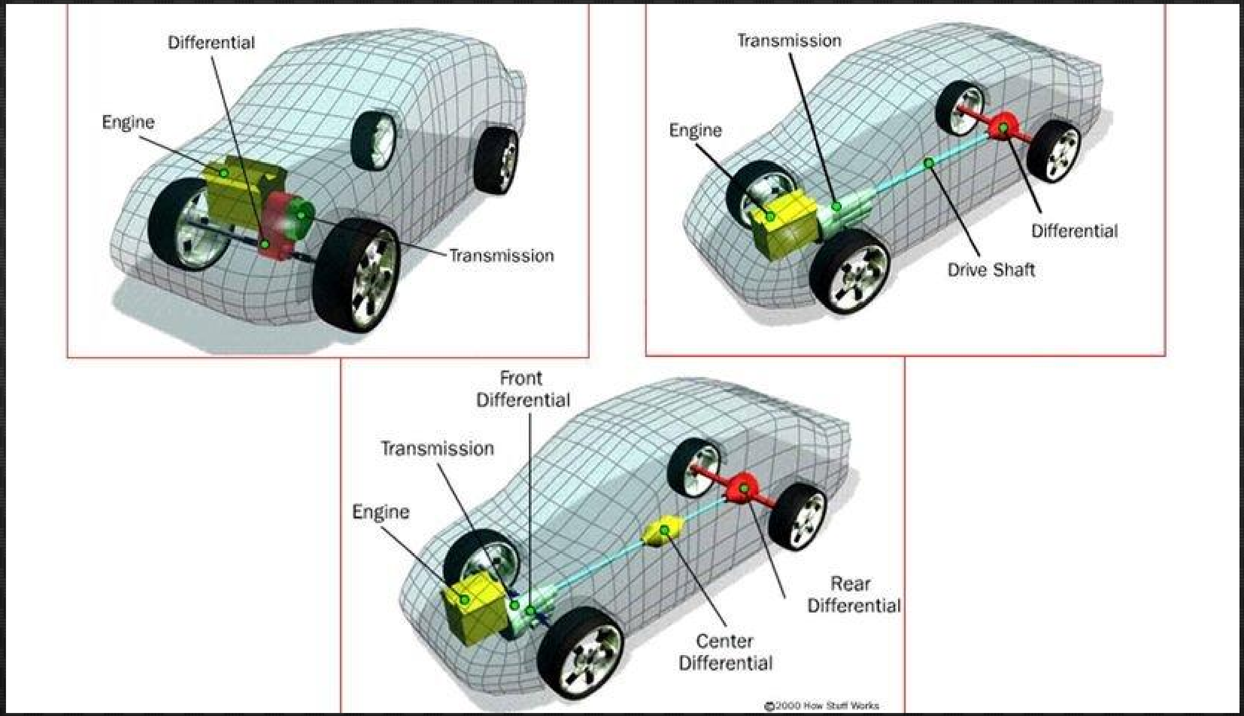
Purdue FSAE – Drivetrain



Sidh Gurnani

08/09/2024

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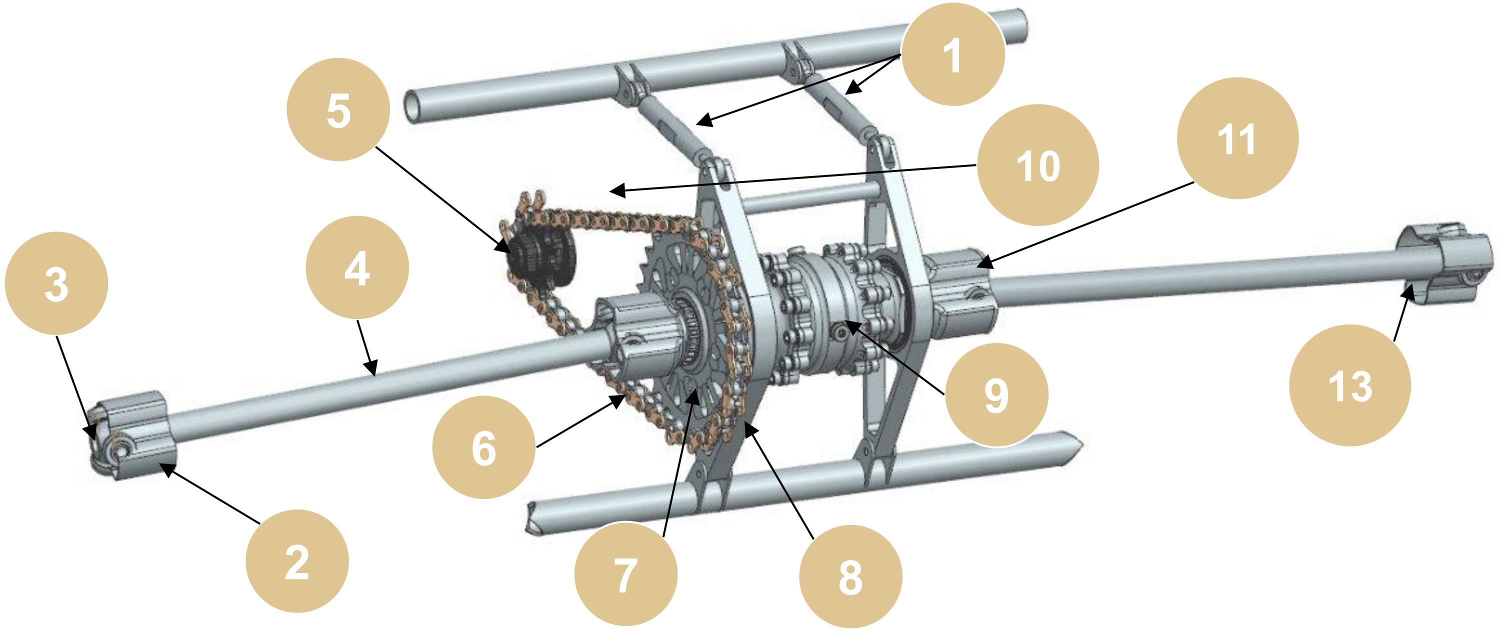
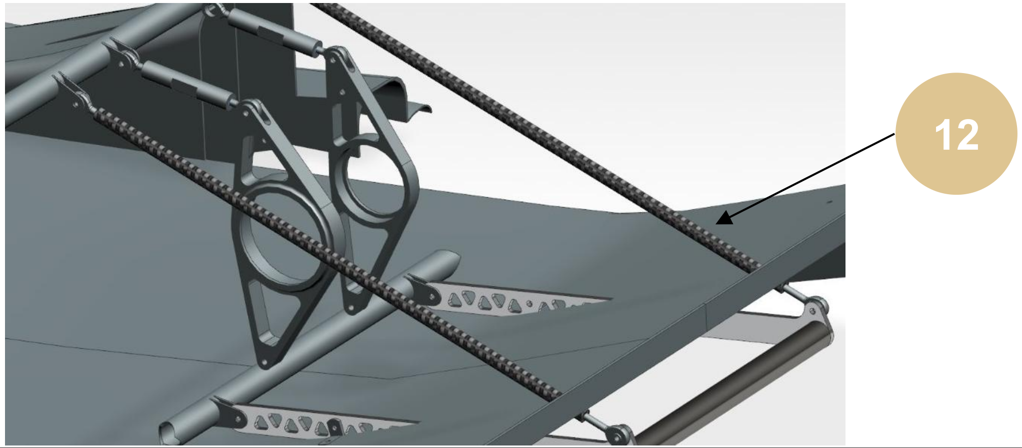
System Knowledge
PF24, PF20, PF19

System Knowledge – PF24

- Final Drive = 31/12 = 2.58





1. Turnbuckles
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard (not pictured)
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots (not pictured)

System Knowledge – PF24

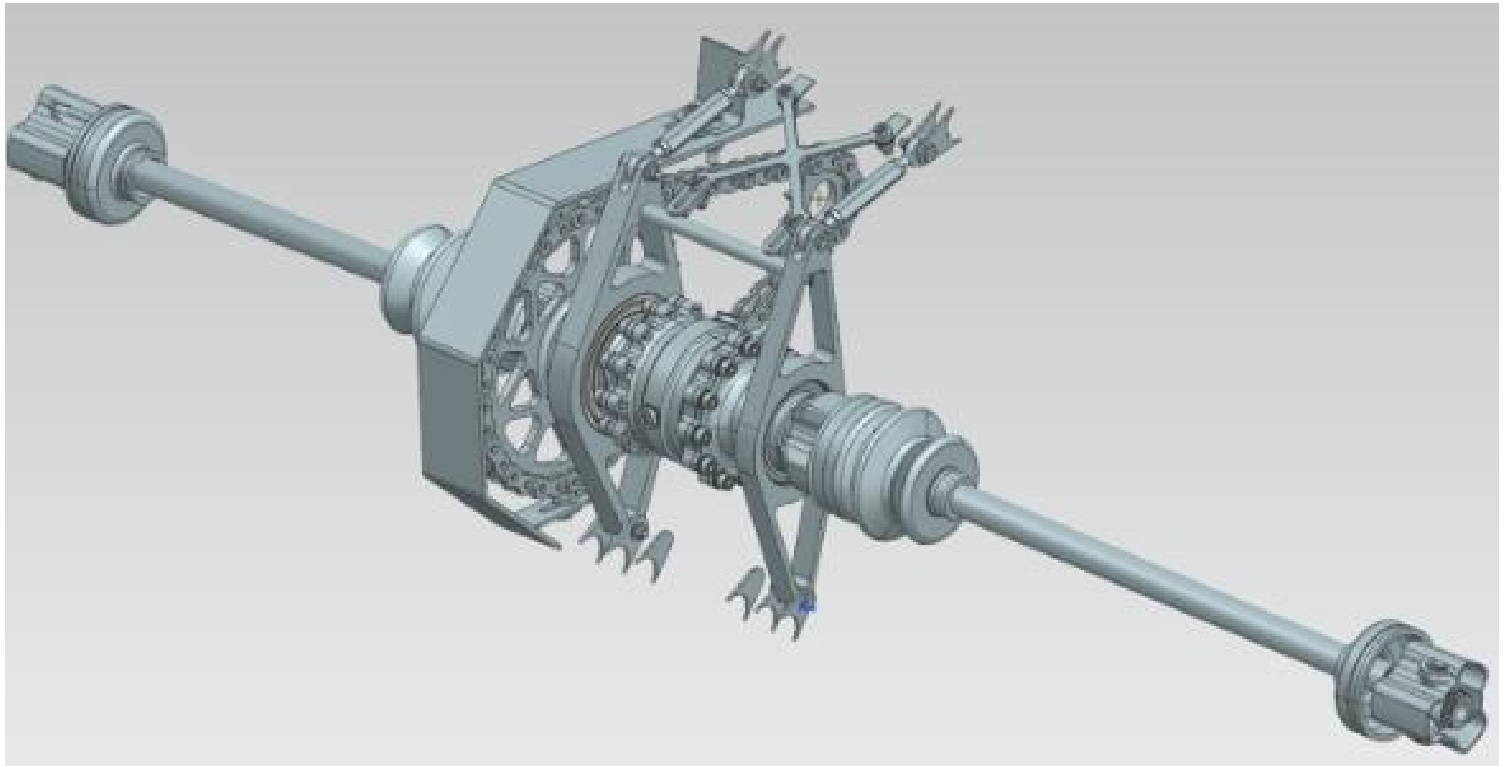
Component	Purchased/Custom	Details/Notes/Info
Rear Sprocket	Custom	• Mass: 0.447 lbm • 31 teeth • Material: Al 7055
Differential Carriers	Custom	• Total Mass: 0.95 lbm • Material: Al 7055
CV Inserts	Custom	• Ran PF20's CV Insert design; changes were made as necessary based on revalidation carried out in FEA with updated loads • Material: 17-4 Prehard Stainless Steel (H900)
Towbar (was drivetrain at one point)	Custom	• Chassis Mounted • Carbon Tubes + Rod Ends • Material: Al
Pushbar	Custom	• Ran older pushbar
Differential	Purchased	• Drexler Salisbury Nonadjustable Limited Slip Differential • To my knowledge, used manufacturer's tune

System Knowledge – PF24

Component	Purchased/Custom	Details/Notes/Info
Turnbuckles	Custom	• Linear chain tensioning system • Material: Al • Purchased Rod Ends
Halfshafts	Purchased	• RCV • Material: 4130 Steel
CV Tripods	Purchased	• RCV • Material: 4340 Steel
Inboard CV's Housing (Tulips)	Purchased	• RCV
Boots	Custom/Purchased	• Initially purchased (rubber) • Later ran custom (sewed up rubber gloves)
Chain Guard	Custom	• Majority of rules related to drivetrain apply here • Material: Steel + OEM • Ran OEM front and custom steel rear
Chain	Purchased	• DID 520 Roller Chain

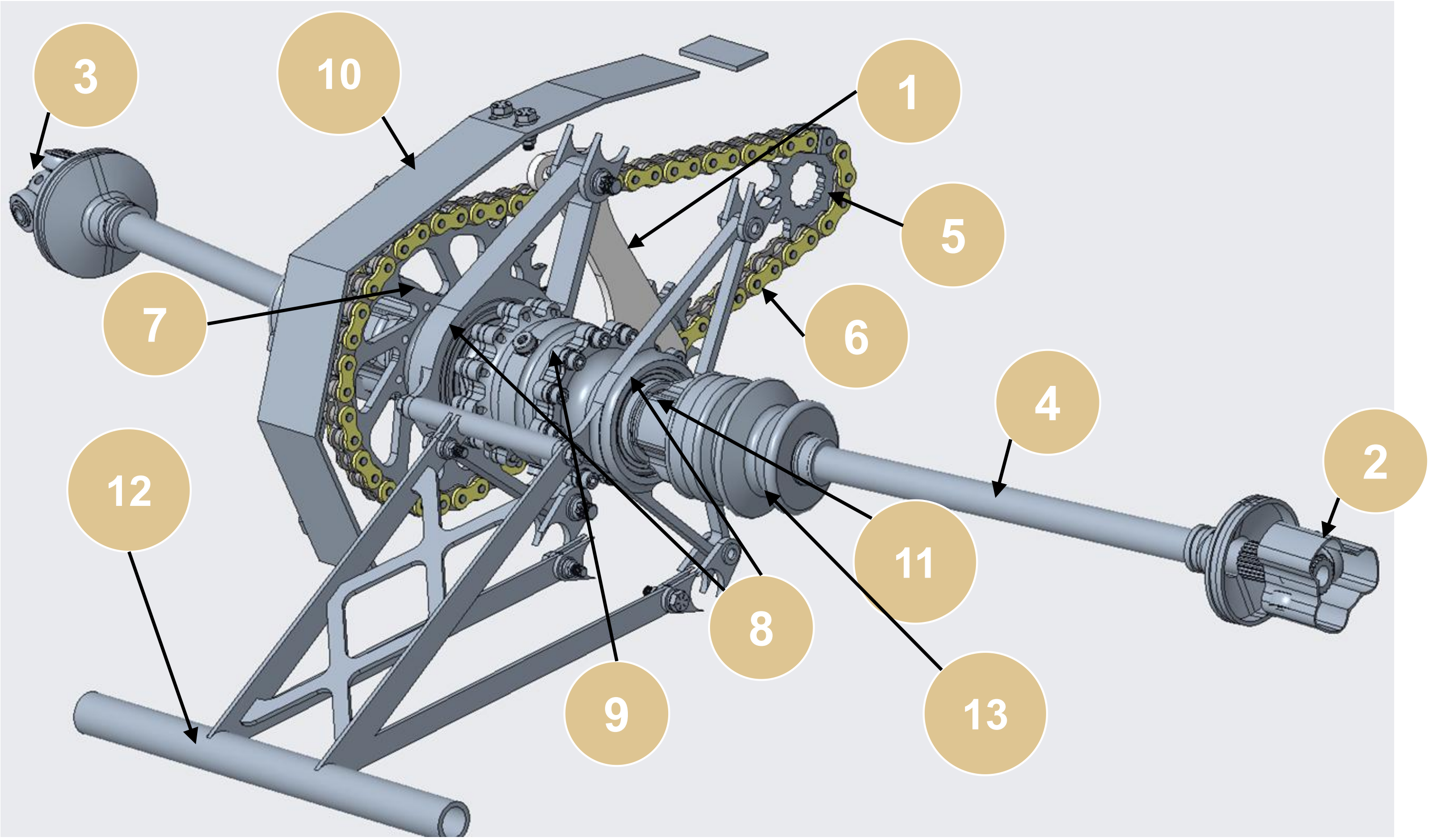
System Knowledge – PF20

- Final Drive = 34/11 = 3.09
- Architecture and philosophy between PF24 and PF20 very similar
  - Similar architecture ran for 5 seasons (PF20-24)
- Differences:
  - Higher FDR compared to PF24
  - Slight design differences



System Knowledge – PF19

- Final Drive = 34/11 = 3.09



1. Chain Tensioning System
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots

System Knowledge – PF19

Component	Purchased/Custom	Details/Notes/Info
Rear Sprocket	Custom	• Unidirectional • Material: Al 7055 • Mass: 0.503 lbm (slightly heavier than PF24)
Differential Carriers	Custom	• Features a more extreme "boomerang" shape than in PF24, PF23 • Material: Al 7055 • Upleft Mass: 0.721 lbm • Upright Mass: 0.244 lbm
CV Inserts	-	-
Towbar	Custom	• Integrated with the undertray to get rid of steel support frames found on PF18 • Mounted on Diff Carriers
Differential	Purchased	• Drexler Salisbury Limited Slip Differential • Ramp Angle Settings: Accel 60%, Decel 29%
Chain Tensioning System	Custom	• Idler Sprocket with Custom Al Bracket • Adjustable mount (to adjust chain tension)

System Knowledge – PF19

Component	Purchased/Custom	Details/Notes/Info
Halfshafts	Purchased	• Taylor Race (most likely) • Material: Gun Drilled 4130 Steel
CV Tripods	Purchased	• Taylor Race (assumption based on above) • Material: Steel
Inboard CV's Housing (Tulips)	Purchased	• Taylor Race / RCV
Boots	Custom	• Material: 3D Printed TPU • Goal was to achieve a better fit with interfacing components
Chain Guard	Custom	• Material: Steel • According to image referenced, ran a steel only configuration, but could have changed to what was ran
Chain	Purchased	• DID 520 Roller Chain

Integrating Systems

Integrating Systems

- POW > Engine
  - Function:
    - Provides the necessary power required to drive the car forward
    - Engine drives the front sprocket, which interfaces with drivetrain
    - Four stroke (Intake, Compression, Power, Exhaust)
  - Drivetrain system has to efficiently, reliably, and safely transmit the power coming from the engine and convert it to usable wheel speed
  - Contact: Hugh
- AERO > Rear Wing
  - Function:
    - Redirect airflow headed towards the back of the car upwards to create a reactionary downward force at the rear (downforce)
  - Pushbar design must not interfere with the rear wing
  - Contact: Ian

Integrating Systems

- AERO > Undertray
  - Function:
    - Generate downforce for the overall vehicle by using Venturi tunnels (ground effect)
  - Undertray, to an extent, dictates the sizing of the overall drivetrain subsystem
  - Drivetrain system must have clearance to the undertray
  - If towbar comes back to drivetrain, then have to ensure that towbar placement does not negatively affect AERO while being rules compliant
  - Contact: Ian, Julia

Integrating Systems

- CHA > Frame
  - Function:
    - Acts as mounting point for all components on the car
    - Frame stiffness and component placement on the frame, affects vehicle handling
  - Frame design dictates placement of the differential axis, which affects drivetrain component placement and respective mounting points
  - Contact: Dien
- SUS > Hubs
  - Function:
    - Connection between the wheels and the CV's
    - Allows the wheels to spin and turn freely
  - CV Insert design will drive hub design, and can have affect on CV-Halfshaft and Hubs architecture
  - Contact: Simon

Integrating Systems

- How does drivetrain make it back to tires?
  - Front sprocket → Chain → Rear Sprocket → Differential → Inboard CV's → Halfshafts → Outboard CV's → Hubs → Tires

Boundaries

Boundaries

Green text indicates responsibility of drivetrain

- Suspension
  - Two sets because final architectural decisions have to be made:
    - Wheel Hubs/**CV Inserts**
    - Wheel Hubs + CV Insert Solution/**CV's (Tripods)**
- Aero
  - Rear Wing/**Pushbar**
  - **Aero responsible for Towbar on PF25 (as of June 2024)**
- Chassis
  - Mounting of Driveline(Frame)/**Tabs (i.e. for Uprights, Chain Guard, etc)**
- Powertrain
  - Engine/**Front Sprocket (Mounting, Selection, etc)**

Requirements

Requirements

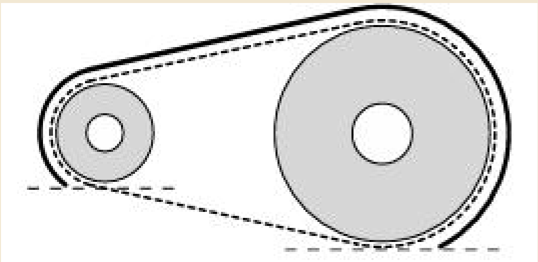
- Problem Statement: Efficiently transmit power from engine to wheels by optimizing FDR, and subsequently performance in dynamic events and keeping system mass as low as possible, while ensuring safe and reliable operation.

- At the minimum, system must be compliant with all relevant rules, specifically related to chain guard, pushbar, critical fasteners, and potentially jacking point.
  - Jacking point rules are not compiled in this document. Reference FSAE rules for information related to jacking point.

Requirements

Rule	Exact Text	Requirements From Rule
T.5.1	Any transmission and drivetrain may be used.	Any configuration can be used as team sees fit. Must comply with rest of rules below.
T.5.2.1	Exposed high speed final drivetrain equipment such as Continuously Variable Transmissions (CVTs), sprockets, gears, pulleys, torque converters, clutches, belt drives, clutch drives and electric motors, must be fitted with scatter shields intended to contain drivetrain parts in case of radial failure.	Drivetrain system must contain "shield" (i.e. Chain Guard) to prevent exposed parts from scattering (i.e. Sprocket, Chain).

Requirements

Rule	Exact Text	Requirements From Rule
T.5.2.2	The final drivetrain shield must: a. Be made with solid material (not perforated) b. Cover the chain or belt from the drive sprocket to the driven sprocket/chain wheel/belt or pulley c. Start and end no higher than parallel to the lowest point of the chain wheel/belt/pulley d. Cover the bottom of the chain or belt or rotating component when fuel, brake lines T.3.1.8, control, pressurized, electrical components are located below	Final guard must be made of a solid material and cover the sprocket-chain system as shown in the image. 
T.5.2.3	Body panels or other existing covers are acceptable when constructed per T.5.2.7 / T.5.2.8.	Body panels can be used as part of the guard system if constructed to rules specification.
T.5.2.4	Frame Members or existing components that exceed the scatter shield material requirements may be used as part of the shield.	Existing frame members and/or components can be used as long as they EXCEED material requirements

Requirements

Rule	Exact Text	Requirements From Rule
T.5.2.5	Scatter shields may be composed of multiple pieces. Any gaps must be small (< 3 mm).	Guard system can be made of multiple components if gaps are small (i.e. less than 3 mm).
T.5.2.6	If equipped, the engine drive sprocket cover may be used as part of the scatter shield system.	OEM guards can be used.
T.5.2.7	Chain Drive - Scatter shields for chains must: a. Be made of 2.66 mm (0.105 inch) minimum thickness steel (no alternatives are allowed) b. Have a minimum width equal to three times the width of the chain c. Be centered on the center line of the chain d. Stay aligned with the chain under all conditions	For chain driven systems (what we historically run), the following must be met: a. Made of 0.105 inch minimum thick steel b. Overall width equal to 3 times width of chain c. Centered along center line of chain at all times d. Stay aligned with chain under all conditions
T.5.2.9	Attachment Fasteners - All fasteners attaching scatter shields and guards must be 6 mm or 1/4” minimum diameter Critical Fasteners, see T.8.2	All fasteners used in guard system must be in accordance to T.8.2

Requirements

Rule	Exact Text	Requirements From Rule
VE.2.2	Each vehicle must have a removable device which attaches to the rear of the vehicle that: a. Allows two people, standing erect behind the vehicle, to push the vehicle around the competition site b. Is capable of slowing and stopping the forward motion of the vehicle and pulling it rearwards	Car must have a push bar that attaches to rear and: a. Allows two people to push car around at comp b. Capable of slowing and stopping forward vehicle motion and pulling it backwards
VE.2.3.1.b	One extinguisher must accompany the vehicle when moved using the push bar	A fire extinguisher must accompany vehicle when moved using push bar
D.2.1.1	Outside of the Dynamic Area(s), vehicles must be pushed at a normal walking pace using the Push Bar (VE.2.2), with a driver in the cockpit and with another team member walking beside	Vehicle to be pushed around outside of dynamic areas

Requirements

Rule	Exact Text	Requirements From Rule
D.2.1.2.b	The team may move the vehicle with: b. The rear wheels supported on dollies, by push bar mounted wheels	Team may move vehicle with dollies that support the rear wheels
D.2.1.3	When the Push Bar is attached, the engine must stay off, unless authorized by the officials	Push bar on car = engine off

Requirements

- Withstand extreme load cases with an adequate factor of safety, as dictated by team standards with regards to safety
- Contain a chain tensioning system to account for approximately 3% of chain stretch due to fatigue throughout the season
- Integrate desired final drive that will break traction
- Hardware within system will be torque spec'd or safety wired to prevent failure on track (with exact torque spec determined by what hardware is used, mostly NAS 3)
- Design to the following boundary conditions while maintaining the aforementioned margins to safety:
  - Peak engine torque (unknown now due to final analysis of dyno data required and will be made known once that said data is analyzed)
  - Tire size (unknown now due to final analysis carried out by suspension and will be known once that data is analyzed)
  - Longtudinal Acceleration (historically done about 1.65G)
  - Approximate Vehicle Weight (unknown right now due to considerations having to be carried out about what weight to consider for drivers and will be known once that metric is set)
  - Final Drive Ratio (unknown right now due to lapsim analysis and case studies not fully carried out at the moment, but will be known once that data is analyzed and results are provided)

Goals

Goals

Vehicle Goals	Subsystem Goals
1) Driver Safety	• System components are designed to a factor of safety in accordance to team safety standards.
2) System Reliability	• Utilize a front and rear sprocket combination that minimizes wear on sprockets • Replace components at the end of their life cycle as needed, which is determined by visual inspection of any wear accumulated. • Ensure robustness of system by manufacturing/acquiring an extra set of drivetrain components (most likely, minus halfshafts) with 2 extra chains
3) Maximum Competition Points (Mass, CG, Yaw Inertia…)	• Strategically reduce mass to keep system mass as low as possible, while ensuring safety standards are met. • Accommodate final drive ratio that allows team to achieve the highest possible competition points in accordance to case studies performed and lapsim

Goals

Vehicle Goals	Subsystem Goals
4) Driver Confidence/Comfort	• No major failures during testing season for any component and mounting mechanisms • Find and set up differential for a tune that yields no driver complaints

5) Serviceability	• Utilize a chain tensioning system that accounts for:
	    • Chain stretch and fatigue throughout the season
	    • Easy chain tension adjustments (should occur under 5 minutes)
	• Allow for relatively easy access to hardware by accommodating space for appropriate tools needed for servicing

Architecture

Differential

	Drexler LSD	Custom Spool	Another Purchased Diff
Team History	Ran by team for several seaons now, and has proven to be a dependable option	Completely new, but team has documented experimentation with designing one	None; this would be a complete experiment to see how it works with our setup
Mass compared to benchmark	~ 8.8 lbs (benchmark) Assuming V3; dry weight	Significantly lower	Comparitively similar to the benchmark
Tuning	Possible	Not possible	Possible
Implementation	Historical knowledge, can tune as needed to improve handling	Architecture on several systems would have to pivot drastically; negative to driveability	No knowledge, would have to rework a lot of components that have been used in the past

My Verdict
Given considerations that suspension would have to completely pivot design for a gain that may or may not be realizable, it is best to stick with what team has been running for now. This would also allow money to be spent on other parts of the car as required, since a new differential will cost about $3000, and there is no issues with our current differential. Additionally, endcaps are available for purchases for our current set up, which allows for further optimization.

Drexler Limited Slip Differential

	Nonadjustable (PF24)	Adjustable (PER)
Team History	Ran for several seasons with no major issues	To my knowledge, never ran

Perks	Decent past knowledge	• Time saving on adjustments made during initial set up and testing
		• Customizable preload adjustment range
		  • Can account for variable race and track condition (more knowledge to do successfully)
		• Relatively compatible to what team has ran historically
		  • Allows us to run both an adjustable and non adjustable and swap as needed or wanted

Verdict

Open for discussion; According to service manuals, both have fairly similar components, so nothing drastic changes from a rebuilding and understanding point of view, but running an adjustable allows us to be more efficient with diff tuning if that is something we are willing to explore this year. We have both, so we can set them up and see what works better for our needs and have one diff as a spare.

Note that this slide assumes we can sort out the seized bearing issue on PER’s adjustable diff

Another Purchased Diff

- Types of diffs available for use:
  - Open Differential/Spool
  - Detroit Locker Differential
  - Cam and Pawl Differential
  - Salisbury or Clutch Pack Differential
  - Automatic Torque Biasing Differential
- The preferred differential among many FSAE teams remains a clutch pack differential
  - Open diff and spool is a negative to driveability
  - Other differentials are more complex and not well supported for FSAE teams

Rear Sprocket

	Custom	Purchased
Team History	Ran successfully in the past with no major issues	To my knowledge, never ran
Flexibility	Ability to control design to exactly how it is required (FDR, mass optimization, etc); can also work in a variety of conditions	Extremely restricted selection and application; would have to design around rear sprocket, which is not a good idea
	Titanium	**Aluminum**
Mass (benchmark = Al)	Slight weight loss (~0.1 lbm loss)	Benchmark (~0.5 lbm)
Machining Time	Much longer machining time compared to Aluminum + Wire EDM	Took me around 5-7 hrs with about 1-3 hrs of stock prep put in beforehand + Wire EDM
Cost	Significantly Higher	Benchmark
My Verdict		
An aluminum custom rear sprocket is best due to the better machining times and the smaller potential weight loss with titanium. In addition, cost would be much higher. Only main benefit of titanium is fatigue life, which can be mitigated by manufacturing spares. An alternate route can be considered by making a Ti sprocket as opposed to multiple spares of Al. The weight loss with rotating mass seems appealing.		

Differential Carriers

	Titanium	Aluminum
Team History	To my knowledge, not run at least in recent history	Traditionally ran for the last couple of seasons
Mass (benchmark = Al)	Slight weight loss (potentially a bit more than sprocket)	Benchmark
Machining Time	Much longer machining time compared to Aluminum	Benchmark
Cost	Significantly Higher	Benchmark

My Verdict
Given there is not so much gains with respect to mass loss and with the added cost that comes with it, it does not make much sense to pursue titanium. Considering that the design of the differential carriers could get more complex this year (a possibility), it is best to stick with aluminum to reduce machining time and avoid extra costs. Further, there is room to play with optimizing overall system mass by using different endcaps for the differential we have.

Chain Tensioning Mechanism

	Linear Translation (aka Turnbuckles)	Idler Sprocket	Eccentric Differential Carriers
Team History	Ran in recent history since PF20	Ran once in recent history (PF19)	To my knowledge, never ran by team, but at least not in recent seasons
Mounting	Refer to PF24 CAD	Along length of chain; placement is key since chain guard has to cover idler sprocket	Same location as differential carries along diff axis, except would connect directly to two points on chassis
Manufacturability	Rod ends purchased; Custom body (relatively simple)	Would probably purchase sprocket, but manufacture adjustable mounting mechanism	Most difficult of the bunch to manufacture due to complexity of components
Approx Mass	Benchmark	Very similar, potential to be slightly higher or lower	Heavier

Chain Tensioning Mechanism

	Linear Translation (aka Turnbuckles)	Idler Sprocket	Eccentric Differential Carriers
Serviceability	Easy to adjust chain tension with excellent tool access	Relatively simple to adjust chain tension with extra measures needed for easy tool access	Similar to turnbuckles, but adjustment takes place on diff carriers (maybe slight issues with tool access)
Simplicity of Design	Benchmark (simple design and manufacturing)	Adjustable mount has potential to be complicated pending mounting location	Adds complexity to the differential carrier system
Aligns with measures to reduce halfshaft angle	Not really	Yes	Yes
Additional Considerations	One turnbuckle takes about 45 mins to make	Analysis for idler sprocket; to my knowledge, no effect on FDR; have to understand why we stopped running; adds chain length; mounting	If running, have to figure out how to simplify this system as best as possible.

Chain Tensioning Mechanism

My Verdict
The safest option is to stick with turnbuckles, but all three options are here for consideration. Looking at PF25, there is high likelihood to run turnbuckles. If a situation arises in the future where other options can be considered, this is a good place to start.

Halfshafts

	Custom (Ti)	Purchased (4130 Steel)
Team History	Idea has been talked about before but would have to do a significant amount of work (obtaining high fidelity laser scan, sourcing manufacturing, analysis, etc)	Used for the last several seasons, serves as a dependable option that is structurally sound; Variety of sizes available for purchase and can be machined to final size
Mass (benchmark = purchased)	Can't get an exact amount in terms of mass saved, but increases as the length of halfshaft increases	Benchmark
Machining Time	MUCH longer (and will most likely have to send this out)	Benchmark; comes with spline
Cost	Significantly higher	Benchmark

My Verdict

Open for discussion, but ability to do this will depend on having the full knowledge and the resources necessary at the correct time. Given other changes that will most likely occur, can't be certain yet about making a custom.

CV Inserts

	Reiteration / Revalidation on PF24's Design	New Design / Purchased
Team History	Ran in the last couple of seasons since PF20; No notable issues to my knowledge	Not run in recent history
Change to recent hubs design philosophy	Zero change	Would be a change depending on design
	17-4 Prehard Stainless w H900 Heat Treatment	**Another Material with Appropriate Hardness**
Team History	Ran on PF24	Not ran on PF24
Manufacturing	Cut to length, HT in ME, Wire EDM	Would look similar to 17-4, might have to HT to a different specification

My Verdict
Open for discussion. The safe option is running with 17-4PH as it gives the desired hardness value (around 55 HRC) and uses H900 to avoid an HT that would make the part brittle (i.e. H1000)

Boots

	Purchased	Custom (Nitrile Glove Special)	Custom (3D Printed)
Team History	Typically ran in recent seasons	Ran on PF24 after purchased boots failed	Ran at least once in recent history (PF19)
Cost	~$12 for 1	~$5 for 2	Filament dependent
Other considerations	Have to fully understand why it failed last year to be able to conclusively say if this was a failure or not	Doesn't take long to make, but definitely has the appearance of a lower fidelity prototype	Can be made to exact specifications based on the design; Is also something else that has to be designed and manufactured

My Verdict

Open for discussion, and something that can be changed down the line if necessary (including during testing season if required).

Other Components

Component	Notes
Chain Guard	Custom Steel by rules and manufactured in house
Chain	Purchased DID 520 Roller Chain
Inboard CV Housing (Tulips)	Purchased – Diff Custom – Spool
CV's (Tripods)	Purchased (RCV)

Burndowns

System Burndown

- Initial Drivetrain Architecture and Design Considerations
  - SUS Points, Rear CHA box, Initial driveline placement, Initial Halfshaft Angles
- Drivetrain DCR
- Finalize Architecture
- Initial Calculations and Analysis
- Initial FEA
- Initial CAD
- Drivetrain PDR
- Final Calculations and Analysis
- IDR
- Final FEA
- Final CAD
- Drivetrain CDR
- Source Stock + Purchased Parts
- Manufacturing
- Assembly
- Testing
  - Pushbar design and manufacturing

Click for Detailed Burndown

Cost

Cost

Major Component	Owned/Sponsored/Purchased	Estimated Cost + Misc Notes
Drexler Salisbury LSD	Owned	$3000
Halfshafts	Purchased	$300 x 2
Tripods	Purchased	$115 x 4
Diff Carrier Bearings	Sponsored (SKF, NTN)	$150 x 4
Inboard CV (Tulip) Housings	Owned	$750
Aluminum Stock	Sponsored (Arconic)	$1000
Chain	Purchased	$100 x 2-3
Hardware	Purchased	$250

Total Estimated Cost (excluding owned and sponsored parts)	$1610

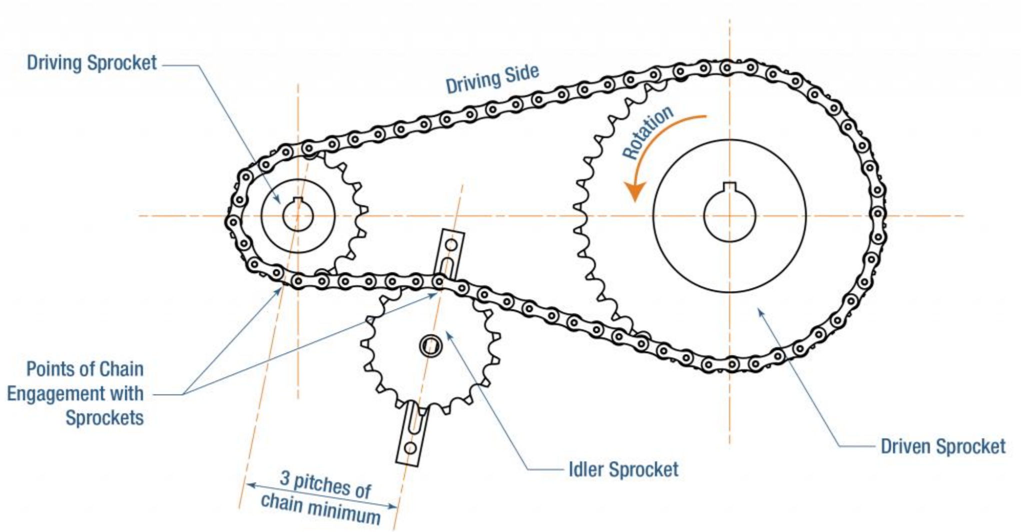
Note that is an estimate and will likely go up depending on final architecture and material selection. Based heavily off of PF24 architecture.

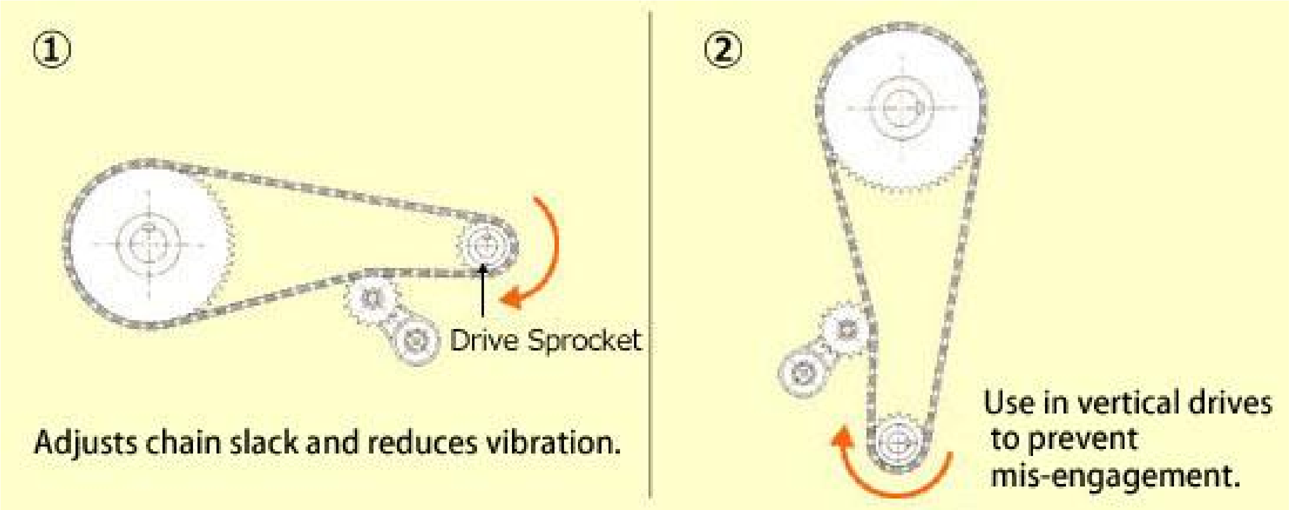
Appendix A:
Basics of an Idler Sprocket

Idler Sprocket Basics

- An idler sprocket is a smaller sprocket that is placed along the length of the chain to allow the chain to maintain constant tension.
  - Chain too loose → risk chain falling out of place and could cause injury
  - Chain too tight → excessive wear on sprockets and chains, which requires replacement more often
- Should be installed on the slack side of the chain
  - Usually the length of the chain that runs closer to the bottom for our purposes
- Loading, chain wrap, and chain speed are important to consider
- A chain rider is an alternative that functions similarly to an idler sprocket (no teeth to worry about, but radial loading still a factor)

Reference Images





Appendix B:
Preliminary Halfshaft Length/Diff Endcap Weight Study

Halfshaft Length/Diff Endcap Study

- General Note: Longer endcap will reduce weight of halfshafts, but increase the weight of diff. However, halfshaft angles will also go up (further compounded by chain stretch), which makes minimizing initial halfshaft angle extremely crucial.

Nominal Halfshaft Length	Weight
11”	1.02 lbm
13”	1.19 lbm
15”	1.36 lbm
17”	1.54 lbm
19”	1.71 lbm
21”	1.88 lbm
23”	2.06 lbm

Source for Weights: RCV FSAE Axle Shaft - FSAEparts.com

- Assumption: we will be running a halfshaft length close to a nominal length.
- We will save 0.17 lbm for every 2 inch reduction.

Halfshaft Length/Diff Endcap Study

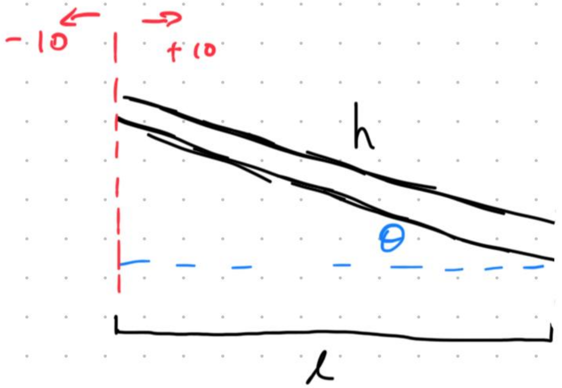
- Below is data compiled for non adjustable diff. Adjustable should yield relatively similar results.
- PF24 ran a bearing spacing of approx 140mm (136mm on calcs). Loads deltas are sourced from PF24 differential carriers hand calculations.

Differential Cover Version	Bearing Spacing	Weight (endcaps only!)	Left Diff Carrier Loads (relative to PF24)	Right Diff Carrier Loads (relative to PF24)
V1	120mm	0.480 lbm	+2.644%	+12.698%
V2	140mm	0.597 lbm	+/- 0%	+/- 0%
V3	160mm	0.730 lbm	-2.99%	-16.108%

- Quick note: weights are not super well documented online. These weights are taken from service manual and is not clear whether it accounts for one or both endcaps. I'm running with assumption that it accounts for both.
- PF24 Diff Carrier Masses (approx.):
    - Left → 0.61 lbm
    - Right → 0.356 lbm

Halfshaft Length/Diff Endcap Study

- Concluding Remarks:
  - Possibility that differential carriers can be mass optimized to reduce mass to potentially offset the gain that a larger bearing spacing would bring
  - Biggest gain to me seems to be the halfshaft weight saving



+/- 0:

$$h = \frac{l}{\cos\theta}$$

-10:

$$h + x = \frac{l+10}{\cos\theta'}, \quad \text{where } \theta' < \theta$$

$$x = \frac{l+10}{\cos\theta'} - h$$

+10:

$$h - x = \frac{l-10}{\cos\theta''}, \quad \text{where } \theta'' > \theta$$

$$x = h - \frac{l-10}{\cos\theta''}$$

Appendix C:
PF24 BOM

PF24 BOM (Drivetrain Only)

Subsytem	Vendor	Link	Item Code	Description	Quantity	Cost Per Unit [$]	Estimated Total Cost [$]	Shipping Cost [$]	Discount [%]	Total Cost With Discount [$]
Drivetrain	RCV Performance	RCV FSAE Axle Shaft - 11" (rcvperformance.com)		Halfshafts	2	$286.00	$572.00	$0.00	0%	$572.00
Drivetrain	RCV Performance			Tripods	4	$115.50	$462.00	$0.00	0%	$462.00
Drivetrain	NTN/SKF			61910 2RS1	2	$150.00	$300.00	$0.00	100%	$0.00
Drivetrain	NTN/SKF			6011 2RS1	2	$150.00	$300.00	$0.00	100%	$0.00
Drivetrain	Motion Industies	Aurora Bearing Company XAM-3T MALE ROD END ALLOY - Motion		XAM 3T Rod Ends	4	$60.00	$240.00	$0.00	0%	$240.00
Drivetrain	Bearing Dist Inc	XAB-3T - AURORA BEARING | Spherical Plain Bearings - Rod Ends | BDI USA (bdiexpress.com)		XAB 3B Rod Ends	4	$52.00	$208.00	$0.00	0%	$208.00
Drivetrain	McMaster	Tight-Tolerance High-Strength 7075 Aluminum Rod, 5/8" Diameter | McMaster-Carr		5/8 Round 1ft 7075	1	$41.78	$41.78	$0.00	0%	$41.78
Drivetrain	McMaster	Multipurpose 6061 Aluminum, 3/16" Thick x 4" Wide | McMaster-Carr		Sheet for Towbussy	2	$28.43	$56.86	$0.00	0%	$56.86
Drivetrain	McMaster	General Purpose Aluminum Tubing, 1" OD, 0.083" Wall Thickness | McMaster-Carr		Towbussy Tubeussy	2	$17.37	$34.74	$0.00	0%	$34.74
Drivetrain	McMaster	Ball Joint Rod End, 10-32 Thread | McMaster-Carr		Carbon Tube Rod Ends	4	$4.40	$17.60	$0.00	0%	$17.60
Drivetrain	McMaster	Low-Strength Steel Hex Nut, Zinc-Plated, 10-32 Thread Size | McMaster-Carr		10-32 Nuts	200	$0.02	$4.40	$0.00	0%	$4.40
Drivetrain	McMaster	Medium-Strength Steel Hex Nut, Grade 5, Zinc-Plated, 1/4"-28 Thread Size | McMaster-Carr		1/4-28 Nuts	100	$0.08	$8.00	$0.00	0%	$8.00
Drivetrain	Rockwest Composites	Rockwest Tubes (Some aero stuff Ill ask Joe when I get a chance smh)		Towbar Tubes	2	$100.00	$200.00	$0.00	100%	$0.00
Drivetrain	Drexler			Differential	1	$2,500.00	$2,500.00	$0.00	100%	$0.00
Drivetrain	Drexler			Short Tripod	1	$300.00	$300.00	$0.00	100%	$0.00
Drivetrain	Drexler			Long Tripod	1	$350.00	$350.00	$0.00	100%	$0.00
Drivetrain	ALRO	ALRO		17-4 PH 3in Round	1	$350.00	$350.00	$0.00	100%	$0.00
Drivetrain	Arconic			7055 Aluminum 4 in thick blocks	4	$250.00	$1,000.00	$0.00	100%	$0.00