Tampereen ammattikorkeakoulu

Brake Caliper Design of a Formula Student Vehicle

Atte Jaakkola

Thesis

March 2026

Bachelor of Automotive Engineering

Intelligent Machines

TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Autotekniikan tutkinto-ohjelma
Älykkäät koneet
Atte Jaakkola
Opinnäytetyö 32 sivua, joista liitteitä 2 sivua
Maaliskuu 2026

Tämä opinnäytetyö käsitteli Tampere Formula Student (TFS) -tiimin vuoden 2027 sähköajoneuvoon kevytrakenteisen jarrusatulan suunnittelun ja rakenteellisen validoinnin. Projektin tavoitteena oli kehittää uusi jarrusatula, joka korjaa edellisen komponentin suunnittelupuutteet samalla noudattaen Formula Student-sääntöjä ja täyttää kaikki asetetut vaatimukset.

Työ alkoi teoreettisella katsauksella Formula Student -ajoneuvoissa käytettäviin jarrujärjestelmiin, keskittyen erityisesti hydraulisten jarrujen toimintaperiaatteisiin, kitkan teoriaan ja termodynamiikan vaikutuksiin. Edellisen jarrusatulamallin rajoituksia analysoitiin, erityisesti jarrutasapainoon, ilmausvaikeuksien ja välysvaatimusten osalta. Näiden havaintojen perusteella määriteltiin selkeät tavoitteet.

Uusi 3D-malli suunniteltiin Autodesk inventor -ohjelmistolla ja rakenteellinen validointi suoritettiin ANSYS-ohjelmistolla, jolla varmistettiin, että satula kestää sisäisen hydraulipaineen ja jarrutuksen tuottavat voimat riittävällä varmuuskertoimella. Valituksi materiaaliksi valikoitui EN AW-7075 -alumiini sen korkean massalujuussuhteen, hyvän työstettävyyden ja saatavuuden vuoksi. Lisäksi suoritettiin yksinkertaistettu hiilijalanjäljen arviointi päästöjen tarkastelemiseksi.

Lopullinen suunnitelma täytti asetetut vaatimukset ja oli valmis valmistukseen. Vaikka fyysiset testit olivat vielä suorittamatta, simulointitulokset osoittivat, että jarrusatula soveltuu Formula Student -käyttöön. Työ toimii myös teknisenä viiteaineistona tuleville tiimin jäsenille ja tukee tiedonsiirtoa organisaation sisällä.

Asiasanat: jarrusatulan suunnittelu, formula student, hydraulinen jarru

ABSTRACT

Tampere University of Applied Sciences
Bachelor of Automotive Engineering
Intelligent machines
Atte Jaakkola
Bachelor's thesis 32 pages, appendices 2 pages
March 2026

This bachelor’s thesis presents the design and structural validation of a lightweight brake caliper for Tampere Formula Student (TFS) 2027 electric vehicle. The objective of the project was to develop a new brake caliper design that addresses the shortcomings of the previous design while complying with Formula Student rules and meeting all the requirements set.

The thesis began with a theoretical review of braking systems used in Formula Student vehicles, focusing mainly on hydraulic braking principles, friction theory and the effects of thermal dynamics. The limitations of the previous caliper design were analyzed, particularly focusing on brake balancing, bleeding difficulties and clearance requirements. Based on these findings, clear design goals were defined.

The new caliper was developed using Autodesk Inventor for the 3D-model, while structural validation was performed using ANSYS to verify that the caliper withstands internal hydraulic pressure and braking forces with an appropriate safety factor. The selected material was EN AW-7075 aluminium due to its high strength-to-weight ratio, good machinability, and availability. Additionally, a simplified carbon footprint estimation was conducted to evaluate the emissions.

The final design met the defined requirements and is ready for manufacturing. Although physical testing remains to be completed, the simulation results indicate that the caliper is suitable for Formula Student application. The thesis also serves as a technical reference for future team members and supports knowledge transfer within the organization.

Keywords: brake caliper design, formula student, hydraulic brake system

AI IN THESIS

Usage of AI in Thesis

- ☐ No
- ☒ Yes

This thesis was made with the assistance of AI, and it is acknowledged that the author takes full responsibility for the accuracy and validity of the content presented.

The usage of AI is restricted to information seeking and inspiration. The sources provided by AI are checked for accuracy by the author.

TABLE OF CONTENTS

Abbreviations

TFS	Tampere Formula Student
TAMK	Tampere University of Applied Sciences
EV	Electric vehicle
CV	Combustion vehicle
AI	Artificial Intelligence
FSG	Formula Student Germany
CNC	Computer Numerical Control
PDM	Product Data Management
FEM	Finite Element Methods
FEA	Finite Element Analysis

1 INTRODUCTION

This is a bachelor's thesis that was initiated to address the need for a new brake caliper design on Tampere Formula Student's new 2027 season open wheel EV design. To achieve optimal design, multiple design teams will need to work in unison and communicate to design something that does not interfere with the design work of others.

To help with new teammates recruited in the future, the thesis is constructed to be used as a teaching tool to help understand brake systems.

There are many different types of brake systems used around the world in various vehicles, commercial vehicles, private vehicles, etc. with all of them having their own technical applications, so there are exclusions done to some of the applications to focus solely on Formula Student classic vehicles.

1.1 Formula Student

Formula Student is an international motorsport class, where university students design, build and compete with a formula-style racecar annually. The goal of the competition is to showcase engineering skills that the students gather during the season and carry out the design to compete in various events that test the vehicle performance and the skills of the designers.

The different events of a Formula Student competition are designed to put the vehicle to the limit. For example, Skid Pad Event measures the lateral grip and handling of the vehicle while driving on a figure-8 track. The most demanding event for the competition would be the endurance event where the track is around 22 km long and is raced with driver changes, to test reliability and efficiency.

The events mentioned above are categorized in the dynamic event section, but the static event section houses events such as Business Presentation, Cost Report and Design. These events test human performance and the way that teams can reason the chosen paths they have taken while designing the vehicle. Business Presentation concentrates on the capability of the team to produce a business plan that could convince corporate executives that the vehicle's design is the best in the market.

1.2 Tampere Formula Student

Tampere Formula Student is an association founded in 2006, by the mechanical engineering students of TAMK. The team consists of 70 student members who all take part in running the team and designing the vehicle.

Tampere Formula Student team consists of 7 different departments each responsible for their contribution to the team

- **Aerodynamics** department is responsible for designing a composite structure that optimizes performance utilizing fluid dynamics
- **Composites** department is responsible for designing and manufacturing lightweight composite components such as carbon fiber monocoque and rims.
- **Mechanical design** department is responsible for designing and manufacturing mechanical components of the vehicle e.g. gearbox, and braking components
- **Electrics and Embedded systems** are responsible for designing an electrical system that works as the brains of the vehicle, gathering data from the components using different sensors.
- **Vehicle Dynamics** department is responsible for optimizing dynamic performance of the vehicle utilizing gathered data to make the vehicle faster on straights and corners.
- **Business & marketing** department is responsible for managing finances, sponsors and creating social media posts.

2 THEORY

2.1 Overview of braking systems for formula student vehicles

The brake system consists of all the elements that the operator of the vehicle can control, directly or indirectly decelerate the vehicle or to bring the vehicle to a halt. Brakes are the part of the system that acts opposing to the forces generated by driving the vehicle or gravitational forces acting on the vehicle on a sloped surface.

To achieve these opposing forces, friction brakes such as disc or drum brakes may be used to apply a force that directly reduces wheel speed. Alternatively, one may use retarders as auxiliary system such as hydrodynamic- or electrodynamic retarders or exhaust brakes to reduce speed without straining the friction brakes.
(Robert Bosch GmbH, 2022, pp.1206,1207)

In Formula Student, for safety it is mandatory to use a hydraulic friction braking system to maintain control on all four corners of the vehicle with a dual hydraulic circuit where in case of failure on one circuit, the other circuit can be used to stop the vehicle.

2.1.1 Hydraulic brakes

Hydraulic brakes weren't always the industry standard for decelerating the vehicle. First patent for hydraulic brakes was in 1917 by Malcolm Loughead. Before hydraulic brakes, cars would use wooden pads directly mounted to the wheels to decelerate the vehicle using a mechanical lever operated by hand.
(Abebrakes.com)

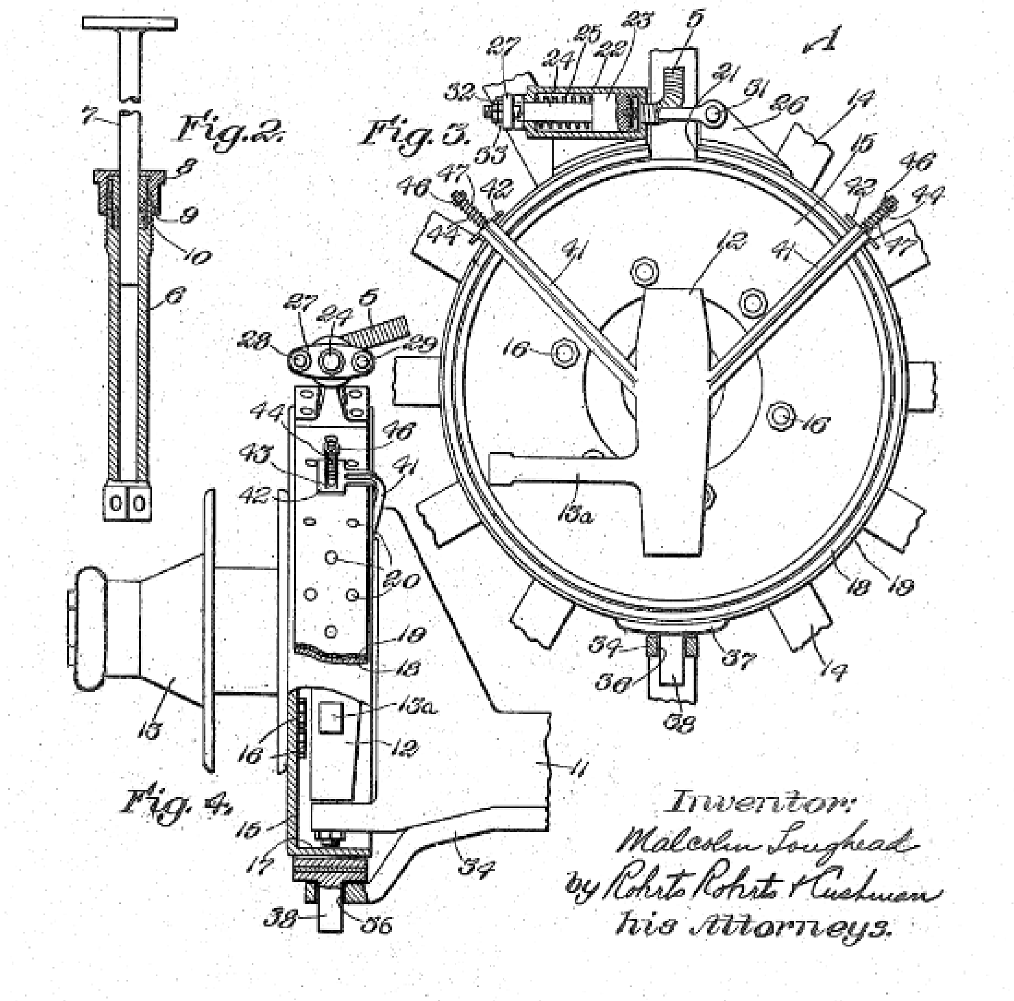


Figure 1. First hydraulic brake patent. (Loughead, M (1917). Google patents)

By observing figure 1, it is possible to notice the thought process while inventing the first hydraulic brake. It is similar to the mechanical lever process.

Loughead (1917) describes in his patent as follows:

> The operation of the system is as follows: -When the plunger 7 is advanced within the casing 6, the fluid, which is preferably oil, is forced into the cylinders 22, thereby forcing the pistons rearwardly against the action of springs 25. This motion is transmitted through the medium of cross-bar 27 and rods 28 and 29 to the lug 26, the eflect being to draw the two ends of the brake ring together, thereby causing the ring to grip and brake the drum. The yoke comprising cross bar 27 and rods 28 and 29 comprises a strong and rigid connection between the two ends the brakes. (para.15)

The claims made by Loughead in his patent describe a simple hydraulic circuit with 2 ends, the other end in the cabin as the brake pedal and the other end attached to the brake disc. The brake pad is attached to the cylinder by mechanical linkage and is forced into the drum when the brake pedal is pressed in the cabin.

2.1.2 Regenerative braking

Regenerative braking system is used in vehicles that have an electric drivetrain, with capabilities of converting into a generator that uses the vehicles forward momentum to generate electricity. They can be used in place of service brakes for vehicle deceleration to recuperate energy into the battery system.

Main way regeneration is implemented is in way of drag-torque, which works by creating a resistive torque opposing the direction of rotation from the wheel, therefore decelerating the vehicle while converting kinetic energy into electricity that can be stored in the battery. Drag-torque can be boosted with an additional generator torque which has a higher deceleration compared.

Regenerative braking is most commonly a feature in vehicles that can be turned on or off, depending on the situation. While the system is on, the vehicle starts automatically decelerating when the operator of the vehicle releases foot pressure on the accelerator pedal.

2.2 Brake Physics

For one to be able to design brakes, they must understand the physics that are utilized in the design process. Why is hydraulic force instead of mechanical force used as the primary source to stop the vehicle? Why is friction used instead of electrical or viscous resistance?

2.2.1 Fluid Mechanics

Fluid mechanics is the primary method in non-commercial vehicles, for bringing the vehicle to a halt. It is way more manageable to route brake lines around the vehicle than it is to create housing for mechanical axles, gears and linkages.

Hydraulic brakes work by utilizing hydrostatic pressure to transfer force applied on the brake pedal to the brake pistons. Hydrostatic pressure can be calculated with

$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2} \qquad 1$$

Where

p = Pressure $(Pa = \frac{N}{m^2})$

F = Force (N)

A = Cross-sectional area (m^2)

(Robert Bosch GmbH, 2022, pp.56,57)

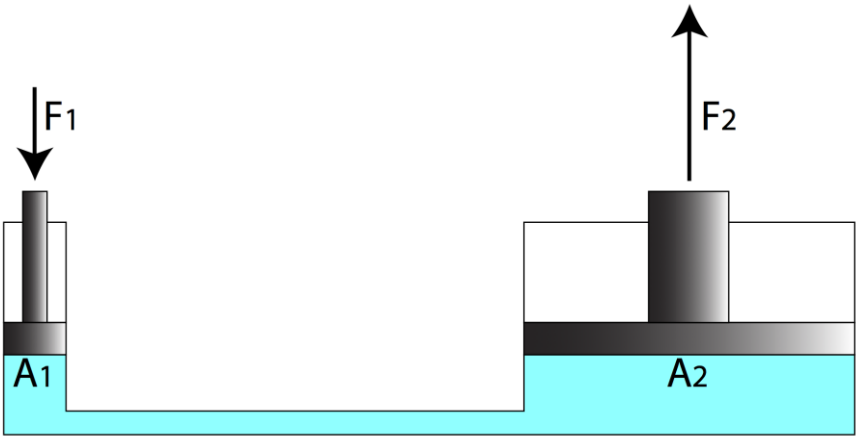


Figure 2. Pascal's law illustration (APlusPhysics, n.d.)

Pascal's law implies that when there is a pressure change inside a container filled with fluid, there is an increase in pressure equally at every other point in the container. Observing figure 2 F_1 can be imagined being the brake pedal and F_2 being the brake piston. Formula 1 can be rearranged and solved for F_2.

$$F_2 = F_1 \cdot \frac{A_2}{A_1}$$

If the driver of the vehicle presses a theoretical brake pedal with the piston size of $10\ mm^2$ With a force of $100N$ and on the other end the brake piston is $100\ mm^2$.

$$100N \cdot \frac{0{,}0001\ m^2}{0{,}00001\ m^2} = 1000N$$

(Hodanbosi, 1996).

2.2.2 Friction

Friction is a force that acts between two surfaces in contact with each other, opposing the motion happening when a force is applied to one or both surfaces. Friction is affected by multiple variables such as the material of the surface, the force pressing the surfaces in contact with each other, texture and temperature of the surfaces and external factors like lubrication. Forces of friction are simplified in figure 3 shown below.
(Britannica.com. Friction)

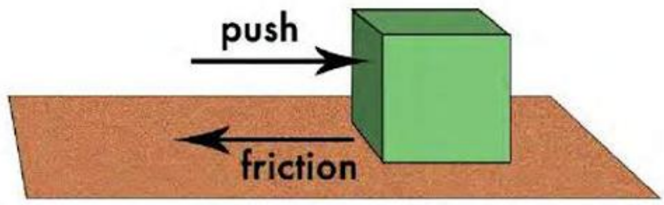


Figure 3. Friction visualized (AmericanPhysicalSociety.com)

Molecular attraction, also known as adhesion, is the primary cause of friction, alongside the roughness of the surface (asperity interlocking). In adhesion friction the two surfaces in contact with each other form a bond on a molecular level that is sheared apart when force exceeds the holding strength of the molecular bond. This energy from the force is then converted into heat that needs to be cooled.
(Robert Bosch GmbH, 2022, p. 1178)

Asperity interlocking is in a way, putting something solid behind the force that is being applied to the surface on a small scale, for example on a larger scale track athletes use a starting block to exert maximal force in line with the direction of the track when they start, referenced in picture 1.

Picture 1. Starting block (Wikipedia.com)

There are two phases of friction, when trying to move an object. First is static friction that happens when the object is at rest. Where it takes a certain amount of force to start to move. When the object is in motion, kinetic friction happens where it takes lower force to keep the object in movement in comparison to maximal force needed at rest.

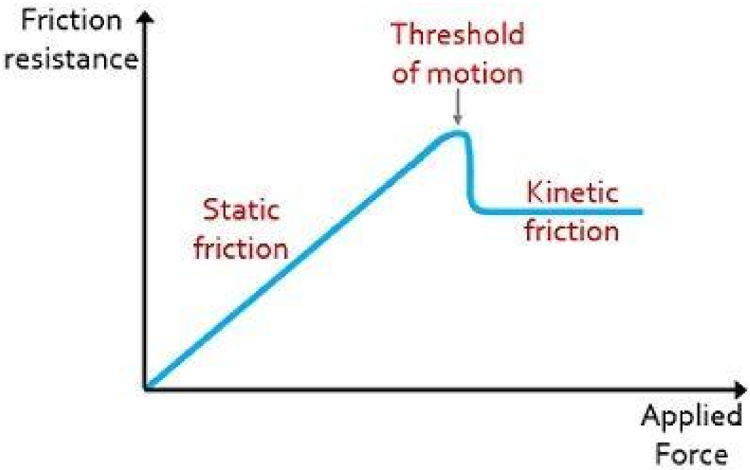


Figure 4. Friction force curve visualized (Circuitglobe.com)

A simple formula can be used for calculating friction coefficient or forces being applied to objects that are moving in a flat plane parallel to each other.

$$F = \mu \cdot F_N \tag{2}$$

Where

$F =$ The force needed to overcome the friction (N)

$\mu =$ The coefficient of friction

F_N = The force acting perpendicularly to the object called normal force (N)

For example, formula 2 can be used to calculate the coefficient of friction of a box, if the box weighs 10 kg and 20 N is needed to overcome the friction.

$$\mu = \frac{F}{F_N}$$

$$\frac{20\ N}{10\ Kg\ \cdot 9{,}81 m/s^2} = \frac{20\ N}{98.1 N} = 0.20$$

(Circuitglobe.com)

2.2.3 Heat

Heat is a major factor in braking that needs to be considered as mentioned earlier in section 2.2.2. braking produces heat that needs to be cooled. Overheating the brakes can cause excessive wear on the components, for example altering the properties of the brake pads or discs. Overheating can also cause the brake discs to warp causing uneven braking surfaces that can be felt through the brake pedal. (Bremboparts.com)

Heat is not inherently bad for brakes. They usually operate better when they are heated to their operating temperature. For example, a regular vehicle driven on the roads is not accelerated and braked continuously, therefore standard brake pads usually have the best performance around 0°C – 350°C. Comparing them to more aggressive driving styles, for example in Formula 1 where the vehicle is constantly accelerated to high speeds and braked with a lot of force. Brake pads designed for racing usually have their best performance when the brake pads are heated to over 100°C.
(Molando-brake.com)

3 PRE DESIGN

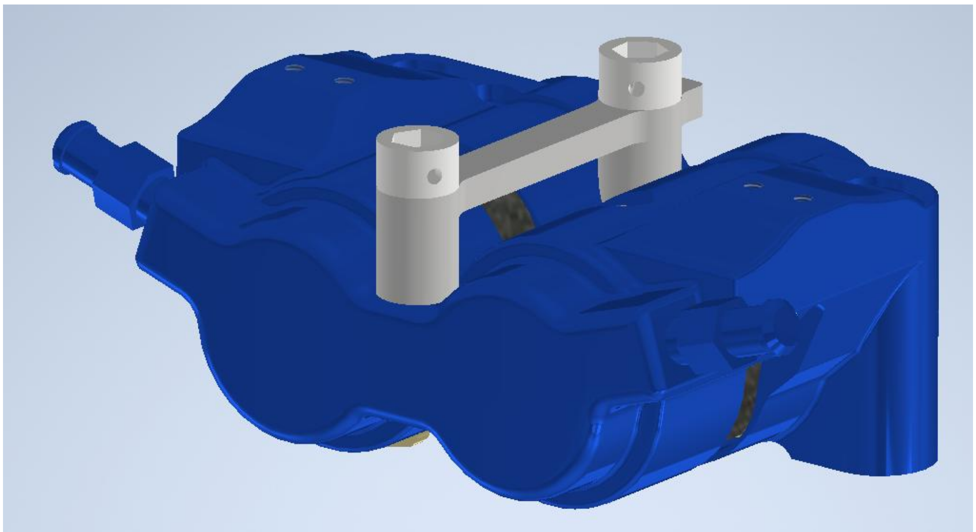
To achieve a suitable design, the criteria are set by analyzing the flaws of old design, the performance goals wanted by the new design, the manufacturing process, the budget and the adherence to the rules. By gathering all the information mentioned above, it is possible to design a component that overall is better than the previous.

Design also needs to be approached with the sense of realism and what benefits different materials have in comparison to each other. For example, you can always design a part to be made with tungsten because of its high yield strength even in high temperatures. But tungsten is too hard to machine in a conventional way and is way too dense, so the final part would be too heavy for the application.

3.1 Flaws of the previous design

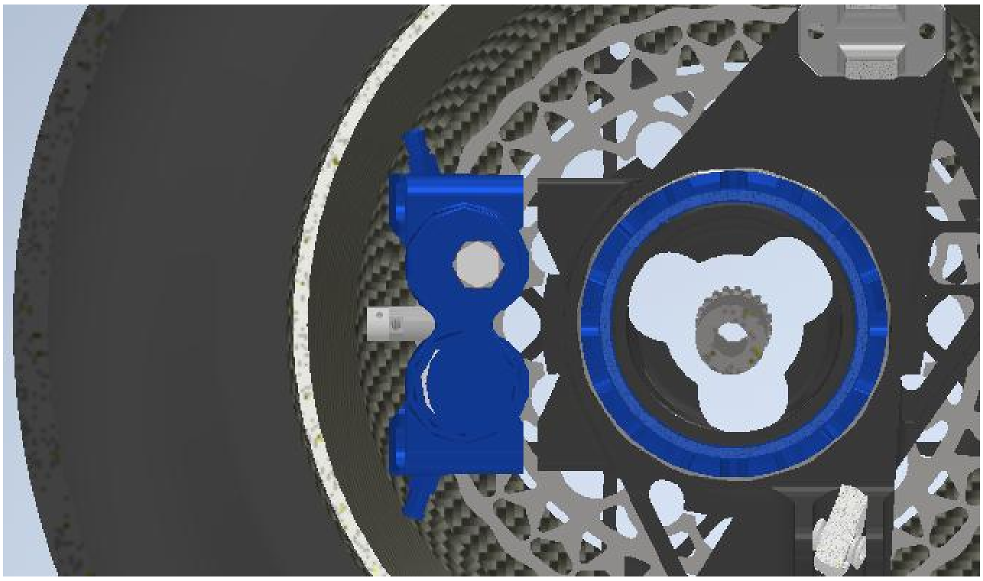
Flaws of the previous design can be traced back to seasons 25 and before. Team used a four-piston brake caliper on all 4 corners of the vehicle to reduce costs and manufacture time. This caused problems for pedal-box design, since they have the responsibility of choosing the right dimensions for the brake master cylinder. The problem is that the front wheels are exposed way more force compared to rear wheels, requiring master cylinders to be chosen in a way that reduces brake pressure significantly on the rear brakes compared to the front brakes. If brake balance is not correct, the rear brakes lock up too early compared to front, causing the rear tires to flat-spot faster and in a worst case the locked up rear wheels can make the vehicle oversteer and lose control.

Mechanically the calipers had a great design for a CNC-machined part, but it had some minor problems. While interviewing teammates with more experience with the brake system, they brought up problems with the bleeding of the brake calipers. By observing picture 2, it can be observed without having done any simulations on how the fluid moves inside. Main flow restrictions and air pockets emerge around the bleeding nipple, and the fluid bridge that goes from the fluid inlet side to the other side.



Picture 2. Season 2025 Brake caliper assembly. (Atte Jaakkola 5.2.2026.)

Other problems brought to the surface were the 5 mm clearance rule in formula student, which means that there needs to be a clearance of at least 5 mm between moving and stationary parts. In picture 3 the clearance is hard to identify, but the team has had problems with the bleed nipples being angled upward pointing to the rim. In the picture the brake caliper is also floating and is not connected to the upright in any form. This is solved with the usage of spacers between the caliper and upright.



Picture 3. Season 2025 Rear corner assembly. (Atte Jaakkola 5.2.2026.)

3.2 Design goals

Determining goals for the new design is usually the first step that happens after flaws have been observed, while using the previous design. Other things that need to be considered are manufacturing capabilities and rules that shape racing in general.

Rules that need to be taken into account can be found in the Formula Student rulebook that is updated constantly. The rules that affect the design are as follows.

T 2.6.4 “The radial clearance between any non-rotating part and the inside of the rim must be at least 5 mm in static condition at any steering angle and any ride height.”
(Formula Student Rules 2026 Version 1.1, p.26)

T 6.1.1 “The vehicle must be equipped with a hydraulic brake system that acts on all four wheels and is operated by a single control”
(Formula Student Rules 2026 Version 1.1, p.49)

In the brake test event, the procedures needed from the vehicle are specified in the same rulebook.
IN 11.1.1 “Lock all four wheels and stop the vehicle in a straight line at the end of an acceleration run specified by the officials”
(Formula Student Rules 2026 Version 1.1, p.107)

These rules and procedures mentioned above force the vehicle to have a hydraulic braking system, which needs to be strong enough to lock all four wheels in the brake test. The brakes cannot also be placed as far out as they physically can be to increase braking force, because of the clearance rule which prevents that.

4 DESIGN PHASE

4.1 Design Flowchart

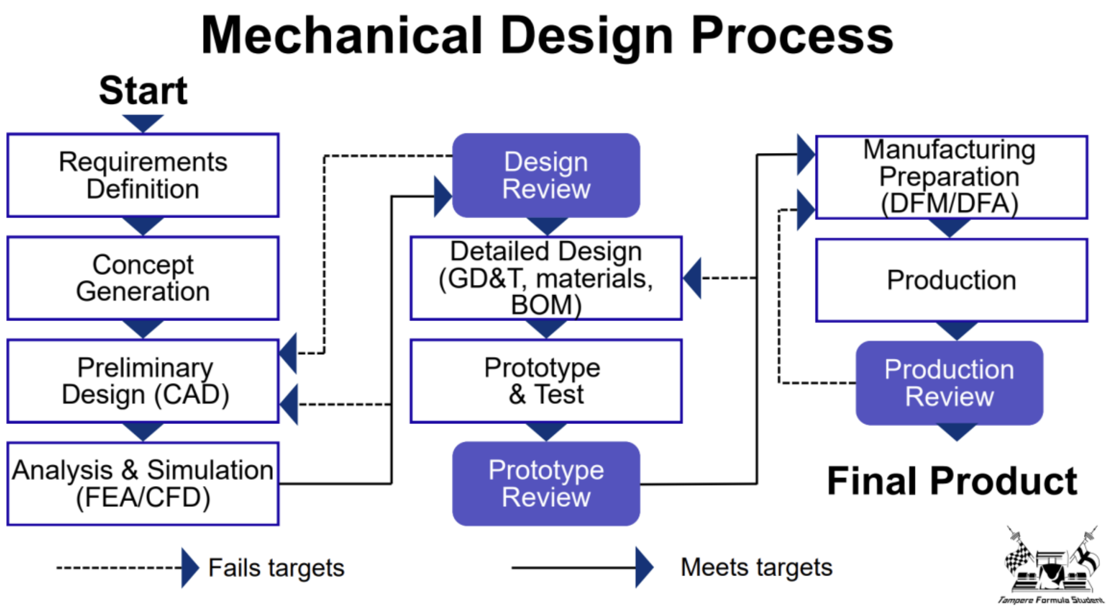


Figure 5. Mechanical Design Process Flowchart. (Graphics from TFS.)

Figure 5 shows a simple flowchart on the process of mechanical design. Everything starts by defining requirements, where performance goals and constraints are set and identifying what the product must do and what a possible customer wants. Second is concept generation where ideas are being brainstormed and sketched on paper to get good and bad ideas on paper. After that comes first 3D-models and simulations to validate the design. Lastly, for the first milestone is the design review. If the design fails, the process rewinds back few steps and starts over.

If the design is suitable on the first review, then a more complex and detailed design can be made, where tolerances are defined and materials are selected that includes complete list of parts and specifications. Next a prototype is created and tested to see if everything is as expected.

Prototype review is the second milestone where the product starts to take shape, and the test data is reviewed to see if the product passes safety inspection. Lastly, small changes are made to the product to simplify the production process, for example easier machining. After production has begun, quality and costs are monitored to ensure that the customer gets the product they ordered.

4.2 Mechanical design

Since the calipers will be used in a formula student vehicle, the design should be considered with ease of manufacturing and safety in mind. The calipers should also be compatible with the components other teammates are designing, so working closely together with other designers is key. Calculations the team has given, created some guidelines for design. Caliper pistons should be 25 mm in diameter; the caliper should be strong enough to withstand an internal pressure of 150 bar and a force of at least 3000 N when the brake caliper grips on to the brake disc.

4.2.1 3D-Modeling

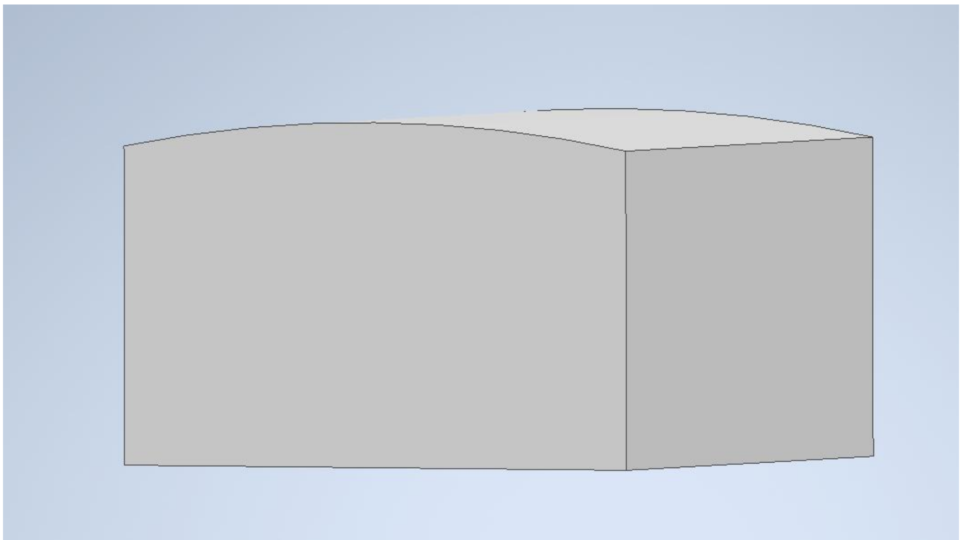
When starting a design for the caliper model, first is the need to search for the components that are compatible with the future design. These components include the brake pads, pistons and bleeding nipples. The main one being the brake pads.

The team has used one brake pad for a long time now and it has been deemed suitable for use, so a decision on whether it is worth the risk to change to a smaller pad for better overall fitment. It is also necessary to figure out the price to performance ratio for the pads. The team has used SBS655DC pad with some modifications to fit better (shown in picture 4), so finding a replacement in this case was not suitable for the needs even though there were some great E-bike brake pads competing.

Picture 4. Modified Brake pads. (Atte Jaakkola. 23.2.2026.)

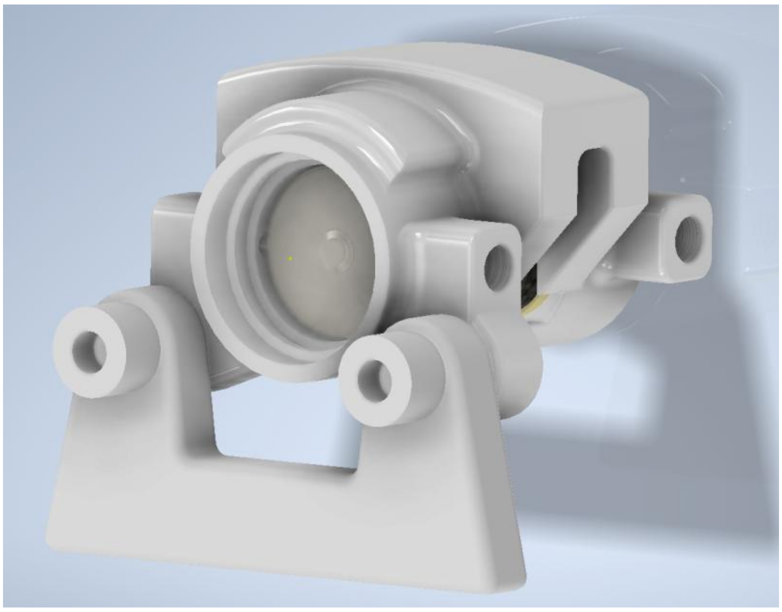
The next step is the pistons which are 25 mm in diameter and the reason for them is the stock that the team has and the calculations based around the pistons have been confirmed in the past and have been calculated to work. They can be either manufactured, or they can be purchased from a supplier.

With this information a rough 3D-model can be made for a space needed for the caliper into Vault which is Autodesk inventor’s PDM system. The reason for the space reservation is that the designer for the rims and the gearbox/upright can see roughly the space needed for the caliper so they can design their components to fit without too much interference.

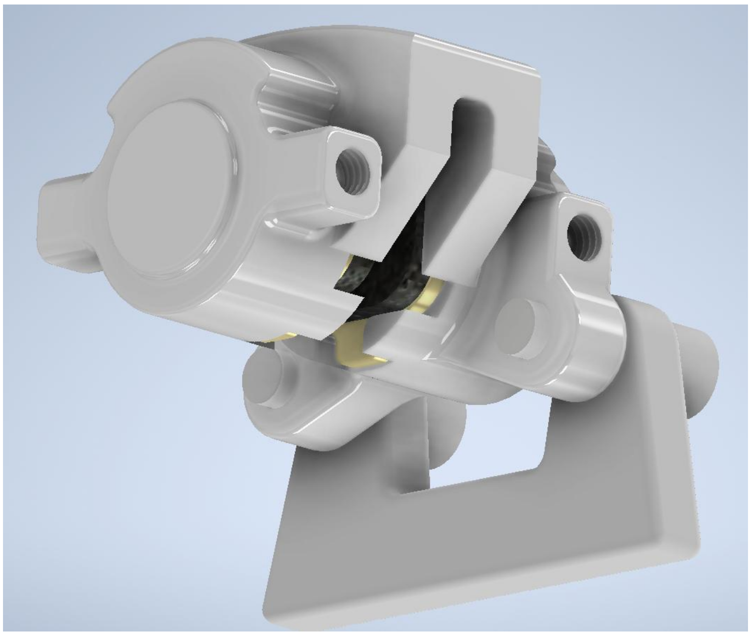


Picture 5. Brake caliper space reservation. (Atte Jaakkola. 23.2.2026.)

Picture 5 shows that the space reservation can just be a block. Dimensions come from the rough idea that is formed in mind for the design and some extra leeway added. The round upper part comes from the rims radius to get as much space as possible. With these first steps for the modeling, thus iteration on the brake caliper can be started



Picture 6. Brake caliper design front side view (Atte Jaakkola. 23.2.2026.)

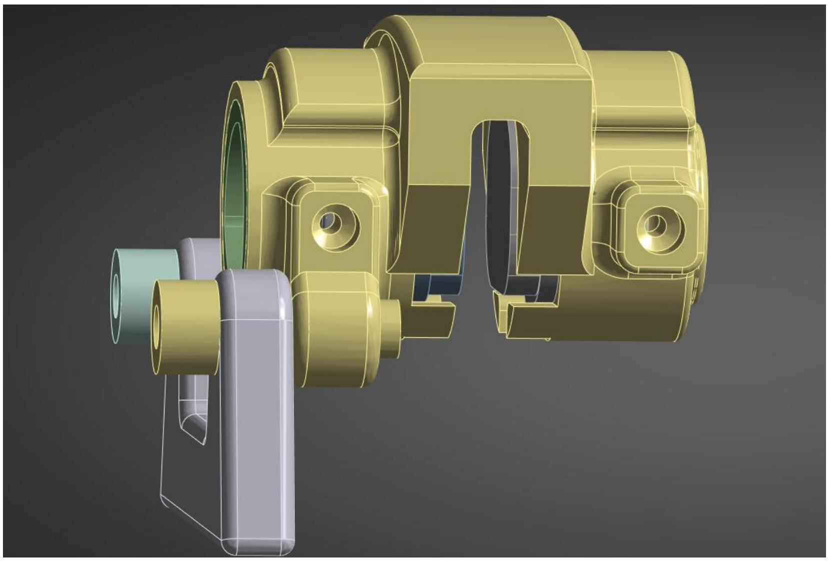


Picture 7. Brake caliper design rear side view (Atte Jaakkola. 23.2.2026.)

Shown in pictures 6 and 7, is the final revision of the brake caliper, that should be easily machined. The brake caliper has also plenty of room to change, for example the bleeding nipple holes can still be adjusted once hardware has been chosen.

4.2.2 FEM Validation

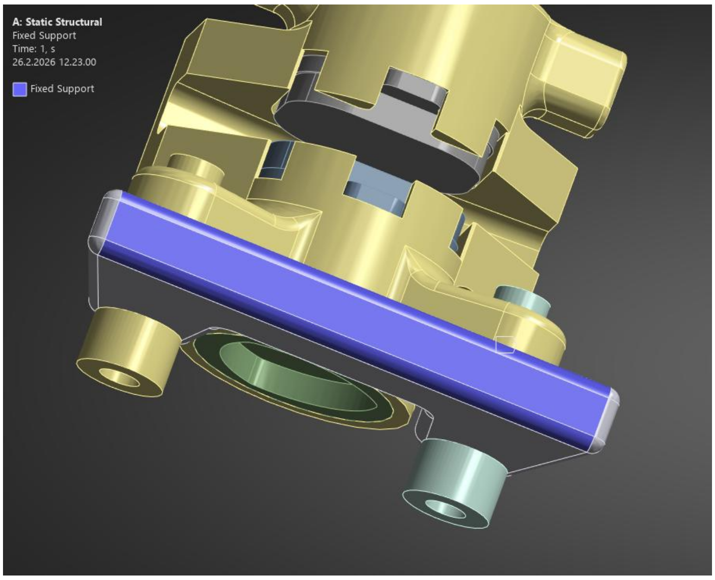
Since brakes are crucial for safety, it is necessary to do FEA on them to prove that they can withstand the forces of the calipers. Tampere Formula Student team uses ANSYS software for their simulations. With multiple setup possibilities in ANSYS, there are many ways to achieve a suitable result.



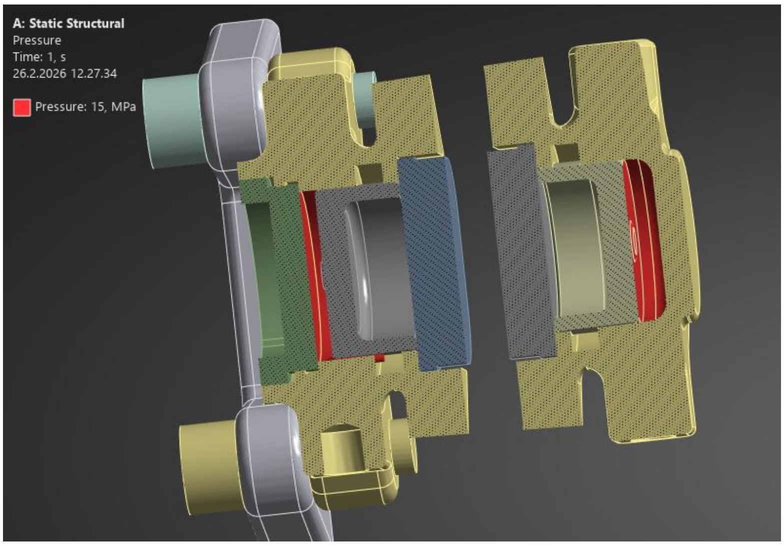
Picture 8. Brake caliper FEA setup (Atte Jaakkola. 26.2.2026.)

Observing picture 8, it can be observed that the whole part is the same assembly from Inventor. ANSYS supports assembly files from Autodesk Inventor and changes made in Inventor also transfer to ANSYS. The assembly contains brake pads, pistons, piston cap and a fixture mimicking upright to hold the caliper in place.

For the setup there has been applied fixed support under the upright mockup shown in picture 9. This allows the brake caliper to move naturally. Displacement of 0 has been applied to both faces of the brake pads to mimic compression to the brake disc. There has been applied a 15 MPa pressure on the inside of the caliper to mimic fluid pressure pressing on the brake pistons shown in picture 10.

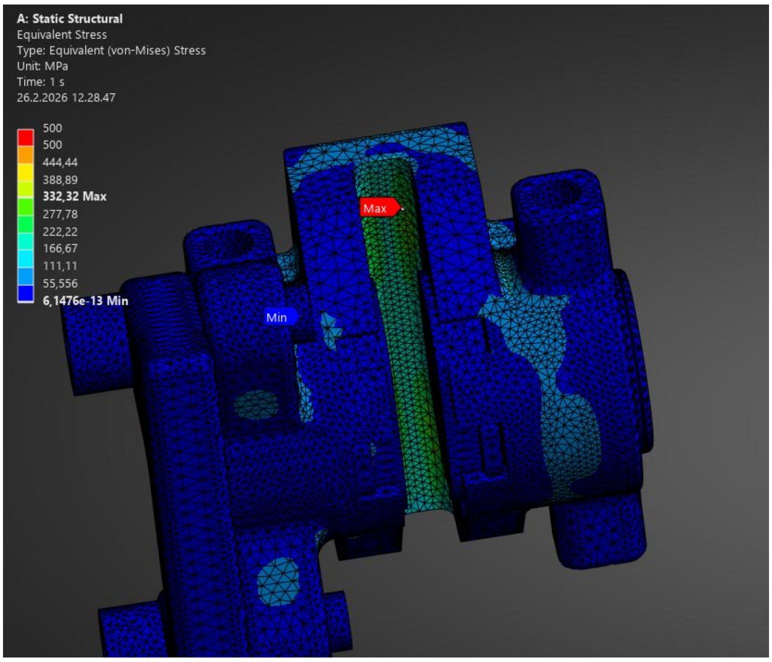


Picture 9. Fixed support. Force of braking (Atte Jaakkola. 26.2.2026.)

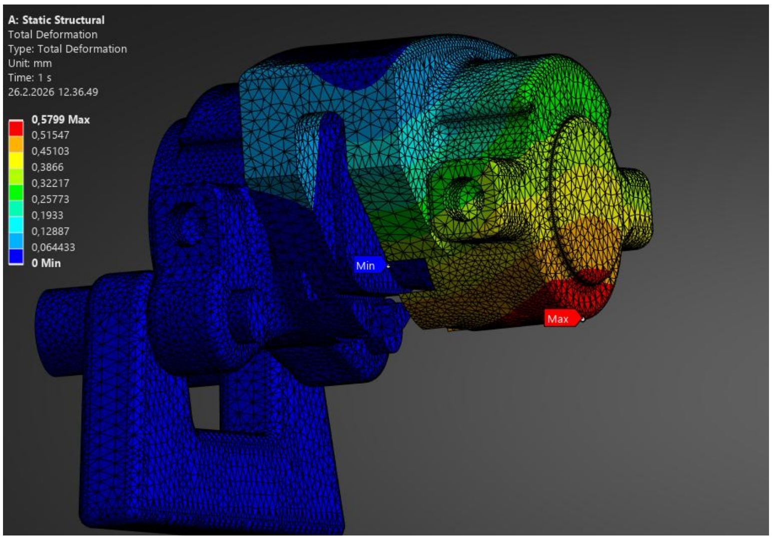


Picture 10. Internal pressure (Atte Jaakkola. 26.2.2026.)

After all the constraints and variables have been set. All the necessary information from can be gathered from different results. ANSYS has a wide selection of results but in this context all that really is needed is stress analysis and deformation that are shown in pictures 11 and 12.



Picture 11. Stress Analysis (Atte Jaakkola. 26.2.2026.)



Picture 12. Total Deformation (Atte Jaakkola. 26.2.2026.)

While observing results from picture 11, the maximum stress points appear underside of the caliper bridge. With the pressure applied, that has a safety factor of 2 and the maximum stress falling to around 340 MPa, the safety factor of the whole caliper is around 3, so it is safe to use.

Since the caliper will be manufactured by the team, a safety factor of 3 is good enough to withstand Formula Student application where service brakes are used for emergencies and one event, so the main deceleration comes from regen braking. In high-speed motorsport it is different and the safety factor should be higher since the vehicles are going faster, and brakes are applied more often.

4.2.3 Material

The chosen material for the calipers is 7075 aluminium, with the reasoning being the availability of it for the team. The team can get high quality aluminium from Alumeco, a global leader in aluminium wholesale and a corporate partner of the team.

7075 aluminium is a high strength aluminium blend with very good workability and good mechanical properties. It is used in places where it is important to have high performance with low weight, for example tools, heavy duty structures and hydraulic systems. The blend is composed of aluminium with 0,4% of silicon, 0,5% of Iron, 1,2-2,0% of copper, 0,3% of manganese, 2,1-2,9% of magnesium, 0,18-0,28% of chromium, 5,1-6,1% of zinc, 0,20% of titanium and 0,15% other elements.

For EN AW 7075 Alumeco claims the properties as follows: Depending on the square stock size, the tensile strength varies for T6 temper. Lowest minimum is 440 MPa and the highest minimum is 560 MPa. The lower strength comes from a thicker stock size and the heat treatment of it, where insides of a thicker stock cool down slower and thus results in a softer material.
(Alumeco.fi)

Since the part will be manufactured by the team itself, the workability of the material is crucial. The 7075 fits that well because of the great machine chip formation, meaning that when the material is machined, the chips are small and get flushed away easily with the cutting fluid rather than long strands of aluminium which might get tangled on the cutting tool causing damage.

4.2.4 Carbon footprint

In the mid-2020s, environmental impact has become an increasingly relevant topic in the world. Although Formula Student vehicles are a class where the designs try to be as innovative as possible, material selection and manufacturing process still contribute to carbon emissions. Therefore, a rough estimation from the mining of the aluminium to the finished product is suitable for this type of application.

Aluminium is found in bauxite, which is a reddish-brown sedimentary rock rich in aluminium oxide commonly found in tropical climates, with the largest producers being Guinea, Australia and China. They start with removing the materials that are not mined on top of the bauxite such as topsoil which is then stored until they have mined the bauxite. After the bauxite is mined, the leftover materials can be laid back to the mine bed to start reclaiming the land, with laying the stored topsoil on last for vegetation to start growing back.
(YouTube, 2020)

Carbon emissions for aluminium production varies a lot with where it was produced shown in figure 6. Typically, if aluminium is produced using coal as an energy source, the emissions could be as high as 20 kg CO2/kg of aluminium. In the European Union, there is a regulation done to prevent high emissions on aluminium products. Aluminium production in the EU now requires a percentage of the production to be done with renewable energy. Usage of renewable energy thus brings down the emissions to around 4-7 kg CO2/kg of aluminium. Depending on the amount of renewable energy used.
(Alumeco.fi)

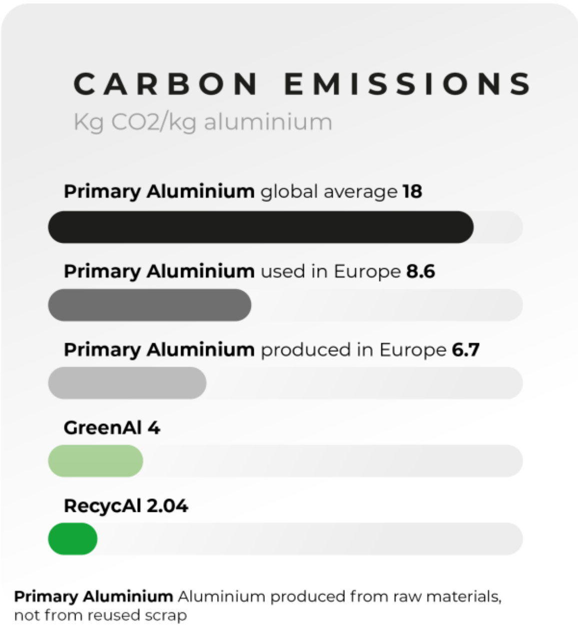


Figure 6. Alumeco.fi Aluminium production carbon emissions

Aluminium is a material that is easily recycled, without the properties being compromised. Recycling aluminium requires around 5% of the energy that is required to produce aluminium from bauxite, meaning a 95% reduction in energy. This also reduces the emissions of aluminium if it has been recycled multiple times.

With this, a rough estimation can be made of the emissions to produce the aluminium calipers. One caliper needs an aluminium billet with a rough volume of $412{,}5cm^3$ which weighs around 1,12 kg. For two calipers that is 2,25 kg rounded up. Team estimates aluminium emissions to be around 10 kg CO2/kg of aluminium. For both calipers the emissions on aluminium alone are 22,5 kg CO2/kg.

The aluminium needs to be shipped from Turku to Tampere which can be estimated with an emissions calculator from the internet. With default road freight settings, the emissions amount to 0,06 kg CO2
(cogoport.com)

Lastly are emissions for the machining. Team has estimated emissions for the machining to be around 1,2 kg CO2/h with total machining taking around 1,5 hours for both, so it would be around 1,8 kg CO2 for the machining.

So roughly the carbon emissions for the calipers would be around 24,36 kg CO2. In comparison air travel can be estimated to be around 90 kg CO2 per passenger per hour on a Boeing 747-400. (Carbonindependent.org)

5 DISCUSSION

The objective of this thesis was to design and structurally validate a lightweight brake caliper for a Formula Student vehicle. Every goal set was met in the design phase, but not without problems. It was rather difficult to go from no experience to designing a crucial safety component of a vehicle. It required a lot of self-studies from various places, and plenty of interviews on what should be done. Many steps of the design phase had to be figured out and scheduled to relieve stress from a project that seems overwhelming if it is viewed from a wide point of view.

Although the design is finished and ready for manufacturing, plenty of questions are still unanswered since the manufacturing of the caliper will happen after the 2026 season competitions. Therefore, the completion of the caliper will be left to a teammate who is still studying for their degree.

For the things that were left uncovered were 3D-printing of metals, which would allow to do topologically optimized calipers, therefore reducing the overall weight of the calipers. Multiple calipers that were analyzed when gathering inspiration for the design were topologically optimized so it would be a great idea for the next generation caliper for one of the future or current teammates to learn topology optimization and search for a possible partner from a metal 3D-printing company that could print titanium calipers.

Other questions left were performance of the caliper, since no physical reference can be used during the making of this thesis. How would the bridge flex feel like when the brake pedal is being pressed. Could the flex translate to a larger movement on the pedal and affect the feeling while braking. This is a crucial step that needs to be tested to not cause any dangerous situations.

Otherwise, this thesis has taught valuable lessons on teamwork, research and how to work on something that is not already there. This project could not have been finished if it were just a single person. Multiple questions had to be asked to get over the finish line and without Tampere Formula Student teammates support, it would not have been possible.

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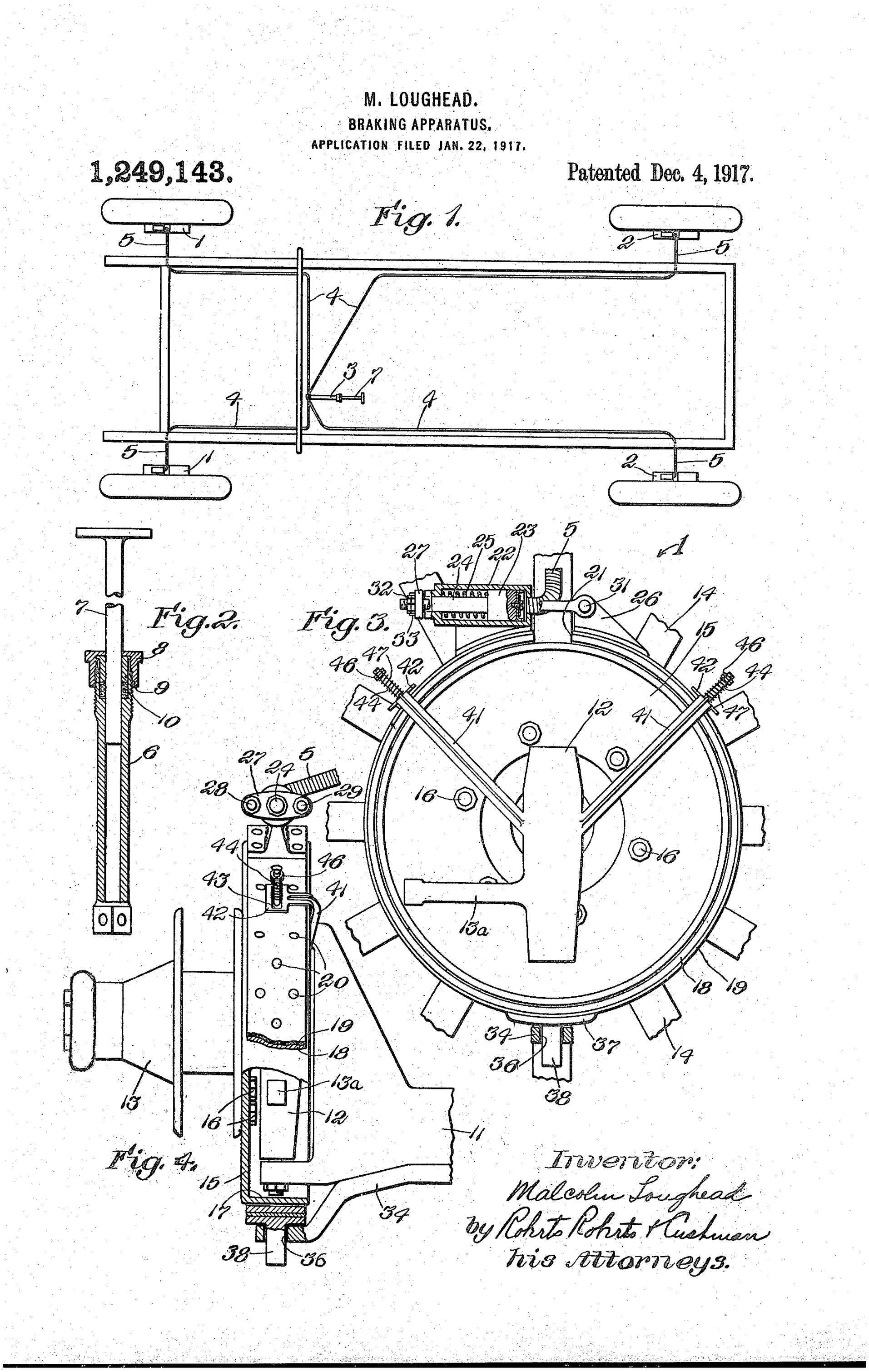
APPENDICES

Appendix 1. First patented hydraulic brake. Loughead, M (1917).



Appendix 2. Alumeco data sheet

alumeco

Datasheet:

EN AW 7075
Bars and Rods - Aluminium

Alumeco ApS
15-12-2025

Internal alloy name:	**7075**
Chemical symbol:	**AW – Al Zn5,5MgCu**
International alloy name:	**AW 7075**
UNS:	**A97075**
DIN-Werkstoff no.:	**3.4365**
Alloy type:	**Heat treatable alloy**

Main usage:

- Machining/machinery
- Forgings
- Tools
- Heavy duty structures
- Hydraulics systems

Main properties:

- Very good workability
- Good machinability
- High strength

Important norms and literature:

General Standards:
EN 573-3:2013: Aluminium and aluminium alloys – Chemical composition and form of wrought products – Part 3: Chemical composition and form of products.

Product standards:
EN 755-2:2016: Aluminium and aluminium alloys – Extruded rod/bar, tube and profiles – Part 2: Mechanical properties.

Geometric Tolerance:
EN 755-5: Aluminium and aluminium alloys – Extruded rod/bar, tube and profiles – Part 5: Rectangular bars, tolerances on dimensions and form

Chemical composition in %: EN 573-3:2013

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Remarks	Other elements Each	Other elements Together
0,40	0,50	1,2 – 2,0	0,30	2,1 – 2,9	0,18 – 0,28	5,1 – 6,1	0,20	Rest	Max. 0,25 Zr + Ti	0,05	0,15

Mechanical properties: EN 755-2:2016 (Extruded)

Temper	Dimensions mm		Tensile Stress R_m MPa	Proof Stress $R_{p0,2}$ MPa	Elongation Min %		Hardness* HBW
	Diameter (Rod)	Width across flats (Bar)			A	A_{50mm}	
O, H111	≤ 200	≤ 200	Max. 275	Max. 165	10	8	60
T6, T6510, T6511	≤ 25 25 < D ≤ 100 100 < D ≤ 150 150 < D ≤ 200	≤ 25 25 < S ≤ 100 100 < S ≤ 150 150 < S ≤ 200	Min. 540 Min. 560 Min. 550 Min. 440	Min. 480 Min. 500 Min. 440 Min. 400	7 7 5 5	5 - - -	150
T73, T73510, T73511	≤ 25 25 < D ≤ 75 75 < D ≤ 100 100 < D ≤ 150	≤ 25 25 < S ≤ 75 75 < S ≤ 100 100 < S ≤ 150	Min. 485 Min. 475 Min. 470 Min. 440	Min. 420 Min. 405 Min. 390 Min. 360	7 7 6 6	5 - - -	135

* Information values only;

Physical properties:

Density g/cm³	Solidification range °C	Electrical conductivity %IACS	Thermal conductivity W/m K	Thermal expansion (µm m^{-1} K^{-1})	Annealing temperature °C	E - modulus (N / mm²)
2,81	475 - 635	38 - 52	130-160	23,5	-	72.000

Properties and information's (3 high/good; 2 Middle; 1 Poor/bad)

Resistance:
Corrosion index, general: 1
Marine Atm. Corr index: 1

Hot workability:
Extrusion: 2
Forging: 2

Cold formability:
Cold formability general: 1
Deep drawing: 1
Bending: 2

Weldability:
TIG welding: 1
MIG welding: 1

Solderability: 1

Machinability:
Machinability index: 3

Anodizing:
Decorative anodizing surface treatment: 1
Protective anodizing index: 2
Hard anodizing: 2
Color anodizing: 1