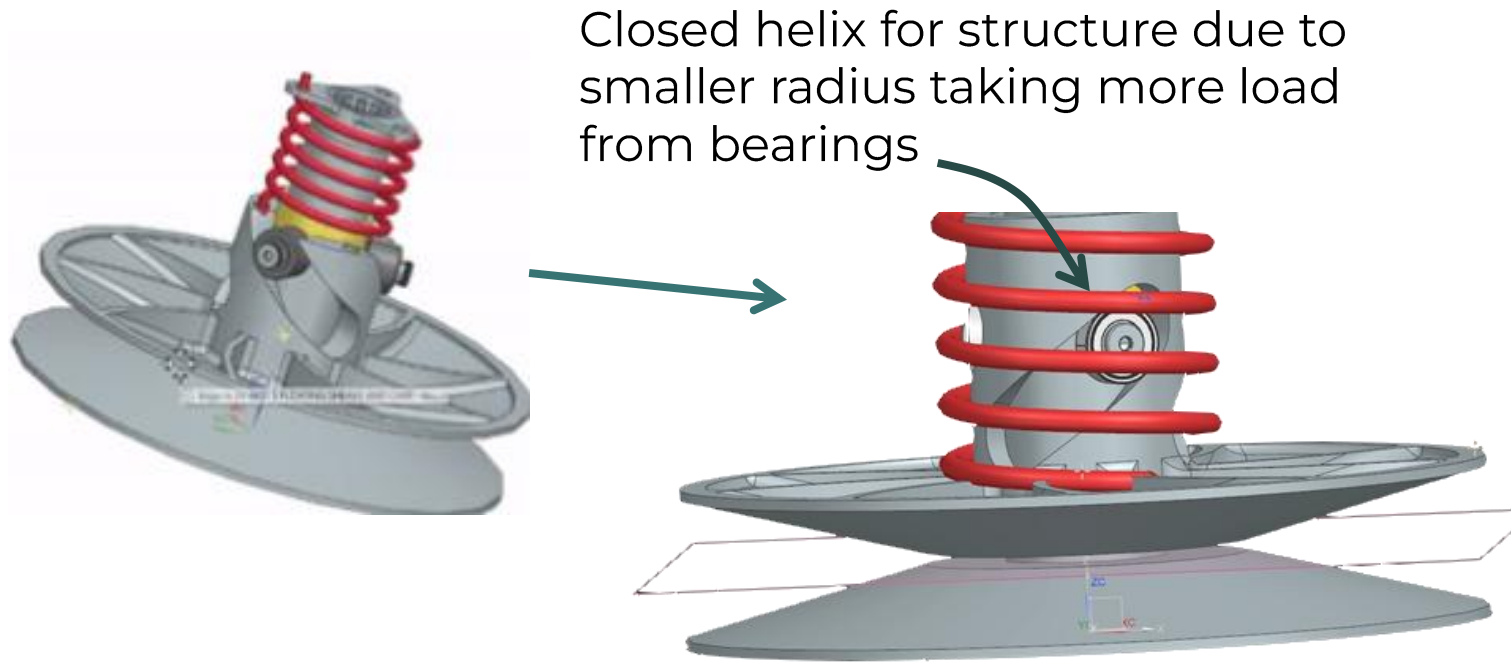
August to November 2024

Complex CNC Components

- Manufacturer required looser tolerances
 - Would the tolerances still allow for proper assembly and fits?
- Catalyst for thinking about a more manufacturable design

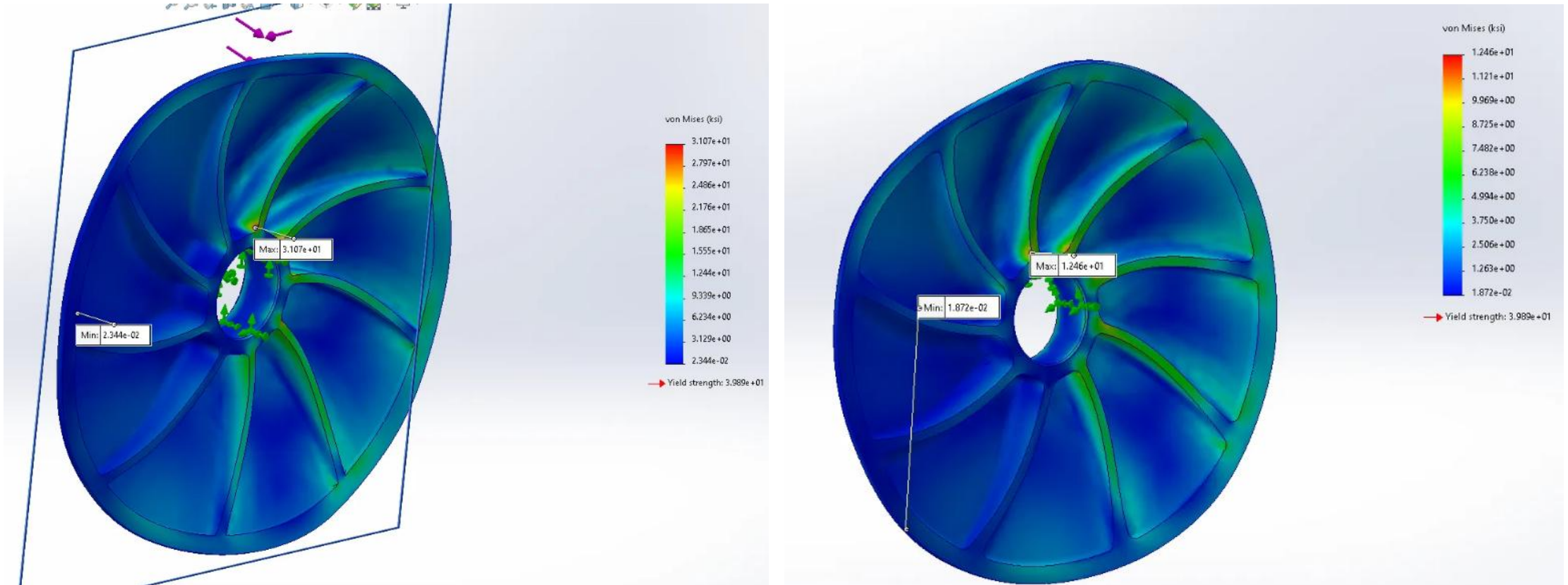


Iteration + Prototyping

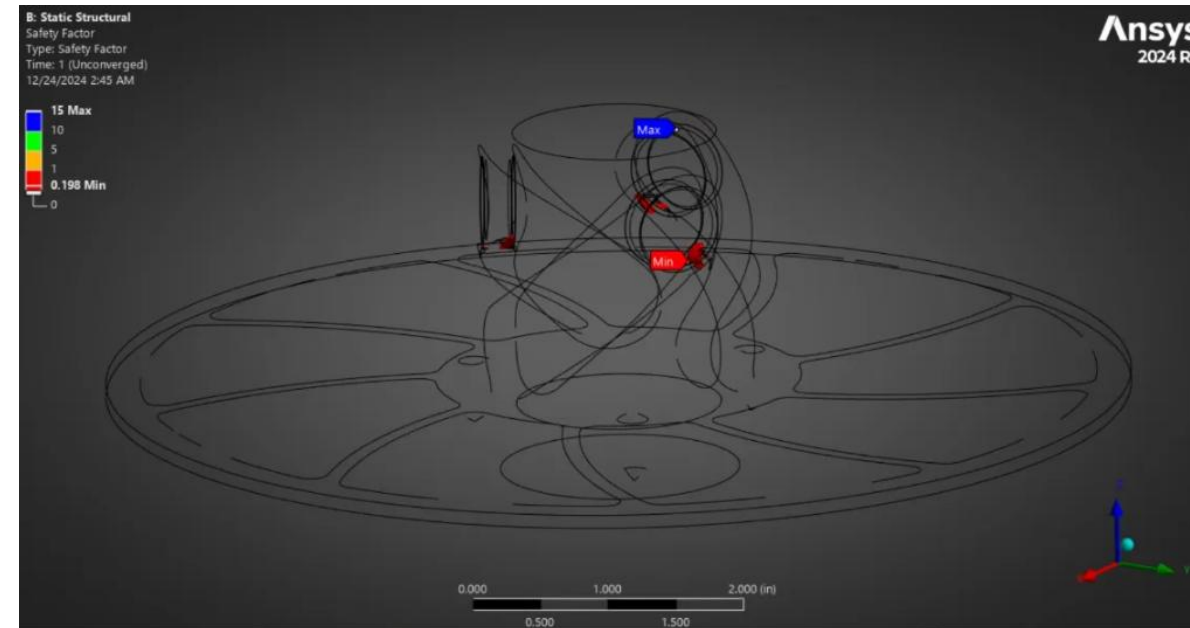
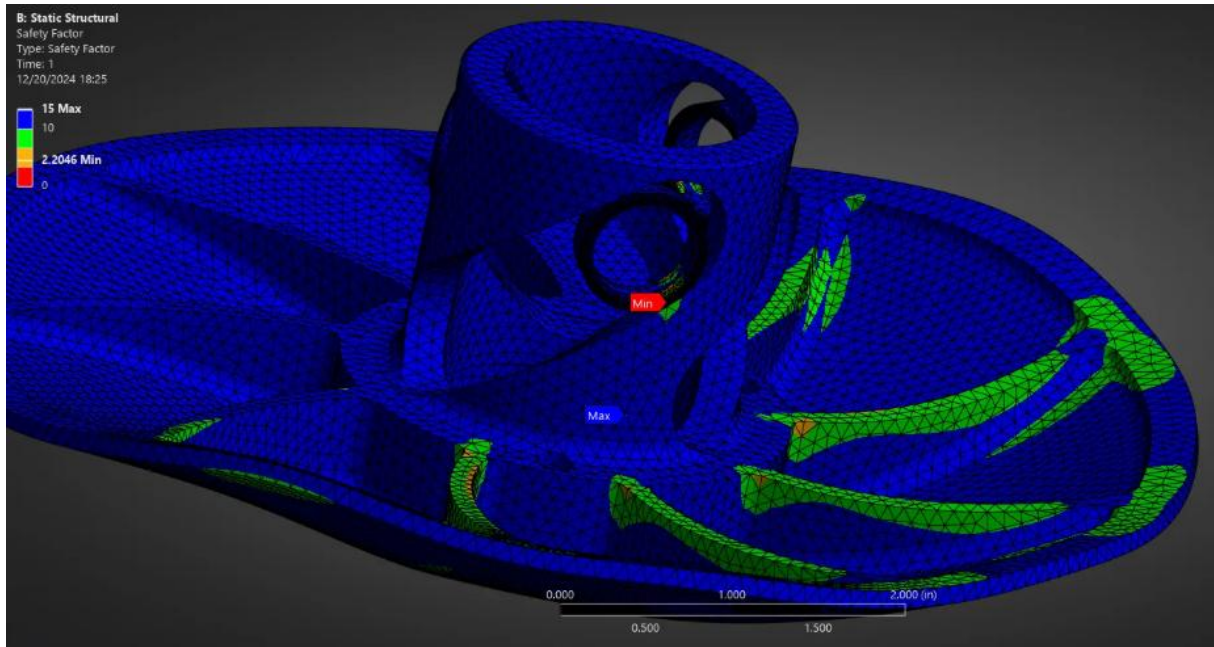


Early November to Mid-December 2024

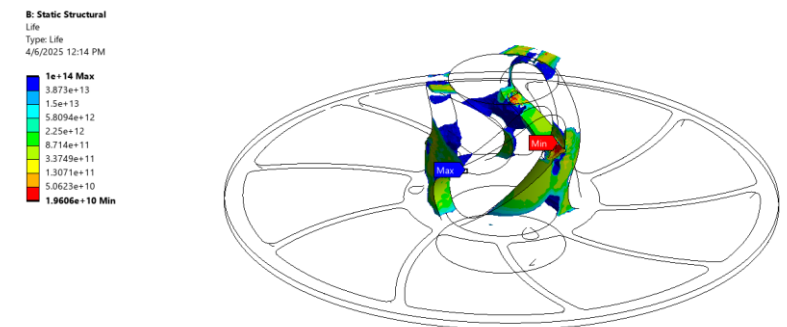
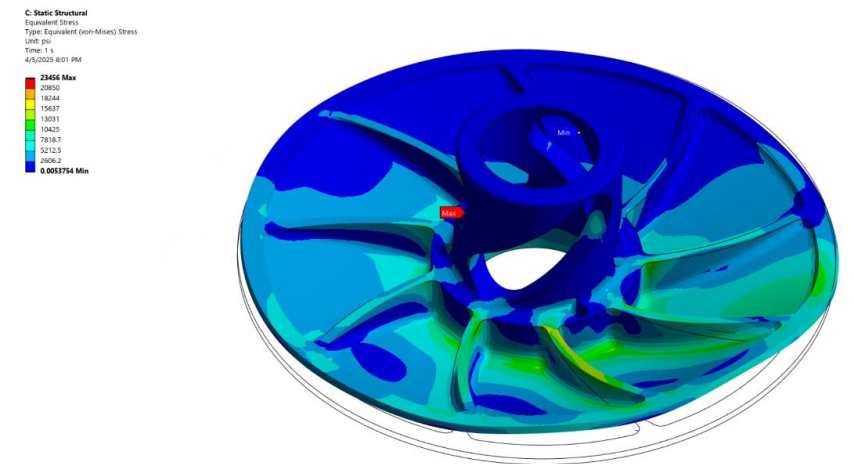
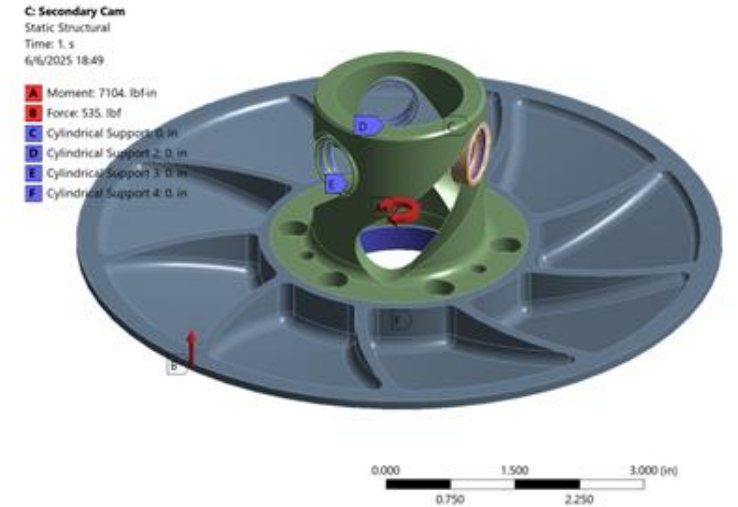
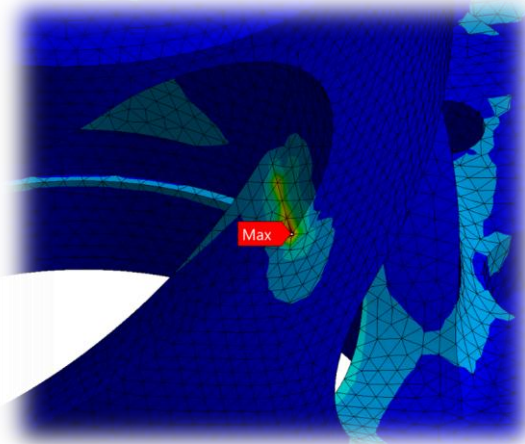
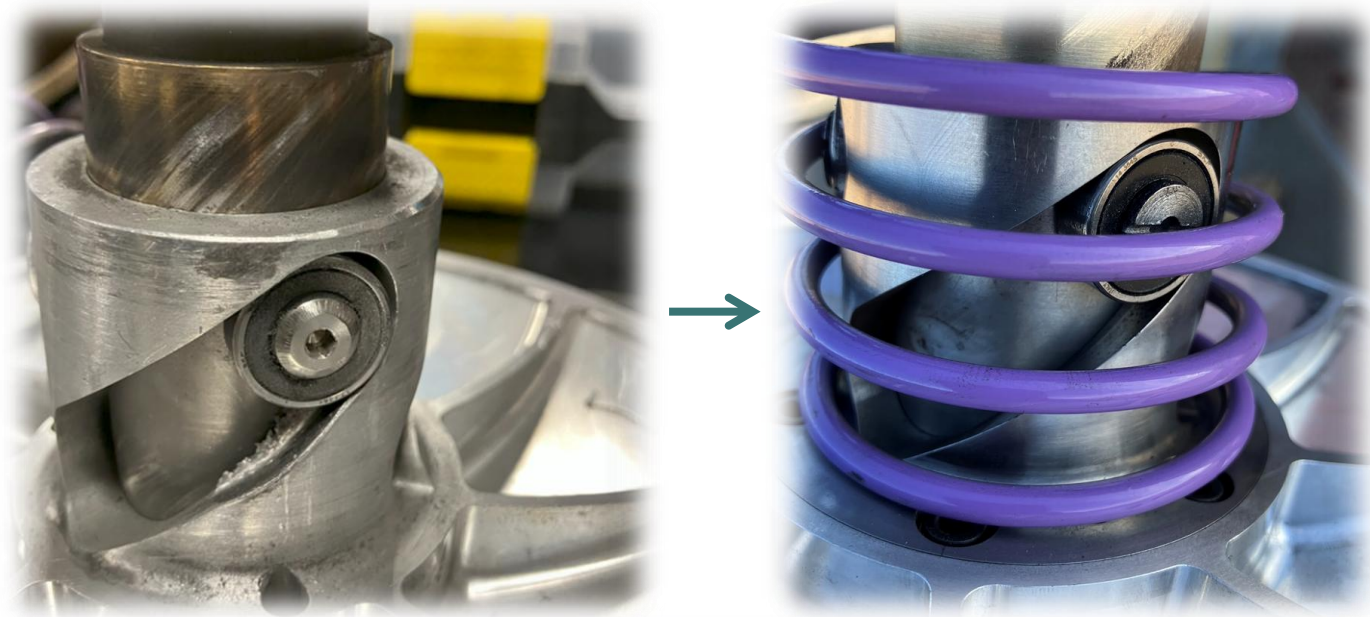
Finite Element Analysis



Finite Element Analysis



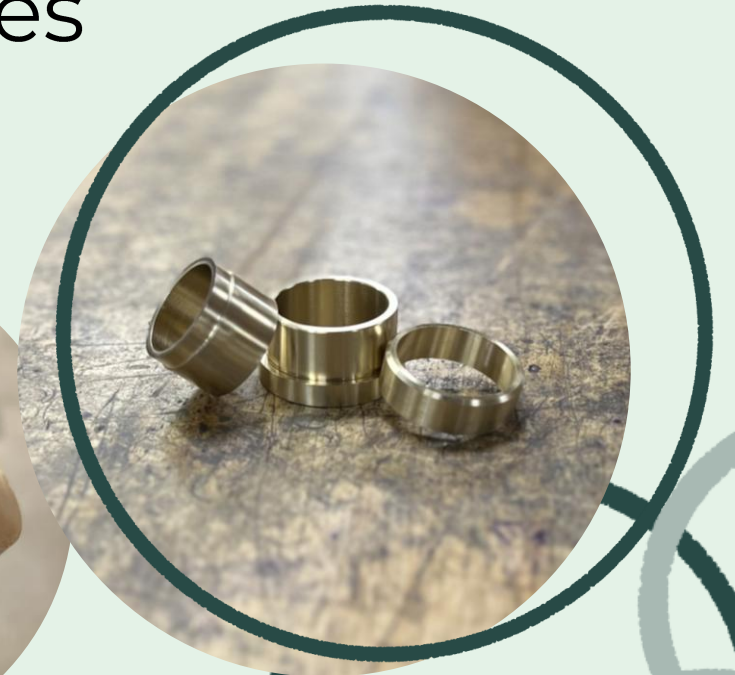
Finite Element Analysis



March to April 2025

Manufacturing

Machined bushings, allowing for control over concentricity and press/slip tolerances



Assembly

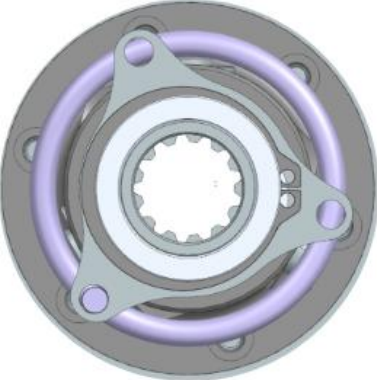
- Many threads and much Loctite → not design for assembly
- Looser tolerances are actually okay



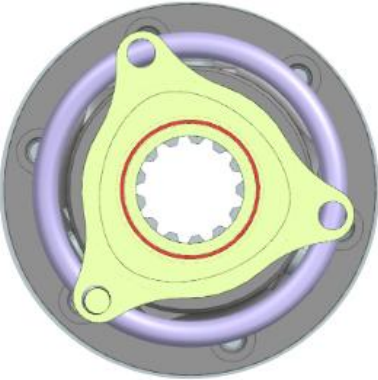
Iteration



Initial Version:
Threaded Spring Retainer

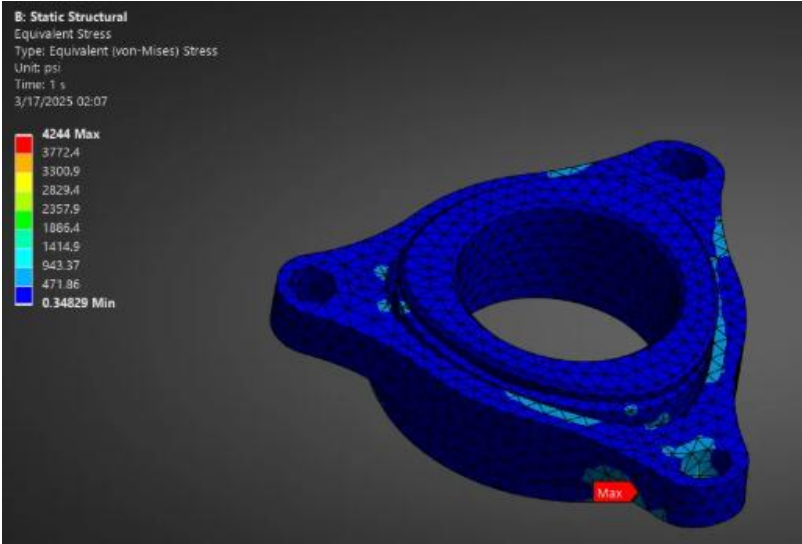


Top View

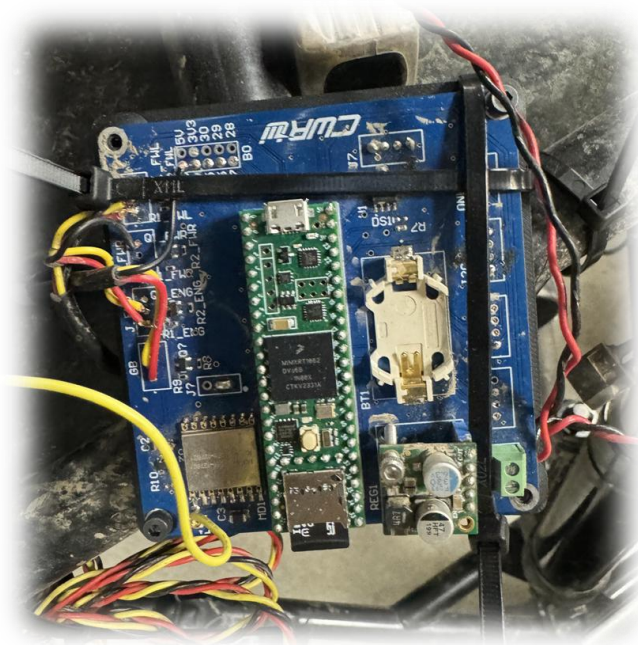


Section View
(Trilobe Profile)

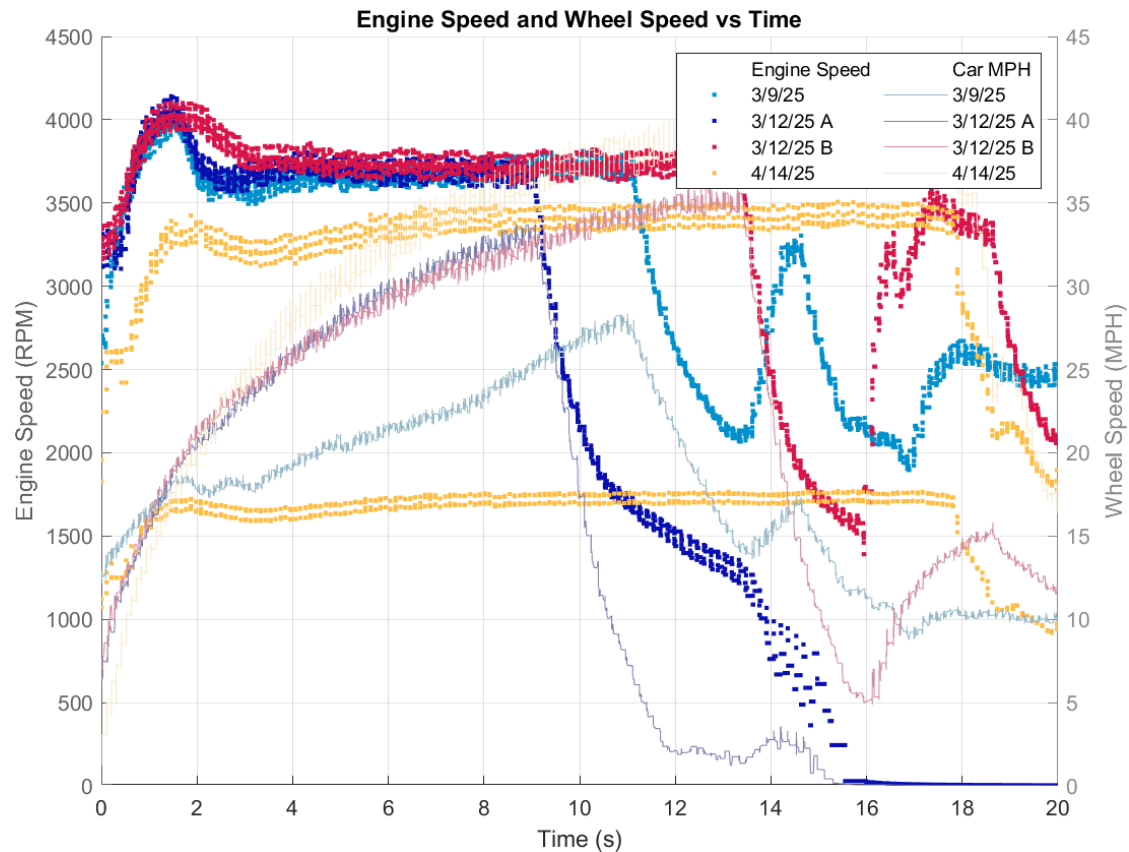
Revision A:
Trilobe Spring Retainer



Testing



Testing



Discrepancies Between Analysis and Testing

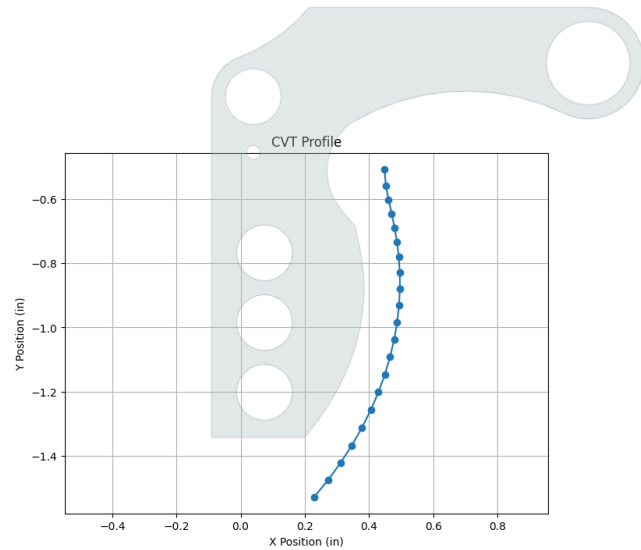
- Friction in system
 - I.e. bushings sliding on post, friction coefficient between belt and sheave material
- Flyweight COM position ineffective

Arizona Competition

- Belt slipping/skipping issues
 - Due to temperature differences
- Not shifting to full range
- Not shifting at peak power



Reflection + Testing + Iteration

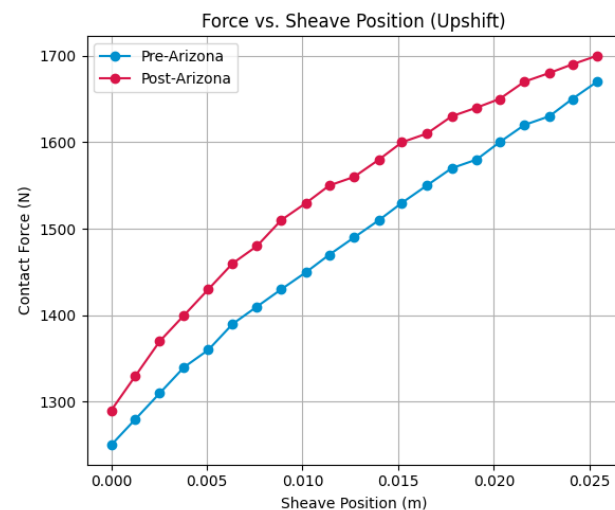


Generating Flyweight Profiles and Masses/Center of Mass

- Python script
- Input desired contact angles based on desired shift RPM
- Variable profile as CVT shifts, lines up with engine RPM

Design Process Between Competitions

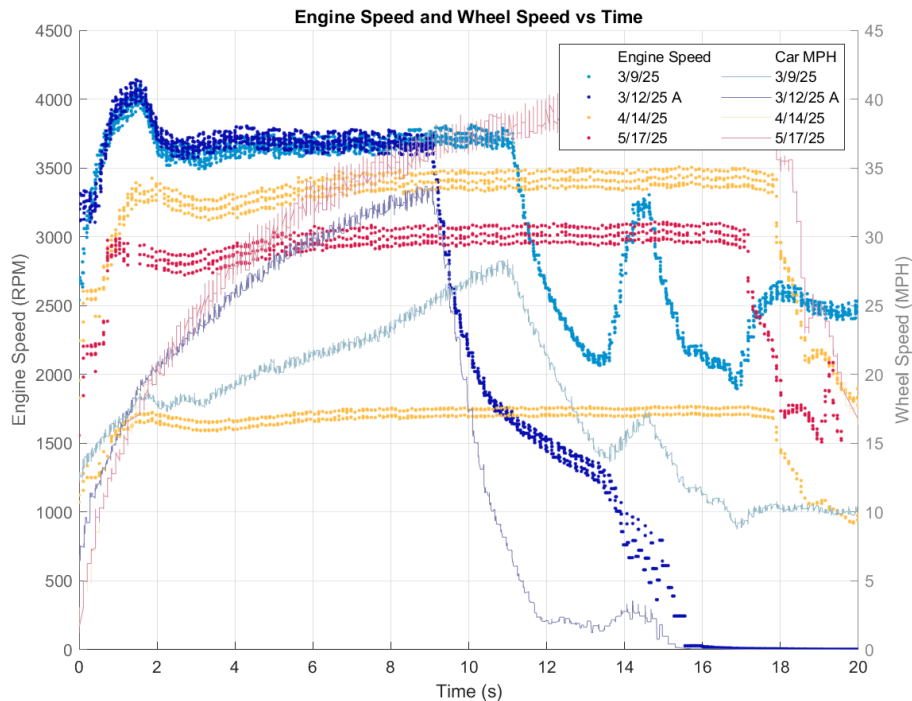
- Based on testing data before Arizona competition, new COM position with more acceleration force
- Secondary sheaves closer together to increase shift range



May to Early June 2025

Reflection + Testing + Iteration

Engine RPM vs Wheel MPH and Engine RPM + Wheel MPH vs Time: CVT Tuning Data
Data used to calculate new system tuning parameters



Correlation of Analysis and Testing

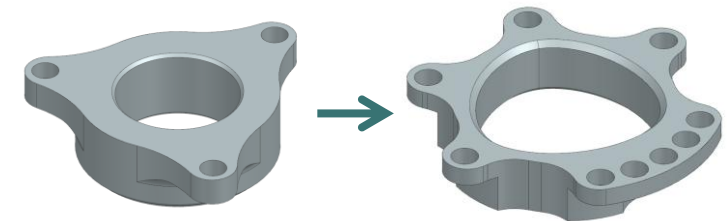
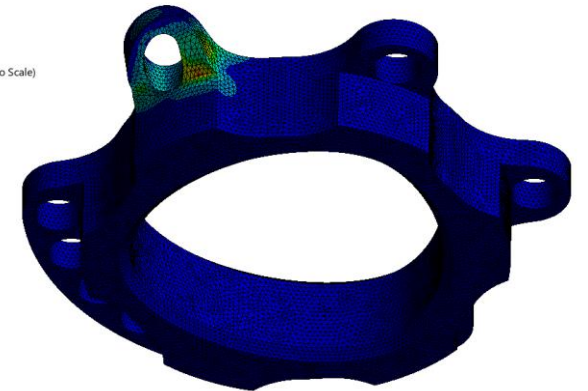
- Greater acceleration force from flyweights → stronger launch and faster acceleration
- Decrease distance between secondary sheaves → increase top speed



New spring retainer design to prevent spring cocking and provide more pretension options

D: Spring Cap
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1 s
Deformation Scale Factor: 2.2e+002 (Auto Scale)
5/29/2025 17:23

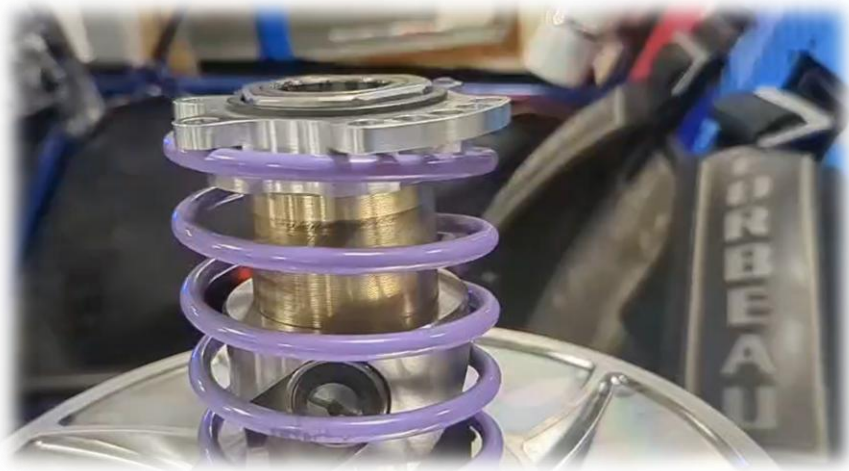
22979 Max
20426
17873
15320
12766
10213
7659.8
5106.5
2553.3
7.5245e-5 Min



May to Early June 2025

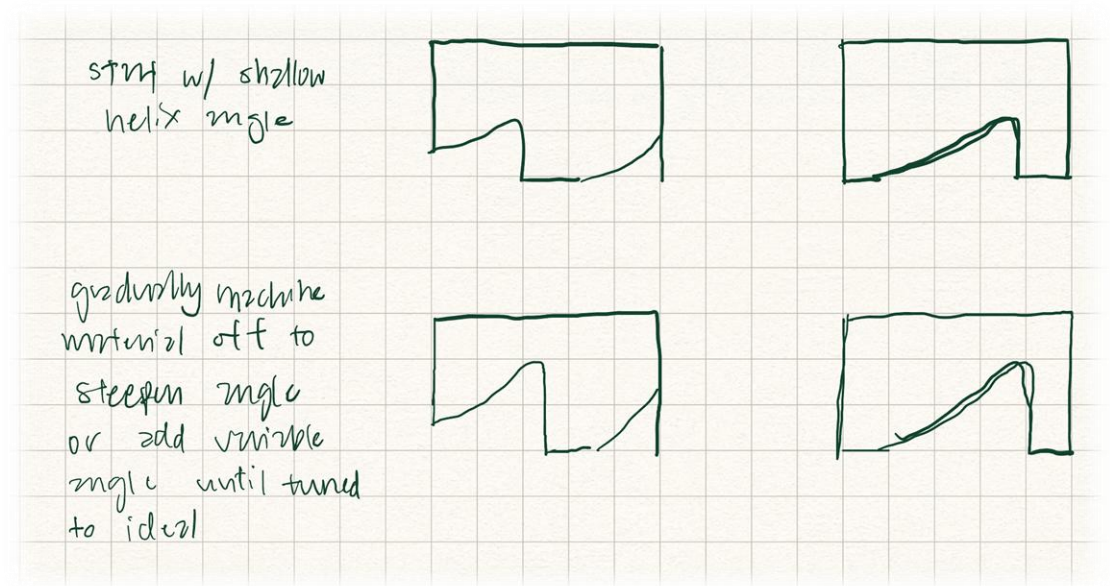
Maryland Competition

- Even wear on bushing
 - Less efficiency lost to friction from cam sliding on bushing
- Still not reaching top speed overall



Improvements + Advice for Future Designers for Secondary CVT

- Helix
 - Manufacturable
 - Tunable
- Spring
 - Finalize decision early-on
 - Test spring rates with higher granularity
- Spring retention
 - Prevent cocking of spring to maintain desired spring performance



CVT Improvements for SR26 (2025-2026 Season)

Free-Body Diagrams

- Fully understand entire system
- Get an idea of what variables to tune

Known

$\theta = 14.25^\circ$

$\mu = 0.5$ (guess) \rightarrow hopefully, data can provide this

$F_{belt} = \frac{\Sigma}{r_{sheave}} = \frac{16.6 \text{ lb} + 16 \text{ lb}}{2.1 \text{ in}} \times \frac{12 \text{ in}}{1 \text{ ft}} = 14.24 \text{ in/lb}$

$\alpha = 23.76^\circ$ ($= 30.78^\circ$ of shaft)

Unknown

ω \rightarrow these are interdependent (I think)

$F_{clamp} = F_{frict} = F_{tight} - F_{slack}$

STATIONARY

$\mu = 26^\circ$ ($= 50^\circ$ of shaft)

is coming a combination of axial force and torque on the sheave \rightarrow from tangential force

note: axial/tangential relative to post axis

this is shown as the rxn force from the stationary cam on the floating bearing (attached to floating sheave) which induces a clamp force on the belt axially and torques the belt to prevent slippage in the direction the engine spins (CCW), but can't resist too much opposing torque otherwise belt will slip? there's a sweet spot

Where does belt clamp force originate from? 7/19/25

\rightarrow using SR24 as model

Let's start from the beginning:

ENGINE IDLE (1800 RPM)

\rightarrow the engine starts applying torque to the primary

\rightarrow primary starts spinning due to torque transfer thru key

\rightarrow belt starts spinning w/ primary due to friction b/n belt and sheaves and thrust/slack force on belt wrap contact

\rightarrow secondary starts spinning w/ belt due to friction b/n sheaves and belt and thrust/slack force on belt wrap contact

FBD belt

$F_{tight} = F_{tension}$

$F_{slack} = F_{tension}$

z-side:

Q: Why is the top side taut and the bottom side slack?

A: because the primary is what pulls on the belt so it rotates

$1.5 > 2 - 2$

$2 - 2 = 0 - 2$

$3 - 2 = 4$

$4 = 5$

$5.4 = 5.5 + m\theta$

$\Rightarrow 1.5 > \frac{1.4}{\tan\theta}$

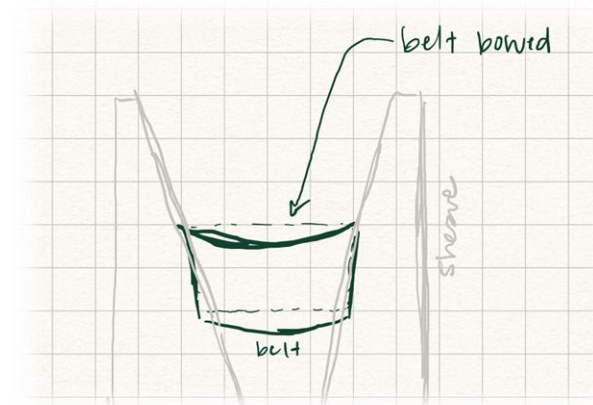
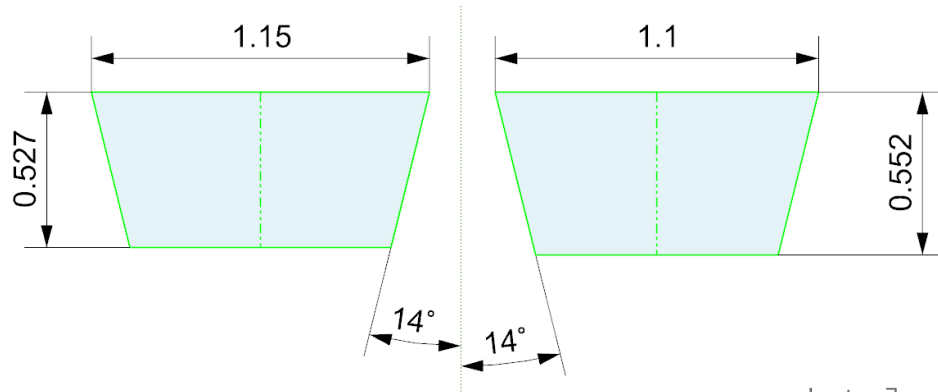
$1.5 = 1 \sin \alpha$

\rightarrow need enough clamp force to allow override (engine speeds up post peak power but CVT doesn't backshift)

\rightarrow torque at this pt is 16.5 ft-lbs

CVT Improvements for SR26 (2025-2026 Season)

Problem	Solution
Belt slip on primary	More belt clamp force
Overheating system	Solve belt slip problem, integrated cooling
Didn't reach full shift range	Increase overall system efficiency, solve belt slip problem
Belt bowed (when looking at cross-section)	Increase height to width ratio by decreasing width



Late June to Early August 2025

CVT Improvements for SR26 (2025-2026 Season)

Problem	Solution
Wear and tear	Design for lower stresses by having greater contact areas and appropriate material pairings for contacting components
Uneven wear and tear	More controlled spacing of pulleys in shroud



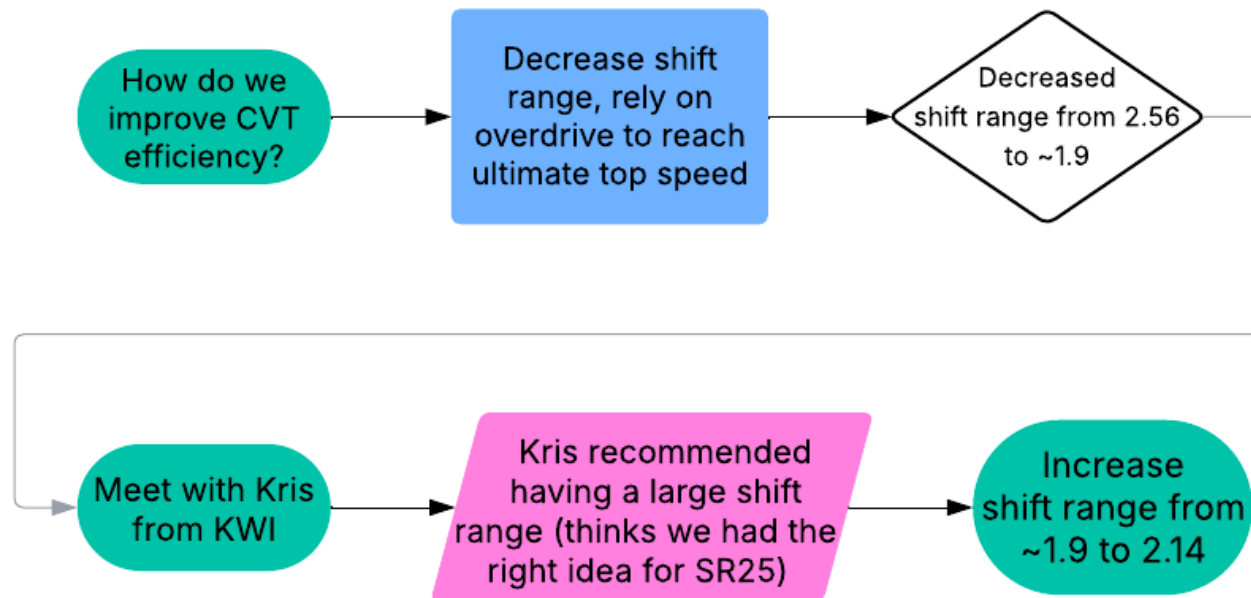
Late June to Early August 2025

CVT Improvements for SR26 (2025-2026 Season)

Ratio Decision-Making

Main Drivers:

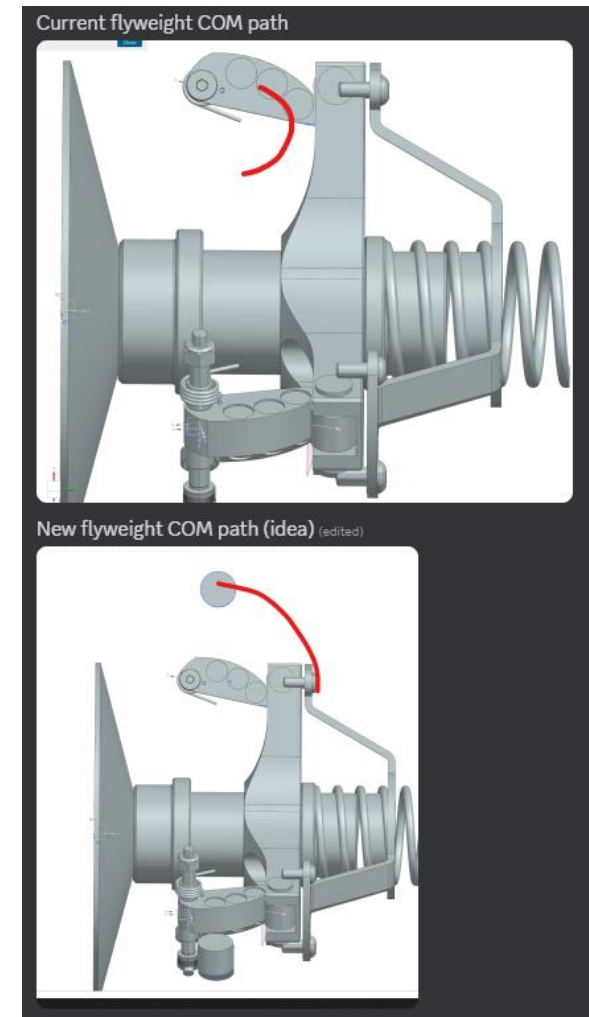
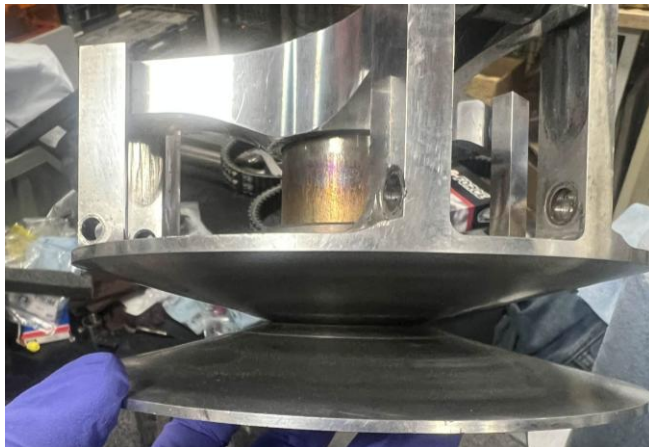
- Increase torque from SR25
- Rely slightly more on overdrive (empirically, efficiency is better that way)
- Primary post one-way bearing diameter



Late June to Early August 2025

CVT Improvements for SR26 (2025-2026 Season)

Problem	General Solution	Design Solution
Belt slip on primary	More belt clamp force	Flyweight COM position + spring rate
Sheave wear on primary	<ul style="list-style-type: none">•Solve belt slip problem•Harder sheave material	<ul style="list-style-type: none">•More clamp force•7075 sheaves (SR25: floating sheave was 7075, stationary was 6061)



Late June to Early August 2025

CVT Improvements for SR26 (2025-2026 Season)

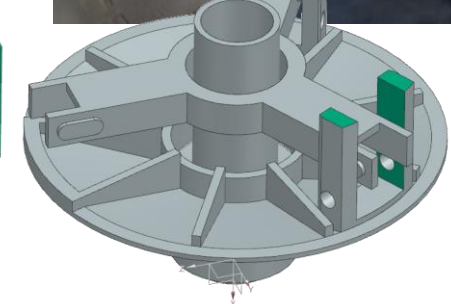
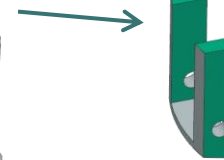
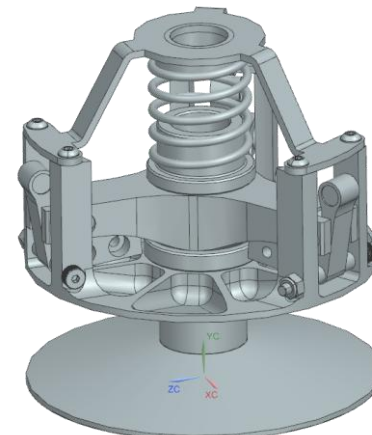
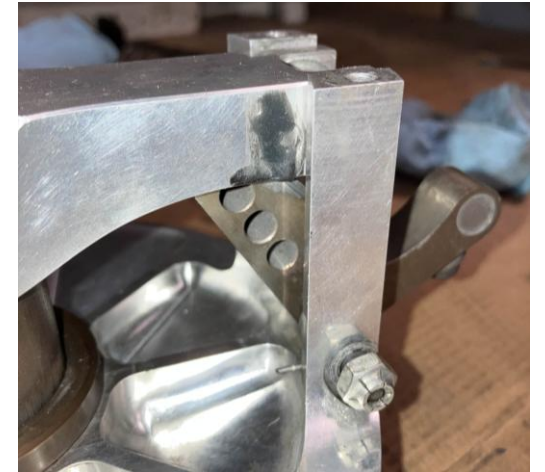
Problem	General Solution	Design Solution
Didn't reach full shift range	<ul style="list-style-type: none">• Solve belt slip problem• Increase efficiency of overall system	<ul style="list-style-type: none">• Flyweight COM position + spring rate• Increase minimum belt wrap radius
Heat build-up	<ul style="list-style-type: none">• Solve belt slip problem• Increase efficiency of overall system• Extra cooling/more shroud ventilation	<ul style="list-style-type: none">• Flyweight COM position + spring rate• Integrated fan/CFD• Increase minimum belt wrap radius



Late June to Early August 2025

CVT Improvements for SR26 (2025-2026 Season)

Problem	General Solution	Design Solution
Roller pins slipping out	Better retention of whatever component the roller is rotating about	Mini circlips on both inner ends
Flyweight/spider not maintaining positions clocked to each other	Prevent wear in mating components	<ul style="list-style-type: none"> Press in one long piece that acts as both the spacers and a bushing to minimize wear on both the shoulder bolts and spacer” Wider PTFE bushing on spider, break edges on floating sheave stands



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