FORMULA SAE®

eCFR-23 Design Briefing

COLUMBIA UNIVERSITY
FORMULA RACING

Car #243

Table of Contents

Columbia FSAE at Michigan International Speedway (May 2022)

FORMULA SAE®

Team Update

History of the Team

Team Update

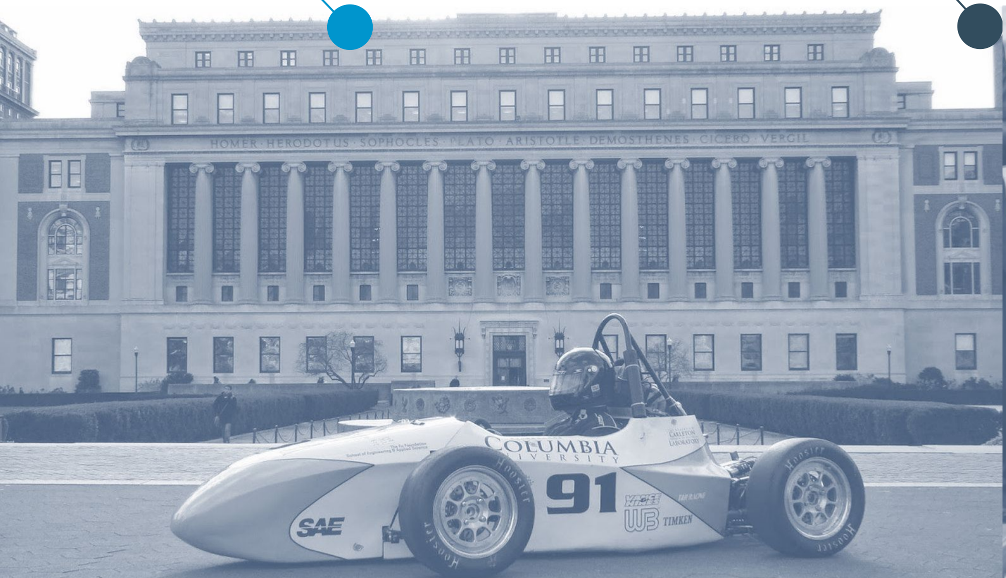
For the first 20 years, we were strictly an internal combustion team. This year, we are transitioning to strictly an electric vehicle team, and eCFR-23 will be the first electric car we race in this new era.

1997-2000
The Early Teams

2000-2008
The First Decade

2008-2019
Superleggera

2019- Future
CFR-22



Team Leadership

Matthew
President

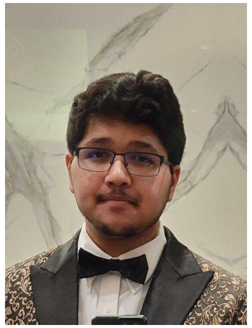
Sanja
VP Tech Ops

Elaine
VP Business Affairs

Kat
ME chief

Rano
EE chief

Jazmyn
Secretary



Vedhas
EE Treasurer

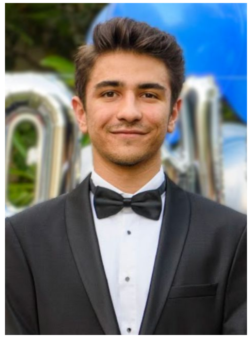
Nika
ME Treasurer

Juan
Frame/Body/Aero

Dairon
Powertrain

Alex
Controls

Jannie
Dynamics



Mert
LV

Matthew
HV

Kade
Social Chair

Team Mission

Our team mission is to educate and develop the next generation of engineers and managers while building a racecar for the Formula SAE competition.

The past year has given us time to adequately plan for the transition from IC to EV, and we are proud to present the design for our first electric car.

FORMULA SAE

Overview

eCFR-23 By the Numbers

68kW Drivetrain

18” 300V, 5.4kWh battery pack

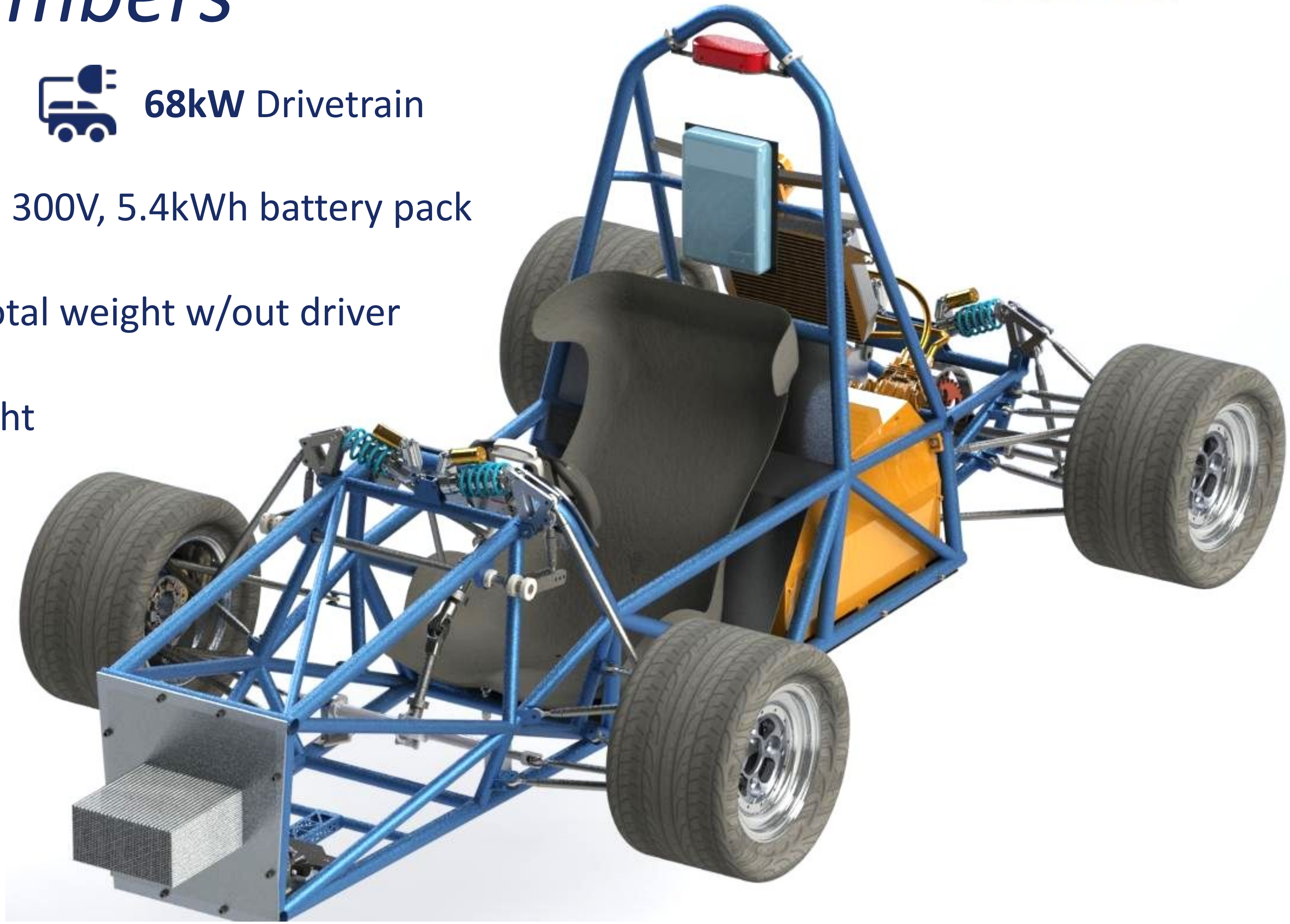
485 lb. Total weight w/out driver

1.25” Ride height

9.83” CoG height

47”/47” TW Front / Rear

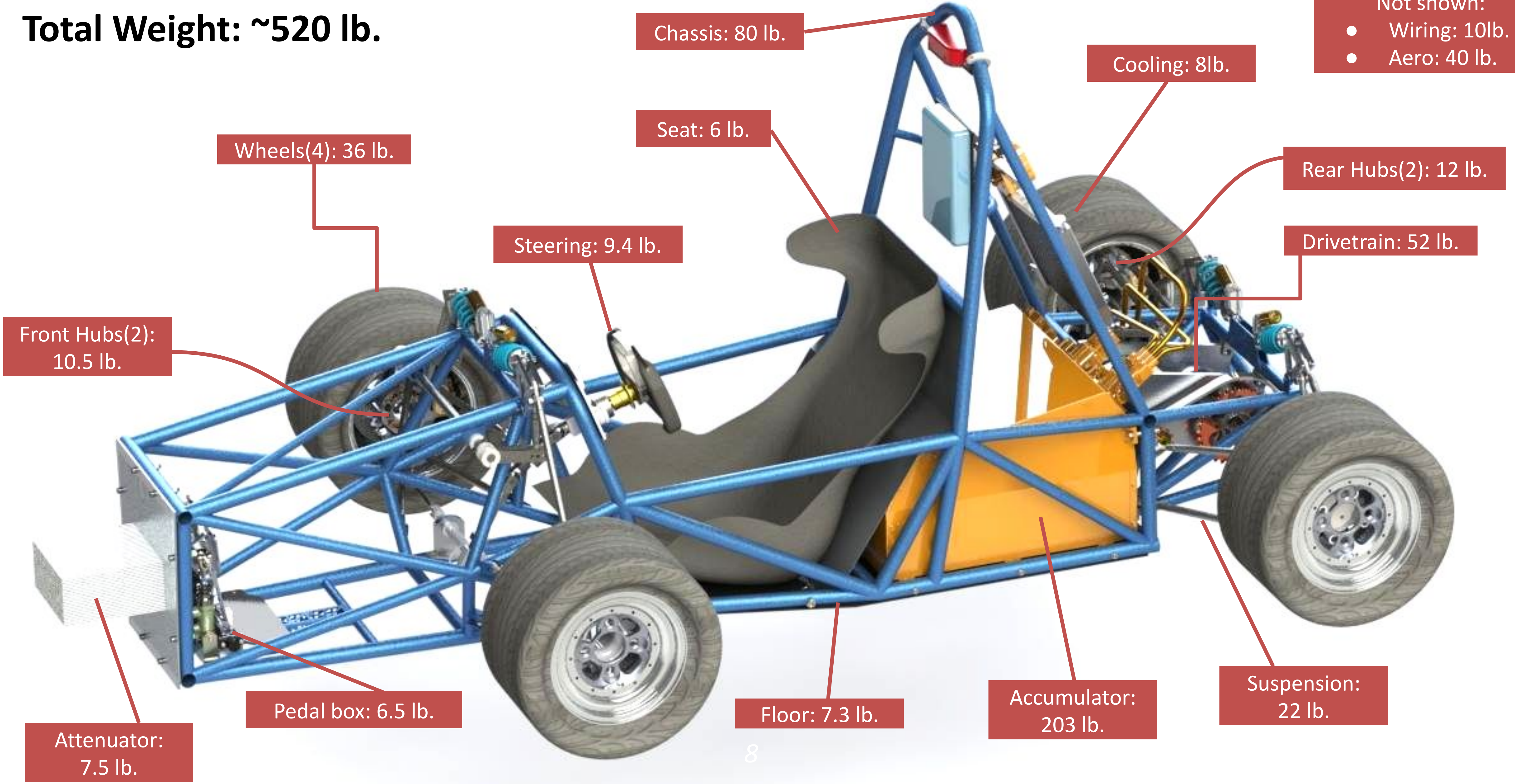
4130 steel space-frame chassis



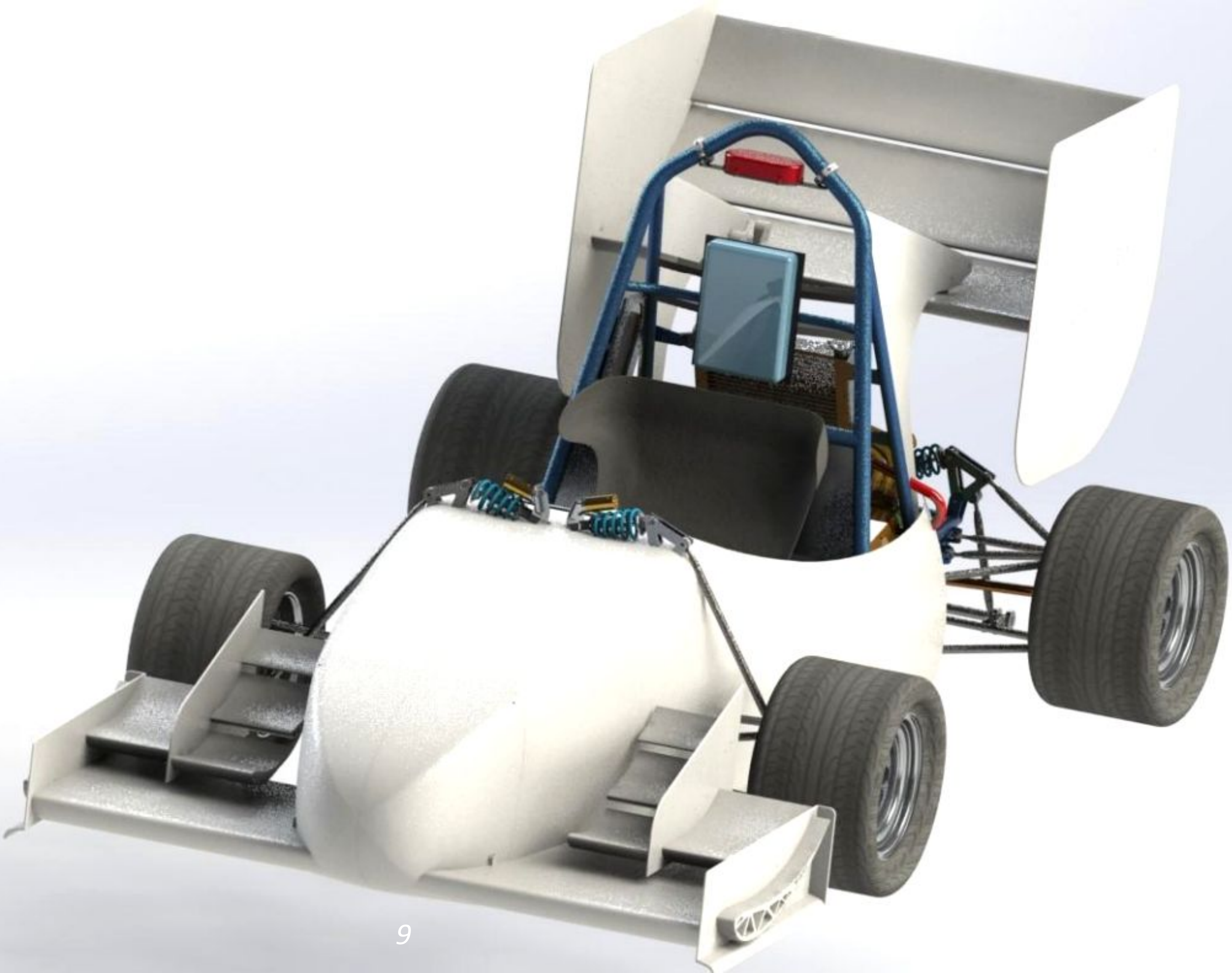
Vehicle Weight Breakdown

Total Weight: ~520 lb.

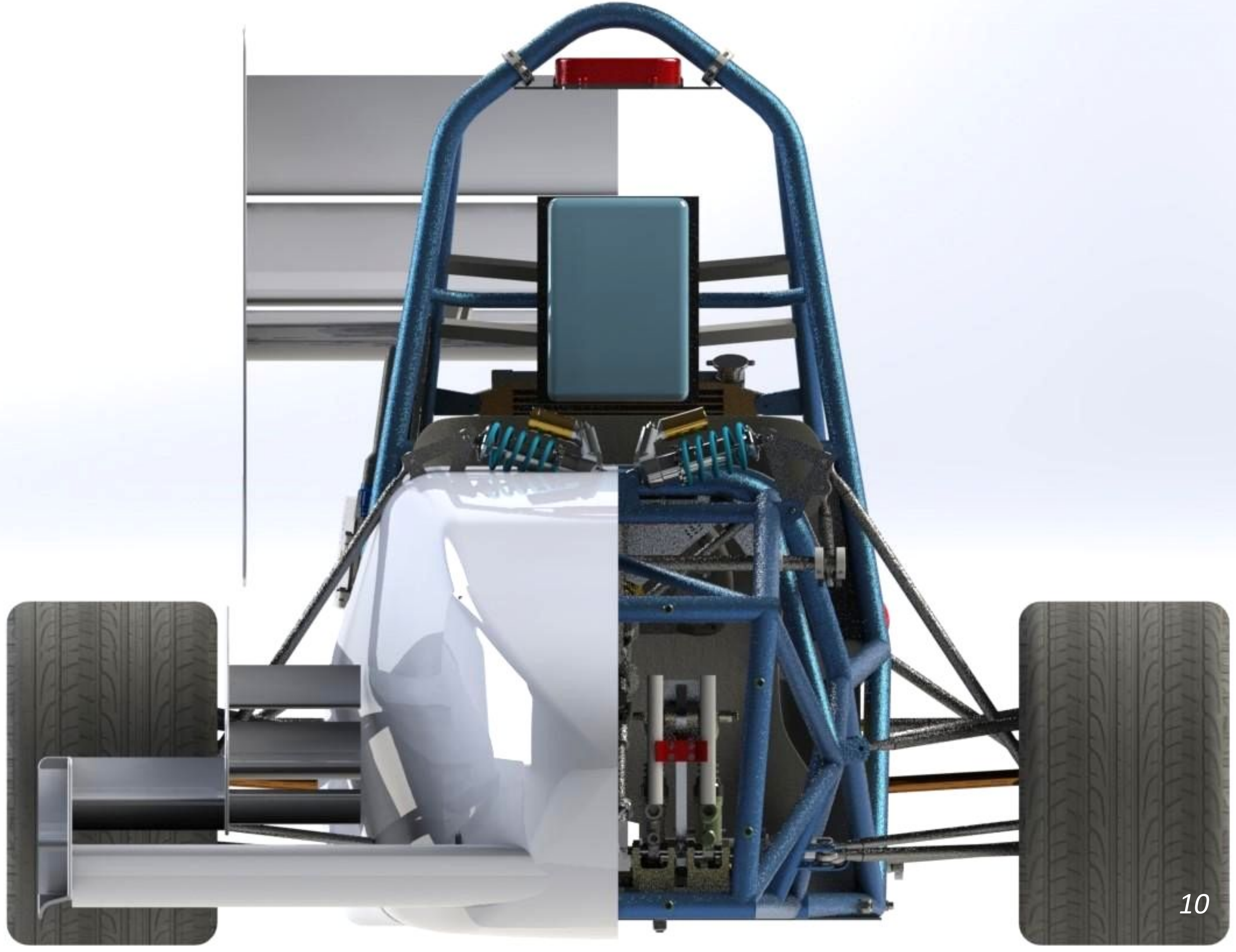
Not shown:
- Wiring: 10lb.
- Aero: 40 lb.



Isometric View

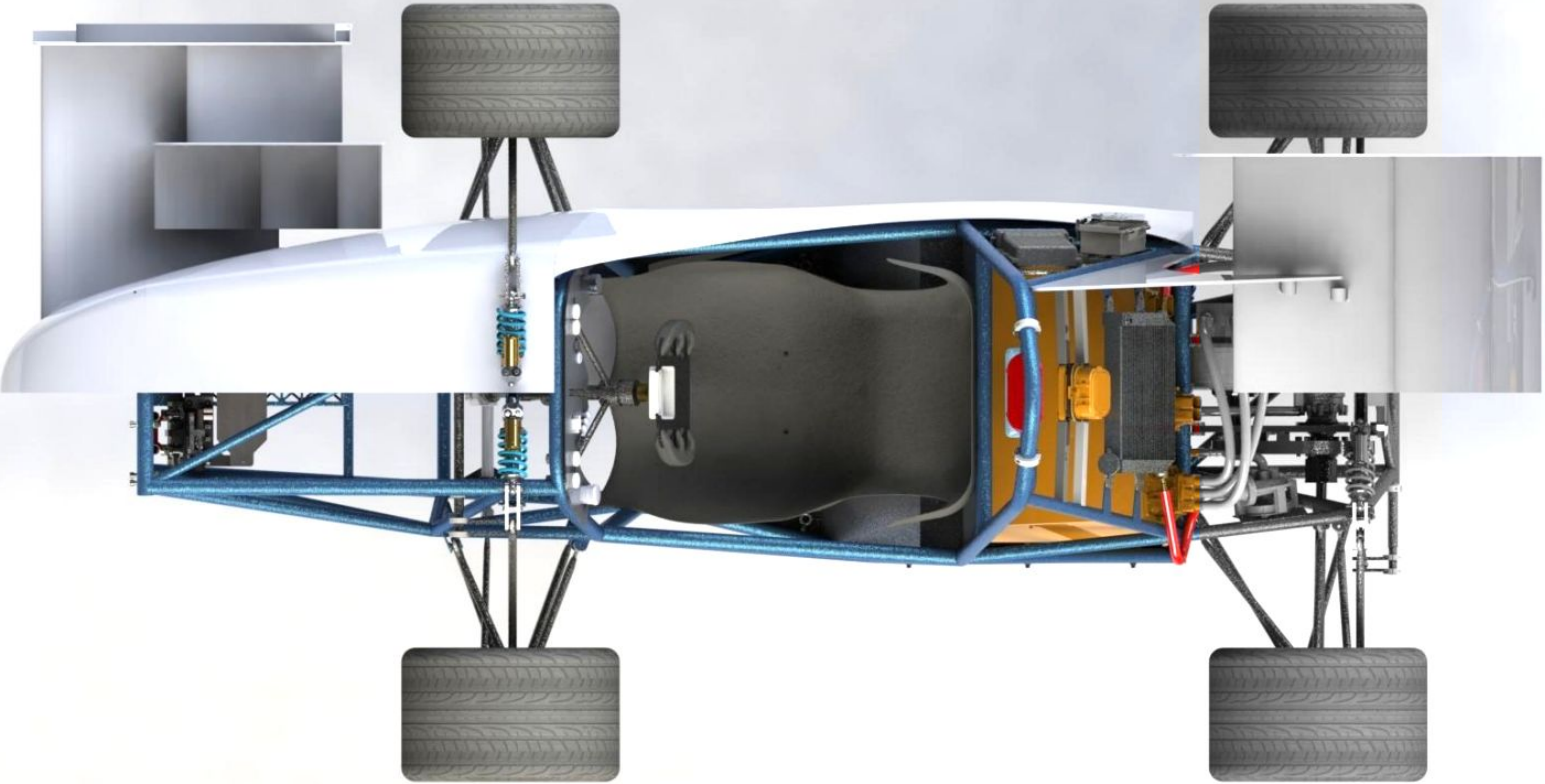


Front View



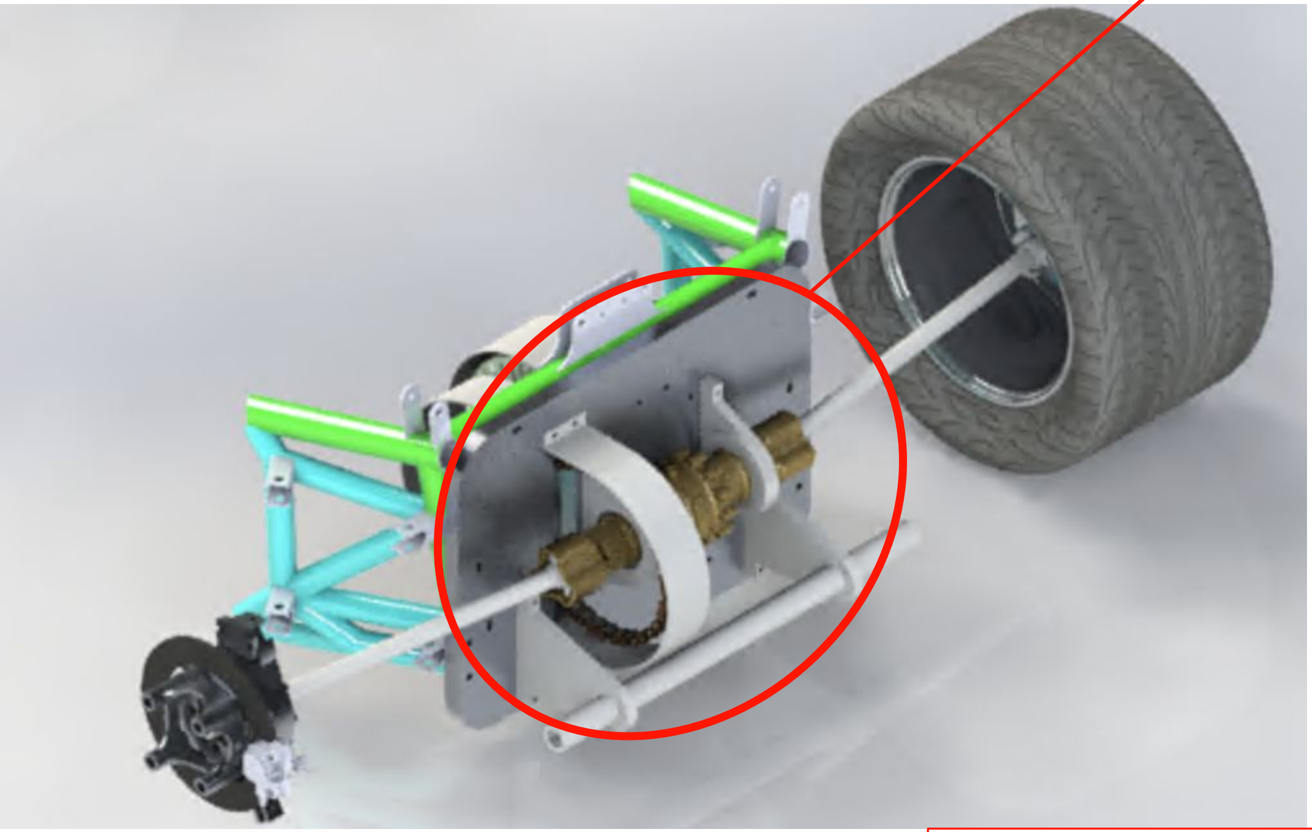
Side View

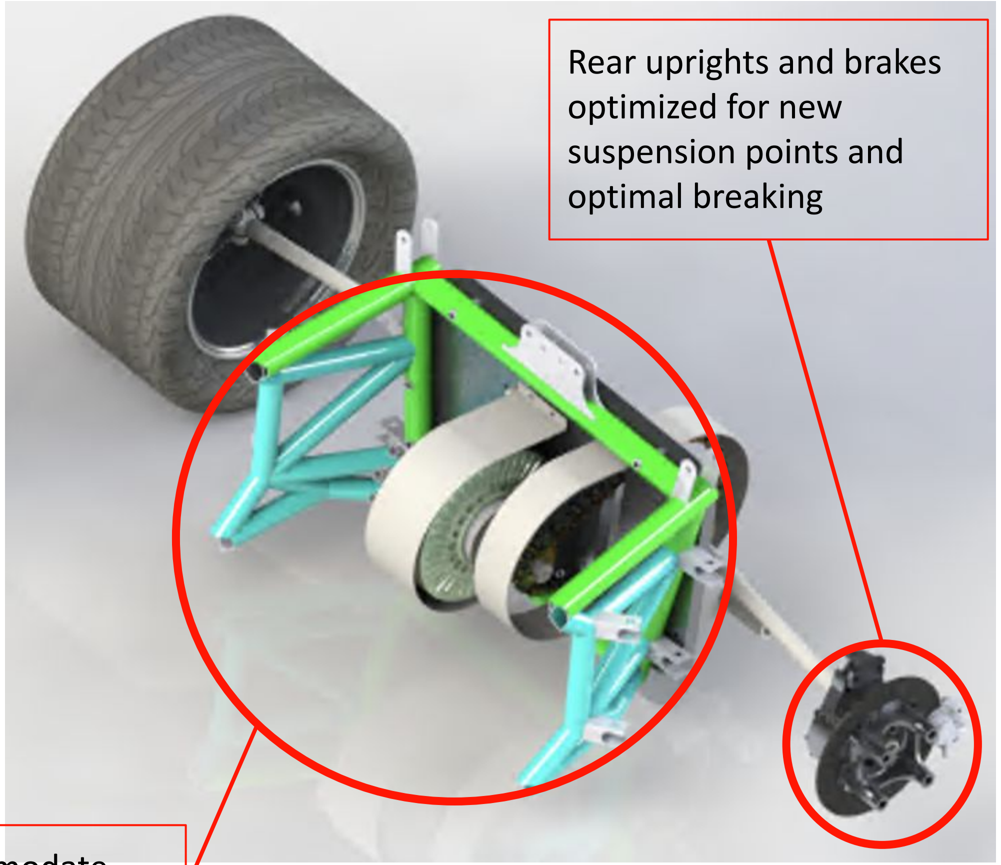
Top View



Rear Redesign

Optimized Powertrain for off car testing and serviceability





Rear uprights and brakes optimized for new suspension points and optimal breaking

Adjusted chassis to accommodate optimal suspension points

System Goals

Main Goal: Reach Ay > 1.5G’s

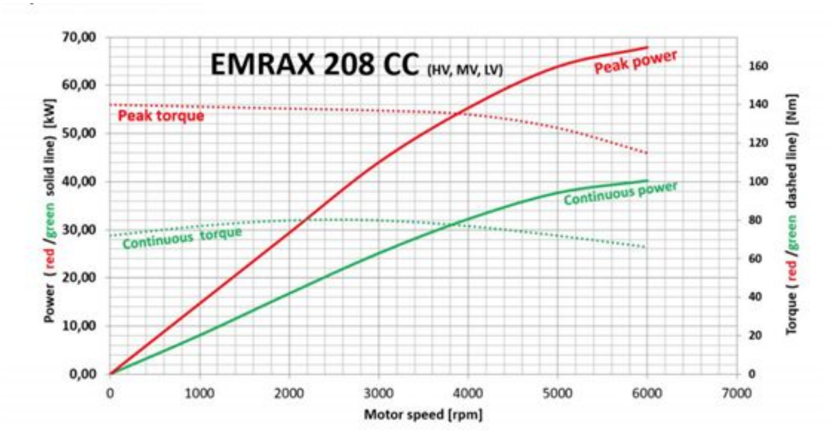
Due to battery and accumulator size restrictions, we were limited to an Emrax 208 motor. We concluded that for our case, it would be harder to improve Ax than it would be to improve Ay. Thus, the goal for our car is to reach a lateral acceleration greater than 1.5G.

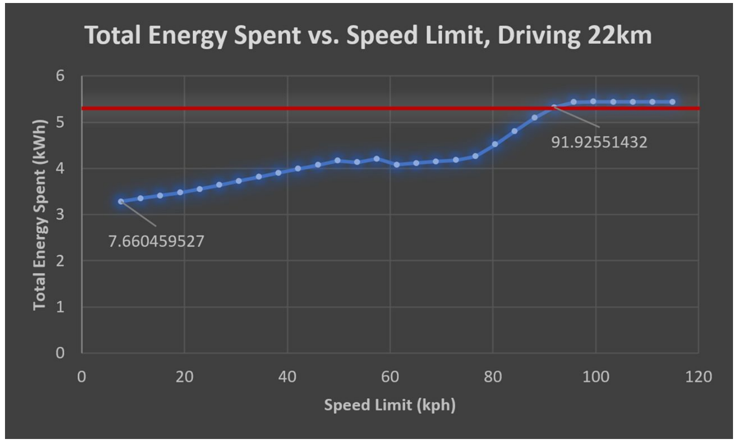
Chassis: Lower chassis CG as much as possible and prioritize torsional stiffness in order to realize cornering gains.	**Suspension:** Design a suspension that can accommodate low CG & improves cornering performance
Accumulator: Design a safe and reliable system that was accessible and easy to remove, as well as low to the ground and near the CG	**Aerodynamics:** Optimize for as much downforce as possible, even at the expense of extra drag.
Drivetrain: Design a simple fixed gear drivetrain that strikes a good balance between torque & speed. Low to the ground & structurally stiff to avoid drivetrain losses.	**Cooling:** Design a system that keeps motor, inverter (liquid cooled) & batteries (air cooled) at operating temperature in order to maximize efficiency of motor.
Steering: Minimize steering column slop in order to maximize slip angle gains & improve cornering potential of the car.	**Brakes:** Create a reliable braking system that also reduces the unsprung mass of the car.
Cockpit & Controls: Driver / pit crew interaction with the car should be safe and easy. Drivers of different sizes accommodated.	**Wiring:** Harness should be robust and serviceable. Minimize stray wiring and prevent user error.

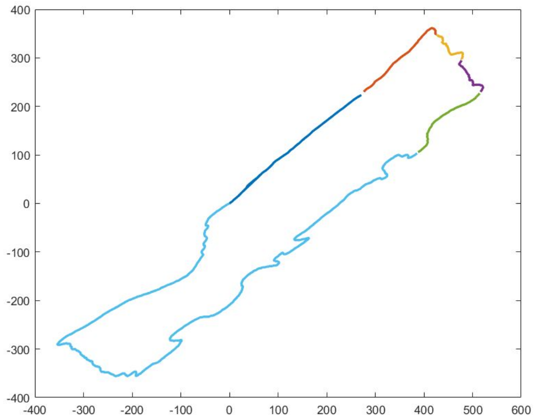
Goals and Capabilities

Primary Design Goal: Finish endurance.

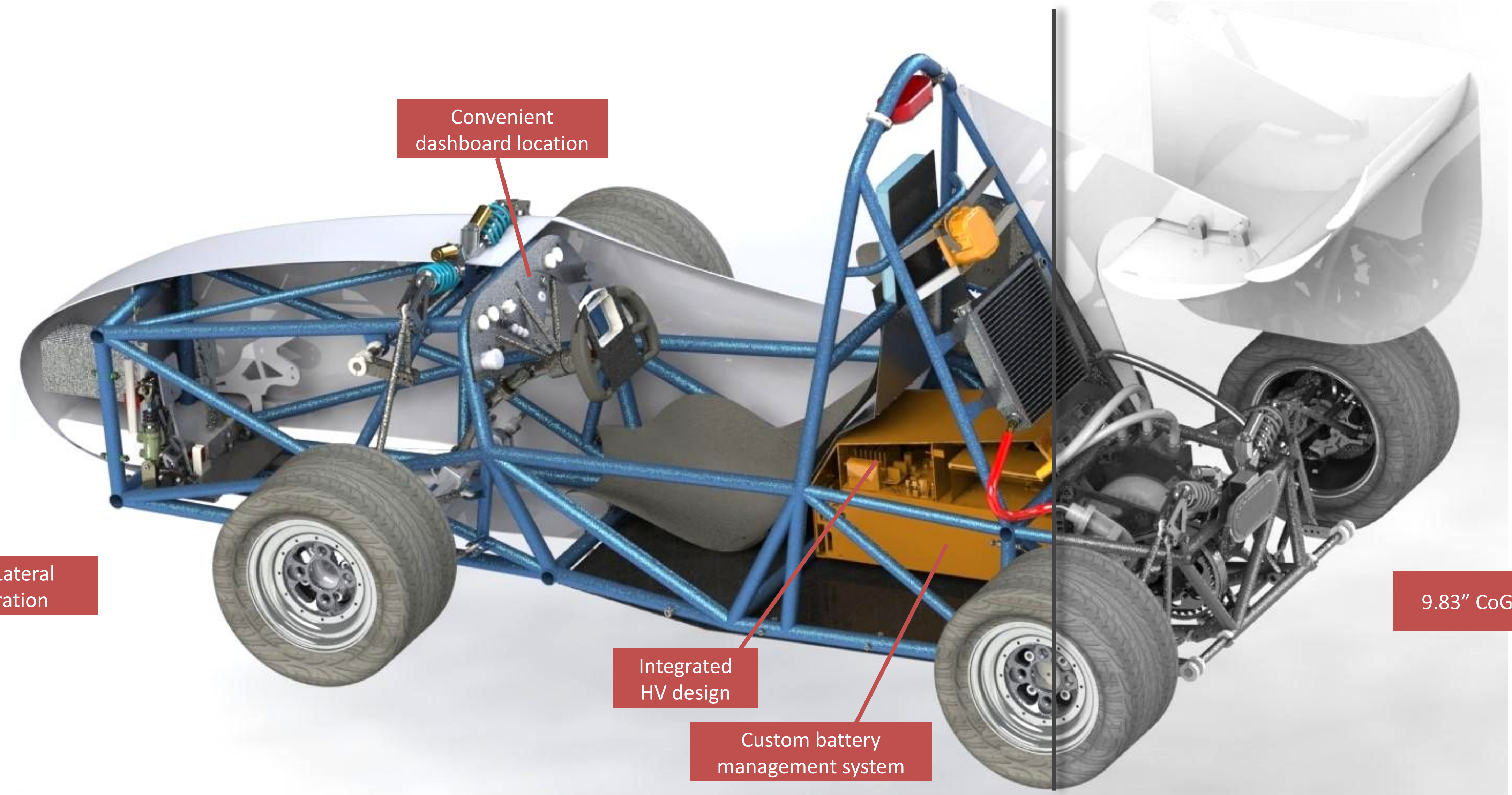
Endurance
Lap time analysis used to determine the average speed that can be used for endurance without batteries running out of energy. **Avg Speed Limit: 91kph**





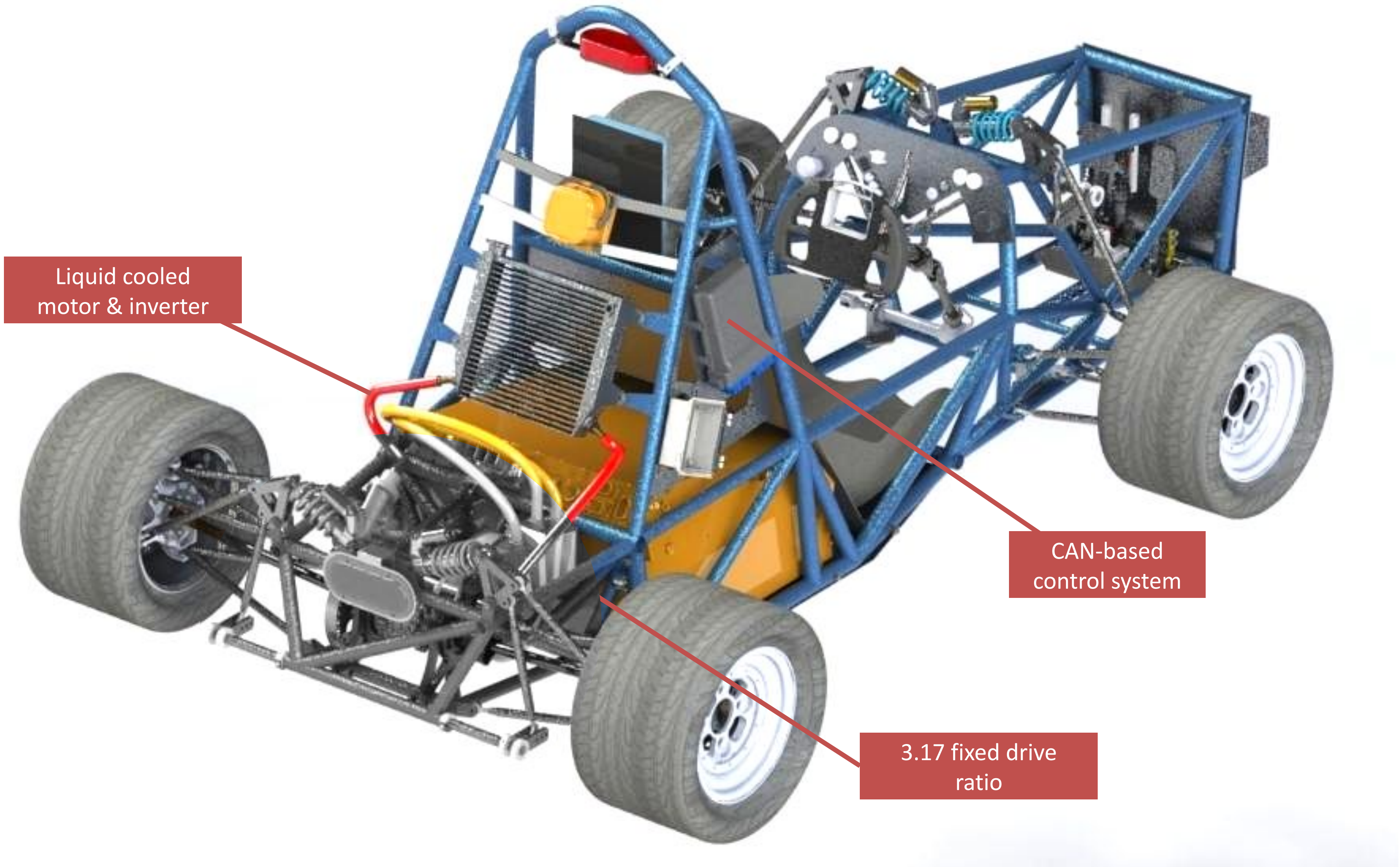


Highlights



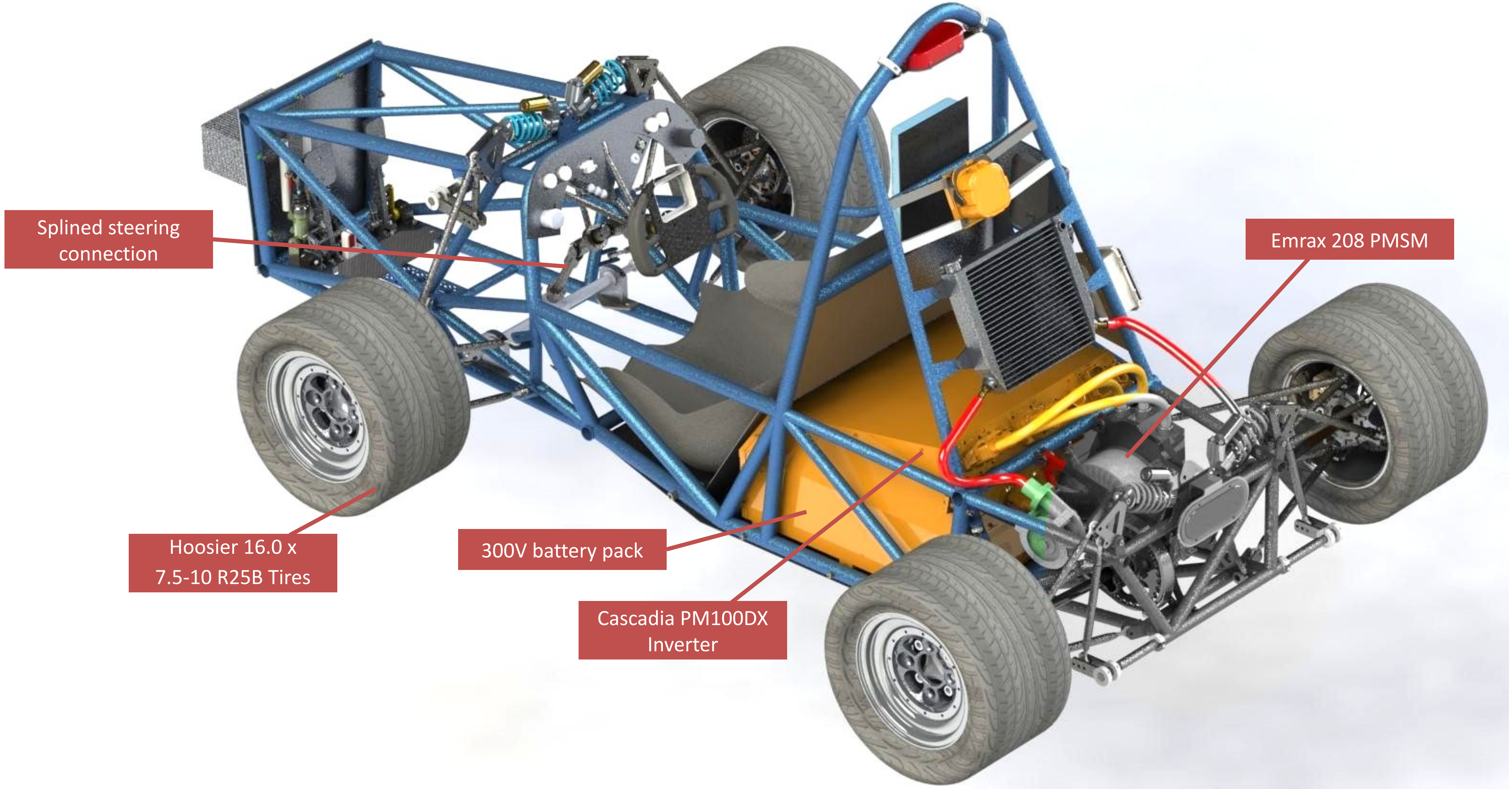
Convenient dashboard location
1.65 G Lateral Acceleration
Integrated HV design
Custom battery management system
9.83” CoG height

Highlights



Liquid cooled motor & inverter
CAN-based control system
3.17 fixed drive ratio

Highlights


Splined steering connection
Emrax 208 PMSM
Hoosier 16.0 x 7.5-10 R25B Tires
300V battery pack
Cascadia PM100DX Inverter

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Systems Management Integration

Team Structure

Bi-weekly System Integration Meetings

System Integration

- Chief Engineers
- Assistant Chief Engineers
- Experienced Team Members

Electrical Systems

EV Powertrain

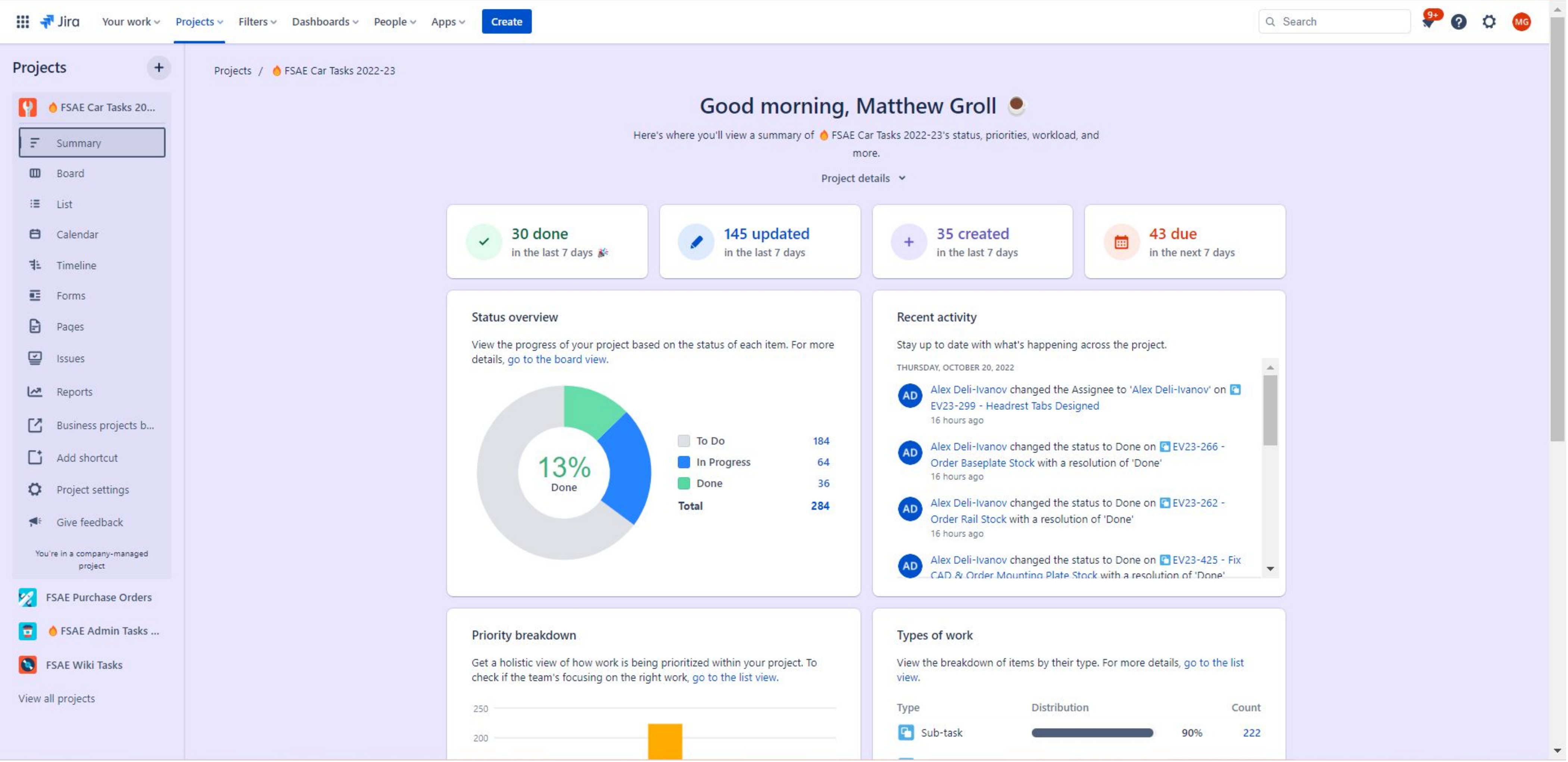
EV Controls

Weekly System Meetings

- **Frame Body Aero**
  - Chassis
  - Body
  - Aero
  - Cooling Airflow
- **Powertrain**
  - Drivetrain
  - Cooling Hardware
  - Accumulator Hardware
- **HV**
  - Tractive System
  - Battery Pack
  - Charging
  - HV Electronics
- **LV**
  - Software
  - Wiring Harness
  - Shutdown System
  - Enclosure boards
  - Telemetry
- **Controls**
  - Pedals
  - Dashboard
  - Ergonomics
  - Steering Control
- **Vehicle Dynamics**
  - Suspension
  - Hubs and Uprights
  - Brakes
  - Steering Geometry

*Tractive system refers to delivery of motor current
*Body refers to the carbon fiber bodywork housing the chassis
*Aero refers to aerodynamic simulation, design, and in future years, downforce components

Jira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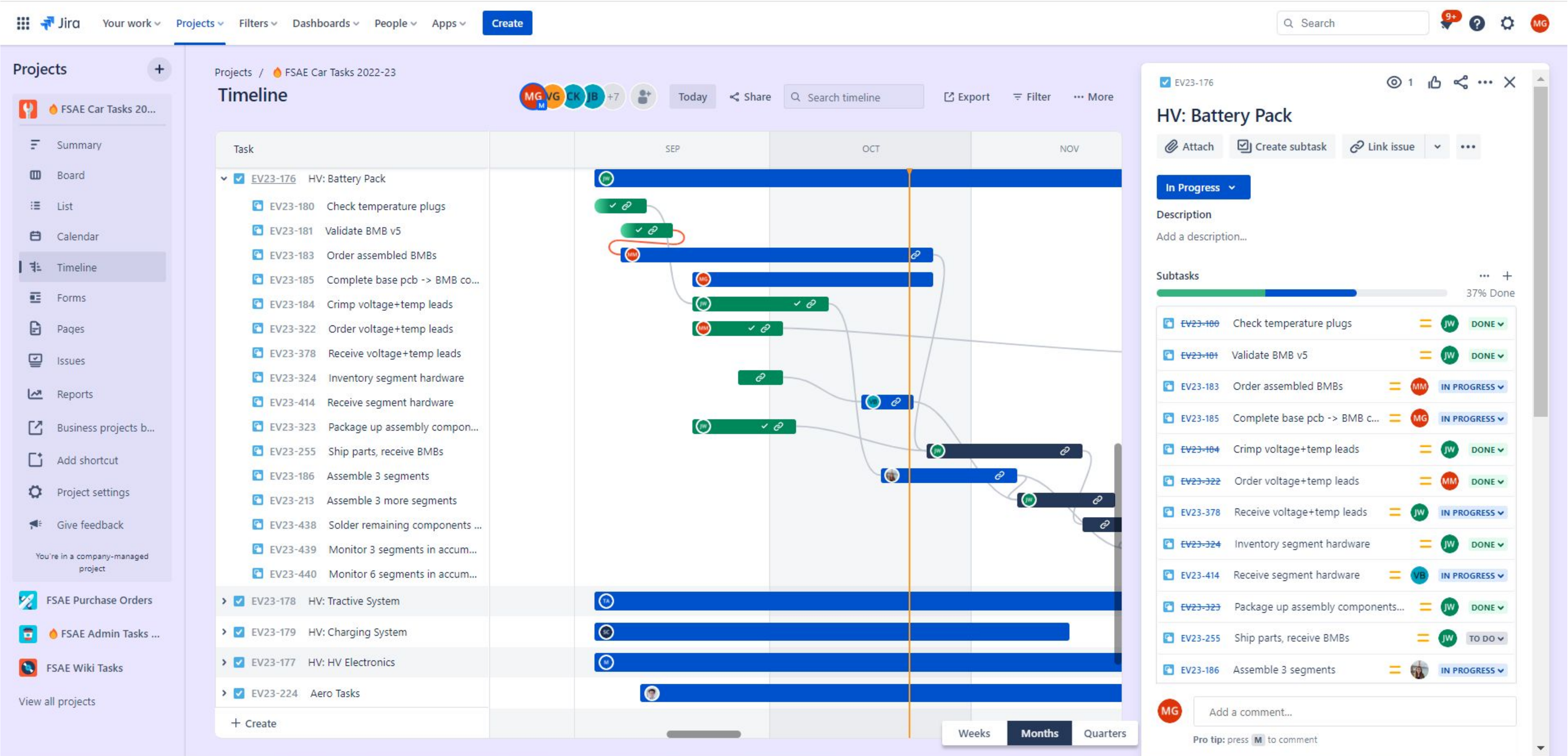
Search
Projects
FSAE Car Tasks 20...
Summary
Board
List
Calendar
Timeline
Forms
Pages
Issues
Reports
Business projects b...
Add shortcut
Project settings
Give feedback
You're in a company-managed project
FSAE Purchase Orders
FSAE Admin Tasks ...
FSAE Wiki Tasks
View all projects
Projects / FSAE Car Tasks 2022-23
Good morning, Matthew Groll
Here's where you'll view a summary of FSAE Car Tasks 2022-23's status, priorities, workload, and more.
Project details
30 done
in the last 7 days
145 updated
in the last 7 days
35 created
in the last 7 days
43 due
in the next 7 days
Status overview
View the progress of your project based on the status of each item. For more details, go to the board view.
13%
Done
To Do 184
In Progress 64
Done 36
Total 284
Recent activity
Stay up to date with what's happening across the project.
THURSDAY, OCTOBER 20, 2022
Alex Deli-Ivanov changed the Assignee to 'Alex Deli-Ivanov' on EV23-299 - Headrest Tabs Designed
16 hours ago
Alex Deli-Ivanov changed the status to Done on EV23-266 - Order Baseplate Stock with a resolution of 'Done'
16 hours ago
Alex Deli-Ivanov changed the status to Done on EV23-262 - Order Rail Stock with a resolution of 'Done'
16 hours ago
Alex Deli-Ivanov changed the status to Done on EV23-425 - Fix CAD & Order Mounting Plate Stock with a resolution of 'Done'
Priority breakdown
Get a holistic view of how work is being prioritized within your project. To check if the team's focusing on the right work, go to the list view.
250
200
Types of work
View the breakdown of items by their type. For more details, go to the list view.
Type
Distribution
Count
Sub-task
90%
222

Jira



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FSAE Car Tasks 20...
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Board
List
Calendar
Timeline
Forms
Pages
Issues
Reports
Business projects b...
Add shortcut
Project settings
Give feedback
You're in a company-managed project
FSAE Purchase Orders
FSAE Admin Tasks ...
FSAE Wiki Tasks
View all projects
Projects / FSAE Car Tasks 2022-23
Timeline
Today
Share
Search timeline
Export
Filter
More
Task
SEP
OCT
NOV
EV23-176 HV: Battery Pack
EV23-180 Check temperature plugs
EV23-181 Validate BMB v5
EV23-183 Order assembled BMBs
EV23-185 Complete base pcb -> BMB co...
EV23-184 Crimp voltage+temp leads
EV23-322 Order voltage+temp leads
EV23-378 Receive voltage+temp leads
EV23-324 Inventory segment hardware
EV23-414 Receive segment hardware
EV23-323 Package up assembly compon...
EV23-255 Ship parts, receive BMBs
EV23-186 Assemble 3 segments
EV23-213 Assemble 3 more segments
EV23-438 Solder remaining components ...
EV23-439 Monitor 3 segments in accum...
EV23-440 Monitor 6 segments in accum...
EV23-178 HV: Tractive System
EV23-179 HV: Charging System
EV23-177 HV: HV Electronics
EV23-224 Aero Tasks
Create
Weeks
Months
Quarters
EV23-176
HV: Battery Pack
Attach
Create subtask
Link issue
In Progress
Description
Add a description...
Subtasks
37% Done
EV23-180 Check temperature plugs DONE
EV23-181 Validate BMB v5 DONE
EV23-183 Order assembled BMBs IN PROGRESS
EV23-185 Complete base pcb -> BMB c... IN PROGRESS
EV23-184 Crimp voltage+temp leads DONE
EV23-322 Order voltage+temp leads DONE
EV23-378 Receive voltage+temp leads IN PROGRESS
EV23-324 Inventory segment hardware DONE
EV23-414 Receive segment hardware IN PROGRESS
EV23-323 Package up assembly components... DONE
EV23-255 Ship parts, receive BMBs TO DO
EV23-186 Assemble 3 segments IN PROGRESS
Add a comment...
Pro tip: press M to comment

Testing

Lamont Doherty Earth Observatory

Testing 4/30/22

FORMULA SAE

Suspension

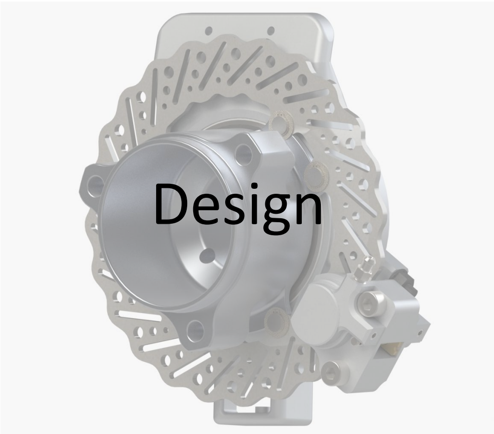
Presenter Info

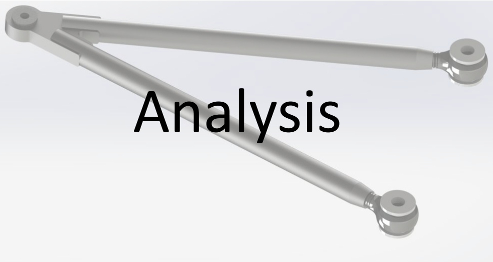
Section:	Suspension
Subteam:	Dynamics
System:	Suspension
System lead:	Sakib Ahmed
Subteam lead:	Jannie Zhong
Car:	eCFR-23

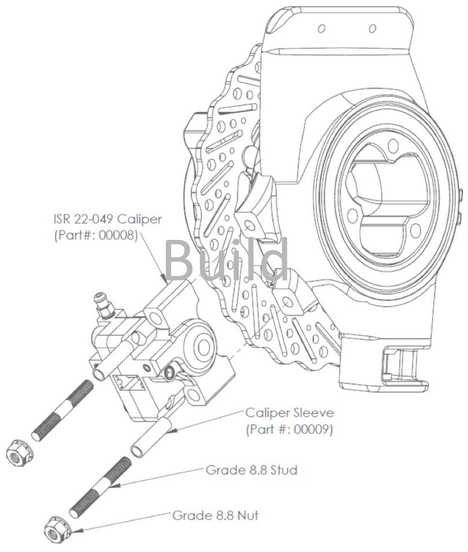
System Overview

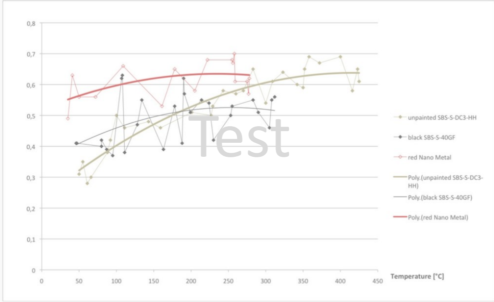
Suspension Overview

Suspension changes were a big portion of the rear redesign push that we made in the last couple months. We've designed the points, run our analysis, and are now working to build out the full CAD.



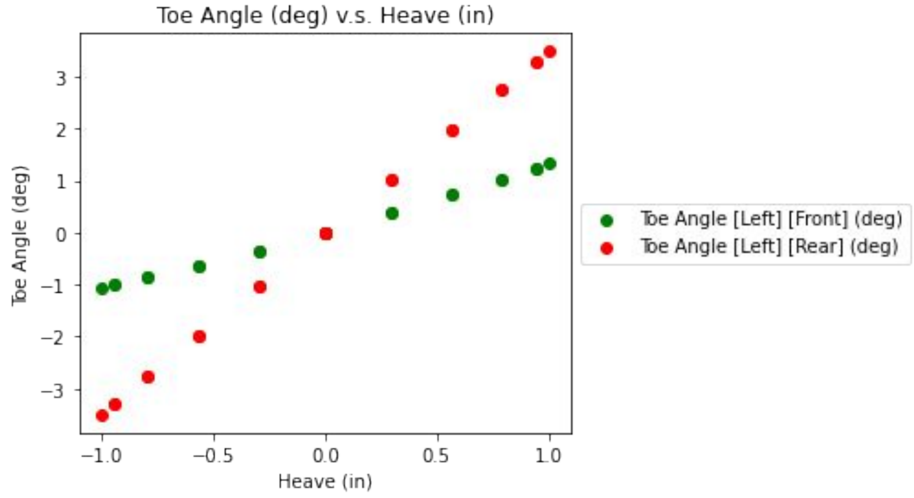


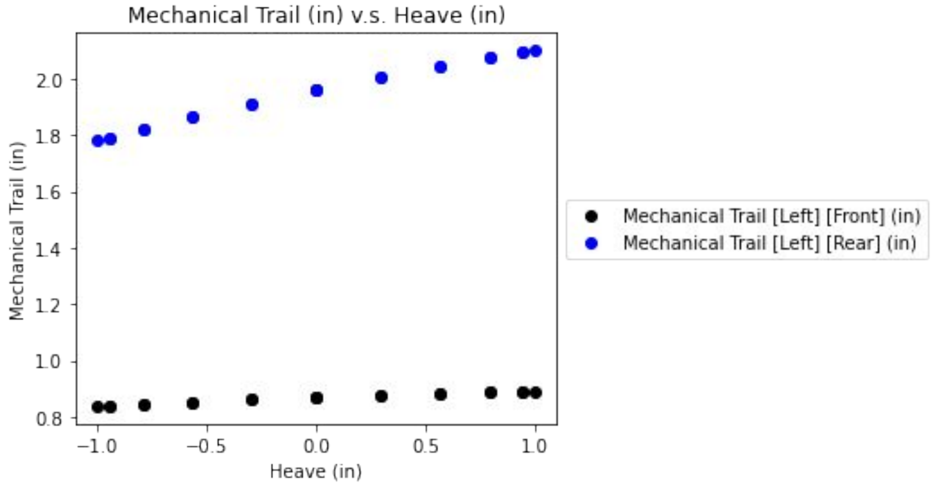


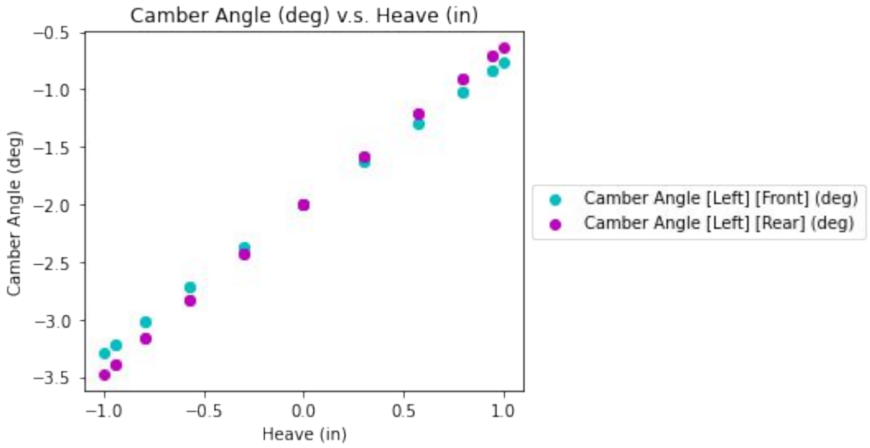


Last year:

- We had a car that had significant dynamic toe-in
- The non-starters:

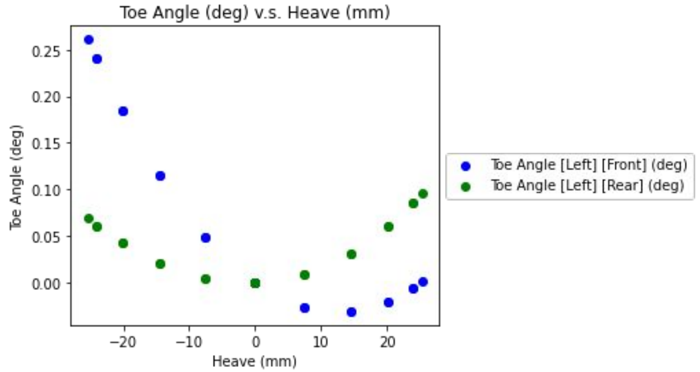


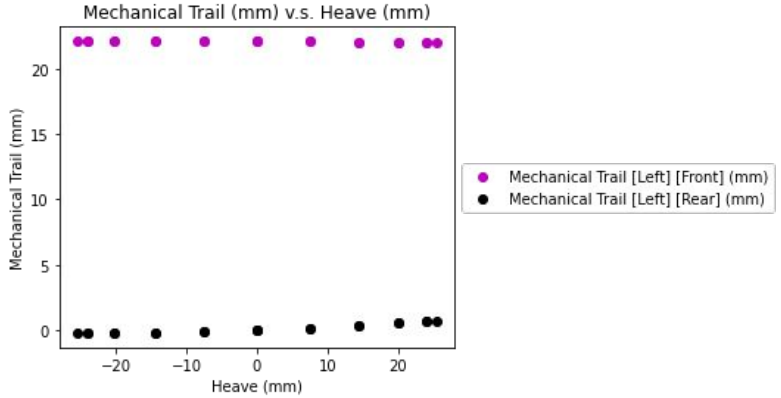


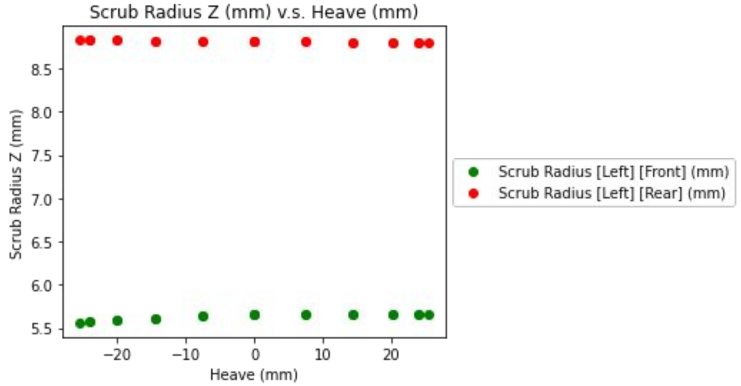


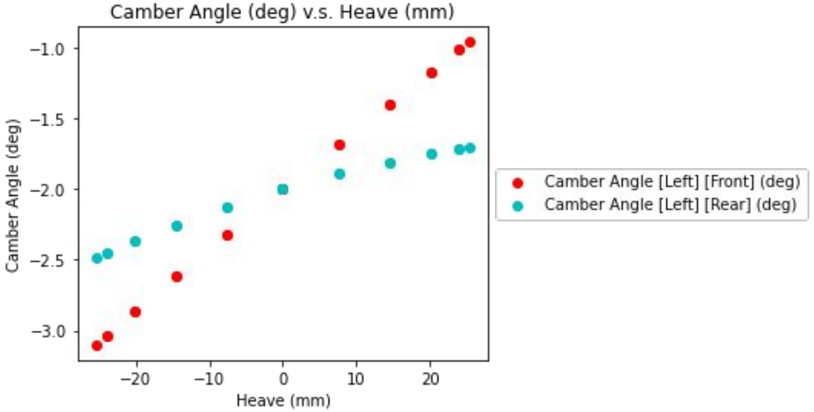
This year:

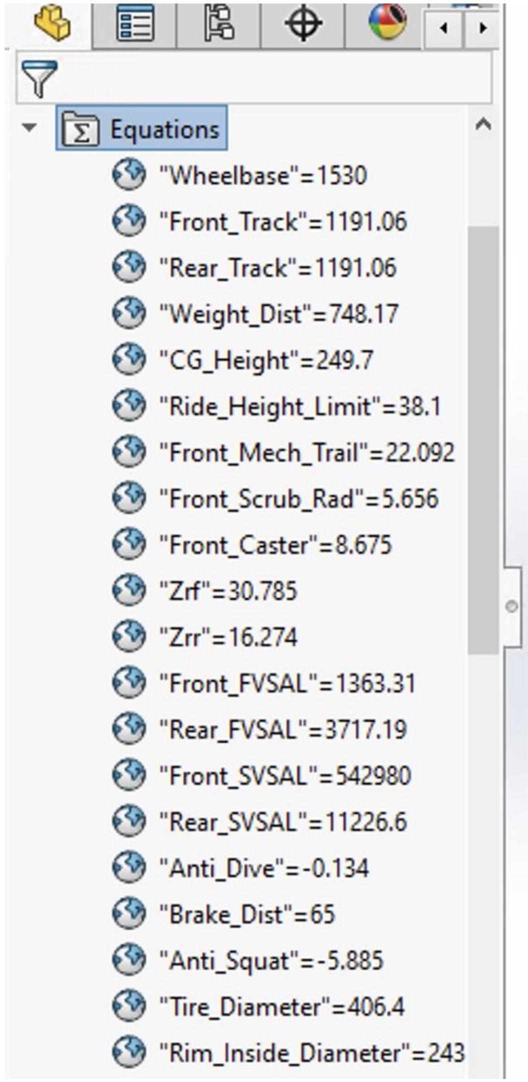
- Design something that has reasonable kinematics (OptK)
- Fits the packaging constraints of the chassis





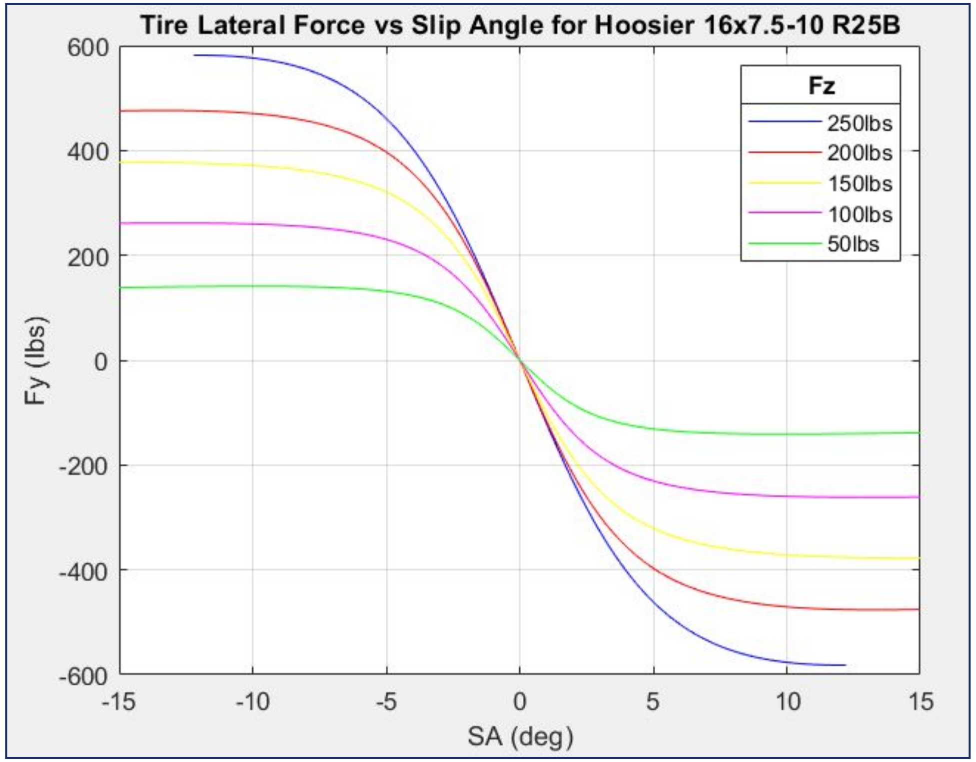






Analysis: Suspension Linkage Forces

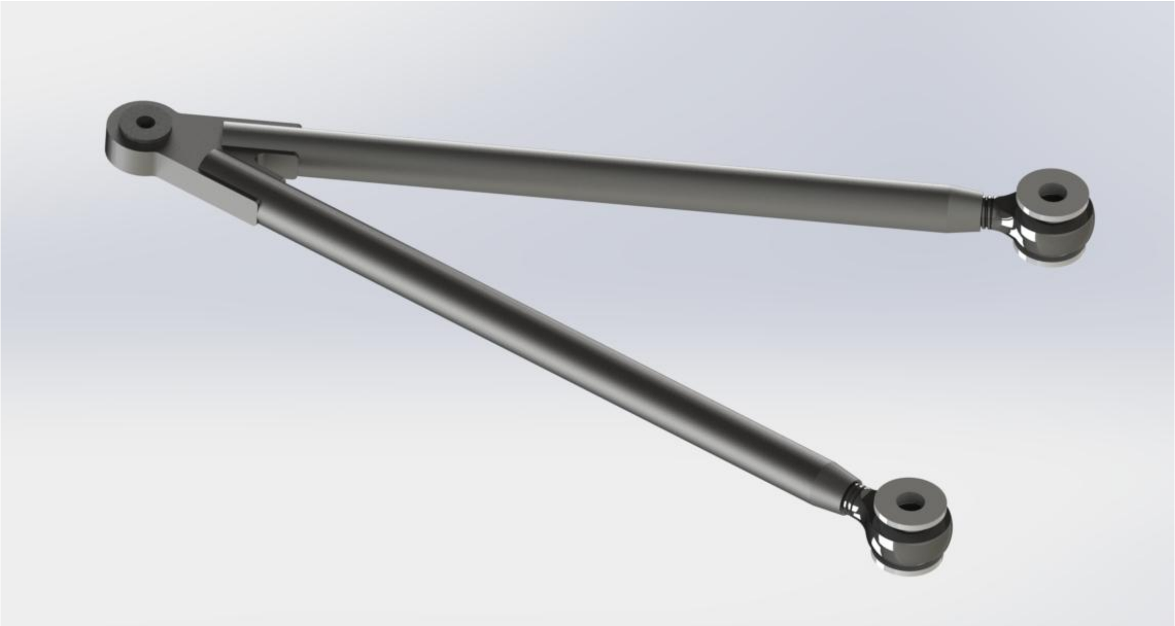
- Forces at the tire contact patch were obtained from Tire Test Consortium (TTC).
- Maximum forces in the suspension members were calculated in three conditions using OptimumKinematics Forces Module:
  - Left-hand turn at 1.4g
  - Acceleration at 1g
  - 5g bump
- Euler's buckling equation was used to determine the minimum tube diameters
- Margin of safety (for highest load-carrying member) = 2.0



	Lower A-Arm To Chassis (Fore) - Force [Rear Right] (N)	Lower A-Arm To Chassis (Aft) - Force [Rear Right] (N)	Upper A-Arm To Chassis (Fore) - Force [Rear Right] (N)	Upper A-Arm To Chassis (Aft) - Force [Rear Right] (N)	Tierod To Chassis - Force [Rear Right] (N)	Push/Pull To Rocker - Force [Rear Right] (N)
Maximum Value	3,800.592	3,268.360	1,337.469	656.867	241.701	965.303

CAD (in progress)

- Suspension tabs have been added to chassis CAD
- Working on improving our A-arm design to reduce manufacturing steps and time



Next Steps

Next Steps:

Analysis:

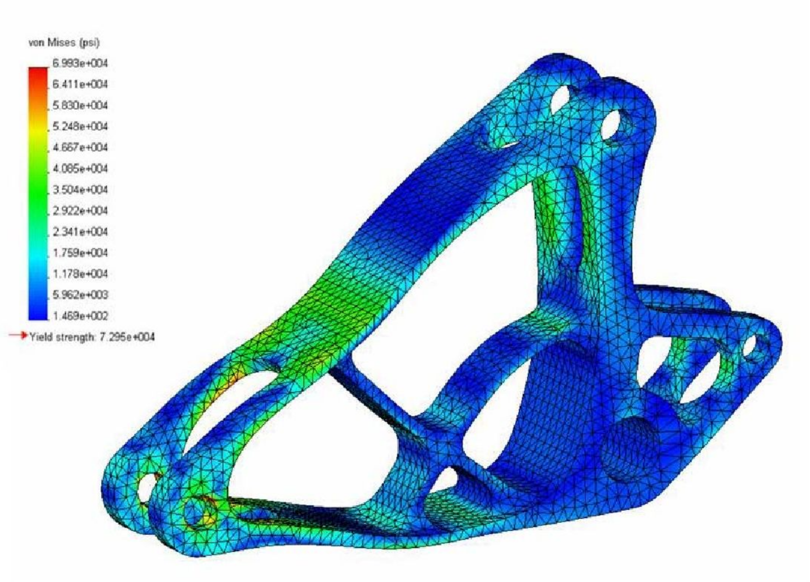
- Finish full suspension CAD assembly
- Design + optimize rocker geometry

Build:

- Test the new a-arm manufacturing method + manufacture all suspension linkages

Test:

- sensors:
    - linear potentiometers, wheel speed sensors
- just drive the car and tune to see how it feels on the track



Steering

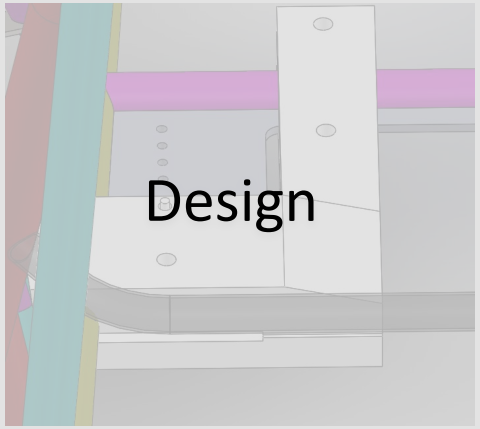
Presenter Info

Section:	Suspension
Subteam:	Dynamics
System:	Steering
System lead:	Cecil Kumah
Subteam lead:	Jannie Zhong
Car:	eCFR-23

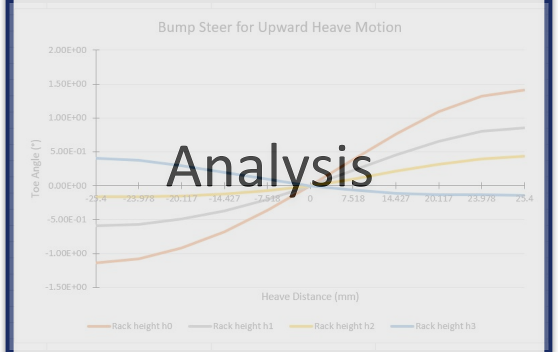
System Overview

Steering Overview

The steering column was designed last year, but the mounting system was found to have issues. Our new design addresses these issues.



Design



Analysis

Build

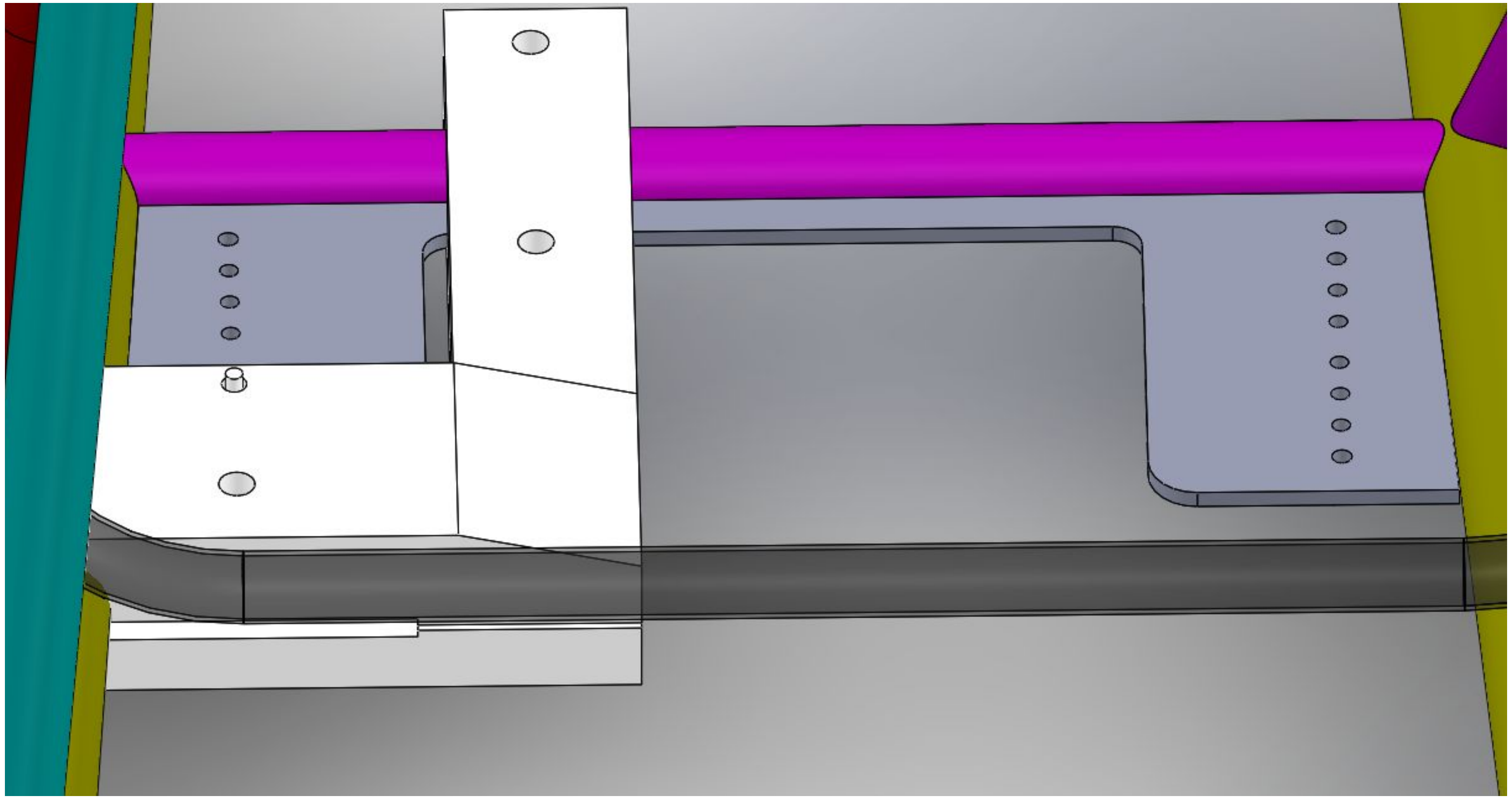
Test

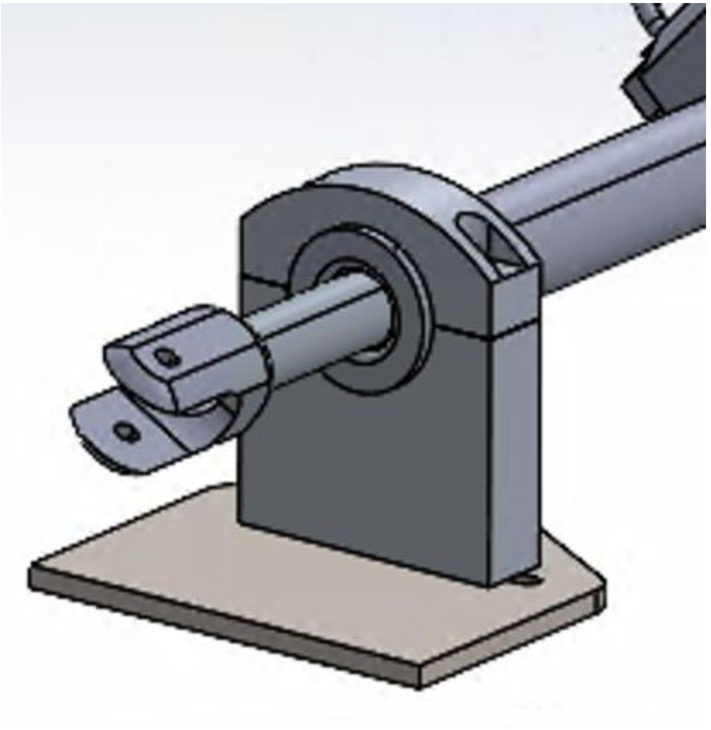
Last year:

- tabs were welded such that the steering rack didn't fit
  - tabs tilted up, placement was incorrect
  - had to dremel slots to get the steering rack mounted

This year:

- one unibody piece across the whole rack
  - ensures consistent spacing for the rack
- in the middle of the chassis tubes (vertically)
  - should make vertical jigging easier

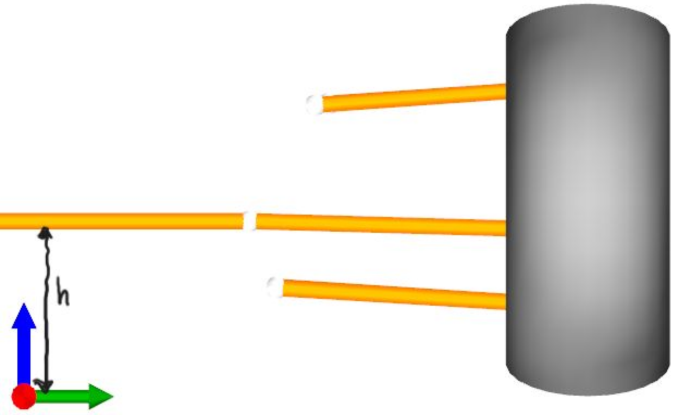


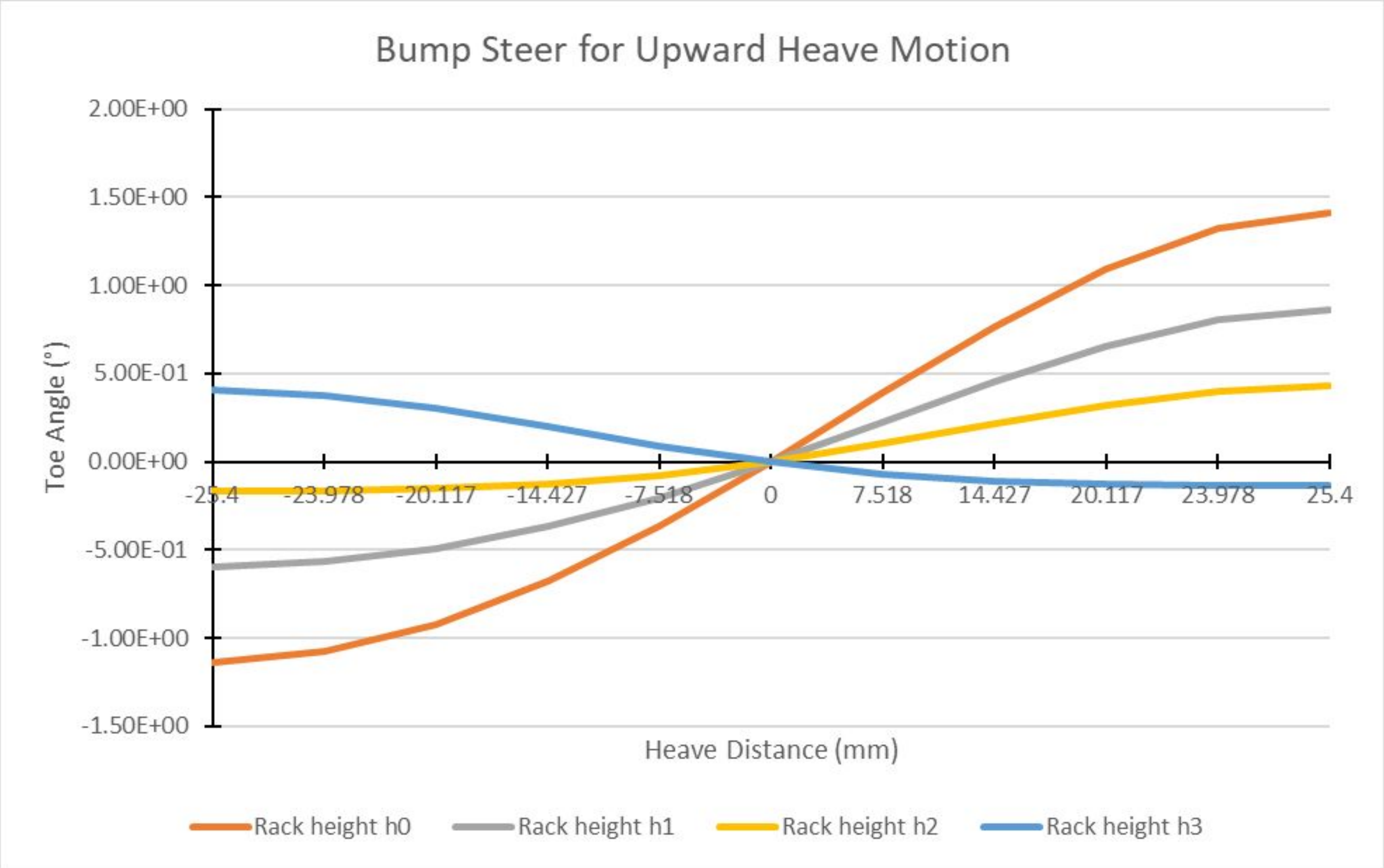


Analysis: Optimization of Bump Steer in Optimum Kinematics

h0: current rack height
h3>h2>h1>h0

Blue curve (h3) ideal for slight toe out in heave





Next Steps:

Build:

- Machine clamps to greater precision (were not accurate last year)

Test:

- bump steer gauge to adjust for bump steer
  - will have spacers to make both lateral and vertical adjustment possible

Chassis

Presenter Info

Section:	Frame Body Aero
Subteam:	Frame
System:	Chassis
System lead:	Juan Zuniga
Team member:	Fabio
Subteam lead:	Juan Zuniga
Car:	eCFR-23

System Overview

The following areas are expected to be discussed during the breakout sessions. Also, reference the score sheet for expected content.

I. <u>Design</u>

II. <u>Analysis</u>

Failure modes, FEA/ANSYS results

III. <u>Build</u>

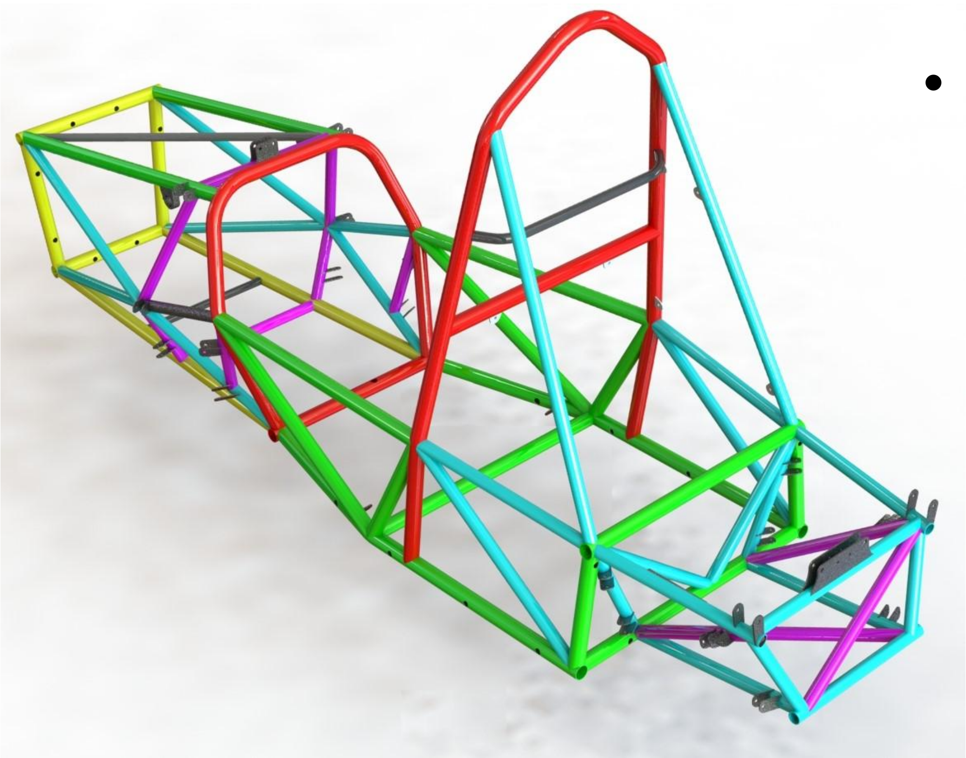
Build

IV. <u>Test</u>

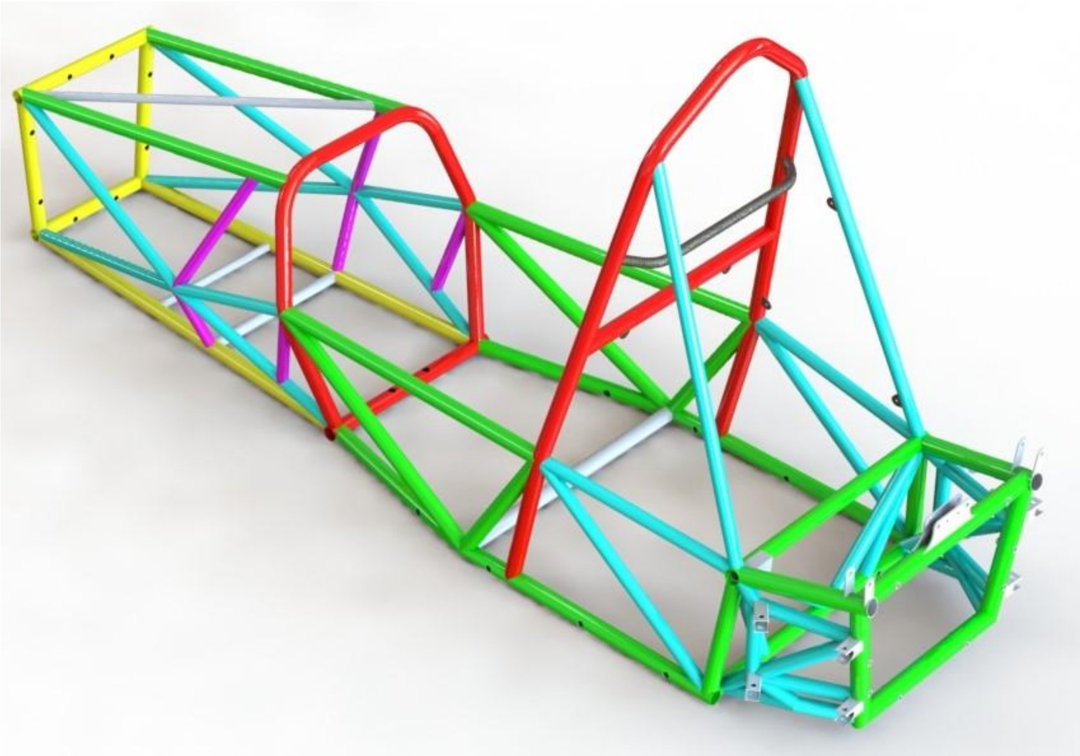
Test

Design Overview, Concept

Design 1



- The chassis is the **exoskeleton of the car to which all over components are mounted**



- Changes year to year include the entire rear clip of the car, to accommodate new suspension points, new drivetrain packaging, and location of the differential

- It is required to have rear protection for the electrical components of the car, and be triangulated at every node.

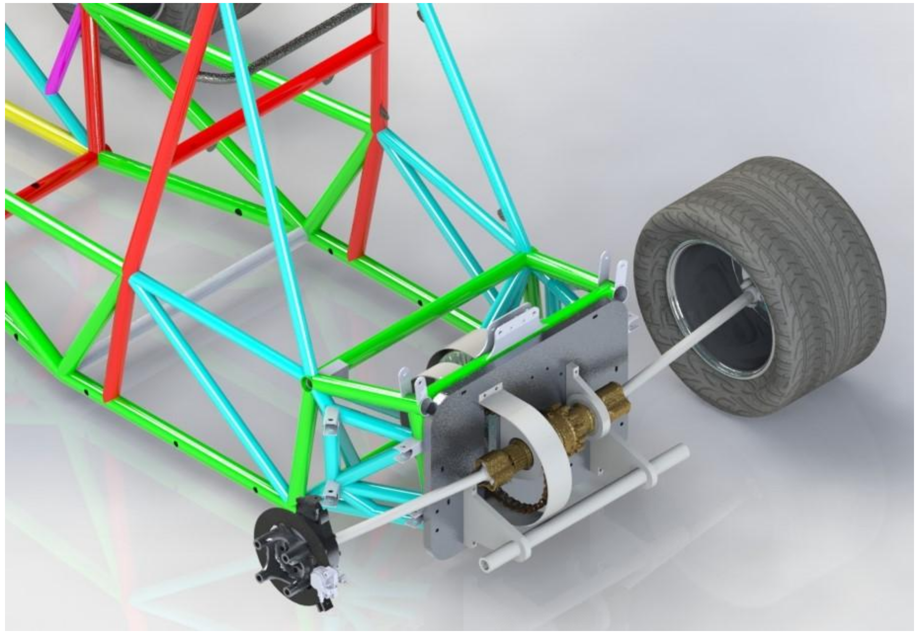
We had to meet all of the rules in the Structural and Chassis Section of the rules. New changes were made specifically with F.11.2.2 in mind.

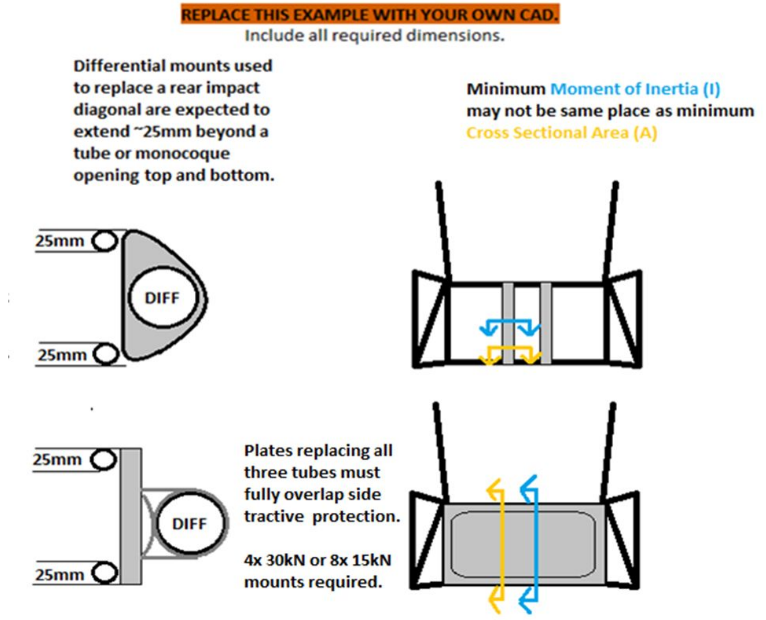
- This deals with Rear Impact Protection which lead to the decision to have a hanging differential mounting plate

We had the choice of using different material to make our frame. We choose **from:**

4130 Steel, Aluminum, Titanium and Magnesium, or Carbon Fiber Composites

1.25 x 0.083 in
1.25 x 0.065 in
1.25 x 0.049 in
1 x 0.065 in
1 x 0.049 in
Non Structural

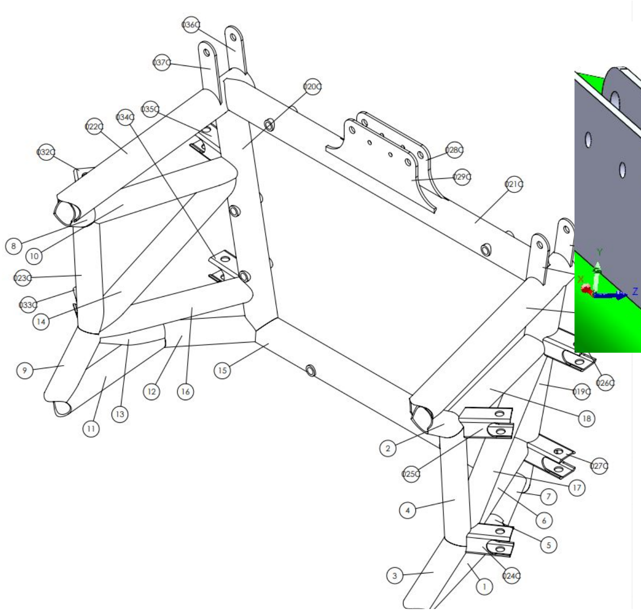


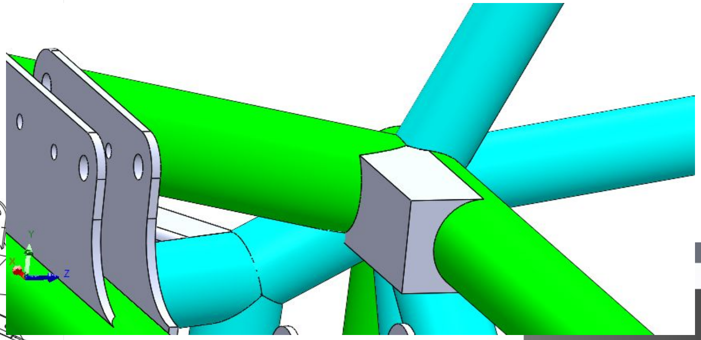


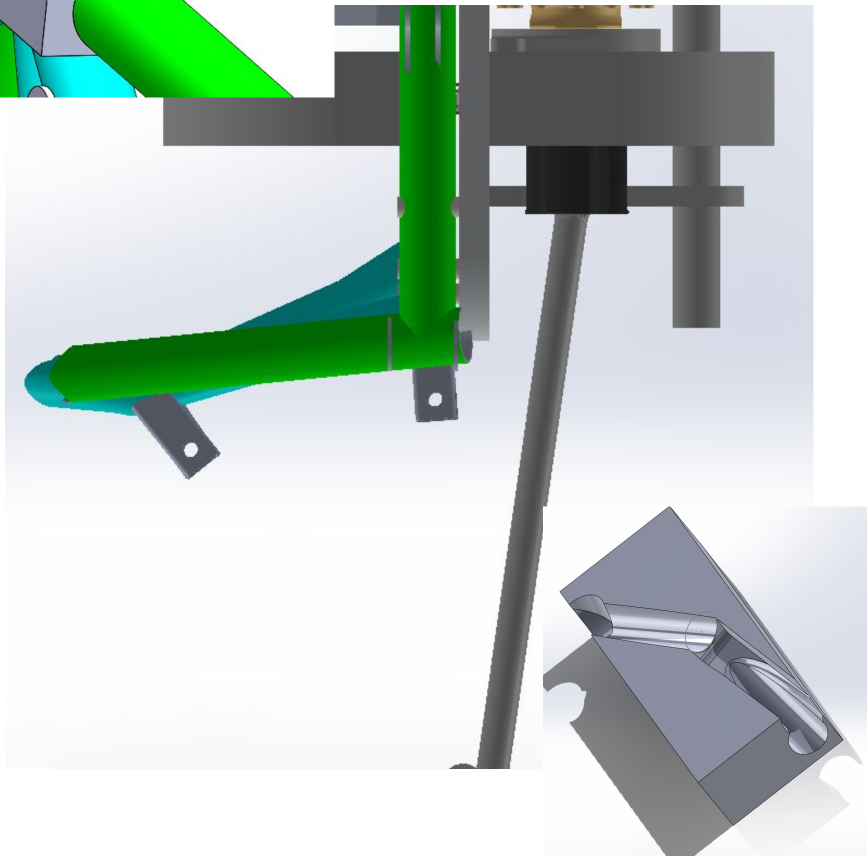
Design Overview

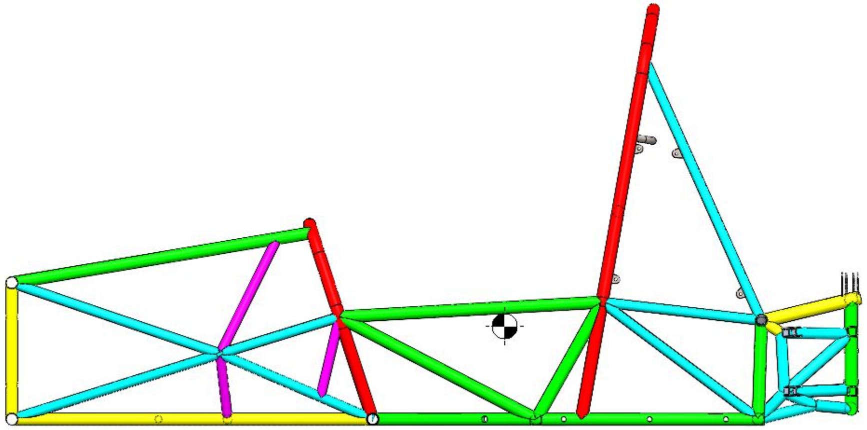
Goals: Lower chassis CG as much as possible and prioritize torsional stiffness in order to realize cornering gains.

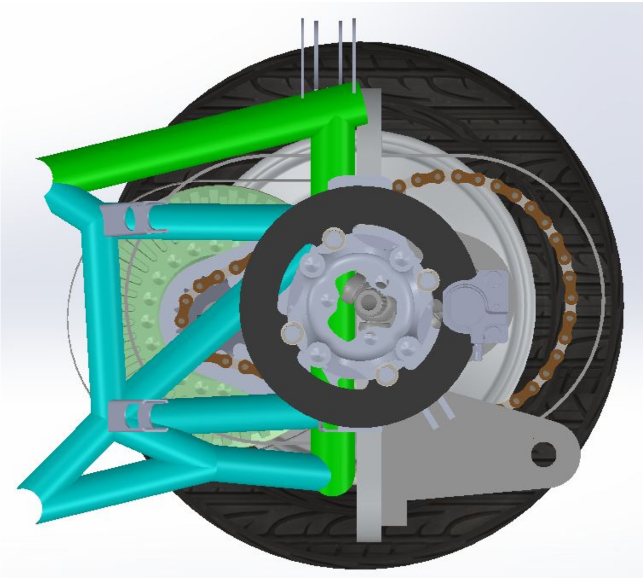
Mass = 82.36 pounds
Number of tubes: 87
Number of tabs: 30











IV: Test

Setup:

- Damper/spring/tires -> solid members
- Car placed on corner scales
- Rear axle incrementally twisted
  - Shims added to right rear plate
- Calculation
  - Rear axle distance measured
  - Load on each corner scale measured
  - Torsional stiffness calculated

Might try to valid it the way Cooper Union Way

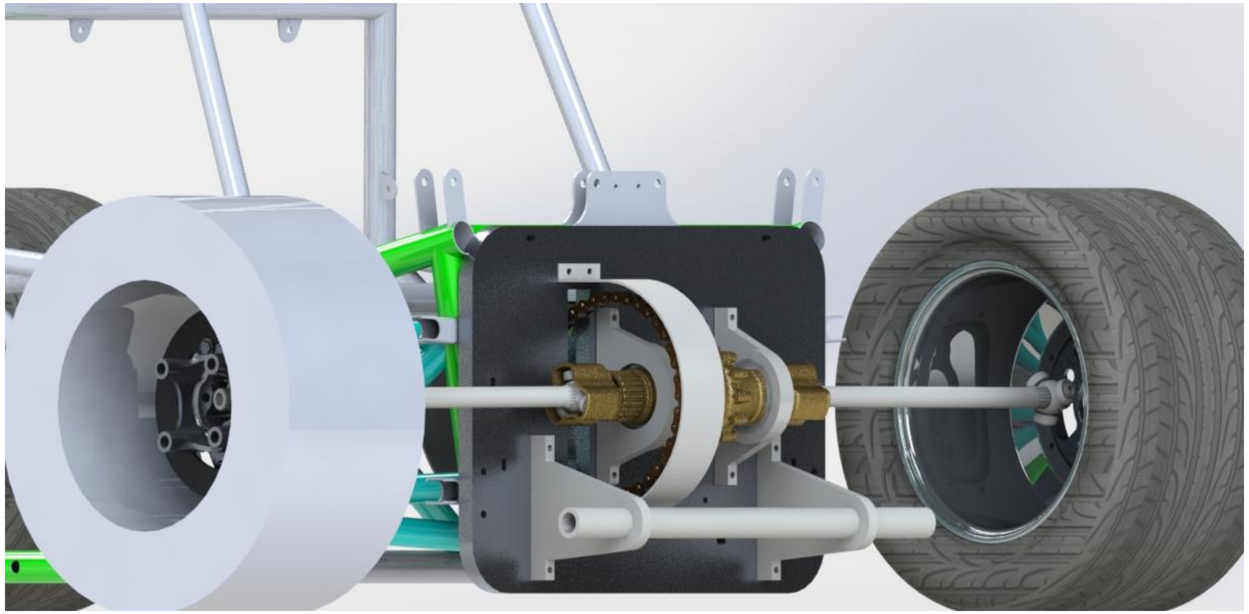
We plan to run a torsional stiffness test once we have a full chassis in the shop in mid December.

Powertrain

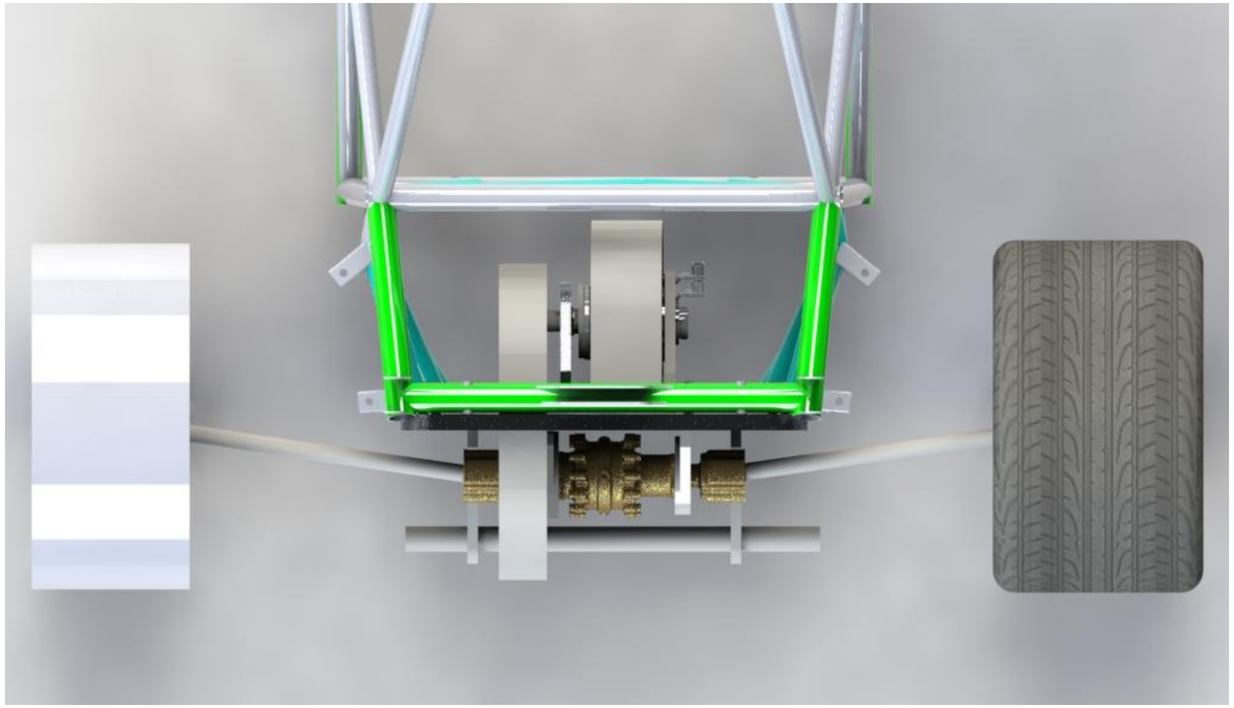
Presenter Info

Section:	Tractive/Drive/Recovery System
Subteam:	Powertrain
System:	Drivetrain
Presenter:	Dairon Estevez
System lead:	Valentina Gonzalez
Subteam lead:	Dairon Estevez
Car:	eCFR-23

Current Packaging Images



Isometric Rear View

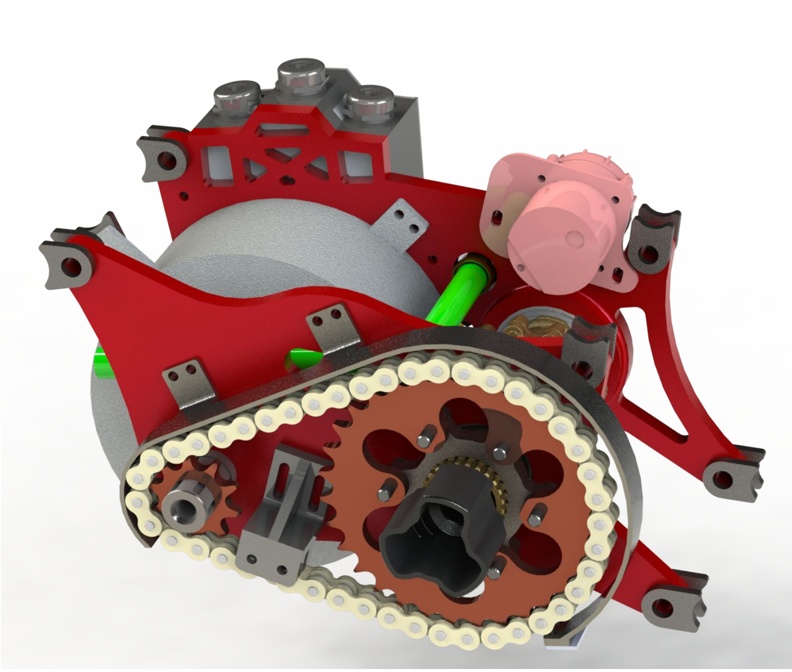


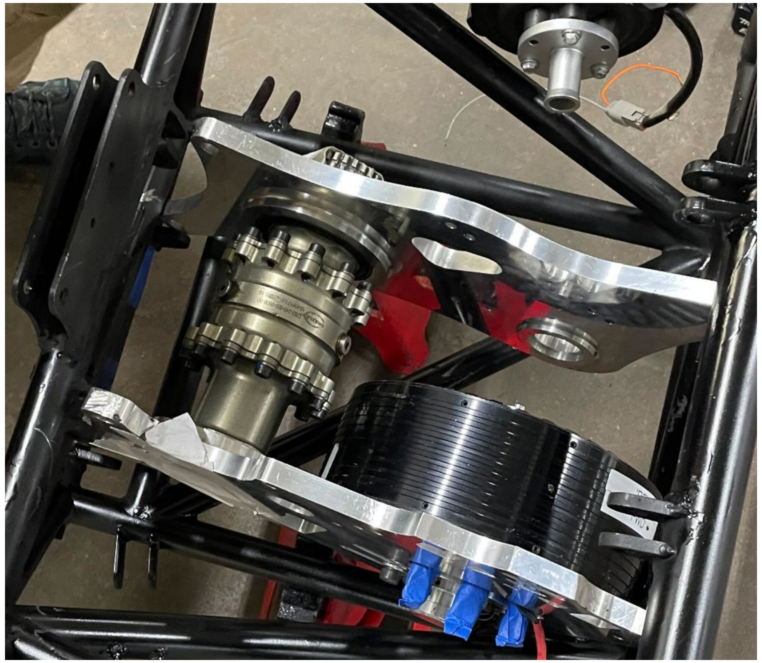
Top View

Previous Design

- The drivetrain system includes an Emrax 208 motor, 2 fixed chain-driven gears, as well as a Drexler Salisbury differential.

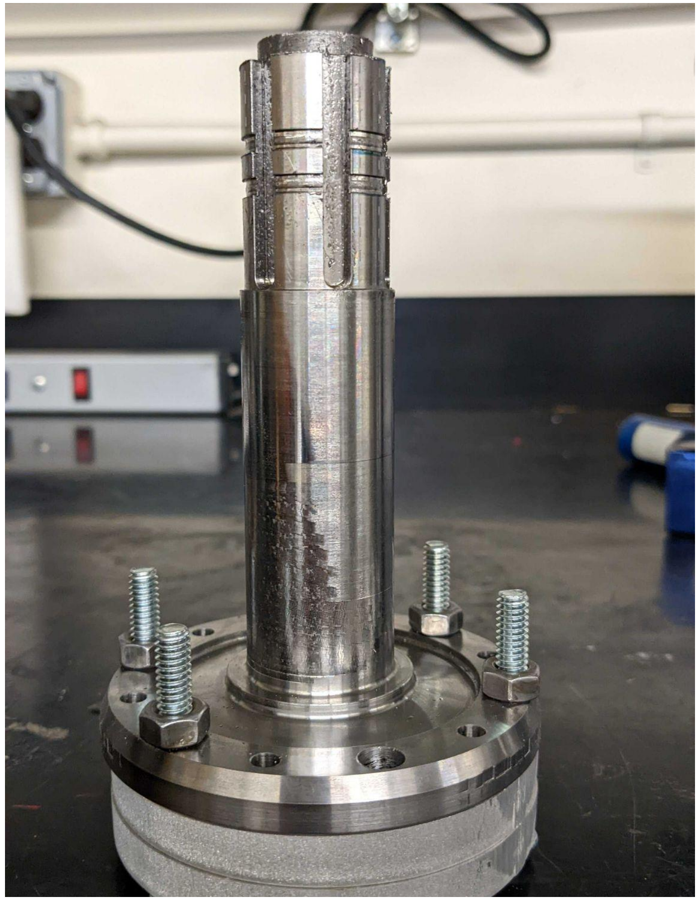
- Design goals included:
  - Maximizing drivetrain efficiency
  - Striking a good balance between acceleration & top speed
  - Ensuring structural rigidity to withstand the forces from both the rotating motor and the differential.

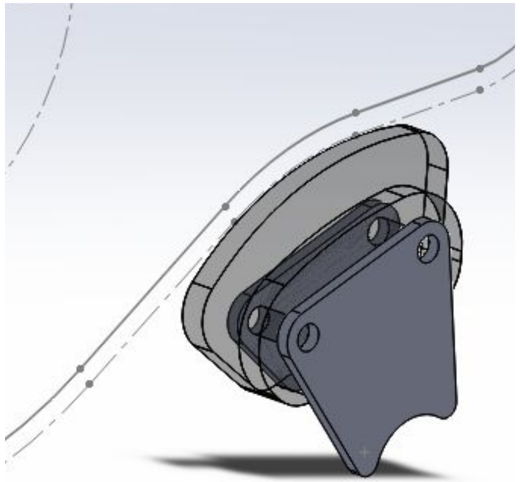




Problems with Previous Design

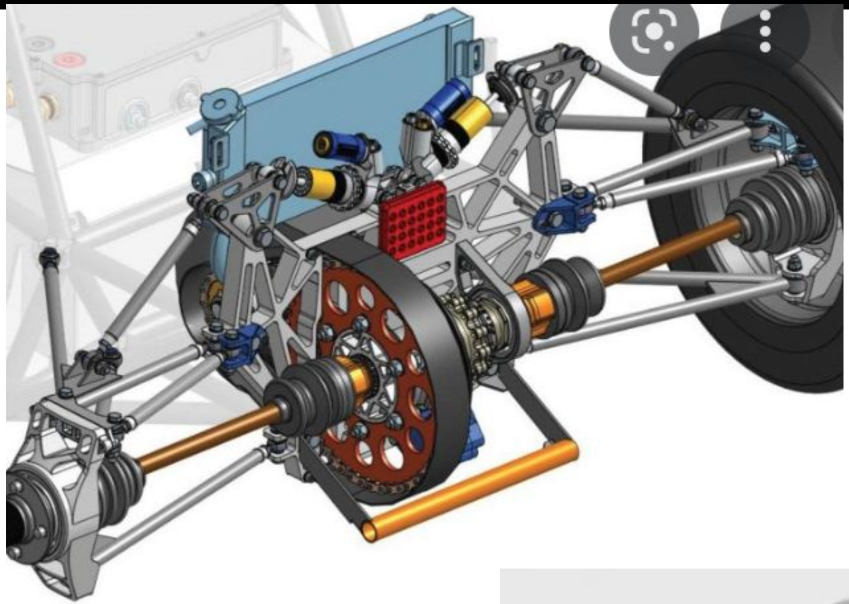
- Plates are not properly aligned, a smaller bolt is needed on one of the mounting points
- Motor shaft issues:
  - Does not align with plate hole
  - Does not match the bearing size in the plate
  - Small sprocket mounting unreliable and difficult
- Both sprockets manufactured in house and performance is uncertain
- Chain tensioning method is destructive and unreliable

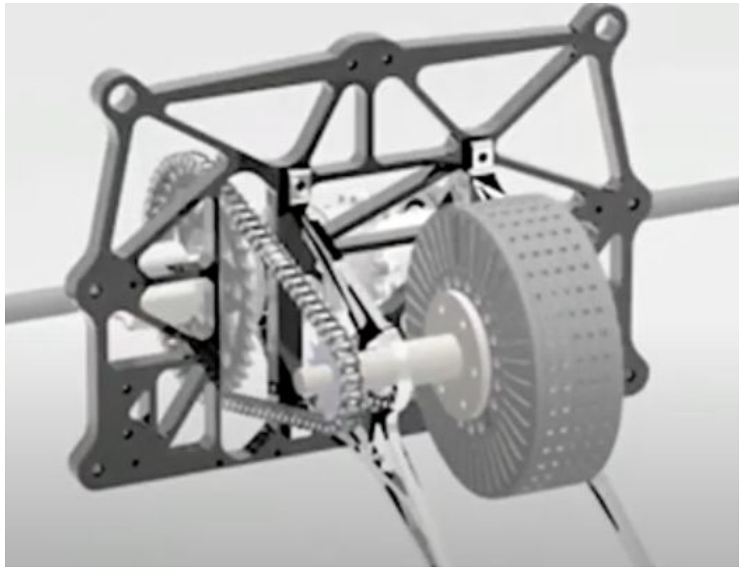




New Design Considerations

- Inspiration images for cross member concept
- Can be assembled outside of the chassis
- Motor and differential can be assembled separately
  - Prevents resolver damage when installing motor
- Adjustable tensioning
- Eliminate alignment issues with separate mounting and slots

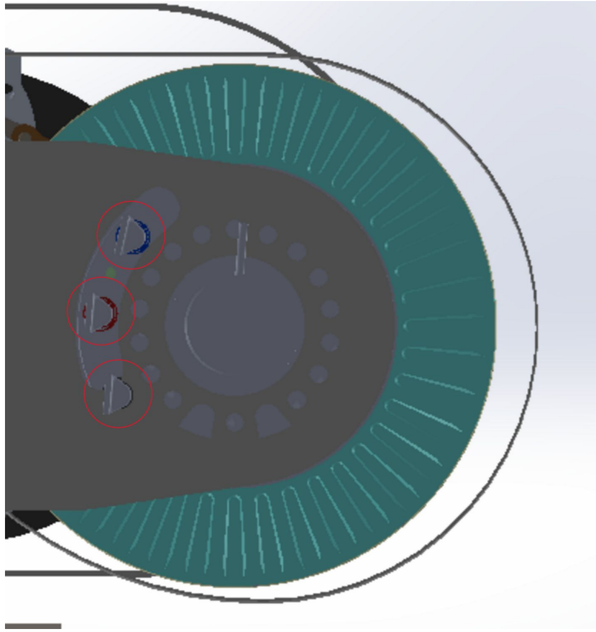


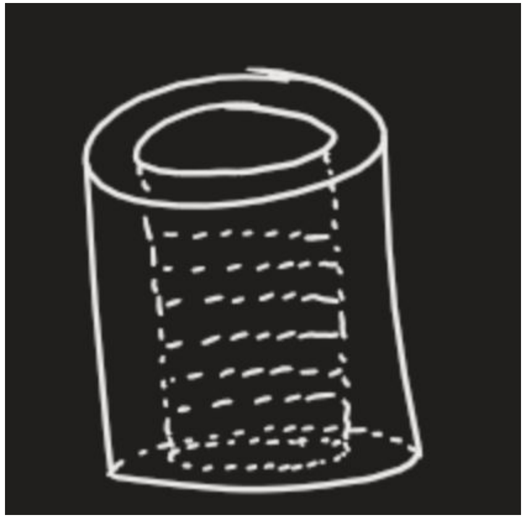


HV Wire Routing

- Previous design: insulating routing plastic box shielded with metal
  - Hard to assembly
  - Packaging/Spacing issues

- Current consideration: threaded cylindrical adapter for each terminal
  - threaded into motor mount
  - cable glands threaded into it
  - nylon
  - easier assembly,less space





FORMULA SAE®

Pedals

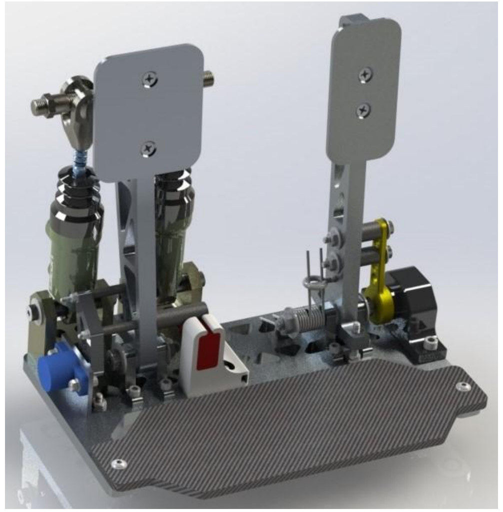
Presenter Info

Section:	Cockpit/Controls/ Brakes/Safety
Subteam:	Controls
System:	Pedals
System lead:	Jillian Busetto
Subteam lead:	Alex Deli-Ivanov
Car:	eCFR-23

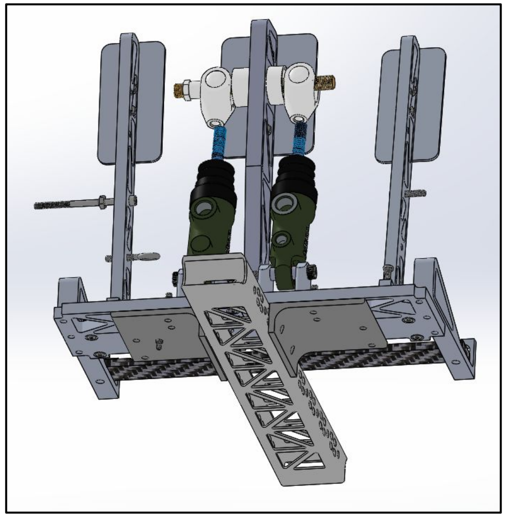
System Overview

We will go through the design rules, what issues we had with the previous design and how we are working around those issues to create a fully adjustable and compliant pedal box.

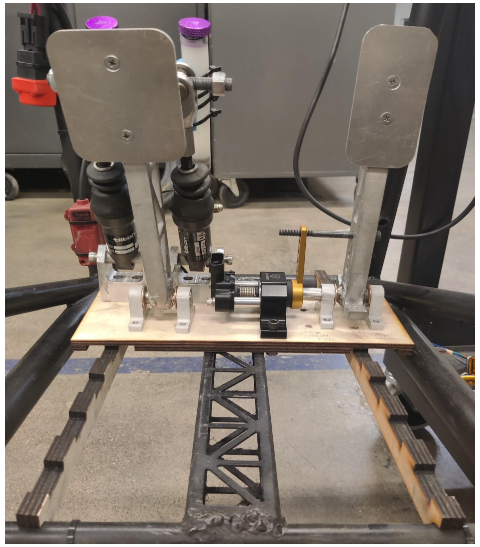
I. Design Specifications



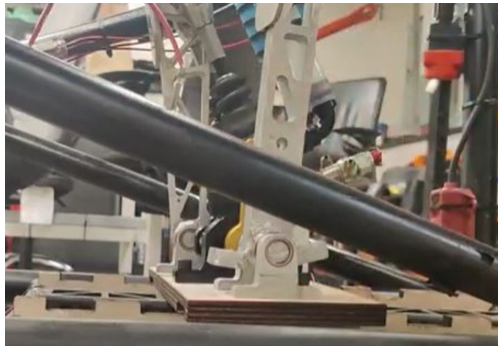
II. Previous Design



III. Build



IV. Test



I. Design

Materials

- 7075 aluminum
- Carbon fibre heel rest
- EV West Billet Al APPS Sensor
- Brake System Encoder (BSE)
- Break Over Travel Switch (BOTS)

Travel Range

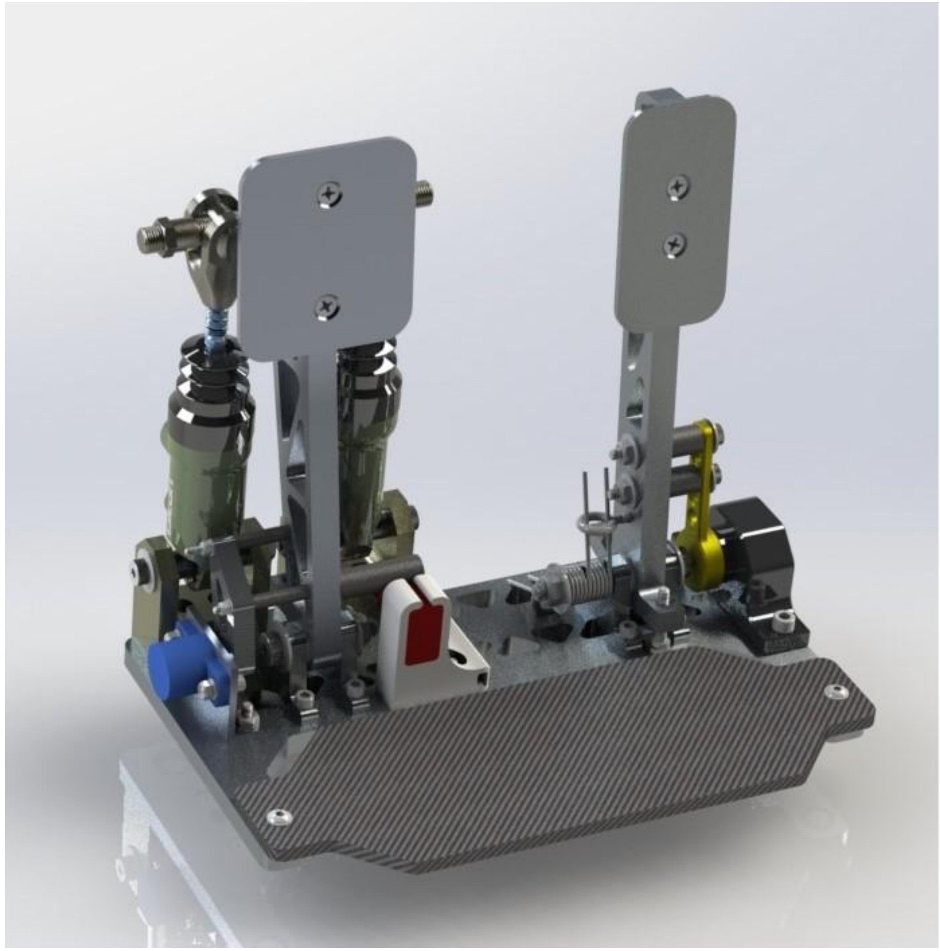
Bias Bar:	5”
Pedal box:	12”

Misc

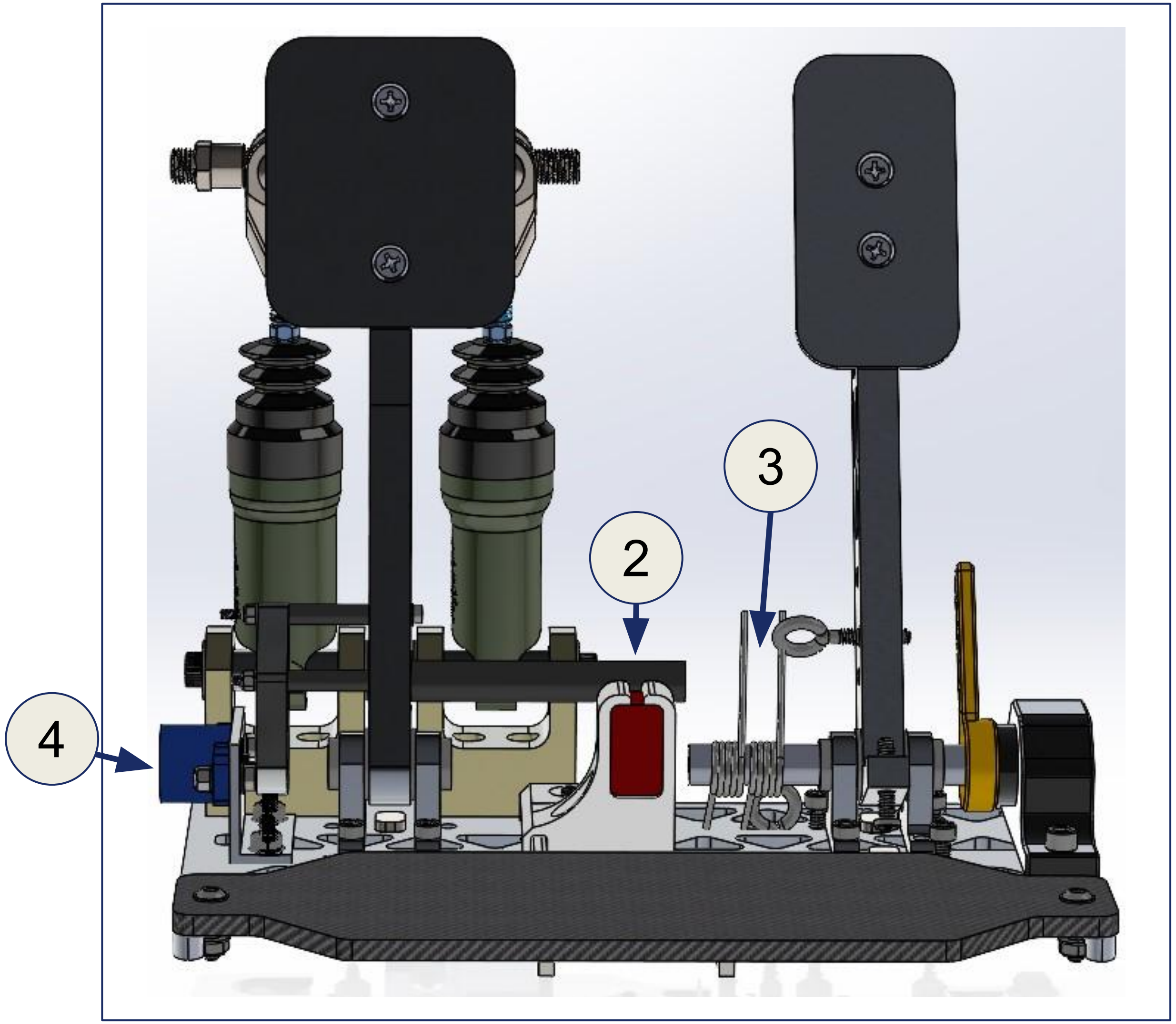
- Pedal Ratio: 4.7

Design Goals

- Adjustability
- Accessibility/Ergonomics
- Rules Compliance



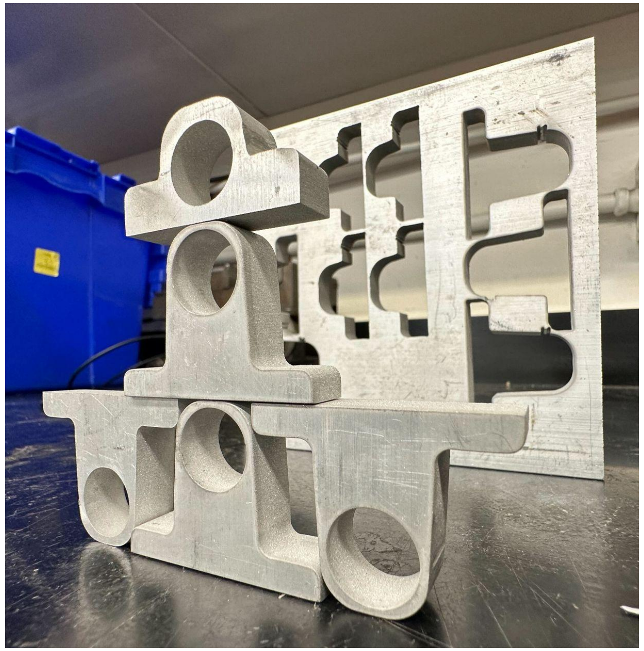
1. Adjustability
   a. Percy Template for 95th percentile male
2. BOTS
   a. Braking in case of failure
3. BSE
   a. Measure brake pedal position
4. Springs on throttle pedal (2)
   a. Return to pedal position
5. Withstand 2000N

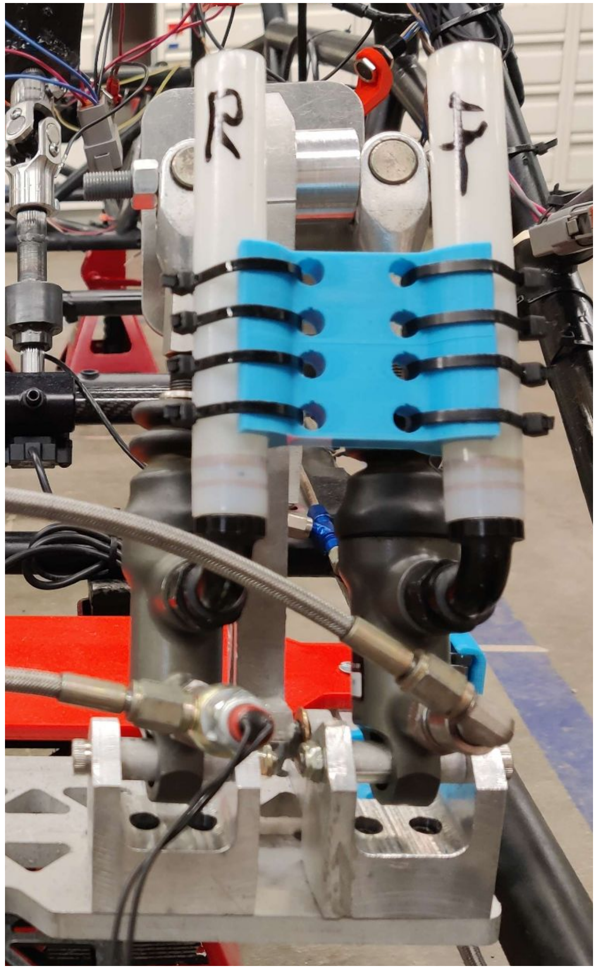


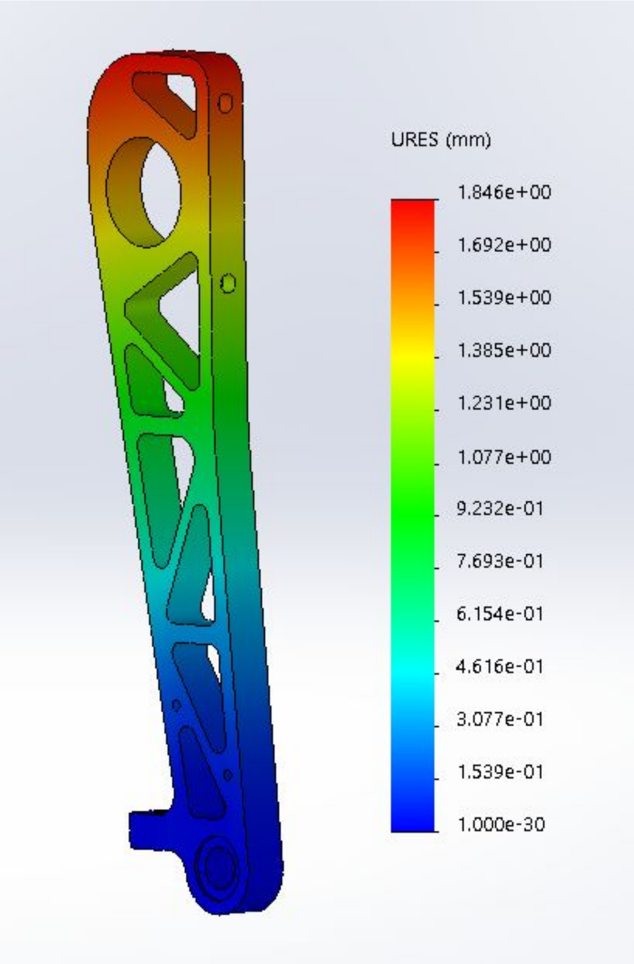
II. Previous Design

Keepers 😀:

- Pedal levers
- Brake assembly
- Clevises



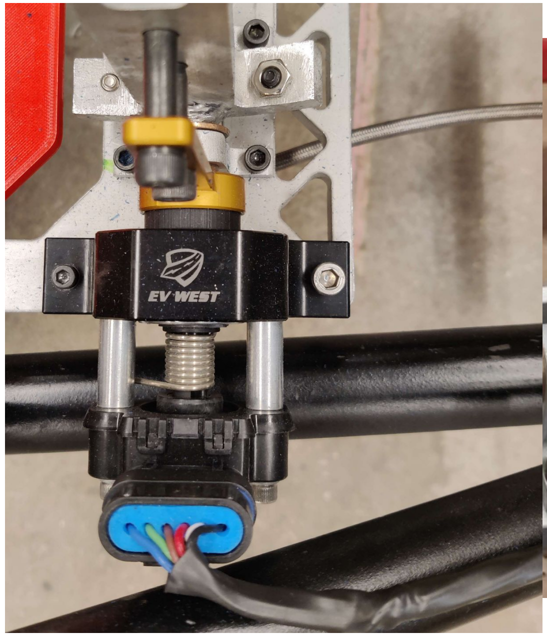


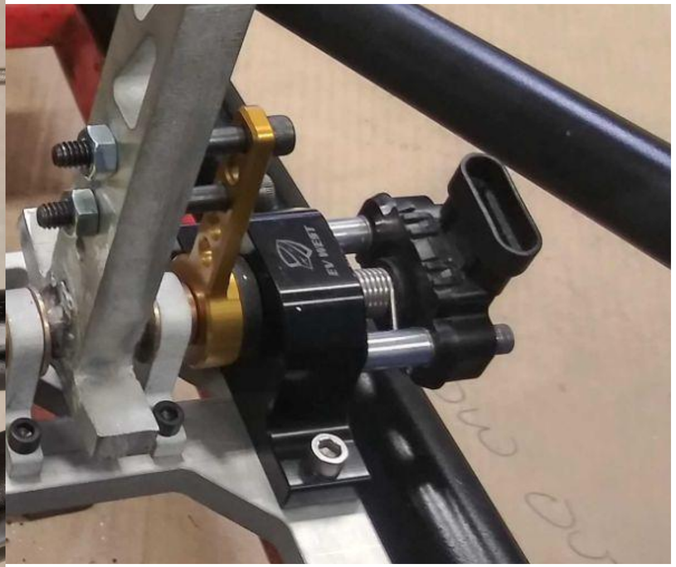


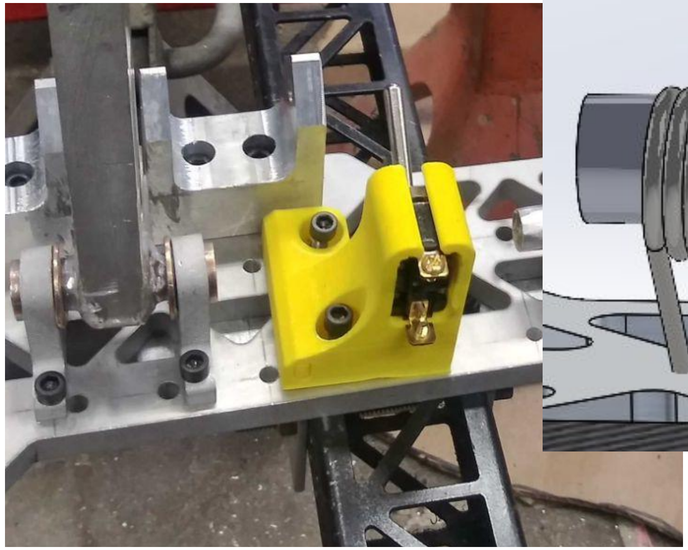
Previous Design: Issues

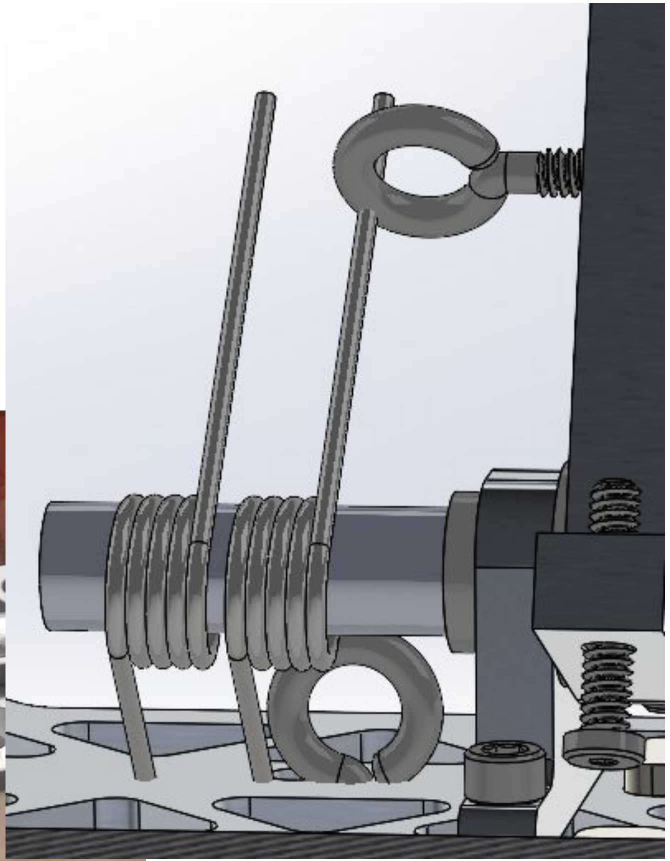
Issues 😔:

- APPS Sensor sticking out
- BOTS attachment jank
- No springs 💀
- Adjusting pedal box position was atrocious



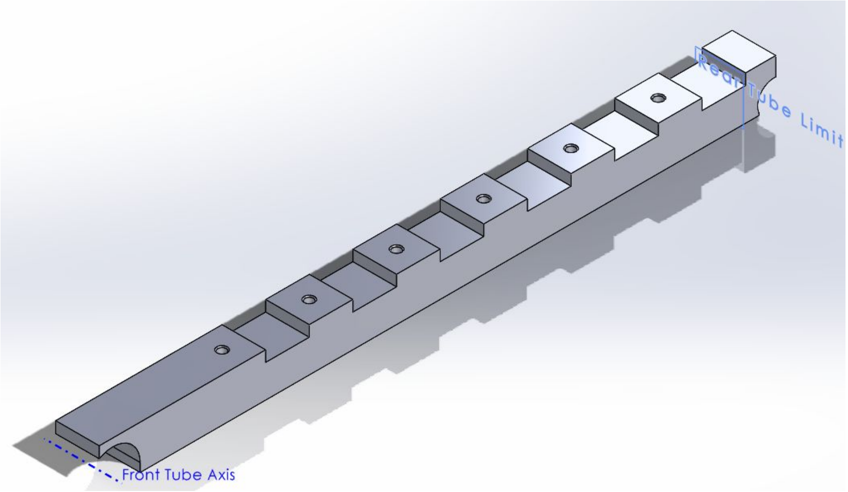


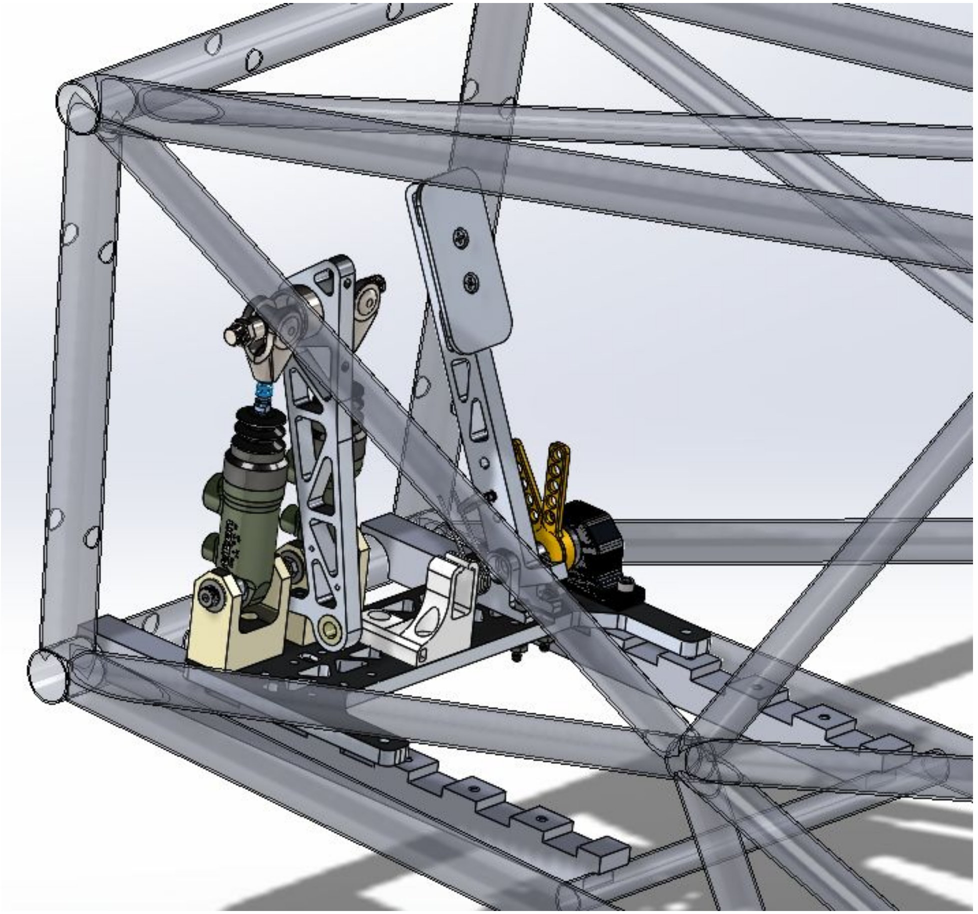




III. Build

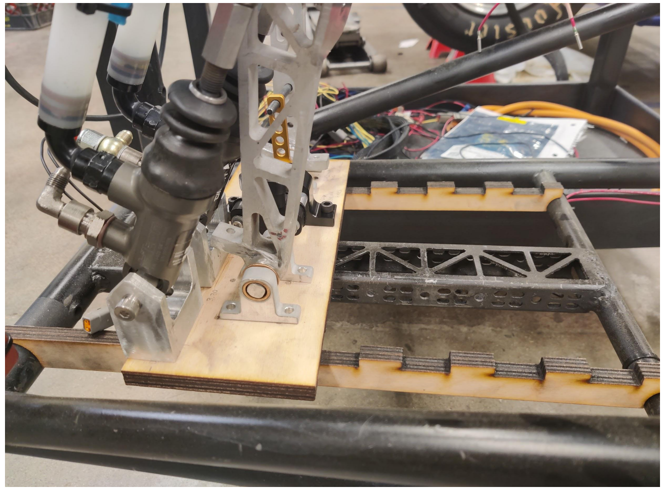
Prototyping new Baseplate and Rails

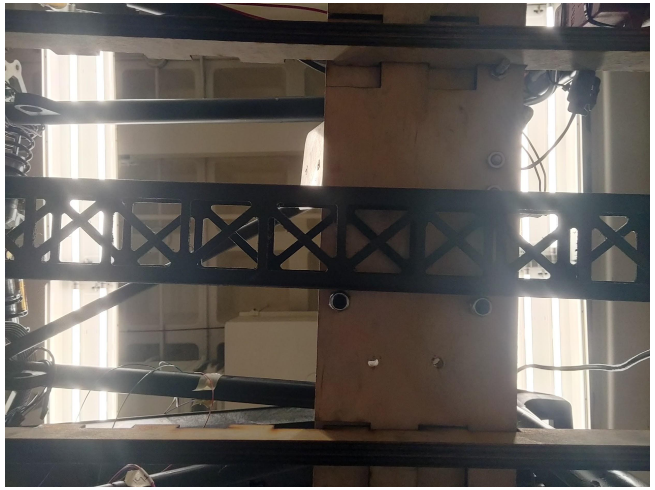


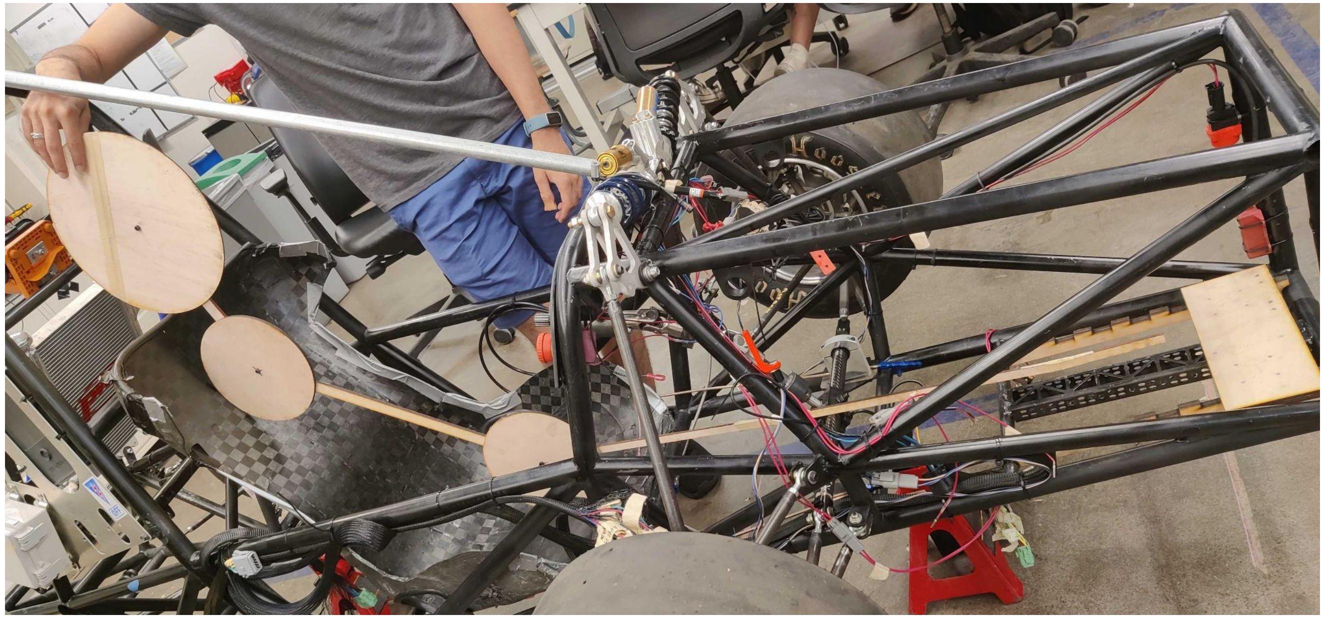


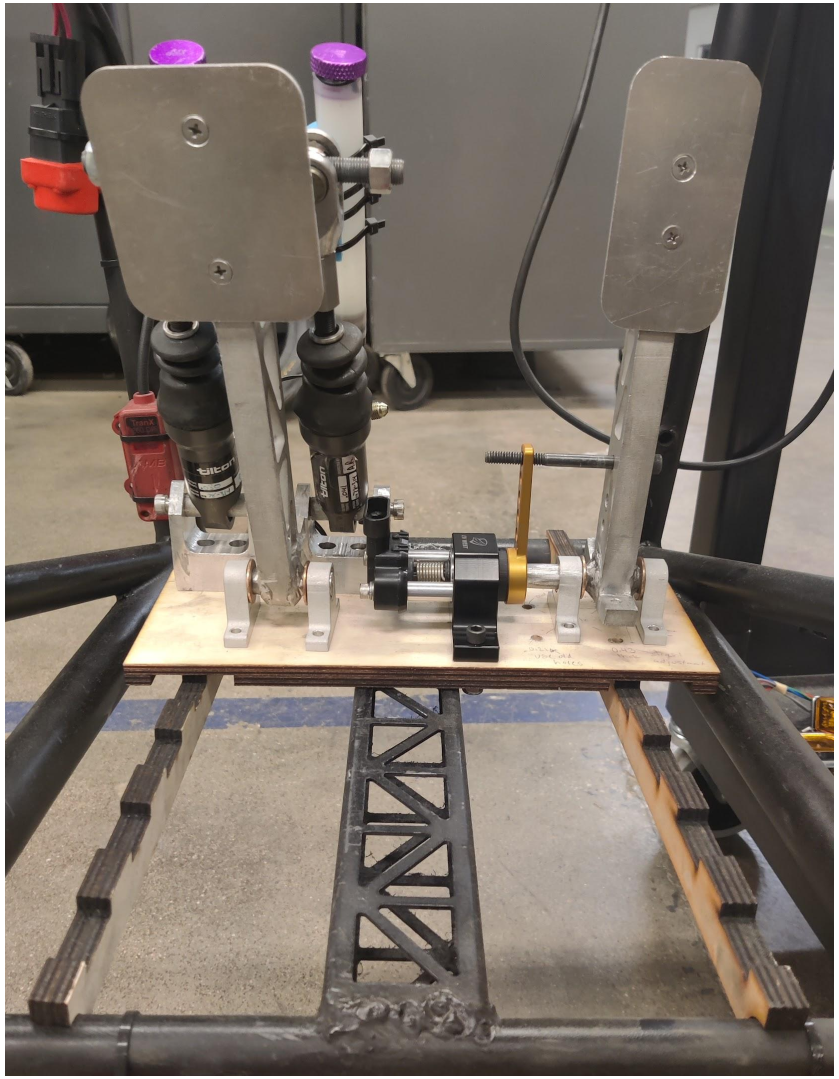
Prototyping

Build

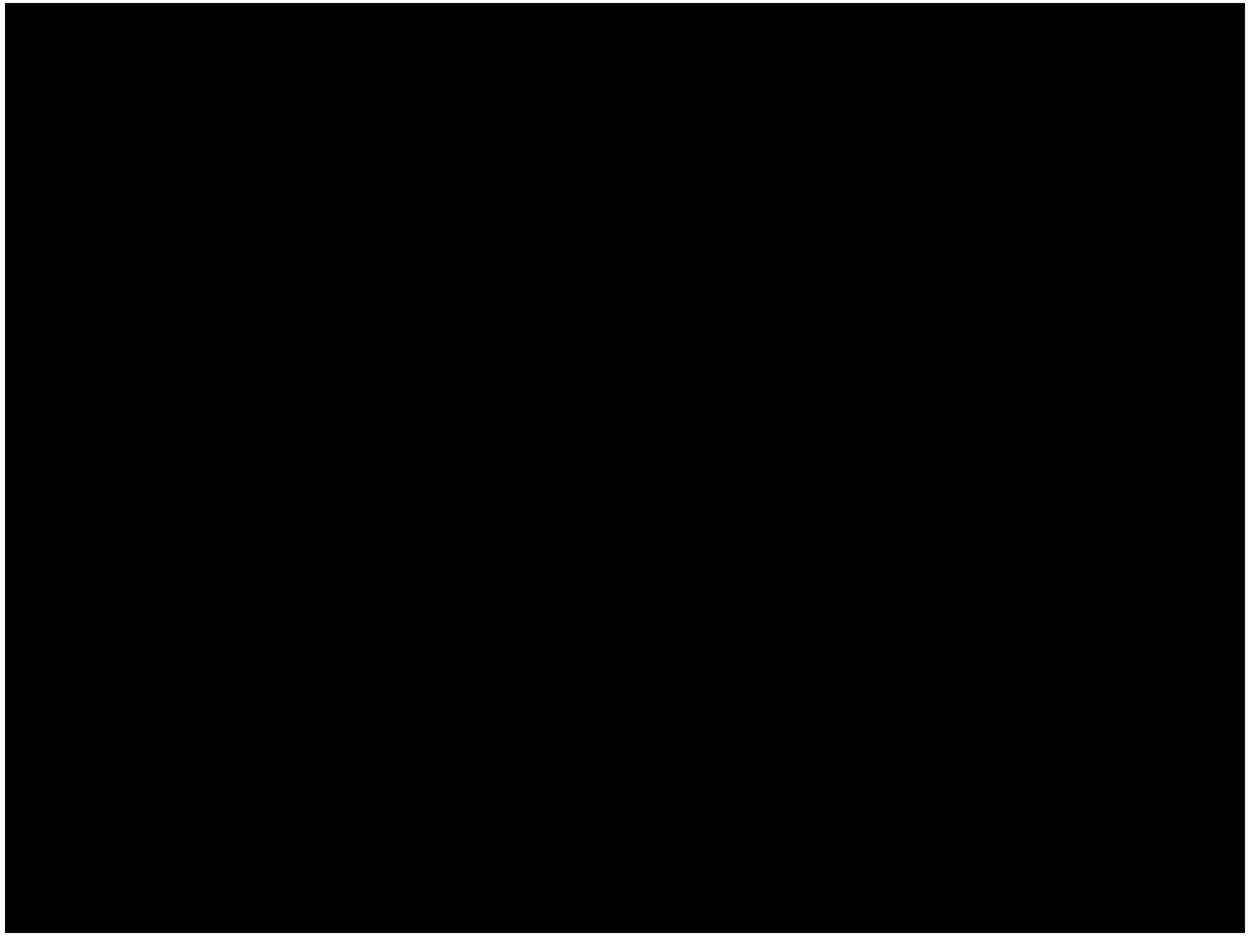








IV. Test



LV Mounting

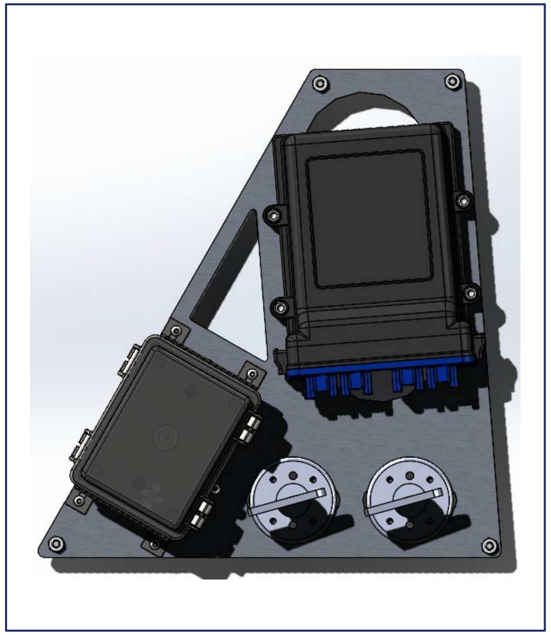
Presenter Info

Section:	Cockpit/Controls/ Brakes/Safety
Subteam:	Controls/LV
System:	LV Mounting
System lead:	Jazmyn Beasley
Subteam lead:	Alex Deli-Ivanov/Mert Saygi
Car:	eCFR-23

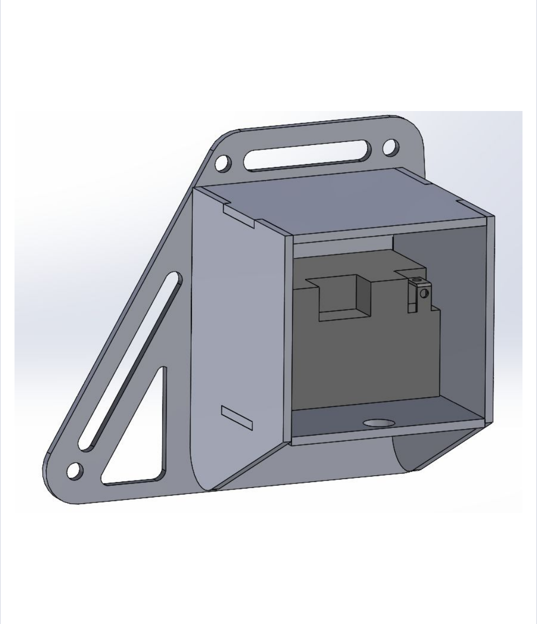
System Overview

We will go through the various components, relevant rules and current progress

I. Design Specifications

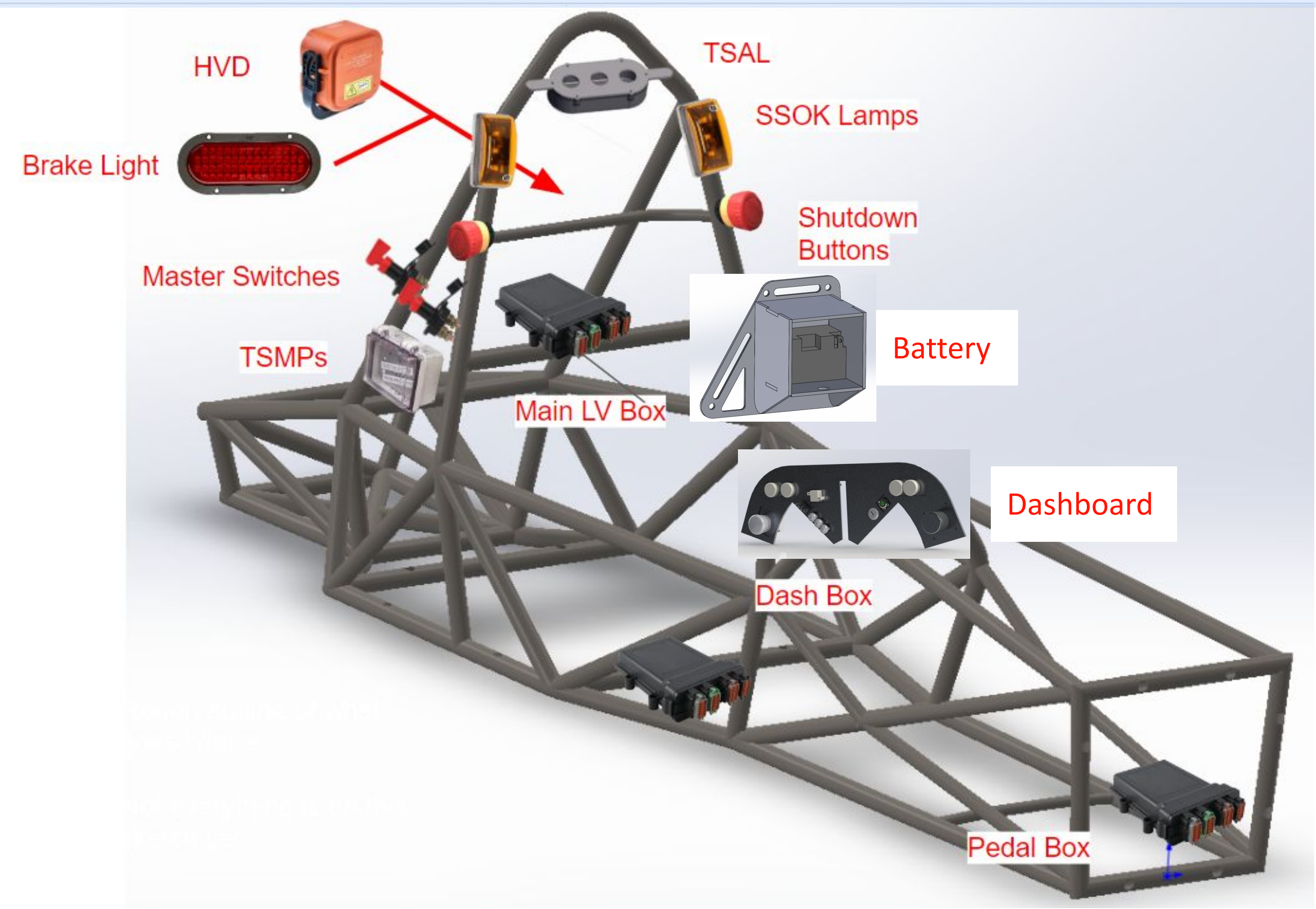


II. Build



III. Test

I. Design


HVD
TSAL
SSOK Lamps
Brake Light
Shutdown
Buttons
Master Switches
Battery
TSMPs
Main LV Box
Dashboard
Dash Box
Pedal Box

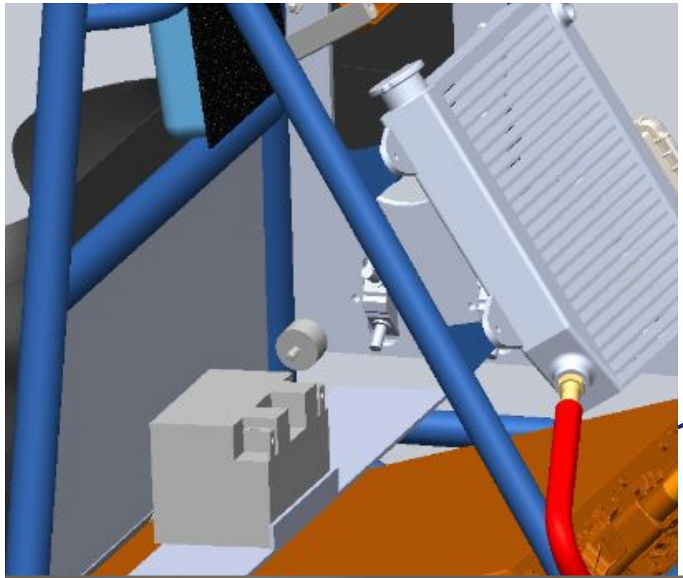
1. Dashboard
    a. Must have all components that the driver would need to interact with

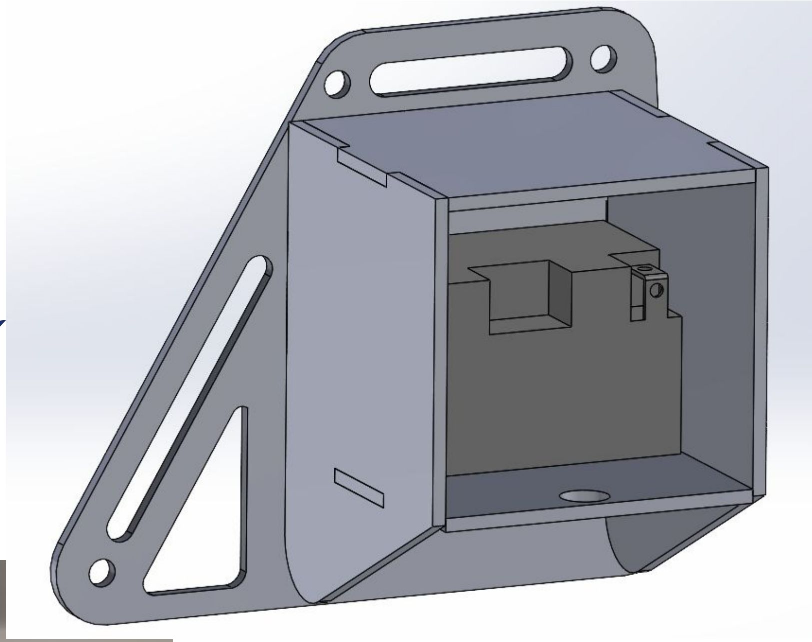
    → a. Move around components to add a motec
      b. Accommodate for chassis tubes

2. Battery
    a. Be behind the firewall
    b. Have rigid, sturdy, fire resistant and waterproof casing

    → a. Better mounting solution and location

II. Build

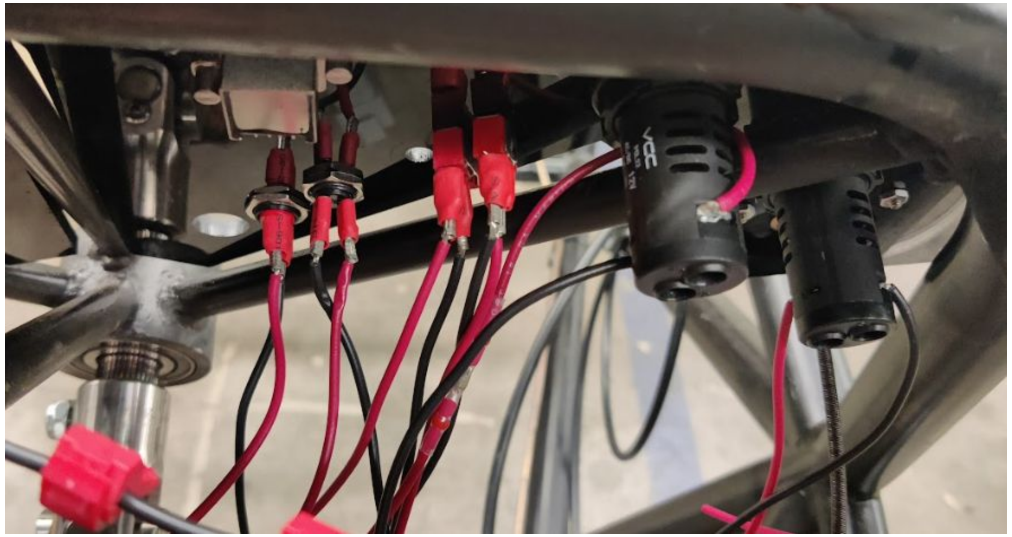


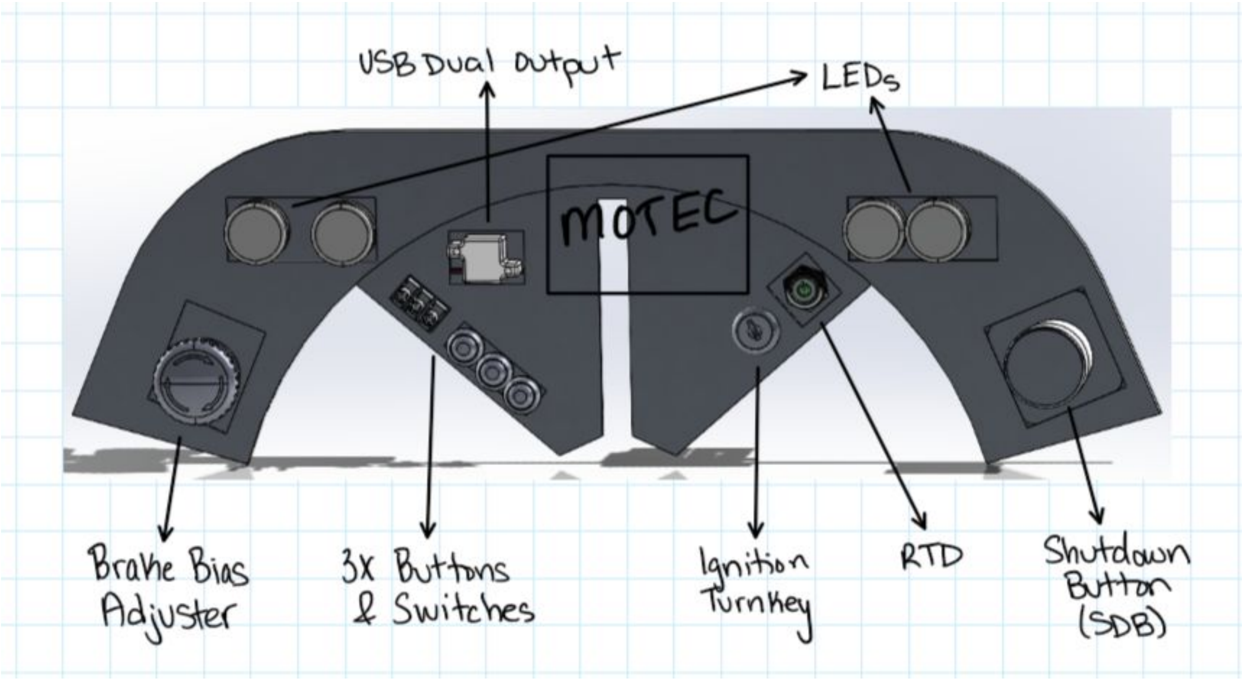


LV Battery Mount

- Sturdy container
- Made of acrylic
  - Lightweight
- Sealant will be used to put the box together and waterproof it
- Front lid will be hinged and sealant tape will be used to secure that
  - Easy access to inside if needed
- Hole for wires

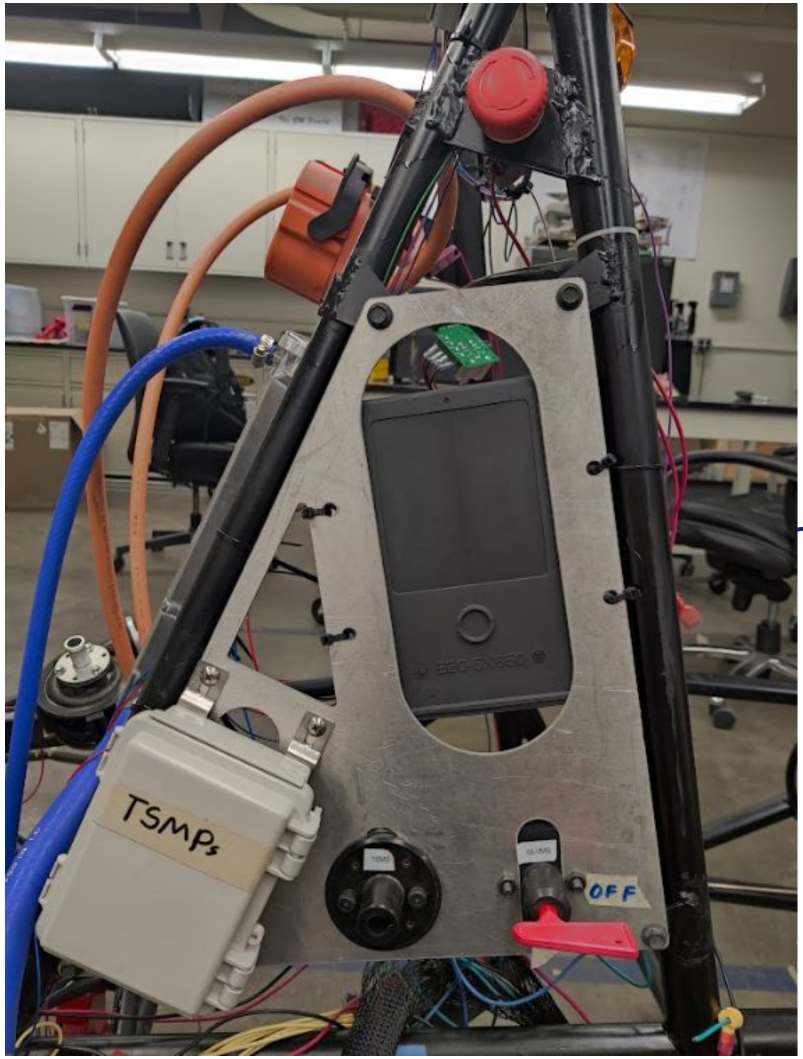
Build pt. 2 - Dashboard

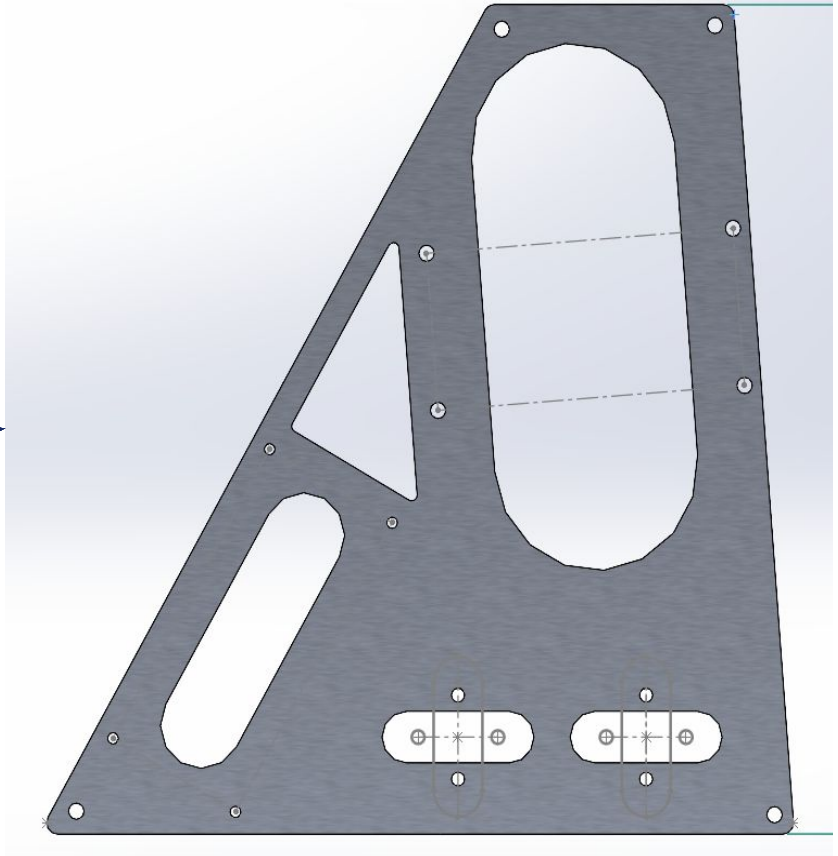




- Move the switches to avoid chassis tubes
- Adjust the positioning of central components to include 4x5 inch Motec Dashboard

Build pt. 3 - Side LV Mount

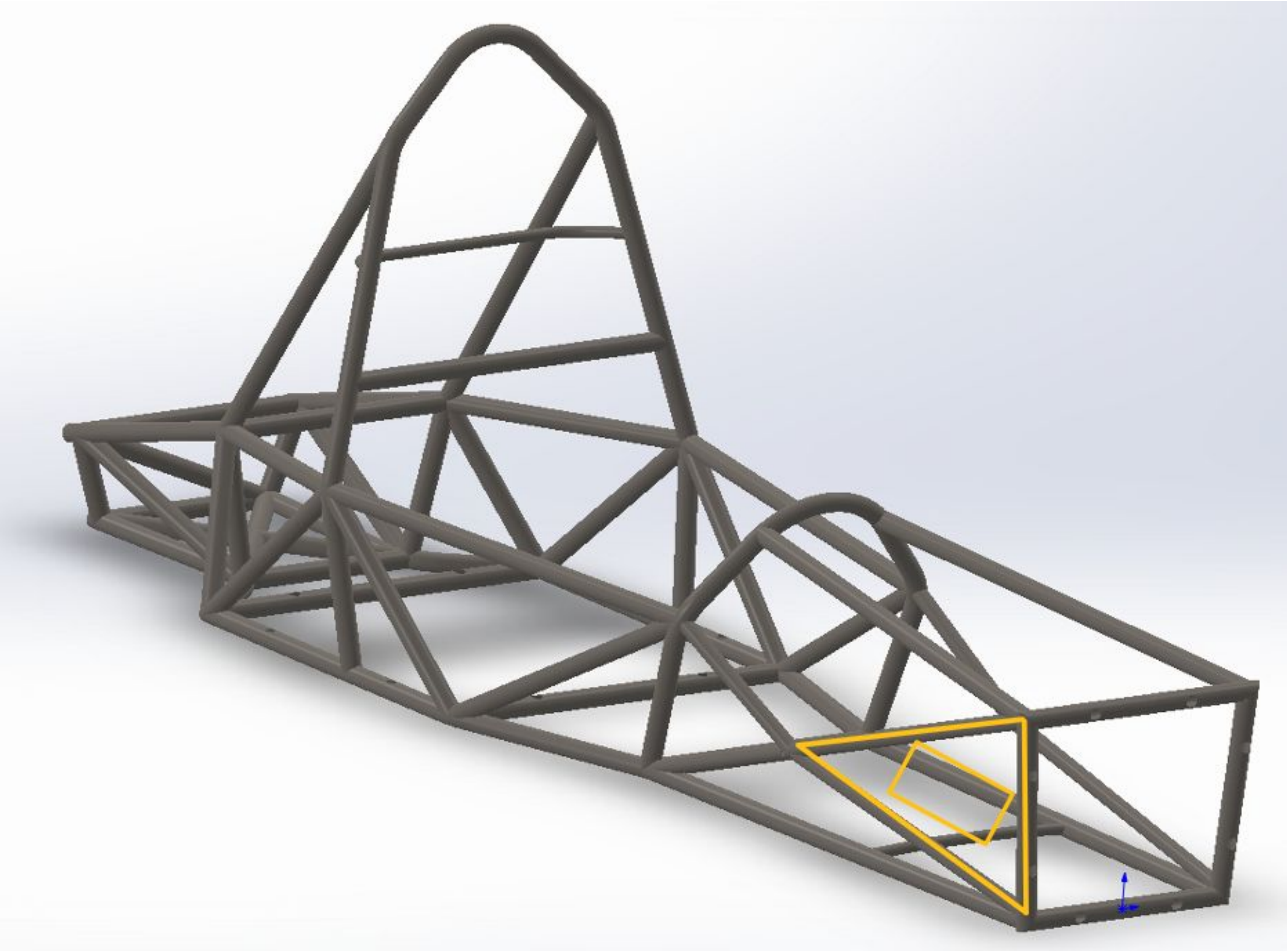




- Rotate the orientation of the holes to properly position the master switches
- Minimize weight while maximizing mounting points for switches, TSMP and Main enclosure

Build pt. 3 - LV Enclosures Mounts

Build



- Minimize wiring -> minimize distance to peripherals
- Secure mounts -> reduce vibrations and risk of disconnected wires

III. Test

1. LV Battery
   a. Must be waterproof in order to pass the rain test so we will test that the container, while empty, does not let water in
      i. dump water on it and conduct our own rain test
2. Dashboard
   a. Align it onto the chassis and continually check that the components do not interfere with each other

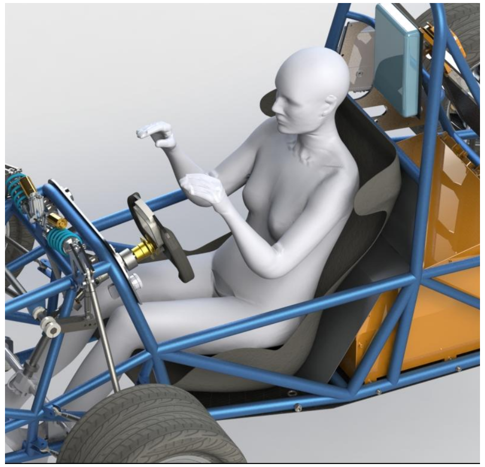
Cockpit

Presenter Info

Section:	Cockpit/Controls/ Brakes/Safety
Subteam:	Controls
System:	Cockpit/Ergonomics
System lead:	Jazmyn Beasley
Subteam lead:	Alex Deli-Ivanov
Car:	eCFR-23

We will go through the various components, relevant rules and current progress

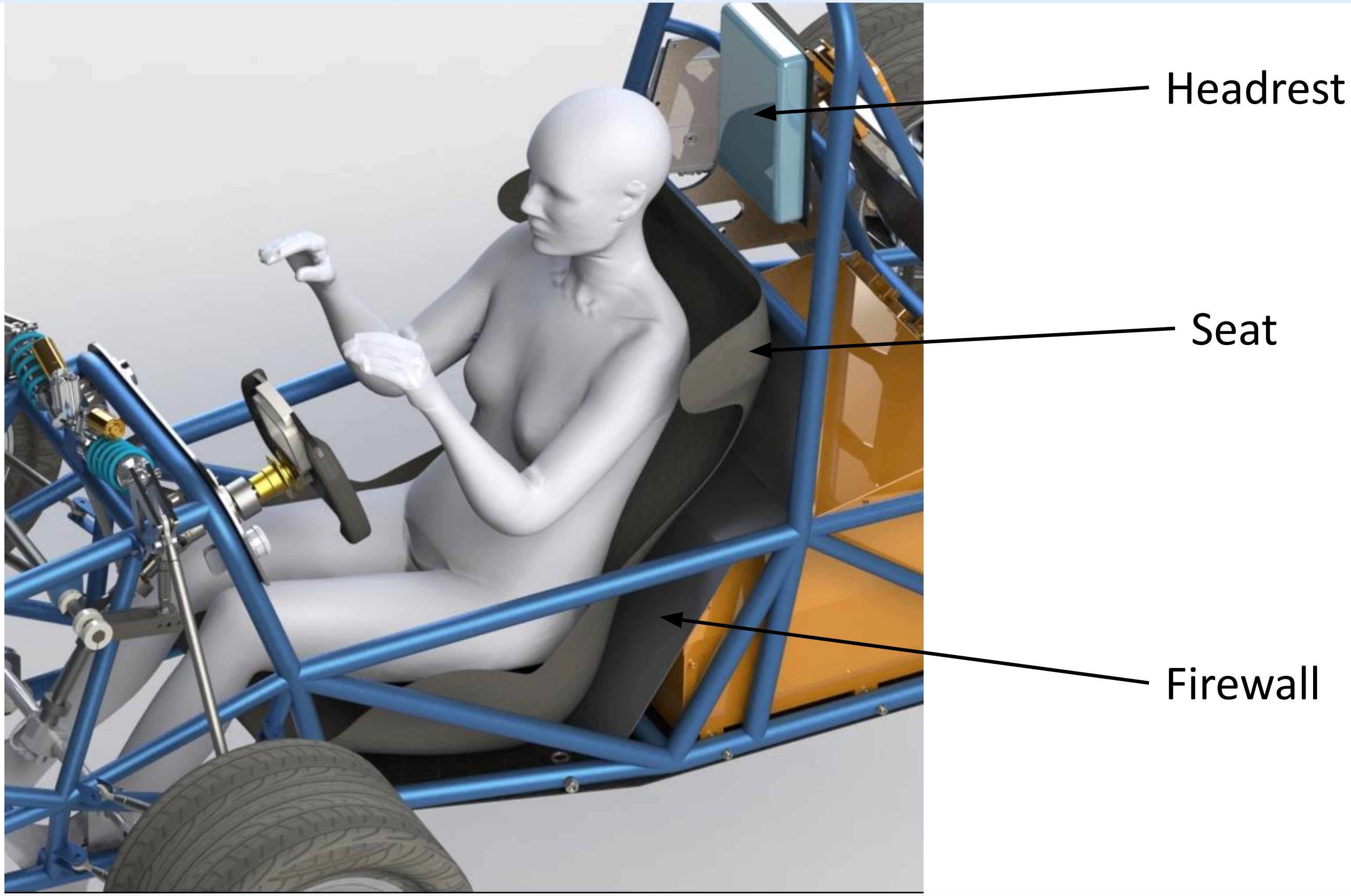
I. <u>Design Specifications</u>



II. <u>Build</u>

III. <u>Test</u>

I. Design



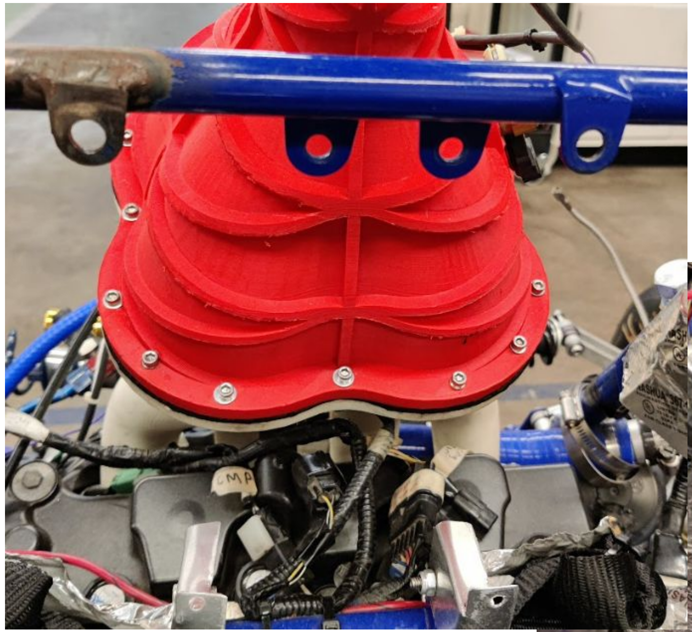
Design Overview, Concept, Requirements *Design 1*

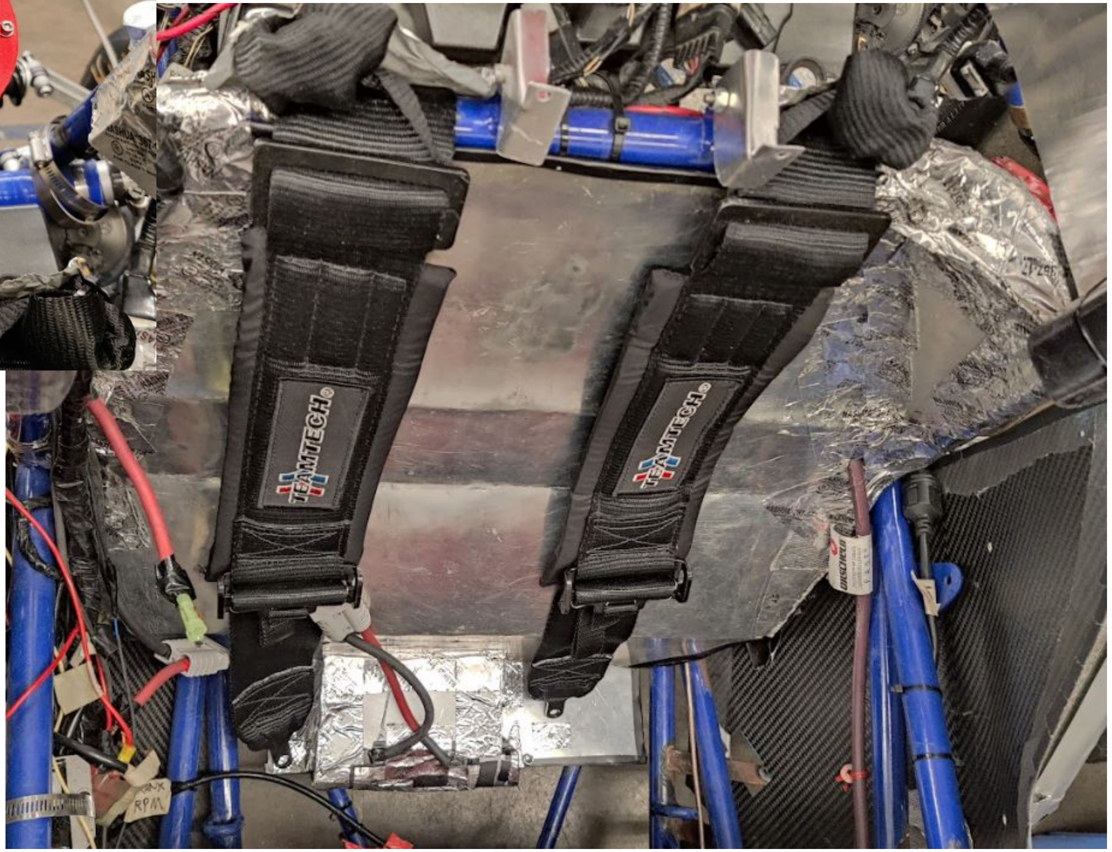
1. Seatbelt
    a. Fully quick adjustable

2. Seat
    a. Fit in car
    b. Not fall through car
    c. Not be falling apart

3. Firewall
    a. Fully encase the chassis behind the driver

4. Headrest
    a. Sturdily attached within proper limits of the driver's head

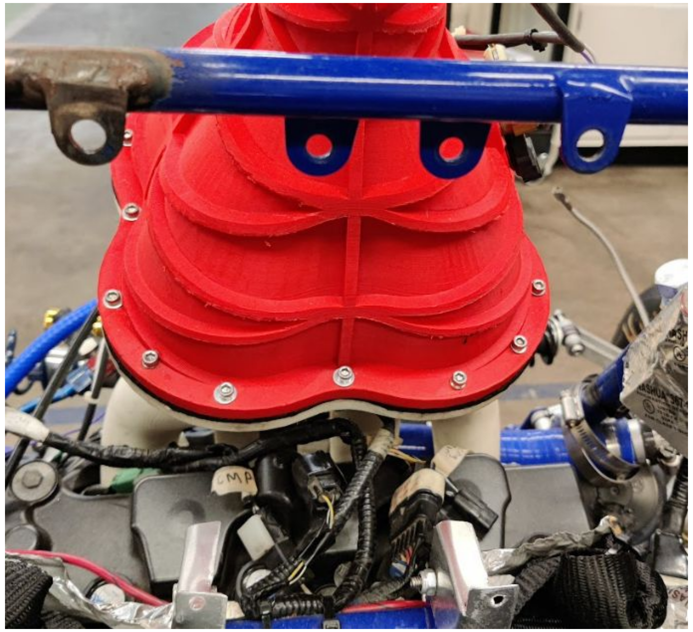


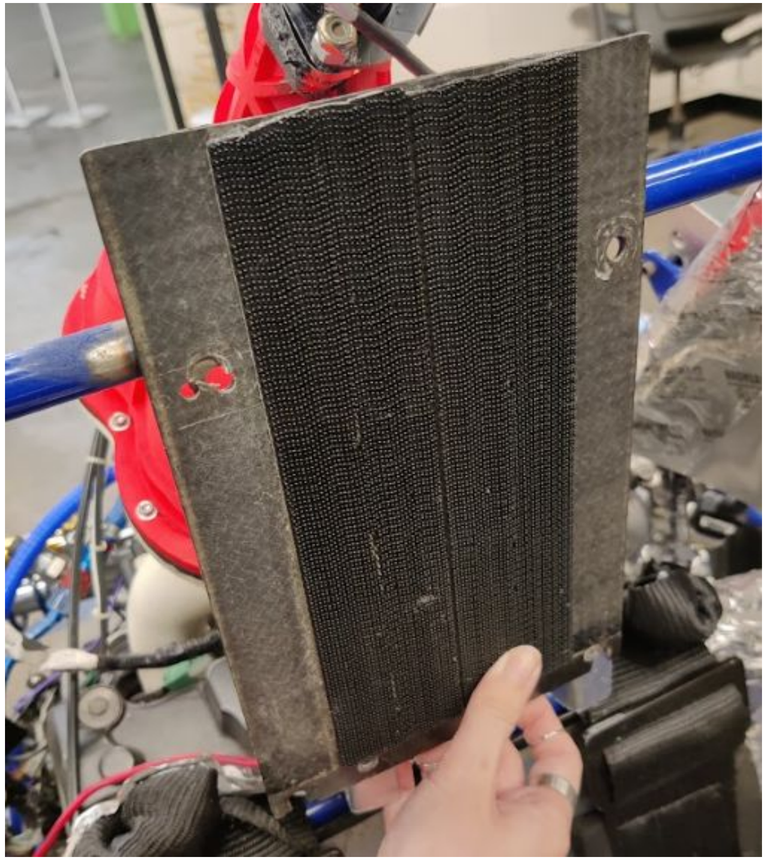


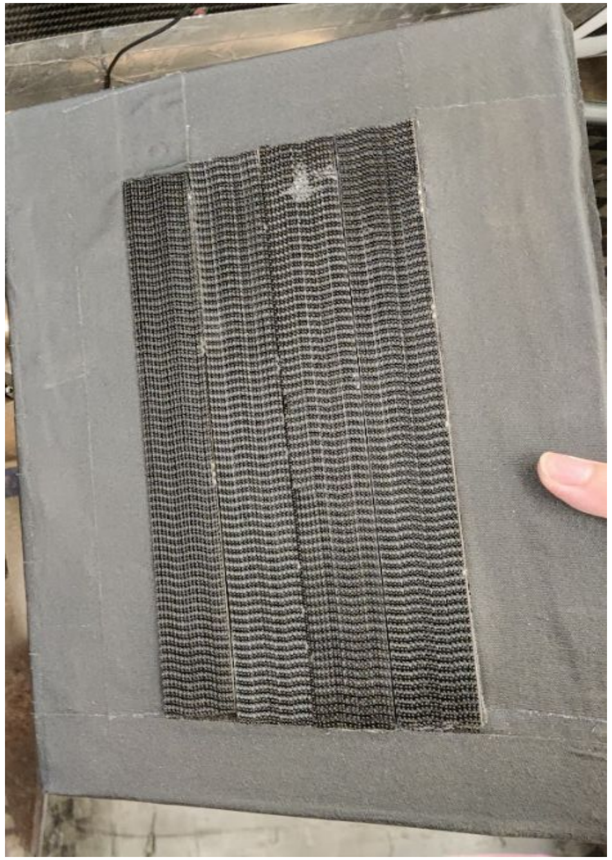
II. Build

- Carbon fiber
  - great opportunity to learn how to make one of these
- Current seats falling apart so we can remake them, accommodate for the new seatbelt we're getting

Build pt. 2







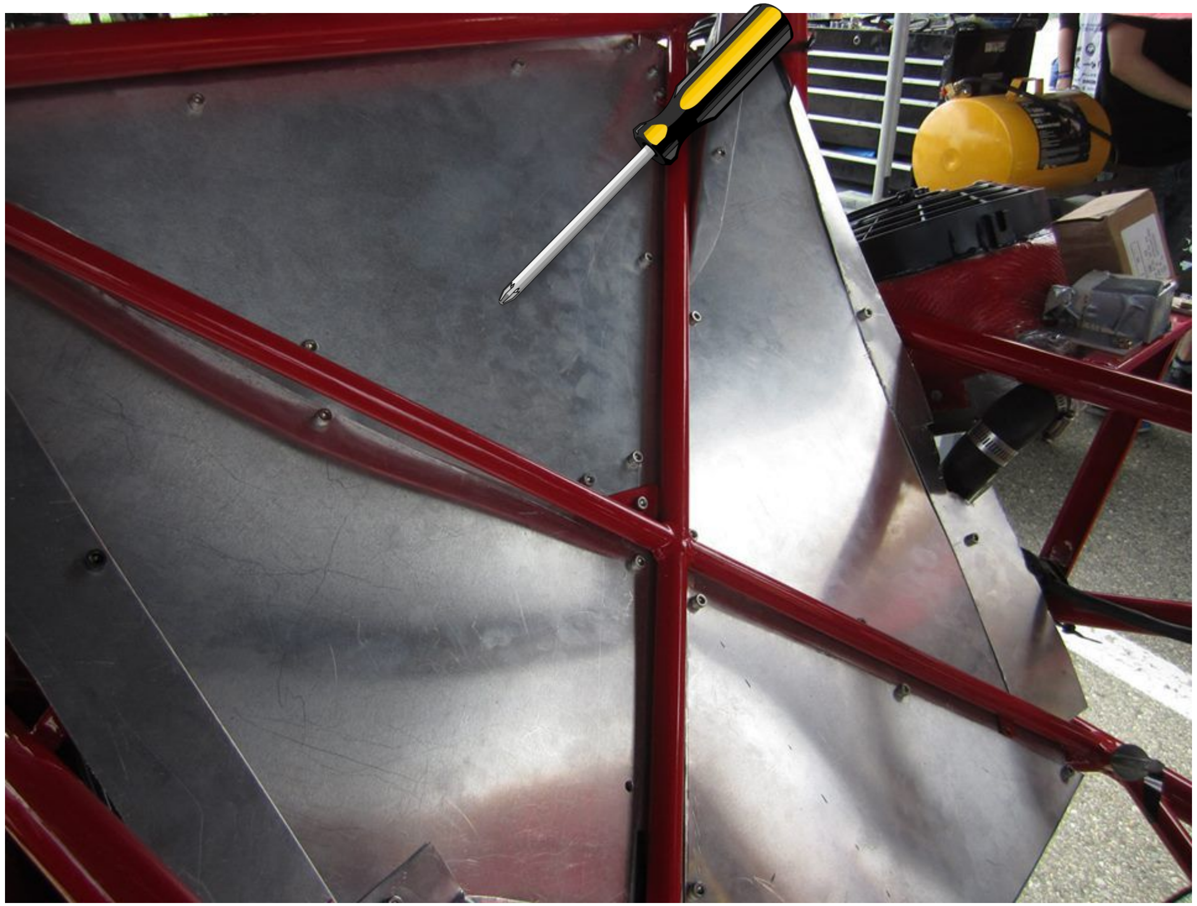
- Remake headrest backing piece
- Better attachment points to the chassis

Build pt. 3

- Get better coverage on the top sides of the chassis

III. Test

1. Firewall
   a. Will make an initial template to test placement on the chassis before making it
   b. Screwdriver stab test
2. Headrest
   a. Punch for stability
3. Seat/Seatbelt
   a. Route seatbelt through seat to confirm that it doesn't interfere with anything
   b. Have drivers sit in car to ensure comfort and that the seat doesn't fall through



Brakes

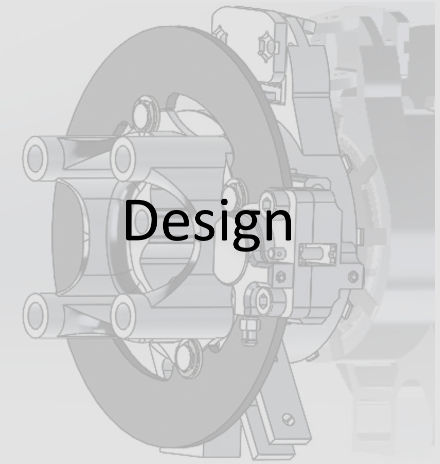
Presenter Info

Section:	Suspension
Subteam:	Dynamics
System:	Brakes
System lead:	Nick Poon
Subteam lead:	Jannie Zhong
Car:	eCFR-23

System Overview

Brakes Overview

The brakes system was designed last year, and we were looking to validate and understand the design through calculations.



Design

Analysis

Build

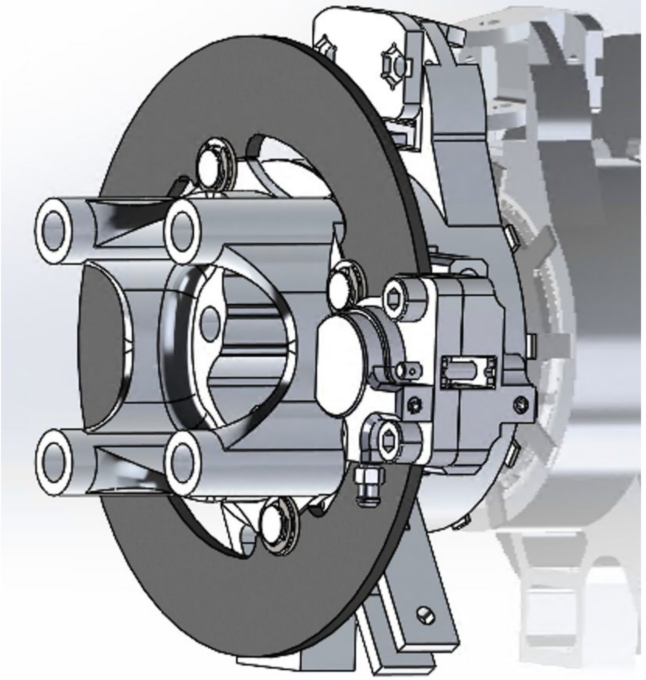
Test

Specifications

- Master Cylinders: Tilton 78-series
  - 13/16” (front), 7/8” (rear)
- Calipers:
  - front: ISR 22-048
    - 4 piston, 25mm diameter
    - Brake pad friction coeff: 0.3
  - rear: ISR 22-049
    - **2 piston**, 25 mm diameter
    - Brake pad friction coeff: 0.3
- Pedal Ratio: 4.16
- Rotor material: 4340 steel, **Dura-Bar G2 Cast Iron**
- Tire friction coeff: 1
- 73/26 front/rear weight transfer

Requirements:

- 4 wheel braking system
- passes the brakes test



Process

1. Weight Distribution
   a. 55/45 → 75/25 weight transfer
2. Rotor/master cylinder/caliper sizing
   a. 4 → 2 piston rear calipers
3. Thermal calculations
   a. G2 Iron works

Rotor Materials to be Considered	Melting Point (C)	Specific Heat [J/kg*C]	Density (kg/m^3)
G2 Gray Iron	1121.111	506.588	7003.0159
4340 Steel	1427	475	7861.0929
Aluminum	660.3	900	2710
Carbon-Graphite (Grade 378)			1874
Boron Composite	2076	960	2340
AISI 1065 Carbon Steel	1420	470	7850
Titanium	1668	544.284	4420

Rotor Mass Calculations	Front	Rear
Volume (m^3)	0.00009578421476	0.00008108548814
Volume w/ Slotting (estimation) [m^3]	0.00008620579329	0.00007297693932
Mass of Rotor [kg]	0.6037005411	0.5110586664

Temperature Change in Max. Braking Event		Notes
Kinetic Energy from Car [J]	138964.7768	Simple kinetic energy equation
Temperature Change [C]	123.037861	Will the temperature change be the same for all four rotors?

Next Steps

Next Steps:

Analysis:

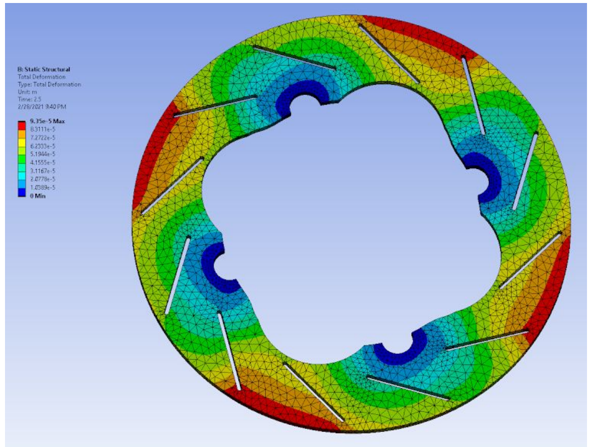
- Design brake rotors
  - perform FEA
  - thermal simulations

Build:

- Previously had to machine stock down to 4mm
- Found 4.75mm blanks, would still need to machine

Test:

- sensors:
  - 2 brake pressure sensors, one brake system encoder
  - brake temperature sensor?
- test for brakes locking



Breakout Groups!