MCG 4322[A]
Literature Review Report
”Mo powa babeh” — FSAE 2

by

AbdalAziz AlGhoul (300005268)
Hasan Shahzad (300001167)
Hisham Ali (300010128)
Peter Saroufim (300015864)
Munir Alsafi (300013845)

University of Ottawa
Department of Mechanical Engineering
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Chapter 1

Problem Statement

1.1 Project Mandate

With FSAE seeing their first electric vehicle in 2016, FSAE teams around the world have been encouraged to start developing their own [42]. Our team of five mechanical engineering students have been tasked to parametrically develop and design a Formula SAE electric car to aid the University of Ottawa's FSAE team. The parametric design will aid the University's team when dealing with cases that require specification changes. The design will include a program that calculates all necessary engineering calculations to resize the design based on the set of ergonomic specifications inputted by the user. These specifications include: various wheel diameters, driver weights and heights, and motor power. Appropriate chassis, suspension system, accumulator, motors and breaks will be designed and assembled as per the 2020 FSAE rules and regulations to ensure vehicle stiffness and safety for the diver. This will be ensured through the use of software simulations to carry out the necessary structural analyses

1.2 Project Scope

The formula electric car that we are tasked to design must be capable of performing well in different driving scenarios such as endurance racing, acceleration, and autocross. The group is tasked with designing the battery, powertrain, chassis, suspension, brakes, and steering system for the vehicle. Detailed models will be provided for each subassembly, demonstrating how each part reacts to different loads and moments. Moreover, the geometry, materials, size, and weight of the subassemblies are essential to the modelling of the vehicle. Finally, the vehicle's design is to comply with all the Formula SAE rules and guidelines.

Chapter 2

Chassis

As per FSAE rules and regulations, the chassis must include roll hoops (front and main hoops), roll hoop bracings, roll hoop bracing supports, front bulkhead, impact attenuator, and rear impact protection [42].

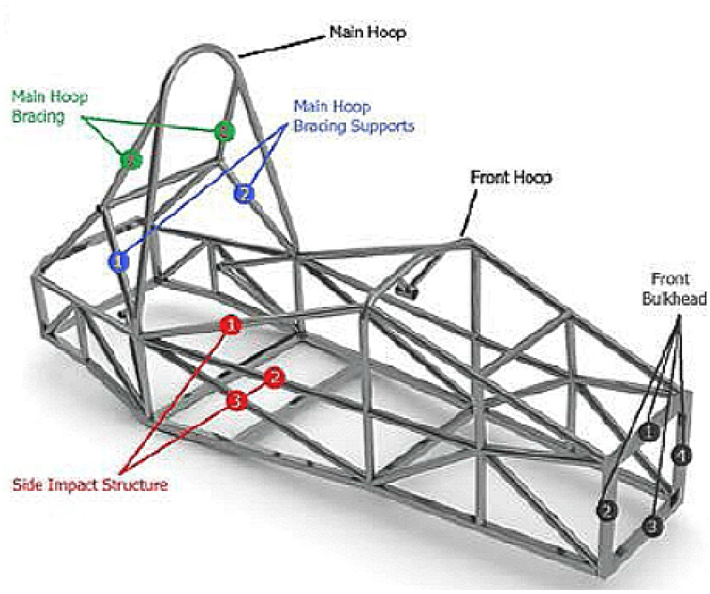


Figure 2.1: Steel Tube Space-Frame Chassis [26]

As shown in figure 2.2, the main hoop is located behind the driver's seat and serves as a protection for the driver in case of a roll over. The main hoop must be constructed from a single piece of uncut, continuous, closed section as stated in the FSAE rules and regulations [42]. The front hoop provides protection for the driver's legs in case of an accident. It must be located no more than 250 mm in front of the steering wheel as specified in the FSAE rules and regulations [42]. Roll hoop bracings are designed to transmit all the loads applied to it. The roll hoop must be supported by two bracings on both sides, two bracings on the main loop, and two bracings on the front loop [42]. The figure below demonstrates the recommended setup.

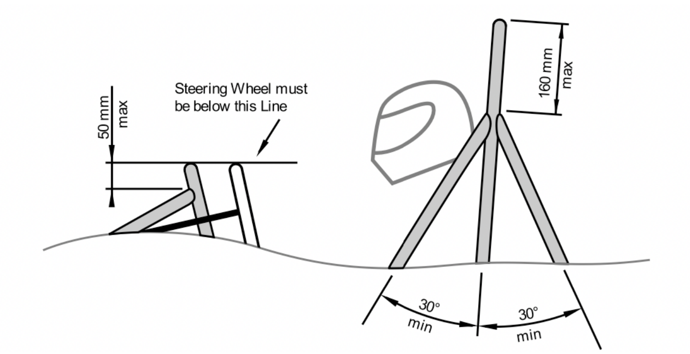


Figure 2.2: Recommended construction of roll hoop bracings [42]

2.1 Chassis Flex and Rigidity

FSAE rules and regulations encourage triangulation in chassis design to avoid chassis flex and promote structural rigidity [42]. When a force is applied to a square structure with four members, the structure is easily deformed and is considered non-rigid [32]. By adding a diagonal member through the process of triangulation, the members are held at a fixed distance. The pivots in the corners ensure that the individual structural members are not subjected to any bending loads. Structural members are completely placed in pure tension or compression [32]. It is important to note that diagonal members need to be connected to the corner of the structure and not in the middle of a member [32].

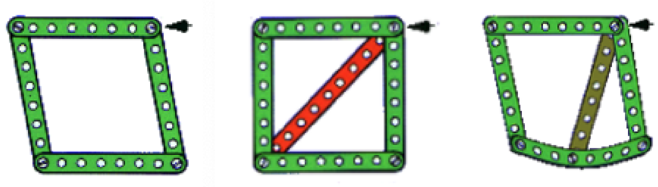


Figure 2.3: No triangulation (left), proper triangulation (middle), and improper triangulation (right) [32]

2.2 Chassis Existing Configurations

Most FSAE chassis designs are either a space-frame structure, monocoque structure, or a hybrid of the two. The space-frame method is very common and constitutes of a skeleton connecting vital parts of the car together through triangular geometry to increase rigidity [69]. On the other hand, monocoques are a single piece made of composites that are lighter and stiffer than metals, but more expensive. Composite monocoques, especially carbon fibre monocoques, are characterized with their strength, rigidity, and low weight [69]. Some FSAE teams produce a hybrid chassis composed of a composite monocoque in the the front half of the vehicle and steel tubes in the other half, as shown in figure 2.5.

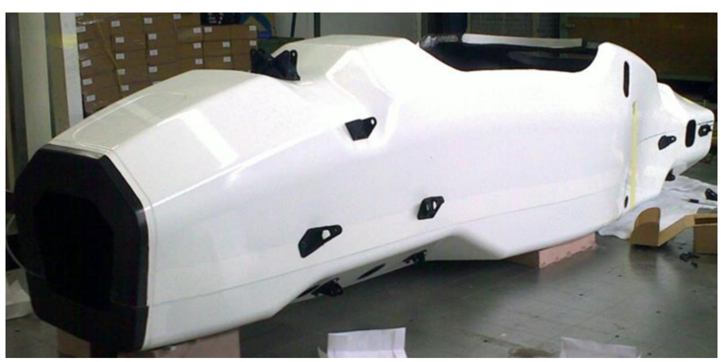


Figure 2.4: Full Composite Monocoque [44]

Figure 2.5: Spaceframe and Carbon Monocoque Hybrid Chassis [67]

All three configurations are suitable design concepts, but they come with advantages and disadvantages. The University of Ottawa's FSAE team has used a steel tube spaceframe in the last couple of years. Spaceframes allow for easy reach for parts during maintenance and would be vital for mounting and dismounting a battery in an electric vehicle (EV). The manufacturing process for creating a spaceframe is simpler and requires less material than a full or semi-monocoque chassis. On the other hand, composite monocoques can be a vital for high aerodynamic performance and better handling. The shape of the monocoque causes drag reduction and an increase in fluid flow [69]. A semi-monocoque offers both, a high aerodynamic and handling performance with the space to easily maintain parts. However, just like the monocoque chassis, it is expensive to produce.

2.3 Impact Protection

The FSAE guidelines specify the need for an impact attenuator which is located at the front and rear of the vehicle [42]. The purpose of an impact attenuator is to absorb energy upon impact to protect the chassis and driver [62]. The impact attenuator acts as a "crumble zone" which helps increase the time taken for the vehicle to come to a complete stop. Since the acceleration is inversely proportional to time, increasing the time taken for the vehicle to stop will decrease the magnitude of deceleration of the vehicle before stopping [62].

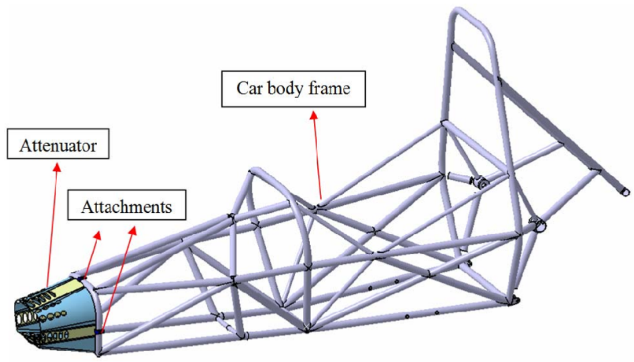


Figure 2.6: Impact attenuator location on chassis [61]

2.4 Tubing and Assembly

The FSAE guidelines state the standard tubing size, thickness, and applicable locations [42]. The guidelines also state how an alternate frame design geometry, excluding the main roll hoop and main roll hoop bracing, can be used which allow for more flexibility during the design of the chassis. Moreover, it allows the use of substitute materials that must match the mechanical properties of the standard tubing design [69]. The FSAE chassis is a spaceframe made from materials that can withstand forces that will not cause the tubes to fail during machining and welding. Steels with a low percentage of carbon content are very popular as they provide for better fusion when welding.

Figure 2.7: 4130 steel tubes welded to form proper triangulation [34]

On the other hand, a monocoque is usually made from composites and its manufacturing process is more complex. Inter-laminar cohesion can be used to join layers of the composites together using epoxy resin and a vacuum bag to absorb the air bubbles. Male epoxy resin molds are used to realize carbon fiber female mold which carries out the first composite lamination.

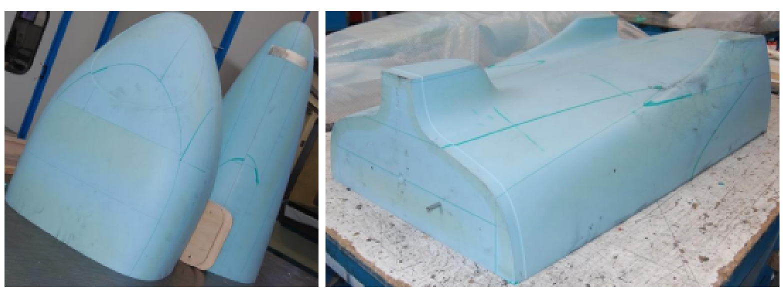


Figure 2.8: Epoxy Resin molds for the front, rear, and central sections of the monocoque [57]

Honeycomb sheets were glued in the central part of the body for the second lamination. The composite layers are then laminated to realize the internal shell. After the second lamination, necessary trimming is performed to accommodate the designer's needs [57].

Figure 2.9: Second lamination in central section [57]

2.5 Driver Accomodation

According to the FSAE rules and regulation document, the vehicle must be able to accommodate drivers of sixes ranging from the 5th percentile of females up to the 95th percentile male. In addition to that, the driver must have sufficient visibility to the front and side of the vehicles. Moreover, when seated in a normal driving position, the driver must have a minimum field of vision of 100 degrees to both sides. If mirrors are required for this rule, they must remain in place and adjusted to enable the required visibility trough all dynamic events. All these rules must be considered when designing the chassis of the car [42].

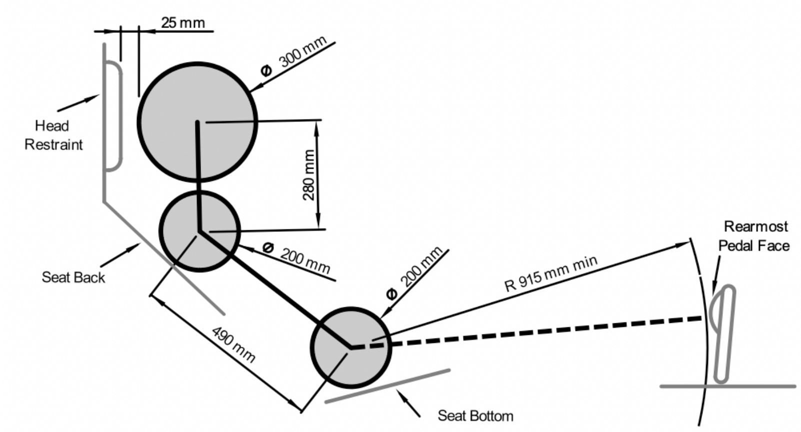


Figure 2.10: Template of 95th percentile male recommended set up [42]

The FSAE guidelines specifies how the straight lines joining the top of the front hoop and the main hoop should always be 50 mm above the top of the driver's head, to ensure drivers safety during a case of rollover [42].

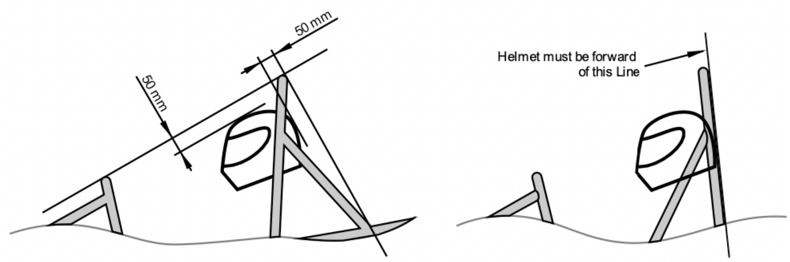


Figure 2.11: Head position regulations demonstration [42]

Chapter 3

Battery

The battery is one of the electric vehicles' most critical components. The battery pack is required to contain battery cells, a battery management system, fuses, and motor controllers. FSAE rules and regulations state that the maximum power drawn from the accumulator must not exceed 80 kW and the maximum voltage that may occur between any two points must not exceed 600 V DC. The cells and/or segments must be appropriately secured against moving inside the Container

3.1 Battery Cells

There are various types of batteries on the market, some of which involve different chemistry. Some commonly used electric vehicle batteries include Lead-Acid, Lithium Ion, and Nickel-metal Hydride batteries.

Firstly, Lead-Acid batteries are some of the oldest rechargeable batteries, however, their low specific energy densities limit the range of an EV. Nickel-metal Hydride (Ni-MH) batteries offer a higher specific energy and longer life cycles than lead-acid batteries, Ni-MH have high self-discharge and heat generation at high temperatures making them hazardous and unsafe to use for an EV battery. Lithium-ion batteries on the other hand have the highest specific energy of the three and despite being more expensive their advantages far outweigh their price points, and with an electric formula vehicle where weight to power ratios play a vital role the choice of a lithium-ion battery is almost inevitable. Another important competitor to Lithium-ion batteries are Lithium-Iron-Phosphate batteries (LiFePO4). Firstly, LiFePO4 batteries have many similar properties, although the power density of a Lithium iron phosphate battery is lower than that of a Lithium-ion battery, it is not significant enough that there is an immediate winner between the two. LiFePO4 batteries have longer storage periods, meaning that it doesn't lose as much charge as a lithium-ion battery would. Secondly, from a safety perspective an LiFePO4 battery is not prone to burning or exploding during overheating or overcharging, they can also remain cooler in high temperature operations which is beneficial from an EV perspective [46]. LiFePO4 batteries also come in pouch formats compared to the common cylindrical cells found for Lithium-ion batteries, which makes a LiFePO4 battery much more space efficient, which is a vital component in formula designs. It is important to note that there are different types of battery configurations and layouts, and they can be set up in several ways. Firstly, cylindrical shell batteries have been around for many years and can be considered the cheapest options. Pouch cells on the other hand although can be more space efficient are not as robust in design. They are more vulnerable to damage from high temperatures and high humidity. It is also important to note that when a single pouch cell becomes faulty, it affects the entire pack's performance, whilst a cylindrical cell will not affect the performance of the pack significantly. figure 3.1. below illustrates a cylindrical cell assembly where multiple cells are stacked and sectioned to create a battery pack.

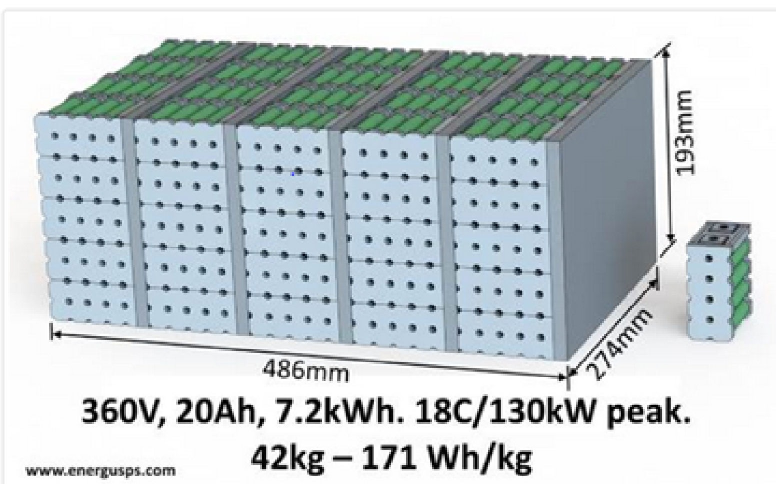


Figure 3.1: Energus PS's Lithium-Ion battery assembly using cylindrical cells. [43]

Given the various lithium-ion battery manufacturers and different specifications for different layouts it is essential that the batteries with the highest energy densities are chosen.

3.2 Battery Sizing

It is important that the battery design for an EV vehicle is done appropriately and as close to the required output as possible. The general method for sizing a battery pack is very straight forward. Provided the SAE restrictions, the battery cell specifications and using a simulation to determine the capacity required from our battery. one can easily determine how many cells are required to be connected in series, and how many are needed to be connected in parallel.

3.3 Battery Cooling Methods

Air cooling, phase change material cooling, and liquid cooling are all different cooling methods which have been applied by different EV models. Between the three cooling methods, liquid cooling is the most efficient due to its high heat conductivity and heat capacity. Nevertheless, liquid cooling systems can be dangerous from a safety perspective as they could leak out. A liquid cooling system also provides a more compact cooling model. According to a study completed in 2015 “an air-cooling system needs 2 to 3 more energy than other methods to keep the same average temperature; an indirect liquid cooling system has the lowest maximum temperature rise; and a fin cooling system adds about 40% extra weight of cell, which weighs most, when the four kinds cooling methods have the same volume.” [3] There are multiple different battery cooling solutions that have been implemented in the formula SAE electric competition, many of which involve a passive cooling system which uses fans as illustrated in the figure below. The main reason for the installation of such a system is due to its simplicity and low cost.

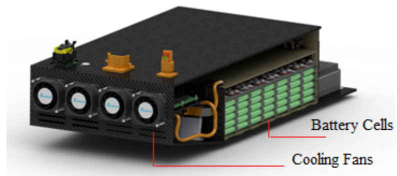
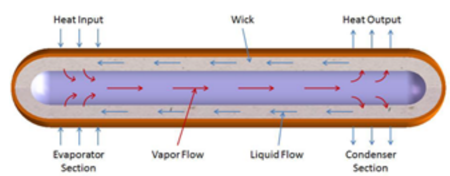


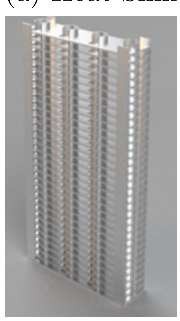
Figure 3.2: Accumulator fan cooling system design. [47]

Admittedly, fan cooling is not considered energy efficient, as it's parasitic in nature, and due to the added weight to the vehicle, more energy will be drained as the vehicle outputs power. An interesting solution however proposed by a formula SAE team involved the addition of heat sinks, which then were connected to copper heat pipes which served as a phase change material, and then connected to fins, as illustrated in figure X below. According to their calculations and research, this system is effective at maintaining the battery at cool operating temperatures. [58]

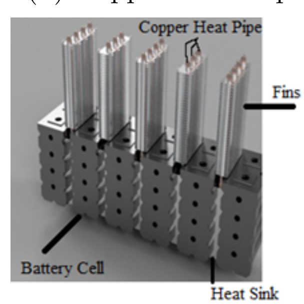
(a) Heat Sink



(b) Copper Heat Pipe



(c) Fins

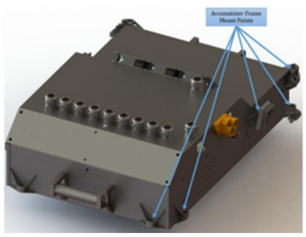


(d) Full Assembly

Figure 3.3: Cooling solution for an FSAE Lithium-Ion accumulator using heat sinks, copper phase change rods, fins and fans to circulate the heat outside the battery pack. [58]

3.4 Battery Mounting Methods

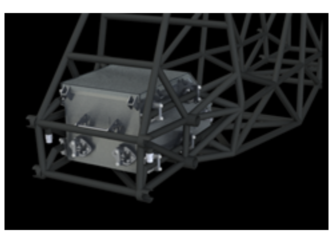
The mounts must withstand 20 kN in any direction. These restrictions illustrate that the mounts used need to be able to withstand high forces.

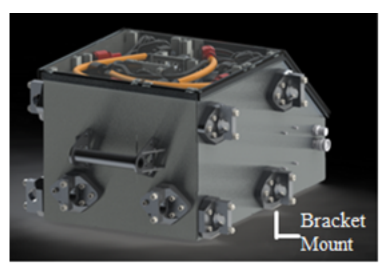

(a) Battery Mounting points


(b) Butteryfly Mount

Figure 3.4: Accumulator Mount Design for Wisconsin Racing [66]

Due to these restrictions however, many mounts available on the market would not be able to withstand such high loads, and thus FSAE teams' resort to designing their own mounts. The figure above illustrates butterfly mounts that were designed by the Wisconsin racing team which could withstand and transmit these high forces efficiently. However, depending on the chassis structure as well different mounting methods may need to apply.


(a) Battery Mounting points



(b) Bracket Mount

Figure 3.5: Battery Bracket Mounts. [63]

Chapter 4

Motor & Powertrain

4.1 Standards

For the formula style electric vehicle, only electrical motors are permitted onboard with no limit on the quantity a vehicle can have. The maximum power drawn from the accumulator must not exceed 80kW and the maximum permitted voltage between any two points must not exceed 600 V DC. Direct connections between the motor(s) and the accumulator are prohibited. Therefore, the motor(s) must be connected to the accumulator through a motor controller. Also, supplying power to the motor to drive the vehicle in reverse is prohibited. The rotating part of the motor(s), including the chain, must be contained and properly guarded in a structural casing. A scatter shield must be included around the motor(s) when the motor casing rotates around the stator, or the motor case is perforated [42].

Any transmission and drivetrain may be used on the formula electric vehicle. Exposed high speed drivetrain equipment such as continuously variable transmissions (CVTs), sprockets, gears, pulleys, torque converters, clutches, belt drives, and clutch drives must be fitted with scatter shields intended to contain drivetrain parts in case of failure. Cooling and lubrication systems should be sealed to prevent leakage as the vehicle must be capable of being tilted to a 45° angle without fluid leakage. Lastly, regenerating energy is allowed and unrestricted when the vehicle speed is over 5 km/hr [42].

4.2 Existing Solutions

There are three main powertrain configurations for the electric vehicle. The first configuration involves the use of two electric motors to power the vehicle. Each electric motor is connected to a chain drive single gear reduction that independently drive the rear axles as shown below.

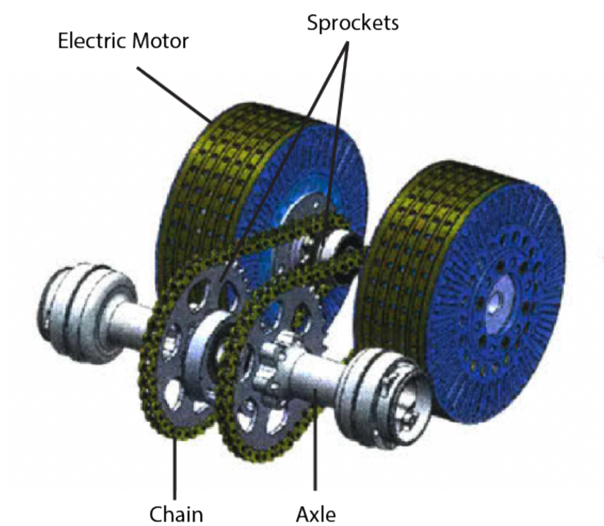


Figure 4.1: Two Electric Motors with Two Chain Drives [29]

The second configuration involves the use of two electric motors with planetary gearboxes instead of a chain drive. The advantage of this configuration is the short longitudinal length of the assembly. Disadvantages include the large width of the assembly in the rear of the frame and the heavy weight associated with the planetary gearboxes. Planetary gearboxes are also complicated and expensive.

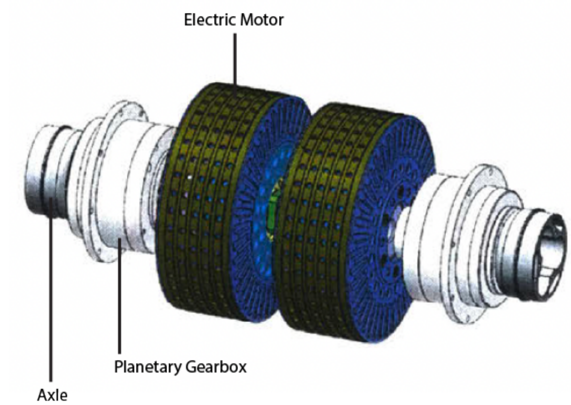


Figure 4.2: Two Electric Motors with Two Planetary Gearboxes [29]

The last configuration involves a single electric motor with a chain drive connected to a limited slip differential. The advantage of this configuration is its light weight and narrow assembly. This configuration occupies the least volume in the rear of the frame.

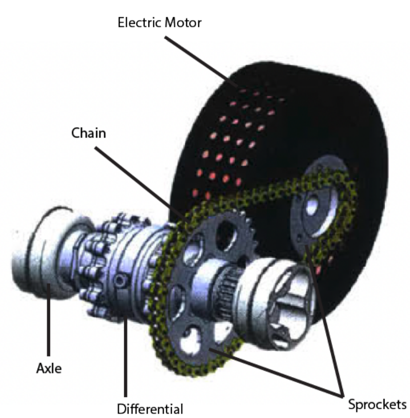


Figure 4.3: Electric Motor with a Differential and Chain Drive [29]

4.2.1 Motor

The three main types of motors that are often chosen to power formula electric vehicles are series DC motors, permanent magnet synchronous motors (PMSM), and induction motors. Series DC motors are a group of self-excited DC motors where a field coil is connected to the armature winding in series with a high current passing through it. Such configuration helps to generate a large quantity of torque by converting electrical energy into mechanical energy using the electromagnetic law. The process occurs through the magnetic field present around the current-carrying conductor and the outside field that creates rotational motion on the output shaft. Series DC motors are cheap and easy to assemble, design, and maintain. They can produce high starting torques and operate under heavy load conditions. However, controlling their speed is challenging and an increase in speed comes with a sharp decrease in torque.

A permanent magnet synchronous motor (PMSM) is the most common type of motor implemented in electric vehicles. A PMSM consists of a rotor and a stator. The stator is the fixed part, and the rotor is the rotating part [56]. The rotor is either located inside or outside the stator of the electric motor. The operation of a synchronous motor is based on the interaction of the rotating magnetic field of the stator and the constant magnetic field of the rotor. The magnetic field of the rotor interacts with the synchronous alternating current of the stator windings and creates torque to rotate the rotor using Ampere's Law [36]. A PMSM has a high torque-to-current ratio and a high power-to-weight ratio. It provides higher efficiency at high speeds and can maintain full torque at low speeds. However, a PMSM is very expensive when compared to other motors.

Figure 4.4: The EMRAX 228 Electric Motor [13]

Lastly the three phase AC induction motor has the same basic stator design as the PMSM, but without the permanent magnets. The magnetic field generated in the stator creates an opposing current in the rotor bars which creates a magnetic field in the rotor laminations [51]. The rotor turns because of the opposing field. Induction motors are robust and relatively cheap to build. However, in automotive applications, the battery's DC power must be converted to three-phase AC power through a DC-to-AC inverter. Induction motors are less efficient than PMSMs as well.

4.2.2 Drivetrain

The drivetrain connects the motor to the wheels to enable the vehicle to move. The drivetrain converts power from the motor to torque at the wheels. The drivetrain consists of a few main components namely transmission, differential, and axle shafts. The drive wheels can be either the front wheels, rear wheels, or all the wheels. There are generally four types of drivetrains: all-wheel drive (AWD), four-wheel drive (4WD), front-wheel drive (FWD), and rear-wheel drive (RWD). AWD and 4WD vehicles have differentials in front and back enabling the motor to send power to all four wheels. FWD vehicles have a differential in the front to allow the motor's power to be sent to the two front wheels. Lastly, RWD vehicles have all the motor's power sent to the back two wheels using a rear differential [45].

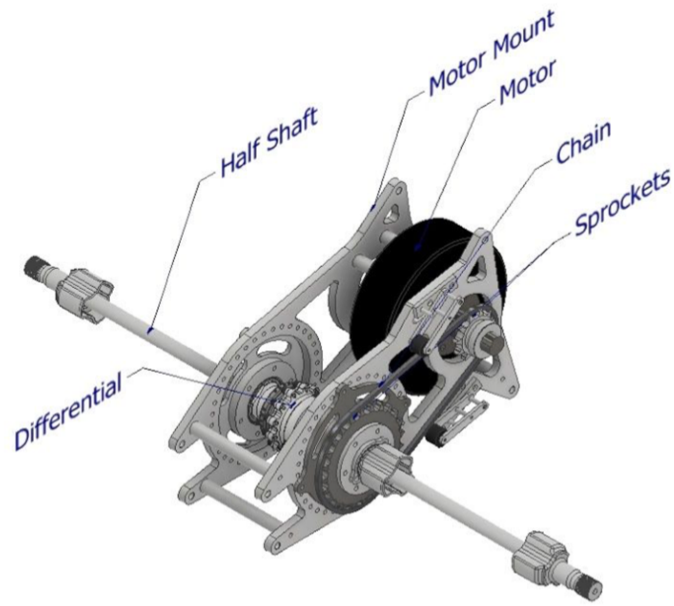


Figure 4.5: Rear Wheel Drivetrain Assembly [60]

The transmission in a formula electric vehicle can either utilize a chain drive, belt drive, or gear drive [38]. A chain drive is the most used transmission in formula electric vehicles to transfer mechanical power to the axle shafts. Power is transferred by a roller chain, known as a drive chain or transmission chain, that passes over two sprockets with the gear teeth intersecting holes in the chain's links [71]. Chains are mostly used to transfer speed and power from one shaft to another when the center distance between the shafts is small. They can transfer a large amount of torque within a compact space. Chain drives do not contain slip or creep and thus, have a high transmission efficiency of up to 98%. Angular velocity remains constant during operation with a high velocity ratio of up to 8:1. However, chain drives are noisy and require regular lubrication. They also have a lower load capacity and service life compared to gear drives.

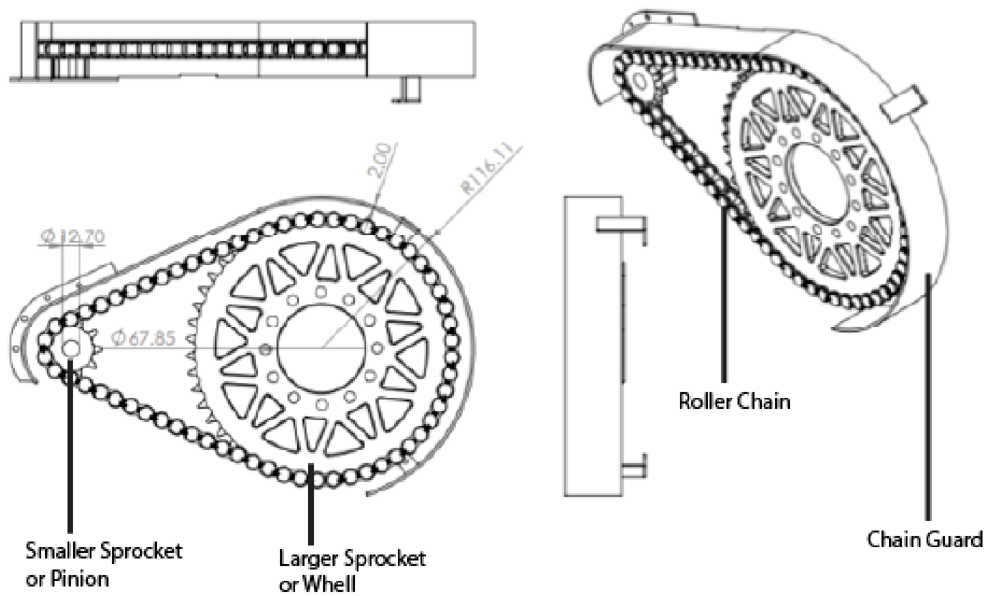


Figure 4.6: Chain Sprocket Assembly [52]

Limited slip differentials are the most common type of differentials due to their wide range of applications. They work by shifting a portion of the torque to the wheel with the most traction while limiting the slip on the wheel with the least traction. In a limited slip differential, the wheels can rotate at different speeds and the torque is not balanced between them [35]. The amount of torque variation shifted between the wheels is referred to as the bias of the differential. Limited slip differentials are driven by a series of clutch discs located behind the side gears and held under tension with springs. As the slip increases, the tension increases between the different discs which provides the resistance to limit the slip between the wheels. They are lightweight and provide excellent traction while maintaining the ability to perform sharp turns without sliding [11].

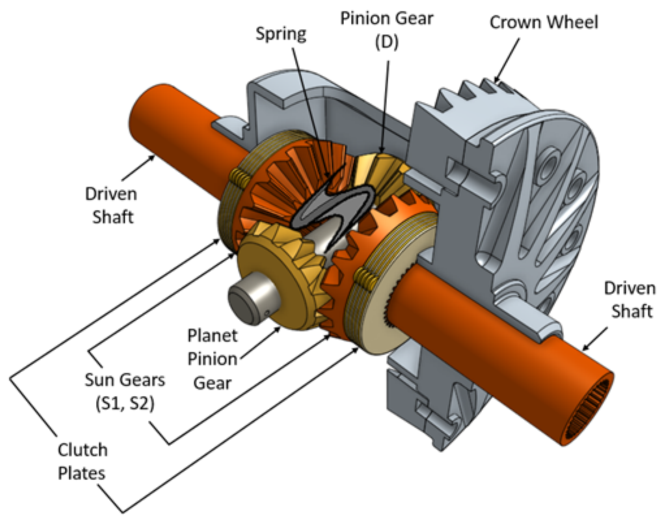


Figure 4.7: Limited Slip Differential Mechanism [24]

Tripod housing plays a major role in transmitting power from the transmission system to the drive wheel. Hence, it undergoes severe torsion and bending type of deformation [33]. Each axle shaft contains two tripod housings with two tripod joints at each end. This allows power to be transmitted, regardless of whether there is angle shifting. The tripod housing has 3 matching grooves for the tripod joint.

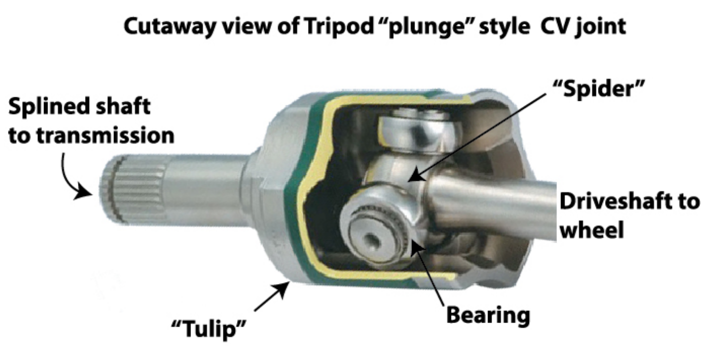


Figure 4.8: Cutaway view of tripod "plunge" style CV joint [68]

The tripod joint is a constant velocity joint that is assembled to transfer uniform torque and constant speed to the axle and wheels at changing angles. The spider transfers the engine power at various angles while the ball case allows for stroke actions at various angles inside the housing track as the vehicle moves. A tripod joint assembly has needle bearing-shaped rollers that are mounted to a three-part yoke. The joint fits inside a cup with matching grooves that attaches to the differential. The rollers are mounted at 120° to one another and slide on tracks inside the housing. The retainer holds parts in position while the ring in the spider groove holds surrounding parts. Each axle shaft is installed between two tripod assemblies giving it about 12° degrees of angle as shown below [9].

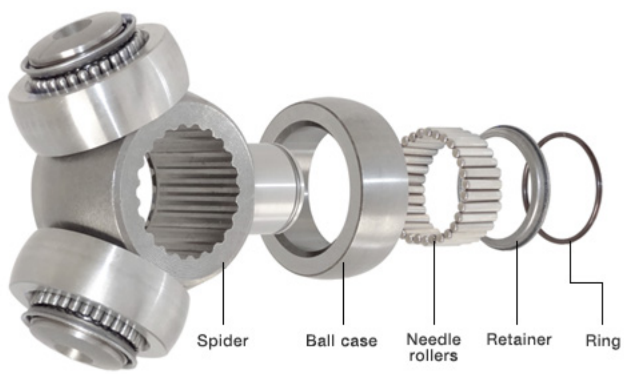


Figure 4.9: Structure of Tripod Joint [18]

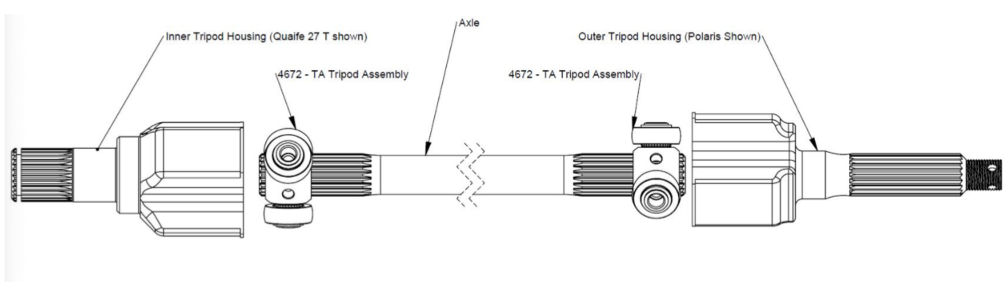


Figure 4.10: Axle Shaft Assembly with Tripod Housings and Joints [15]

Motor mounts have a critical role of firmly containing the electric motor and powertrain components of the vehicle. Correct geometry and positioning of the motor mounts on the chassis ensure a good ride quality and performance. The motor mounts undergo high static and dynamic stresses. In addition, the motor mounts tend to undergo continuous vibrations and varying stresses. The diagram below illustrates the components of the drivetrain including the motor mounts and the chain guard. There are two motor mounts on either side of the motor and differential. The motor and differential are mounted on the motor mounts which are fastened to the chassis. The motor mounts are fastened to the welded brackets on the chassis using bolts on either side.

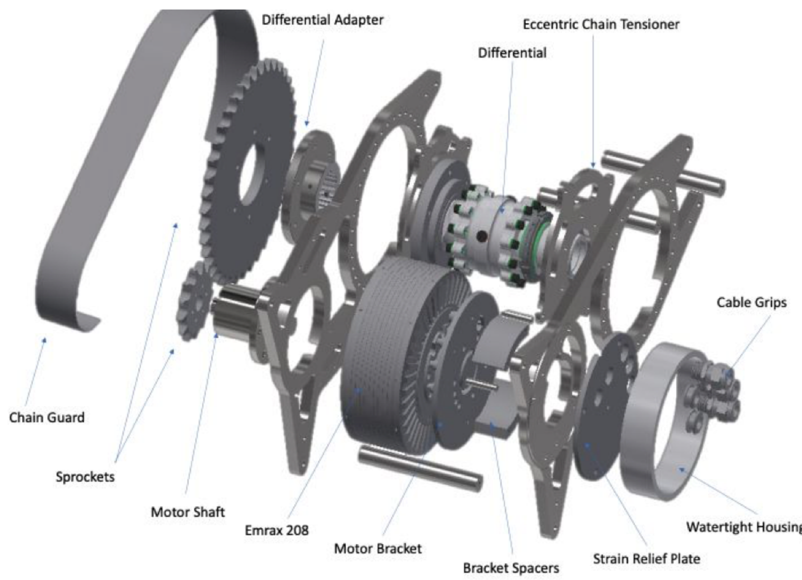


Figure 4.11: Drivetrain Exploded View [22]

Chapter 5

Bearings

5.1 Motor Bearing

There are several locations where bearings must be used to constrain motion. Within the electrical motor exists a bearing to protect the inner components. There are several types of bearings that can be included in the motor, such as single deep groove ball bearings or double groove ball bearings. These bearings are pre-mounted in the motor [12].

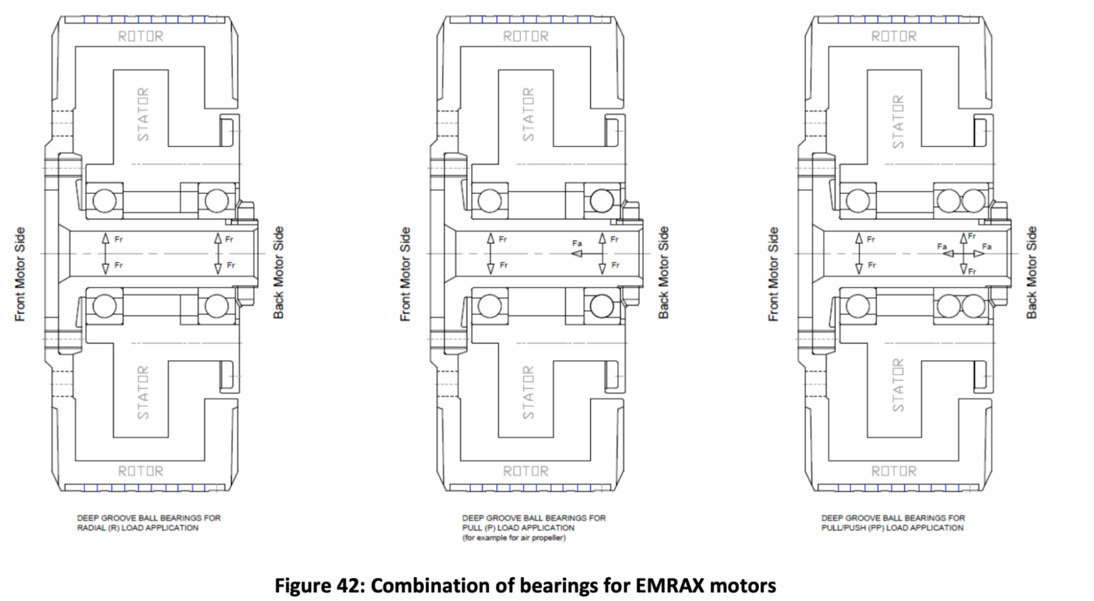


Figure 5.1: Combination of bearings found in EMRAX motors [12]

5.2 Differential Bearing

To determine the type of bearing to use in the differential, several variables must be determined, such as the load ratings, direction of applied load, rpm ratings. Typically, tapered roller bearings are used since their rigidity and life are sufficient for differentials. Tapered roller bearings within the differential can be mounted by clamping the outer bearings, preventing the bearings from moving outwards. This design however creates an axial pre-load and can damage the bearing balls [20].

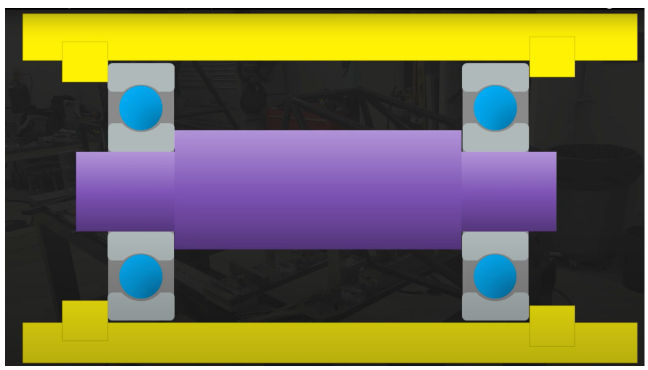


Figure 5.2: Mounting the bearings by clamping the outer race [20]

Another method is to mount the outer and inner race of a single bearing. This setup allows the force to focus on the outside of the bearing rather than the bearing balls.

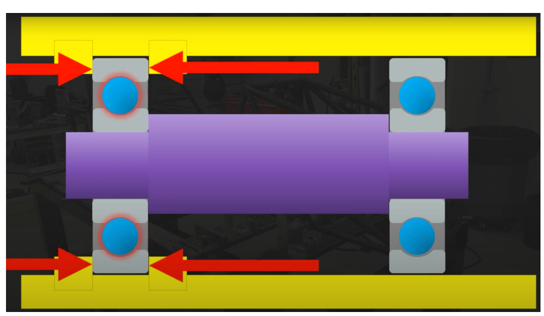


Figure 5.3: Mounting the bearings of a differential by clamping the inner and outer race of a single bearing [20]

5.3 Wheel Bearing

The wheels of a vehicle also experience axial and radial forces. Mounting two tapered bearings along the shaft can cancel out these types of forces. The arrangement of these two bearings can either be face-to-face to back-to-back. The correct arrangement of bearings is determined by analysing the moment of inertia of the shaft.

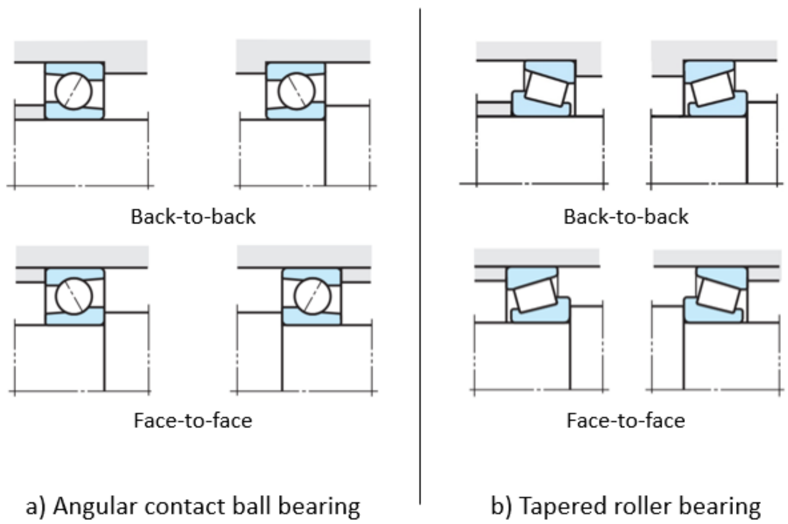


Figure 5.4: Face-to-face and back-to-back tapered roller bearing [21]

Chapter 6

Suspension

The suspension of a car serves the purpose of maintaining optimal contact of each of the vehicle's tires with the road, while isolating the driver and vehicle components from imperfections within the driving surface. When designing a suspension system, trade-offs must be made between enhancing the car's handling ability and its road comfort as emphasizing one aspect compromises the other. In the case of a performance-oriented formula racing car, the suspension usually caters to handling ability at the expense of comfort. As such, specific arrangements of linkages, pivot points, and spring-damper systems must be selected and tuned to yield the desired result [8].

6.1 Springs

The purpose of a spring within a suspension system is to store the energy generated by the movement of the car when it is driven. This is done when the spring compresses in size, converting a force into energy. The magnitude of energy stored is determined by a multitude of factors including the length of the spring, stiffness coefficient, and material [2]. Additionally, when a spring is being uncompressed, it releases energy in an uncontrolled manner resulting in oscillations before returning to its initial position.

6.2 Dampers

Dampers are hydraulic systems that are composed of piston in a cylinder filled with pressurized oil as seen in the figure below. The piston moves within the damper when an external force is applied, which in the case of a suspension system comes from the springs. The purpose of a damper within a suspension system is to control the rate of energy transfer to the springs and the rate at which the energy is released by the springs. So, when energy is being transferred from the springs to the damper, the piston within the damper moves through the pressurized oil, converting the energy from the spring into heat. In doing this, oscillations that are induced by the springs' behavior are reduced and in turn any energy that may have otherwise caused a jump in the car is negated [2].

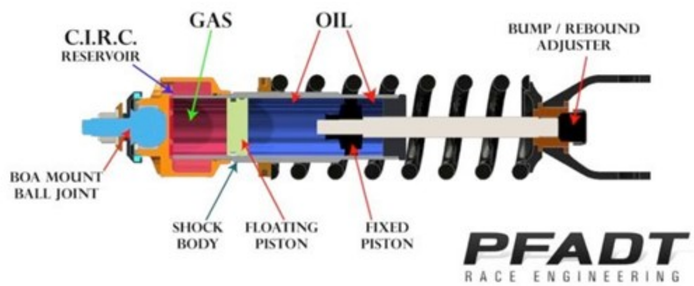


Figure 6.1: Cross section of a coil-over shock absorber spring-damper system [5]

6.3 Spring and Damper Systems

To help understand the role of spring and damper systems, the dynamics of a formula race car and how loads are distributed along the chassis must be analyzed. That is, when the sprung mass of the vehicle chassis and its contents are accelerated, reactive forces are produced which must be balanced and utilized to prioritize traction of the tires with the driving surface. There are two main scenarios that may be used to explain this. The first scenario involves acceleration of the car from a stop to a certain speed as fast as possible while moving straight. In this scenario, the goal is to allow the vehicle's inertia to shift to the power producing wheels (rear wheels) which increases the normal force on them and in turn increases the force of friction, thus allowing for more traction and power delivery. The second scenario involves maintaining the highest speeds possible when turning. The goal of this scenario is similar to the first in that the inertia and momentum of the sprung mass must be controlled when changing yaw as the vehicle turns to prevent excessive roll of the chassis. That is, during a turn, the center of mass shifts so that the load is transferred to the outside wheels thus increasing the normal force on them. From these scenarios, it can be seen how altering the parameters of spring-damper systems on each axle can manipulate the magnitude and rate at which loads are transferred to each wheel [10].

To accommodate for the scenarios outlined above, formula cars typically include an overall spring-damper system that consists of the following subsystems: coil-over shock absorbers for each wheel (seen in the figure below), and an anti-roll bar system between each axle (example of anti roll bar shown in later section in figure 6.8). The transfer of loads and degree of body roll is directly affected by the stiffness of the springs in the coil-over shock absorber systems combined with the stiffness of the anti-roll bar linkages which act as torsional springs [10]. Moreover, the coil-over shock absorbers serve a purpose beyond what was described precedingly, being that they must manage the effects of high frequency road inputs (less than 0.15 m/s) on the unsprung mass that may cause undesirable vibrations. Additionally, the coil-over shock absorbers are also needed to mitigate effects of high impulses created by road imperfections such as bumps and pothole [30].

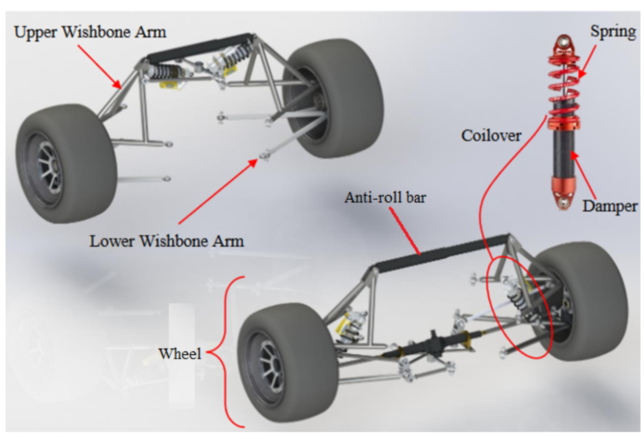


Figure 6.2: need to add and remove label to pic and add caption [10]

Furthermore, control systems theory must be used to conduct a frequency response analysis with a selection of input parameters to find the coefficients that are best optimized for the springs and dampers to benefit the performance of the vehicle. That is, a suspension system can either be underdamped, overdamped, or critically damped. An underdamped suspension will follow a behavior such that the system will have a multitude of oscillations before going back to its original, or steady state. On the other hand, an over-damped suspension will follow a behavior such that the system incurs a high initial impulse and is followed by little or no oscillations before reaching its steady state. Both underdamped and overdamped suspensions are undesirable as unwanted consequences arise and the settling time for the system, or the time it takes the system to reach the steady state after the initial load is applied, is usually increased. Finally, critically damped systems follow a pattern where the steady state is reached in an optimal settling time and with a small initial overshoot. Ultimately, it is ideal to find a balance of spring stiffness and damping for the suspensions' components in order to make the system as close to critically damped as possible [30].

6.4 Suspension Geometry

An important component of suspension design is the system's geometry, all of which share common components being control arms, linkages, and connection angles between the chassis and wheels. Various types of suspension geometry configurations exist such as the MacPherson Strut, leaf spring suspension, trailing arm suspension, etc. each with their own unique characteristics and benefits. However, within the field of formula racing, the most implemented suspension geometry that is used is the double-wishbone suspension which can be seen in the figure below [7]. The advantages of a double-wishbone suspension that make it suitable for formula racing cars are as following:

- The sharper the turn, the more control is provided.
- High range of motion of the control arms allows for the suspension to withstand large imperfections within the driving surface, increasing the force deflection capabilities.

- Versatility in where the coil-over shock absorbers can be mounted, allowing for space to be optimized.

Some disadvantages are that double-wishbone suspensions can be more costly to design and the abundance in parts leads to more points at which failure can occur [2].

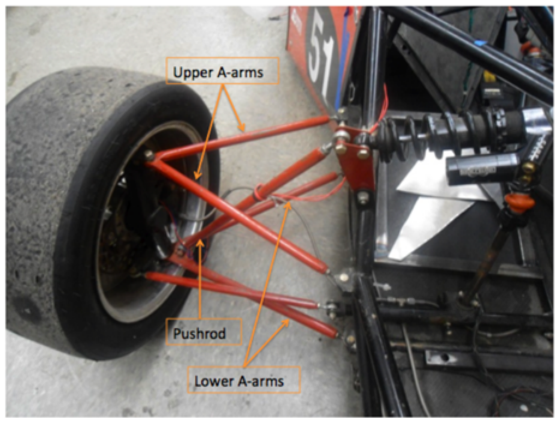


Figure 6.3: Double-Wishbone Suspension Linkages [7]

The double-wishbone design consists of an upper and lower control arm with a triangular geometry that resemble the letter “A” thus referred to as A-arms. These A-arms are often crafted from steel or carbon fiber tubes and serve the purpose of acting as linkages that connect the wheels to the chassis [7]. Often, it is found to be advantageous for the upper A-arms to be shorter in length than the lower A-arms. The reason for this is to induce negative camber onto the wheel when the car sits at rest, so that the contact pitch between the tire on the road surface is increased when loads are transferred to the wheels when driven at speeds. If the A-arms were left to be equal lengths and thus induce a neutral camber, it is likely that the contact pitch of the tires would not be optimized for performance driving. A visual representation for the different types of camber is illustrated in the figure below [10].

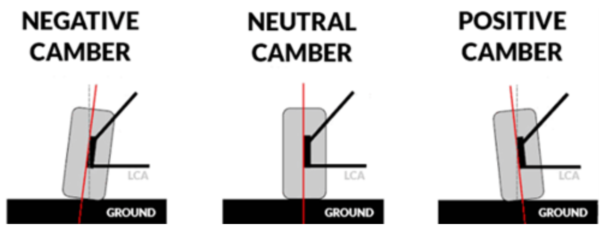


Figure 6.4: Double-Wishbone Suspension Linkages [10]

Within a double-wishbone setup a linkage separate from the control arms must be included that connects the wheel to the coil-over shock absorbers. This linkage can either be in the form of a pushrod or a pull-rod as seen in the figure below. While the effectiveness of controlling the wheels itself has no apparent advantage from selecting one linkage over the other, there are some benefits to choosing a specific arrangement for the suspension geometry. In the case of pull-rod suspension, the center of mass is shifted lower with the compromise of hindering the component's accessibility and intrusion into other usable spaces such as the cockpit. For example, a pull rod suspension may not be able to fit within a chassis without increasing the size of the chassis itself to fit other components that would otherwise be blocked off by the pull-rod. With the pushrod arrangement, since the linkages can be fitted higher up within the chassis, it is less intrusive. However, the load that a pushrod linkage bears can often be higher than that of its pull-rod counterpart when the wheel is raised. This is due to the applied compression forces in bump (wheel rising) which can give a linkage the tendency to want to bow outwards. Depending on the specific requirements of the vehicle it may be favorable to use only one arrangement on both front and rear suspension systems, or a combination of either or in the front and rear. For example, the front suspension geometry could include a pushrod while the rear suspension uses a pull-rod or conversely the front suspension could include a pull-rod while the rear suspension used a pushrod [28].

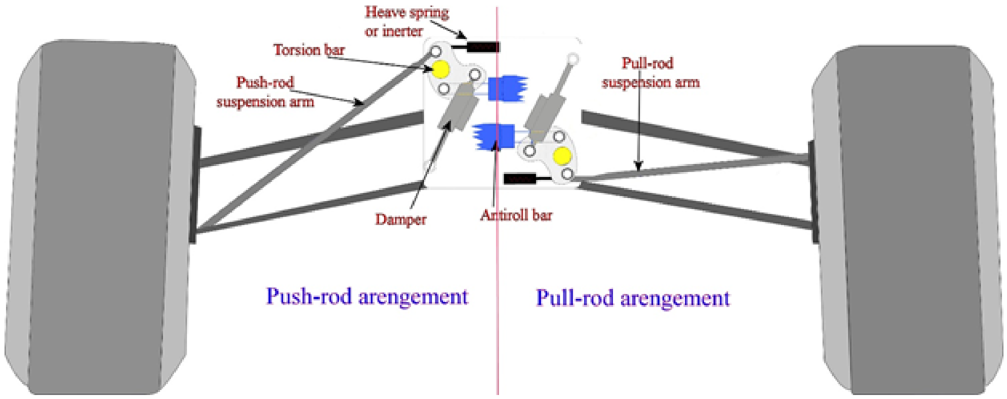


Figure 6.5: Push-rod vs pull-rod suspension arrangements [28]

6.5 Mounting and Working Principle of a Double-Wishbone Suspension

The suspension components are mounted to the wheel and chassis using a combination of bushings to and ball joints to allow for the correct range of motion of parts. Bushings are used at the joints when mounting suspension components wherever vibrations may be of concern. Some components that may require bushings are, control arms, shock absorber mounts, anti-roll bars, stabilizing linkages, etc. Ball joints allow for limited range of motion in all directions and act as a pivot point between the wheels and suspension [27].

The control arms of the double-wishbone connect the wheel hub and steering knuckle to the frame of the vehicle. Typically, bushings are included on the frame side of the vehicle and a ball joint on the wheel side. The control arm bushings consist of an outer metal sleeve, durable rubber or polyurethane bushings, and an inner metal sleeve. These bushings are important to include as they enhance driver comfort and handling by cushioning the effect of vibrations due to road imperfections. An illustration of the control arms and their respective joints is shown in figure below. Moreover, a pushrod linkage would be connected to the lower control arm via a ball joint whereas a pull-rod linkage would be connected to the upper control arm, as is seen in the figure above [27].

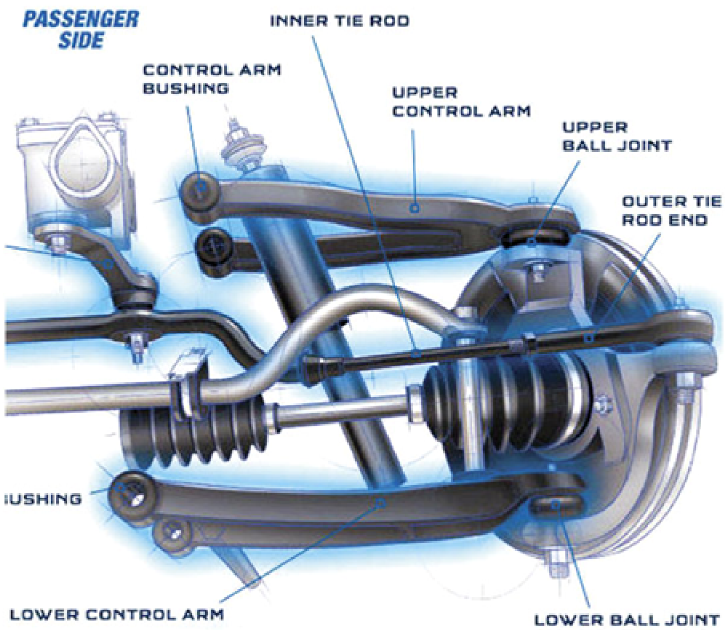


Figure 6.6: Ball joints and bushings of control arms and linkages in a double-wishbone suspension [3]

Perhaps the most important linkage within a double-wishbone suspension, is the bell crank linkage. Shown below in the figure, the bell crank connects the pushrod or pull-rod linkage as well as the anti-roll bar to the shock absorbers, and in turn allows for the system to act together in tandem. The bell crank itself is attached to the frame using a pivot joint which also bears a bushing to prevent the vibration of the chassis. Essentially, the bell crank acts to translate the motion from the wheels to a different axis in which the shock absorbers are installed [14].

Furthermore, the bell crank must be able to withstand high stresses and strains as it bears the load of the push or pull-rod linkage, the shock absorber reaction forces, and the anti-roll bar reaction forces. A free body diagram of the forces that may be experienced by the bell crank are shown from an analysis done on an existing formula SAE car in figure below. In this illustration, the bell crank is attached to the chassis at pivot point A, to the pushrod or pull-rod linkage at point B, to the shock absorbers at point C, and to the anti-roll bar at point D.

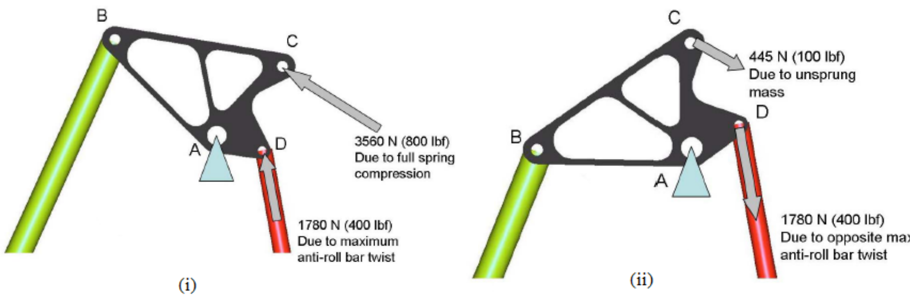


Figure 6.7: Free-body diagram of a bell crank linkage [14]

Lastly, the anti-roll bar is connected to the bell-crank using vertical drop links that connect to the ends of the bar. The bar itself is attached to the chassis using supporting flanges that have bearings built in. An example of an anti-roll bar is seen in the figure below, where the ends have links that can be connected to vertical linkages and the bar itself has two support flanges across the shaft that attach to the frame of the car. Finally, the anti-roll bar acts to connect the suspension of the two wheels on an axle together which would otherwise act independently of the other [10].

Figure 6.8: Configuration of double-wishbone pushrod suspension with anti-roll bar [14]

Chapter 7

Steering

7.1 Steering Mechanisms

Designing the steering system of an FSAE vehicle can be one of the more complex parts of the task as the steering system is linked to other structures and parts of the car such as the chassis, wheels, driver cockpit, and the electrical systems [6]. Currently, the two most popular steering systems are the pitman arm and the rack and pinion assemblies. The two mechanisms follow the FSAE rules and regulations for the steering system which specify that the steering wheel must be mechanically connected to the front wheels. In addition to that both steering systems must use rigid linkages that are in tension or compression during operation [42].

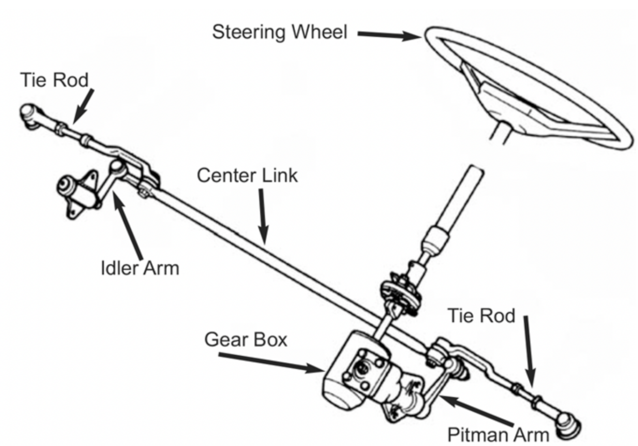


Figure 7.1: Pitman Arm Steering Assembly [54]

As shown in figure 7.1, the mechanism allows the input from the steering wheel into a gear box which converts the rotation around the steering wheel shaft into rotation around the output shaft of the gearbox which is connected to the pitman arm. The pitman arm then rotates to either side depending on the input from the steering wheel. The pitman arm is then connected to the center link shown in the Figure which allows linear movement to the left or right which then steers the car [49]. The gearbox connecting the steering shaft to the pitman arm uses a recirculating all nut type steering gear. Helical grooves in the inside the ball nut match the helical grooves on the worm gear which are filled with ball bearings. These ball bearings move the ball nut assembly up and down the worm gear when the steering wheel is turned [23].

Figure 7.2: Gearbox connecting to pitman arm cross section [55]

The rack and pinion mechanism is the steering design that is most used today. This is due to its simplicity, low cost, compared to the pitman arm mechanism, and how smoother it is for the driver. Instead of a small gearbox like the pitman mechanism, the steering shaft ends with a small gear called a pinion which meshes into a steering rack. The steering shaft's pinion will move the steering rack to left or right, depending on the drivers input. The steering ratio and range can be manipulated much easier using this mechanism which is convenient in the design stage as it saves time [49].

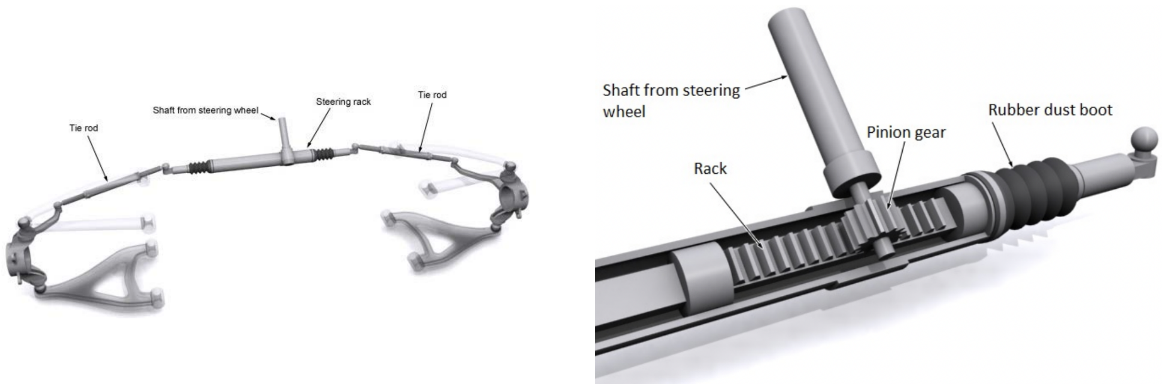


Figure 7.3: Rack and pinion steering mechanism [49]

7.2 Steering Joints and Mounts

Every steering system has a steering tilt and telescope function that needs to be accounted for. This is done by using universal shafts and joints as the mating shafts in the steering system will be rotating at an angle to transmit rotation to the pinion. Most steering systems have two universal shafts. One universal joint connects the steering wheel to the intermediate steering shaft which then connect to the steering rack as shown in figure 7.4 [31].

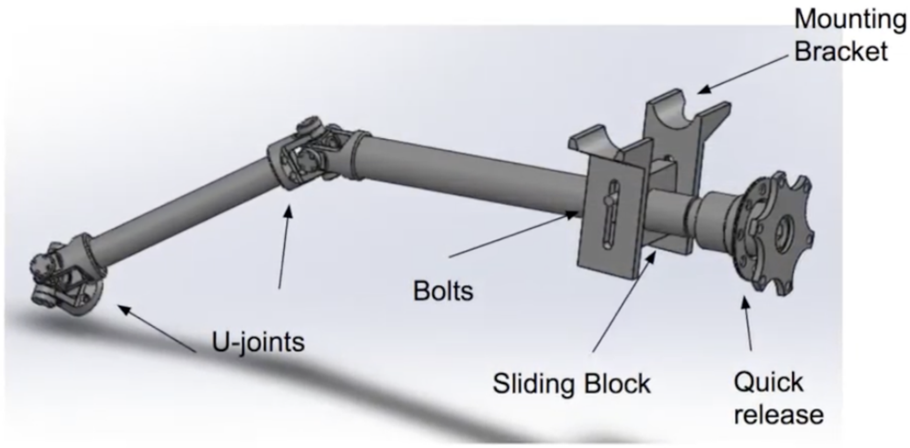


Figure 7.4: Sub-assembly of the U shaft and joints, mounting bracket, and quick release mechanism [17]

The mounting bracket shown in Figure X is normally attached to a sub-frame or the chassis to remain in place. Also, the quick release part in Figure X is used to easily disconnect the steering wheel as the FSAE rules and regulations document specifies to be part of the steering system [42]. This is usually done by means of cams, push or pull rings, pins, or a large nut that is usually hidden by some trip pieces [37]. It is important to note that the FSAE guidelines specify that a maximum allowable steering free play of 7 degrees is acceptable [42]. The steering free play can be manipulated by how loose the universal joints are if they are coupled using bolt-through techniques. However, if splined ends automatically low and non-existent if welding is used [65].

Chapter 8

Brakes

The primary function of the braking system is to allow the driver to decelerate the vehicle at the fastest rate possible. The braking system found in the vehicle must endure high temperatures and stresses [59]. There are a number of regulations from FSAE guidelines that the vehicle design must adhere to. First, the braking system must act on all four wheels. Second, there must be two independent hydraulic circuits, each with its own reservoir. Lastly, the brake pedal must be either fabricated or machined from steel or aluminum [42].

8.1 Brake Pedal & Master Cylinder

The brake pedal is capable of compressing the master cylinder using a linkage. The master cylinder is a control device that contains compressible brake fluid that can sustain high temperatures. Master cylinders can be mounted in various ways using spherical bearing and traditional flange mounts [59]. Spherical bearing mounts allow the master cylinder to rotate with the arc of the pedal and offset of the balance bar to minimise side loads at the push rod [1]. Flange mounted master cylinders are fixed and oppose rotations and movement.

(a) A spherical bearing master cylinder. [1]

(b) A flange mounted master cylinder [39]

Figure 8.1: Various types of master cylinders

FSAE regulations require vehicles to contain two independent master cylinders with their own reservoirs [42]. Master cylinders can be connected to the wheels in a front and rear split, or in a diagonal split.

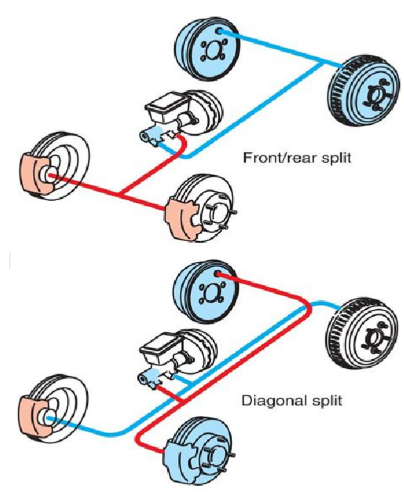


Figure 8.2: Configurations of dual master cylinders to wheels [64]

These configurations are meant to provide backup braking in the event of a master cylinder failure. A master cylinder failure in the diagonal split configuration will provide more braking, since there is a front and rear wheel braking, but will be much harder to control. The front rear split however will provide less braking, but will be easier to control in case of a master cylinder failure.

8.2 Brake lines, Calipers, Brake Pads and Rotors

The compressed brake fluid from the master cylinder travels to the caliper through a brake line. The brake fluid causes the pistons within the calipers to compress. Compressing the pistons forces the brake pads to make contact with the brake rotor, creating friction and slowing down the wheel. The wheel slows down with the rotor since the rotor is mounted onto the wheel hub.

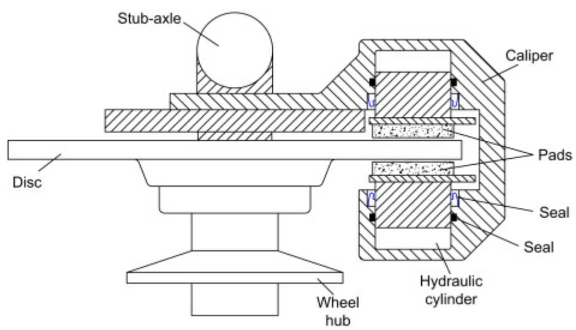


Figure 8.3: Configuration of the caliper, pads, disc, wheel hub [40]

8.2.1 Calipers

There are two types of calipers: floating calipers and fixed calipers. Floating calipers contain one piston that press the brake pads onto the rotors. As the piston extends, the caliper slides along a pin to make contact with the braking pad on the opposite side. Floating calipers are cheap, common, and are easy to bleed. [4].

Fixed calipers contain a piston on both sides of the rotor. The caliper does not need to slide since there is a piston on both sides of the rotors. Fixed calipers generate more braking torque and are more durable than floating calipers. However, they are more costly and are more complex [41].

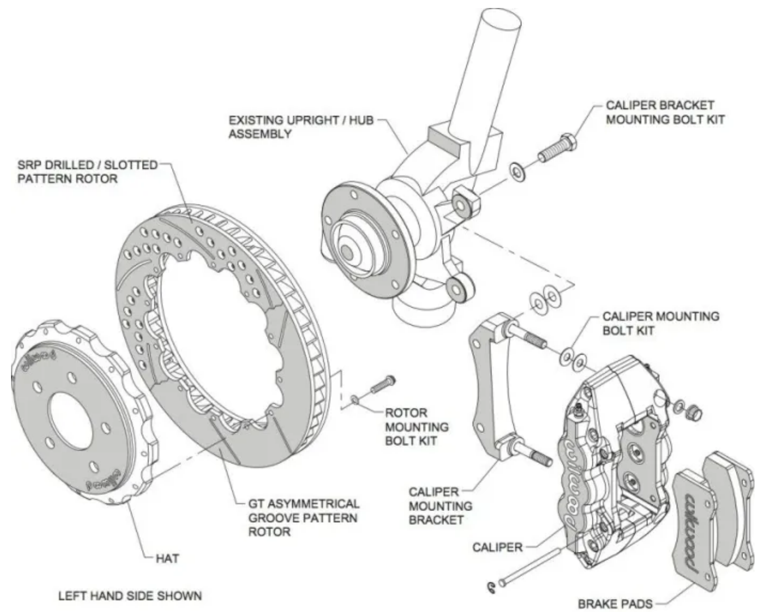


Figure 8.4: Assembly of a Fixed Caliper mounted to the upright assembly [25]

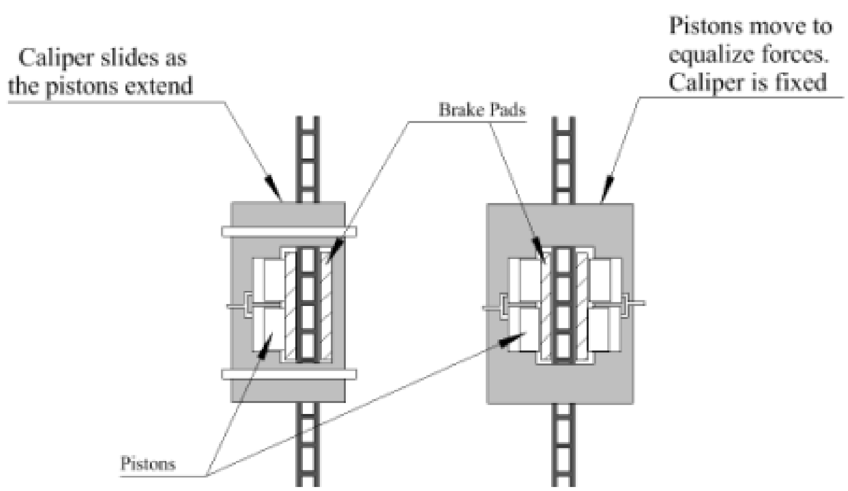


Figure 8.5: Cross section of Fixed Caliper and Floating Caliper [4]

8.2.2 Brake Rotors

Brake rotors are mounted on the wheel hub to absorb friction from brake pads and reduce the rotational speed of the wheels. Brake rotors can absorb excess heat when put under constant stress, which results in warping. Rotors can be manufactured with various slot geometries to dissipate the heat, as shown in figure below.

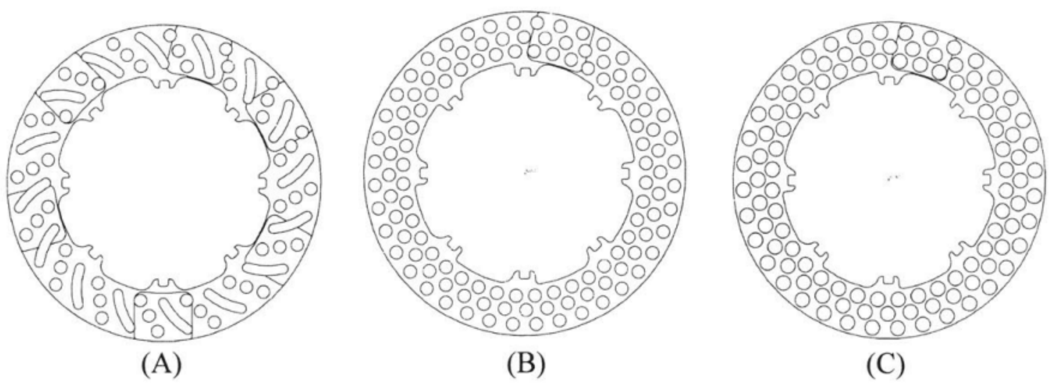


Figure 11. Three conceptual rotors considered for cooling effectiveness testing. Rotor (A) is named "Holes and Slots" and features large slot cutouts that may help increase cooling. Rotor (B) is "Standard" and features hole cutouts with a radius equal to the thickness of the plate such that the net area change from the cutouts is zero. Rotor (C) is "Lite" and features large hole cutouts that significantly reduce the mass of the rotor. These concepts were chosen for their likelihood to produce good cooling performance as well as meeting the stress requirements of the braking load case.

Figure 8.6: Various geometries of rotors [50]

Chapter 9

Tires & Wheels

Tires are a critical aspect of an FSAE vehicle as they are the main contact point with the ground, and thus have a large impact on the safety, performance and stability of the vehicle [70].

9.1 Standards

FSAE guidelines require teams to dry tires and wet tires depending on the condition of the track. Both tires can be of any size, and dry tires can contain slicks or treads. Wet tires however must have treads [42].

(a) Dry Slick Tire [19]

(b) Wet Treaded Tire [19]

Figure 9.1: Physical difference between Dry Slick Tire and Wet Treaded Tire

9.2 Variations of tires

Larger tires provide more contact with the tire and the pavement, improving driving stability and decreasing the braking distance since more friction is produced. However, larger tires add a considerable amount of weight to the vehicle, reducing overall speed. Smaller tires are more suitable for tight turns and improves overall speed due their lighter weight. However, smaller wheels provide less space for internal components such as brake and suspension components. There are many other parameters that can be examined when selecting a tire, such as tread width, section width, and weight [48].

9.3 Wheels

The purpose of wheels is to hold the tire in place and connect to the wheel hub. Materials such as carbon fibre are durable and light, but are expensive. Other affordable but less durable options include aluminum and steel.

9.4 Manufacturing Wheels

The manufacturing method of rims also affects their performance. Wheels can be casted, flow formed, or forged. Casted wheels are the most common where molten aluminum or steel is poured into a mold to form the shape. This method is inexpensive, but is brittle and is prone to cracking and failure due to any potential air pockets [53]. Flow formed wheels also use a mold and molten aluminum or steel, however the mold is made to be more narrow. The cast is placed through a heat spinning process to widen the barrel of the wheel, forming the final shape, strengthening the material, and reducing overall weight. However, flow formed wheels are still prone to failures since they utilize a mold [53]. Forged wheels are manufactured by lathe and turning a solid block of material into the final shape. This process dramatically reduces the final weight of the wheel. Forged wheels are the strongest and can withstand the highest amount of load, but are the most expensive [53].

9.5 Variations of Wheels

Wheels can be mounted on to the wheel hub with a single large mononut, or with a configuration of smaller nuts alongside a mononut.

(a) Multi-nut Wheel [16] (b) Mononut Wheel [16]

Figure 9.2: Wheels with different lug nut configurations

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