LASSONDE MOTORSPORTS

Final Report

Team H: FSAE Drivetrain

Executive Summary

This report represents the culmination of work over the past 8 months which has been dedicated to designing an FSAE drivetrain for implementation in the first official Lassonde Motorsports vehicle. Summarized in detail in the design section is the as-built design with reference to interfacing, budget and performance, as well as implementation procedures in what's referred to as, “Package A: Manufacturing, Assembly and Testing”. To establish compliance, an in-depth review of the completed test campaign has been detailed along with results. Based on the findings from the thorough testing campaign, confidence in the drivetrain system has been well justified. Additionally, comprehensive project management practices are summarized to display the structure and quantity of resources allocated to this project. Based on project management tools such as the work breakdown structure, work package descriptions and scheduling, a detailed understanding of the management operations can be gained. Further evaluating the now finished drivetrain system, preliminary project aims have been revisited, such as proposed value and stakeholder needs. Now in the final stages of the project, reflections have been made regarding deviations from preliminary designs as well as lessons learned from specific failures along the way. This year, the members of Team H have collaborated to produce a fully designed drivetrain system along with detailed implementation instructions for future LM members use. Following our collective effort this year, the primary goal remains to see Lassonde Motorsports produce an FSAE eligible car in the near future.

Contents

This document is released with PDF bookmarks for ease of navigation.

Appendices

Figures

Tables

Volume I:

Design

As-Built Design

This section will showcase the overall design as well as the specific details and interfacings. The drivetrain is divided into three subsystems: differential, axle and wheel hub; tagged with the identifiers **[DIFF]**, **[AXLE]**, and **[WHUB]** respectively. Each subsystem has its own function in the drivetrain system however, all working together to achieve the overall goal of effectively transmitting power from the engine to the wheels. Rationale for specific design choices are outlined with respect to the most important performance factors for the drivetrain. As this is a drivetrain designed for a powerful racing vehicle, the performance factors are directly related to the effectiveness of the design delivering balanced power at all operation conditions, ranging from launch to cornering to high-speed straights. Along with the performance parameters, the loading conditions coupled with them are outlined which dictate the absolute minimum performance conditions the vehicle should be able to withstand.

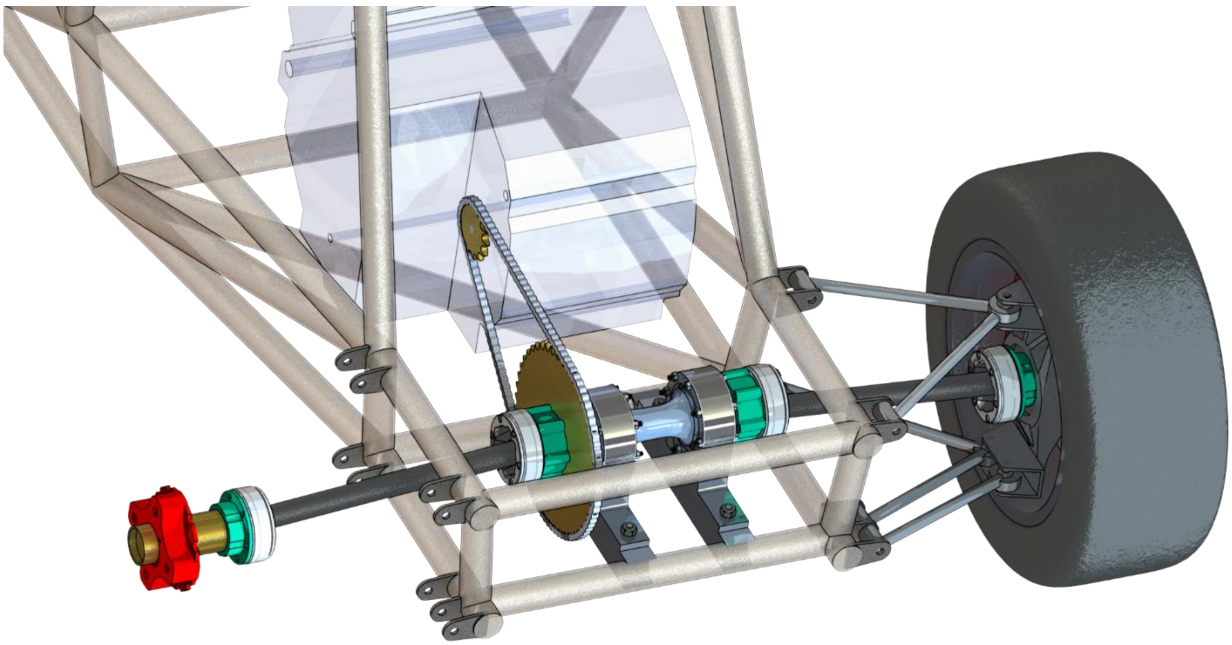
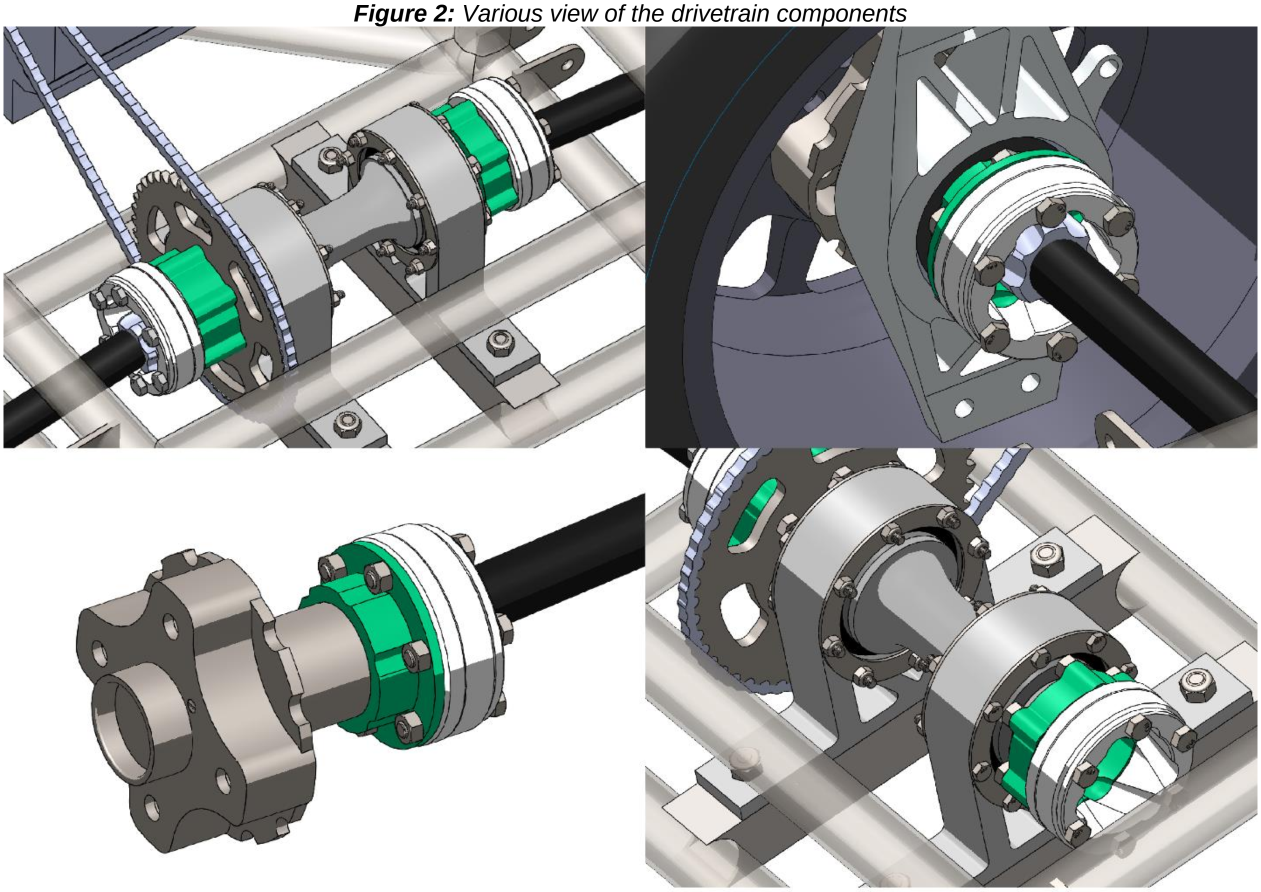


Figure 1: *Drivetrain system render*

An introduction to the drivetrain system can begin at its basic functional overview; the drivetrain operates by utilizing a sprocket-chain combination to accept and transfer rotation from the engine, a locked differential (commonly known as spool drive) to split that rotation to either side, a set of continuous velocity Rzeppa joints on either side of a solid axle to transfer it towards the wheels, and a bolted connection hub to finally accept that rotation and carry it to the wheels. This configuration was the result of a trade study completed early on in the project. The drivetrain was created as a combination of bought part and components designed from the group up; heavy considerations were made in both respects to ensure that it could perform the task it was required to do while withstanding the extreme loading encountered during operation. Throughout the design phase, there were many points of uncertainty such as the engine position and suspension points. As a response to this, the team has made the design modular and modifiable so that anyone can view the designs and compare them to the existing physical vehicle to make adjustments to dimensions. These modifications and adjustments are thoroughly documented to help the designer move step by step to perfectly assembly the drivetrain system in the vehicle.

Figure 2: *Various view of the drivetrain components*



System Interface Protocols

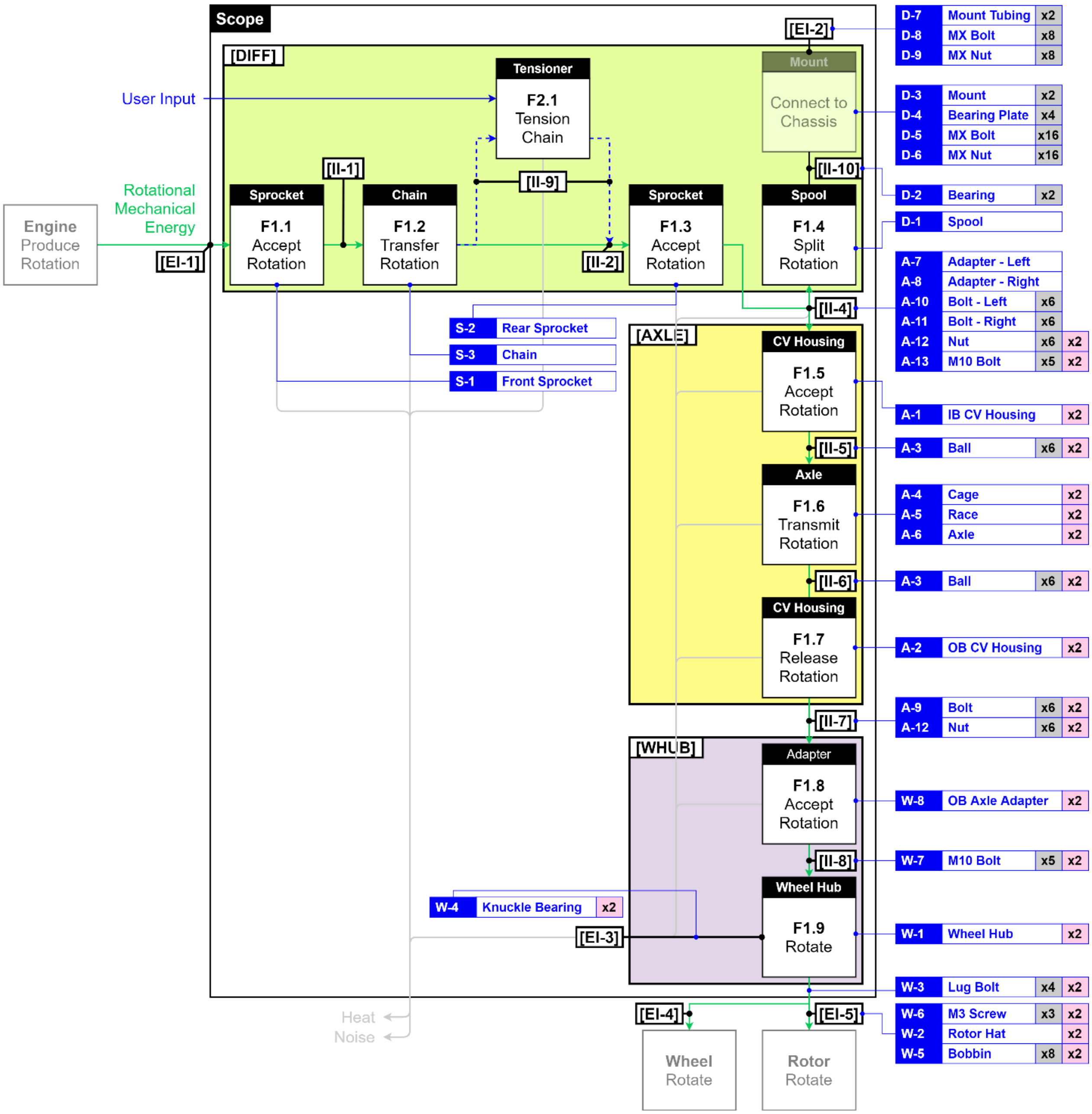
Being truly a "bridging" subsystem of the vehicle, the drivetrain interfaces with the engine and the wheels while transferring rotation between the two, as well as with other subsystems of the vehicle. Due to its intermediary role, its design is driven by those of the systems it interfaces with, and not the other way around.

Functional analysis of the drivetrain conducted in the preliminary design stage had made these interfaces to other vehicle systems clear and also revealed distinct interfaces between its own functional units. The external interfaces were used to shape the drivetrain design, whereas the internal interfaces guided the internal hierarchy and divisions, helping with splitting of work and responsibilities between team members. ***Table 1*** summarizes the nature and role of internal and external interfaces of the assembly, and ***Figure 26*** provides the functional breakdown of the system with the embodying components.

Table 1: *Internal and external interfaces of the system*

ID	Interface Between		Description
[EI-1]	Engine	Front Sprocket (**S-1**)	Rotational mechanical energy enters the system through this interface, physically occurring on the connection of the engine output shaft and the front sprocket, **S-1**.
[EI-2]	Spool Mount Tubing (**D-7**)	Chassis	The **[DIFF]** subassembly is connected to the chassis through the welded contact between the spool mount tubing (**D-7**) and the chassis tubing. This interface is not functional in terms of its contribution to the drivetrain functioning, however, is needed for physical support.
[EI-3]	Bearing (**W-4**)	Knuckle	The wheel bearings (**W-4**) are fitted to the knuckles, which are components of the suspension system. While the wheels themselves are outside the scope of the drivetrain, they need to be connected to the suspension subsystem, and this connection is achieved indirectly through **[WHUB]** components. This interface does not directly contribute to the drivetrain's primary function, however, is imposed by other vehicle systems.
[EI-4]	Wheel Hub	Wheel	Rotational mechanical energy leaves the system through these interfaces. After rotation is transmitted through the various internal interfaces, it is imparted on the wheel and the brake rotor though the interfaces on the wheel hub, **W-1**. Wheels are attached to the hubs with lug bolts, whereas the connection to the rotor is through the rotor hat, **W-2**.
[EI-5]	Wheel Hub	Brake Rotor	
[II-1]	Front Sprocket (**S-1**)	Chain (**S-3**)	Rotation which has been accepted a system component (**S-1**) is moved to the driveshaft through the chain, **S-3**. The interface occurs on the teeth of the front sprocket and involves a conversion of rotational mechanical energy to linear mechanical energy.
[II-2]	Chain (**S-3**)	Rear Sprocket (**S-2**)	Mechanical energy is delivered to the driveshaft component **S-2** and is converted back to rotation.
[II-4]	Rear Sprocket (**S-2**), Spool (**D-1**), Left Inboard Axle Adapter (**A-7**), Inboard CV Joint Housing (**A-1**)		This 3-way interface connects 3 driveshaft components and distributes the rotational mechanical energy to the two sides of the vehicle. Components are connected to each other with mechanical fasteners. The connection between **A-7** and **A-1** use the outer set of 6xM8 bolts, whereas **A-7**, **S-2** and **D-1** are connected with 5xM10 bolts.
[II-5]	Inboard CV Joint Housing (**A-1**)	Race (**A-5**)	Rotation of the center stack is transmitted to the **[AXLE]** in the constant velocity joint. Balls (**A-3**) fill the grooves between the housing and the race and provide a path for rotation to cross the gap in the housing. The joint structure allows transmission at a variety of angles of the axle (**A-6**).
[II-6]	Race (**A-5**)	Outboard CV Joint Housing (**A-2**)	Rotation is delivered to the **[WHUB]** the same way as in **[II-5]**, using a Rzeppa style joint with balls on grooves of the race and housing.
[II-7]	Outboard CV Joint Housing (**A-2**)	Outboard Axle Adapter (**W-8**)	Rotation taken up from the **[AXLE]** is transferred to the **[WHUB]** through the intermediary adapter piece. The connection is mechanical with 6xM10 bolts.
[II-8]	Outboard Axle Adapter (**W-8**)	Wheel Hub (**W-1**)	Rotation of the housing is transmitted to the axle adapter simply using mechanical fasteners, in the same arrangement used in **[II-4]** between **A-7**, **S-2** and **D-1**.

Figure 3: *Functional structure diagram with embodying components*



Design Budget

The drivetrain is a mechanical system handling rotational mechanical energy with physical components. This section details the parameters whose variations and distributions were tracked on the system level.

- **Mass**
  Mass is the only quantifiable technical design characteristic that the client had specified as a priority in the preliminary design stage. Vehicle speed and handling characteristics being dependent on the magnitude and distribution of mass, it needs to be monitored in the design.

- **Torque**
  Distribution of torque in the system is design dependent and was manipulated in the design iterations through different connection arrangements between components. Torque distribution determines the fraction of loading components will experience and has guided design decisions and test package definitions.

- **Factor of Safety**
  Factors of safety indicate the proximity of components to failure for a given loading scenario. Failure of a component could prevent the system from achieving its primary function of delivering power from the engine to the wheels. Distributions of factors of safety can be used to determine the first components to fail in an assembly and predict the events that will follow their failure.

Figure 4: *Mass distribution across system components*

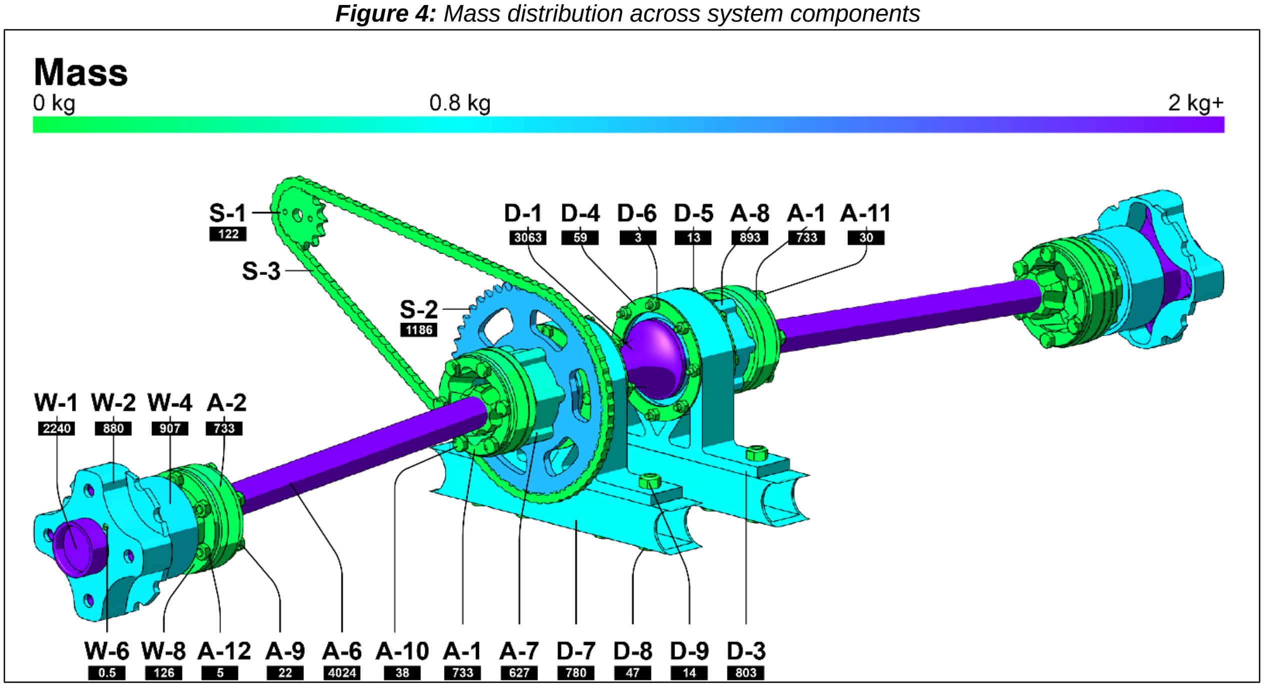


Figure 4 visualizes the distribution of mass across the system. Weight is concentrated in the final axes of rotation, with the heaviest components being the spool (**D-1**), axles (**A-6**), and wheel hubs (**W-1**). Connector components such as the CV joint housings (**A-1**, **A-2**), axle adapters (**A-7**, **A-8**, **W-8**); and support components such as the mounts (**D-3**), mount tubing (**D-7**) are seen to have masses in the 600-800 g range. Fasteners and aligners are the lightest components.

The system is estimated to have a total mass of 33.3 kg. ***Table 2*** provides the complete mass breakdown of the components. The **[DIFF]**, **[AXLE]**, **[WHUB]** subassemblies make up 31%, 45% and 24% of the total mass, respectively. It should be noted that the **[AXLE]** and **[WHUB]** subassemblies have most of their components duplicated for the left and right sides of the vehicle. The purchased axle assembly, consisting of components **A-1** to **A-6**, make up most of the **[AXLE]** mass.

ID	Component	Quantity	Unit Mass	Total Mass
S-1	Front Sprocket	1	121.62	121.62
S-2	Rear Sprocket	1	1185.54	1185.54
S-3	Chain	1	64.24	64.24
D-1	Spool	1	3062.88	3062.88
D-2	Spool Bearing	2	907	1814
D-3	Spool Mount	2	803.16	1606.32
D-4	Mount Bearing Plate	4	59.37	237.48
D-5	Mount Bearing Plate Bolt	16	12.48	199.68
D-6	Mount Bearing Plate Nut	16	2.85	45.6
D-7	Mount Chassis Tubing	2	780.27	1560.54
D-8	Mount Chassis Tubing Bolt	8	46.59	372.72
D-9	Mount Chassis Tubing Nut	4	13.94	55.76
			[DIFF] Total	**10326.38**
W-1	Wheel Hub	2	2240.43	4480.86
W-2	Rotor Hat	2	880.45	1760.9
W-4	Bearing	2	907	1814
W-6	Slotted Flathead Screw M3x1.5x10mm	4	0.53	2.12
			[WHUB] Total	**8057.88**
A-1	Inboard CV Housing	2	5900	11800
A-2	Outboard CV Housing			
A-3	Ball			
A-4	Cage			
A-5	Race			
A-6	Axle			
A-7	Inboard Axle Adapter – Left	1	627.44	627.44
A-8	Inboard Axle Adapter – Right	1	893.38	893.38
A-9	CV Housing to Adapter Bolt – Outboard - M8 45mm	12	22.18	266.16
A-10	CV Housing to Adapter Bolt – Inboard Left - M8 85mm	6	37.96	227.76
A-11	CV Housing to Adapter Bolt – Inboard Right - M8 65mm	6	30.07	180.42
A-12	CV Housing to Adapter Nut - M8	24	5.3	127.2
A-13	Adapter to Spool Bolt - M10 35mm	20	25.42	508.4
W-8	Outboard Axle Adapter	2	125.61	251.22
			[AXLE] Total	**14881.98**
			System Total	**33266.24**

Table 2: *Mass breakdown of the system*

Figure 5 presents the torque factors of the system components. With T being assumed the torque experienced by each wheel at a given operation condition (e.g. launch, second gear), 2T is the total torque delivered to the driveshaft by the rear sprocket, **S-2**. The torque at the front sprocket **S-1** is 0.6T as per the gear ratio of the two sprockets (14:47).

The central components of spool (**D-1**), axle adapters (**A-7**, **A-8**) and CV joint housings (**A-1**) are the first recipients of the torque delivered to the driveshaft and could experience its total amount (2T) or split amount (T). This ambiguity has been a matter of discussion among the team. The “effective” location where torque is split has been assumed as the center stack of components, between the inboard axle adapters **A-7** and **A-8**. To ensure their integrity in the case they do experience the total torque of 2T, even if that may not commonly occur, components in the center stack were tested for their strength under 2T different operation conditions (e.g. launch).

Components other than those in the center stack, which repeat in both sides of the vehicle, were tested for their performance at T, assuming the total torque of 2T will not reach them, based on the assumption that both wheels will always be in contact with the ground.

Figure 5: *Torque distribution across the system*

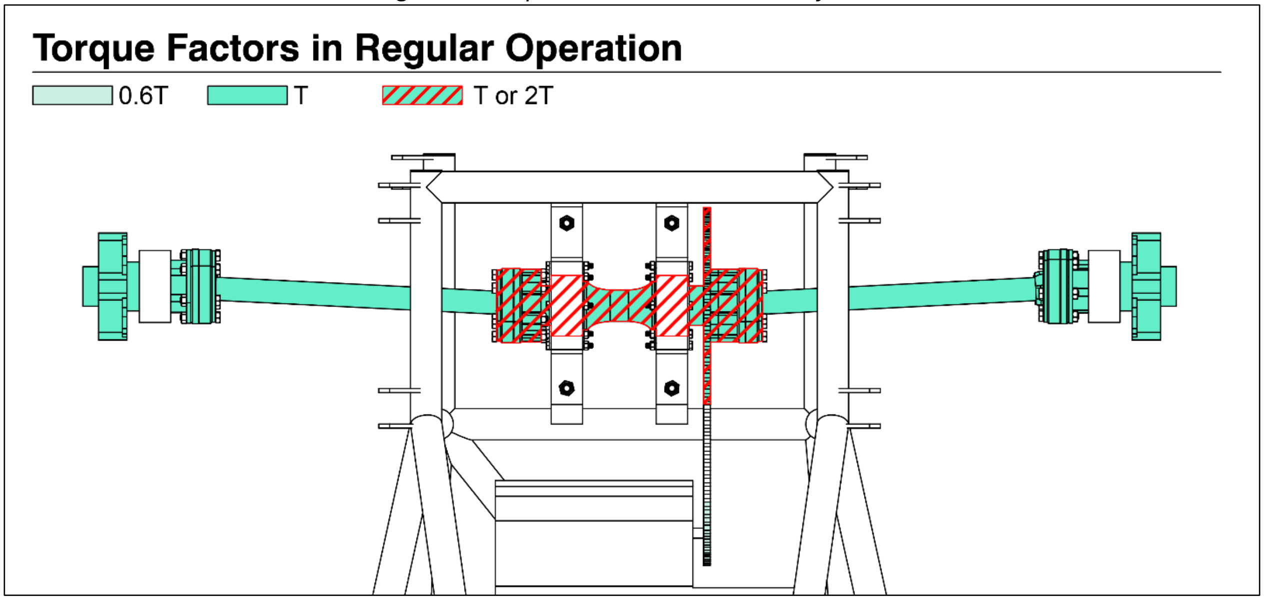


Figure 6: *Minimum expected factors of safety of tested system components*

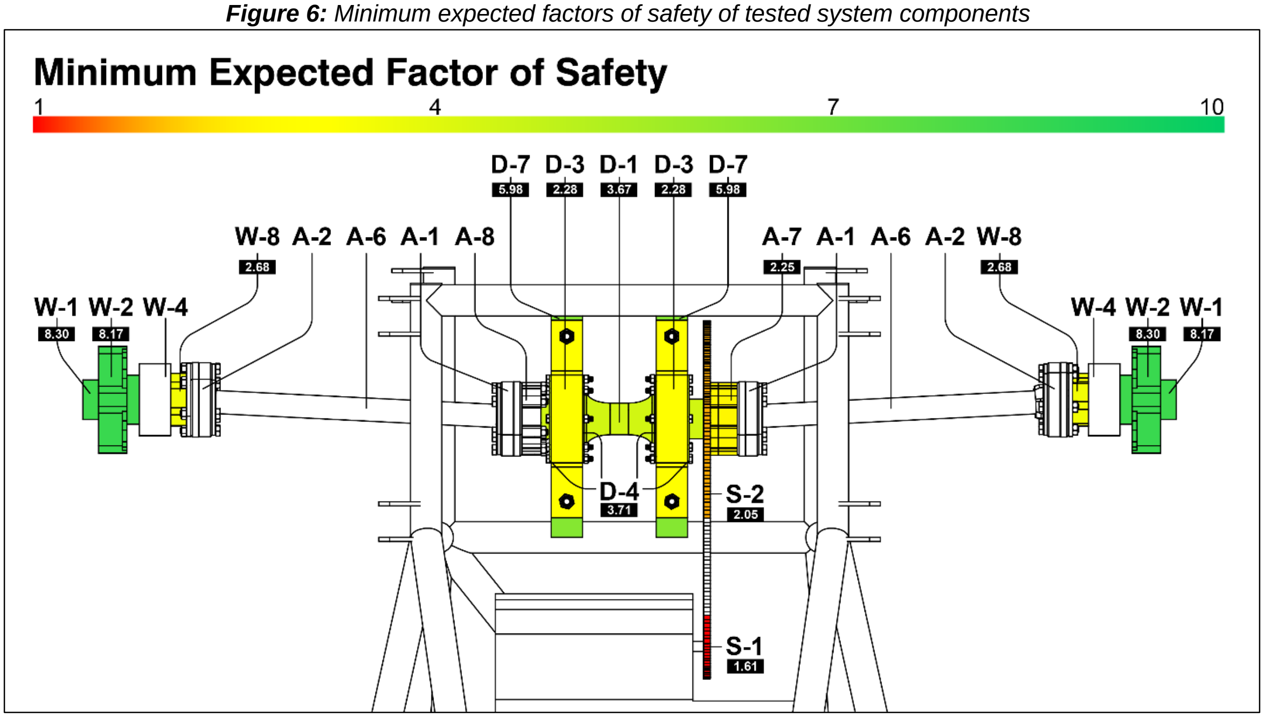


Figure 6 visualizes the minimum expected factors of safety for the components that have been tested by the project team as part of the test campaign. The “minimum expected” factors may belong to any operation condition considered (e.g. launch, cornering, braking). All such conditions are expected during the regular operation of the vehicle.

Not all components of the system have a factor of safety reported, as some components have been excluded from the test campaign. Exemptions for components such as the purchased axle components (**A-1** to **A-6**) and bearings were detailed in the Test Readiness Review gate report. Fasteners were also exempted from testing due to them being standardized components used in connector roles.

All components have a factor of safety higher than 1 and the system is expected to perform without failure under the design conditions. The component with the overall lowest factor of safety expected in regular vehicle operation is the front sprocket **S-1** with a factor of 1.61. Wheel hubs (**W-1**) and rotor hats (**W-2**) have the highest factors of safety of 8.17 and 8.30 respectively. Components in the center stack have factors of safety in the range of 2 to 6.

The front sprocket **S-1** has its minimum factor of safety of 1.61 at launch conditions, meaning that in case of an irregular launch with higher torque than the design value, the front sprocket will fail first before the extreme torque reaches the center stack and the wheels. This effectively reduces the need for these other components to have high factors of safety. Component designs were not optimized within the timeframe of the project, however, future work may involve design optimization of driveshaft components to reduce their weight, as the resulting reduction in factor of safety is affordable.

Performance Metrics

The design philosophy with the drivetrain system has been reliability above all else. As such, the drivetrain system has been designed to handle the unrestricted engine power output from the 1990 Suzuki Katana engine, that is 65 horsepower and 36.3 lb-ft (40 Nm) of torque. During FSAE events, the engine output will be restricted with a 20 mm intake, reducing overall horsepower and torque.

Gear Ratios

The gear train system allows the wheels to rotate at a different speed than the engine. The 6 gear sets within the transmission allow for a wide range of speeds while maintaining the engine RPM at a fixed range. The gear ratio is determined by the following:

- Primary Drive: gear ratio between engine and transmission: the 6 gear sets within the drivetrain
- Final Drive: gear ratio between front and rear sprockets

The ideal gear ratio is different for each racetrack. The optimum gear ratio should allow the engine to stay in the maximum power rpm band for the longest amount of time and allow for the minimum number of gear changes during a lap around the track. A high number of gear changes are undesirable because during a gear change, the clutch is disengaged thus no power is being sent to the wheels. In addition, a bad gear change can disrupt the balance of the vehicle, both scenarios lead to slower lap times.

The components which can be easily modified to adjust the gear ratio is the final drive system, consisting of the front and rear sprockets. The stock final drive ratios (front - 14 teeth, rear - 47 teeth) from the original bike were selected as a baseline to be refined during physical track testing of the vehicle. If during testing it is determined that the final drive ratio is not optimal, new sprockets can be machined and fitted to the drivetrain.

Operation Concepts

All components in the assembly have been designed with considerations for strength under maximum loading conditions, represented in the following operation concepts:

Launch

One of the extreme loading conditions the drivetrain system will experience is during vehicle launch from a standstill. During launch, the vehicle is static, and with the clutch disengaged (no power transfer to drivetrain), and the engine RPM is raised to approximately 4000 RPM. Then, with the instantaneous engagement of the clutch, torque starts to be transferred to the drivetrain.

At 4000 RPM the unrestricted engine produces 40 Nm of torque, which equates to 722 Nm at the rear sprocket (361 Nm per axle) with the gear ratios. Assuming the tires are fixed at the moment of launch, the 361 Nm will cause torsional stress rather than being converted into kinetic energy with wheel rotation. Thus, all simulations will be performed using 722 Nm and 361 Nm as the maximum loading condition where applicable. Note it is assumed that the spool splits the torque equally between the two axles. That is each axle experiences 361 Nm of torque.

For a spool differential, the torque split between the two axles is directly proportional to the loading of each wheel. For example, if the car is driving on a straight-away load distribution between the two wheels is 50/50 therefore torque split is also 50/50. If during a corner the inside wheel lifts off the ground, then 100% of the torque is going to the outside wheel.

Cornering

During cornering, there is lateral load transfer between the left and right wheels, causing additional loading on the outside wheel hubs. Additionally, the lateral forces produced at the tires create a moment at the wheel hub.

- **Lateral Load Transfer**
  Assuming the vehicle is capable of cornering at 1.4Gs of lateral acceleration, the load transfer between the inside and outside wheels is 612 N of radial force. Thus, the radial load on the inside wheels is decreased by 612 N while the outside wheel hubs are increased by 612 N.

- **Lateral Force**
  Assuming the vehicle is capable of cornering at 1.4Gs of lateral acceleration, this results in a centripetal force of 4353 N acting at the tires. The centripetal force with a tire radius of 0.26 m creates a moment of 283 Nm acting at the wheel hub.

Braking

During straight line braking, the braking torque applied to the brake rotor directly translates to the wheel hub through the wheel studs. In addition, longitudinal load transfer occurs between the front and rear wheels, changing the radial loading experienced by the wheel hub.

- **Braking Torque**
  The torque applied from the brakes is transferred from brake rotor/rotor hat to the wheel hub through the lug bolts. The brake torque experienced at the front is 342 Nm per front wheel hub and 105 Nm at the rear wheels. For simulations, the front braking torque was used.

- **Longitudinal Load Transfer**
  Assuming the vehicle is capable of decelerating at 1.3Gs, the load transfer between the front and rear wheels is 445.92 N of radial force per wheel hub. Thus, the radial load on each front wheel hub is increased by 445.92 N while the rear wheel hubs are decreased by 445.92 N.

Table 3 provides a high-level results summary of the test campaign, detailed in the following section, in which performance during the introduced operation concepts were tested. The table shows that the component with the lowest factor of safety is the front sprocket with an FOS of 1.6. Thus, if a failure were to occur, it is expected that it would be at the front sprocket. Front sprocket being the first component to fail would prevent extreme loadings from propagating to the driveshaft components, saving them from potential damages.

Operation Concept	Affected Components	Minimum Factor of Safety	Associated Component
Launch	All drivetrain components	1.6	Front Sprocket (**S-1**)
Cornering and Braking	Wheel Hub (**W-1**)	8.1	Wheel Hub (**W-1**)

Table 3: *Minimum factors of safety for operation concepts*

As proven through the test results, simulations of all the components show that the drivetrain can operate under all loading conditions the vehicle will experience on a racetrack. As a reminder, all tested loading conditions are produced by an unrestricted engine. In a competition setting the engine will produce less power and torque, thus ensuring an even higher factor of safety for our drive train system.

Compliance Analysis

Test Campaign

The drivetrain system design in its mature state at the end of the Test Readiness Review gate has been tested in a dedicated campaign. The test campaign focused on validation of individual components in relevant operation concepts. With the end deliverables adjusted to virtual design assets and their design and implementation documentation, the campaign involved testing the design through computer aided design (CAD) and finite element analysis (FEA) methods.

Test cases were defined for loadings occurring in three distinct operation concepts - **L**aunch, **C**ornering and **B**raking - for which the system performance parameters such as torque were prescribed. Test cases were formalized in test packages, which were tagged with identifiers of the following format:

Component	Description	Values
CATG	Test category / subassembly related to the test package	ASSM: Assembly level DIFF: Differential subassembly AXLE: Axle subassembly WHUB: Wheel hub subassembly
C	Operation concept simulated in the test package	M: Measurement / inspection L: Launch C: Cornering B: Braking
XX	Number of test package in the specific CATG-C group	

Table 4: *Test package identifier format*

Each package targeted the validation of a relevant group of project requirements for individual components or assemblies, and had the passing criteria aligned with performance and functional requirements defined in the foundational stages. Thus, the test campaign served as a formal mechanism for verification of requirement compliance. ***Table 5*** lists the project requirements and validating tests, whereas ***Table 6*** lists the tests in relation to the components tested. Brief descriptions of test packages and results can be found in the appendix.

A testing workflow was established to standardize testing efforts and documentation. As illustrated in ***Figure 7***, the workflow took into account the iterative nature of design and testing. Tests passed marginally based on the testers' opinion were planned to go through a design change process out of desire to improve the component performance to above marginally acceptable. For failed tests, non-conformance reports (NCRs) were issued to formally recognize faults in design and plan a path for resolution. Subsequent iterations of design and testing were conducted to reach a passing test.

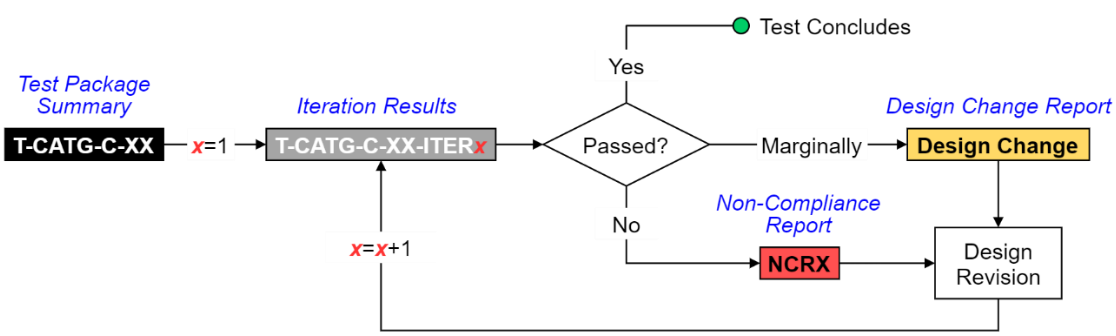


Figure 7: *Workflow for a test package*

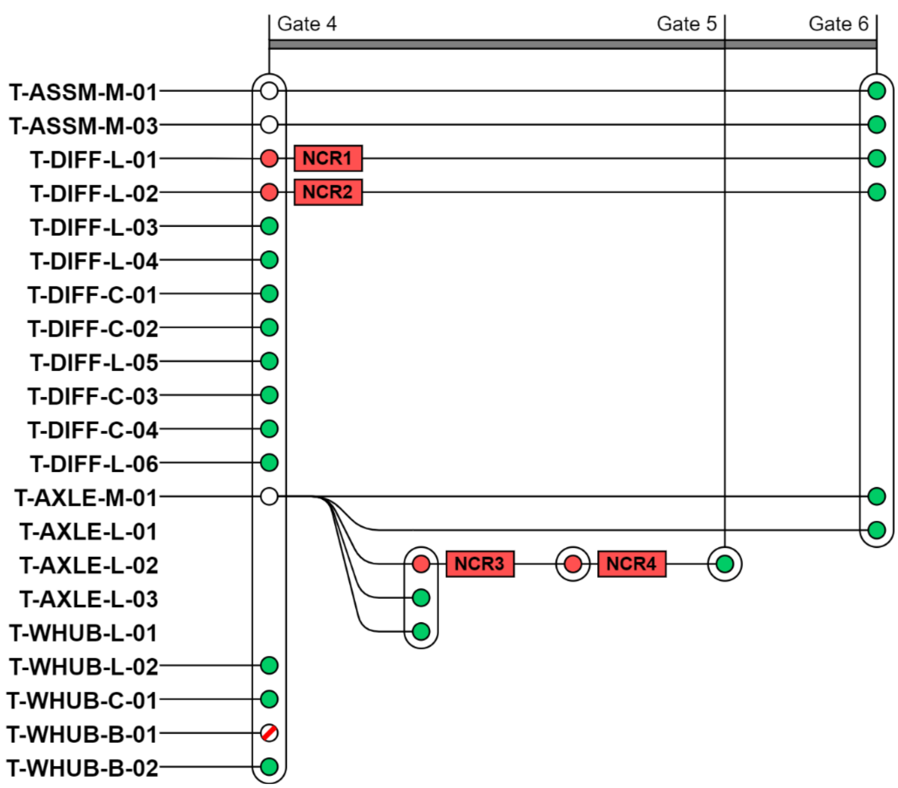
Requirement	Requirement Description	Tests Addressing Requirement
[RREQ-1]	Engine is connected to the wheels	**T-DIFF-L-01**, **T-DIFF-L-02**, **T-WHUB-L-01**, **T-AXLE-L01**, **T-AXLE-L-02**, **T-AXLE-L-03**, **T-DIFF-L-03**, **T-DIFF-L-04**, **T-DIFF-C-01**, **T-DIFF-C-02**, **T-WHUB-L-02**, **T-WHUB-C-01**, **T-WHUB-B-01**
[RREQ-2]	Chain and sprocket are shielded	**T-ASSM-M-01**
[RREQ-3]	Shield is solid, covers chain fully	**T-ASSM-M-01**
[RREQ-4]	Panel shield requirements, if used	No panels are used
[RREQ-5]	Frame member shield requirements	No frame members are used
[RREQ-6]	Gaps between shield parts	N/A – Shield is a single part
[RREQ-8]	Shield dimensions & alignment	**T-ASSM-M-01**
[RREQ-9]	Shield fasteners	**T-ASSM-M-01**
[RREQ-11]	Fastener requirements	No fasteners of the designed system are considered critical fasteners as per rulebook [1]
[RREQ-12]	Fastener requirements	
[RREQ-13]	Fastener securing – positive locking	
[RREQ-14]	Full engagement with lock nuts	
[RREQ-17]	Accepted positive locking mechanisms	
[RREQ-18]	Tie rod requirements	No tie rods used
[PREQ-1]	Top speed requirement	
[PREQ-2]	Static loading requirement	**T-DIFF-L-01**, **T-DIFF-L-02**, **T-WHUB-L-01**, **T-AXLE-L01**, **T-AXLE-L-02**, **T-AXLE-L-03**, **T-DIFF-L-03**, **T-DIFF-L-04**, **T-DIFF-C-01**, **T-DIFF-C-02**, **T-DIFF-L-05**, **T-DIFF-C-03**, **T-DIFF-C-04**, **T-DIFF-L-06**, **T-WHUB-L-02**, **T-WHUB-C-01**, **T-WHUB-B-01**, **T-WHUB-B-02**
[PREQ-3]	Fatigue testing requirement	**T-DIFF-L-01**, **T-DIFF-L-02**, **T-WHUB-L-01**, **T-AXLE-L01**, **T-AXLE-L-02**, **T-AXLE-L-03**, **T-DIFF-L-03**, **T-DIFF-L-04**, **T-DIFF-C-02**, **T-DIFF-L-05**, **T-DIFF-C-03**, **T-DIFF-L-06**, **T-WHUB-L-02**, **T-WHUB-C-01**, **T-WHUB-B-01**, **T-WHUB-B-02**
[FREQ-1]	Engine connected to the wheels	**T-DIFF-L-01**, **T-DIFF-L-02**, **T-WHUB-L-01**, **T-AXLE-L01**, **T-AXLE-L-02**, **T-AXLE-L-03**, **T-DIFF-L-03**, **T-DIFF-L-04**, **T-DIFF-C-01**, **T-DIFF-C-02**
[FREQ-2]	Component availability	**T-ASSM-M-03**
[IREQ-1]	Fit to the chassis	**T-ASSM-M-01**, **T-DIFF-L-05**, **T-DIFF-C-03**, **T-DIFF-C-04**, **T-DIFF-L-06**
[IREQ-2]	Must interface rotor, wheel, and knuckle	**T-ASSM-M-01**
[IREQ-3]	Axle plunging	**T-DIFF-C-01**, **T-DIFF-C-02**, **T-AXLE-M-01**
[GREQ-1]	Budget requirement	**T-ASSM-M-03**

Table 5: *Requirement - test package listing*

Test ID	Description	Tested Component
T-ASSM-M-01	Drivetrain Assembly – CAD Measurement and Inspections	Assembly
T-ASSM-M-03	Component, Material and Manufacturing Availability	BOM
T-DIFF-L-01	Front Sprocket Static Stress and Fatigue Analysis	**S-1**
T-DIFF-L-02	Rear Sprocket Static Stress and Fatigue Analysis	**S-2**
T-DIFF-L-03	Spool Bending	**D-1**
T-DIFF-L-04	Spool Torque	**D-1**
T-DIFF-C-01	Spool Axial	**D-1**
T-DIFF-C-02	Bearing Plate Shear	**D-4**
T-DIFF-L-05	Mount Bending in X	**D-3**
T-DIFF-C-03	Mount Bending in Z	**D-3**
T-DIFF-C-04	Mount Tubing Torque	**D-7**
T-DIFF-L-06	Mount Tubing Bending	**D-7**
T-AXLE-M-01	Axle Assembly Plunging	**A-1**, **A-2**
T-AXLE-L-01	Right Inboard Axle Adapter in Torsion at Launch	**A-8**
T-AXLE-L-02	Left Inboard Axle Adapter in Torsion at Launch	**A-7**
T-AXLE-L-03	Left Inboard Axle Adapter under Chain Tension at Launch	**A-7**
T-WHUB-L-01	Outboard Axle Adapter in Torsion at Launch	**W-8**
T-WHUB-L-02	Wheel Hub - Launch	**W-1**
T-WHUB-C-01	Wheel Hub - Cornering	**W-1**
T-WHUB-B-01	Wheel Hub – Maximum Braking	**W-1**
T-WHUB-B-02	Rotor Hat – Braking	**W-2**

Table 6: *Test package - component listing*

Figure 8: *Test campaign progress timeline*



End Status of Test Packages

Figure 8 displays the progress of the test campaign in terms of the iterations of individual test packages; where 🔴 indicates failed tests, 🟢 indicates passed tests, and ○ indicates tests on hold. No tests were passed marginally. Most of the tests were conducted in the period between project gates 4 and 5, in the designated testing phase. While most tests were passed in their first iteration, designs had to be iterated and tests had to be repeated for some parts. Second iterations of some parts (**S-1** and **S-2**) were tested after gate 5, by the time of the final delivery.

Some **[AXLE]** tests were initially planned to be conducted following the assembly-level test **T-AXLE-M-01** to ensure correct sizing. However, with the assembly-level test not being possible to complete due to other ambiguities with the vehicle design outside the scope of the project team, the dependent tests were conducted first. With a change in design strategy, specifically, leaving design flexible to allow adjustments by the client in the future, the assembly level test was completed later by the final project gate.

By the final project gate, all NCRs have been closed and all tests have been passed. Test results and NCRs (1, 2, 3, 4) can be found in the Appendix.

Review of Project Requirements

The final satisfaction status of project requirements is reviewed in the Project Requirements section of the appendix. Readers are directed to the results of the test packages corresponding to the requirements as listed in ***Table 5:*** *Requirement - test package listing* for queries regarding validation methods.

Below are discussions regarding the requirements and wishes that could not be satisfied:

- **[IREQ-4]**: Plunging
  The axle plunging system prevents excessive axial movement within the axle housing. For our project it was a requirement to have one to keep the axle in the optimal location and prevent potential damage to the axle. Due to uncertainties revolving around the exact engine placement, track width, and time constraints the plunging system was not developed. As a result, the requirement **[IREQ-4]** was not met. In the future, the Lassonde Motorsports team will have to develop an active plunging system once the exact placement and track width are defined.

- **[WREQ-1]**: Weight
  One of our goals was to have the entire drivetrain system weigh under 20 kg. This goal was not met as the current design weighs approximately 33 kg. The plan was to optimize the weight of each component after completing and reviewing the first round of simulation. This would have provided us the information to know where weight could be cut. For example, if a component had a very high factor of safety, more material could be removed to reduce weight. Due to time constraints, weight optimization was never performed after simulations. Although quickly analyzing the results, the mass of the wheel hubs and spool can easily be reduced. The Lassonde Motorsports team will have to continue this task past the capstone project.

Evaluation

With a successful test campaign which ended in all test packages being passed, and most project requirements satisfied, **the project team is of the belief that the designed drivetrain system is satisfactory in all capacities and can be implemented by the client with ease**. We therefore believe that the project concludes successfully, achieving most goals and leaving a useful end product. The reasoning for this conclusion is further detailed in this report through review of various aspects of the project, as well as in Package A.

Volume II:

Management

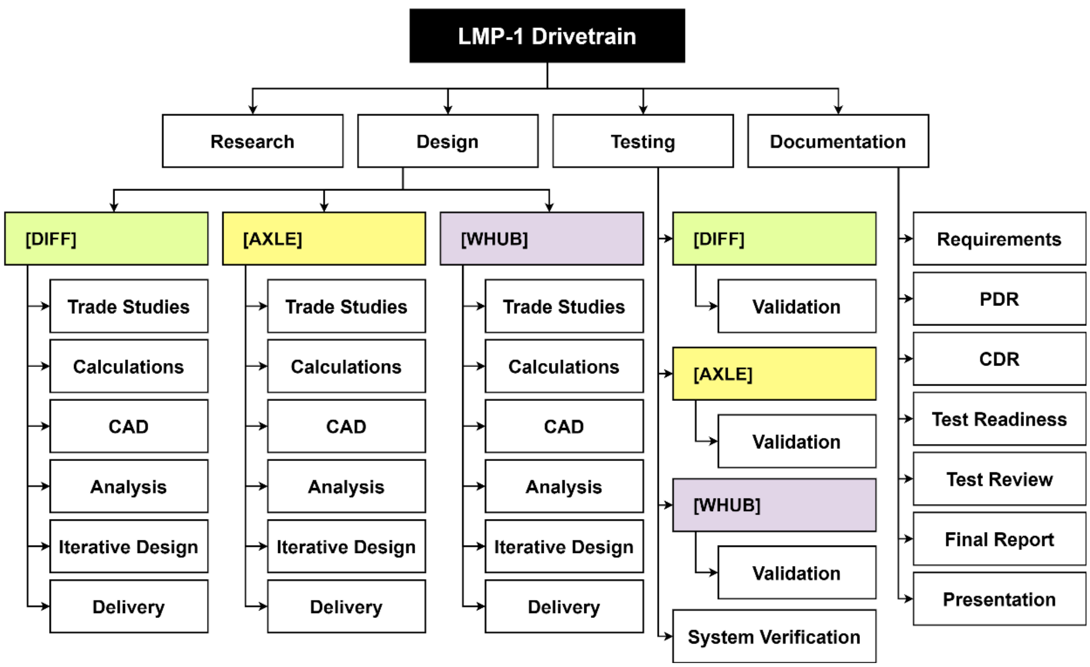
Project Management

This section presents the management mechanism and organization in this project through a number of tools including the work breakdown structure, work packages, resource allocation matrices and Gantt charts. Discussions of changes since the preliminary design report (PDR) are also included.

Work Breakdown Structure

Work breakdown structure (WBS) of ***Figure 9*** has been used as the hierarchical structure to organize work and team efforts around. Team members were assigned to different subsystems of the vehicle, each of which had its own branch in the main work categories of the project such as design and testing. Preliminary research and documentation efforts were conducted independent of subsystem responsibilities. Work packages were also organized in a folder structure mirroring the WBS.

Figure 9: *Work breakdown structure*



Work Packages

Since the PDR, the structure of work packages has not changed. As represented in the PDR, work packages have been completed in LiquidPlanner to represent the fields shown in the figure below.

WP ID:	WP Name:
Hours of Effort:	Work Package Manager(s):
Start Date:	Start Date:
Inputs Needed:	
Tasks to be Performed:	
Outputs Generated:	

Figure 10*: Work Package Entries*

The only change that has been made since the PDR is to the type of work packages created. As opposed to using work packages exclusively as a tool for planning, represented by fields such as expected work hours, expected start and finish date, the work packages now completed represent the as-built system. Thus, the exact start and finish dates are recorded along with accurate work hours. Additionally, to accurately capture the time committed to this project, unplanned hours contributed have been recorded in addition to the planned work hours.

Resource Allocation

In ***Table 7*** below, each group member's hours of work are represented per month. From the member totals shown, the total hours spent of the project is approximately 500 with an average of approximately 125 hours per member. As seen, all total work hours are within 10 hours of the average representing a close to even contribution from all team members.

What we can see from this table is that a large majority of work hours were done in the later months of each semester. This presents an opportunity for future projects to complete more work in advance in an effort to even the workload throughout the duration of the project.

Table 7*: Resource allocation matrix*

	2020				2021				
Member	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**March**	**April**	**Total**
Alex	2	5	15	28	0	8	10	52	120
Can	2	3	20	24	0	8	13	65	135
Navid	2	8	12	24	0	3	20	56	125
Peter	2	7	32	16	0	3	11	51	122

In ***Table 7*** above, the hours have been compiled from individual work packages entered into LiquidPlanner. As seen, a significant number of work packages have been added since the PDR to record working hours.

All work packages created throughout the duration of the project can be found here.

Project Schedule

The final Gantt chart for Team H's 2020-2021 Capstone project can be found in the Appendix. The generated Gantt chart has been made according to the structure outlined in the WBS above and serves as a project management tool to organize the allocation of resource through this project as well as reflect the amount of time committed to tasks within the scope of Research, Documentation & Reporting, Design, and Testing.

Since the PDR, a number of changes have been made to the Gantt chart through the addition of work packages. The predominant additions include:

- Documentation for gate reports, presentations and final deliverable packages
- Design of individual components and system assembly
- Purchasing of components for design purposes
- Simulated testing procedures

Additionally, as the project scope was changed in the Test Readiness review gate, changes were also made to the project schedule. First, manufacturing and conducting physical testing is no longer within scope and is therefore not represented in the project schedule. Alternatively, two new deliverables have been added to the project - Package A: Manufacturing, Assembly and Testing, and Package B: Design Development Package - which are now represented in the project Gantt chart through the addition of work package descriptions.

Project Expenses

Below is the listing of project expenses.

ID	Date	Item	Cost
C1	01/29/2021	CV Axle TRAKMOTIVE FD8038 (Ford Focus) RockAuto Order 165397482	$46.06 CAD $16.72 CAD Shipping $8.16 CAD GST/HST (13%) **$70.94 CAD Total**
C2	02/18/2021	CV Axle TRAKMOTIVE FD8023 (Ford F150) RockAuto Order 166875820	$73.40 CAD $21.58 CAD Shipping $12.35 CAD GST/HST (13%) **$107.32 CAD Total**
C3	02/24/2021	Refund for **C1** (RockAuto Order 165397482) Return Label 9035795823	$12.65 USD ($16.01 CAD) **-$16.01 CAD Refunded**
C4	02/27/2021	CV Axle TRAKMOTIVE VW8043 (Volkswagen Beetle) RockAuto Order 167626667	$55.78 CAD $15.27 CAD Shipping $9.23 CAD GST/HST (13%) **$80.28 CAD Total**
C5	03/25/2021	1.75mm Pink PLA 3D Printer Filament - 1kg Spool (2.2 lbs) - Dimensional Accuracy +/- 0.03mm 1.75mm Lake Blue PLA 3D Printer Filament - 1kg Spool (2.2 lbs) - Dimensional Accuracy +/- 0.03mm OVERTURE PETG Filament 1.75mm with 3D Build Surface 200mm × 200mm 3D Printer Consumables, 1kg Spool (2.2lbs), Dimensional Accuracy +/- 0.05 mm, Fit Most FDM Printer, Purple Amazon.ca order 702-0798038-8543436	$98.97 CAD $8.58 CAD GST/HST **$107.55 CAD Total**
		Total Expenses	**$350.08 CAD**

Documentation regarding expenses listed is available online.

Business Case

In the early stages of the project value propositions and stakeholder needs were defined. Now in the final stages of the project, these initial aims are evaluated below.

Value Proposition

The value propositions below will now be evaluated as the project approaches completion. How we believe the work conducted over the past year has created value for Lassonde Motorsports, new FSAE teams, and Lassonde school and students is discussed.

A cost-effective and reliable solution for LM

According to the Bill of Materials, the total component cost comes to $1,514.42 CAD, if we assume manufacturing and material process is an additional 25% and extra tooling is 10% the system total comes to $2,082.33 CAD. This total system cost is almost $1,000 under the team's original goal of keeping the cost under $3,000 CAD. With purchased pre-built components, this value never could have been achieved. With LM being a new, and relatively low budget team, this cost-effective drivetrain creates great value.

Novel in drivetrain design space, exemplary for new teams

In such a well-studied field, novel design is a true challenge, but with the use of custom components, unique solutions can be made. While the overall design of the drivetrain system is well established, the use of custom sprockets, spool differential, axle mounts and wheel hubs result in a novel design. With the use of custom components, each part is much more effectively tailed to the existing specifications on the LM vehicle. With access to design documentation, new teams can draw great value from this year's Team H FSEA drivetrain.

Contributing to a vehicle with high sentimental value for the school and students

With the completion of a near ready to install drivetrain design, LM team members have gained great value and are significantly closer to their goal of producing a competition ready car. Additionally, from the material produced by Team H, the LM team members have much to learn about the full design process. Finally, with additional design material and the necessary information to implement a complete drivetrain system, LM is in a much greater position to recruit new and excited student members.

SWOT Analyses

The following is a comprehensive list of the predominant stakeholders associated with this project. These stakeholders include those relevant to capstone Team H: Drivetrain System. Below, LM will be represented as the client, where Team H is responsible for delivering a comprehensive drivetrain system complying with requirements set by pre-existing components. The stakeholders listed below are each given a brief introduction and are then followed by a list of what they require from the primary stakeholder, Capstone Team H: Drivetrain System.

Capstone Team H: Drivetrain System

We, as Capstone Team H, have been contracted by the LM team to design a comprehensive drivetrain system that will work effectively in conjunction with a partially pre-existing vehicle to compete in an official FSAE competition. As stakeholders, Team H has had the following needs:

- A budget for purchasing components
- Stated requirements and restraints from LM and Capstone course administrators
    - LM: Provide FSAE rules as well as limitations imposed by pre-existing design
    - Capstone: Comprehensive gate deliverable outlines
- Technical understanding of the drivetrain system
- Knowledge of existing drivetrain systems

Strengths
The team's main strength is that it has a history of working together in past projects including motorsports projects on the Lassonde Motorsports team. The dynamic that's been developed has been proven to work since there's a great awareness of each other's abilities and flawless communication.

The team has been very involved in the Lassonde Motorsports team and has worked on numerous projects including chassis, brakes, steering, and suspension. The background knowledge the team has gained over that time is very valuable in developing a drivetrain system for the same racing vehicle.

Weaknesses
One weakness the team faces is having to balance everything happening in capstone with regular schoolwork. Since this is the final year, the team finds it very important that not only does the project have the proper attention it needs, but also that the members are still able to succeed at their own course work. At times, there seems to be a trade-off between regular course work and capstone work.

Opportunities
From this project, many opportunities sprout. Mainly, the team's ability to build up from the project and sprout better designs in the future. Part of the project's goals was to have more students gaining interest in Lassonde Motorsports in the future and this is a great opportunity to showcase how the material learned in mechanical engineering can be applied to the automotive industry.

Threats
The team does not face many threats however, one looming threat which its likely on all teams' minds are the challenges that the team could face in light of the COVID-19 pandemic. The team has already been limited significantly by the current restrictions in place however, there is always a threat that restrictions could

Lassonde Motorsports
The members of the LM team (the client) are responsible for the design and construction of a regulation FSAE vehicle. As stakeholders, LM team members have the following needs:

- Capstone Team H to design a complete drivetrain system within the constraints of pre-existing components and FSAE rules
- A cost-effective solution
- Effective communication with a design team representative
- For the project to be completed by the end of April 2021
- Thorough documentation explaining every step of the design process to be used as an educational tool for new and existing members

Strengths
As mentioned, the team is composed of members who have had past experience in the Lassonde Motorsports team. The teams thorough background of the motorsports competition and the vehicle gives an advantage in this project.

Weaknesses
A key weakness of the team is the disconnect between the current project and the team's current operations. There hasn't been much clarity regarding some design specifications such as engine placement which is critical to the drivetrain design however, the team has combatted these ambiguities by making the design adjustable.

Opportunities
An exciting opportunity in this project is that if done successfully and to the liking of Lassonde Motorsports, they could continue to provide in depth automotive and motorsport related capstone projects for future students which could develop the student body's understanding of motorsports but also develop the racing team - a symbiotic relationship.

Threats

Threats to this stakeholder relationship is the possibility of Lassonde Motorsports temporarily terminating its operations due to COVID-19 or them no longer being able to provide guidance and support.

Lassonde School of Engineering Students

The students, even those not involved in ENG4000 or the LM team, play a role in this project, as the hope is they will become motivated to join the LM team as a result of the work that is being done and the opportunity this presents them to learn. As stakeholders, Lassonde students have the following needs:

- A well designed and thoroughly documented drivetrain system for use as an educational tool to help students learn about the design and implementation of complex systems

Strengths

The students outside the project are very much involved in this project since there have been peer review sessions every couple weeks or so since the beginning of the project. Those meetings have them involved and allows them to give feedback on the team's progress which is very valuable for the team. The team is usually caught up in all the minor details that it can be easy to forget come critical components or to overlook something but the student body, having that external look on things, makes it clearer.

Weaknesses

A weakness in this relationship is that the general student body might not be too knowledgeable in drivetrain design so it could be difficult to grasp concepts the team is trying to present and the benefits that have been developed as a result of this project.

Opportunities

A great opportunity in this relationship is that the general student body could become much more interested and involved in this project and Lassonde Motorsports in general which would allow the team to continue to develop competition vehicles in the future.

Threats

On the other side of the same coin, the students could also not find interest in this subject matter and the general interest in these sorts of projects could fade if its importance is not stressed well enough or the opportunities are not well highlighted.

Suppliers, Manufacturers & Specialists Conducting Outsourced Work

Outsourcing can be an effective tool when conducting a complex project, especially under the current pandemic conditions with machine shop access being limited. The students that make up the LM team (the client) are not experts in every field that a project such as building a race vehicle requires. With this limited knowledge, it is important to realise that outsourcing can be effective, predominantly for manufacturing and specialty trades. As stakeholders, specialists have the following needs:

- Clear and comprehensive specifications (e.g. part and assembly drawings)
- Payment
- Shipping Information and school affiliation
- Clear and comprehensive communication regarding work to be done

Strengths

One key strength the team has in terms of this kind of relationship is that the external groups that assist the team in completing its project have some sort of grace for student groups. The supporters of this project know what it was like to once be a student in their final year completing a project, so they've always been very gracious in assisting the team in getting to their goal.

Weaknesses
A weakness in this relationship is that there can be a disconnect between what needs to be achieved versus what's actually being communicated. The team has found that it's been making several simplifications in nomenclature which can be difficult to translate to industry professionals.

Opportunities
An opportunity in this relationship is that the team gets to make a name for Lassonde School of Engineering and Lassonde Motorsports which could be beneficial for teams in the future that might need their assistance for their own capstone projects.

Threats
A threat in this sort of relationship is always the possibility that the external party could always become disinterested in assisting the team or not be able to help by some other means down the line. This means that the team would have to reconfigure its plans, which at any point, is a burden.

Other Schools' FSAE Teams
Oftentimes, new teams - such as LM - will gain a large portion of information from other, more established, teams. Thus, the relationship between new and established teams created a productive community for students to thrive. As stakeholders, FSAE teams from other schools have the following needs:

- Easy access to communication from those actively working on projects for the LM team
- A sense of give and take; when teams are new and often require more assistance, relationships can become one sided, so for new teams it is essential to help out wherever possible

Strengths
Utilized before this project, other FSAE teams have the ability to give insight into projects that the motorsports team is taking on for the first time, in this case drivetrain. Their experiences have tonnes of value and could be critical in guiding the team in the right direction.

Weaknesses
Much of the time, teams rotate their members, and they don't have the specific members who had worked on that specific section of the vehicle which could leave the team without answers.

Opportunities
Partnerships between teams are always welcome. Having worked together teams could always create opportunities for future partnerships which could benefit both teams.

Sponsors of LM
Sponsors play an essential role in the process of developing an official FSAE competition car through means of financial support, professional advice and outsourcing. As stakeholders, sponsors have the following needs:

- A thorough list of what has been accomplished with respect to design
- How being a sponsor will benefit their business - likely through promotion and marketing
- How their business can contribute and how much - often communicated in terms of sponsorship 'tiers' all with possible contributions (monetary or service related) followed by the type of promotion they can expect to receive as a result
- Effective communication with a design team representative

Strengths
LM sponsors can ease the financial burden that the drivetrain brings come time to manufacture and assemble.

Weaknesses
There is not much that the team can offer back in terms of service.

Opportunities
In this relationship, the team receives the service while the company receives promotion via all the publications and presentations.

Threats
Corporate sponsors could always be “poached” by other FSAE teams since many companies choose to be exclusive with a single team.

Capstone Course Facilitators at the Lassonde School of Engineering
By providing guidance and advice, those facilitating the Capstone course, including course instructors, project advisors, and teaching assistants all play an essential role in assisting students. Additionally, faculty representing The Lassonde School of Engineering have a large contribution in terms of financing and providing a space and platform for students to collaborate. As stakeholders, course facilitators as well as faculty representing The Lassonde School of Engineering have the following needs:

- Communication from team members
- Students perceptive to input
- Timely deliverables (i.e. gate reports)
- All budget limitations and requirements outlined by the Capstone course to be met

Strengths
The team is a part of the Lassonde School of Engineering so it's very much aware of how to approach this project with Lassonde and York in mind as a stakeholder. The school wants nothing more than the success of the team which is a very valuable strength since the team needs all the help it can get in completing the project.

Weaknesses
It is not as if the drivetrain team is the only group this year completing a capstone project so it must remember that when seeking assistance from Lassonde and York that requests are reasonable, fair, and in order.

Opportunities
Lassonde and York have proven to be a great supporter of this project and there can be many more opportunities in the future for them to support the team and the club.

Threats
There is little that can happen that could disrupt this relationship without stopping the project as a whole - except for a strike.

Volume III:

Reflection

Deviations

A significant deviation from the original plan for the project was changing the scope in the test readiness review gate. At a state in the project where we knew we had to make a decision, we decided that manufacturing, assembling and physically testing the drivetrain would not be an effective use of our time. Given the situation resulting from this year's pandemic, necessary equipment would not be available as well as a platform for in person collaboration. As a result, the team shifted its scope to focus on delivering an amazing design for the drivetrain system. This includes defining new deliverables, Package A: Manufacturing, Assembly and Testing Manual, and Package B: Design Development. Collectively, these new deliverables are meant to give a more comprehensive understanding of the system allowing for easy implementation at a later date when the necessary equipment and collaborative platform are accessible.

The following subsections include examples design changes for each subassembly since the preliminary design stage.

[DIFF] Deviations

Sprockets

In the initial drivetrain design, we planned on using the stock sprockets from the 1990 Suzuki Katana 600 motorcycle, which utilized size 50 roller chains and sprockets. In the final design, it was decided to switch to a custom manufactured solution switching to size 40 roller chains and sprockets.

The advantage of using size 40 sprockets and chain is that the physical size of the sprockets is smaller for the same gear ratio (dimensions are shown in the table below). With the new size 40 sprockets it will allow for larger rear sprockets (over 47 teeth) to be exchanged in the future for testing gear ratios without having the sprocket extend past the bottom chassis tube (Requirement: [IREQ-1]), decreasing ground clearance. In addition, having a custom sprocket will also allow us to have a create our own mounting solution rather than having to conform to the stock mounting location.

Table 8: *Sprocket dimensions*

Dimensions	Size 50 (chain #530)	Size 40	Difference
Front Sprocket diameter (14 teeth)	2.8 in	2.25 in	-0.55 in
Rear sprocket diameter (47 teeth)	9.35 in	7.48 in	-1.87 in
Chain pitch	0.625 in	0.5 in	-0.125 in

Spool

When first creating potential spool designs, it was not certain where the differential would be placed in the vehicle with respect to the engine. Because of this, we could not be sure what the order of components would be. It was certain that the spool must have space for the bearings to be inserted from the ends while also having space for the sprocket to be attached. The total sequence for installation of parts on the spool was unknown. After some research and debate, it was determined that the spool would have the sprocket sat on the far-left side and the two bearings and mounts slightly biased to the right.

Adjustments to the dimensions of the spool varied throughout the development of the drivetrain, however, the overall configuration had never changed. A noteworthy change to the spool somewhat late in the development was the fillet feature seen in the middle of the spool.

Initially the fillets were created by using the “Fillet” feature in Solidworks on the solid body that was created by revolving a sketch along the center axis. This feature proved to be difficult to dimension when drawings for the components had to have been made since the fillets were skewed. To address this, the fillets were added as arcs in the base sketch. With the fillets defined this way, the features could be fully defined and dimensioned in the drawings.

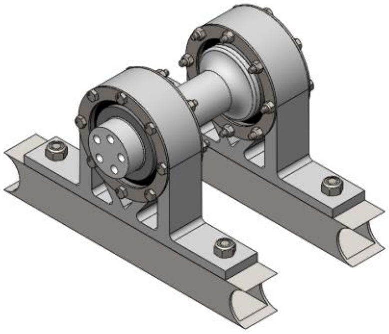


***Figure 11**: Differential assembly*

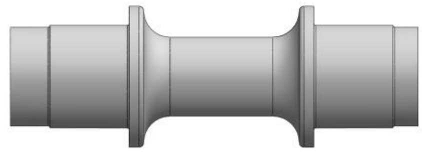


***Figure 12**: Spool component*

Mount and Bearing

Up until CDR, the bearing was assumed to be sat in the differential mount simply by a friction fit. After review and meetings with the team's faculty advisor, it was determined that the bearings should be secured to the mount not only by a friction fit but also by a plate of some sort that could be added on once installed in the mount. The bearing mount plate was created before test readiness and added in as a design revision. The bearing mount plate is secured to the mount by eight nuts and bolts; there are a total of 4 bearing plates covering the two bearings from either side.

The mount was always designed to be fixed onto two parallel square tubes situated on the bottom portion of the rear suspension box of the chassis. The mount was initially designed to have four nuts and bolts to connect the mount to those tubes with two bolts on the outside of the mount and two under the bearing hole feature.

It was realized that the nuts that would fasten the two inner bolts would be difficult to access during insulation and maintenance. It was one of the goals of the team to create a design that would be easy to install and maintain for the team, so it was seen necessary to address this difficulty. The second iteration of the mount had the two inner bolts secured by an internal threading in the mount.

This also eliminated the need for the two nuts which would marginally decrease the mass of the drivetrain.

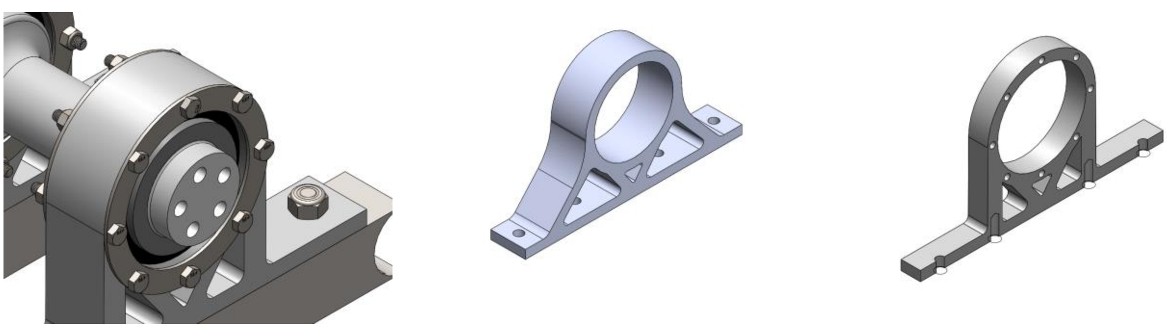


***Figure 13**: Differential mounting*

[AXLE] Deviations

The design strategy for the axle subassembly underwent significant changes since the preliminary design stage. The preliminary design stage involved component selection based on the assumption that a unique axle assembly with individually procured components will be composed. Upon further design and budgeting work, it was determined that the [AXLE] subassembly would be the most significant contributor of the system and procuring individual and dedicated components from specialty suppliers would be costly. Therefore, in the critical design stage, the idea of utilizing a pre-built axle assembly for a conventional vehicle was adopted. Research for axles of suitable length was conducted, and an ATV axle was determined as a likely option, as detailed in the Critical Design Review Gate Report.

Detailed design specifications for pre-built axle assemblies are not widely available. Realizing that the exact axle dimensions can only be measured once the part arrives, and the interfacing components can only then be designed; we developed plans to integrate the final **[AXLE]** design to the system later than other subsystems.

At the CDR stage, plans involved purchasing a built assembly and replacing its CV joint housings with custom made ones in order to connect the housings to the rest of the system with ease. This was a particular area of concern and thought, as the most pre-built axles for consumer vehicles had splined end connections; and the project team believed that it would be difficult to measure the splines on the purchased parts and manufacture matching splines.

Moving forward with the pre-built axle integration plan, the team identified several other axle options with simpler integration methods which would not involve making custom housings. We iterated with several axle options, actually purchasing a few to take measurements. The first purchased axle assembly (cost item **C1**) was found to be different than the design inferred from online photographs and was returned due to difficulty of integration. The second purchased axle (cost item **C2**) was found to be defective, could not be disassembled, and was damaged during disassembly efforts. Finally, in the Test Readiness Review stage, an axle assembly made for 1968 Volkswagen Beetle was found as the simplest to integrate with low costs.

From this point onward, the final **[AXLE]** design revolved around integrating the Beetle axle assembly to the drivetrain. Adapter parts to interface joint housings were developed. Joint housings were 3D scanned by our sponsor Objex Unlimited, and we were able extend the ball grooves on the joint housings inside the adapter parts as shown in ***Figure 14***, to enable higher degrees of plunging, which is governed by **[IREQ-3]**.

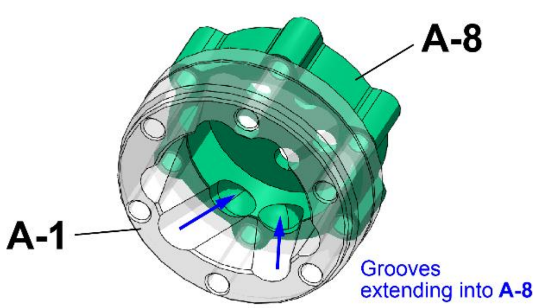


Figure 14: *Grooves of the joint housing continuing in axle adapter*

Preparing the final **[AXLE]** design, the project team had difficulties determining exact component dimensions due to ambiguous engine dimensions and positioning. Due inability to access the Lassonde Motorsports facilities to take measurements off of the engine, the plane of the sprockets remained uncertain, which led to uncertainty in the position of the center stack components, as further detailed in **Package A - Design Completion**. The asymmetry in positioning of the center stack was planned to be compensated by making the left inboard axle adapter **A-7** a flexible length component, ready to be extended further towards the left wheel, based on the distance of the right axle housing to the right wheel.

[WHUB] Deviations

This section will cover the design changes to the wheel hub sub assembly since the preliminary design determined in the Critical Design Review. Based on consultation with faculty advisor Garrett Melenka, independent research, and collaboration with capstone Team G: FSAE Brake Systems, the following changes have been made.

[II-8] Interface Connection

First, the previously implemented protruding threaded bolt and dowel pattern (***Figure 15***) has been replaced by a 5 times M10x1.5 circular bolt pattern (***Figure 16***). This change was prompted by the advice from faculty advisor, Garrett Melenka, who advised our group that threaded holes would be more effective for axle interfacing compared to a protruding threaded bolt. This design change has eliminated the need for dowel pins as torque can now be sustained by 5x M10x1.5 bolts, each 35mm long. Additionally, due to the superior performance of the threaded bolt pattern, the rear cylindrical portion has been shortened to the minimum length - just long enough to rotate within the full thickness of the bearing and long enough to house the 35mm bolts connecting the outboard axle housing to the rear of the wheel hub.

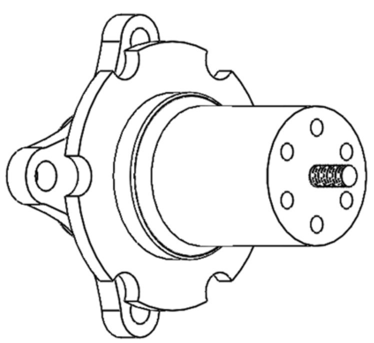


Figure 15*: Wheel hub - original - extruding bolt*

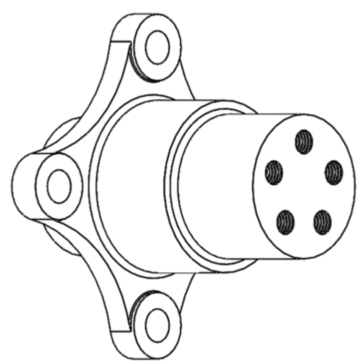


Figure 16*: Wheel hub - new - 5 x threaded bolt pattern*

Brake Rotor Mounting

Second, based on collaboration with capstone Team G: FSAE Brake Systems, the brake rotor mounting method has been changed from a protruding ring offset from the wheel mounting towards the center of the car ***Figure 17*** to what is referred to as a rotor hat (***Figure 18***). The implementation of a rotor hat will mean easier assembly / disassembly as the brake / wheel hub sub assembly can be assembled outside of the car - this is advantageous as the wheel well is one of the most densely packed and complex areas of the car. Through assembly and testing of the car, greater accessibility to this area is of great value. This change will mean that torque coming from the braking force acting on the rotor, as well as the torque being delivered to the wheels from the engine, will both be acting on the now shared mount for both the wheel and braking rotor. Thus, as seen clearly in ***Figure 16*** above, the wheel mounting holes have been made thicker with an added fillet to account for the additional stress of braking force.

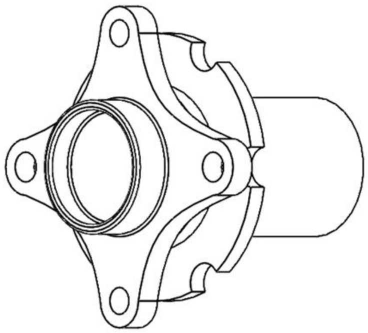


Figure 17*: Wheel hub - original - integrated rotor mount*

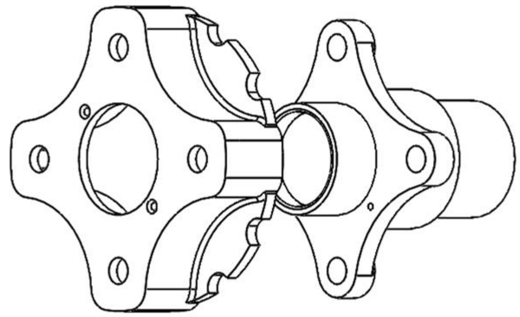


Figure 18*: Wheel hub - new - rotor hat*

Wheel Mounting

The initial wheel mounting solution utilized wheel studs and lug nuts ***Figure 19***. Wheel studs allow for easier installation of the wheel because the wheel can be aligned and held in place by the wheel studs. But they are required to be installed from the back of the wheel hub. This was an issue because there was minimal spacing behind the wheel hub, meaning the wheel hub would have to be pressed out of the bearing for a wheel stud replacement. The second iteration switched from wheel studs to lug bolts ***Figure 20***, this allowed the threads to be installed from the front side of the wheel allowing for easy replacement if they were to break. The issue with lug bolts is it makes it harder to install the wheels because you have to manually align the holes of the wheel and wheel hub. The final solution was to utilize a lug bolt conversion kit ***Figure 21***. This combined the best features of both the wheel studs and lug bolts. The threaded studs are installed into the wheel hub from the front side, making it easier to replace and having studs makes wheel installation easier.

Figure 19*: Wheel studs - first consideration*

Figure 20*: Lug bolts - second consideration*

Figure 21*: Lug bolt conversion kit - third consideration*

Failures & Lessons Learned

Below is a summary of the project failures and the lessons that followed. Here we discuss how we plan to more effectively deal with similar situations moving forward.

- **Time Management**
  As noted in Resource Allocation, time dedicated to this project is heavily skewed towards the gate report submission date, predominantly towards the end of each semester. This was a failure for our group as we were unable to regularly commit time to working on the project when a gate report or deliverable was not in the near future. With the addition of other course work, work aside from Capstone was often prioritized towards the beginning of each semester. In defense of our resource allocation strategy, working closer to due dates allows for more effective prioritization within a smaller amount of time, easier collaboration as each member is actively working on the project and great system level understanding as each member of the team is actively communicating capstone related information at all times. In the future, we realize that although a majority of work may be completed close to deadlines, setting compulsory work hours each week for team members would allow for a more progressive workflow and lower stress. An added benefit is being able to run into challenges early. When unexpected challenges arise close to deadlines either compromises must be made, or long work hours and stressful work environments arise. With a more progressive workflow, problem solving can be done much more effectively and stress can be reduced prior to project deliverables.

- **Component Purchase**
  The axle assembly and 3 iterations with purchased axles will remain in our minds as a cautionary tale. Due to our late realization that a uniquely composed axle assembly would be too expensive, we did not have enough time to look for and query about axle specifications once we decided to use a pre-built axle assembly. The lesson learned is to make decisions regarding part sourcing early on, keeping the economics of the design in mind from the beginning. Having a set track to follow will give more time to conduct in-depth research. Still, we do realize that the situation we faced is not unique or extraordinary, and such changes in design approach can happen in other projects as well. For a case where procurement strategy was changed radically towards the midpoint of the project, we believe that we handled the situation rather well.

- **Concise Reporting**
  Throughout the duration of the project, the primary goal for reporting was to produce quality information on each and every section outlined by Capstone Project Deliverables Document. At times this results in exhaustive report writing with the intent to not miss a possible marking criterion. We believe this is the most effective strategy for achieving success in the Capstone course with respect to grading, although a more concise reporting strategy may be more effective for delivering important information to the reader. In the future, we plan to shift the style of our report writing to prioritize convey technical information in the most effective way.

- **Focus on Design**
  As mentioned in Concise Reporting, for the purpose of developing and evaluating student's management and learning, the Capstone course emphasizes these sections in report writing. In the future, we hope to refocus our sights on the technical design aspects of reporting. To effectively convey the information for our drivetrain design, a more effective approach would have been to prioritize design documentation. Additionally, as reporting management and lessons learned takes a significant amount of time in the Capstone course it takes away from student's time available to focus on the development of their design. We do not believe this is a fault of the Capstone course but something to consider moving forward where we expect the quality of design to be the priority.

Gate Reflections

Below is a final reflection on how we would have run each of the project phases differently if we had the hindsight available to us now, and what we would suggest doing differently moving forward.

- **Project Definition and Requirements Review Gate**
  - With this gate having less focus on design, this would have been a good opportunity to conduct further Market Review, and Component Identification in an effort to prioritize design elements.
  - As resource allocation proved to be a monotonous task, the lower workload of this gate would have been a good opportunity to begin laying out the planning and scheduling for the project.

- **Preliminary Design Review Gate (PDR)**
  - A more effective approach to resource allocation at this stage would have been to prioritize doing it accurately and thoroughly the first time as this is easier than having to fix it later when each member will have to rely on their memory of completed tasks.
  - As the bill of materials proved to be a difficult task to finalize, this gate would have been a good opportunity to ensure accuracy in the early stages.
  - At this stage of the project a large portion of the calculations were completed for the drivetrain. Thus, this gate would have been a good time for each member of the project to review the calculations and have a more thorough understanding of the system as we head into the design phase.

- **Critical Design Review Gate (CDR)**
  - At this stage in the project preliminary finite element analysis was conducted. However, the loading conditions were not fully understood at this time as the testing procedure had not yet been detailed. It may have been more effective to spend more time on modeling the designs and leave testing to the following reports. As loading was not fully understood, many of the simulations were slightly less than ultimate loading, which gave a rough idea but also gave us false confidence in some ponents as initial FOS was very high
  - In the CDR the resource allocation records could have been refined to reduce work later on, but this was instead delayed. The accurate work hours were represented for this report but timelines showing progression of work done lacked accuracy. For planning it would have been better to address this issue at this gate

- **Test Readiness Review Gate (TRR)**
  - In the test readiness review it would have been ideal to layout physical testing procedures for the drivetrain. However, we did not feel we had enough time to do this, and they were delayed until the final report. This was found to be acceptable as physical testing was not conducted in the following test result gate.
  - At this stage in the project the change in scope was detailed with explanations for packages A and B. Therefore, we could have started laying out these reports, despite them not being a deliverable as part of this gate report.

- **Test Review Gate (TR)**
  - The quality of simulations may have been improved if we had consulted with faculty advisor Garrett Melenka prior to our submission. If the timeline for this gate's resource allocation started earlier, consultation may have been possible.

- **Final Project Gate**
  - In hindsight, packages A and B should have been started much earlier as these are design heavy documents. We could have been more effective with our time by focusing our efforts on reporting for this gate as to most effectively represent our efforts through the Capstone project.

Self-Evaluation

Criterion

The criterion for this deliverable, originally defined in the Capstone project deliverables document, are represented in the structure of this report.

Criterion for this deliverable as defined by the team include a finished and computationally tested drivetrain as well as previously defined packages A and B. As stated, these team defined criteria are in addition to those detailed in the Capstone project deliverables document.

This deliverable representing the end of this project, all goals and deliverables defined in previous reporting must be completed with the submission of this deliverable as no more resources are to be allocated to this project within the scope of the ENG4000 course. Additionally, this deliverable again being the final one, all criterion outlined in deliverables leading up to this must be satisfied to ensure the thorough completion of the project.

Self-Evaluation Ranking

While the team has certainly met the criterion for including all necessary documentation and deliverables, the quantity of the work alone is not enough to judge. Throughout the development of this drivetrain system the team has sought to give attention to every small detail not only in design but in documentation and deliverable packages to Lassonde Motorsports. Consistent meetings with the team supervisor and peer review TA had allowed the team to gain constructive feedback throughout the project which was implemented every step of the way. The team believes that given the conditions, it has performed very well, a sentiment that is also shared by the team supervisor, Professor Garrett Melenka.

Justification

The team has gone above and beyond providing the necessary packages and deliverables. For the entirety of this project, the team's motivation was not the mark, however, the quality of the product we could deliver to the Lassonde Motorsports racing team since we had significant roles in the team previously. The team believes that FSAE clubs are a great opportunity for students to apply what they've learned in the classroom on the racetrack and the as Team H our intention has been to keep that tradition going. The team worked diligently to make sure that our final product was not only competition ready but also a key educational tool for students. This can be seen in the great detail given in the adjustment and modification section come time for implementation, detailed assembly instructions, drawings, test packages, physical testing procedures, and the overwhelming satisfied requirements.

With respect to reporting and documentation, specifically referencing the level of detail that the team has implemented, deliverables have been conducted useaccording to the highest possible quality within the time given. This claim is well justified by the extensive figures used representing design details such as system FOS and mass, as well as project management where work breakdown, functional structure and test campaign results have all been recorded in great detail.

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[9] M. Williamson, "How Lubricants Affect Climate Change and Our Planet," Machinery Lubrication, [Online]. Available: https://www.machinerylubrication.com/Read/314/lubrication-environment. [Accessed 23 12 2020].

LMP-1 Drivetrain

Package A

Manufacturing, Assembly and Testing Manual

Prepared by 2020-2021 Capstone Team H
Navid Alaee
Peter Fung
Alexander Pady
Can Unlusoy

LASSONDE MOTORSPORTS

with the support of OBJEX UNLIMITED

Introduction

Package A is intended for use by the members of Lassonde Motorsports to gain the necessary understanding to manufacture, assemble and test the drivetrain system designed as part of the 2020-2021 ENG4000: Engineering Project course.

As the project was conducted under the circumstances of COVID-19, the project team did not have access to the club or manufacturing facilities and chose to deliver a ready-to-build design. The design is left with some unfinalized aspects, detailed further in the section Design Completion along with the procedure to completion.

This document outlines every aspect of the manufacturing, assembly and testing processes required to construct the drivetrain system compliant with the regulatory and design requirements in a step-by-step and self-sufficient manner such that the team can conduct them using only the information provided without having to refer to any other document or do additional research. No details regarding the design processes are provided in this package, and it is intended to be a manual for the physical processes deferred to the client as a result of the scope revision.

The document comprises:

- Bill of materials (BOM) with links and necessary information to guide material and part procurement
- Technical drawings of all components to be manufactured
- Manufacturing and assembly instructions
- Physical testing procedures for the built assembly to verify compliance with the regulatory, performance, functional and interface requirements

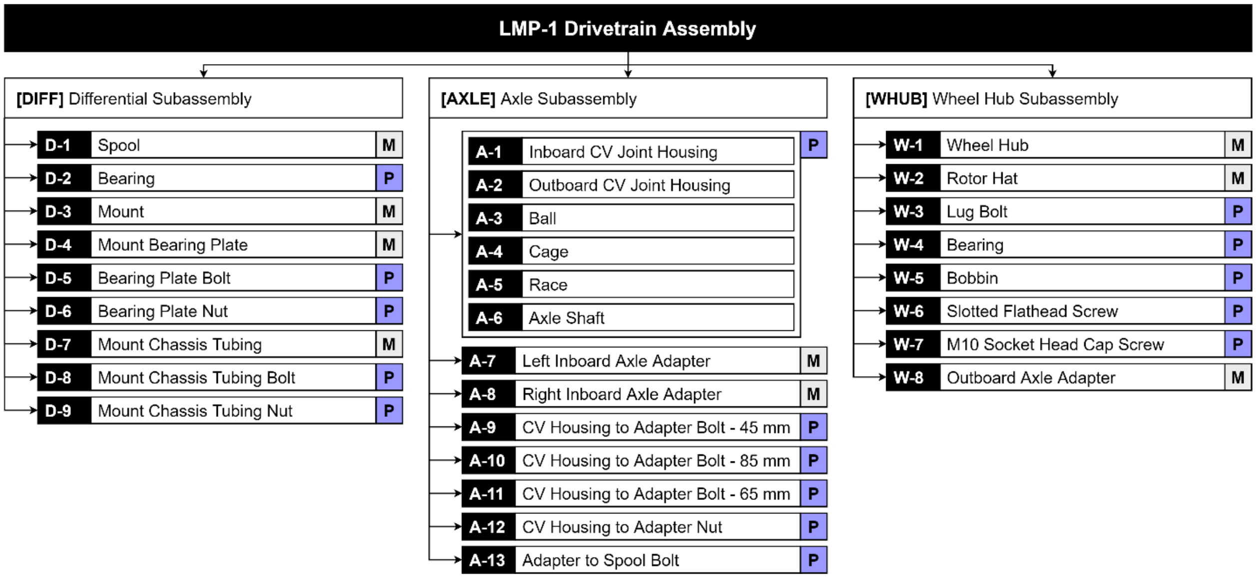
CAD models of the system are provided through Google Drive.

Readers are referred to Package B, which is a compilation of the project gate reports, to learn about the design of the system in depth. Package B complements the information provided in Package A, by providing the methodology for every aspect of the design process. Essentially, through the information provided in Package B, any question of why or how regarding the design of the drivetrain system can be answered.

Final Design

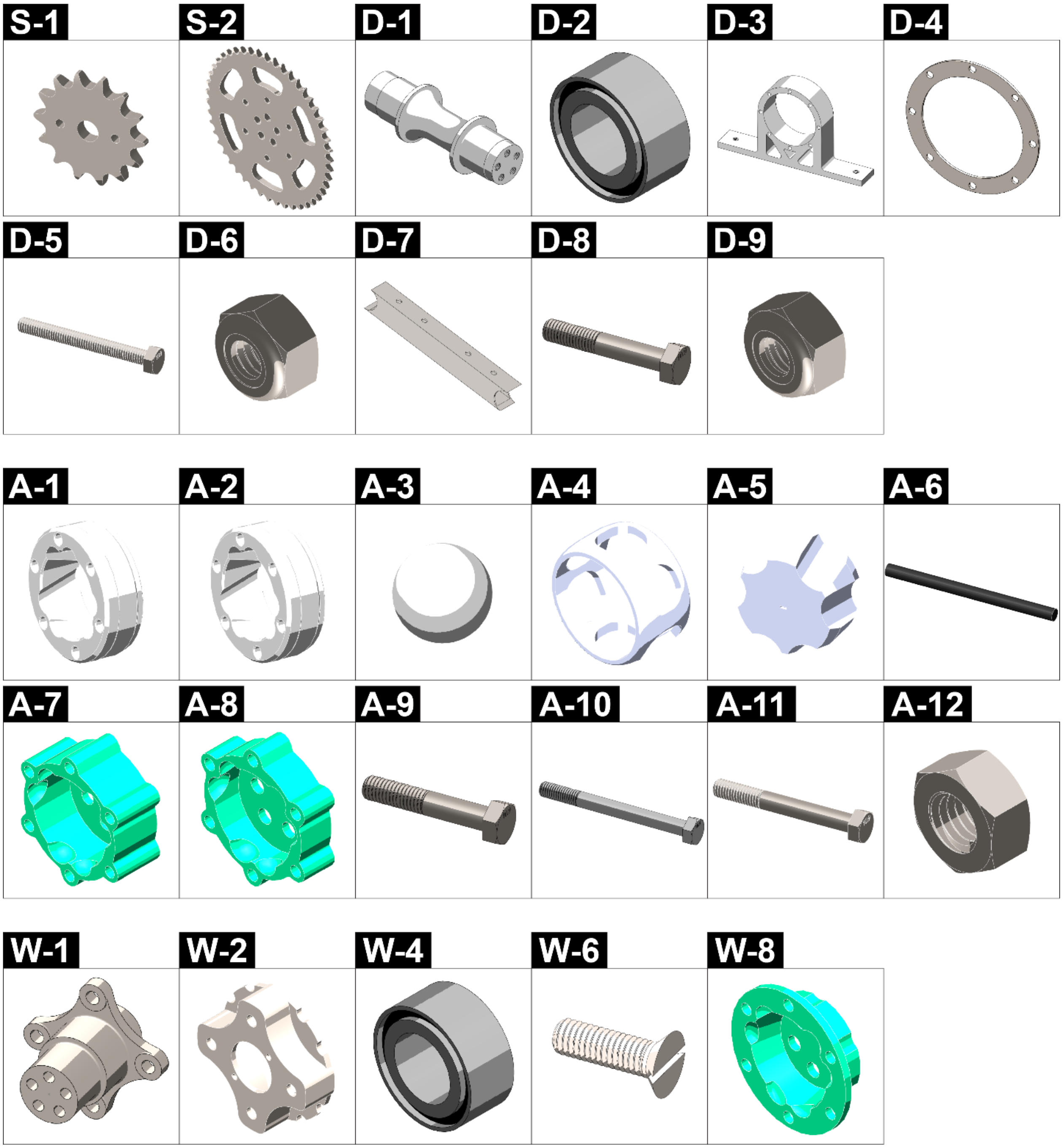
Figure 22 is the design tree showing the system hierarchy. Components in the tree are visualized in ***Figure 23***.

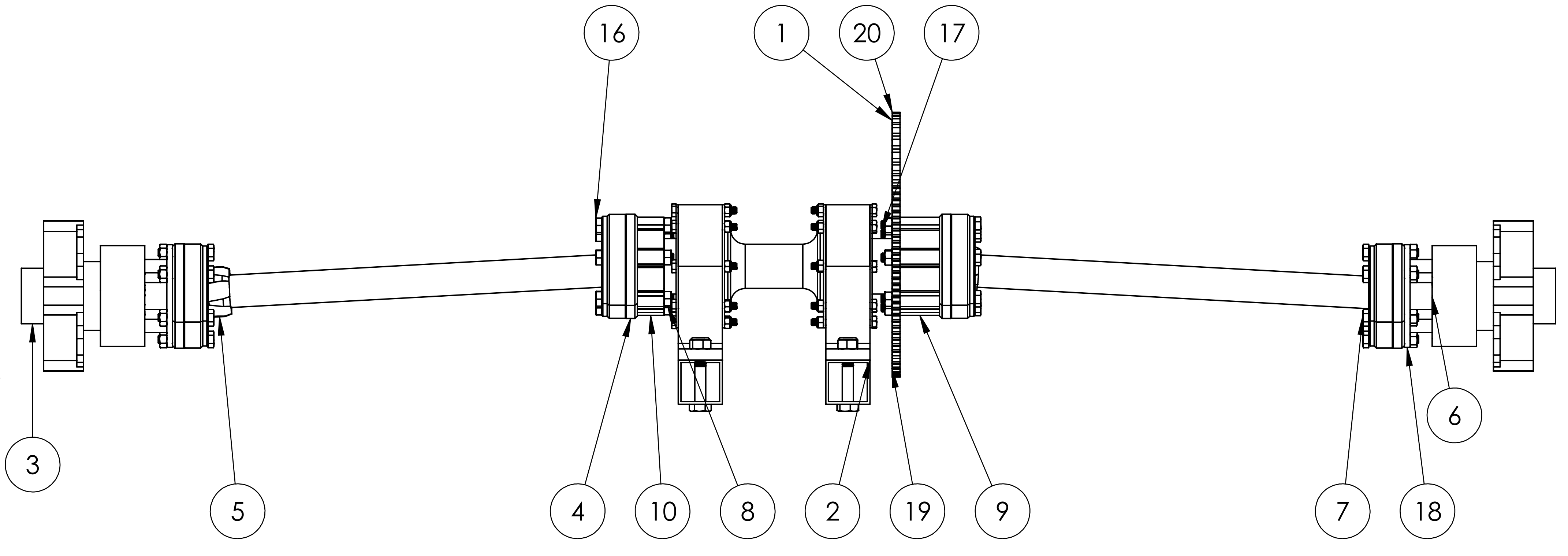
Figure 22: *Design tree*



An assembly drawing is provided in the following pages. The full set of component drawings can be found here.

Figure 23: *Component visuals*





ITEM NO.	PART NUMBER	QTY.
1	Chassis+Engine_EngineMovable	1
2	DifferentialAssembly	1
3	WheelAssembly	2
4	A-1_A-2_CVHousing.step	4
5	A-5_A-6	2
6	93070A219	20
7	91310A544	12
8	90592A022	24
9	A-7 Left Inboard Axle Adapter - SCANCompatible - HoleFix	1
10	A-8_Right_InboardAxleAdapter_SCANCompatible_ExtendedGrooves	1
11	SUSP_TopMount	2
12	SUSP_BottomMount	2
13	SUSP_BallJoint	6
14	SUSP_ControlArm_Rear_Upper	1
15	SUSP_ControlArm_Rear_Lower	1
16	90854A415	6
17	90447A150	6
18	W-8_OutboardAxleAdapter	2
19	40-0.5P1ST47T47SN3.0H2.0L0.5000N	1
20	S-3_Chain	1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 0.05mm ANGULAR: +/- 0.1 Deg	FINISH: N/A	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN	Navid Alaee		2021-04-21
CHK'D			
APPV'D			

MATERIAL: Aluminum 6061-T6

WEIGHT (Grams): ~33,000

NOTES:

TITLE:

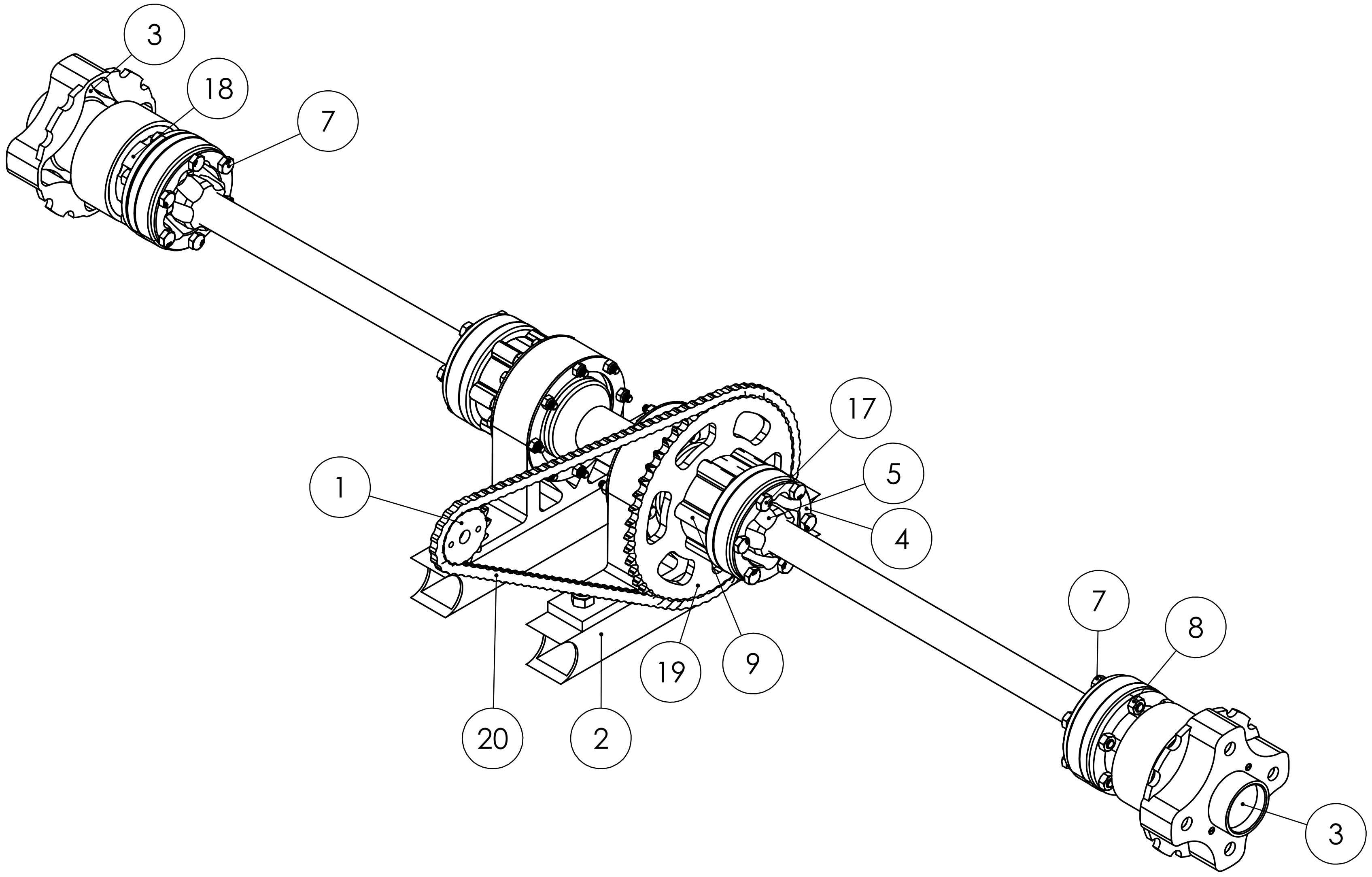
Mount Drawing

DWG NO. DrivetrainAssembly_V2.7

A3

SCALE:1:5

SHEET 1 OF 2



ITEM NO.	PART NUMBER	
1	Chassis+Engine_EngineMovable	1
2	DifferentialAssembly	1
3	WheelAssembly	2
4	A-1_A-2_CVHousing.step	4
5	A-5_A-6	2
6	93070A219	20
7	91310A544	12
8	90592A022	24
9	A-7 Left Inboard Axle Adapter - SCANCompatible - HoleFix	1
10	A-8_Right_InboardAxleAdapter_SCANCompatible_ExtendedGrooves	1
11	SUSP_TopMount	2
12	SUSP_BottomMount	2
13	SUSP_BallJoint	6
14	SUSP_ControlArm_Rear_Upper	1
15	SUSP_ControlArm_Rear_Lower	1
16	90854A415	6
17	90447A150	6
18	W-8_OutboardAxleAdapter	2
19	40-0.5P1ST47T47SN3.0H2.0L0.5000N	1
20	S-3_Chain	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: +/- 0.05mm
ANGULAR: +/- 0.1 Deg

FINISH: N/A

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Navid Alaee		2021-04-21
CHK'D			
APPV'D			

MATERIAL: Aluminum 6061-T6

WEIGHT (Grams):

NOTES:

TITLE:

Mount Drawing

DWG NO. DrivetrainAssembly_V2.7

A3

SCALE:1:5

SHEET 2 OF 2

Design Completion

[DIFF] - Differential Subassembly

The following changes need to be made to the **[DIFF]** subassembly to finalize the design: finalizing front sprocket features and adding a chain tensioning system.

Because of the lack of access to the physical engine components, the mounting holes on the front sprocket CAD model are not accurate and needs to be updated to include the splined center hole and accruement placement of the two alignment holes. The two figures below show the visual difference between the CAD model and updates needed.

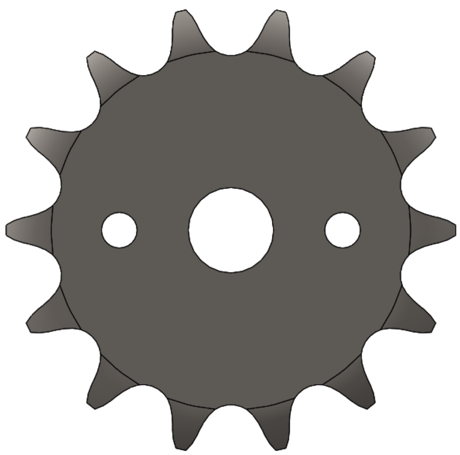


Figure 24*: Front sprocket solid model*

Figure 25*: Commercially available sprocket*

In addition, a chain tensioner needs to be designed for the differential subassembly to ensure the chain stays attached to the sprockets while driving. Due to the uncertainty of the engine position, it was not feasible to design a chain tensioner. Thus, Lassonde Motorsports needs to develop a chain tensioner to ensure reliability of the vehicle.

[AXLE] – Axle Subassembly

The **[AXLE]** subassembly, which acts as the connector between the **[DIFF]** and **[WHUB]** subassemblies, has ambiguous dimensions resulting from the project team's inability to access and accurately measure the engine. The engine dimensions and its position in the chassis affects the positioning of the center stack (**[DIFF]** subassembly and **A-1**, **A-7**, **A-8**), and therefore the locations where the left and right axles connect to the center stack.

- The front sprocket key is known to extend from the left half of the engine. The front and rear sprockets (**S-1**, **S-2**) are required to be coplanar in order for the chain (**S-3**) to function properly.
- The rear sprocket **S-2** is fixed between the spool (**D-1**) end surface and the left inboard axle adapter **A-7**. The plane of the sprockets determines the positioning of the center stack in the x-direction. The center stack can be slid on the chassis tubing in order to position it along the x-axis as required to make the sprockets coplanar.
- Once the center stack is positioned appropriately in the x direction, wheel-facing surfaces of the inboard CV joint housings (**A-1**) will likely have different distances to the vehicle center plane as a result of the center stack not being exactly centered along the chassis tubing.
- If axles are to be connected to the inboard housings in this state, the wheels won't be symmetric around the center plane of the vehicle due to the center stack's non-centered position.

In order to account for the non-centered position of the center stack with respect to the vehicle center plane, and to keep the wheels and axles equally distant from the vehicle center, the left inboard axle adapter **A-7** has been designed to be a variable-length component.

Figure 26 illustrates:
- the measurements that need to be completed to determine the exact position of the central stack
- the relevant design parameters that need to be updated in the CAD models

in order to update the virtual assembly, and to modify the flexible-length axle adapter **A-7**
- to reflect the actual engine position and dimensions
- to ensure symmetric positioning of the wheels and axles with respect to the vehicle center plane.

Design parameters 1, 2 and 5 in ***Figure 26*** have been defined as global variables in the SolidWorks part files for the relevant components and can be conveniently edited. Design dependent parameters 3 and 4 have been defined as sensors in the system assembly and can be read directly from the "Sensors" category in the design tree. ***Table 9*** provides a listing of the parameters to be edited and their parent files, included in the CAD asset package delivered to the client. The SolidWorks assembly for the system has been constructed to allow automatic updates based on changes to the parameter values.

Step	Parameter Name	File of Parameter
1	Engine_CenterOffset	Chassis+Engine_EngineMovable.SLDASM
2	frontSprocket_keyLength	enginev2.SLDPRT
3	A-8_EndFace_to_RightReferencePlane	DrivetrainAssembly_v2.x.SLDASM
4	A-7_EndFace_to_LeftReferencePlane	DrivetrainAssembly_v2.x.SLDASM
5	A-7_Extension	A-7 Left Inboard Axle Adapter – HoleFix.SLDPRT

Table 9: *Design parameters to be updated and monitored*

The procedure for completion of the design in accordance with the previously outlined constraints is detailed in ***Table 10***.

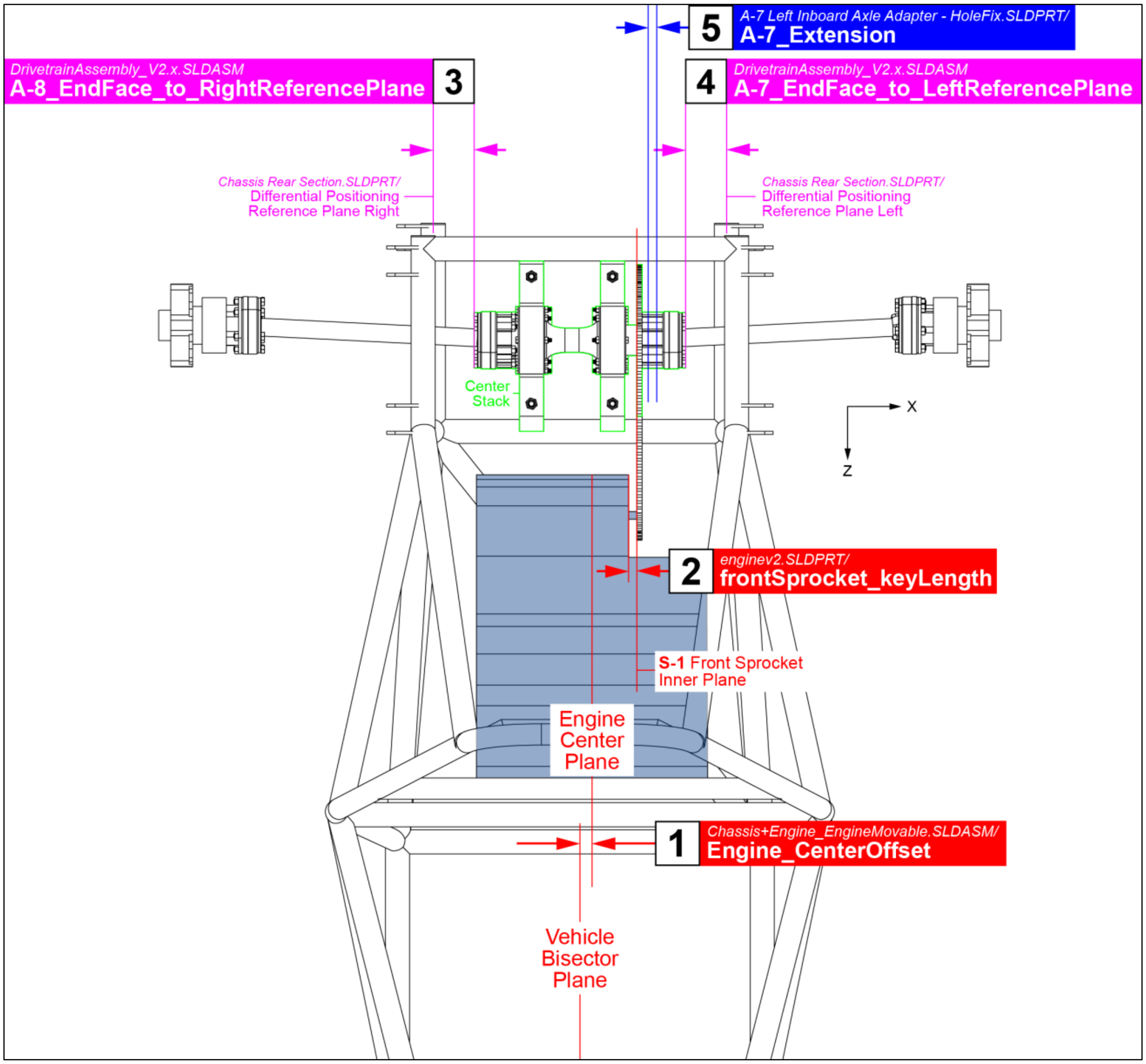


Figure 26: *Parameters to update and monitor for design completion*

Step	Parameter Name
1	Determine the distance of the engine center plane in the z-direction to the vehicle center plane. Update the Engine_CenterOffset variable to the determined value.
2	Measure the length of the key extending from the engine on which the front sprocket is to be mounted. Update the frontSprocket_keyLength variable to the determined value.
3	Record the reading from the A-8_EndFace_to_RightReferencePlane sensor.
4	Record the reading from the A-7_EndFace_to_LeftReferencePlane.
5	Set the A-7_Extension variable to the value given by: A-8_EndFace_to_RightReferencePlane - A-7_EndFace_to_LeftReferencePlane which is the difference between readings recorded in steps 3 and 4, respectively.

Table 10: *Design completion procedure*

Bill of Materials

The comprehensive bill of materials covering each individual component required for the drivetrain system is provided in the following page along with design quantity, bill item, supplier, purchase quantity and total cost. Keep in mind, the following table does not include any manufacturing, material heat treatment or additional tool costs.

To note:

- W-2 Rotor hat has not need included in this bill of materials as it falls predominantly under the scope of Team G: FSAE Brake system.
- Cost values for S-1 Front sprocket, S-2 Rear Sprocket and D-10 Chain guard have been estimated as quotes could not be obtained

ID	Component	Design Quantity	Bill Item	Supplier	Unit Price	Unit	Purchase Quantity	Total Cost	Currency
S-1	Front Sprocket	1	4340 plate 3/8 thick, 5in x 5in	Metal Supermarkets	$50.00	unit	1	$50.00	CAD
S-2	Rear Sprocket	1	4340 plate 3/8 thick, 10in x 10in	Metal Supermarkets	$75.00	unit	1	$75.00	CAD
S-3	Chain	1	Koch 7440100 Roller Chain, 40, 10 Feet	Amazon.ca	$23.12	unit	1	$23.12	CAD
D-1	Spool	1	Alloy Round 4340 HR Heat Treated	Metal Supermarkets	$85.50	unit	1	$85.50	CAD
D-2	Bearing	2	BCA WE60387	RockAuto	$56.03	unit	2	$112.06	CAD
W-4		1x2			$56.03	unit	2	$112.06	CAD
D-3	Mount	2	Aluminum Flat Bar 6061T6511	Metal Supermarkets	$131.42	unit	1	$131.42	CAD
D-4	Mount Bearing Plate	4	Aluminum Sheet 6061T6	Metal Supermarkets	$190.56	unit	1	$190.56	CAD
D-5	Mount Bearing Plate Bolt	16	Zinc Yellow-Chromate Plated Steel Hex Head Screw High-Strength, M6 x 1 mm Thread Size, 55 mm Long	McMaster-Carr	$11.82	pack	1	$11.82	CAD
D-6	Mount Bearing Plate Nut	16	High-Strength Steel Nylon-Insert Locknut Class 10, Zinc Plated, M6 x 1 mm Thread, 6 mm High	McMaster-Carr	$11.59	pack	1	$11.59	CAD
D-7	Mount Chassis Tubing	2	Steel Square Tube A500/A513 (Welded)	Metal Supermarkets	$19.98	unit	1	$19.98	CAD
D-8	Mount Chassis Tubing Bolt	8	High-Strength Steel Nylon-Insert Locknut Class 10, Zinc Plated, M6 x 1 mm Thread, 6 mm High	McMaster-Carr	$7.30	pack	1	$7.30	CAD
D-9	Mount Chassis Tubing Nut	4	High-Strength Steel Nylon-Insert Locknut Class 10, Zinc Plated, M10 x 1.5 mm Thread, 10 mm High	McMaster-Carr	$10.96	pack	1	$10.96	CAD
D-10	Chain Guard	1	Carbon Steel	Metal Supermarkets	$25.00	unit	1	$25.00	CAD
	1968 Volkswagen Beetle Axle Assembly		CV Axle TRAKMOTIVE VW8043 (Volkswagen Beetle)	RockAuto	$56.15	unit	2	$112.30	CAD
A-1	Inboard CV Joint Housing	2							
A-2	Outboard CV Joint Housing	2							
A-3	Ball	6x2x2							
A-4	Cage	2x2							
A-5	Race	2x2							
A-6	Axle Shaft	2							
A-7	Inboard Axle Adapter – Left	1	AISI 4340 4 in Round Bar	Metal Supermarkets	$22.99	in lg	2.5	$57.48	CAD
A-8	Inboard Axle Adapter – Right	1							
A-9	CV Housing to Adapter Bolt – Outboard - M8 45mm 22mm Thread	6x2	90447A150 Alloy Steel Socket Head Screw M8 x 1.25 mm Thread, 45 mm Long, Fully Threaded - Pack of 10	McMaster-Carr	$10.00	pack	2	$24.98	CAD
A-10	CV Housing to Adapter Bolt – Inboard Left - M8 85mm 22mm Thread	6	91290A116 Black-Oxide Alloy Steel Socket Head Screw M8 x 1.25 mm Thread, 85 mm Long - Pack of 10	McMaster-Carr	$8.83	pack	1	$11.03	CAD
A-11	CV Housing to Adapter Bolt – Inboard Right - M8 65mm 22mm Thread	6	91290A458 Black-Oxide Alloy Steel Socket Head Screw M8 x 1.25 mm Thread, 65 mm Long - Pack of 25	McMaster-Carr	$9.69	pack	1	$12.10	CAD
A-12	CV Housing to Adapter Nut - M8	6x2x2	90592A022_STEEL HEX NUT - Pack of 100	McMaster-Carr	$5.32	pack	1	$6.65	CAD
A-13	Adapter to Spool Bolt - M10 35mm Fully Threaded	5x2x2	93070A219_LOW-PROFILE SOCKET HEAD CAP SCREW - Pack of 10	McMaster-Carr	$7.30	pack	2	$18.24	CAD
W-1	Wheel Hub	1x2	5 in Alloy Round 4340 HR Heat Treated, 10in length	Metal Supermarkets	$229.91	unit	1	$229.91	CAD
W-2	Rotor Hat	1x2							
W-3	Wheel stud conversion (M12 x 1.5mm x 90mm)	4x2	BMW Stud Racing Conversion 12x1.5 With Black Lug Nuts Full Kit Conical Lug Nuts	Ebay.ca	$99.81	pack	1	$99.81	CAD
W-4	Conical Lug Nut	4x2							
W-5	Bobbin	8x2							
W-6	Slotted Flathead Screw (M3x1.5x10mm)	3x2	91430A120 18-8 Stainless Steel Slotted Flat Head Screws M3 x 0.5 mm Thread, 10 mm Long - Pack of 100	McMaster-Carr	$6.61	pack	1	$6.61	CAD
W-7	M10 Socket Head Cap Screw	5x2							
W-8	Outboard Axle Adapter	1x2	Aluminum 6061-T6 4 in Round Bar	Metal Supermarkets	$29.28	in lg	2	$58.56	CAD
							TOTAL	**$1514.42 CAD**	

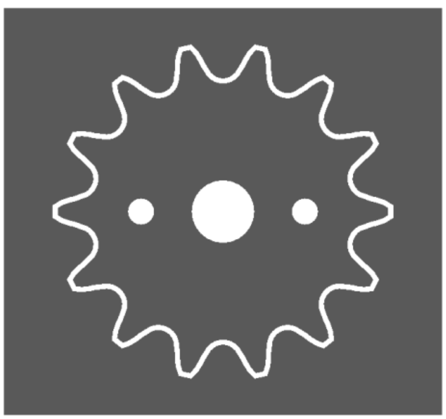
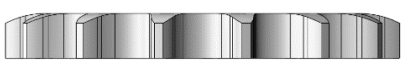
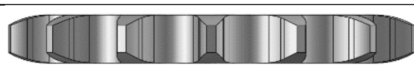
Manufacturing Guide

[DIFF]: Differential Subassembly

The differential components were designed keeping in mind ease of manufacturing. That means most parts could be manufactured from the material to the final component in a few steps. To make manufacturing easier, components were also duplicated to restrict the number of unique parts in the differential assembly. In total, the differential assembly consists of ten unique components - six of which require manufacturing. Only the manufactured components will be discussed in this section since parts that are bought out do not need any modifications to be used in the final assembly.

S-1 & S-2: Sprockets

The sprockets will be made from 4340 steel with a combination of water jet cutting and 3 axis CNC machining.

1		Starting with a 1 cm thick 4340 plate, a 2D profile of the sprocket will be cut with a water jet cutter. The interior features are complete and do not require any more processing.
2		Using a 3 axis CNC machine, the 2D sprocket profile will be cut down to the sprocket thickness and the teeth profile will be cut for one half.
3		The sprocket is then to be flipped in the 3-axis CNC. Teeth profile for the other half will be cut.

D-1: Spool

The spool begins as an AISI 4340 round bar that is roughly 3 inches in diameter and 10 inches long. Like every other component discussed in this section, the spool will follow a subtractive manufacturing method where the initial cylindrical part is spun on a lathe and the material is removed according to the varying diameters.

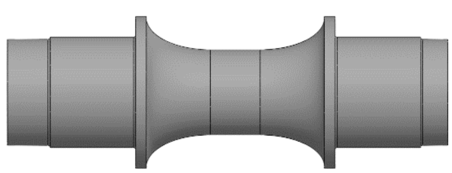


Figure 27: *Spool (***D-1***)*

- The largest diameter on the spool is 2.81 inches at the section which holds the inner section of the bearings in place; the smallest diameter is 1.57 inches near the center of the spool.

- It is recommended that this operation be done on a CNC lathe available in the Bergeron machine shop due to the intricate fillet operation in the middle of the spool. This feature may be difficult to reproduce on a typical lathe.
- Once the lathe operation is complete, the spool requires 5 holes drilled into either side which should be done on a mill with an 8.5 mm bit followed by an M10 tap.

D-3: Mount

The mount is made from 6061-T6 aluminum which starts as an aluminum block that is 15 by 7 inches and 1.57 inches wide. Since the two mounts are identical, the same block will be used to reduce material waste since significant space is needed for a one mount. The cutting patterns for the two mounts can be arranged on the block as shown in ***Figure 28***.

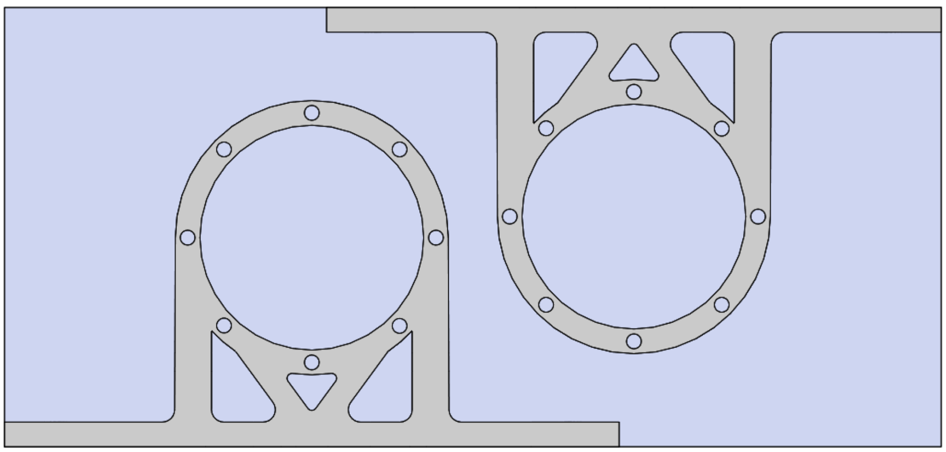


Figure 28: *Proposed mount (***D-3***) cutting pattern arrangement*

- The majority of the mount can be completed using water jet cutting to remove the negative material from the design and finished with drilling and tapping on the bottom side to create the mounting holes.
- The only holes that require threading are the four bottom mounting holes; the 8 holes placed radially to the bearing hole rely on the bolt and nut to hold the bearing plate in place. Like the spool, the holes are to accommodate an M10 bolt so they must be drilled with an 8.5 mm bit and then tapped with an M10 tap.

[AXLE]: Axle Subassembly

The axle subassembly has 3 unique components to be manufactured, **A-7** left inboard axle adapter, **A-8** right inboard axle adapter, and **W-8** outboard axle adapter. This section will present the proposed manufacturing methods for the components. The remaining components are to be purchased and assembled with the manufactured items as described in the assembly section.

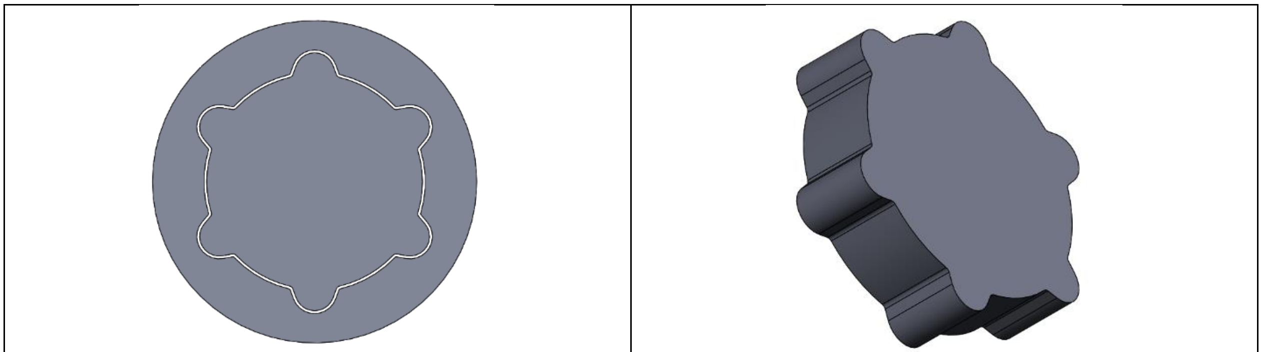
A-7 & **A-8:** Left & Right Inboard Axle Adapters

The left inboard axle adapter has an extruded hexagon shape in essence, with bolt holes positioned at its corners, and its sides given a circular form. Due to the extension of the outer bolt holes from the circular outline, the part has to be manufactured from round stock of AISI 4340 with diameter larger than distance between the bolt hole extensions.

The BOM includes a round stock order for both **A-7** and **A-8** since they have the same surrounding diameter. The length of the round stock included in BOM is the value needed for the components provided in the delivered assembly. However, length of **A-7** is to be finalized at time of manufacture upon measurements on the engine.

The length of **A-8** is fixed at 24 mm. **A-7** has a minimum length of 24 mm, with an extension equal to A-7_Extension (variable introduced in **Design Completion**). Therefore, (48 mm + A-7_Extension) is the minimum length of round stock to be ordered. We suggest ordering a 5-10 mm longer stock to account for machining errors and imperfections.

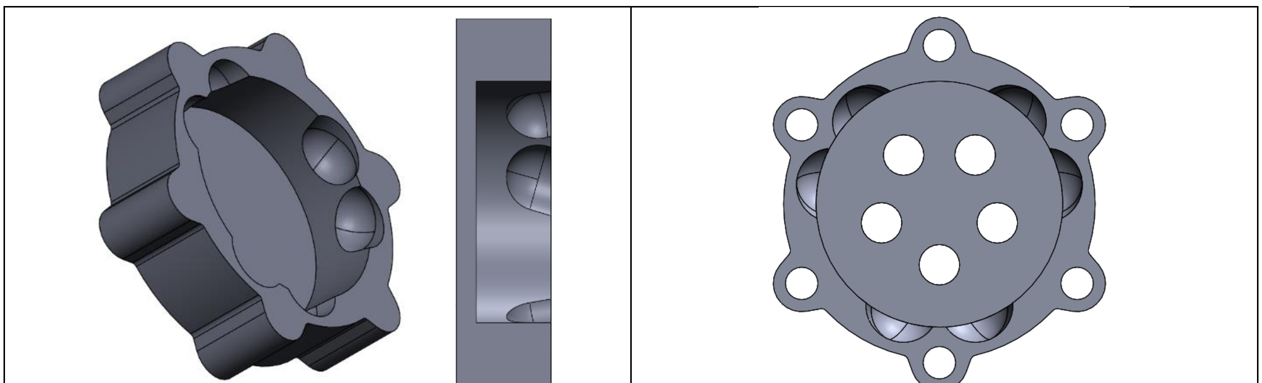
- At least a 24 mm long segment of the round stock should be cut using a horizontal bandsaw for later machining into **A-8**.
- The remaining length of round stock should have a length of at least (24 mm + A-7_Extension) to be machined into **A-7.**
- **A-7** and **A-8** share the same hexagonal-circular outline. The round stocks allocated for each part are suggested to be cut using a water jet cutter to obtain the design outline.
  - Water jet cutting is recommended to be done after splitting of the raw round stock into 2, in order to do the jet cutting operation on lower thickness materials and thus to achieve higher accuracy in the cut profile.



(a) Cut profile on the raw round stock *(b) Round stock after water jet cutting*

Figure 29: *Axle adapters (***A-7** *&* **A-8***) water jet cutting visuals*

- The bodies for **A-7** and **A-8** are then to be machined using a vertical mill. Ball grooves follow an oblique line with respect to the component outlines. Therefore, we propose at least the grooves to be cut using a CNC programmable mill. The bulk of the inner circular volume can be cut using a manual milling machine. The depth of the inner volume is different between **A-7** and **A-8** and should be cut according to the individual part drawings.
- The outer and inner bolt holes (M8 and M10 respectively) can be cut using manual or CNC programmable mills.



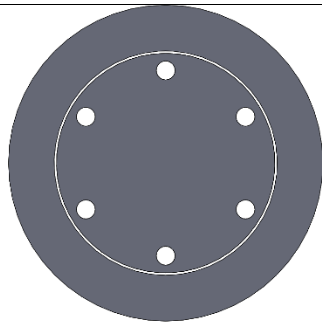
(a) Inner volume and grooves of axle adapters *(b) Outer bolt holes*

Figure 30: *Axle adapters (***A-7** *&* **A-8***) after operations on the mill*

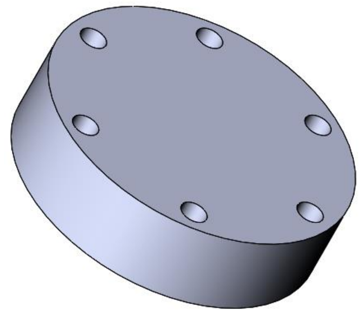
W-8: Outboard Axle Adapter

The outboard adapters are manufactured out of 6061-T6 aluminum. Both instances of **W-8** have the same dimensions. A single round stock of aluminum is included in the BOM for use in manufacturing the parts. The diameter of the round stock is larger than the diameter of the flange. The length specified for the material order is enough to manufacture 2 instances of the part, however, we recommend ordering longer stock to account for errors and machining imperfections.

- The raw round stock is to be cut into two equal pieces for the two instances of **W-8**.
  The following steps are to be repeated for both instances of **W-8**.
- The piece of round stock is to be cut using a water jet to the flange diameter.



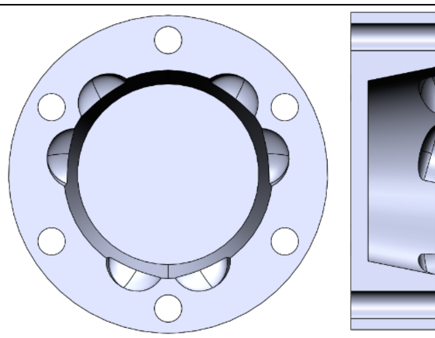
(a) Raw round stock with flange profile and hole overlay



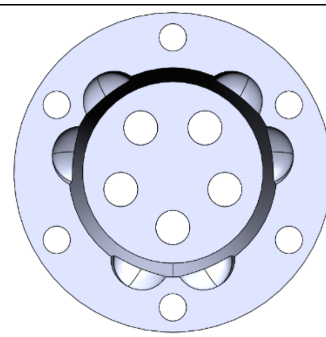
(b) Water jet cut round stock

Figure 31: *Water jet cutting of round stock for* **W-8**

- The inner volume of W-8 has a decreasing diameter towards the back wall. Furthermore, the grooves have an elliptical end form and are cut in an oblique line. Therefore, we propose the inner volume and the grooves to be cut on a CNC programmable mill.



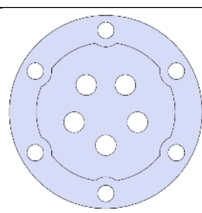
(a) Inner volume and grooves



(b) Completed **W-8** *with inner bolt holes*

Figure 32: *Milling processes on* **W-8**

- The stock is then to be turned 180° and machined to remove material behind the flange area. This operation should also be done using a CNC mill to achieve the wide diameter of the component. The bolt holes on the flange can be cut using the manual or CNC mills.



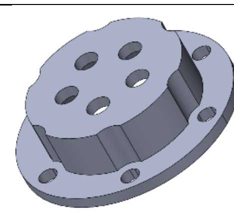
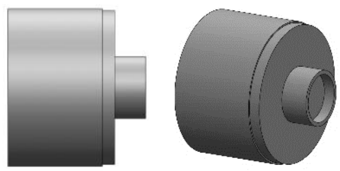
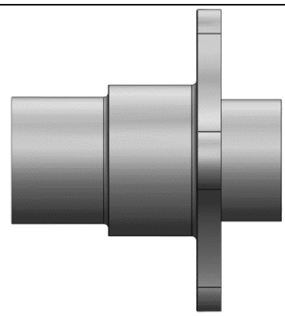
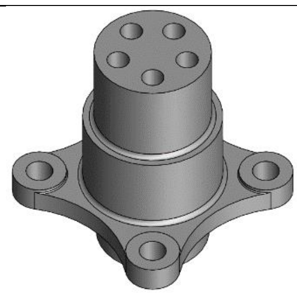


Figure 33: *Completed* **W-8** *with material behind flanges removed*

[WHUB]: Wheel Hub Subassembly

W-1: Wheel Hub

The wheel hubs will be produced from AISI 4340 steel, using a lathe and a 3-axis CNC machine.

1		Start with 4340 steel – 5 in diameter round bar of 5 in length. Using a lathe, cut the side profile of the front face of the wheel hub
2		Remove the part from the lathe to flip the piece, clamping in on the hub-centric ring. Cut the side profile of the back of the wheel hub.
3		Moving on to the 3-axis CNC machine, hold the piece by the hub-centric ring. Cut the following features: • Four M12 x1.5 wheel stud holes • Five M10x1.5 axle adapter holes • Remove material from the back of the wheel mounting surface

Assembly Guide

This section will outline the necessary steps to assemble the drivetrain in the LMP-1 vehicle. The drivetrain was designed with ease of assembly and manufacturing in mine and as such, assembly of the drivetrain can be done in parallel according to the different subassemblies of the drivetrain: **[DIFF]**, **[AXLE]**, and **[WHUB]**.

For the purposes of this assembly instruction, these three sub-assemblies will be defined as the following:

Table 11: *Component organization for assembly processes*

[DIFF] concerns the components physically between (and including) components **A-7** and **A-8**, the left and right inboard axle adapters.	• **A-7**: Inboard Axle Adapter – Left • **A-8**: Inboard Axle Adapter – Right • **A-13**: M10-35mm Fully Threaded • **D-1**: Spool • **D-2**: Bearing • **D-3**: Mount • **D-4**: Bearing Mount Plate • **D-5**: Mount Bearing Plate Bolt • **D-6**: Mount Bearing Plate Nut • **D-7**: Mount Chassis Tubing • **D-8**: Mount Chassis Tubing Bolt • **D-9**: Mount Chassis Tubing Nut • **S-2**: Rear Sprocket
[AXLE] concerns the components physically between (and including) **A-1** and **A-6**.	• **A-1**: Inboard CV Joint Housing • **A-2**: Outboard CV Joint Housing • **A-3**: Ball • **A-4**: Cage • **A-5**: Race • **A-6**: Axle Shaft • **A-11**: M8-65mm, 22mm threaded bolt
[WHUB] concerns the components physically between **W-1** and **W-8**.	• **W-1**: Wheel Hub • **W-3**: Lug Bolt (M12 x 1.5mm x 42mm) • **W-4**: Bearing • **W-6**: Slotted Flathead Screw (M3x1.5x10mm) • **W-7**: M10 Socket Head Cap Screw • **W-8**: Outboard Axle Adapter

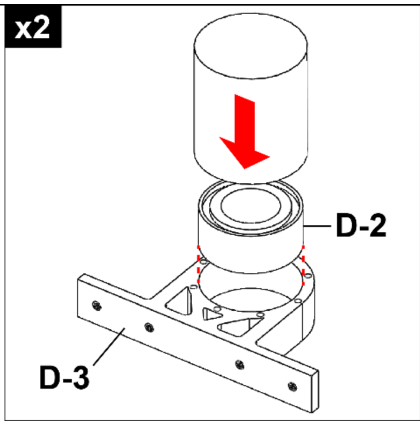
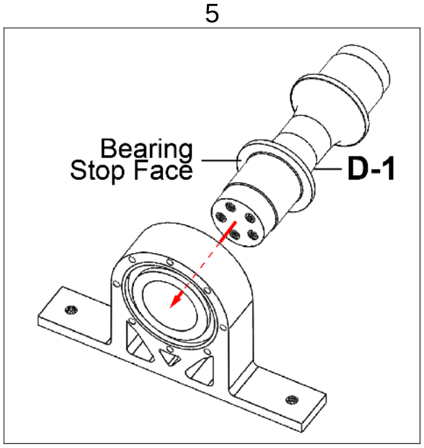
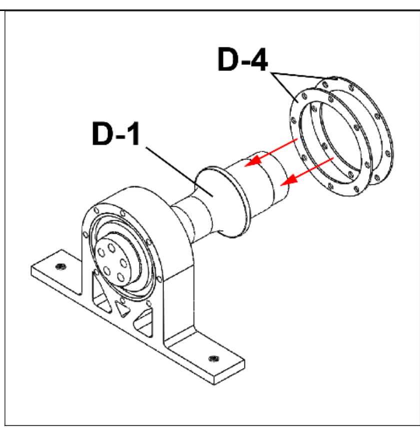
The following components are excluded from these three subassemblies and are reserved for interfacing the assemblies. These components are:

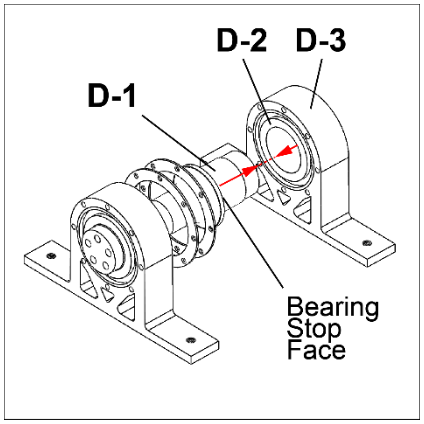
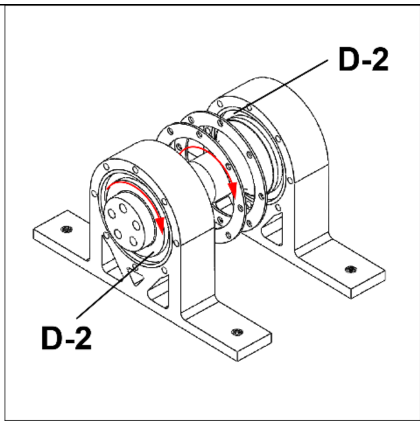
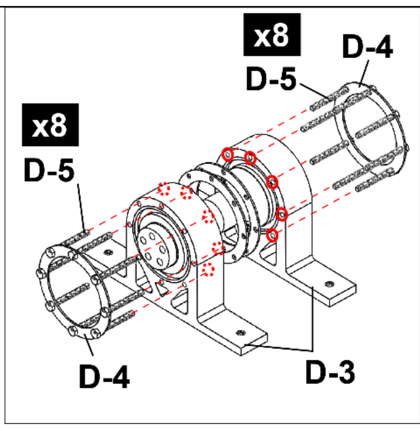
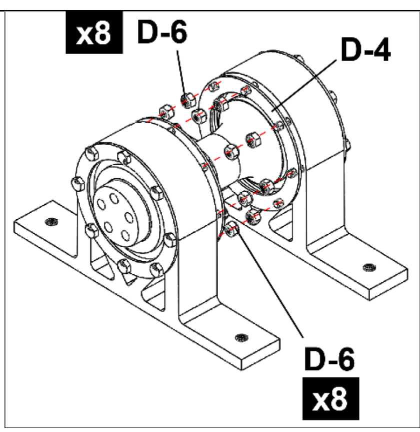
- **A-9**: M8-45mm, 22mm threaded bolt
- **A-10**: M8-75mm, 22mm threaded bolt
- **A-12**: M8 nut

Note that the grouping in ***Table 11*** is different than the hierarchy illustrated in ***Figure 22:*** *Design tree*. This re-organization is only for a more logical organization in the assembly processes.

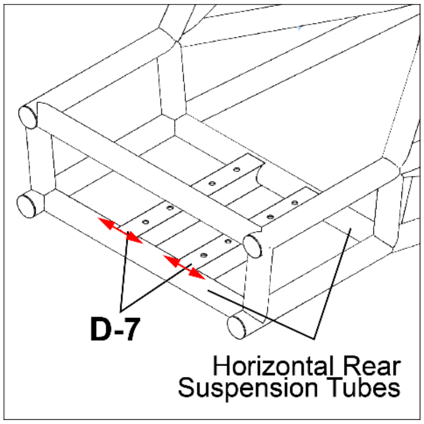
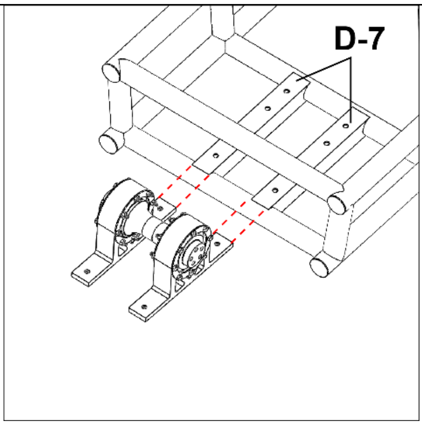
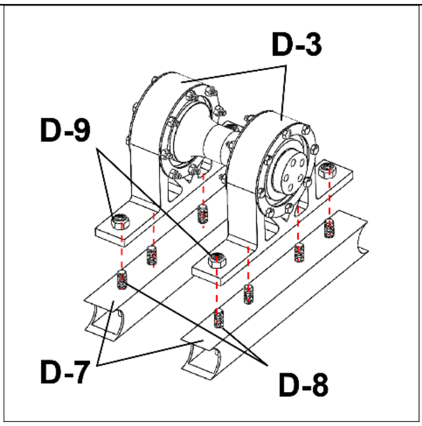
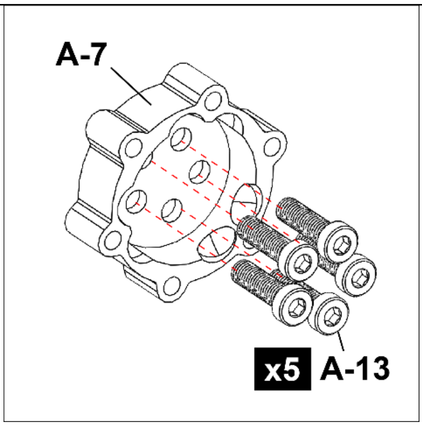
The drivetrain requires one **[DIFF]** assembly, and two of both **[AXLE]** and **[WHUB]** assemblies. The following subsections of the document outline assembly processes for each of the subassemblies, using the components grouped in ***Table 11***.

[DIFF] Subassembly

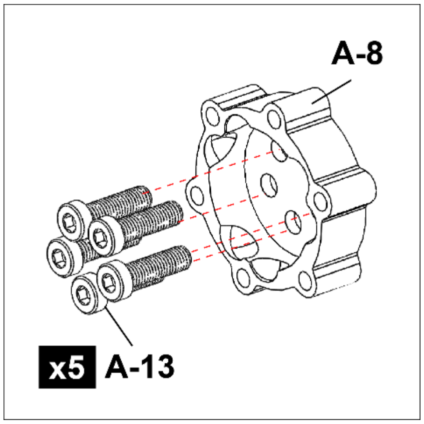
0		**Note** All bolts should be coated with Loctite (blue) to ensure proper fastening of components. **Note** There are no torque specifications for the bolts or nuts, so the operator must use their best judgement when fastening the components.
1		Using a hydraulic press, lay the mount (**D-3**) down flat with the bearing (**D-2**) loosely fit on top of the bearing hole opening and press the bearing (**D-2**) into the mount **D-3** until the bearing and mount are flush. Repeat for the second mount and bearing.
2	5 	Securing the bearing and mount, press one side of the spool (**D-1**) onto the bearing until the bearing stop face on the spool (**D-1**) has contact with the inner race.
3		On the opposite end of the spool (**D-1**), insert 2 bearing plates (**D-4**).

<table>
<tr><td>4</td><td>
</td><td>Press the opposite end of the spool (D-1) onto the other bearing (D-2) fixed on the mount (D-3) until the bearing stop face on the spool (D-1) has contact with the inner race, while making sure to support the entire bearing and mount.</td></tr>
<tr><td>5</td><td>
</td><td>Ensure that the D-2 components are not damaged and can freely rotate once fixed in place.</td></tr>
<tr><td>6</td><td>
</td><td>On either side of the opposing mounts (D-3), place the 2 remaining bearing plates (D-4) and use the eight bolts (D-5) to secure it in place by sliding it through the mount (D-3) to the other side.</td></tr>
<tr><td>7</td><td>
</td><td>With the two remaining bearing plates (D-4) on the inside of the spool (D-1), place them on the eight bolts (D-5) and use the matching nuts (D-6) to secure them into place using a wrench.

Note
Apply equal torque and ensure that the bearing plate (D-4) does not warp or damage under the torque applied.</td></tr>
</table>

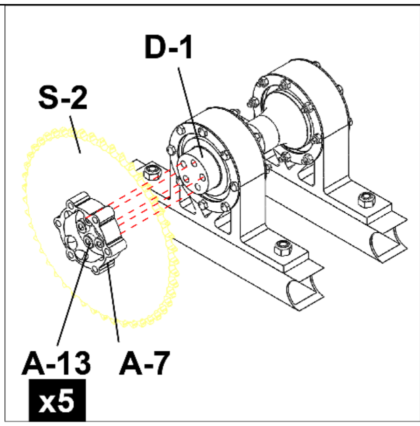
8		At this point, the mount chassis tubes **D-7** should be fitted onto the chassis in anticipation for spacing and welding. The two **D-7** components should be placed between the horizontal rear suspension tubes such that they are free to slide to set the exact spacing.
9		Once inserted, the tubes should be roughly spaced to match the assembly and the existing **[DIFF]** assembly placed on top of the mount tubes **D-7**.
10		Use **D-8** and **D-9** to fix the **[DIFF]** assembly by connecting **D-3** to **D-7**. Do this by loosely connecting **D-8** in the two inner holes with internal threading followed by inserting the same bolt through the two outer holes and securing them with **D-9**. Once in place, torque the bolts/nuts such that they are firmly secured to the tube. ⚠ **Note** There are no torque specifications for the bolts or nuts, so the operator must use their best judgement when fastening the components.
11		On the side, take the five **A-13** bolts and place them through the inner holes on component **A-7**.

12



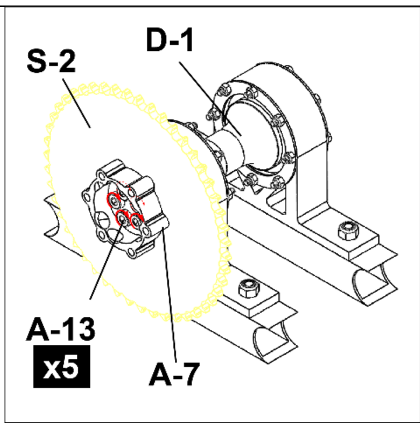
Fit the same five **A-13** bolts on **A-8**.

13



Fit **S-2** on the other side of the **A-7** and **A-13** combination and hold it up to the left side of the **[DIFF]** assembly at the 5 threaded holes on component **D-1**.

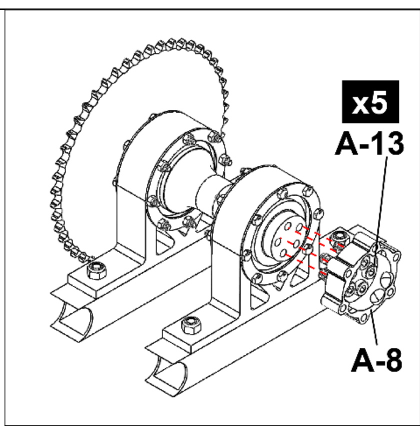
14



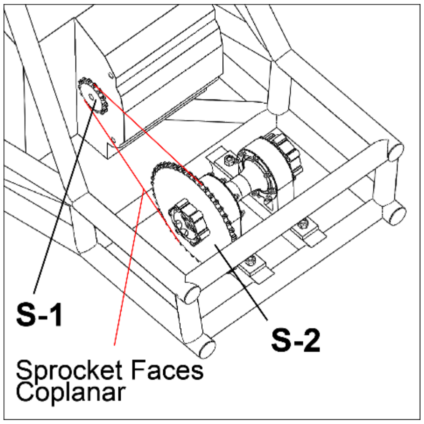
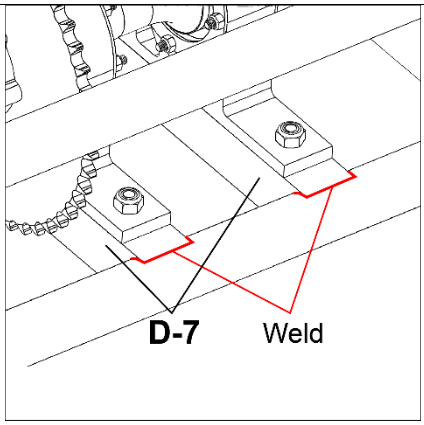
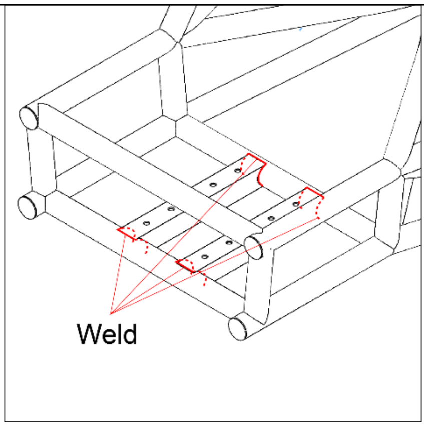
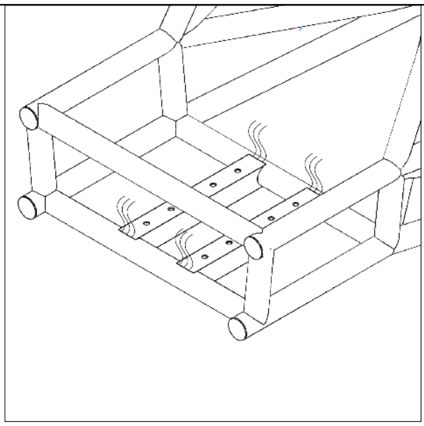
Carefully screw the 5 bolts onto the **[DIFF]** assembly and secure them tightly using a ratchet with an extension bit if necessary.

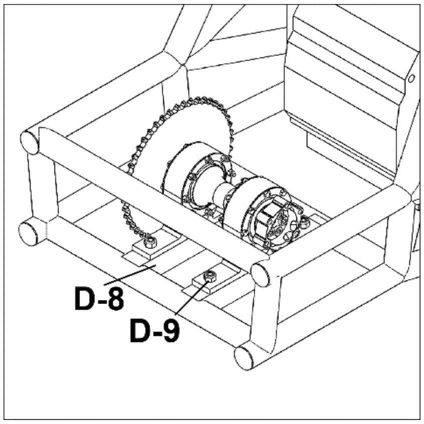
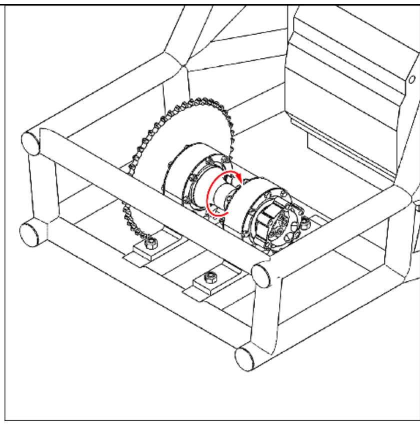
> **⚠ Note**
>
> It would be helpful to secure the **[DIFF]** assembly in place such that it does not rotate during fastening. A clamp secured to the spool **D-1** rested on the chassis is an easy option, however, be mindful of potential slips resulting in injury.

15

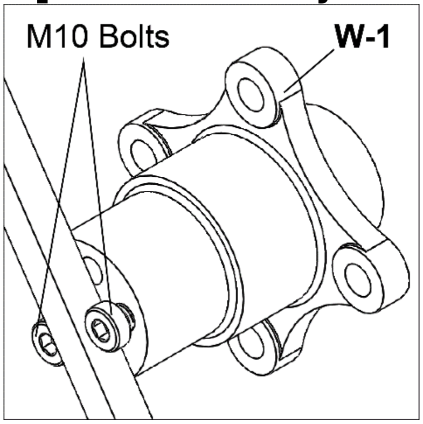
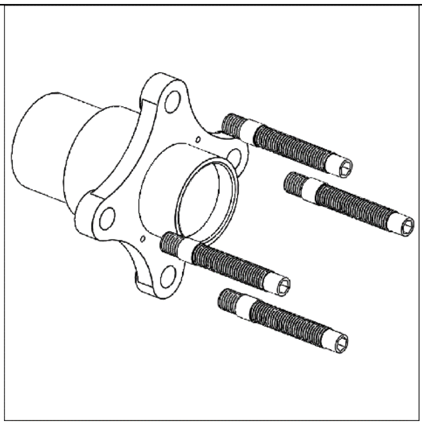
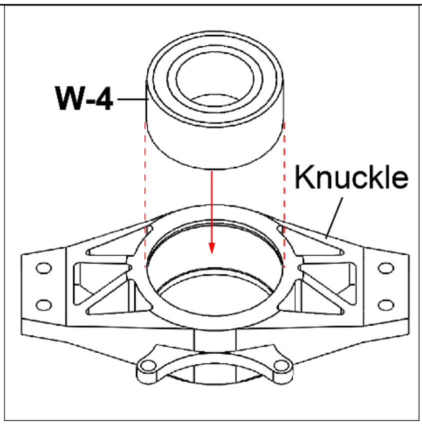
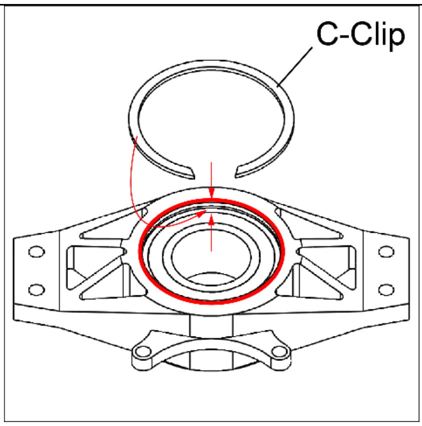


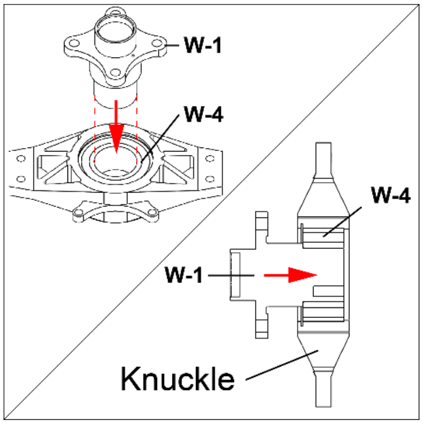
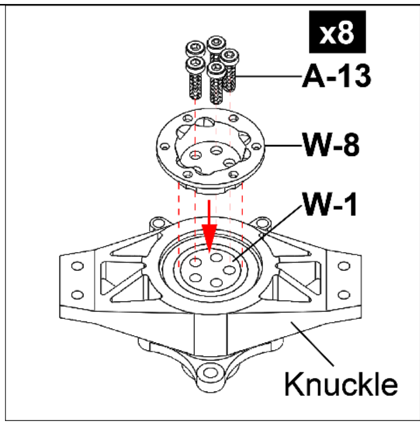
Complete the same action on **A-8** on the right side of **D-1** using the **A-13** bolts.

16		Once secured, align the assembly with the front sprocket **S-1** which is fixed on the engine using a chain.
17		Once aligned, tack weld the mount tubes **D-7** onto the chassis so that it cannot move. **Note** Be really careful.
18		Remove the **[DIFF]** assembly from the chassis and finish the weld on the mount chassis tubes.
19		Allow to cool, then remove any imperfections and clean the weld.

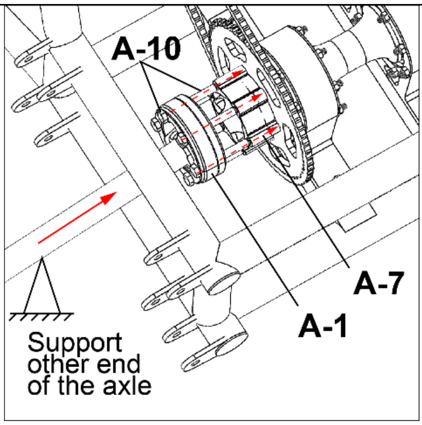
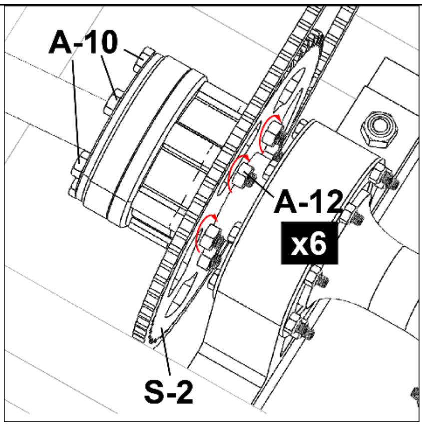
20		Remount the **[DIFF]** assembly using **D-8** bolts and **D-9** nuts to the mount tubing.
21		Give the assembly a flick at the rear sprocket to ensure it can rotate properly in place. ⚠ **Note** Spin it multiple times for satisfaction.

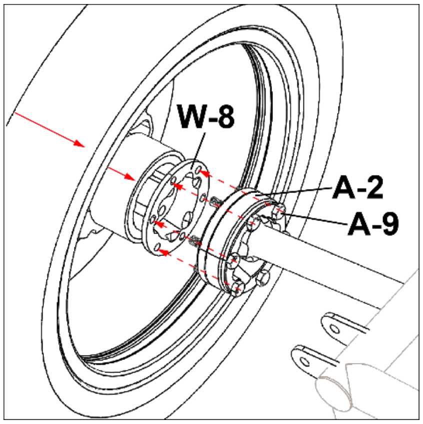
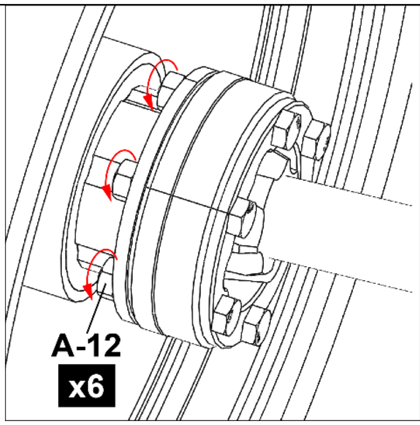
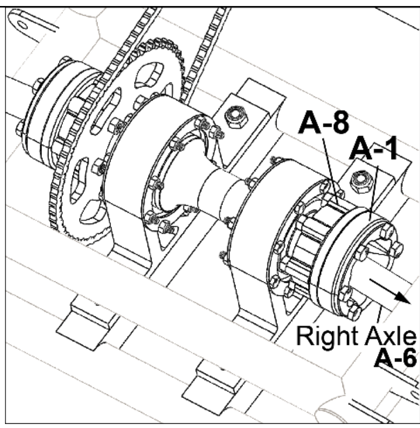
[WHUB] Subassembly

0	 	Secure the wheel hub (**W-1**) to prevent rotation. This can be done by installing two M10 bolts on the back side and holding it in place with a bar across the two bolts or clamping the hub centric ring in a vice. ⚠ **Note** Do not clamp the bearing surface or wheel mounting surface.
		Follow the wheel stud conversion kit instructions for steps and torque specifications to install the studs onto the wheel hub. Apply red Loctite to the wheel studs before installation. Repeat steps 1-2 for all wheel hubs
1	 	Using a hydraulic press, press the bearing (**W-4**) into the knuckle until it is fully seated in the knuckle. • Use a plate on top of the bearing to evenly distribute pressure against the outer and inner race of the bearing. • Do not apply pressure to only the inner race.
2	 	Using c-clip pliers, install the c-clip into the internal groove on the knuckle, on the outboard side of the bearing.

3		Using a hydraulic press, install the wheel hub (**W-1**) into the bearing (**W-4**) by applying pressure onto the hub centric ring. The wheel hub should fit flush against the inner race of the wheel bearing.
4		Install the outboard axle adapter (**W-8**) onto the backside of the wheel hub (**W-1**) using the M10x35mm low profile socket head bolts (**A-13**).
5		Repeat steps 1-4 with for the other wheel.

[AXLE] Subassembly

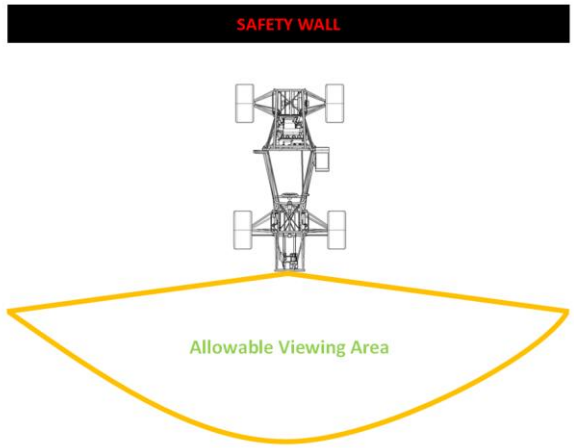
1		The purchased axle assembly is packed in a semi-assembled state, with the races (**A-5**) connected to the axle (**A-6**), and cages (**A-4**) inserted around the races. The CV joint housings are loose in the box. Assemble the inboard (**A-1**) and outboard CV joint housings (**A-2**) onto either side of the axle. ⚠ **Note** The inboard and outboard CV joint housings (**A-1** and **A-2**) are exactly the same components but are tagged differently for specificity. • Align the joint housings with the races (**A-5**) at the ends of the axle. • Pay attention to orientation of the CV joint housing when installing onto the axle. The side with the smaller diameter faces the center of the axle. • Make sure the grooves on the housing inner surface and the race are aligned.
2		Insert balls (**A-3**) into each of the 6 grooves on the race and housing surfaces. Repeat for both ends of the axle.
3		Cover the interior surfaces of the left inboard axle adapter (**A-7**), outboard axle adapter (**A-8**) and the CV joint housing (**A-1**) with a generous amount of axle grease.
4		Lift the axle and align the outer bolt holes of the inner CV joint housing (**A-1**) with the matching bolt holes on the left inboard adapter (**A-7**); supporting the outboard end of the axle. Connect the inboard boot endplate, inboard CV joint housing and the inboard adapter with 6 M8x85mm bolts (**A-10**).
5		Apply blue Loctite to 6 M8 nuts (**A-12**) and install onto the M8 bolt threads sticking out the rear sprocket (**S-2**). Using an open-ended wrench, hold the nut, and with a torque wrench on the bolt, torque to bolt to a specified value.

6		Remove the support from the outboard end of the axle, and connect the outboard boot endplate, outboard CV joint housing (**A-2**) and the outboard axle adapter (**W-8**) on the left wheel using 6 M8x45mm bolts (**A-9**). As the axle is fixed on the inboard side, move wheel closer to the axle to connect.
7		Install 6 M8 nuts (**A-12**) on the free ends of the bolts (**A-9**).
8		Repeat steps 1-8 with the other axle, connecting it to the right inboard axle adapter (**A-8**) instead of the left adapter (**A-7**) and the outboard axle adapter on the right wheel.

Physical Testing Procedures

The physical testing of the vehicle is to be done once the drivetrain is installed and operable in the vehicle. Physical testing requires the driver to be in the cockpit of the vehicle in full safety gear operating the engine by the throttle and shifter as they would in typical driving conditions. The physical testing is broken down into four main tests - three of which are based on the maximum loading conditions used in simulation and design. The physical tests are start-up testing, launching, cornering, and braking. These tests are detailed in the test packages below. It is always recommended that the testing team follow the proper safety procedures and have emergency aid and fire extinguishers on deck in case of failure.

T-PHYS-M-01	Physical Start-up Testing
Components	Vehicle
Requirements to Validate	All
Associated Operation Concept	Start-up



Procedure:

Material specifications

- Entire vehicle with installed drivetrain

Loading specifications

- The vehicle is to be secured and lifted from the ground such that the rear wheels are free to rotate.
- This can be achieved by using a propping block at the rear wheels and checking for free rotation with the engine in neutral.
- The driver is to sit in the cockpit – wearing the necessary safety equipment – and progress through all gears in the engine to ensure that the drivetrain can rotate at all levels of RPMs.
- It is CRITICAL that all observing members are not near the end of the vehicle during testing and that proper fire suppressants are on standby in case of failure resulting in fire.
- It is recommended that the vehicle is also facing a wall of some sort in case of rapid high-speed disassembly in which components could fly from the vehicle at fatal speeds.

Outputs to be generated:

- Validation of drivetrain operation in high speeds

Justification:

This test is to be conducted to ensure that the drivetrain can handle the high rotational speeds accompanied with on-track testing. This test is the precursor for all other physical tests.

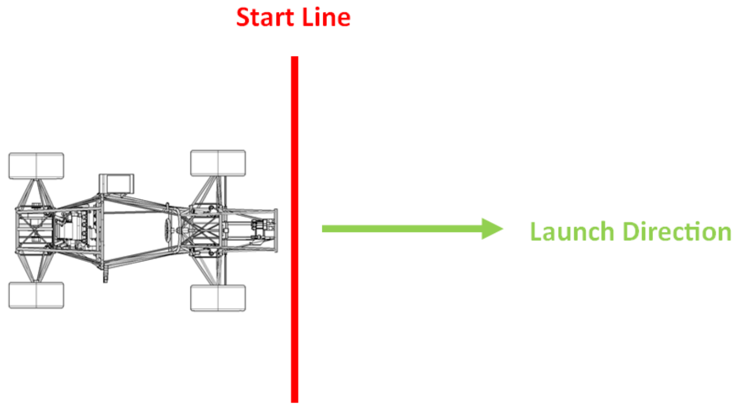
Criteria:

A successful test would have the drivetrain operating smoothly at all gears and speeds for a duration of time seen fit by the team – recommended 10 minutes.

Failed Test Procedure:

In case of failure, meaning disassembly, smoke, fire, or ceased drivetrain, the team must perform a failure analysis to determine the root cause and remedy it through maintenance or drivetrain modifications.

T-PHYS-M-02	Physical Launch Testing
Components	Vehicle
Requirements to Validate	All
Associated Operation Concept	Launch



Procedure:

Material specifications

- Entire vehicle with installed drivetrain

Loading specifications

- The vehicle is to launch from a starting line on a secure and safe open track free from obstacles and a safe distance away from spectators – recommended 50 meters.
- The driver is to sit in the cockpit – wearing the necessary safety equipment – and launch the vehicle in first gear.
- It is CRITICAL that all observing members are not near the end of the vehicle during testing and that proper fire suppressants are on standby in case of failure resulting in fire.

Outputs to be generated:

- Validation of drivetrain operation in launch

Justification:

This test is to be conducted to ensure that the drivetrain can handle the launching forces accompanied with on-track testing. This test is one of the most stressful tests so passing this is a good indication of a solid built drivetrain

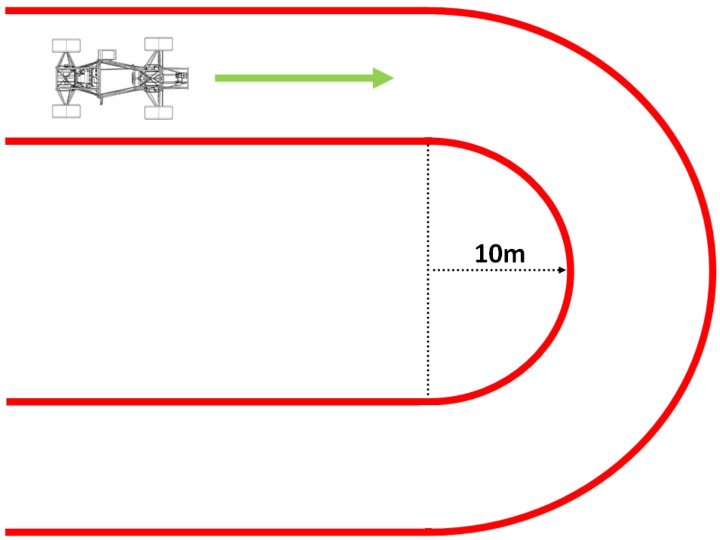
Criteria:

A successful test would have the drivetrain launching smoothly in first gears repeatedly without any failures or ceasing.

Failed Test Procedure:

In case of failure, meaning disassembly, smoke, fire, or ceased drivetrain, the team must perform a failure analysis to determine the root cause and remedy it through maintenance or drivetrain modifications.

T-PHYS-M-03	Physical Cornering Testing
Components	Vehicle
Requirements to Validate	All
Associated Operation Concept	Cornering



Procedure:

Material specifications

- Entire vehicle with installed drivetrain

Loading specifications

- The vehicle is to drive around a 10-meter radius corner on a track at a speed of 11.7 meters per second to achieve the 1.4g force required. Both sides of the vehicle are to be tested.
- The driver is to sit in the cockpit – wearing the necessary safety equipment – cornering the vehicle after achieving the required speed.
- It is CRITICAL that all observing members are not near the vehicle during testing and that proper fire suppressants are on standby in case of failure resulting in fire.
- A dry track on a 20ºC to 27ºC day is preferred to ensure proper traction.

Outputs to be generated:

- Validation of drivetrain operation in cornering

Justification:

This test is to be conducted to ensure that the drivetrain can handle the cornering forces accompanied with on-track testing. This test is to validate the drivetrains capabilities with the axial loading conditions

Criteria:

A successful test would have the drivetrain cornering smoothly repeatedly without any failures or ceasing.

Failed Test Procedure:

In case of failure, meaning disassembly, smoke, fire, or ceased drivetrain, the team must perform a failure analysis to determine the root cause and remedy it through maintenance or drivetrain modifications.

T-PHYS-M-04	Physical Brake Testing
Components	VEHICLE
Requirements to Validate	ALL
Associated Operation Concept	Braking

Procedure:

Material specifications

- Entire vehicle with installed drivetrain

Loading specifications

- The vehicle is to achieve top speed in its final gear and brake at full force as to lock the wheels bringing the vehicle to a full stop.
- The driver is to sit in the cockpit – wearing the necessary safety equipment – applying all their force onto the brake pedal and keep the vehicle in a straight line after reaching top speed.
- It is CRITICAL that all observing members are not near the vehicle during testing and that proper fire suppressants are on standby in case of failure resulting in fire. No persons should be in the path of the vehicle in case of loss of traction.
- A dry track on a 20ºC to 27ºC day is preferred to ensure proper traction.

Outputs to be generated:

- Validation of drivetrain operation in braking

Justification:

This test is to be conducted to ensure that the drivetrain can handle the braking forces accompanied with on-track testing. This test is to validate the drivetrains capabilities with the braking loading conditions which is mainly experienced on the wheel hub.

Criteria:

A successful test would have the drivetrain withstand the braking forces repeatedly without any failures or ceasing.

Failed Test Procedure:

In case of failure, meaning disassembly, smoke, fire, or ceased drivetrain, the team must perform a failure analysis to determine the root cause and remedy it through maintenance or drivetrain modifications.

Appendix

Appendix

Test Results

Test results are presented in this section using the documentation structures introduced in the Test Review Gate Report.

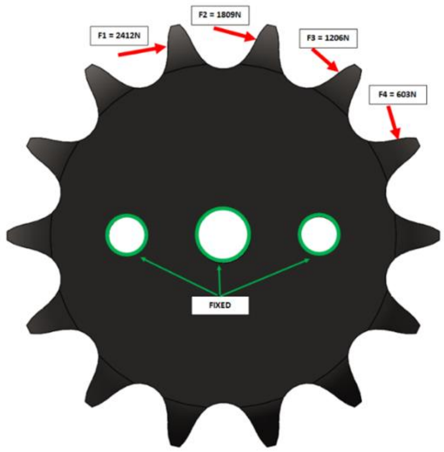
Readers are directed to the Test Readiness Review Gate Report for more detailed descriptions of test packages.

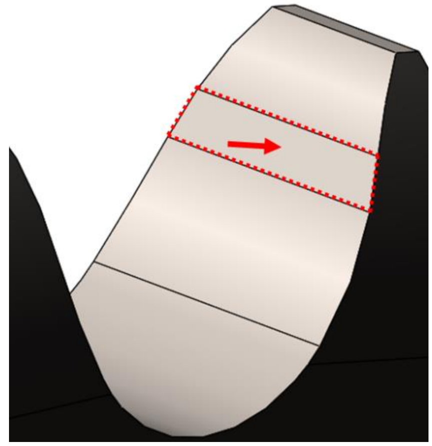
All FEA simulations have been checked for mesh independence of results. Unless specified otherwise, results were considered to be mesh independent once the difference between consecutive refinements is below 5%.

Sprocket Test Packages

T-DIFF-L-01	Front Sprocket Static Stress and Fatigue Analysis
Components	**S-1**
Requirements to Validate	**[RREQ-1] [PREQ-2] [PREQ-3] [FREQ-1]**
Associated Operation Concept	**Launch**

FBD:





Procedure:

Material specifications

- **S-1**: AISI 4130 Normalized at 870°C

Loading specifications

- Loading Conditions
  The total chain tension applies a force of 6029.95N to the sprocket. The sprocket distributes this force predominantly over 4 teeth. The tooth with highest stress experiences 40% of the force, second tooth-30%, third tooth-20%, fourth tooth-10%.
  - Tooth 1 = 0.4F = 2412 N
  - Tooth 2 = 0.3F = 1809 N
  - Tooth 3 = 0.2F = 1206 N
  - Tooth 4 = 0.1F = 603 N
  - Loading is applied normal to a small area (6.9 mm x 1.5 mm) at the pitch diameter of the sprocket to represent contact stress from the chain.
- Fixed locations
  - Cylindrical face of the 2 dowel pin holes on each side
  - Cylindrical face of center hole (representing a spline)
- Fatigue
  - Zero based loading
  - 100,000 cycles

Simulation methodology

- SolidWorks will be used to produce all outputs
- Mesh independence will be achieved when difference in results is less than 5%

T-DIFF-L-01-ITER1		
Overall Result	Fail	
Criteria	Relevant Requirement	Result
FOS > 1.5	**[PREQ-2]**	Fail
Number of cycles > 100,000	**[PREQ-3]**	Pass

Results

FOS (Minimum)	1.042
Von Misses (Maximum)	4.414×10^{8} Pa
Displacement (Maximum)	2.16×10^{-2} mm
Total Life (Minimum)	2.933×10^{5} Cycles
Damage (Maximum)	3.409×10^{1}

Base Mesh	Local Mesh Control	Mesh Control Ratio
Fine	0.1 mm	1.1

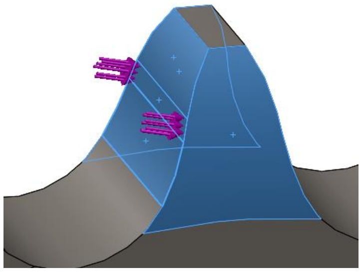


Figure 34: S-1 *local mesh control surface application on the tooth with highest force*

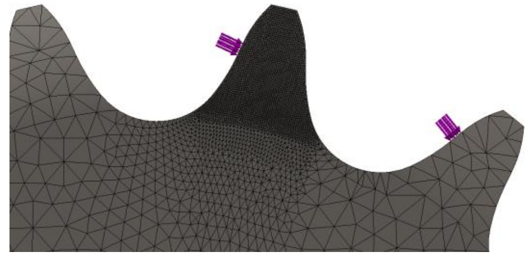


Figure 35: S-1 *mesh with refinement*

Results

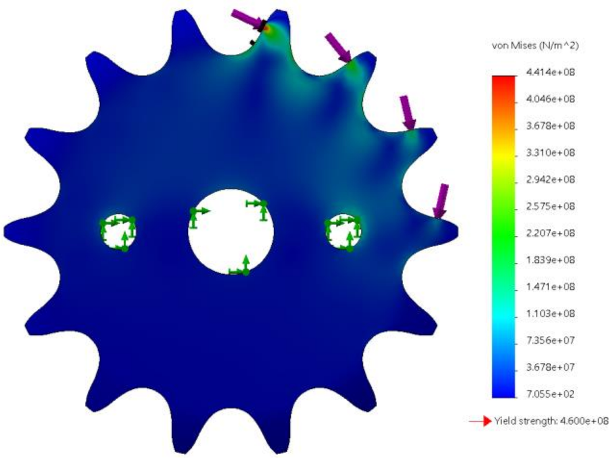


Figure 36: **S-1** *Von Mises stress plot*

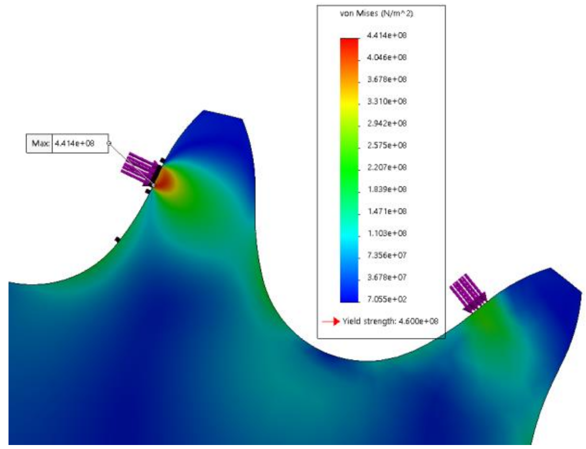


Figure 37: **S-1** *maximum Von Misses stress location*

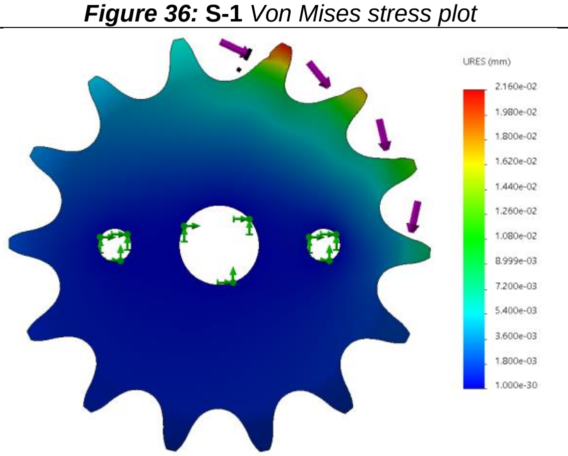


Figure 38: **S-1** *displacement plot*

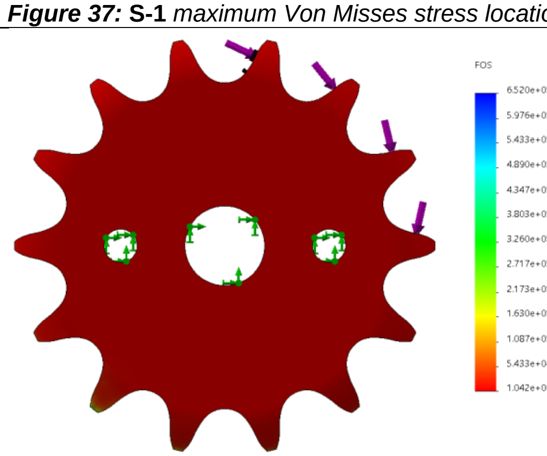


Figure 39: **S-1** *factor of safety map*

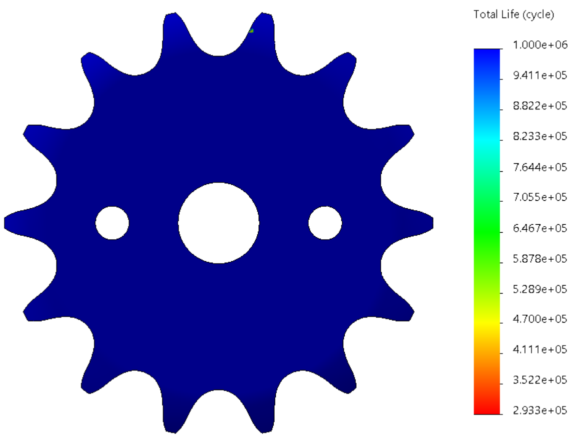


Figure 40: **S-1** *total life plot*

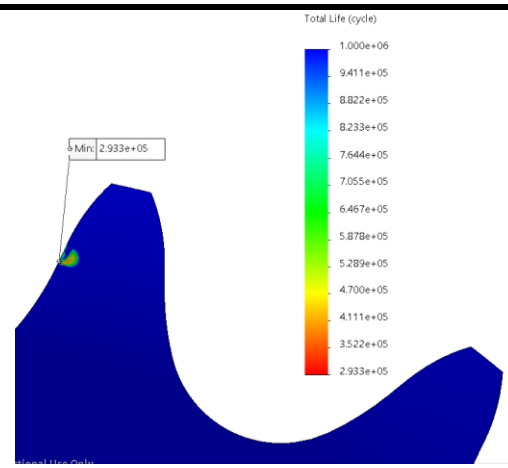


Figure 41: **S-1** *minimum total life cycle location*

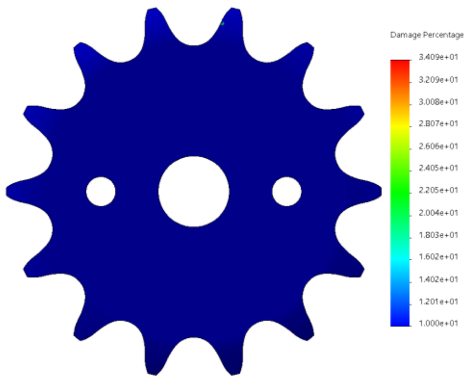


Figure 42: **S-1** *Damage percentage plot*

NCR1	
Event Description	Does not meet factory of safety criteria
Severity	1
Impact	Sprocket failure would result in an undrivable vehicle as power cannot be transferred to the wheels.

Review

The front sprocket experiences the highest force on the tooth which experience the highest force from the chain (40% of the chain tension). It is at this location in which the factor of safety is below the minimum criteria of 1.5. The failure occurs due to the high stress concentration from the small contact patch in which the force is applied.

Path to Resolution

To fix the issue a material change is required. **The material shall change from AISI 4130 to AISI 4340 (normalized**). AISI 4340 has a yield strength of 710 MPa, and could increase the factor of safety to 1.6.

Material	Yield Strength	Stress	Factor of Safety
AISI 4130	460 MPa	441 MPa	1.04
AISI 4340 (normalized)	710 MPa	441 MPa	1.61 (Expected)

Table 12: **T-DIFF-L-01** *results with AISI 4130 and AISI 4340*

T-DIFF-L-01-ITER2		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 1.5	**[PREQ-2]**	Pass
Number of cycles > 100,000	**[PREQ-3]**	Pass

Results

FOS (Minimum)	1.604
Von Misses (Maximum)	4.428×10^{8} Pa
Displacement (Maximum)	2.176×10^{-2} mm
Total Life (Minimum)	2.06×10^{4} Cycles*
Damage (Maximum)	4.855×10^{2}

Base Mesh	Local Mesh Control	Mesh Control Ratio
Fine	0.1 mm	1.1

Review

As a result of changing the material from AISI 4130 to AISI4340 normalized, the factor of safety has increase from 1.04 to 1.6, passing the FOS criteria. The fatigue analysis shows a minimum total life of 2.06 x10^4 cycles on the tooth with the highest loading. This is still considered a pass because in reality, the sprocket is spinning, and the highest force is being applied to every single tooth rather than only one. Therefore, the total life should be 2.06 x10^4 cycles x 14 teeth = 2.88 x 10^5, which meets the total life criteria.

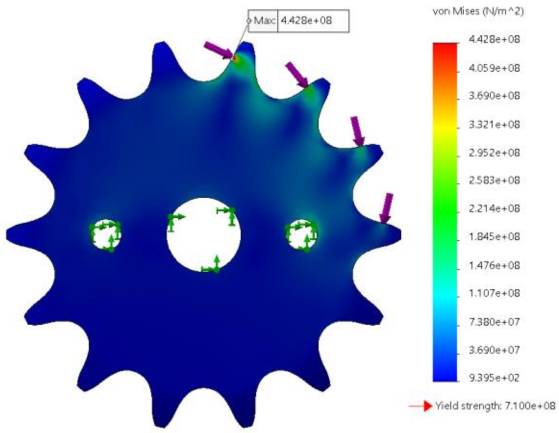


Figure 43: **S-1** *Von Mises stress plot – ITER2*

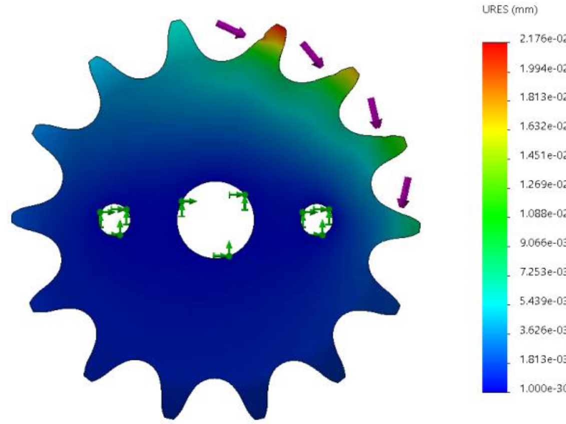


Figure 44: **S-1** *displacement plot – ITER2*

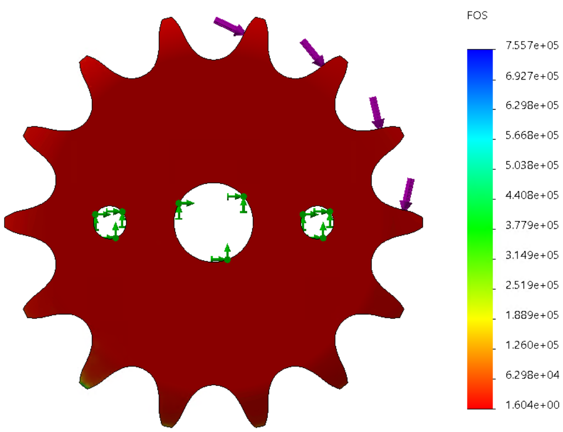


Figure 45: **S-1** *factor of safety plot – ITER2*

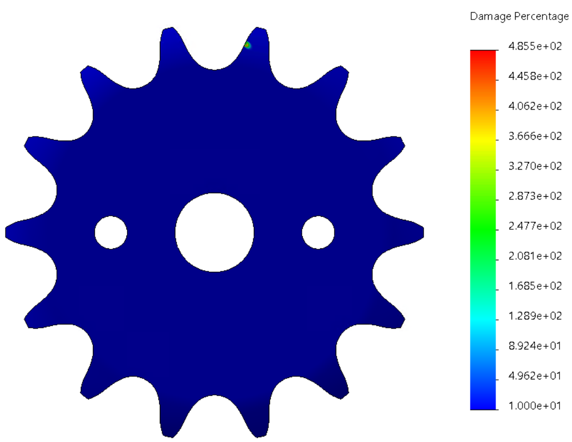


Figure 46: **S-1** *damage percentage plot – ITER2*

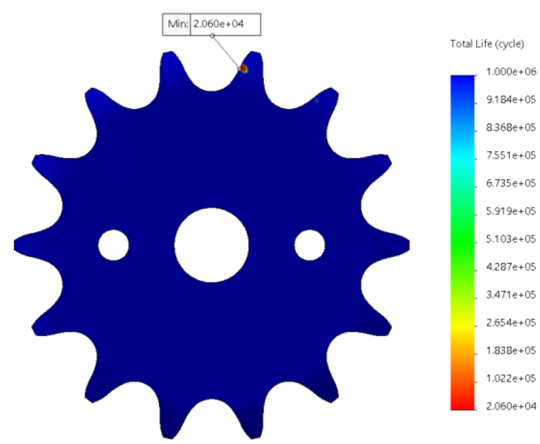
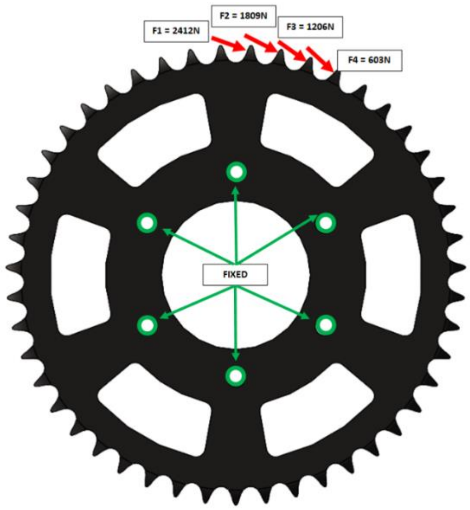
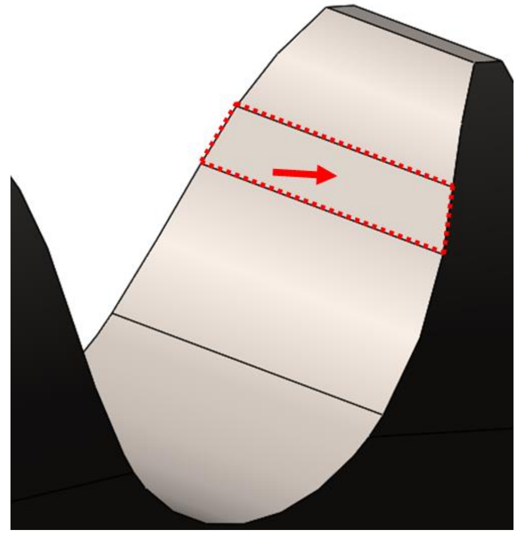


Figure 47: **S-1** *total life plot – ITER2*

T-DIFF-L-02	Rear Sprocket Static Stress and Fatigue Analysis
Components	**S-2**
Requirements to Validate	**[RREQ-1] [PREQ-2] [PREQ-3] [FREQ-1]**
Associated Operation Concept	**Launch**

FBD:





Procedure:

Material specifications

- **S-2**: AISI 4130 Normalized at 870°C

Loading specifications

- Loading Conditions
  The total chain tension applies a force of 6029.95 N to the sprocket. The sprocket distributes this force predominantly over 4 teeth. The tooth with highest stress experiences 40% of the force, second tooth-30%, third tooth-20%, fourth tooth-10%.
  - Tooth 1 = 0.4F = 2412 N
  - Tooth 2 = 0.3F = 1809 N
  - Tooth 3 = 0.2F = 1206 N
  - Tooth 4 = 0.1F = 603 N
  - Loading is applied normal to a small area (6.9 mm x 1.5 mm) at the pitch diameter of the sprocket to represent contact stress from the chain.
- Fixed locations
  - Cylindrical face of the 6 bolt holes
- Fatigue
  - Zero based loading
  - 100,000 cycles

Simulation methodology

- SolidWorks will be used to produce all outputs
- Mesh independence will be achieved when difference in results is less than 5%

T-DIFF-L-02-ITER1		
Overall Result	Fail	
Criteria	Relevant Requirement	Result
FOS > 1.5	**[PREQ-2]**	Fail
Number of cycles > 100,000	**[PREQ-3]**	Fail

Results

FOS (Minimum)	1.324
Von Misses (Maximum)	3.473×10^{8} Pa
Displacement (Maximum)	2.433×10^{-2} mm
Total Life (Minimum)	4.463×10^{4} Cycles
Damage (Maximum)	2.24×10^{2}

Base Mesh	**Local Mesh Control**	**Mesh Control - Ratio**
Fine	0.05 mm	1.1

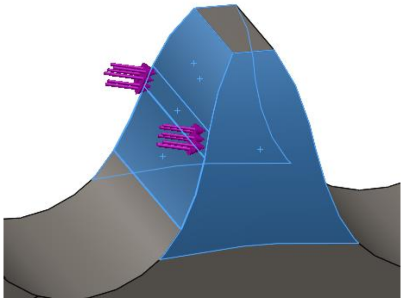


Figure 48: **S-2** *local mesh control surface application on the tooth with highest force*

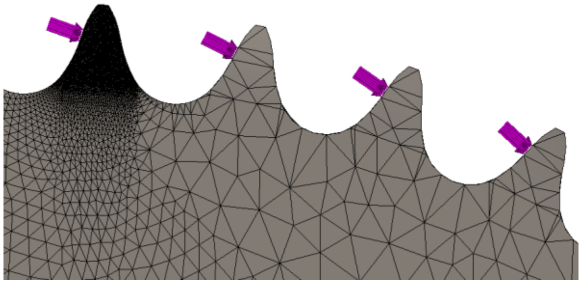


Figure 49: **S-2** *mesh with refinement*

Stress Analysis Results

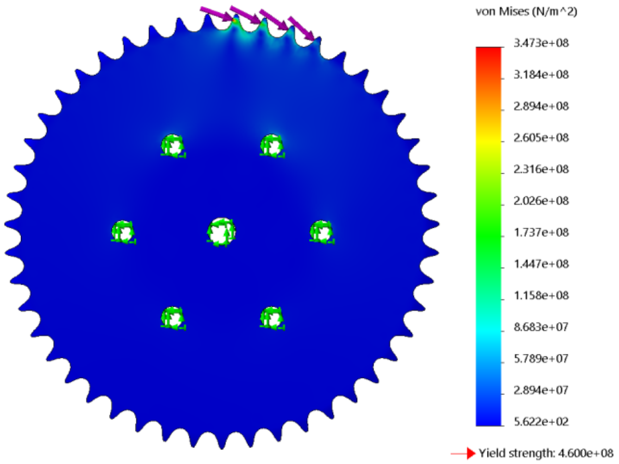


Figure 50: **S-2** *Von Mises stress plot*

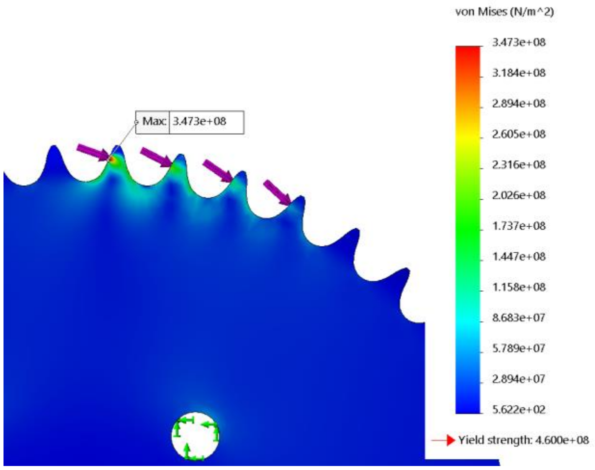


Figure 51: **S-2** *maximum Von Mises stress location*

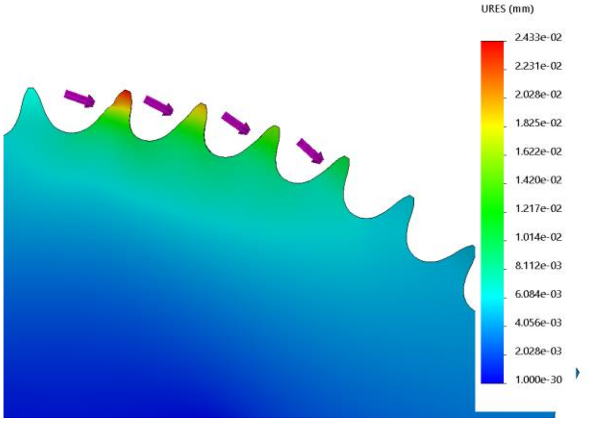


Figure 52: **S-2** *displacement plot*

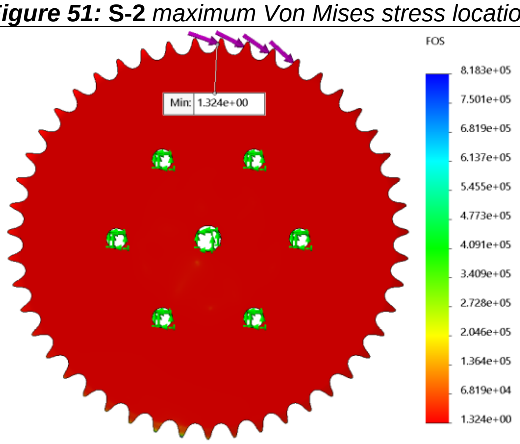


Figure 53: **S-2** *factor of safety plot*

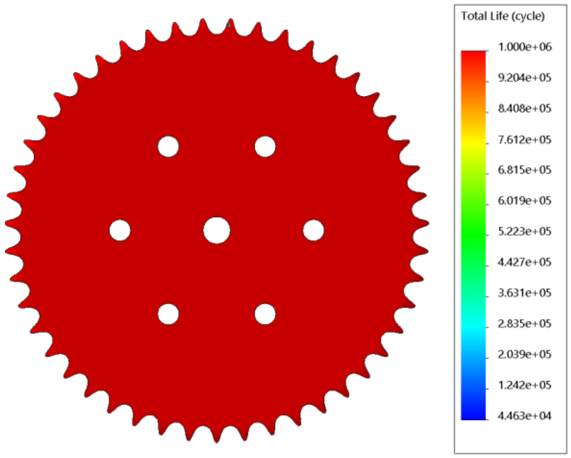


***Figure 54:* S-2** *total life plot*

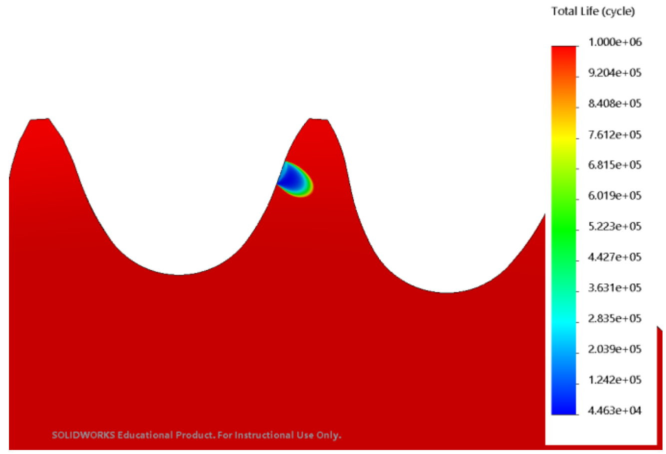


***Figure 55:* S-2** *minimum total life cycles location*

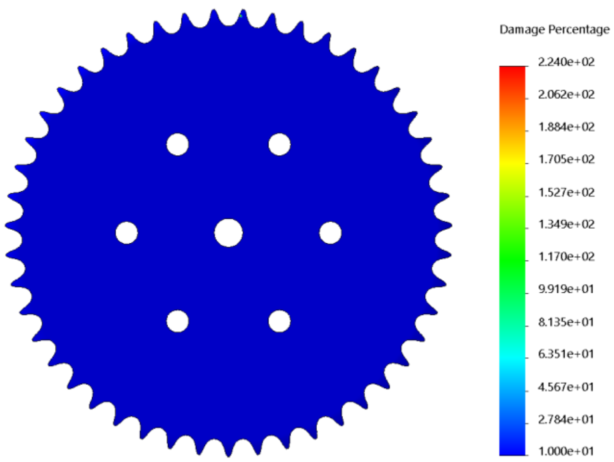


***Figure 56:* S-2** *damage percentage plot*

NCR2	
Event Description	Does not meet factory of safety criteria
Severity	1
Impact	Sprocket failure would result in an undrivable vehicle as power cannot be transferred to the wheels.

Review

The rear sprocket experiences the highest force on the tooth which experience the highest force from the chain (40% of the chain tension). It is at this location in which the factor of safety is below the minimum criteria of 1.5. The failure occurs due to the high stress concentration from the small contact patch in which the force is applied.

Path to Resolution

To fix the issue a material change is required. **The material shall change from AISI 4130 to AISI 4340 (normalized**). AISI 4340 has a yield strength of 710 MPa, and could increase the factor of safety to 2.05.

Material	Yield Strength	Stress	Factor of Safety
AISI 4130	460 MPa	347 MPa	1.36
AISI 4340 (normalized)	710 MPa	347 MPa	2.05 (Expected)

***Table 13:* T-DIFF-L-02** *results with AISI 4130 and AISI 4340*

T-DIFF-L-02-ITER2		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 1.5	**[PREQ-2]**	Pass
Number of cycles > 100,000	**[PREQ-3]**	Pass

Results

FOS (Minimum)	2.00
Von Misses (Maximum)	3.550×10^8 Pa
Displacement (Maximum)	3.868×10^{-2} mm
Total Life (Minimum)	5.284×10^4 Cycles*
Damage (Maximum)	5.284×10^4

Review

As a result of changing the material from AISI 4130 to AISI4340 normalized, the factor of safety has increase from 1.36 to 2, passing the FOS criteria. The fatigue analysis shows a minimum total life of 5.284×10^4 cycles on the tooth with the highest loading. This is still considered a pass because in reality, the sprocket is spinning, and the highest force is being applied to every single tooth rather than only one. Therefore, the total life should be 5.284×10^4 cycles x 47 teeth = 2.48×10^6, which meets the total life criteria.

Base Mesh	Local Mesh Control	Mesh Control - Ratio
Fine	0.05 mm	1.1

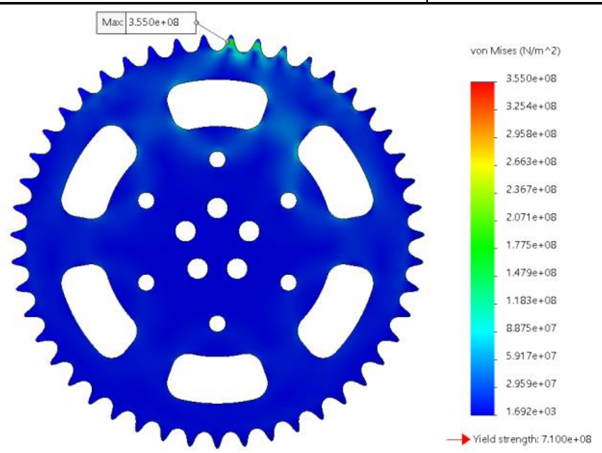


Figure 57: **S-2** *Von Mises stress plot – ITER2*

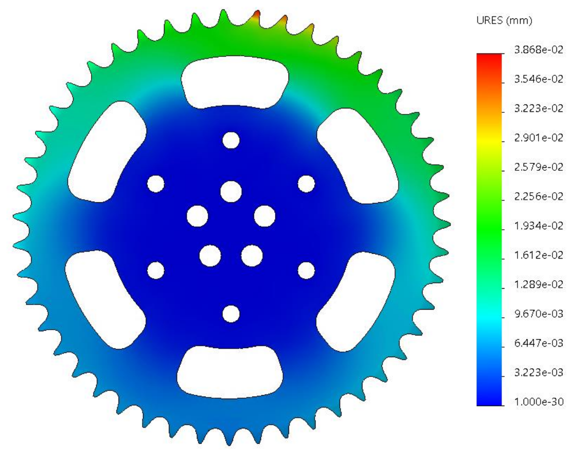


Figure 58: **S-2** *displacement plot - ITER2*

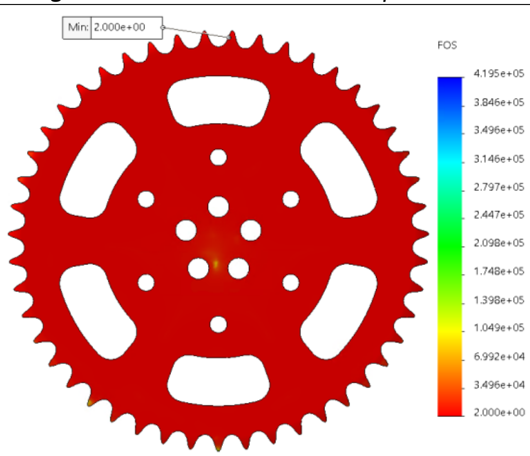


Figure 59: **S-2** *factor of safety plot - ITER2*

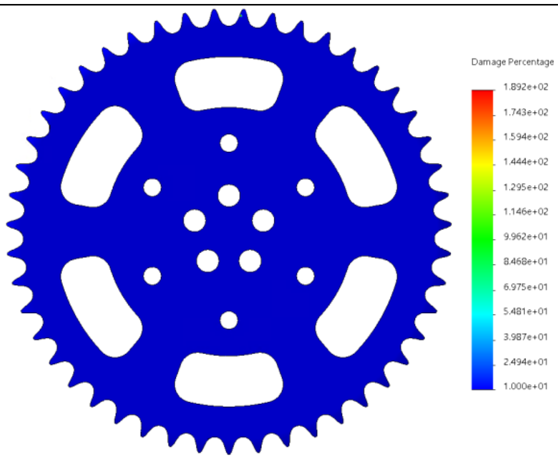


***Figure 60:* S-2** *Damage percentage plot - ITER2*

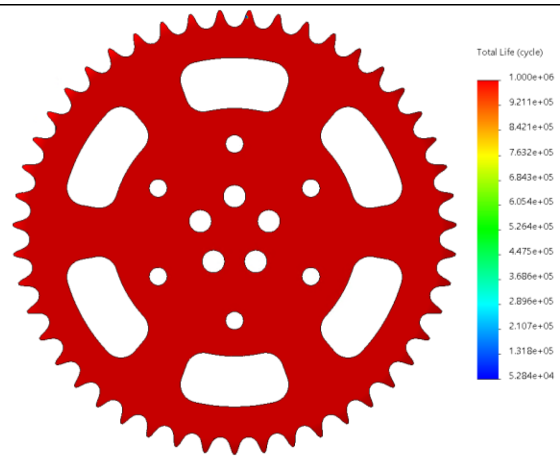
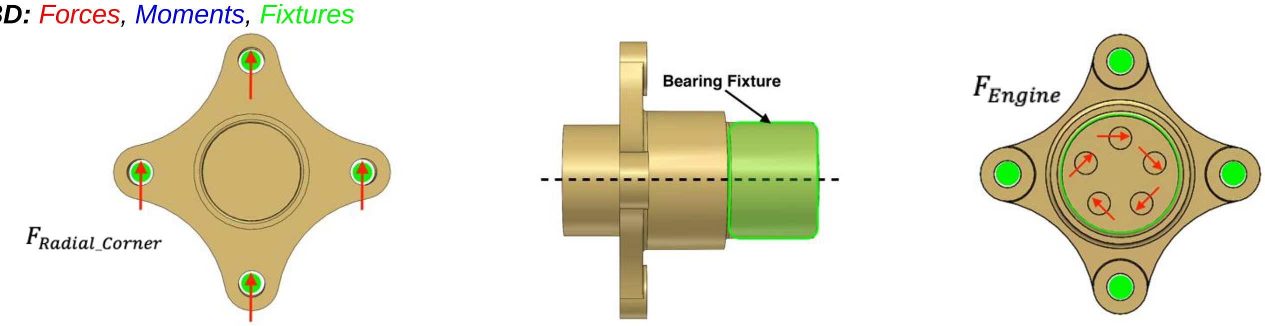


***Figure 61:* S-2** *total life plot - ITER2*

[WHUB] Test Packages

T-WHUB-L-02	Wheel Hub - Launch
Components	**W-1**
Requirements to Validate	**[PREQ-2] [PREQ-3] [IREQ-2]**
Associated Operation Concept	**Launch**

FBD: *Forces, Moments, Fixtures*



Material specifications

- **W-1**: AISI 4340N: Alloy Steel - Normalized

Loading specifications

Static:

- Loads → $4x\left(F_{Radial\_Launch}=271.54N\right)=1{,}086.16N$
  $5x\left(F_{Engine}=4{,}519N\right)=22{,}595\ N$
- Fixed → Cylindrical extrusions going through each wheel mounting hole are made both fixed and rigid. Additionally, a bearing type fixture is located on the smaller cylindrical portion as indicated on the FBD above.

Fatigue:

- Same loading conditions as static case
- Zero based loading
- 10,000 Cycles

Simulation methodology

- SolidWorks will be used to simulate all outputs
- Mesh independence will be achieved when difference in results is less than 5%

T-WHUB-L02-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2 & Deflection ≤ 1mm	**[PREQ-2]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3]**	Pass
Interface with rotor, wheel and knuckle	**[IREQ-2]**	Pass

Results

Value	**Result**
Stress (N/m^2)	$5.095\text{x}10^{7}$
Strain	$2.017\text{x}10^{-4}$
Deformation (mm)	$1.021\text{x}10^{-2}$
Factor of Safety	13.93

Mesh

Global Mesh Size	**Tolerance**	**Local Mesh Control**			**Mesh Elements**
		Size	**Ratio**	**Locations**	
2 mm	0.5 mm	1 mm	2	Edges of wheel mount holes	354,058

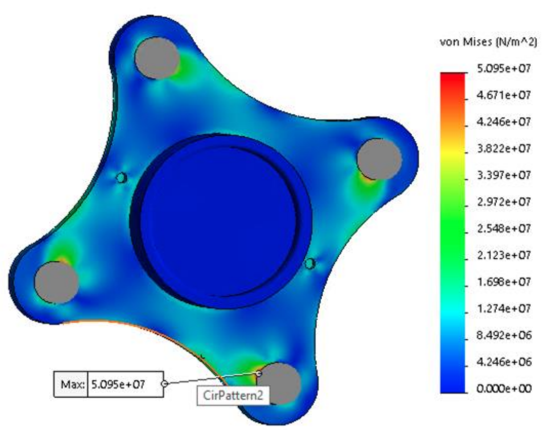


Figure 62: **W-1** *wheel hub stress results – launch*

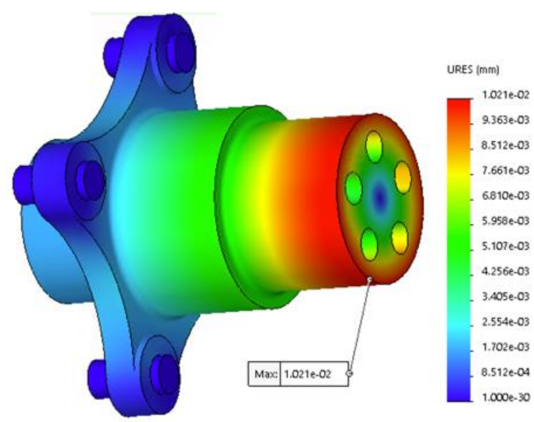


Figure 63: **W-1** *wheel hub displacement results – launch*

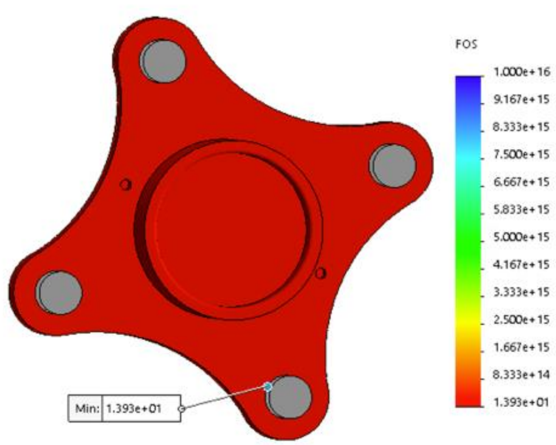


Figure 64: **W-1** *wheel hub factor of safety results – launch*

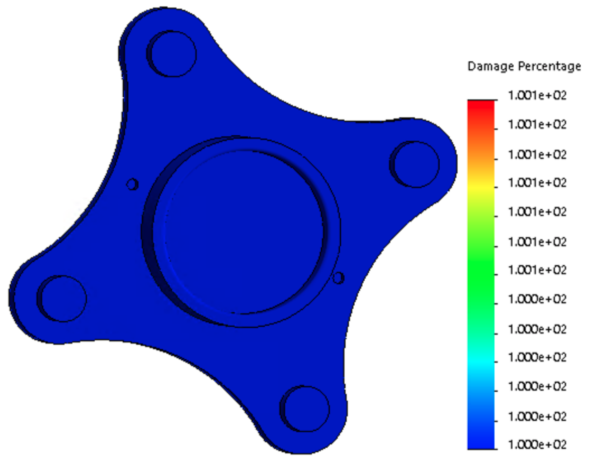


Figure 65: **W-1** *wheel hub damage percent results – launch*

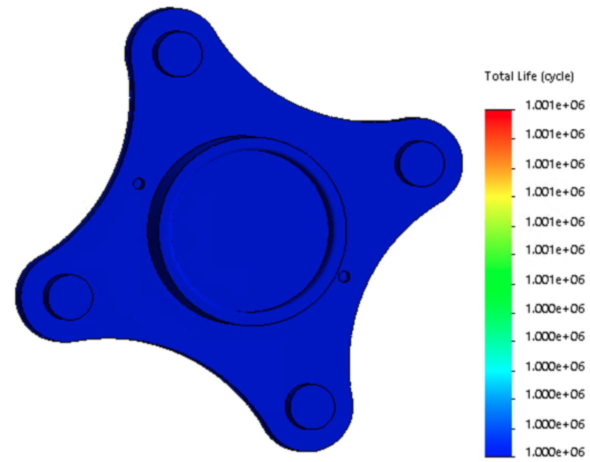
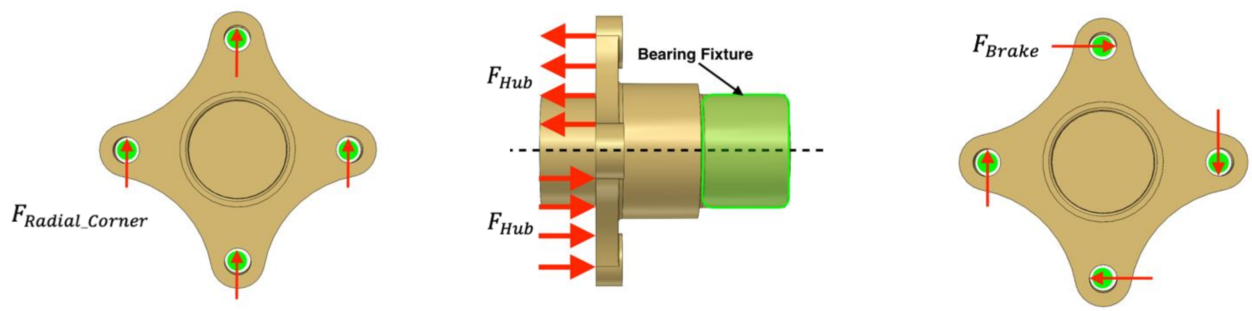


Figure 66: **W-1** *wheel hub total life results – launch*

T-WHUB-C-01	Wheel Hub - Cornering
Components	**W–1**
Requirements to Validate	**[PREQ-2] [PREQ-3] [IREQ-2]**
Associated Operation Concept	**Cornering**

FBD: *Forces*, *Moments*, *Fixtures*



Material specifications

- **W-1**: AISI 4340N: Alloy Steel - Normalized

Loading specifications

Static:

- Loads → 4x(F_{Radial_Corner}=347.35N)=1389.39N
  4x(F_{Brake}=1711.15)=6844.6N
  F_{Hub}=544.21 N
- Fixed → Cylindrical extrusions going through each wheel mounting hole are made both fixed and rigid. Additionally, a bearing type fixture is located on the smaller cylindrical portion as indicated in the middle FBD above.

Fatigue:

- Same loading conditions as static case
- Zero based loading
- 10,000 Cycles

Simulation methodology

- SolidWorks will be used to simulate all outputs.
- Mesh independence will be achieved when difference in results is less than 5%

T-WHUB-C-01-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2 & Deflection ≤ 1mm	**[PREQ-2]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3]**	Pass
Interface with rotor, wheel and knuckle	**[IREQ-2]**	Pass

Results

Value	**Result**
Stress (N/m^2)	8.693×10^{7}
Strain	3.372×10^{-4}
Deformation (mm)	3.656×10^{-3}
Factor of Safety	8.168

Mesh

Global Mesh Size	**Tolerance**	**Local Mesh Control**			**Mesh Elements**
		Size	**Ratio**	**Locations**	
2mm	0.5mm	0.5mm	1.5	Faces of wheel mount ends	484,058

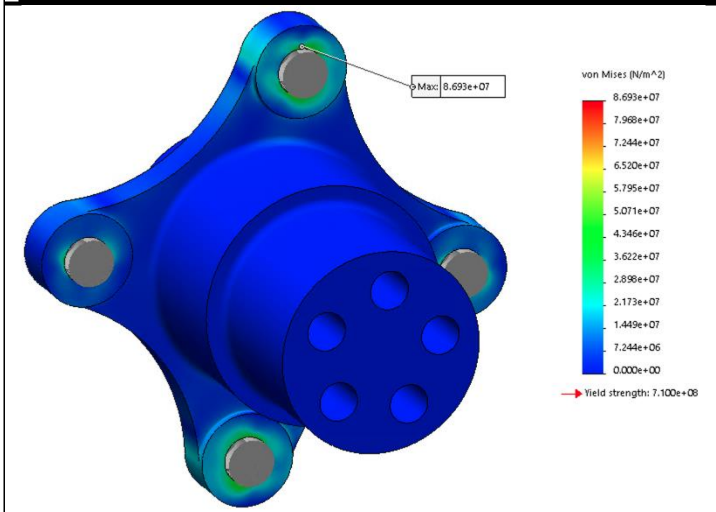


Figure 67: **W-1** *wheel hub stress results – cornering*

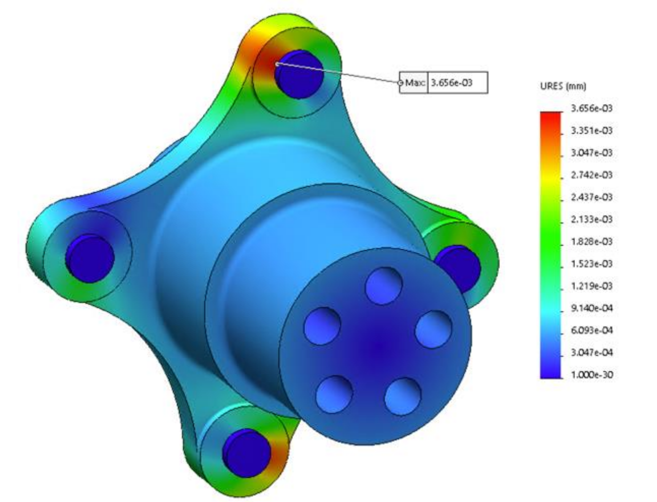


Figure 68: **W-1** *wheel hub displacement results – cornering*

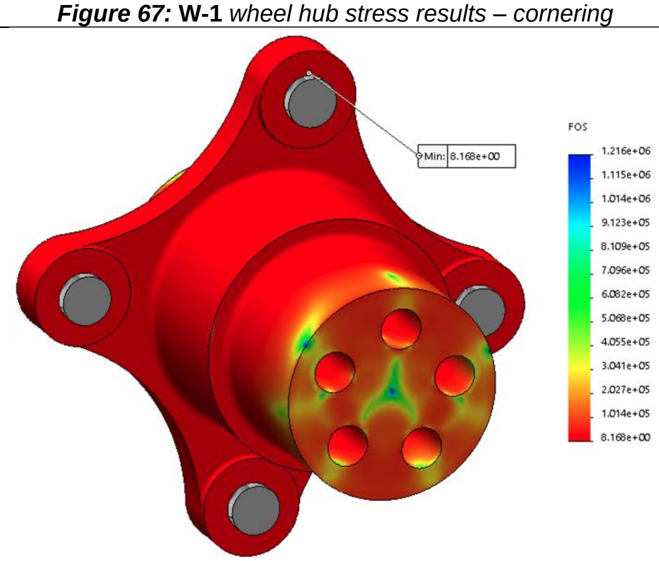


Figure 69: **W-1** *wheel hub factor of safety results – cornering*

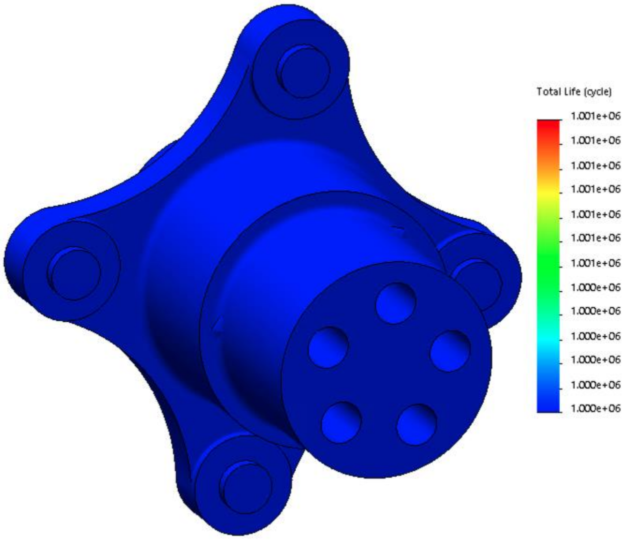


Figure 70: **W-1** *wheel hub damage percent results – cornering*

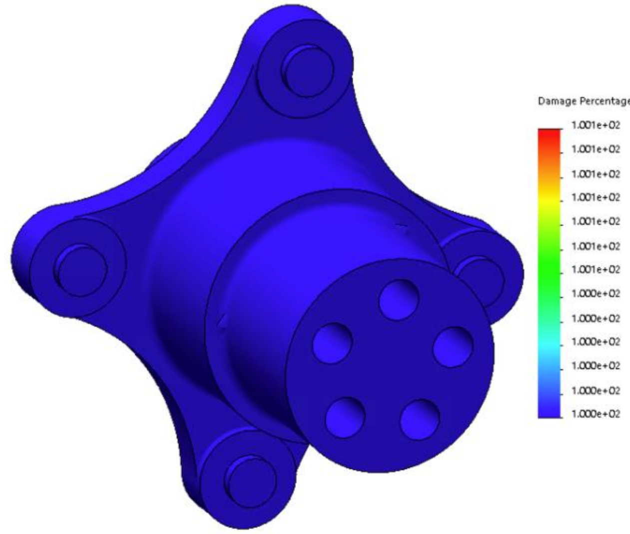
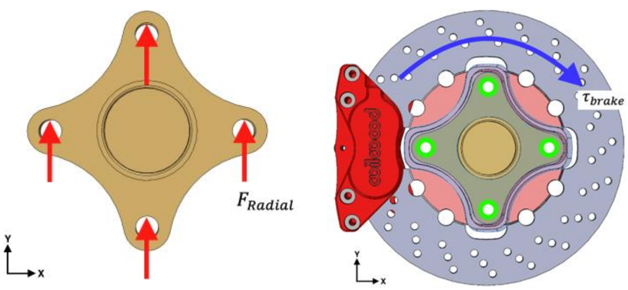


Figure 71: **W-1** *wheel hub factor total life results – cornering*

T-WHUB-B-01	Wheel Hub – Maximum Braking
Components	**W–1**
Requirements to Validate	**[PREQ-2] [PREQ-3] [IREQ-2]**
Associated Operation Concept	**Braking**

FBD: *Forces*, *Moments*, *Fixtures*



Material specifications

- **W-1**: AISI 4340N: Alloy Steel - Normalized

Loading specifications

Static:

- Loads → 4x($F_{Radial\_Braking}$ = 305.84 N) = 1223.36 N
- Moments → τ_{Brake} = 342.23 Nm
- Fixed → Cylindrical portion of the wheel hub, where the bearing, fixed on the wheel hub, will be fixed in the knuckle

Fatigue:

- Same loading conditions as static case
- Zero based loading
- 10,000 Cycles

Simulation methodology

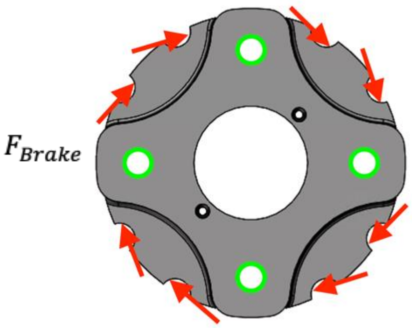
- SolidWorks will be used to simulate all outputs
- Mesh independence will be achieved when difference in results is less than 5%

Changes

This testing procedure has not been completed as it does not represent a maximum loading case. Compared to testing procedure **T-WHUB-C-01** – the cornering loading condition – the same braking force is represented as the car approaches the apex of the turn and a greater radial force is represented due to the lateral load transfer of the vehicle in the corner.

T-WHUB-B-02	Rotor Hat - Braking
Components	**W–2**
Requirements to Validate	**[PREQ-2] [PREQ-3]**
Associated Operation Concept	**Braking**

FBD: *Forces*, *Moments*, *Fixtures*



Material specifications

- **W-1**: AISI 4340N: Alloy Steel - Normalized

Loading specifications

Static:

- Forces
  - 8x(F_{Brake}=641.6 N)=5,131.8 N
- Fixed
  - Fixed on the faces of the four holes where the rotor hat is mounted between the wheel and wheel hub

Fatigue:

- Same loading conditions as static case
- Zero based loading
- 100,000 Cycles

Simulation methodology

- SolidWorks will be used to simulate all outputs
- Mesh independence will be achieved when difference in results is less than 5%

T-WHUB-B-02-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2 & Deflection ≤ 1mm	**[PREQ-2]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3]**	Pass

Results

Value	**Result**
Stress (N/m^2)	8.556×10^{7}
Strain	3.458×10^{-4}
Deformation (mm)	1.909×10^{-2}
Factor of Safety	8.298

Mesh

Global Mesh Size	**Tolerance**	**Local Mesh Control**			**Mesh Elements**
		Size	**Ratio**	**Locations**	
1mm	0.03mm	0.25mm	1.5	Area of maximum stress (fillet between rotor mount and wheel mount)	748,102

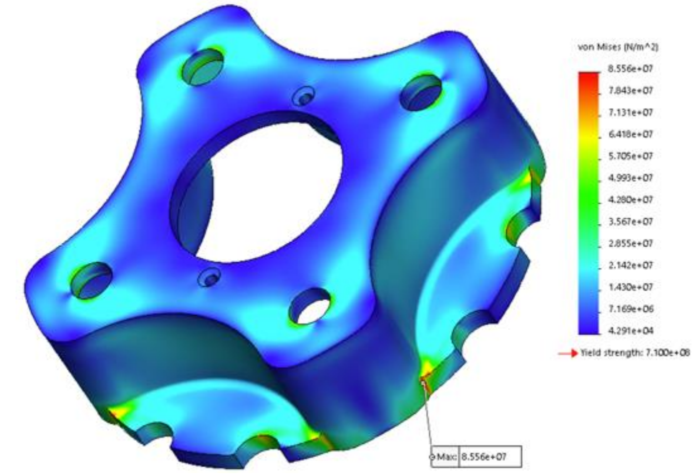


Figure 72: **W-2** *rotor hat stress results – braking*

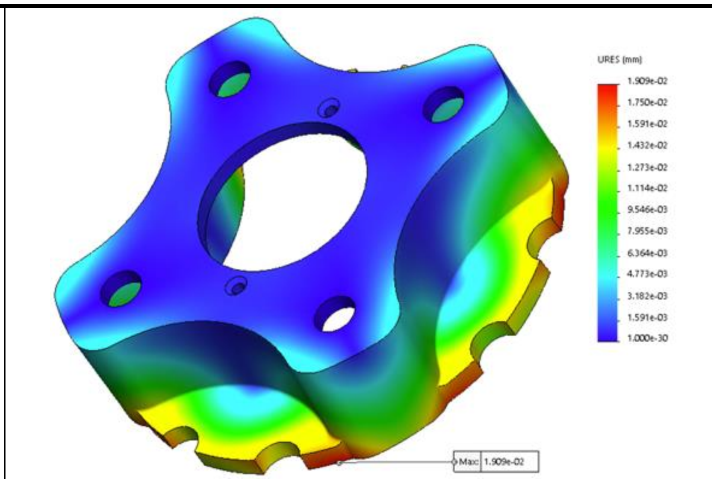


Figure 73: **W-2** *rotor hat displacement results – braking*

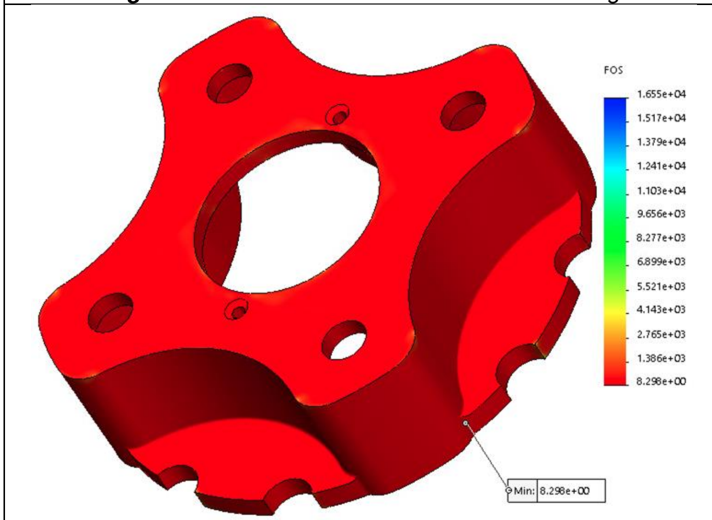


Figure 74: **W-2** *rotor hat factor of safety results – braking*

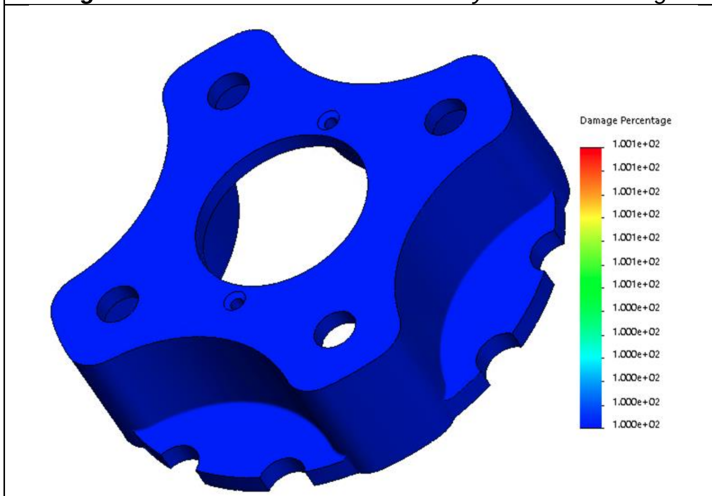


Figure 75: **W-2** *rotor hat damage percent results – braking*

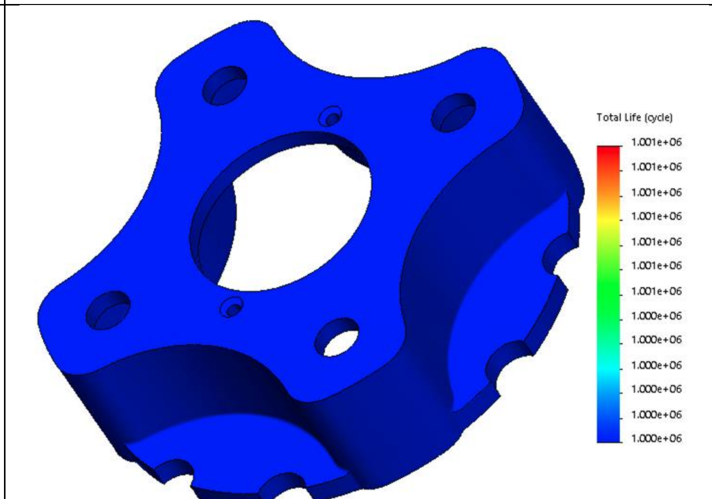
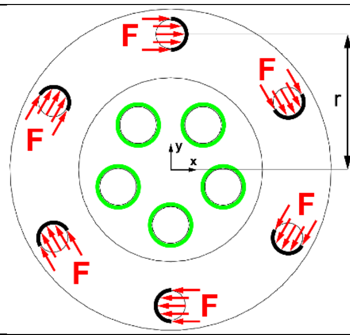


Figure 76: **W-2** *rotor hat factor total life results – braking*

[AXLE] Test Packages

T-WHUB-L-01	Outboard Axle Adapter in Torsion at Launch
Components	**W-8**
Requirements to Validate	**[RREQ-1] [FREQ-1] [PREQ-2] [PREQ-3]**
Associated Operation Concept	**Launch**

FBD:



Material specifications

- **W-8**: Aluminum 6061-T6

Loading specifications

- F = (361 Nm)·$\frac{1}{6}$ / r is applied to half-surface of all the bolts holes on the flange, where r is the distance between centers of the adapter body and the flange bolt holes. 361 Nm is the torque delivered on one axle as per the **Launch** conditions. Forces on each bolt hole is to be directed perpendicular to the angular position of each bolt hole.
- Cylindrical surfaces of the outboard (wheel hub side) bolts are fixed.

Simulation methodology

- The simulation is considered simple and is to be run in SolidWorks.
- Mesh independence of static results are to be verified by achieving less than 5% difference between the maximum stress values of consecutive mesh refinements.
- Simulation with the finest mesh is to be used for the cyclic, zero-based application of the same loading.

T-WHUB-L-01-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Pass

Results

Maximum Stress	96 MPa
Minimum FOS	2.682
Maximum Displacement	0.0397 mm

Final Mesh Settings

Global Cell Size			1 mm
Local Mesh Control		Area	Behind the flange, around the edge of the extrusion
		Cell Size	0.5 mm
		Growth Rate	1.5

Observations

- Stresses are seen to accumulate around the holes. The set of holes on the flange receive the loading, however highest stresses are seen to emerge at the fixed holes, representing the connection to the wheels.
- Stresses on the inner set of holes appear on a limited angular segment of the hole. The stresses are uniform across the thickness.
- Deformation emerges on the flange and is reinforced at each hole. Magnitudes are negligible.

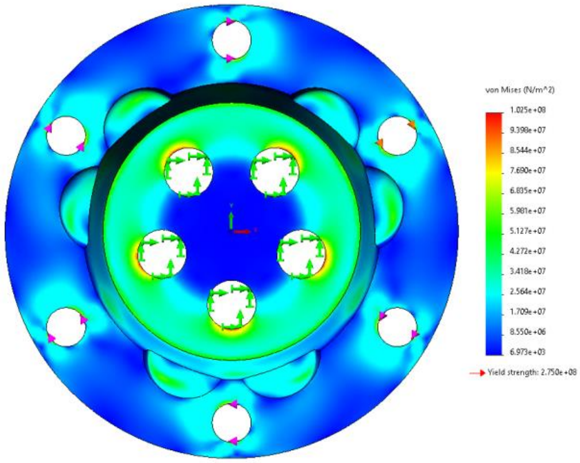


Figure 77: **W-8** *Von Mises stress map – front view*

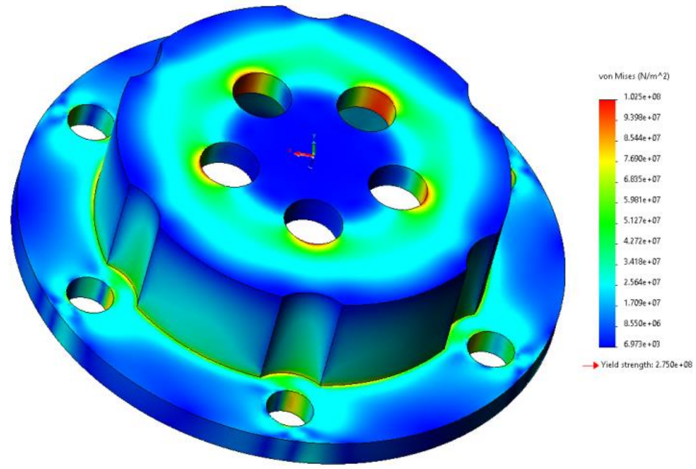


Figure 78: **W-8** *Von Mises stress map - back view*

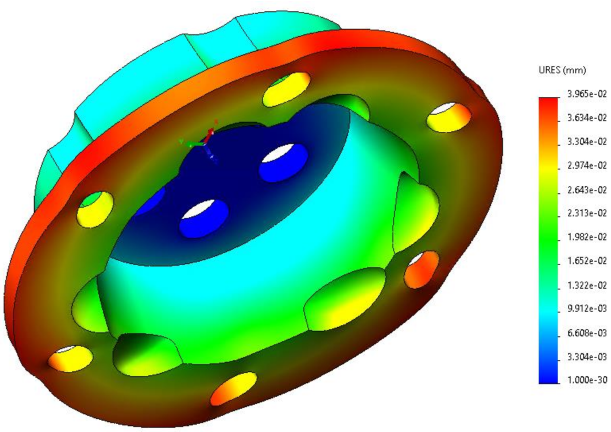


Figure 79: **W-8** *displacement map*

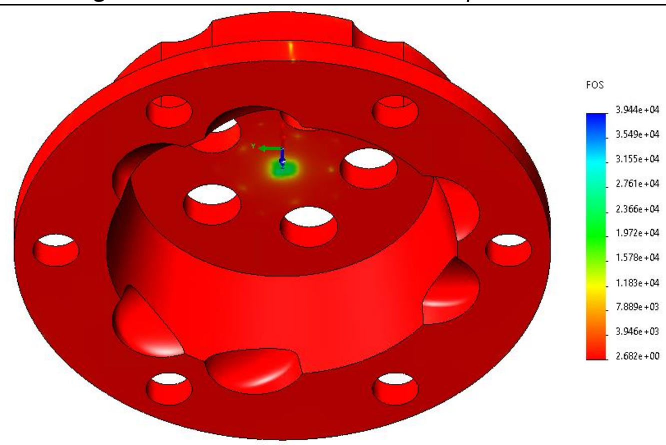
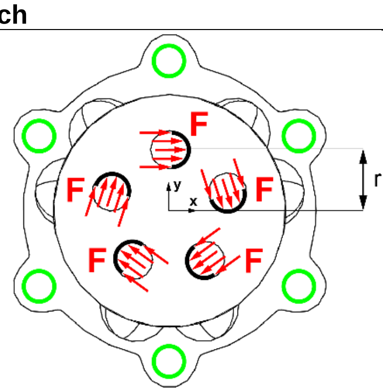


Figure 80: **W-8** *factor of safety map*

T-AXLE-L-01	Right Inboard Axle Adapter in Torsion at Launch
Components	**A-8**
Requirements to Validate	**[RREQ-1] [FREQ-1] [PREQ-2] [PREQ-3]**
Associated Operation Concept	**Launch**

FBD:



Changes to the test package

The test procedure and load modelling has changed since the definition of this package in TRR. Fixing the outer bolt holes which transmit rotation to the right wheel side and giving the torque through the inner bolt holes which are receiving rotation from the spool was determined to be a more accurate model of the loading. The condition simulated is one where the spool receives torque from the rear sprocket, the torque is split evenly to the left and right wheel sides, and the right wheel is instantaneously resisting rotation while **A-8** tries to get the axle to rotate.

Material specifications

- **A-8**: AISI 4130 Normalized

Loading specifications

- F = (361 Nm)$\cdot\frac{1}{6}$/r is applied to half-surface of all the bolts holes in the center, where r is the distance between centers of the adapter body and the inner bolt holes. 361 Nm is the torque delivered on one axle as per the **Launch** conditions. Forces on each bolt hole are to be directed perpendicular to the angular position of each bolt hole.
- Cylindrical surfaces of the inside bolts (connecting to spool) are fixed.

Simulation methodology

- Mesh independence of static results are to be verified by achieving less than 5% difference between the maximum stress values of consecutive mesh refinements.
- Simulation with the finest mesh is to be used for the cyclic, zero-based application of the same loading.

T-AXLE-L-01-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Not available

Results

Maximum Stress	213 MPa
Minimum FOS	2.162
Maximum Displacement	0.00908 mm

Final Mesh Settings

Global Cell Size	1 mm

Observations

- Outer set of bolts resist the rotation as per the model definition and have the lowest stresses and displacements. The inner bolt holes experience high stresses and displacement concentrated in the direction of rotation.
- Maximum deformation appears along the circle that connects the inner set of bolts, whereas the center of the circle is static. Similarly, stresses are also lower at the center of the circle.
- Because of the way the loading is modelled, highest stresses in each bolt hole appear as a high stress strip at the beginning and end of the loaded half.

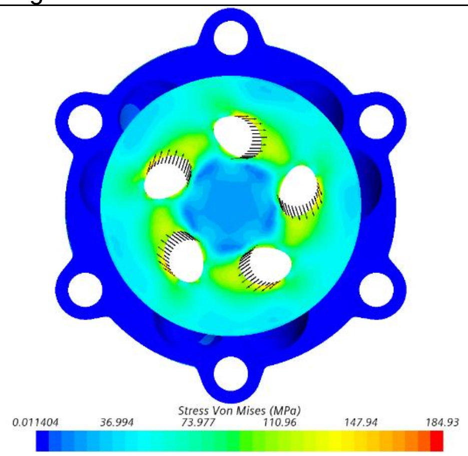


Figure 81: **A-8** *Von Mises stress map, front view, with forces*

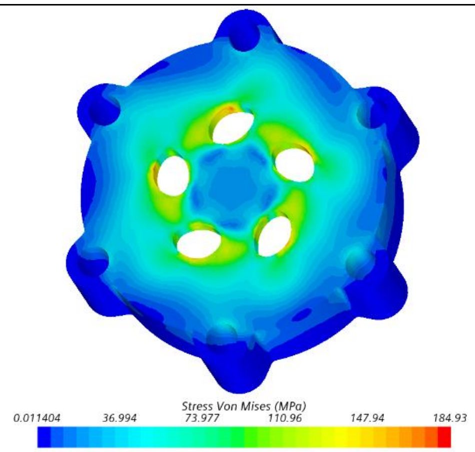


Figure 82: **A-8** *Von Mises stress map, back view*

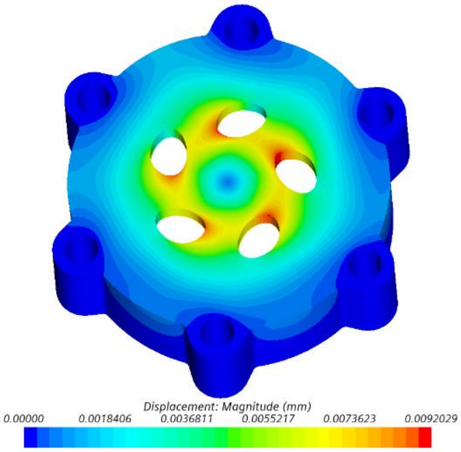
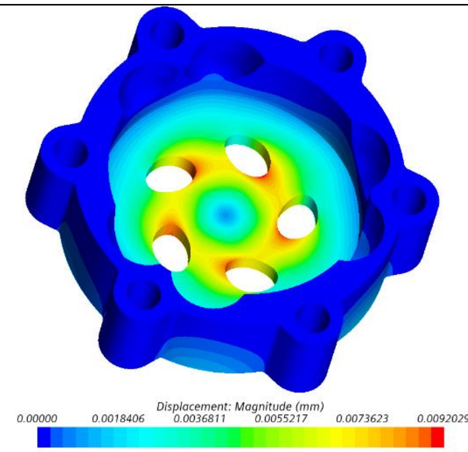
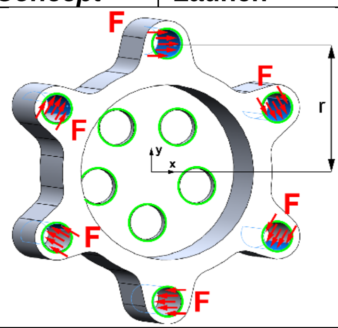
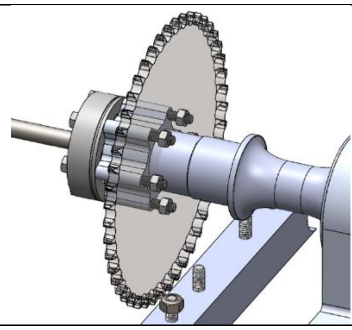
	

Figure 83: **A-8** *displacement map*	***Figure 84:*** **A-8** *factor of safety map*

T-AXLE-L-02	Left Inboard Axle Adapter in Torsion at Launch
Components	**A-7**
Requirements to Validate	**[RREQ-1] [FREQ-1] [PREQ-2] [PREQ-3]**
Associated Operation Concept	**Launch**

FBD:





Material specifications
- **A-7**: Aluminum 6061-T6

Loading specifications
- Cylindrical surfaces of the inner bolts (connecting to the spool) are fixed to simulate the spool resistance.
- Outboard circular edges of the outer bolts are fixed to simulate the resistance of left CV joint housing.
- F = $(722\ \text{Nm})\cdot r \cdot \frac{1}{6}$ is applied to half-surface of all the outer bolt holes (see blue surfaces and outlines in the FBD), where r is the distance between centers of the adapter body and the flange bolt holes. 722 Nm is the torque delivered by the rear sprocket to the driveshaft as per the **Launch** conditions. Forces on each bolt hole is to be directed perpendicular to the angular position of each bolt hole.

Simulation methodology
- The simulation is considered simple and is to be run in SolidWorks.
- Mesh independence of static results are to be verified by achieving less than 5% difference between the maximum stress values of consecutive mesh refinements.
- Simulation with the finest mesh is to be used for the cyclic, zero-based application of the same loading.

T-AXLE-L-02-ITER1		
Overall Result	Fail	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Fail
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Pass

Results

Maximum Stress	206 MPa
Minimum FOS	1.335
Maximum Displacement	0.0528 mm
Maximum Damage in 10000 cycles	2.6%
Minimum Life	38460 cycles

Final Mesh Settings

Global Cell Size	1 mm

Observations

- The outer set of bolt holes have low stresses despite receiving the loading. Maximum stresses occur at the inner set of bolt holes, which are modelled as fixed. The maximum stresses appear at a limited angular segment of the holes and are constant throughout the part thickness.
- **A-7** receives the total torque delivered by the rear sprocket and is under a more extreme loading compared to the outboard adapters (**W-8**, tested in **T-WHUB-L-01**).
- Maximum deformation appears at the holes on the flange.

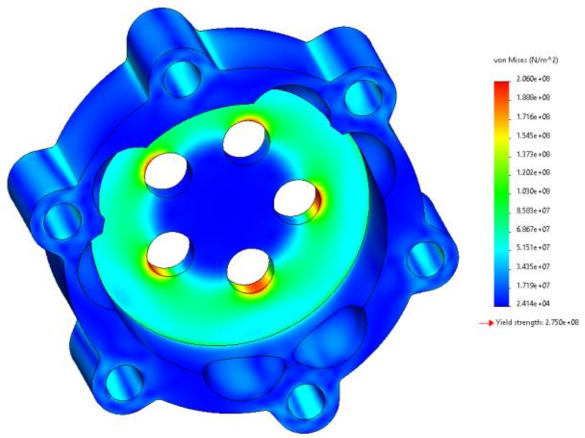


Figure 85: **A-7** *Von Mises stress map, front view*

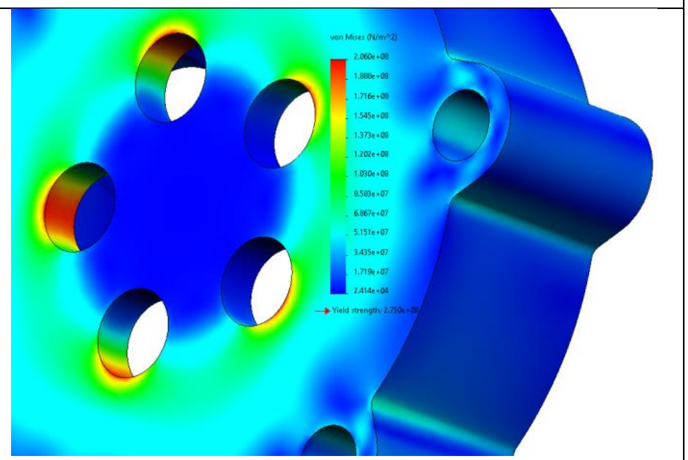


Figure 86: **A-7** *Von Mises stress map, back view*

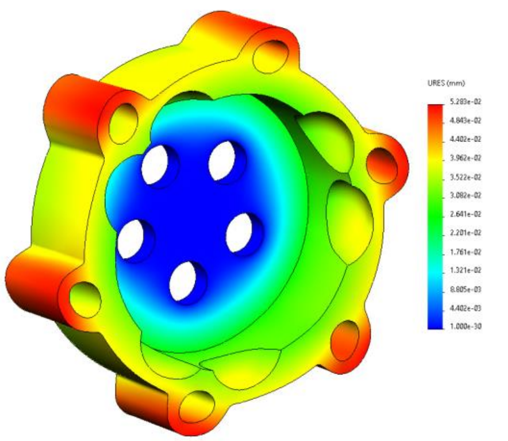


Figure 87: **A-7** *displacement map*

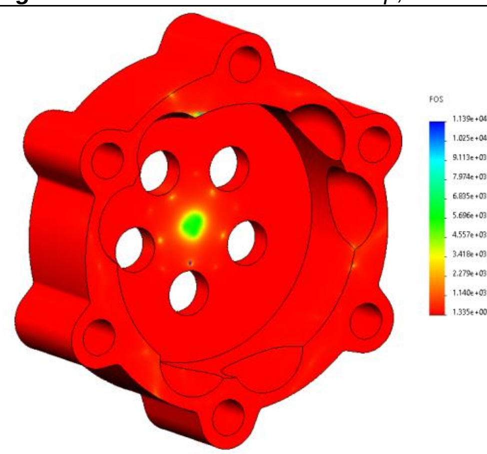


Figure 88: **A-7** *factor of safety map*

NCR3	
Event Description	Failure to meet minimum FOS
Severity	3
Impact	Performance below targets

Review

High stresses at the 5 holes interfacing the spool led to a minimum FOS below the target of 2. The part still does not fail and is considered safe. High stress is uniform across the thickness of the back wall. The high stress region at each hole covers a limited angular segment of the hole.

Path to Resolution

Two options are considered to achieve the minimum FOS target:

(1) Material of **A-7** can be changed to one with a higher yield strength
(2) Design of **A-7** can be revised to better support the high-stress locations

- Option (1) is likely to resolve the issue, however, will also increase the weight of the component. Considering the project objectives, a design revision will be tried first.
- Highest stresses were seen to occur at the face of **A-7** interfacing the spool. Thickening this back wall can be considered.

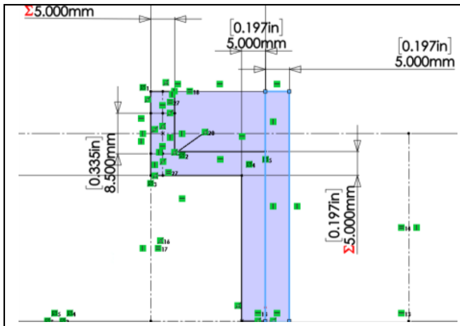


Figure 89: *Revised sketch of the revolved profile*

The revolved profile of the adapter has been thickened at the back wall as illustrated in the sketch on the left. The thickness has been increased from 5 mm to 10 mm.

T-AXLE-L-02-ITER2		
Overall Result	Fail	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Fail
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Pass

Results

Maximum Stress	206 MPa
Minimum FOS	1.335
Maximum Displacement	0.0528 mm

Final Mesh Settings

Global Cell Size	1 mm

Observations

- Maximum stresses at the inner bolts appear same as in the first iteration despite the increased wall thickness.

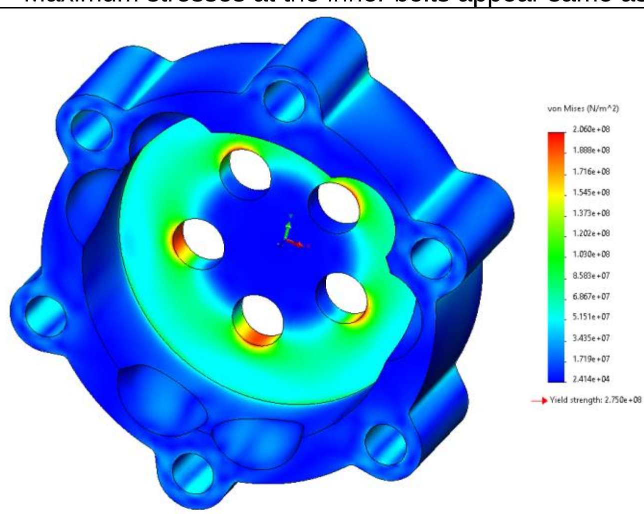


Figure 90: **A-7** *Von Mises stress map - ITER2*

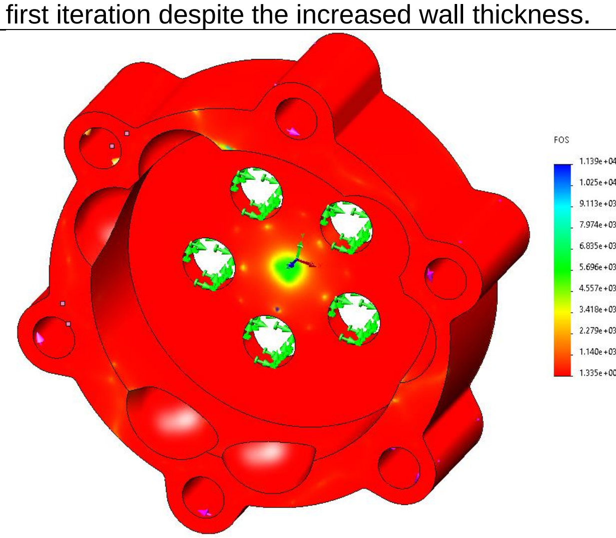


Figure 91: **A-7** *FOS map - ITER2*

NCR4	
Event Description	Failure to meet minimum FOS
Severity	3
Impact	Performance below targets

Review

The back wall reinforcement through thickening was not observed to improve the FOS. The stresses on the holes connecting to the spool are distributed the same way, with the high stress being present across the thickness of the back wall.

Path to Resolution

Option (1) presented in NCR***X*** will be followed. The design will be reverted to the original (with the back wall having a 5 mm thickness), and normalized **AISI 4130** alloy steel will be assumed the new material.

T-AXLE-L-02-ITER3		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Pass

Results

Maximum Stress	205 MPa
Minimum FOS	2.246
Maximum Displacement	0.0173 mm
Maximum Damage in 10000 cycles	No Damage

Final Mesh Settings

Global Cell Size	1 mm

Observations

- With the increased yield strength of the alloy steel, the part has a factor of safety above target, despite experiencing approximately the same maximum stress as in the previous iteration with Aluminum as the material.
- Maximum stresses are concentrated on a limited angular segment of inner holes. A ring of intermediate stress surrounds the inner group of holes. Outer group of holes experience low stresses but are the locations where the displacement is felt the most due to the additive nature of displacements from the part center to the tips.

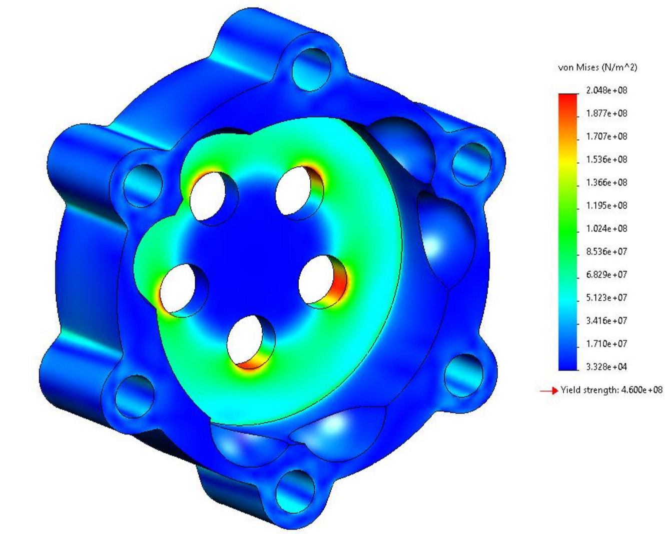


Figure 92: **A-7** *Von Mises stress map – front view*

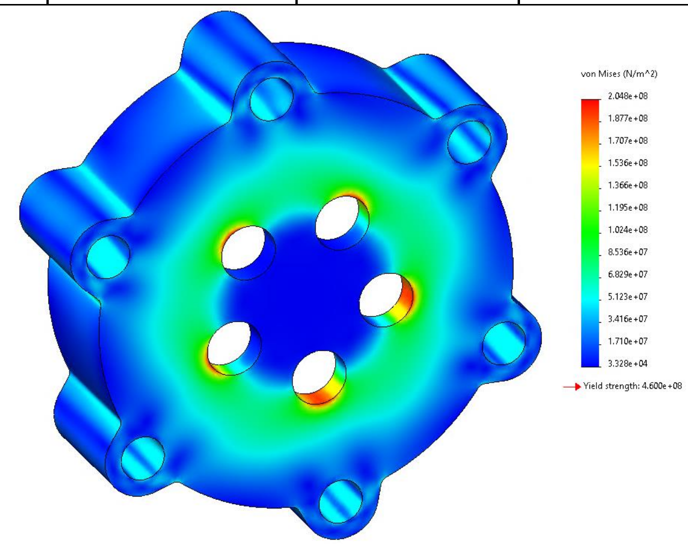


Figure 93: **A-7** *Von Mises stress map - back view*

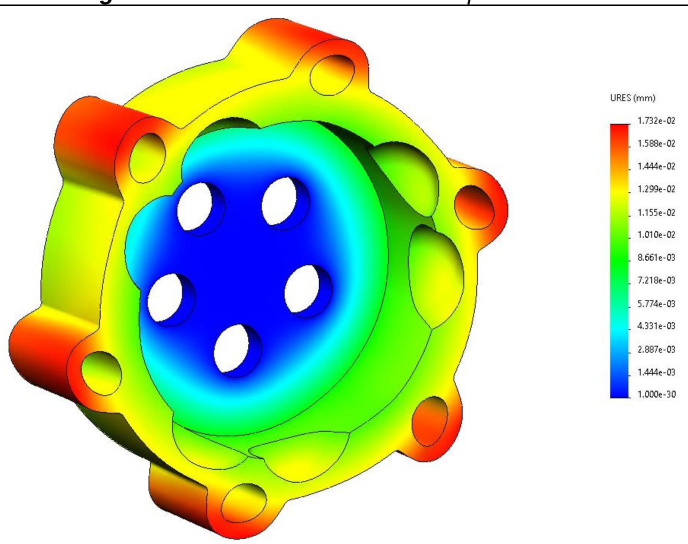


Figure 94: **A-7** *Displacement map*

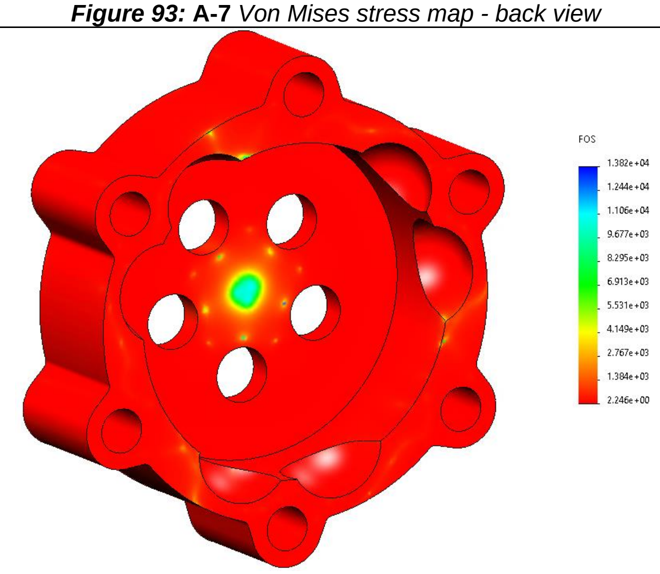
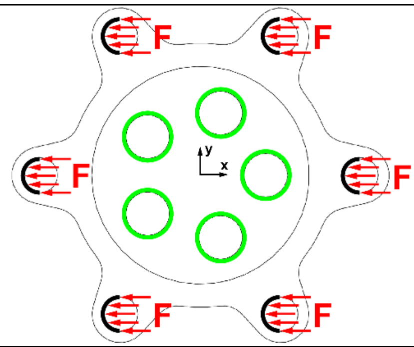


Figure 95: **A-7** *Factor of safety map*

T-AXLE-L-03	Left Inboard Axle Adapter under Chain Tension at Launch
Components	**A-7**
Requirements to Validate	**[RREQ-1] [FREQ-1] [PREQ-2] [PREQ-3]**
Associated Operation Concept	**Launch**



Material specifications

- **W-8**: Aluminum 6061-T6

Loading specifications

- Cylindrical surfaces of the inner bolts (connecting to the spool) are fixed.

Simulation methodology

- The simulation is considered simple and is to be run in SolidWorks.
- Mesh independence of static results are to be verified by achieving less than 5% difference between the maximum stress values of consecutive mesh refinements.
- Simulation with the finest mesh is to be used for the cyclic, zero-based application of the same loading.

T-AXLE-L-03-ITER1		
Overall Result	Partial Pass	
Criteria	Relevant Requirement	Result
FOS ≥ 2	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Deflection ≤ 1mm	**[PREQ-2] [RREQ-1] [FREQ-1]**	Pass
Number of cycles ≥ 10,000	**[PREQ-3] [RREQ-1] [FREQ-1]**	Not available

Procedure Changes

- Due to difficulties in reaching mesh independence in SolidWorks, StarCCM+ was used.
- Fatigue simulations could not be conducted in StarCCM+. However, the chain tension simulated is experienced momentarily only during launch. The vehicle likely won't be launched more than 10,000 times. Fatigue simulations were deemed not critical, as further supported by the results:

Results

Maximum Stress	115 MPa
Minimum FOS	3.99
Maximum Displacement	0.0189 mm

Final Mesh Settings

Global Cell Size	0.8 mm

Observations

- The high factor of safety gives confidence regarding the part's integrity in tension loading. The part can be exempted from fatigue simulations.
- Like in the test cases simulating torsion (**T-WHUB-L-01**, **T-AXLE-L-02**), highest stresses are experienced at the inner set of holes. The two holes to the left and right of the bottom hole experience the highest stresses. These two holes have their centers in a line parallel to the direction of tension loading.
- Stresses are below the maximum allowable values, and the part has a high factor of safety.

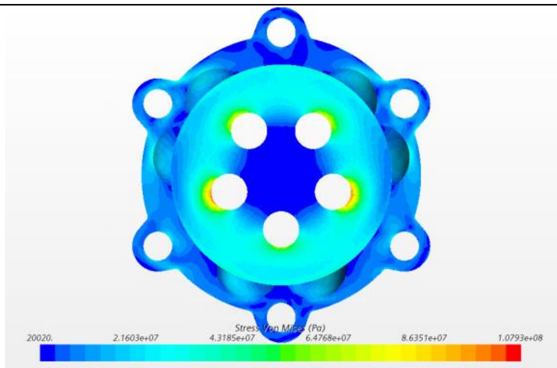


Figure 96: **A-7** *Von Mises stress map - front view*

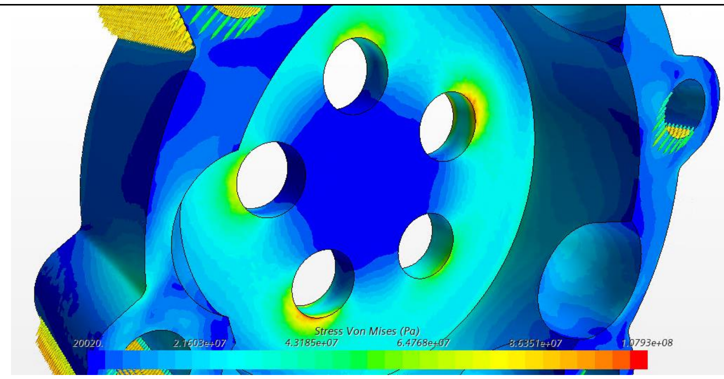


Figure 97: **A-7** *Von Mises stresses in the inner volume*

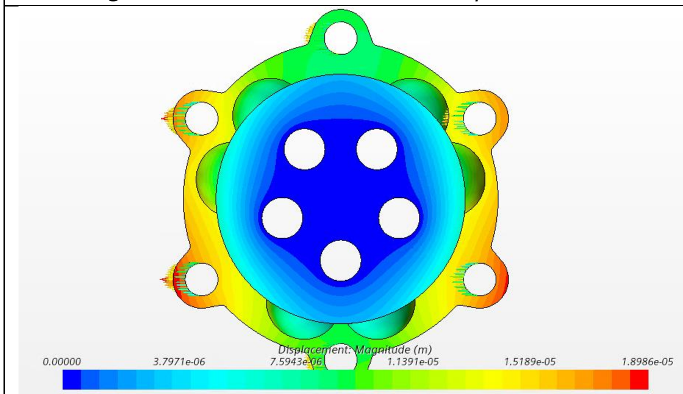
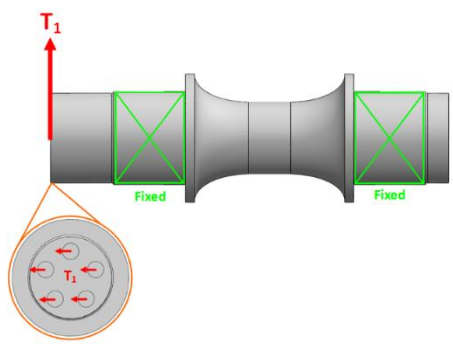


Figure 98: **A-7** *displacement map*

[DIFF] Test Packages

T-DIFF-L-03	*Spool Bending*
Components	**D-1**
Requirements to Validate	**[RREQ-1] [PREQ-2] [PREQ-3] [FREQ-1] [FREQ-2]**
Associated Operation Concept	**Launch**

FBD:



Material specifications

- **D-1:** AISI 4340 Steel Alloy

Loading specifications

- Bearings fix the component on either end of the spool marked in green.
- Chain tension is loaded where the rear sprocket would connect via the axle adapter.
- Assuming total system lock – right before vehicle movement
- T_1 = 6029 N
- A fatigue study will also be completed to determine whether the component can withstand the loading 10,000 cycles.

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-L-03-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2]**	Pass
Life > 10,000 cycles	**[PREQ-3]**	Pass

Results

- ***Figure 98***: FOS plot showing that the minimum FOS on the component is 13.9 which is significantly above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.
- ***Figure 100***: The stress distribution chart shows that concentrations occur on the filet between the bearing fitting and the diameter stepdown towards the sprocket side adapter.
- ***Figure 101***: The displacement plot shows that there is minimal flex in the component during the launch operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 102***: The fatigue simulation had proved that the component would have an infinite life given the loading conditions. As a default, the damage plot shows 1% damage for 10,000 cycles along the entire component.

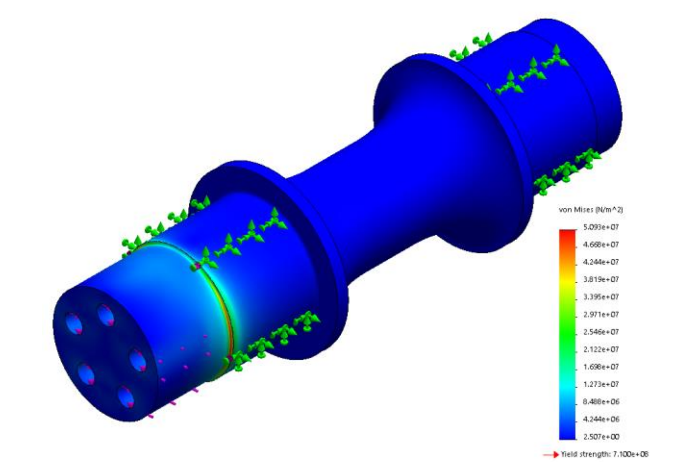


Figure 99: **D-1** *spool bending stress diagram*

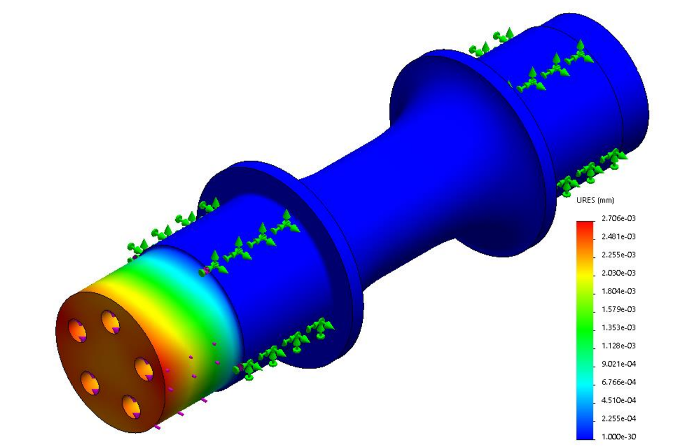


Figure 100: **D-1** *spool bending displacement diagram*

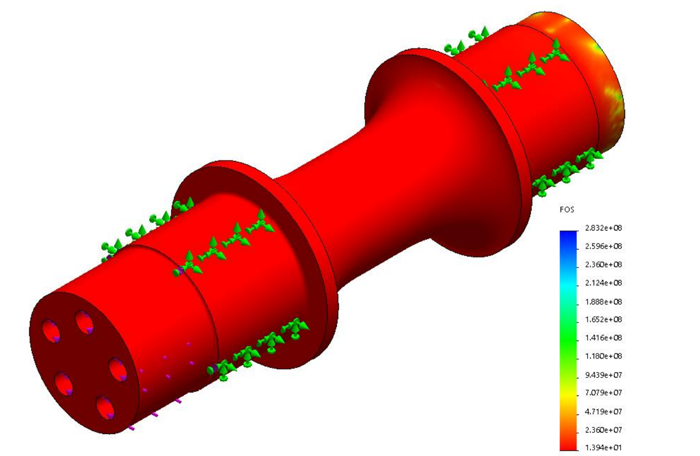


Figure 101: **D-1** *spool bending FOS diagram*

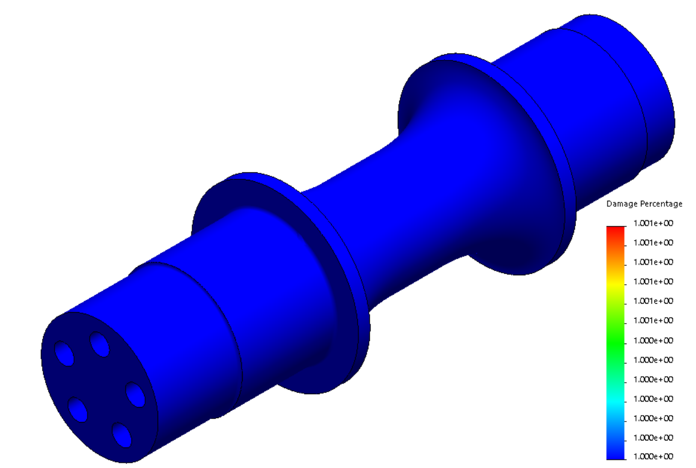
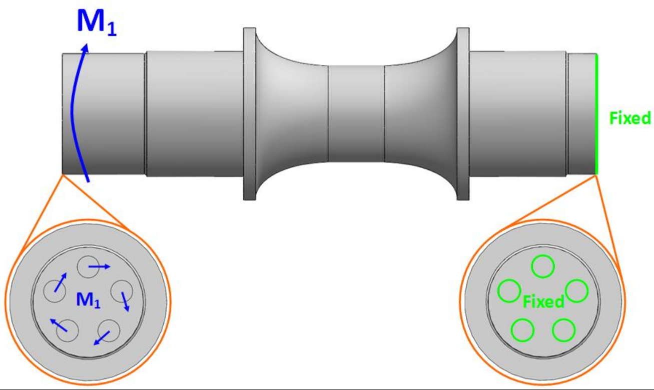


Figure 102: **D-1** *spool bending fatigue diagram*

T-DIFF-L-04	Spool Torque
Components	D-1
Requirements to Validate	**[RREQ-1] [PREQ-2] [PREQ-3] [FREQ-1] [FREQ-2]**
Associated Operation Concept	**Launch**

FBD:



Material specifications

- **D-1**: AISI 4340 Steel Alloy

Loading specifications

- The spool will be fixed by the screw holes on the right and the torque will be applied by the opposite end screw holes by moment M_1.
- $M_1 = 722$ Nm
- A fatigue study will also be completed to determine whether the component can withstand the loading 10,000 cycles.

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-L-04-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2]**	Pass
Life > 10,000 cycles	**[PREQ-3]**	Pass

Results

- ***Figure 103*****:** The stress distribution chart shows that concentrations occur in the hole of the fixed end however, it is still much below the yield stress.
- ***Figure 104*****:** The displacement plot shows that there is minimal flex in the component during the launch operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 105*****:** FOS plot showing that the minimum FOS on the component is 3.67 which is above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.
- ***Figure 106*****:** The fatigue simulation had proved that the component would have an infinite life given the loading conditions. As a default, the damage plot shows 1% damage for 10,000 cycles along the entire component.

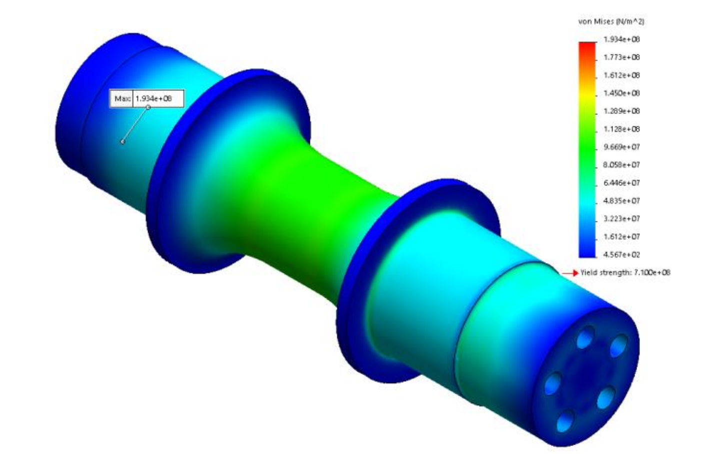


Figure 103: **D-1** *spool torsion stress diagram*

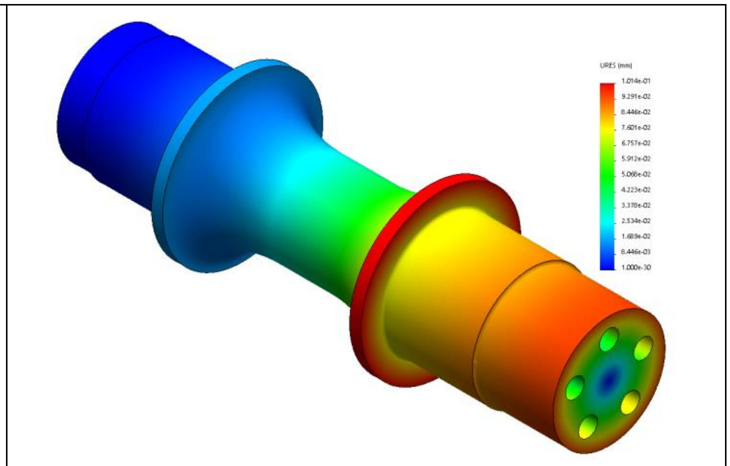


Figure 104: **D-1** *spool torsion displacement diagram*

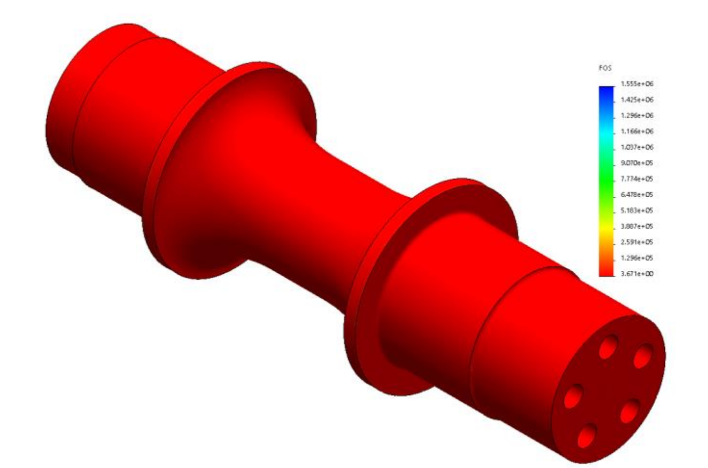


Figure 105: **D-1** *spool torsion FOS diagram*

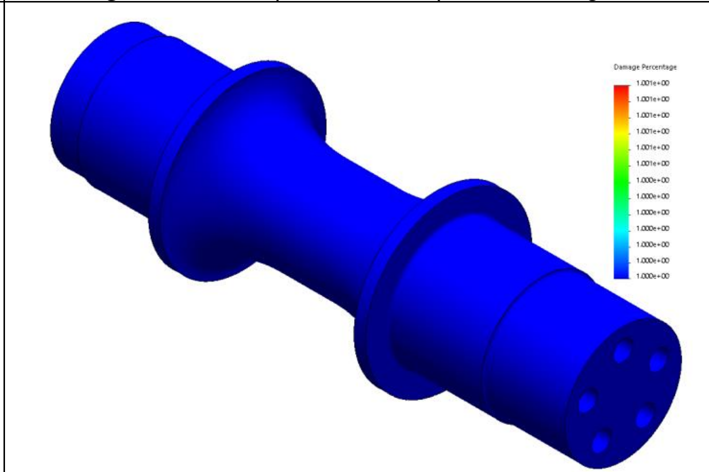
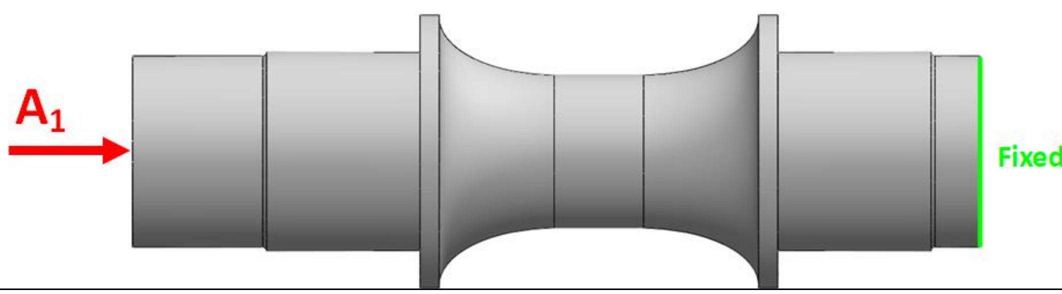


Figure 106: **D-1** *spool torsion fatigue diagram*

T-DIFF-C-01	Spool Axial
Components	**D-1**
Requirements to Validate	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2] [IREQ-3]**
Associated Operation Concept	**Cornering**

FBD:



Material specifications

- **D-1**: AISI 4340 Steel Alloy

Loading specifications

- The spool will be loaded from the left end screw holes while the opposing end screw holes will be fixed.
- This study will consist of a static and fatigue study.
- A_1 = 1088.42 N

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-C-01-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2]**	Pass
Displacement < 2cm	**[IREQ-3]**	Pass

Results

- ***Figure 107*****:** The stress distribution chart shows that concentrations occur in the hole of the fixed end however, it is still much below the yield stress.
- ***Figure 108*****:** The displacement plot shows that there is minimal flex in the component during the cornering operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 109*****:** FOS plot showing that the minimum FOS on the component is 425 which is significantly above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.

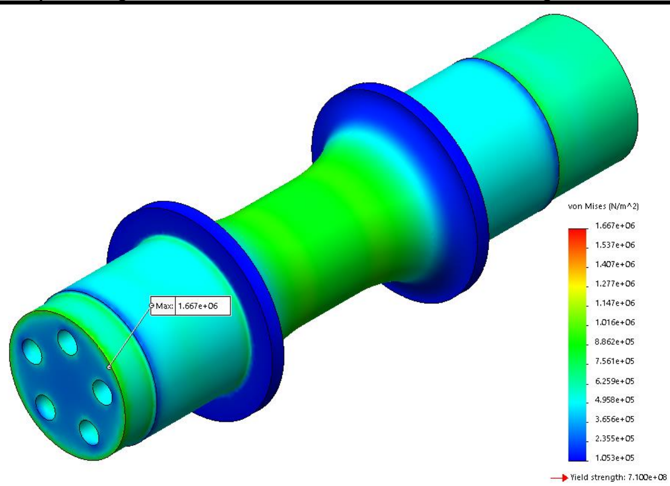


Figure 107: **D-1** *spool axial stress diagram*

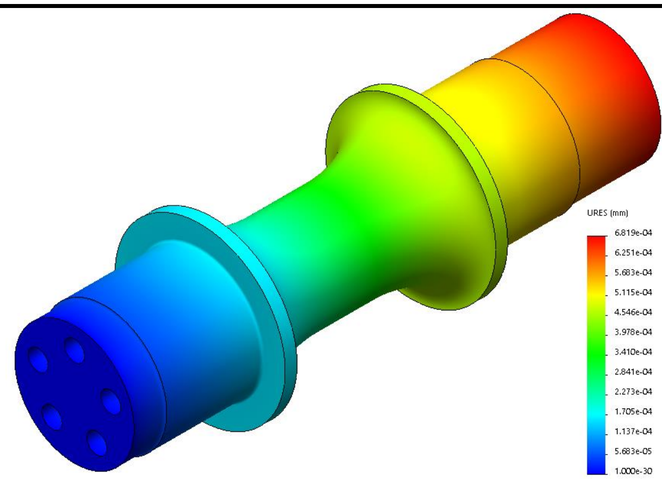


Figure 108: **D-1** *spool axial displacement diagram*

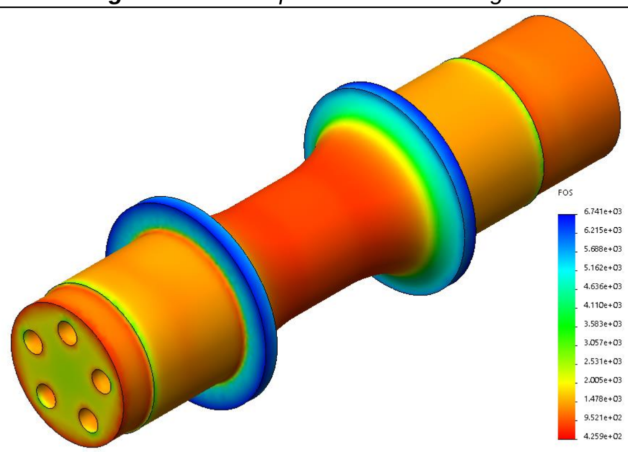
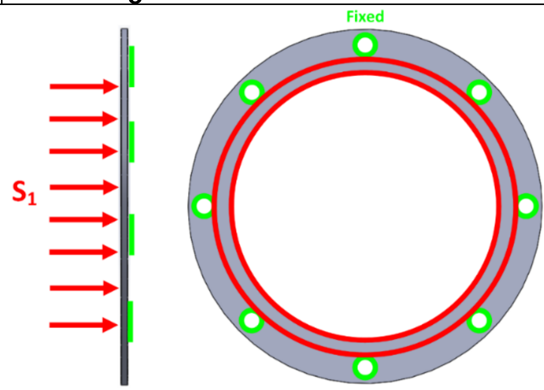


Figure 109: **D-1** *spool axial FOS diagram*

T-DIFF-C-02	Bearing Plate Shear
Components	**D-4**
Requirements to Validate	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2] [IREQ-3]**
Associated Operation Concept	**Cornering**

FBD:



Procedure:

Material specifications

- **D-4**: Cold Rolled Steel C1008 Flat Sheet

Loading specifications

- The plate is fixed onto the mount to stop the outside of the bearing from shifting position.
- The plate will be fixed by its 8 screw holes and loaded as if the bearing were pushing onto it.
- A surface will be created marking the inner diameter surface of the bearing and the load, S_1, will be distributed along it – as if the bearing were pushing against the plate.
- S_1 = 544.21 N

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-C-02-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[RREQ-1] [PREQ-2] [FREQ-1] [FREQ-2]**	Pass
Displacement < 2cm	**[IREQ-3]**	Pass

Results

- ***Figure 110***: The stress distribution chart shows that concentrations occur in the hole of the fixed end however, it is still much below the yield stress.
- ***Figure 111***: The displacement plot shows that there is minimal flex in the component during the cornering operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 112***: FOS plot showing that the minimum FOS on the component is 3.711 which is above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.

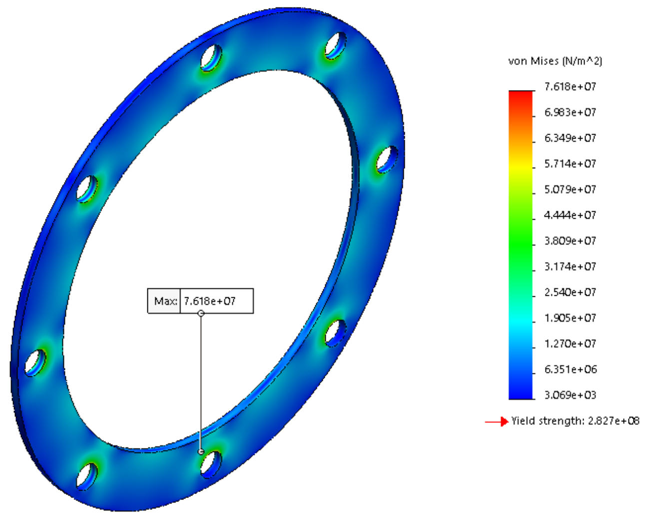


Figure 110: **D-4** *bearing plate shear stress diagram*

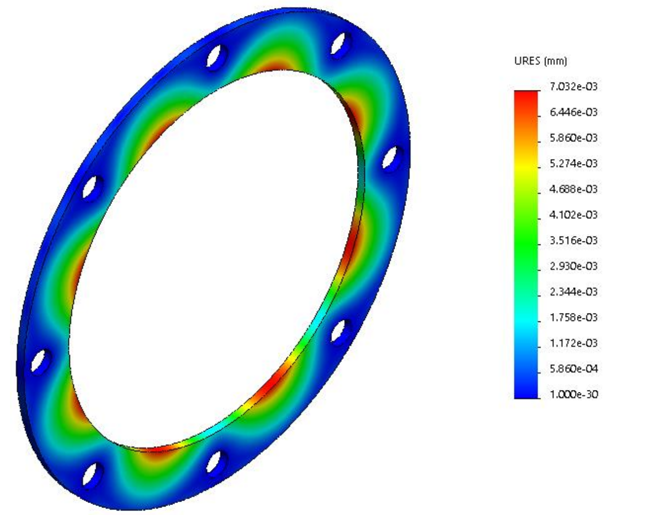


Figure 111: **D-4** *bearing plate shear displacement diagram*

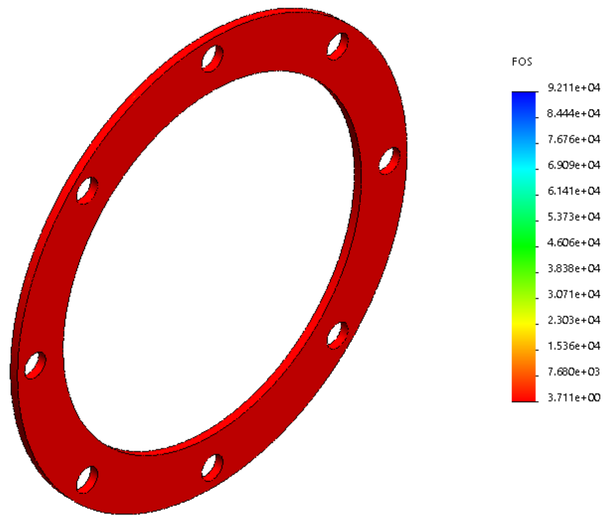
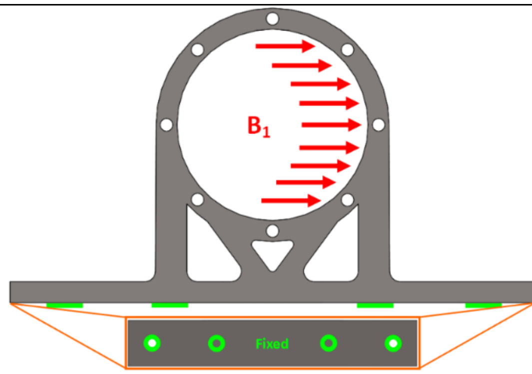


Figure 112: **D-4** *bearing plate shear FOS diagram*

T-DIFF-L-05	Mount Bending in X
Components	**D-3**
Requirements to Validate	**[PREQ-2] [PREQ-3] [FREQ-2] [IREQ-1]**
Associated Operation Concept	**Launch**
FBD:	

Material specifications

- **D-3**: Aluminum 6061-T6

Loading specifications

- The mount is fixed to the chassis at the bottom by 4 bolts.
- Two bolts are fastened by nuts and the other two are secured by internal threads in the mounts.
- The holes fastened with the bolt and nut will be fixed using a surface on the top of the mount plate to simulate a nut pressing on it as if it were holding it down.
- The loading comes only from the bearing which it houses in its larger opening.
- The force will be applied outwards as if the bearing is pressing up against it as if its total lock before launching.
- A static loading and cyclic study will be conducted since the vehicle will be launched several times over testing and competition.
- B_1 = 8315.6 N (Maximum case)
- Cycles = 10,000

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-L-05-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[PREQ-2] [FREQ-2]**	Pass
Life > 10,000 cycles	**[PREQ-3]**	Pass
Displacement < 2cm	**[IREQ-1]**	Pass

Results

- ***Figure 113***: The stress distribution chart shows that concentrations occur in the bottom hole where the bearing plate connects however, it is still much below the yield stress.
- ***Figure 114***: The displacement plot shows that there is minimal flex in the component during the launch operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 115***: FOS plot showing that the minimum FOS on the component is 2.28 which is above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.
- ***Figure 116***: The fatigue simulation had proved that the component would have an infinite life given the loading conditions. As a default, the damage plot shows 1% damage for 10,000 cycles along the entire component.

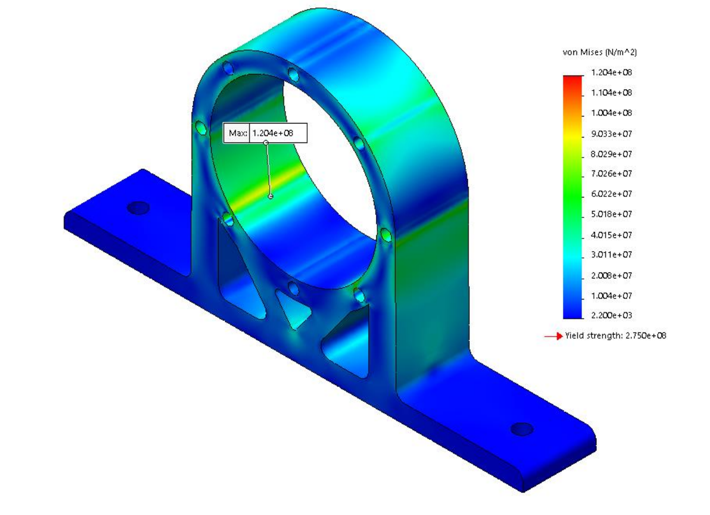


Figure 113: **D-3** *mount bending in x stress diagram*

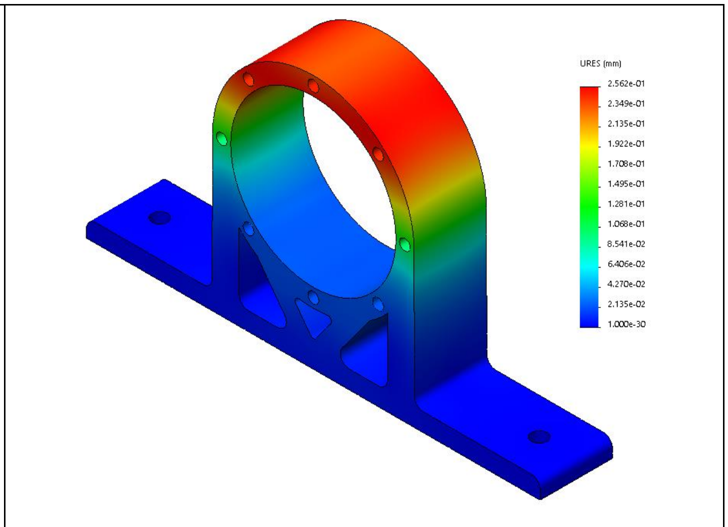


Figure 114: **D-3** *mount bending in x displacement diagram*

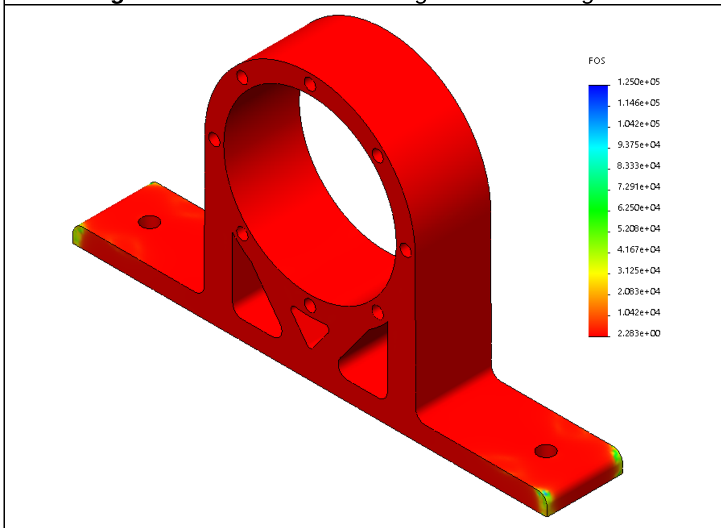


Figure 115: **D-3** *mount bending in x FOS diagram*

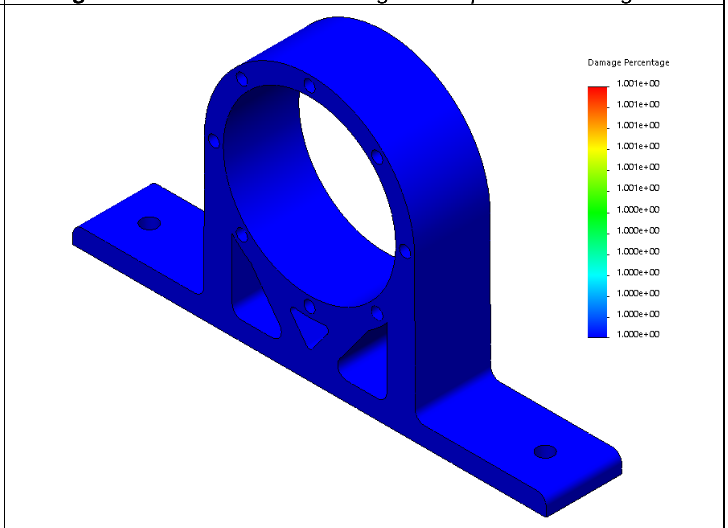
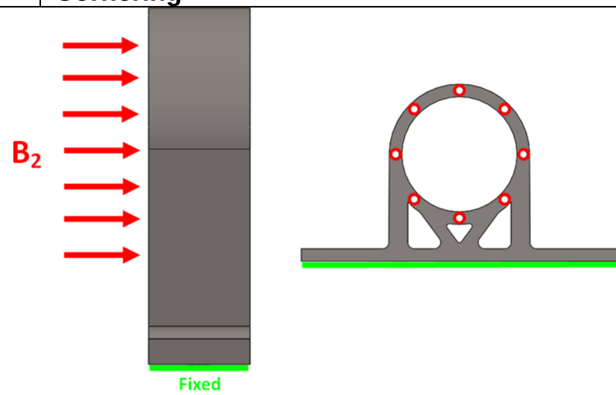


Figure 116: **D-3** *mount bending in x fatigue diagram*

T-DIFF-C-03	Mount Bending in Z
Components	**D-3**
Requirements to Validate	**[PREQ-2] [FREQ-2] [IREQ-1]**
Associated Operation Concept	**Cornering**

FBD:



Material specifications

- **D-3**: Aluminum 6061-T6

Loading specifications

- The mount is fixed to the chassis at the bottom by 4 bolts as well as the bottom surface as it would rest on the bottom chassis tube. This had been added after the test review gate since it was determined that this fixing method is a better reflection of a real loading scenario.
- The loading comes only from the bearing plate which is fixed onto the 8 bolt holes on the mount.
- This will be a static study with no cyclic study due to the irregularity of the loading.
- B_2 = 544.21 N

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-C-03-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[PREQ-2] [FREQ-2] [IREQ-1]**	Pass

Results

- ***Figure 117***: The stress distribution chart shows that concentrations occur in the hole of the fixed end however, it is still much below the yield stress.
- ***Figure 118***: The displacement plot shows that there is minimal flex in the component during the cornering operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 119***: FOS plot showing that the minimum FOS on the component is 32.42 which is significantly above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.

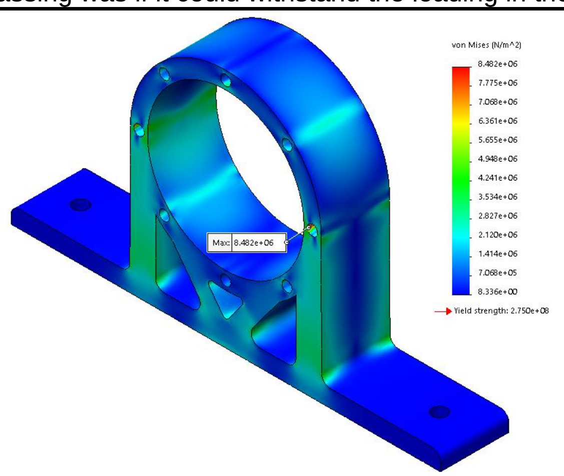


Figure 117: **D-3** *mount bending in z stress diagram*

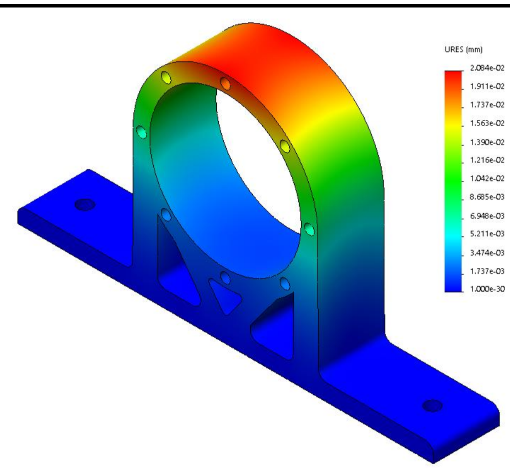


Figure 118: **D-3** *mount bending in z displacement diagram*

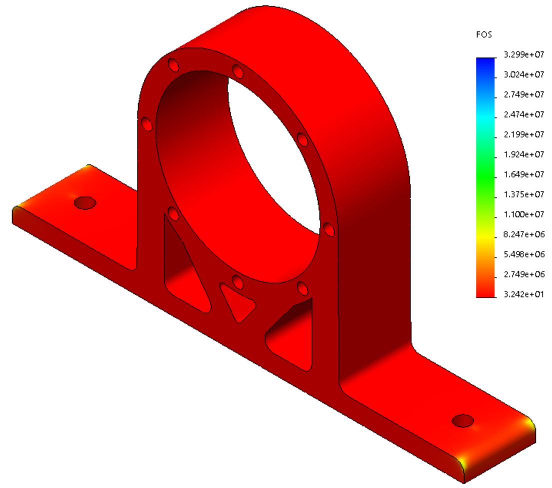
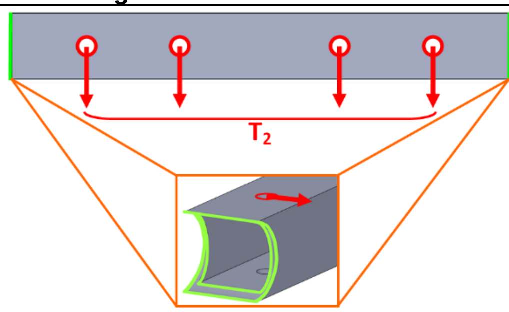


Figure 119: **D-3** *mount bending in z FOS diagram*

T-DIFF-C-04	Mount Tubing Torsion
Components	**D-7**
Requirements to Validate	**[PREQ-2] [FREQ-2] [IREQ-1]**
Associated Operation Concept	**Cornering**
FBD:	

Material specifications

- **D-7**: AISI 1020 Steel Alloy

Loading specifications

- The mount tubing is the component that interfaces the differential mount to the chassis.
- For this study, the mount will be fixed to the chassis and loaded perpendicular to the tube through the 4 holes which connect the mount.
- $T_2 = 544.21$ N
- This will be a static study with no cyclic study due to the irregularity of the loading.

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-C-04-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[PREQ-1] [FREQ-2] [IREQ-1]**	Pass

Results

- ***Figure 120***: The stress distribution chart shows that concentrations occur in the tube cut situated at the end however, it is still much below the yield stress.
- ***Figure 121***: The displacement plot shows that there is minimal flex in the component during the cornering operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 122***: FOS plot showing that the minimum FOS on the component is 18.71 which is significantly above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.

Notes: When completing the simulation, mesh independency was not determined on the stress value however the displacement settled at a value of 5e-4 mm. Since the factor of safety is so high, it can be assumed that with more computational power, mesh independency of the stress value can be achieved. At this point, stress was only increasing around 14% per iteration.

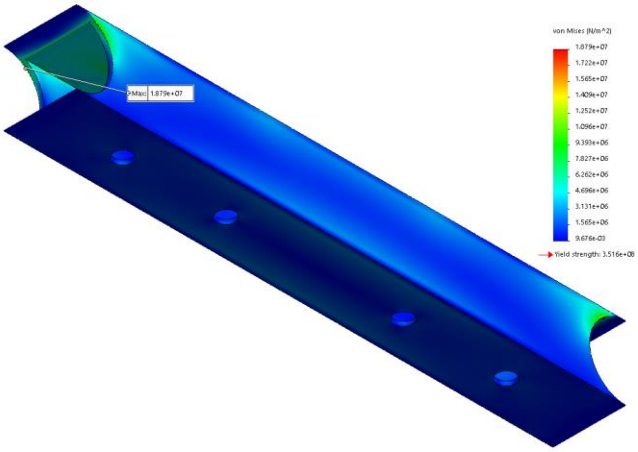


Figure 120: **D-7** *mount tubing torsion stress diagram*

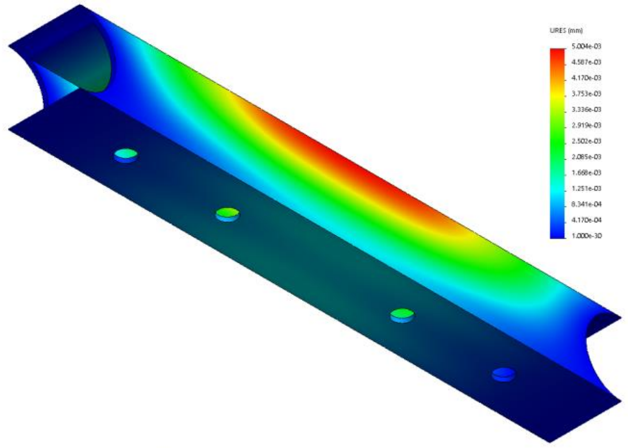


Figure 121: **D-7** *mount tubing torsion displacement diagram*

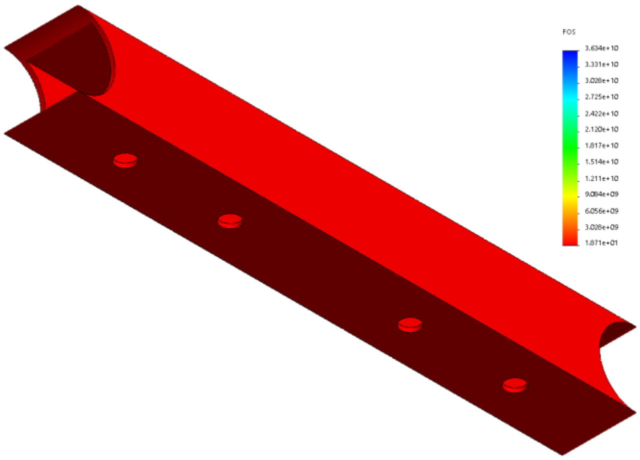
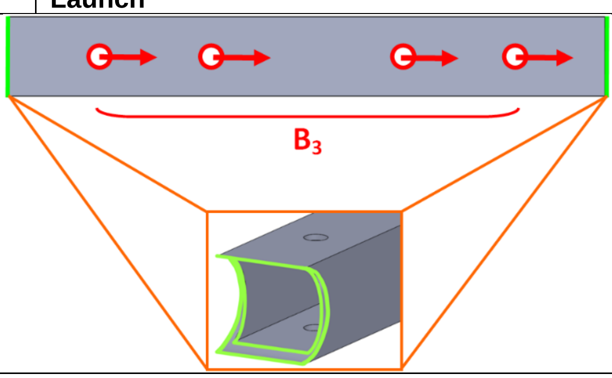


Figure 122: **D-7** *mount tubing torsion FOS diagram*

T-DIFF-L-06	Mount Tubing Bending
Components	**D-7**
Requirements to Validate	**[PREQ-2] [PREQ-3] [FREQ-2] [IREQ-1]**
Associated Operation Concept	**Launch**

FBD:



Material specifications

- **D-7**: AISI 1020 Steel Alloy

Loading specifications

- The mount tubing is the component that interfaces the differential mount to the chassis.
- For this study, the mount will be fixed to the chassis and loaded parallel to the tube through the 4 holes which connect the mount.
- T_2 = 8315.6 N
- Cycles = 10,000

Simulation methodology

- Completed in SolidWorks due to simple nature of simulation.
- The simulation will be completed at a minimum of 3 times to determine mesh independency

T-DIFF-L-06-ITER1		
Overall Result	Pass	
Criteria	Relevant Requirement	Result
FOS > 2	**[PREQ-2] [FREQ-2]**	Pass
Life > 10,000 cycles	**[PREQ-3]**	Pass
Displacement < 2cm	**[IREQ-1]**	Pass

Results

- ***Figure 123*:** The stress distribution chart shows that concentrations occur in one of the mount holes where the spool mount connects however, it is still much below the yield stress.
- ***Figure 124*:** The displacement plot shows that there is minimal flex in the component during the launch operation. This means that no components will be misaligned causing any unusual vibrations or failure
- ***Figure 125*:** FOS plot showing that the minimum FOS on the component is 5.98 which is above the minimum of 2. FOS is used as the passing criteria for most of the requirements since the only factor relying on it passing was if it could withstand the loading in the first place.
- ***Figure 126*:** The fatigue simulation had proved that the component would have an infinite life given the loading conditions. As a default, the damage plot shows 1% damage for 10,000 cycles along the entire component.

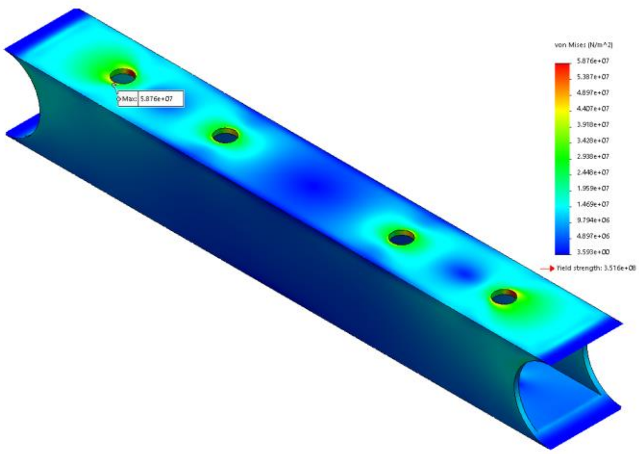


Figure 123: **D-7** *mount tubing bending stress diagram*

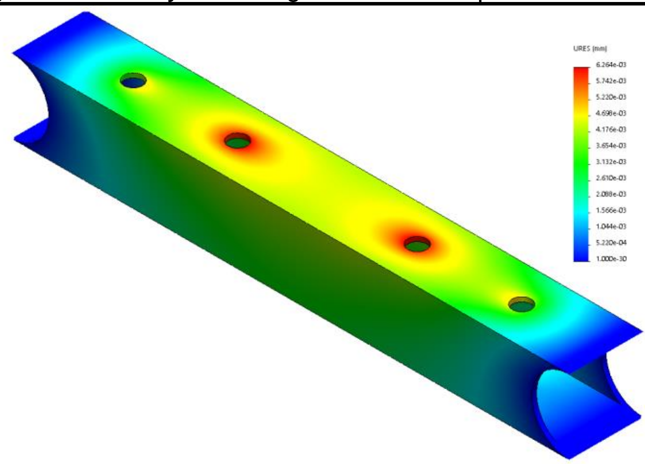


Figure 124: **D-7** *mount tubing bending displacement diagram*

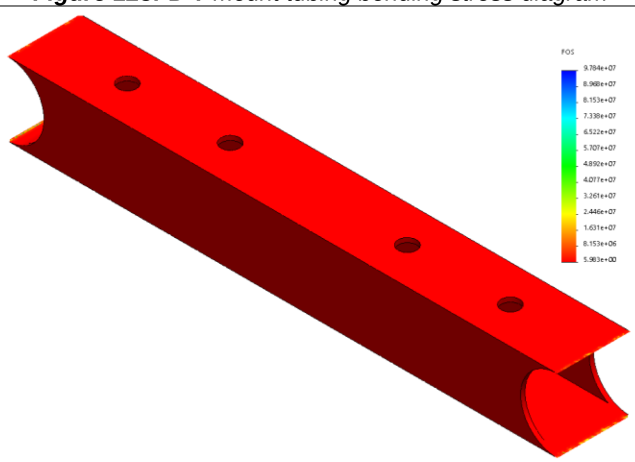


Figure 125: **D-7** *mount tubing bending FOS diagram*

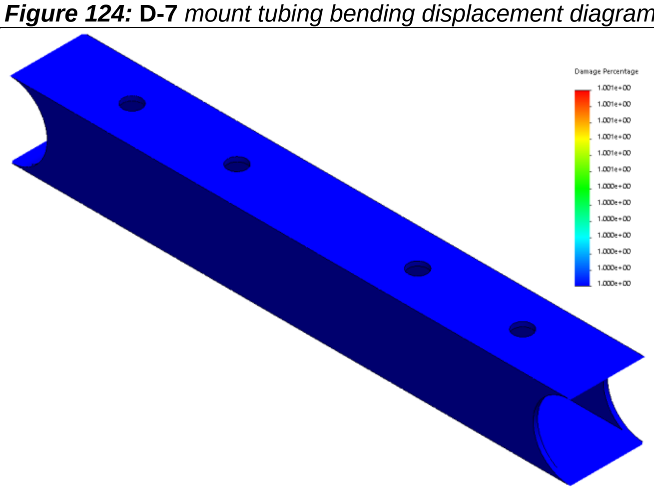


Figure 126: **D-7** *mount tubing bending fatigue diagram*

Project Requirements

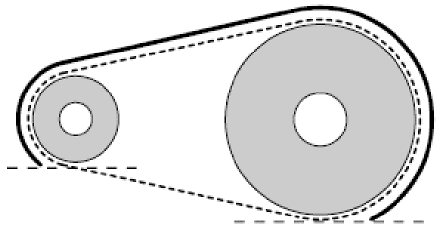
Project requirements were previously revised at the PDR stage based on feedback from the first gate. The requirement listing below also includes comments on compliance with the requirements.

Regulatory Requirements

Requirements below were derived from 2021 FSAE rulebook [1] , section T.5 - Powertrain.

Table 14: *Regulatory requirements – Powertrain*

ID	Rule Number	Rule Description	Rationale	Want Need	Status	Comments
[RREQ-1]	T.5.1	**Transmission and Drive** The vehicle shall use any transmission and drivetrain.	FSAE teams are free to select any drivetrain systems that are best suitable for their vehicle allowing for creativity.	Need	Pass	
[RREQ-2]	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 failure.	In case of any unforeseen failure in any of the drivetrain components, shields and guards can collect any debris from ejecting from the vehicle and damaging other components, driver, or bystanders.	Need	Pass	
[RREQ-3]	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	• Perforated material, although reduced in weight, can create weak points and	Need	Pass	A preliminary shield design is included in the drivetrain model.

		sprocket/chain wheel/belt or pulley. (c) Start and end no higher than parallel to the lowest point of the chain wheel/belt/pulley: 	areas for objects to get stuck. • A covered chain ensures that no material can fall into its moving path and cause critical failure. This also ties into guarding parts from ejecting in case of explosive failure.			Drivetrain shield must be redesigned once engine and drivetrain positions are finalized.
[RREQ-4]	T.5.2.3	Body panels or other existing covers are acceptable when constructed per T.5.2.7 / T.5.2.8	The drivetrain system can be covered with panels to further contain the system if it follows existing panel guidelines	Need	N/A	
[RREQ-5]	T.5.2.4	Frame Members or existing components that are used as part of the shield must exceed the scatter shield material requirements.	If chassis components exist that already cover the drivetrain, we do not need to have a specialized scatter guard.	Need	N/A	
[RREQ-6]	T.5.2.5	Scatter shields composed of multiple pieces must have gaps smaller than 3 mm.	Due to the complex and compact nature of the drivetrain, the scatter shields can be pieced up if the gaps are smaller than 3mm and cover the required areas.	Need	N/A	Scatter shield will be one piece
[RREQ-8]	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)	There must be appropriate coverage of the drivetrain chain throughout its cycle so that debris that ejects	Need	Pass	All bolts in the drivetrain are M8 or bigger.

		(b) Have a minimum width equal to three times the width of the chain (c) Be centered on the centerline of the chain (d) Remain aligned with the chain under all conditions	from other directions are caught and covered.			
[RREQ-9]	T.5.2.9	Attachment Fasteners - All fasteners attaching scatter shields and guards must be 6mm or 1/4" minimum diameter no matter what length. Critical Fasteners, see T.8.2.	6mm or ¼'' diameter fasteners have been deemed to be the minimum allowable fastener size for the best protection against potentially having the guard detach.	Need	Pass	
[RREQ-10]	T.5.2.10	Finger Guards (a) Must cover any drivetrain parts that spin while the vehicle is stationary with the engine running. (b) Must be made of material sufficient to resist more than 1mm of strain under 5N of loading (~0.5kg). (c) Mesh or perforated material may be used but must prevent the passage of a 12 mm diameter object through the guard.	In the event that we may include a component that is moving while the vehicle is not moving, we must sufficiently cover it to resist any material or "finger" insertion. Perforation is allowable but with size restrictions to discourage material moving through.	Need	N/A	

Requirements below were derived from 2021 FSAE rulebook [1] , section T.8 - Fasteners.

Table 15: *Regulatory requirements - Fasteners*

ID	**Rule Number**	**Rule Description**	**Rationale**	**Want Need**	**Status**	**Comments**
[RREQ-11]	T.8.2.1	Any Critical Fastener must meet, at minimum, one of the following: (a) SAE Grade 5 (b) Metric Grade 8.8	Fasteners used in critical safety components or high stress components must	Need	Pass	All fasteners are Metric Grade 8.8 and 10.9 composed of High-Strength Class Steel

		(c) AN/MS Specifications (d) Equivalent to or better than above, as approved by a Rules Question or at Technical Inspection	meet the following specifications to ensure safety from bolt failure.			
[RREQ-12]	T.8.2.2	All threaded Critical Fasteners must be one of the following: • Hex head • Hexagonal recessed drive (Socket Head Cap Screws or Allen screws/bolts)	Hex headed fasteners are easier to validate torque requirements and mark with torque strips. They are also the most common.	Need	Pass	
[RREQ-13]	T.8.2.3	All Critical Fasteners must be secured from unintentional loosening by the use of Positive Locking Mechanisms see T.8.3	Additional security measure to prevent the fasteners from backing out unintentionally.	Need	Pass	The only critical fasteners for the drivetrain system are the drivetrain shield
[RREQ-14]	T.8.2.4	A minimum of two full threads must project from any lock nut.	Ensures all bolts have full thread engagement	Need	Pass	
	T.8.3	Positive Locking Mechanisms				
[RREQ-17]	T.8.3.2	**Acceptable Positive Locking** Mechanisms shall include, but are not limited to: (a) Correctly installed safety wiring (b) Cotter pins (c) Nylon lock nuts (where temperature does not exceed 80°C) (d) Prevailing torque lock nuts Lock washers, bolts with nylon patches and thread locking compounds (Loctite®), DO NOT meet the positive locking requirement.	Locking mechanisms must be mechanical and evident. Chemical locking agents are no suitable due to variance in application.	Need	Pass	Drivetrain scatter shield uses nylon locking nuts.

[RREQ-18]	T.8.4	**Requirements for All Fasteners** Adjustable tie rod ends must be constrained with a jam nut to prevent loosening.	A nut at the end of a tie rod can ensure that no part can become loose during operation potentially causing critical failure.	Need	N/A	

Performance Requirements

Requirements below were set by our team.

Table 16: *Performance requirements*

ID	Rule Description	Rationale	Want Need	Status	Comments
[PREQ-1]	At the highest gear, the sprocket ratio must be selected to be able to reach a minimum of 100 km/h.	As required by LMP-1 performance targets.	Need	Pass	Theoretically the vehicle should be able to reach 100km/h. This will need to be confirmed with physical testing.
[PREQ-2]	Drivetrain components must be able to withstand maximum torque produced by the engine without any components coming within 90% of yielding stress.	Vehicle components must not fail under normal use. Such an event would cause loss of vehicle control.	Need	Pass	
[PREQ-3]	Drivetrain system must be able to withstand fatigue of minimum one event and 1 month of testing, 100 hours of zero to maximum engine output loading.	Vehicle components must not fail under normal use. Such an event would cause loss of vehicle control.	Need	Pass	

Functional Requirements

Table 17: *Functional requirements*

ID	Rule Description	Rationale	Want Need	Status	Comments
[FREQ-1]	The system must transmit power from engine / transmission to rear drive wheels.	LM is required to design a rear wheel drive vehicle do all engine power must be delivered to the rear wheels	Need	Pass	
[FREQ-2]	Drivetrain components must use common and easily acquirable and manufacturing equipment.	Using standardized material and equipment reduces cost and complexity in the manufacturing phase, ultimately saving money.	Need	Pass	

Interface Requirements

Table 18: *Interface requirements*

ID	Rule Description	Rationale	Want Need	Status	Comments
[IREQ-1]	Drivetrain components must fit within the existing chassis and not mounted lower than the chassis	The drivetrain cannot occupy the same space as other parts. Not being mounted lower than the chassis is also mandated by FSAE rules V.1.4.1 and V.1.4.2.	Need	Pass	The only part which extends past the chassis are the differential mounting bolts.
[IREQ-2]	Drivetrain must provide attachment surfaces for: • brake rotors • wheels • suspension knuckles	Wheels and the braking subsystem rely on attachment surfaces to be provided by drivetrain components. The suspension knuckle also has to be	Need	Pass	

		supported by the drivetrain through a bearing as per LMP-1's design requirements.			
[IREQ-3]	Either drive shaft must be able to translate axially more than 1 cm between its respective housing components.	Movement of the final drive shaft in the axial direction can cause additional unwanted wear. This also runs the risk of having the axel pop out of place in extreme conditions.	Need	Pass	
[IREQ-4]	The chain drive system must not be able to move more than 1 cm when 10N of force is applied to it along its opening side.	Too much movement of the chain causes opportunities for the chain to skip and become dislodged from either sprocket causing critical failure.	Need	Fail	A plunging system needs to be developed to prevent excessive plunging.

Programmatic Requirements

Table 19: *Programmatic requirements*

ID	Rule Description	Rationale	Want Need	Status	Comments
[GREQ-1]	Drivetrain system must cost less than 3000 CAD (from LM and ENG4000) including manufacturing cost, any special tools required for assembly, purchased components.	The funding provided for this project will come from both capstone and possibly from the LM team. This is likely not to exceed 3000 CAD so we must plan our system under this value.	Want	Pass	The drivetrain system costs approximately $1500
[GREQ-2]	All project related documents must be stored in a Google Drive folder	To ensure all team members are working in sync an in the correct format, a single shared drive space should be used for easy reference and updates.	Want	Pass	
[GREQ-3]	Google Drive folder must be systematically organized to reflect all work done in each stage of the project	On top of having a single shared space, all members must agree upon a single organization structure so no work can be misplaced. This includes breaking capstone work their respective deliverables clearly outlined by ENG4000.	Want	Pass	

“Wants”

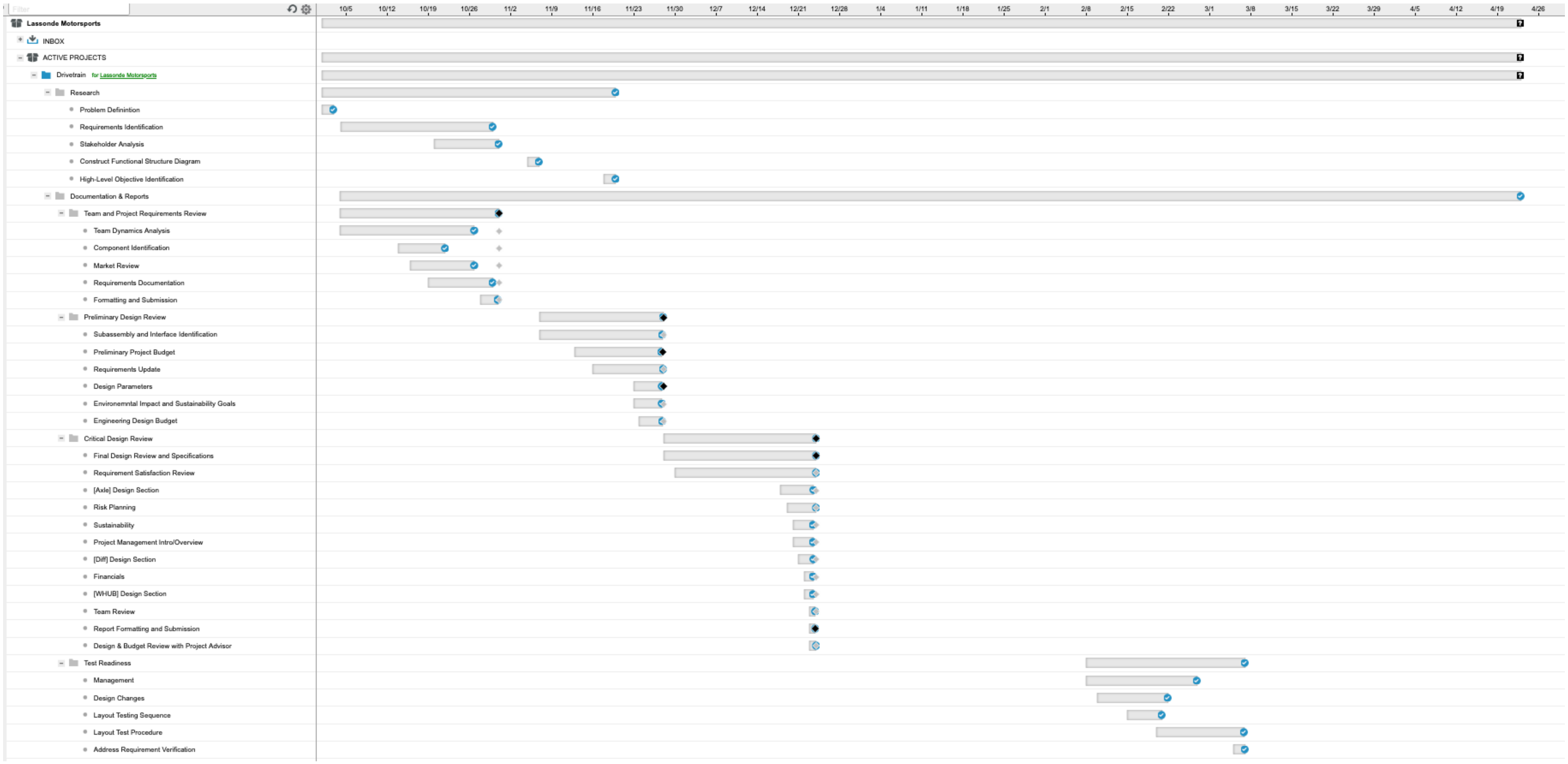
Table 20: *Project "wants"*

ID	Rule Description	Rationale	Want Need	Status	Comments
[WREQ-1]	Entire drivetrain system must weigh less than 20 kg.	A heavy drivetrain system will decrease performance of the vehicle by increasing overall vehicle mass and decreasing powering sent to the driven wheels (higher rotational inertia).	Want	Fail	The drivetrain system weighs approximately 33 kg.
[WREQ-2]	Drivetrain parts must use easily accessible parts, manufacturing methods and time spent to manufacture the parts must be below 100 hours.	LM does not have the means required to conduct any advanced manufacturing methods outside the machine shop and tools that members already own. That is why we must make sure that all parts that the drivetrain require are simple to assemble by using standard parts and tools. Furthermore, we do not want to spend a significant amount of time and resources to manufacture parts ourselves or via a third party.	Want	N/A	Parts are easily accessible, but manufacturing time has not been determined

Project Management

Gantt Chart

Scheduling of work packages is illustrated in the following Gantt chart.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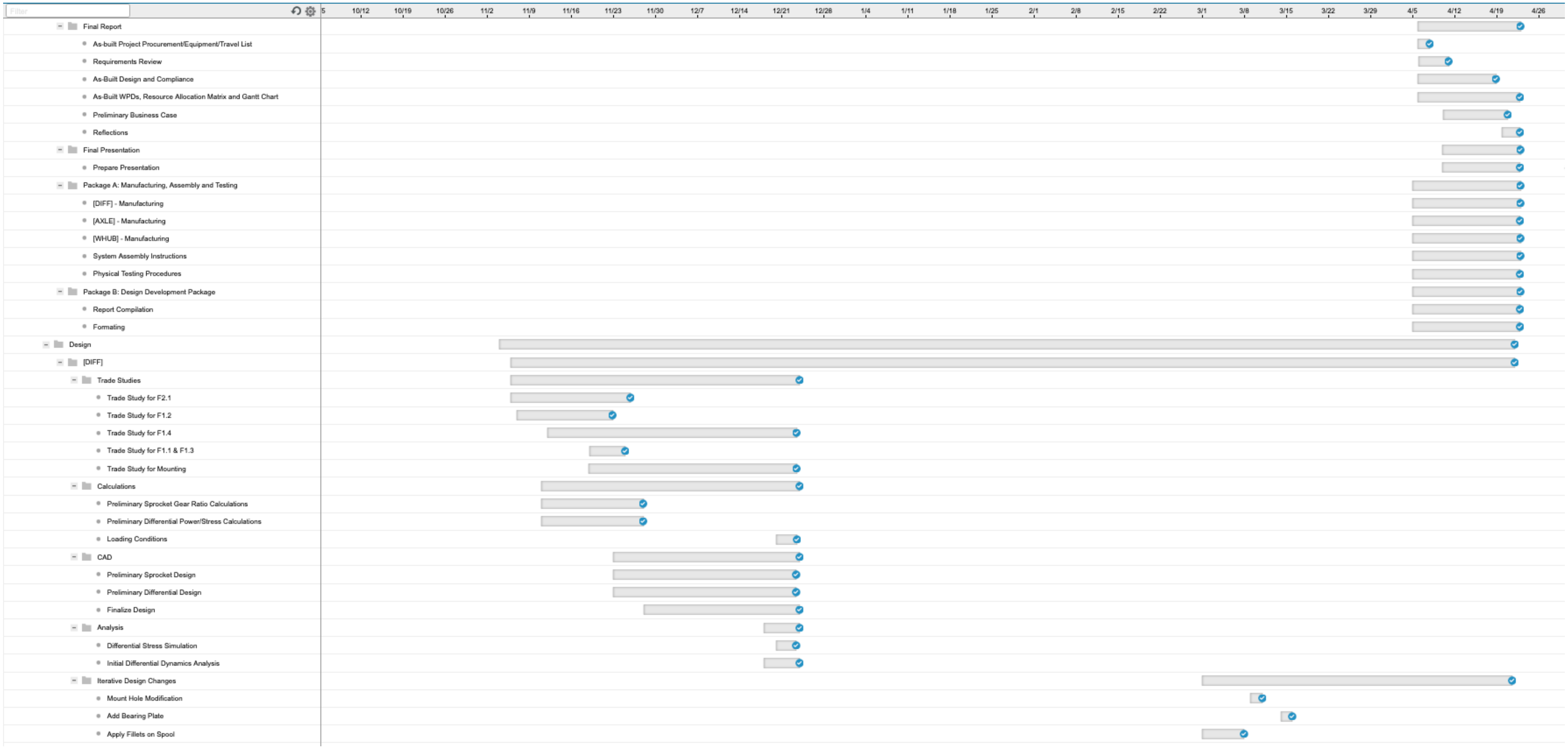
Lassonde Motorsports
INBOX
ACTIVE PROJECTS
Drivetrain for Lassonde Motorsports
Research
Problem Definition
Requirements Identification
Stakeholder Analysis
Construct Functional Structure Diagram
High-Level Objective Identification
Documentation & Reports
Team and Project Requirements Review
Team Dynamics Analysis
Component Identification
Market Review
Requirements Documentation
Formatting and Submission
Preliminary Design Review
Subassembly and Interface Identification
Preliminary Project Budget
Requirements Update
Design Parameters
Environemntal Impact and Sustainability Goals
Engineering Design Budget
Critical Design Review
Final Design Review and Specifications
Requirement Satisfaction Review
[Axle] Design Section
Risk Planning
Sustainability
Project Management Intro/Overview
[Diff] Design Section
Financials
[WHUB] Design Section
Team Review
Report Formatting and Submission
Design & Budget Review with Project Advisor
Test Readiness
Management
Design Changes
Layout Testing Sequence
Layout Test Procedure
Address Requirement Verification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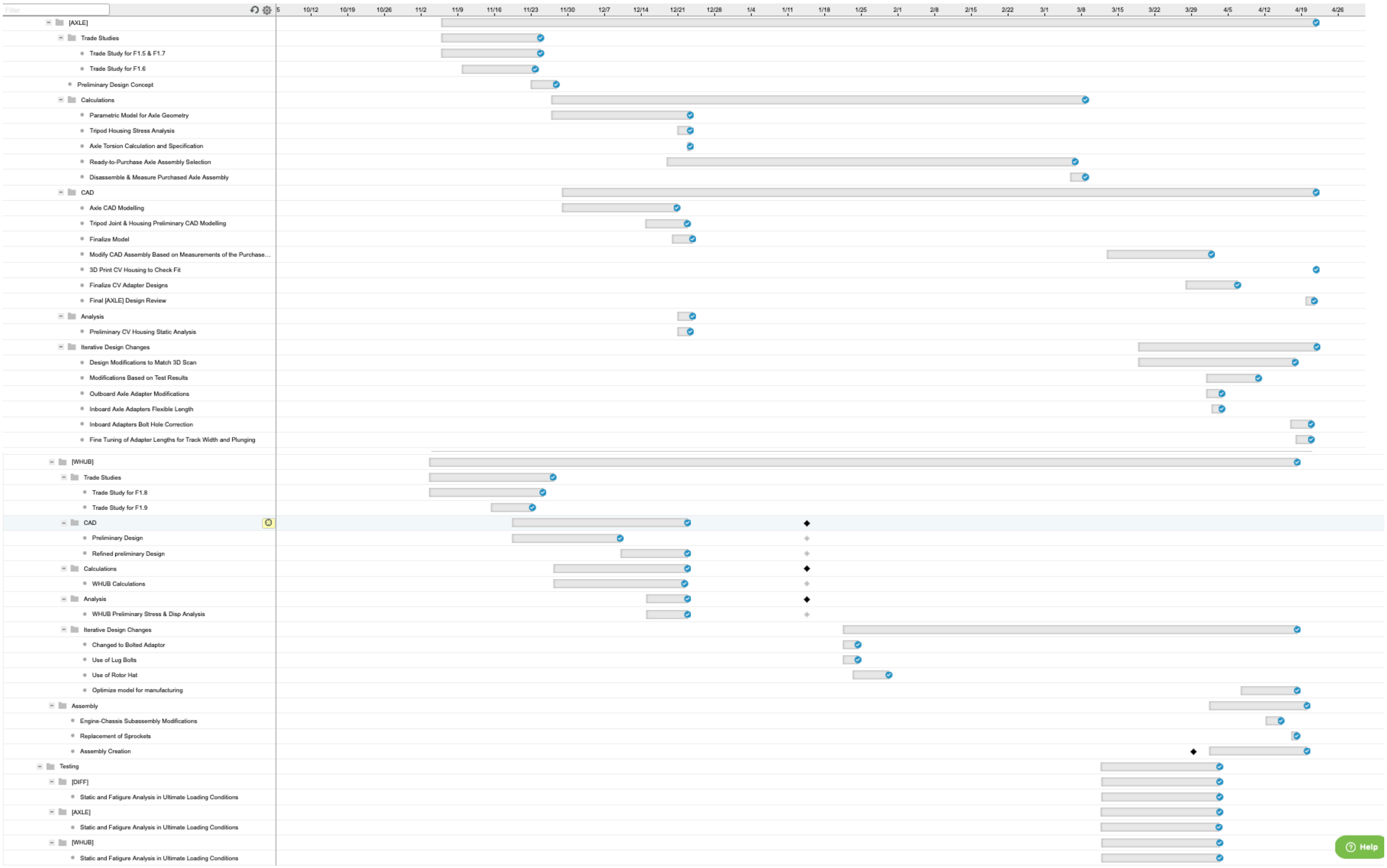
Final Report
As-built Project Procurement/Equipment/Travel List
Requirements Review
As-Built Design and Compliance
As-Built WPDs, Resource Allocation Matrix and Gantt Chart
Preliminary Business Case
Reflections
Final Presentation
Prepare Presentation
Package A: Manufacturing, Assembly and Testing
[DIFF] - Manufacturing
[AXLE] - Manufacturing
[WHUB] - Manufacturing
System Assembly Instructions
Physical Testing Procedures
Package B: Design Development Package
Report Compilation
Formating
Design
[DIFF]
Trade Studies
Trade Study for F2.1
Trade Study for F1.2
Trade Study for F1.4
Trade Study for F1.1 & F1.3
Trade Study for Mounting
Calculations
Preliminary Sprocket Gear Ratio Calculations
Preliminary Differential Power/Stress Calculations
Loading Conditions
CAD
Preliminary Sprocket Design
Preliminary Differential Design
Finalize Design
Analysis
Differential Stress Simulation
Initial Differential Dynamics Analysis
Iterative Design Changes
Mount Hole Modification
Add Bearing Plate
Apply Fillets on Spool



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[AXLE]
Trade Studies
Trade Study for F1.5 & F1.7
Trade Study for F1.6
Preliminary Design Concept
Calculations
Parametric Model for Axle Geometry
Tripod Housing Stress Analysis
Axle Torsion Calculation and Specification
Ready-to-Purchase Axle Assembly Selection
Disassemble & Measure Purchased Axle Assembly
CAD
Axle CAD Modelling
Tripod Joint & Housing Preliminary CAD Modelling
Finalize Model
Modify CAD Assembly Based on Measurements of the Purchase...
3D Print CV Housing to Check Fit
Finalize CV Adapter Designs
Final [AXLE] Design Review
Analysis
Preliminary CV Housing Static Analysis
Iterative Design Changes
Design Modifications to Match 3D Scan
Modifications Based on Test Results
Outboard Axle Adapter Modifications
Inboard Axle Adapters Flexible Length
Inboard Adapters Bolt Hole Correction
Fine Tuning of Adapter Lengths for Track Width and Plunging
[WHUB]
Trade Studies
Trade Study for F1.8
Trade Study for F1.9
CAD
Preliminary Design
Refined preliminary Design
Calculations
WHUB Calculations
Analysis
WHUB Preliminary Stress & Disp Analysis
Iterative Design Changes
Changed to Bolted Adaptor
Use of Lug Bolts
Use of Rotor Hat
Optimize model for manufacturing
Assembly
Engine-Chassis Subassembly Modifications
Replacement of Sprockets
Assembly Creation
Testing
[DIFF]
Static and Fatigue Analysis in Ultimate Loading Conditions
[AXLE]
Static and Fatigue Analysis in Ultimate Loading Conditions
[WHUB]
Static and Fatigue Analysis in Ultimate Loading Conditions
Help