# Design of a Compact Rear Brake Calliper for the QUT QEV3 FSAE Electric Race Car

*Systems Design and Analysis*

Group M5

EGH420 – Mechanical Systems Design

Submitted: 19th September 2021

Faculty of Mechanical, Medical and Process Engineering

Queensland University of technology

Australia

| | |
|---|---|
| Fletcher Johnson | N9896791 |
| Jacob Garcia-Pavy | N10012478 |
| Todd Dalgliesh | N6004075 |
| William Whigham | N10232869 |

# Contents

## Table of Figures

# 1 Introduction

In the design of a new compact, custom rear brake calliper for the QUT Motorsport QEV3 FSAE car, concept designs were developed before selection of a preferred option was made. The proceeding report details the development of a brake calliper design based on the previously submitted scoping and literature review document and includes all relevant details to support the design development and selection. Following selection of a concept design, an analysis proposal was developed, and systems level design was undertaken with supporting explanations included in the following sections. The aim of this report was to document the systems-level design development of the brake calliper.

## 1.1 Design Development – Sizing Methodology

The brake calliper fundamentally operates on the principle of linear force generated by a fluid pressure explained by equation 1; where $F_N$ is normal force exerted on the pads, $P_f$ is brake fluid pressure and $A_{piston}$ is the total hydraulic cross-sectional area of the pistons. The linear (normal) force resultant then generates a torque based on the principle of sliding (kinetic) friction between the brake pads and rotor. To ensure a design delivers the required braking (clamping) force, the piston size and number of pistons was determined for the QEV3 car by considering the application's specific parameters. A methodology for brake calliper design by Seward [1] was used to calculate the required system pressure based on established vehicle parameters. A snapshot of the spreadsheet implementing this methodology is shown in Appendix A.

$$F_N = \frac{P_f}{A_{piston}} \tag{1}$$

The following parameters were deduced and were applied in Appendix A:

- The car weighs 235 kg without the driver. An average driver weight of 70 kg was assumed.
- The average/expected tyre-road friction coefficient was assumed at μ = 1.4 based on findings and suggestions from multiple sources regarding the Hoosier tyres used on QEV3 and typical FSAE cars [2-4].
- A conservative value for the average friction coefficient between steel brake rotor and sintered metallic brake pads was taken as μ = 0.32 based on Usama [2] and Seward [1].
- The centre of mass (COM) of the car is laterally central and at a height of 300 mm from the ground at rest. The COM is located 830.5 mm from the centreline of the front axle.
- The rolling radius of the rear tyre is 210 mm and the mean radius of the rotor (with respect to the pad contact area) is 81.25 mm.

Using the theory of mass transfer under deceleration, the maximum deceleration event (in a straight line) was assumed. The calliper was assumed to apply enough force to be capable of locking the rear wheel under peak braking requirements. This sizing methodology is implemented later in this report.

# 2 Conceptual Design

## 2.1 Design Concept 1

The proposed design comprises of a four-piston fixed caliper design. Fluid pressure generated by the brake system pushes on the pistons which apply a force to the brake pads. This caliper is unique because the spacing between the piston on each side is larger than a conventional 4 piston brake caliper. The aim of this design is optimal heat dissipation around the brake caliper; additionally, there will be holes drilled in the caliper housing to allow for excess heat to be removed efficiently by increasing the total surface area of the caliper body. These holes will also help reduce the total mass of the caliper and subsequently reduce the total un-sprung mass of the wheel assembly.

It is predicted that by having a high rate of cooling for the caliper then the braking performance will improve as brake fade due to excessive heat is a common issue on race cars, particularly in longer events. The high-cooling-rate brake caliper will be beneficial as the rear wheels on this race car do not receive much fresh flowing air to cool them down because of the space constraint. Furthermore, the electric hub motors will be generating significant heat, further increasing the importance of an effective cooling system to reject waste heat from the brakes under high loads.

Another unique design feature of this brake caliper is the integration of a small heat-sink system where there are small fins on the housing of the caliper. The purpose of this is to run the brake fluid through the caliper, where it will pass over the heat-sink fins and help cool down the brake fluid. This is important as the brake fluid can boil, causing ineffective brake actuation and soft braking feel for the driver. This design fulfills the design requirements as this caliper is a high-performance orientated design with the purpose of operating in a hot climate like Australia, whilst being able to integrate into the QUT racecar wheel assembly with an appropriately compact fit and form. Figure 1 illustrates the design features mentioned in an assembled view, while an architectural exploded diagram is shown in figure 2. The internal features are shown in a detail cut-away in figure 3. The design follows a traditional performance brake philosophy by having large vents at the top of the caliper for provision of air flow around the brake pads. This feature, in combination with the widely spaced pistons, makes for a design that will deal with heat well in endurance events.

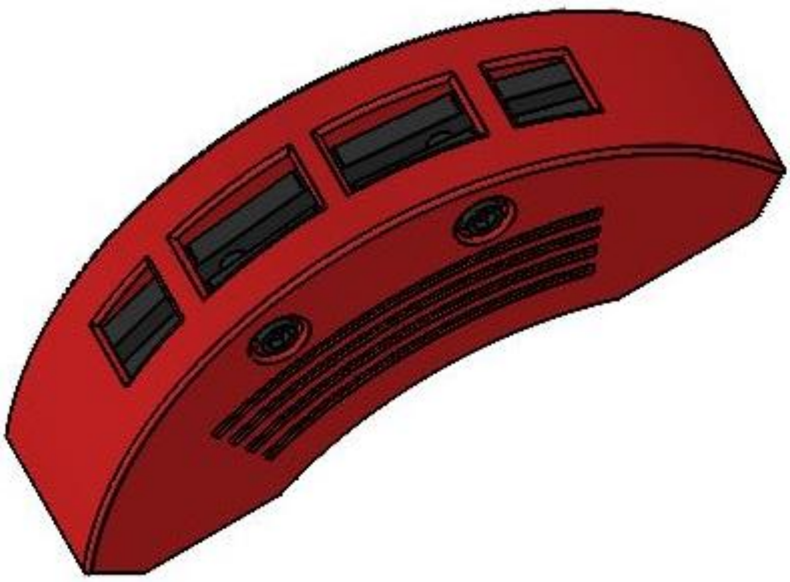
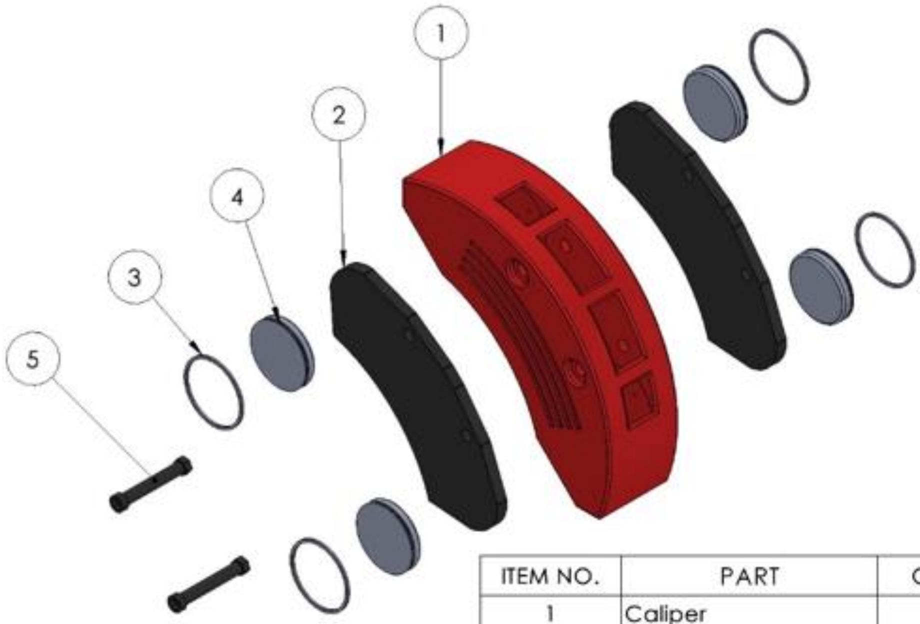


*Figure 1 - Assembly view of calliper design concept 1.*




| ITEM NO. | PART | QTY. |
|---|---|---|
| 1 | Caliper | 1 |
| 2 | Brake Pads | 2 |
| 3 | O-Ring | 4 |
| 4 | Piston | 4 |
| 5 | Bolt | 2 |

*Figure 2 - Exploded architectural view of concept 1 calliper design.*

FFBDs indicating the function of this design are shown in Appendix B. The advantages and disadvantages of this concept design were evaluated against the design criteria:

- **Advantages**
  - Large brake pads provide longer wear life and heat dissipation due to larger surface area.
  - 4 piston design provides even pressure across the brake pads and means pistons can deliver higher total thrust force for a given brake system pressure.
  - Calliper has large openings at the top and cut-outs along the side to ventilate heat and by increasing airflow and surface area; making it less susceptible to brake fade in particularly long races.
  - Compact height dimension ensures minimal material protrudes beyond the brake rotor outer diameter. This leaves more room between the wheel and hub assembly.
- **Disadvantages**
  - Large form means more material is used and the calliper is overly heavy. 2-piston designs generally use less material; however, the trade-off for performance must be considered.
  - Non-standard brake pads and pistons will increase the cost substantially, as will the single-piece design which is likely to be difficult to machine given the designed shape.
  - Internal brake line paths are concaved and may be particularly difficult to manufacture as their internal routing is not accessible.
  - Entire calliper needs to be removed from race car to change the brake pads, increasing maintenance time.
  - Hydraulic fittings and mounting interface have poor accessibility, making it difficult to install and maintain.

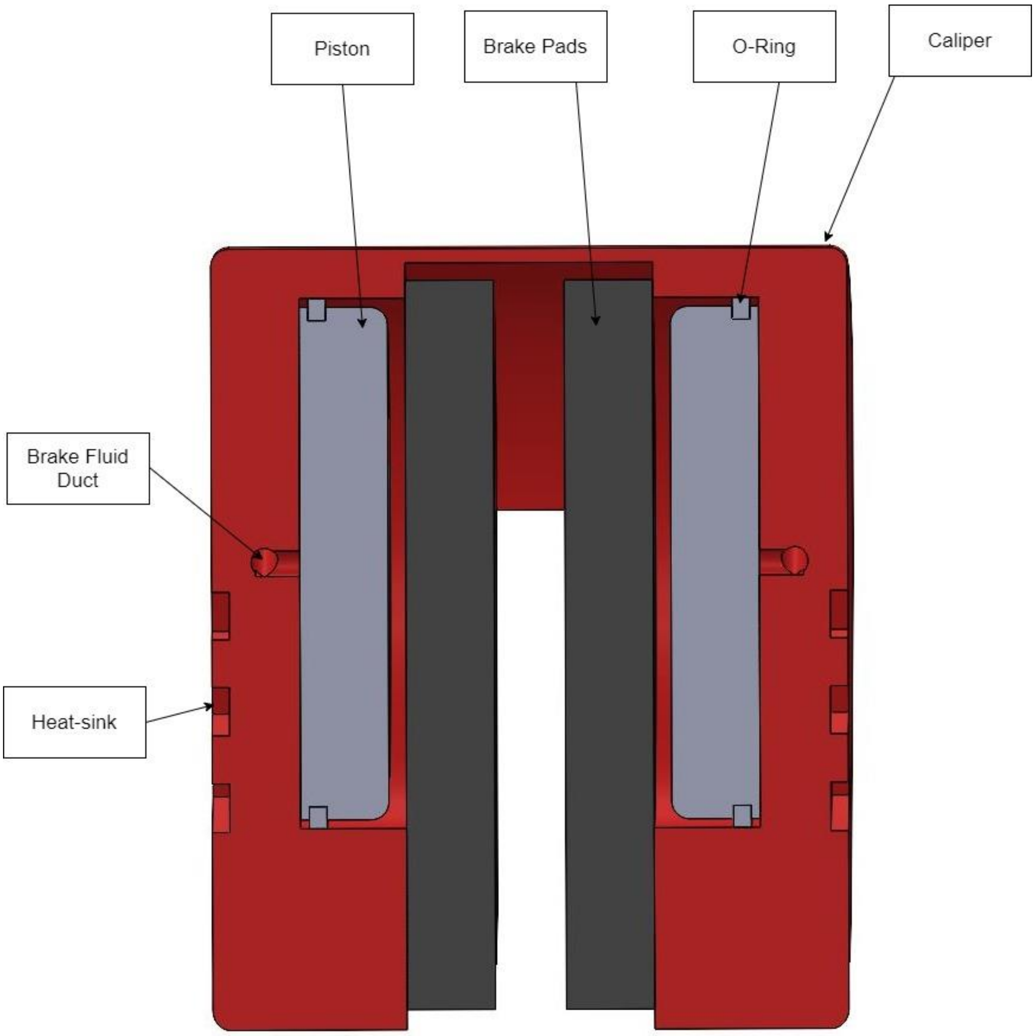



*Figure 3 - Cut-away architectural diagram of concept 1 design.*

## 2.2 Design Concept 2

**Explanation of the proposed design**

The design evolution (concept 2) of the rear calliper can be seen in Figure 4. The first iteration used a full-size calliper as a starting point; next the calliper was reduced to align with the scope of the project. This included minimizing the piston size and removing material to allow for a minimal-weight design. The third concept took the reduction of the material to the limit with a shell design for the outer brake half and removing material on the hub side as near to the piston bore as possible. The third concept allows for brake pads to be changed in place and would use off-the-shelf parts to fulfil the serviceability component of the scope. With the calliper halves and brake connection tube to be made to suit this compact design, the manufacture of custom components is kept to necessary items.

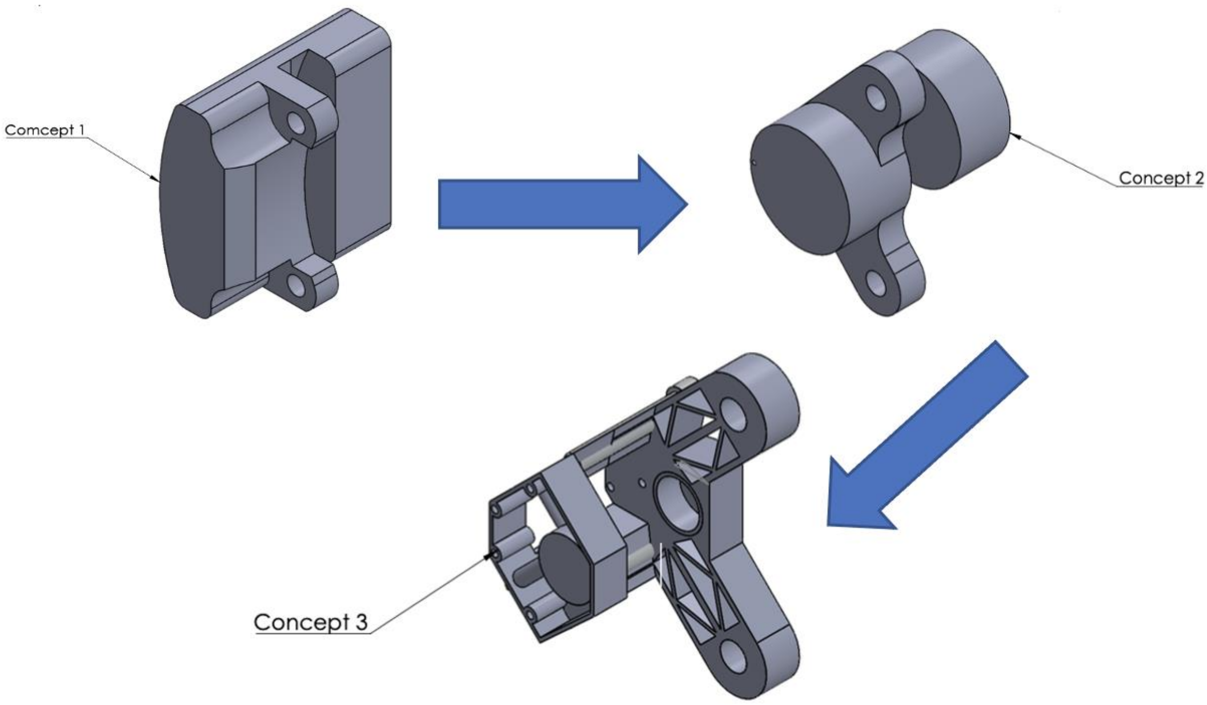
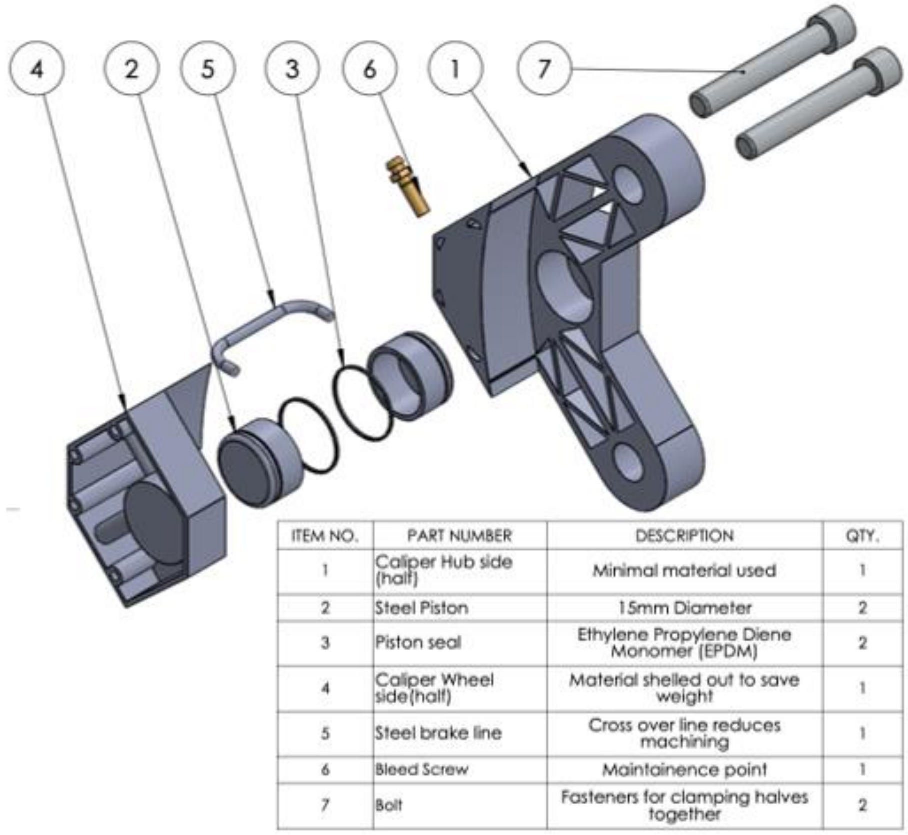



*Figure 4 - Concept design 2, iteration of initial design.*

The proposed design aims to reduce weight in as many locations across the calliper as appropriate. Using simple truss shapes to reduce material on the calliper and removing material on the outer calliper face, a minimalist form was generated. The design uses shallow style pistons with less travel and follows the 2-piston fixed calliper configuration. The design requirements are fulfilled due to the rear brake calliper having all the features of an off-the-shelf assembly whilst removing as much material as possible and remaining rigid enough to resist flexure using bracing material in key stress points. The calliper uses brake fluid to move the two pistons using hydraulic pressure and the piston size will be minimised while still providing adequate clamping force for a reasonable system pressure to fulfill the brake stopping requirements on an FSAE vehicle. Banjo style brake fittings will be used to connect to system lines and a hard cross over line will be used to eliminate the need to machine internal fluid passages. Brake pads can be removed without removal of the calliper by removing the clevis pin and retaining clip to slide them out the top for ease of maintenance. The calliper will be made from two halves held together with multiple fasteners, either M8 or M10 bolts. The components that form part of the design are shown in Figure 5. Additionally, an architectural design diagram can be seen in figure 6 which shows the inputs from the driver to the pedal box, the movement of the brake fluid, movement of brake pads and the brake rotor rotation for the rear calliper design.

Additional views of the calliper body are shown in figure 7 to further illustrate the form and design features used to shed extra weight from the calliper. Furthermore, the location of the pistons, fluid paths and fastener locations are shown for reference. A full set of FFBDs applicable to the specific design are included in Appendix C.




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Caliper Hub side (half) | Minimal material used | 1 |
| 2 | Steel Piston | 15mm Diameter | 2 |
| 3 | Piston seal | Ethylene Propylene Diene Monomer (EPDM) | 2 |
| 4 | Caliper Wheel side(half) | Material shelled out to save weight | 1 |
| 5 | Steel brake line | Cross over line reduces machining | 1 |
| 6 | Bleed Screw | Maintainence point | 1 |
| 7 | Bolt | Fasteners for clamping halves together | 2 |

*Figure 5 - Exploded view of concept design 2 showing all the components with functional description.*

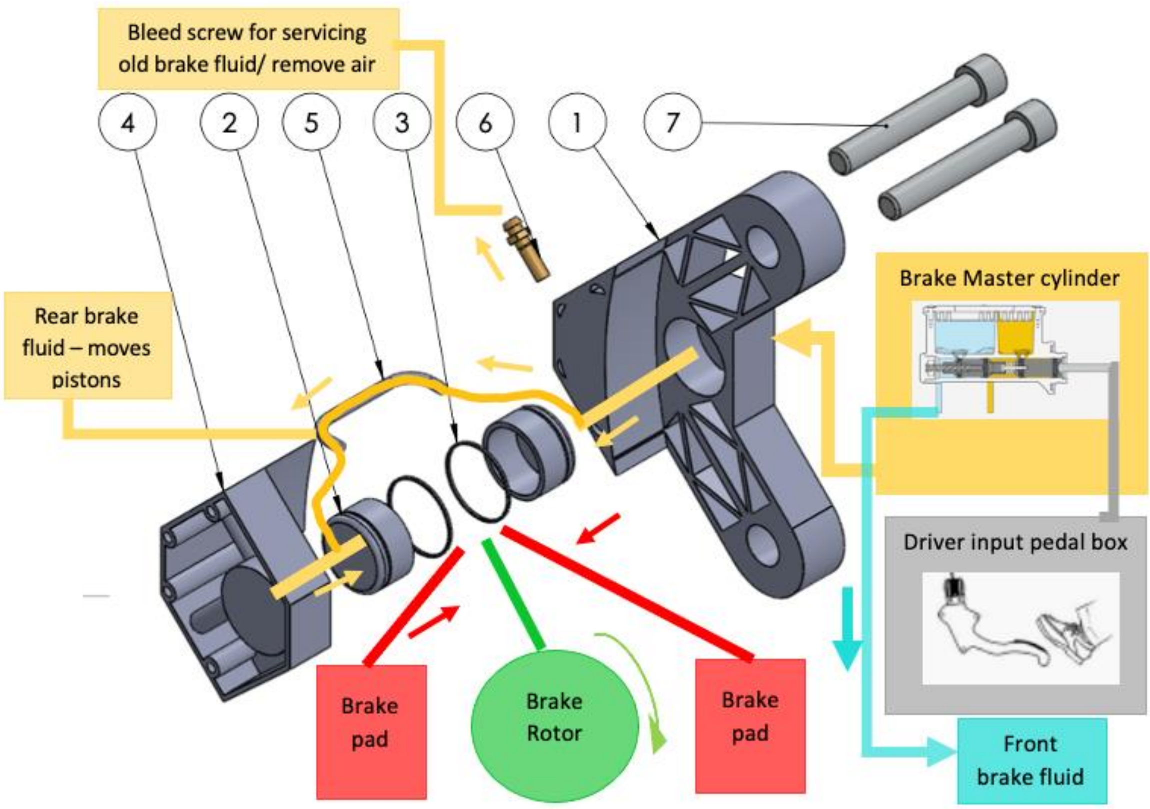



*Figure 6 - Architectural diagram for concept design 2.*

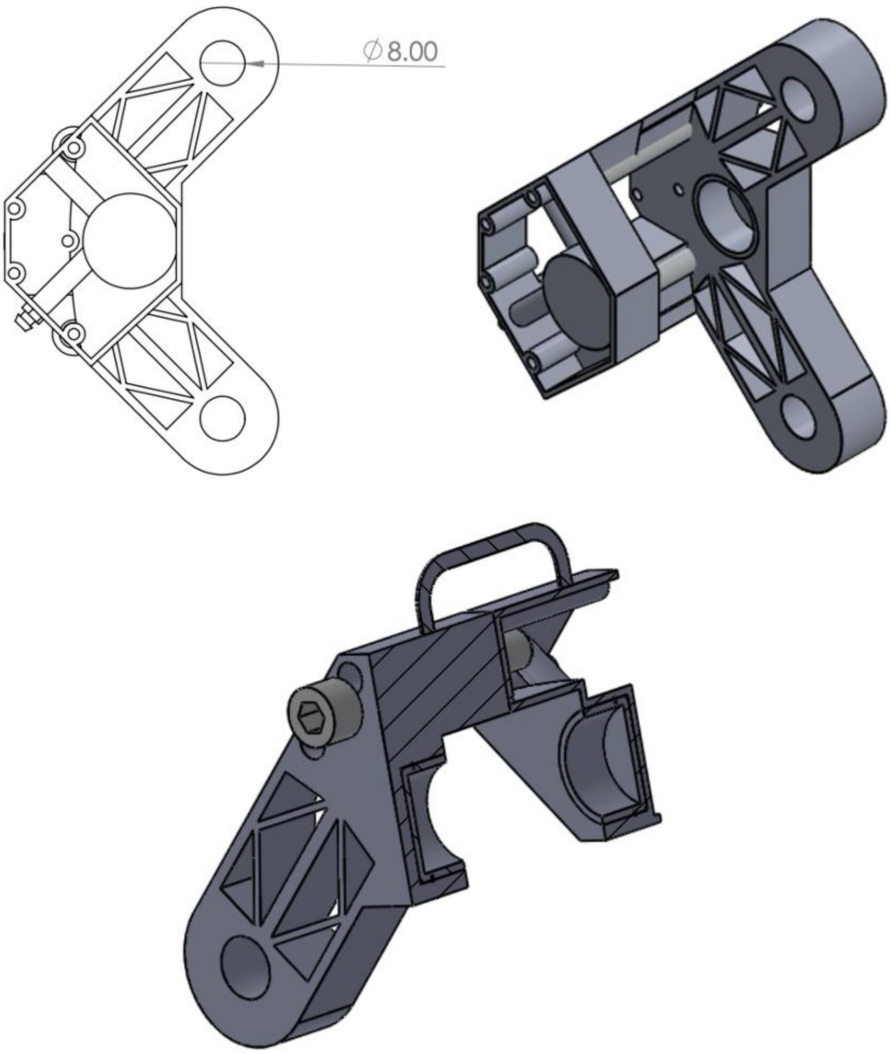



*Figure 7 - Additional design views illustrating form and internal details of concept 2.*

**Strengths:**

- Minimal use of material in less critical areas should make a design that is exceptionally light weight.
- Uses smallest brake pads available as rear braking capacity is low on EV vehicle. This reduces the need for large size calliper and improves compact form factor.
- Design uses cross-over fluid duct to reduce internal machined features, lowering cost and complexity. Also improves serviceability.
- Can use existing off-the-shelf brake components such as pistons, pads and bolts to reduce production cost and maintenance costs.
- Design can be scaled up or down regarding the piston bore size (to be done in analysis)

**Weakness:**

- Would require a long production time due to complex geometrical features. This drives the cost up. Requires expensive facilities to machine.
- Increased cost (labour) for assembly and maintenance of complex parts.

- Increased number of failure points if not manufactured precisely, due to potential for stress concentrations. Likely low FOS.
- If pads were required to be cut down to use would not be able to replace at track if a failure occurred and additional pads were not available. Lack of compatibility with off-the-shelf pads reduces overall effectiveness.
- Extensive FEA would need to be undertaken over each section at higher computational cost because of complex geometry.
- Possibility that stronger materials would be required if the design would flex using generic calliper materials. This, again, drives the likely cost up.
- Lack of pad support structure may introduce unmanageable forces on upper structure of calliper body.

## 2.3 Design Concept 3

The proposed concept 3 design is a fixed, two-piece and piston calliper seen in figure 8. This preliminary design encapsulates the calliper body and the required internal components excluding the fluid interface. It was assumed that fluid passages would be designed in detailed design stages later in this project. The fluid passages may be internally routed through machined ducts, taking fluid from the brake line and transferring pressure to the back side of the pistons. The assembly is broken down in an exploded view in figure 9 which shows the interface and relative position of each component. The calliper has been designed around the specified parameters required by QUTM's vehicle. The calliper consists of two asymmetrical pieces connected via two 8mm bolts. Additionally, a guiding pin is used to correctly position the brake pads which does not add structural strength but acts as a retention mechanism. The calliper mounts directly onto the QEV3 upright via the two 8mm hex bolts located at the bottom of the calliper body. Overall, the concept has been designed to be compact and symmetrical such that it can be effectively used on either side of the car.

*Figure 8 - 3D view of concept 3 calliper body.*

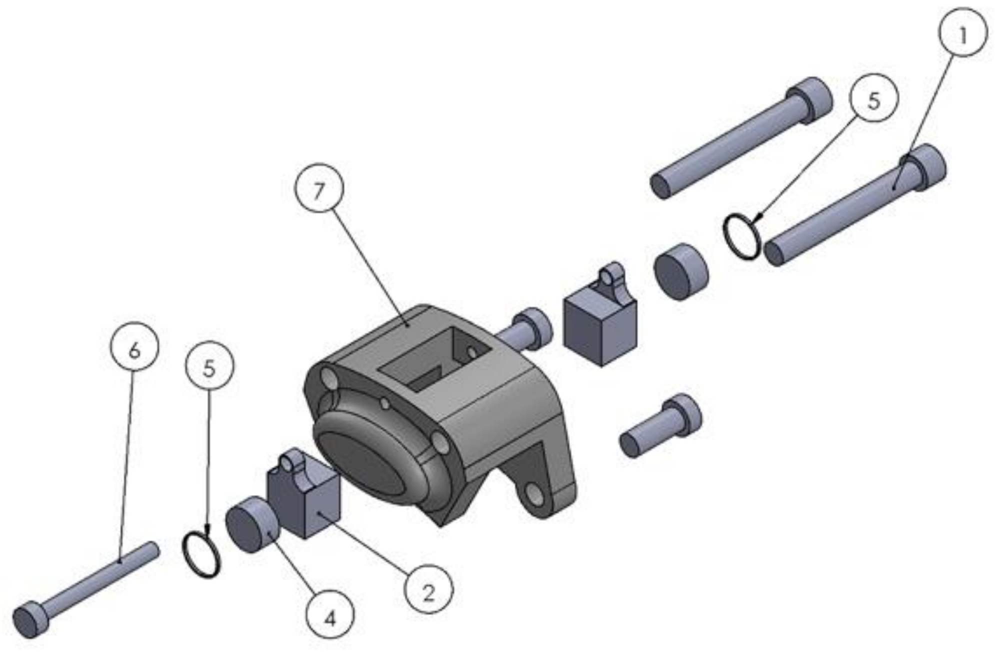
While offering several distinct features which aids the calliper's performance. The calliper has been designed to save weight around the piston bore, reducing the vehicle's gross and unsprung mass to improve acceleration. The piston housing located at the rear of the calliper has been filleted and rounded to reduce weight while providing sufficient strength without stress concentration. The edges of the design have been tapered off to further reduce unnecessary material. The two-piece design allows ease of machining of the piston bores and intricate internal geometries. The large top vent increases heat dissipation and cooling by promoting greater air flow towards the brake pads and rotor. Overall, the design aims at fulfilling the performance requirements and contains significant strengths and weaknesses which are listed below. The relating FFBD's regarding design concept 3 are illustrated in Appendix D.

**Strengths**

- Reduced calliper weight from excess material removal improves performance due to less unsprung mass.
- Simple two-piece design reduces manufacturing and servicing complexities associated with single-piece callipers.
- Can be manufactured via CNC or similar subtractive manufacturing methods such that QUTMS can have them manufactured in-house.
- Compact form factor and simple geometry should make fitment easy.

**Weaknesses**

- Reduced stiffness likely due to two-piece design introducing flexure load on bolts.
- Shape of the calliper and piston housing wastes material and may add unnecessary mass.
- Small brake pads and pistons may not be suitable for stopping requirements. Need to consider much greater detail in analysis.
- Pads cannot be removed with calliper attached to car.




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Calliper Bolt | 8mm Hex bolt connects the two pieces | 2 |
| 2 | Brake pad | Off the shelf brake pad | 2 |
| 3 | Mounting Bolt | 8mm Hex bolt mounted to QUTM rotor | 2 |
| 4 | Piston | Brake calliper Piston | 2 |
| 5 | Gasket | Brake calliper piston gasket | 2 |
| 6 | Guiding Pin | Brake pad guiding pin that fits with off the shelf brake pads | 1 |
| 7 | Two piece Calliper | Two piece calliper | 1 |

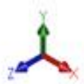


*Figure 9 - Exploded architecture of concept 3 calliper design.*

## 2.4 Design Concept 4

This concept design takes a traditional approach to the brake calliper form with a compact opposed two-piston configuration. The concept emphasises compact form and heat management foremost with several weight-saving design choices incorporated. SolidWorks was used to create a rough 3D model of the calliper assembly which is depicted in Figure 10. Notable unique and innovative aspects of the design are:

- 2-piece calliper body held together by threaded bolts allows for ease of manufacture due to the piston bores being openly accessible to tooling (considering machining). This also improves serviceability.
- Finned proprietary brake pad design (although not off-the-shelf) aimed at improving heat dissipation by increasing surface area and wasting heat before it travels into the piston. This potentially improves performance in extreme braking scenarios where heat generation cannot be dissipated fast enough and results in brake fade.
- Compact calliper body has only necessary structural material above the rotor diameter. Curved, concave top side allows for pad fins and retaining pin support to show minimal protrusion above the rotor diameter. This furthers the compact nature of this concept and may allow more options in terms of wheel size. Should QUTMS desire a smaller rim diameter in the future, clearance is available for them to do so.
- Pistons make use of low pad-piston contact area to minimise conduction between pad and piston and (ultimately) brake fluid.
- Single pad retaining pin is threaded in but also has recess for a clip. Clip provides backup retention should the pin become loose so pads cannot become detached unless intentionally removed.
- Open-top design of calliper allows pads to be removed and replaced without removal of the calliper or rotor from the upright/hub assembly. In a race scenario, this may save time in replacing brake pads. Additionally, this feature facilitates greater airflow through the pad/rotor interface.
- Drilled fluid channels within calliper body are capped with grub screws to facilitate serviceability and ease of manufacture.
- Bleed ports may be used where grub screws are located to bleed from different angles. This could allow otherwise trapped air bubbles to escape.

The use of two 20 mm diameter pistons was found to be sufficient for the clamping force requirements based on the methodology described in section 1.1. The resulting peak fluid pressure was calculated to be approximately 530 PSI which QUT Motorsport representative indicated was well below the maximum allowable pressure in the system.

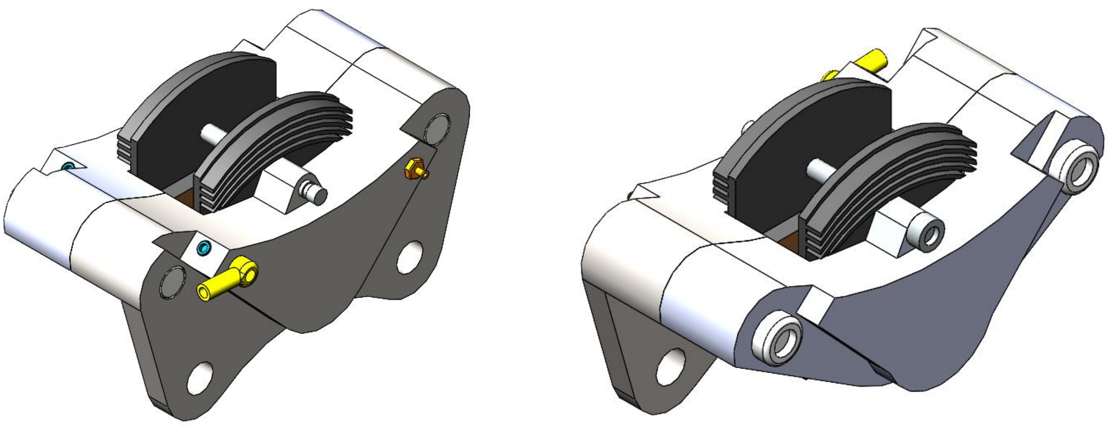
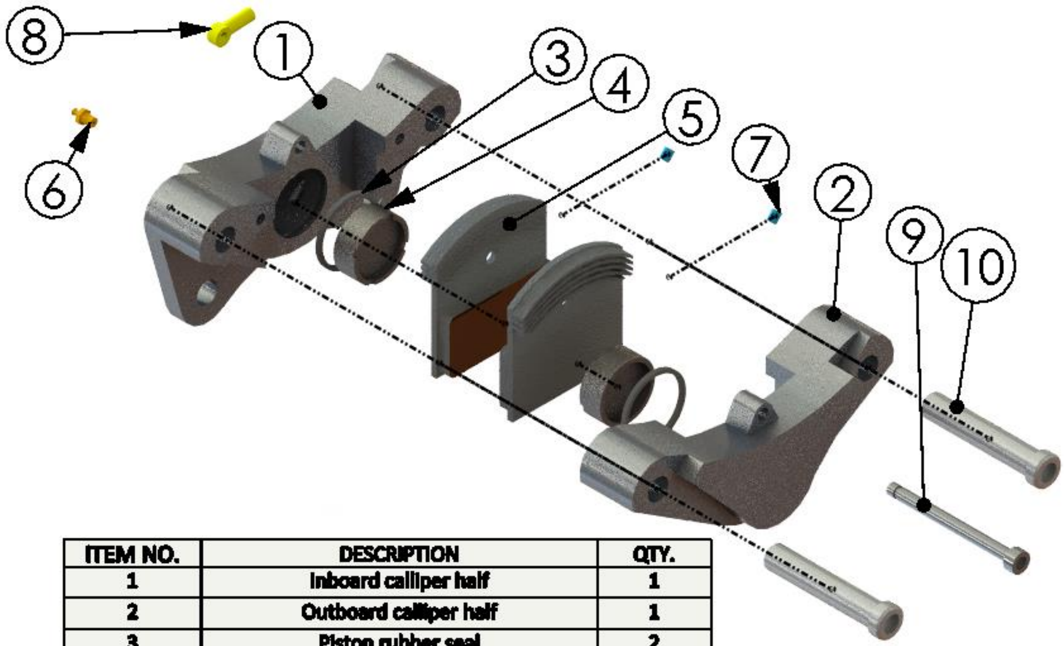


*Figure 10 - Concept 4 assembly view.*

The architectural views in Figures 11 and 13 illustrate the components included in the design and their interface with the overall assembly. Figure 12 illustrates key detail views of the fluid passages within the calliper assembly as this is an important consideration for functionality. The provision of fluid channels between the calliper halves means external routing is not required. This does pose the challenge of possible leakages between the halves. However, a rigid gasket material could act as a suitable sealing medium. A possible fault with the design can be deduced from Figure 12 (left) whereby the fluid passage may become completely blocked by the piston if it is pushed all the way back during maintenance. To remedy this, a stop could be included in the piston bore to limit the piston travel.




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Inboard calliper half | 1 |
| 2 | Outboard calliper half | 1 |
| 3 | Piston rubber seal | 2 |
| 4 | Piston | 2 |
| 5 | Brake pad | 2 |
| 6 | Bleed port/nipple | 1 |
| 7 | Fluid channel grub screw | 2 |
| 8 | Line-in fitting (banjo) | 1 |
| 9 | Brake pad retaining pin | 1 |
| 10 | Calliper body bolt | 2 |

*Figure 11 - Concept 4, exploded view architectural diagram with all components labelled.*

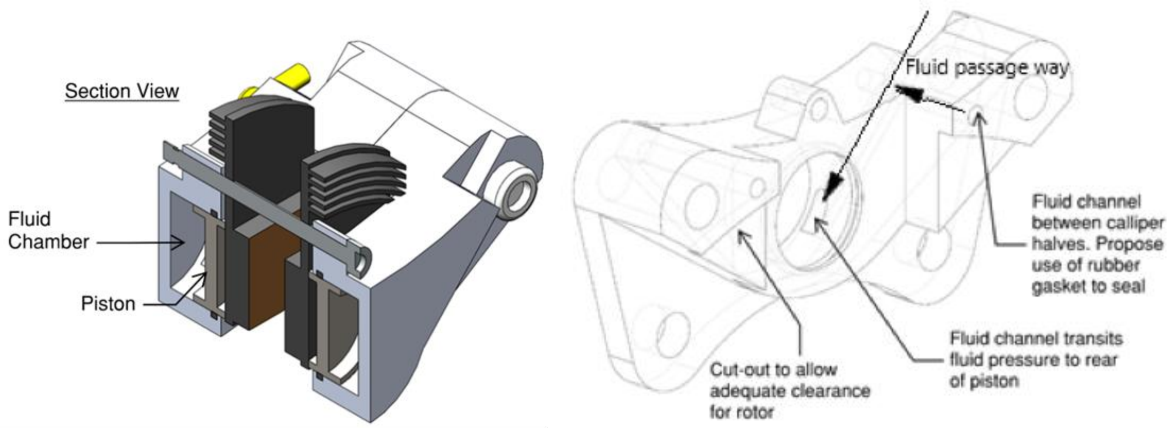



*Figure 12 - Detail views of concept 4 illustrating assembled features (left) and internal fluid channels (right).*

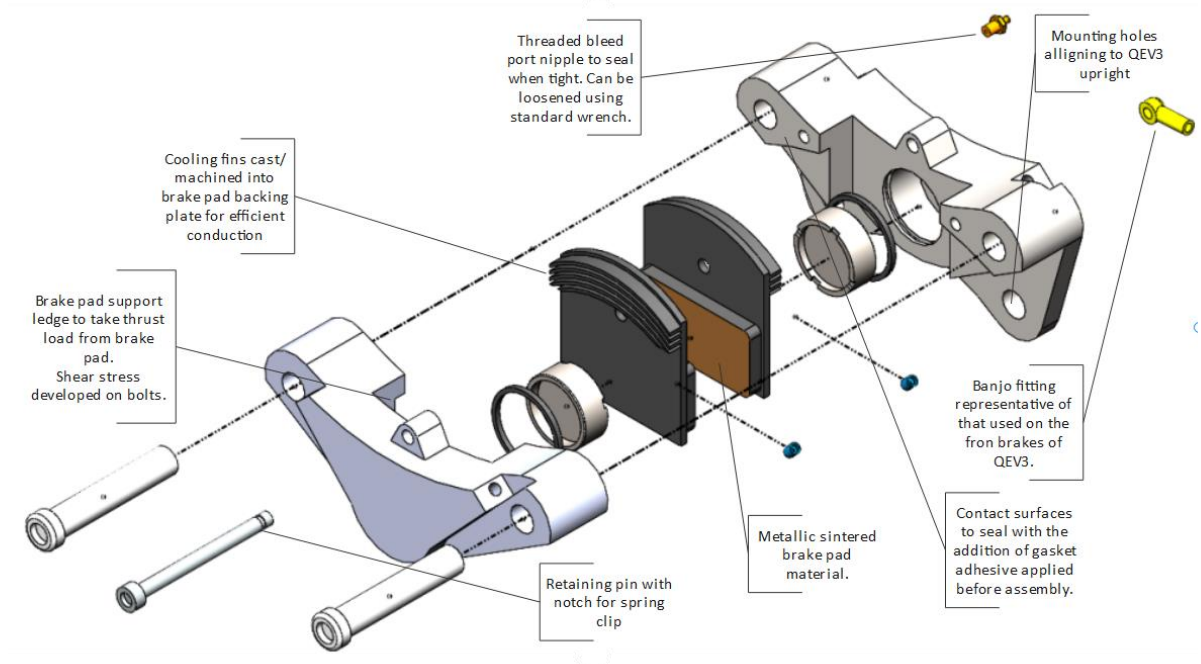



*Figure 13 - Annotated exploded Architectural view of calliper assembly concept.*

**Strengths of concept 4:**

- Comparatively compact design using simple shapes and two opposing pistons. This allows less material to be used and added clearance between calliper and wheel rim.
- Added cooling capacity from brake pad fins.
- Redundancy built into pad retention from safety clip on retention pin.
- 2-piece design improves manufacturability and serviceability.
- Limited heat transfer from brake pads to brake fluid due to minimal (and lightweight) piston design.
- Minimal use of fasteners to assemble.
- Brake pads supported by calliper body rather than retention pin likely to improve reliability and fatigue strength compared to designs where pad retention pins support brake pads.

**Weaknesses of concept 4:**

- Use of proprietary brake pads is not strictly in-line with initial scope, making it likely more costly to produce and less practical for maintenance purposes.
- 2-piece designs have been known to result in increased deflection under high clamping loads. Compared to many off-the-shelf callipers, this design uses a much smaller volume calliper body (overall) which may be an indication of under-design in terms of rigidity and overall failure strength.
- Lack of stopper included in design may allow pistons to travel too far into piston bore causing loss of fluid transmission and possible failure.
- Figure 12 (left) shows thin material at the back of piston bore. It was speculated that possibly material allocation to this high-pressure environment was too lean.

A comprehensive set of functional flow block diagrams (FFBDs) can be found under Appendix E. These cover operation of the brake, fluid bleed, pad replacement due to wear and overhaul of the calliper assembly. Each operation was considered fundamental to the design. The scope of the FFBDs extends beyond the brake calliper assembly as a sub-system because the whole brake system directly effects/is affected by the calliper.

## 2.5 Design Selection

A decision matrix was formulated to critically compare and evaluate the four concept designs against the relevant criteria for the overall application. Table 1 details this comparison. From this process, concept design 4 was chosen as the most appropriate option as it had the highest score. Various design aspects were also taken from the other three concepts to improve the design.

The criteria in the table were weighted based on their perceived importance for the scope of this design. Compact form, weight, function and integration featured as the highest weighted categories dur to the importance of these to make this design different from an off-the-shelf calliper. Cost, complexity, maintainability and structure featured as slightly less weighted as these were deemed more detailed design factors that can be worked around the basic concept with smaller changes. Part count and heat management were weighted the lowest as all designs featured similar part number and thermal considerations and heat management was not cited as a prominent issue for QUTMS currently.

*Table 1 – Weighted decision matrix for conceptual designs*

| | | | Alternatives | | | |
|---|---|---|---|---|---|---|
| | | Wt. | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
| Criteria | Compact Form & Weight | 1.00 | 3 | 4 | 4 | 5 |
| | Cost to produce | 0.70 | 3 | 2 | 3 | 2 |
| | Heat Management | 0.50 | 4 | 3 | 2 | 4 |
| | Structure | 0.80 | 5 | 3 | 4 | 3 |
| | Complexity | 0.70 | 4 | 3 | 4 | 4 |
| | No. of Parts | 0.50 | 5 | 4 | 5 | 4 |
| | Functionality | 1.00 | 4 | 5 | 3 | 5 |
| | Maintainability | 0.80 | 3 | 5 | 4 | 5 |
| | Integration | 0.90 | 5 | 4 | 4 | 5 |
| | **Total** | 1.00 | 36 | 33 | 33 | 37 |
| | **Weighted Total** | | 27.8 | 26.4 | 25.8 | 29.3 |
| * Each item ranked on scale of 1-5, with 5 being the highest score. | | | | | | |

The features that will be incorporated into the final design will be the heat sinks from design 1 which aims to lower the operating temperature of the calliper to improve braking performance and brake fade resistance. The weight reduction aspect from design 2 aims to reduce the unsprung mass of the vehicle thus improving vehicle handling. To save weight in a similar fashion, material will be removed where possible from the chosen design. The Fillet edges along the calliper body from design 3 to reduce the stress concentrations that are present in the system to increase the strength versus weight of the calliper. Additionally, the team opted for an off-the-shelf brake pad instead of the proprietary finned pad as it was decided that the cost/benefit was in favour of the stock pad for this case. The cost and lack of availability of a proprietary pad was deemed not worth the extra cooling that could be provided by the finned design. The pad chosen was the AP Racing CP4226D27 used in their CP4226 calliper; one commonly used by FSAE teams with similar dimensions to the original pad used in this design [5]. The modified design is shown in Figure 14 and a supporting architectural view can be found in Appendix F.

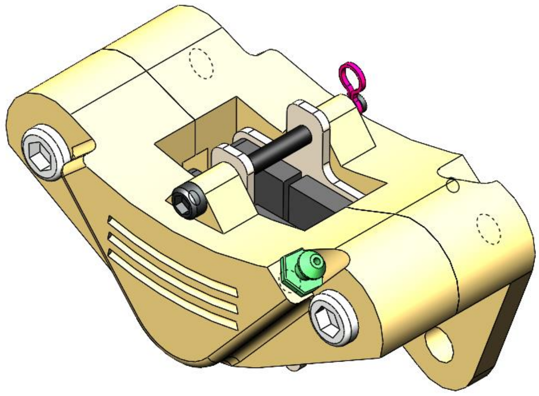


*Figure 14 - Assembly view of final concept design brake calliper.*

# 3 Analysis Proposal

The chosen design will be analysed for failure using both structural and thermal analysis techniques. The overall system was partitioned to identify an approach to analyse each item in accordance with its function and the mechanical and thermal loads associated with its expected service conditions and interactions with other components. As it is not necessarily comprised of multiple sub-systems itself, the calliper assembly was partitioned into its individual components for the purpose of this analysis.

## 3.1 System Partitioning

The brake calliper system was partitioned into key components for analysis in the proceeding sections of this report. Figure 15 indicates the individual component partitions made for the analysis of the system. The first partitioned component was the calliper body (2 halves: inboard and outboard). The calliper body houses all the other components and is completely responsible for transferring the brake torque load to the upright. Stiffness and structural integrity under peak braking loads is critical to brake calliper function.

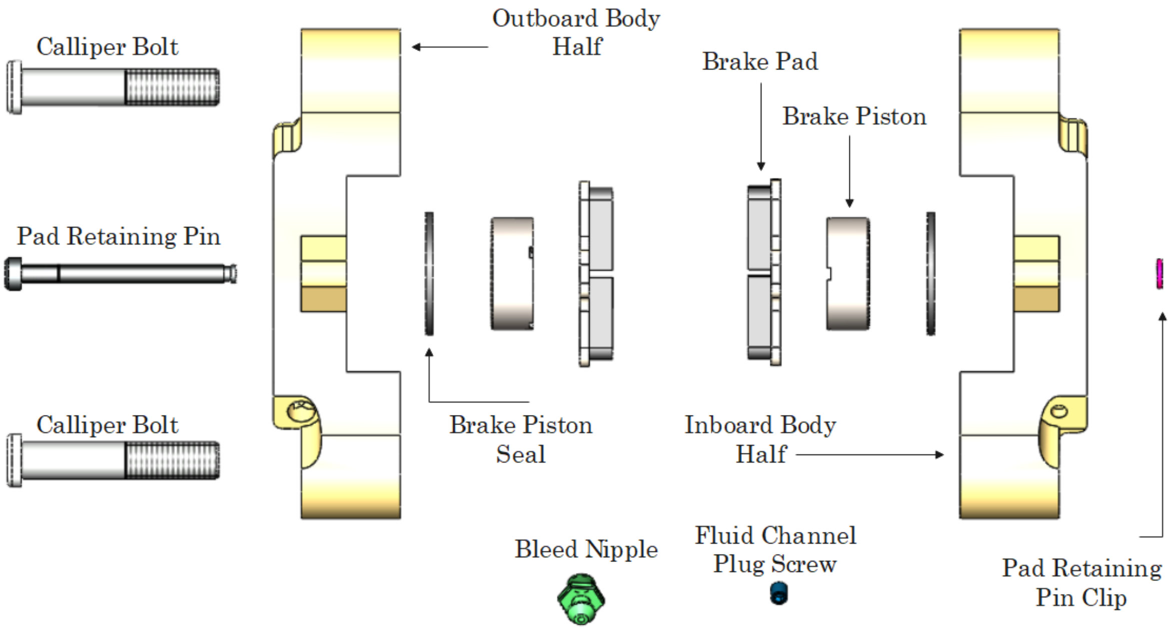



*Figure 15 - Partitioned view of the concept brake calliper design.*

The next component was the brake pads. The brake pads are an off-the-shelf item; however, they are a critical element of the force and thermal analysis. Heat flux through the brake pad and pad/rotor friction coefficient are two factors that directly influence the design of other calliper components. Proper selection and validation of the brake pads will influence overall braking performance and considerations for the interactions with other components of the calliper such as pistons and body. The brake rotor will also be analysed as an individual component despite it being outside the design scope. The existing rotor will form part of the thermal analysis of the brake, but its structural design will not be analysed in detail.

The piston and piston seal are the next two component partitions. The piston interface with the calliper body is sealed via the piston seal which sits in a grove within the piston bore. The function of these two components is to convert fluid pressure to thrust force on the brake pad without fluid loss. It must also act to limit heat transfer to the fluid and provide an independent mechanism to elastically retract the piston after brake operation. The brake pad retaining pin and retaining pin clip are to be analysed separately as well. These do not incur brake force loads but act to retain the brake pads and allow maintenance to be undertaken as needed. Finally, the two calliper body bolts and the mounting bolts will be analysed for design as they are important in carrying and transferring brake loads through both halves of the calliper and keeping the two halves in correct alignment under opposing forces.

## 3.2 Analysis Proposal

### 3.2.1 Calliper Body

The brake calliper body performs several functions; however, its primary function is supporting structural loads from braking operation. As braking operations occur in repetitive fashion, at varying amplitude and in quick succession, all indicated loads on the calliper body will be subject to fatigue. The loads on the calliper body are considered distributed loads which result from two primary sources: fluid pressure and part-to-part contact load. Only one loading scenario exists for the calliper body which is generated by braking force (varied magnitude). It is assumed that no other loading scenarios form part of the design as these would be considered misuse. Figure 16 illustrates the planar force load generated from pad-rotor friction supported by the pad cavity and the bolt holes to the upright on the car. Also shown is the in-plane fluid pressure load (purple) within the piston bore. During normal use, no appreciable load is assumed on the pad retaining pin support. The blue arrows represent friction force from the outboard calliper half acting on the entire contact face. Figures 16, 17 and 18 shows the in-plane loads on the outboard and inboard halves of the calliper.

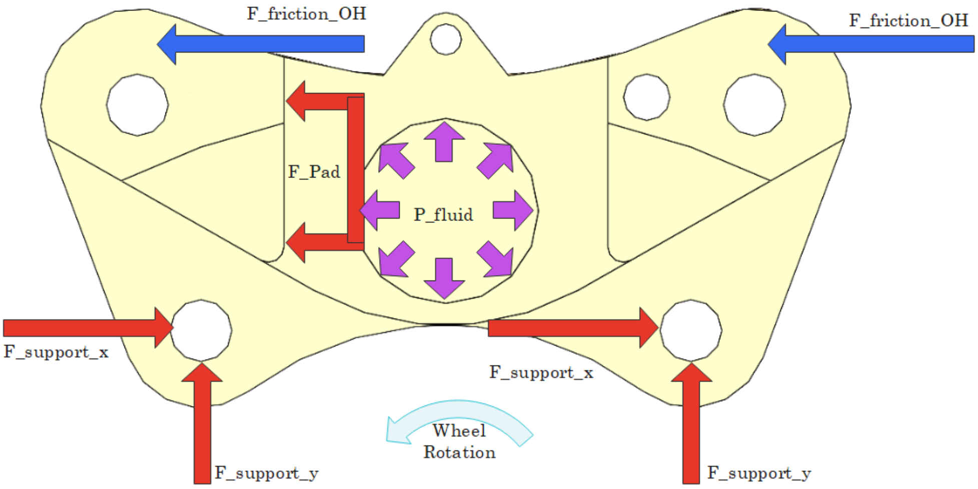



*Figure 16 - In-plane FBD of calliper body inboard half.*

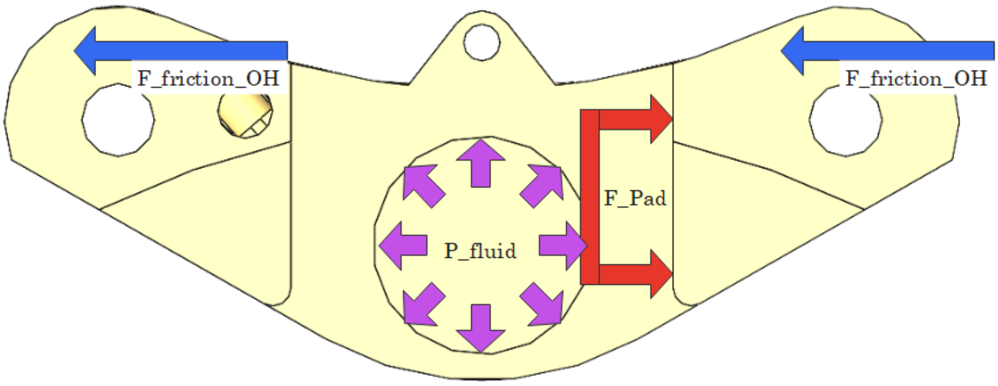



*Figure 17 - In-plane FBD of calliper body outboard half.*

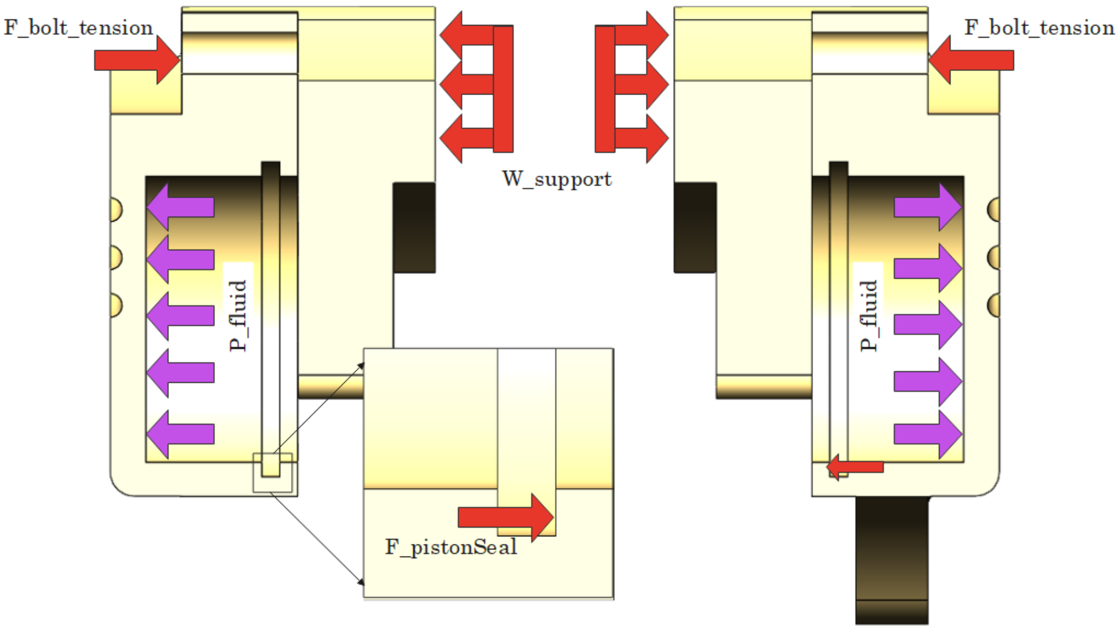



*Figure 18 - Cross-section perpendicular to rotor plane. Calliper body FBD.*

To analyse the calliper body loading, a FEA simulation will be conducted using ANSYS Static Structural with the boundary conditions given by the loads indicated in figures 16, 17 and 18. A static load analysis will first be carried out assuming the highest applied load to evaluate stress areas of interest. Secondly, a fatigue simulation will be run to evaluate resistance of the component to fatigue failure. The fatigue loads are to be applied in a zero-based loading regime as fully reversed loading is not applicable. The two halves can be mated/constrained using a friction support at the joining faces. Multiple works by other authors have cited acceptable safety factors for the static structural load analysis of 1.6-1.7 [6, 7]. A safety factor of 1.8 or greater will be considered acceptable for this design to account for additional error in the analysis.

$$Heat\ flux\ in = Heat\ flux\ out + Heat\ stored \tag{2}$$

Following FEA simulation, the calliper body will be analysed for thermal performance. Multiple authors have undertaken thermal analysis of FSAE calliper designs, most using simple thermodynamic calculations and others using ANSYS Transient Thermal simulations, with some not considering thermal conditions at all [6, 8]. Heat transferred through the pad and piston was found to heat the brake calliper body and fluid up to 150°C with successive braking events of 3 seconds in one study [9]. This definition of brake temperature design will be adopted, and the thermal performance of the component will be done using the principle of heat flux into and out of the calliper body. Equation 2 is a representation of this methodology. Material selection will be influenced by this analysis with respect to strength at operational temperatures. The thermal analysis will be verified using a simple ANSYS transient thermal simulation, time and resources permitting.

### 3.2.2 Brake Piston

The brake piston load has two components which is a pressure force via the brake fluid on the piston and a force against the brake pad. Seen in Figure 19, the purple arrows indicate the in-plane fluid pressure force acting on the piston from below the seal height. Also seen in Figure 19, the red arrows represent the force acting on the brake pad which is a distributed load across the four raised sections of the front piston face. The highest applied pressure case will be used to analyse the static load scenario of the piston with expected pressure levels to be included into the calculations to ensure the part remains serviceable for the life of the brake system. Analysis of the piston will be performed first with hand calculation using the pressure equation 3, then with ANSYS static structural to check for deformation that could be introduced via the severe operating conditions brake components are prone to during operation. Followed by a fatigue simulation which will be performed to verify the components capacity to resist fatigue for the life of operation.

$$Pressure = Force/Area \tag{3}$$

Combining all the analysis steps for this component will allow for the material selection to be performed. The boundary conditions will be the fluid pressure and the front face will be set as a support. As Limpert [8] outlines, having the proper brake balance established is a key step to allow for a thorough brake analysis, therefore in this case the assumption is that all pistons will operate in a uniform manner with no drag greater than other rear cylinder bores allowing for correct brake balance already to be in place. As mentioned in the calliper body analysis proposal, heat transferred from pad to piston to brake fluid is possible therefore a thermal analysis will be performed time permitting as much of the focus will be on the calliper body.

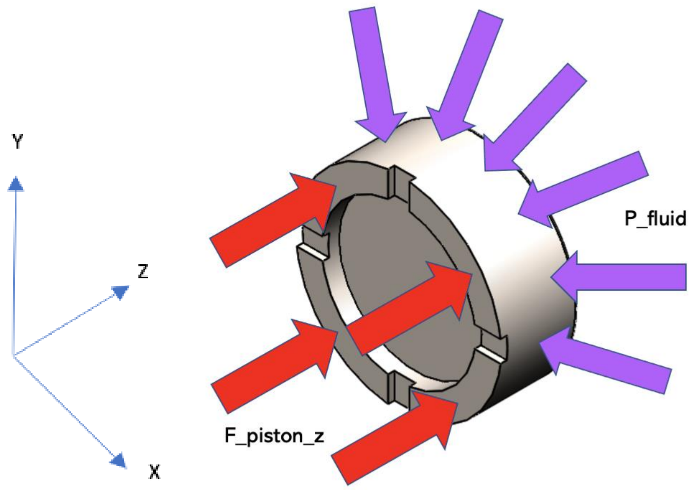



*Figure 19 - Isometric FBD of brake calliper piston*

### 3.2.3 Piston Seal

The brake seals primary function is to maintain hydraulic pressure to the piston and is vital that this component can function throughout the operating temperatures. As the seal is in constant movement within the load case it will be analysed at full compression when the brake system is under full load and highest hydraulic pressure is present. This results in force being applied to the seal and the friction the seal has while resisting the movement due to the rubber seal. The seal also has a force normal to the operating direction on the piston and the piston bore; however, as the seal will be considered to have an adequate ability to resist fluid movement, these will be in equilibrium. These forces are seen in figure 20 below with blue arrows representing the rubber friction and the red arrows representing the force due to fluid pressure which will be calculated from the fluid pressure applied to the piston from the previous section. Once the hydraulic pressure is transferred to the brake pad the seal does not take any force apart for the force from the pressure in the system.

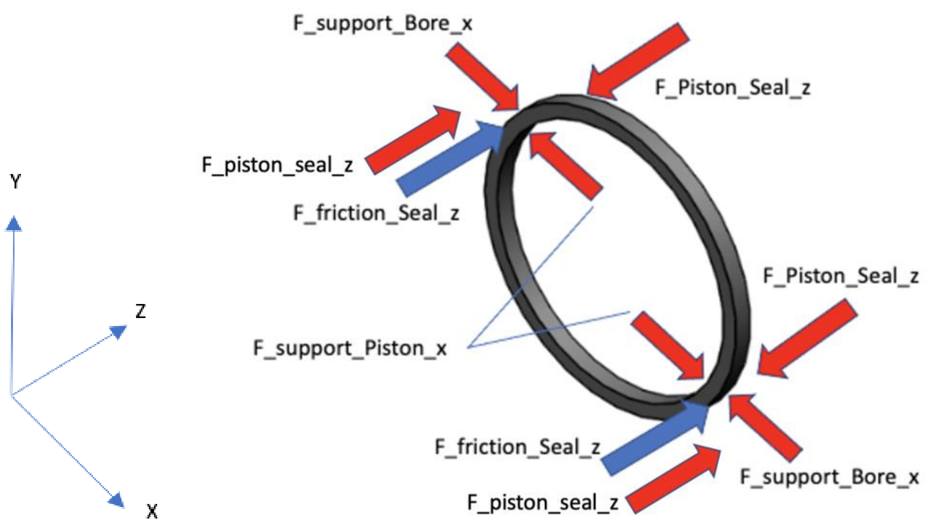



*Figure 20 - Piston seal free body diagram*

Hand calculations will be performed to determine the force the seal must resist and a FEA simulation will be performed in static structural to verify these calculations align with real operating conditions. As the seal will be an off-the-shelf item the material selected will be EPDM (Ethylene Propylene Diene Monomer) as this is widely used in automotive applications. Ouddane [10] measured the changes due to diffusion of brake fluid on EPDM from 23℃ to 150℃ therefore using the highest temperature as the condition to test in simulations will be the benchmark [10]. Brake seals also incorporate 'rollback' which assists the piston in returning to position so the pads can clear the disc when not under pressure [11]. This elastic load will be incorporated into the friction force as it will be relatively small compared to the pressure force generated via the hydraulic system. Provided the material has suitable elastic properties, it was assumed that this design criteria could be met with suitable geometrical refinement in the component level design.

### 3.2.4 Brake Pad

The brake pads will experience the highest thermal load in the system as they are the contact face used to slow down the vehicle. The brake pads to be used are an off-the-shelf item, however the selection of brake pads will influence the thermal properties and braking ability of the entire brake assembly. The thermal load occurs through friction between the brake pads and brake rotors. Computer software will be used to conduct an FEA where the thermal ability of the system can be investigated. The exact thermal load will vary depending on the characteristics of braking duration, braking severity, braking frequency, and environmental conditions. However, for the purposes of this report, the worst-case scenario will be investigated. It is predicted that most of the heat generated from braking will be passed through the brake pads and to the calliper body, and the rest will be radiated into the air. There are three major forces acting on the brake pad during a braking event; the force exerted by the pistons, the normal force exerted from the brake rotor, and the shear force generated along the face of the brake pads because of kinetic friction and hence, heat due to sliding. These forces are shown in the FBD in figure 21. All forces are distributed loads on a surface. Fatigue loading will not be considered for this off-the-shelf part, however a high factor of safety of at least 1.7 will be required so that extreme cases and prolonged service is accounted for. Material data will be sourced from the respective manufacturer's datasheets.

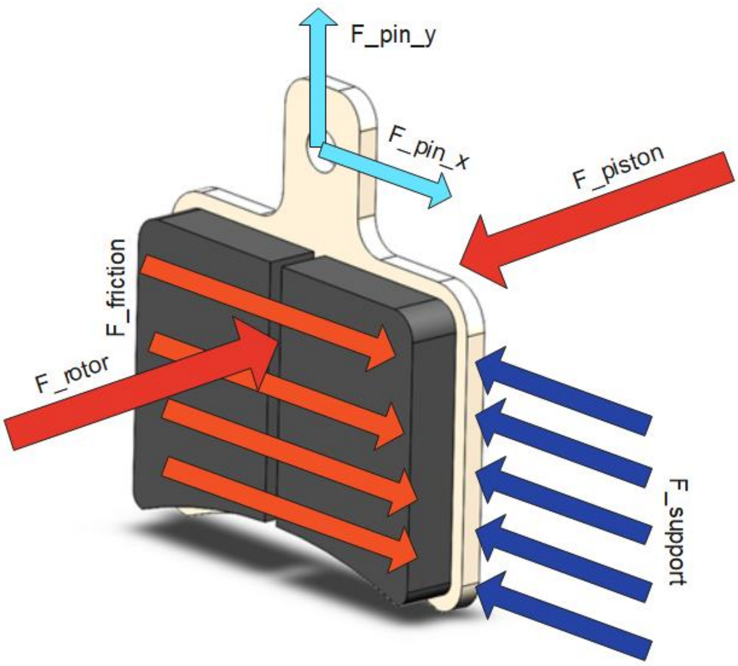



*Figure 21 - Brake pad free body diagram.*

### 3.2.5 Brake Pad Retaining Pin and Spring Clip

The brake pad retaining pin and clip were designed to allow easy accessiblity to the brake pads, and are intended to guide and retain the brake pads. They are both considered non-loaded components based on the design not transmitting any braking loads directly through them. The loading components include the weight of the brake pads (which was assumed negible), and the axial forces induced by tightening of the pin in the calliper body. This force will be determined through analysis and design related to bolt torque. Figure 22 shows the forces acting on the pin and spring clip. The retaining pin will be analysed for static load based on the small tensile force within the pin. This will be done using simple hand calculations as FEA is not needed in this simple case. The spring clip will be an off-the-shelf item and will not be analysed directly. Manufacturer specifications will be considered and its funnction will be justified based on the specified limits. One special consideration that will be made is the ability for the clip to be retained during high vibration events. This may involve hand calculations with a safety factor to reflect its function as a safety-backup.

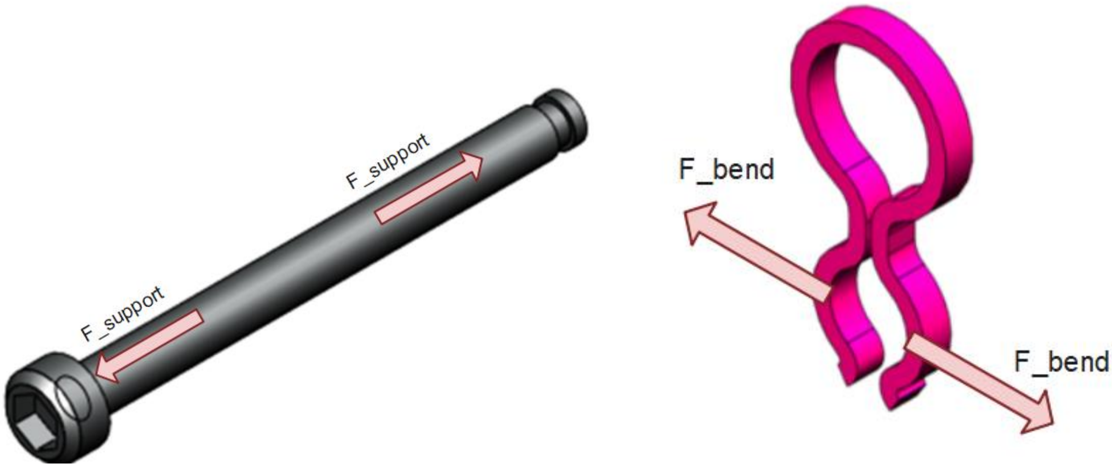



*Figure 22 - (left) FBD of brake pad retaining pin and (right) spring clip FBD.*

### 3.2.6 Calliper & Mounting Bolts

The calliper bolts connect the two piece calliper halves together and experience high tensile force and a possible moment from the two loadings. The bolts experience a sustained tensile load that acts to hold the two calliper halves together. Under braking load, the force exerted by the pistons induces additional tensile load and flexes the calliper halves outward. It was assumed that no shear load is carried by the bolts as tension produces a frictional support between the calliper halves shown in figure 16 & 17. Figure 23 shows the multiple views of the bolt and the loadings experienced. The braking force created by the piston on the calliper body is illustrated P away from the origin the calliper's pivot point. The calliper bolts will be located b away from the origin and produces an equalivent axial load required for equilibrium combined with the insignificant axial load created at p. These dimensions will be verified later during the analysis and calculations. In addition, the bolts will be initially tightened creating a clamping force on the piston bodies which forms non-zero-based loading. The FBDs in figure 23 show the action of tensile force on the bolts. Initial hand calculations will be done to verify correct sizing of the bolts and required torque and, hence, tensile force. FEA analysis will then be completed using the boundary conditions derived from Figure 23. Static worst-case load analysis will be done using ANSYS, as well as fatigue loading (non-zero-based cyclic) to ensure the bolt can be reasonably assumed to last inifinitely (based on S-N curve).

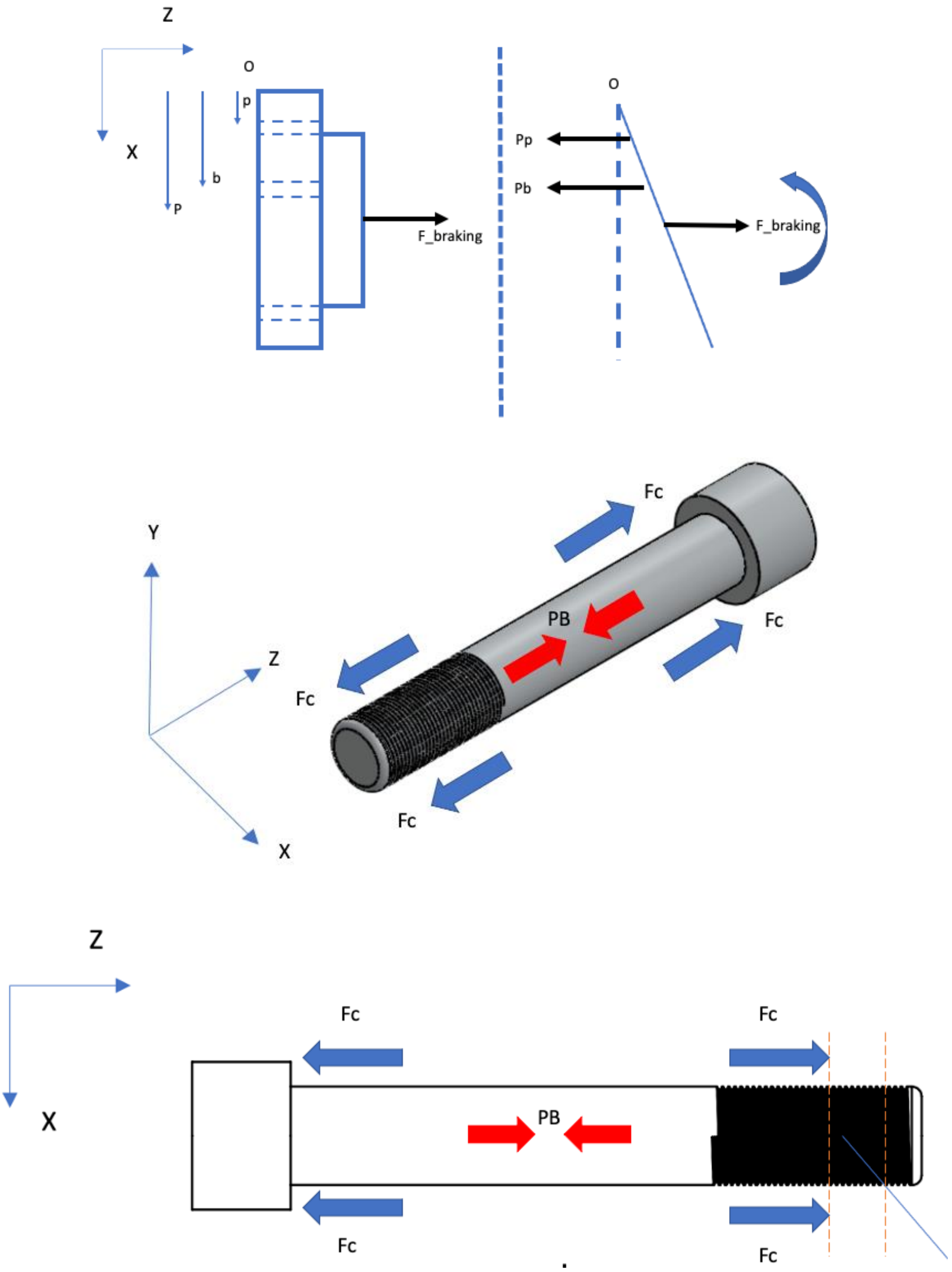



*Figure 23 - Calliper body bolts FBD views and load applications as indicated in (top) diagram.*

The mounting bolts secure the inboard calliper side to the hub allowing the brake assembly to operate and transfer load to the upright. The mounting bolts need to be put under tension to induce frictional support that resists the braking torque. Figure 24 shows the applied loads. Despite being shown on the FBD, shear force was considered to have magnitude of zero due to the frictional support and its magnitude can be ignored. First, hand calculations will be done to establish the required tensile force on the bolts (and resulting tightening torque) and the bolt size will be verified accordingly. Consideration of the length of engaged thread in the calliper body will be made here. It was assumed that the mounting bolts do not themselves experience cyclic stress and will therefore not be analysed in FEA for fatigue. Regardless, bolt selection will consider a high FOS of 1.5 to ensure any overload is accounted for.

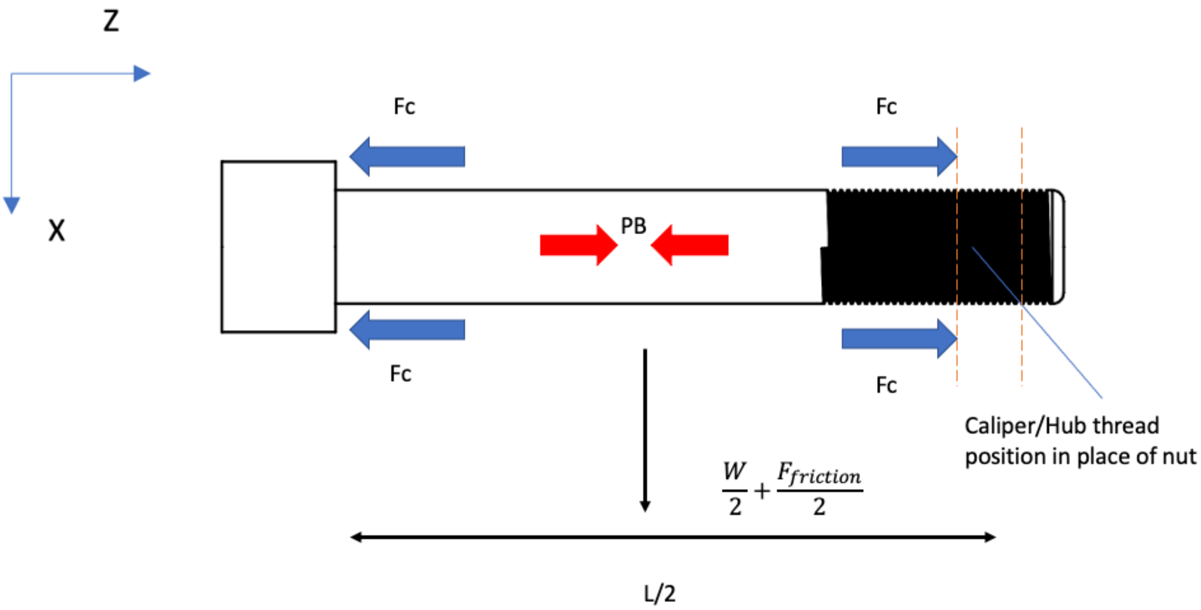



*Figure 24 - FBD of calliper-upright mounting bolt.*

### 3.2.7 Brake Rotor (Outside Design Scope)

Although the brake rotor is out of the scope of this project, it is still an import aspect of the design iteration process and must be considered. The brake rotor will only interact with the brake pads in the calliper assembly. The forces which act on a brake rotor are the axial force applied from the brake pads, and the friction force generated from the brake pads. Additionally, the brake rotor will exert a normal force on the brake pads as the rotor is fixed in position. The brake rotor temperature will increase rapidly when a braking load is applied. The heat generated is largely dissipated through radiation into the surrounding atmosphere. The thermal properties of the rotor will be analysed using thermodynamic principles, with supporting FEA analysis using ANSYS, to incorporate its effect on thermal loads of the calliper. The forces acting on the brake rotor can be seen in Figure 25:

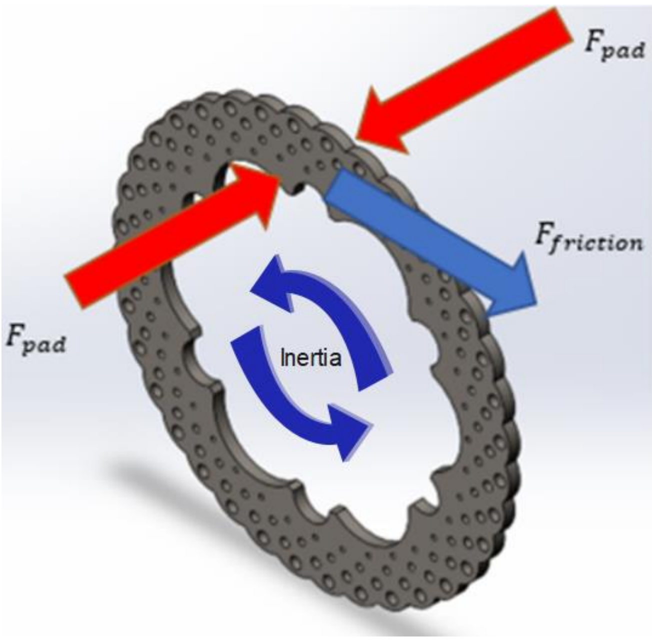



*Figure 25: QUT EV Standard Brake Rotor FBD*

## 3.3 Analysis Workflow (Gantt Chart)

A Gantt chart was created to capture the critical path process for the remainder of this project with particular attention given to the delegation and scheduling of activities proposed in the analysis proposal. This Gantt chart can be found under Appendix I. The structural analysis of each component was generally scheduled as an individual task and includes fatigue analysis where needed. Thermal analysis was grouped as a single task due to the continuity and interactions associated with this analysis. Upon further progress, this methodology may be altered; however, it was decided that, most likely, the thermal techniques will be fundamentally hand calculations and shall be completed in one task as such.

# 4 Systems Level Design

A systems level design approach was taken before component level design and analysis was initiated. The aim of the systems level design was to analyse all subsystems/components with respect to overall system function and performance. To do this, first a systems level analysis of the primary brake operation mode was undertaken and is detailed in section 4.1. This analysis focused on analysing the applied force on each operation-critical component based on the worst-case (hard braking) scenario where the wheel is at lock-up threshold. A DFM analysis (4.2) was then completed with the aim of analysing manufacturability of the constituent calliper components and identifying areas where component design and material selection could be altered to improve cost and ease of manufacture. Additionally, a DFA analysis (4.3) was performed on each component of the design to identify assembly parameters. The outcome of this analysis was the identification of component interfaces that could be improved in detailed design. Finally, a FMEA analysis (4.4) was conducted, resulting in the identification of multiple unforeseen failure modes to be actioned on in detailed design and analysis.

## 4.1 Systems Level Load Analysis (Fletcher Johnson, N9896791)

This section of the report will focus on the static loads experienced by all primary load-bearing components during the highest load braking scenario. The thermal, FEA and fatigue analyses will be discussed in subsequent documents as future work. The purpose of this analysis is to determine the worst-case loading scenario of each major component in the system and to rationalise the key design parameters. The parts which were analysed are:

- Calliper body
- Pistons
- Calliper bolts
- Brake pads
- Spring Clips

The calculations forming the table in Appendix A have been performed using the formulae extracted from the book, Race car design by Derek Seward [1]. The vehicle parameters applicable to determining the load case for this analysis were previously discussed in section 1.1 of this report and should be referred to as the preliminary of this section. Example calculations fundamental to the analysis are shown; however, not all associated calculations are shown as they were not required for the reader's understanding of the loads. The spreadsheet depicted in Appendix A calculates the maximum braking forces required to slow the car down as fast as possible, considering maximum brake capacity as governed by the tyres on the QEV3 car. A summary of the forces on the calliper system is shown in figure 26. Based on those parameters, the analysis progressively analysed the "train" of components from the brake pads, through to the calliper bolts to evaluate the static resultant loads. Firstly, the brake pad reaction forces were calculated.

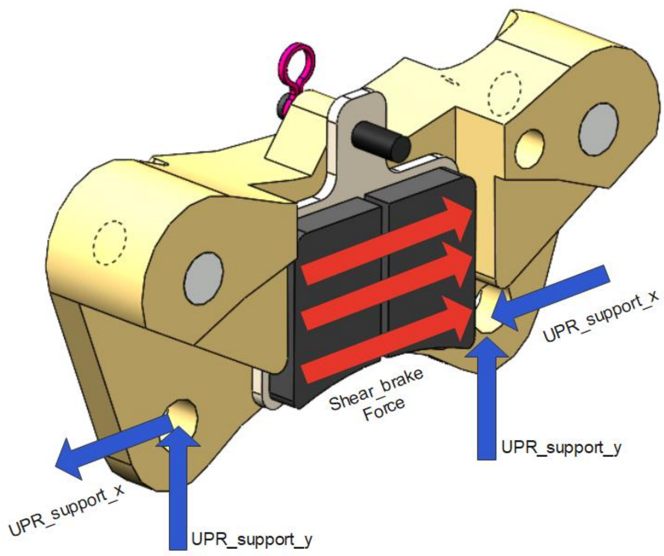



*Figure 26 – System cutaway FBD showing external forces on calliper system (resultants not shown).*

### 4.1.1 Brake Pads

#### *4.1.1.1 Applied Load*

Axial force is applied by the pressure behind the piston and is equal to the calculated peak clamping force of 2299.42 [N] (per calliper). The pad backing and friction material must be able to withstand this compressive load combined with a shear load. Thus (in reference to figure 21):

$$F_{rotor} = F_{piston} = 2299.4\ N$$

#### *4.1.1.2 Friction Force and Reaction Force*

When the braking force is applied, there is a resulting friction force which causes the vehicle to slow down. This friction generates shear force across the pad friction material, where it is supported by the pad backing generating a thrust force on the calliper body. In reference to the FBD in figure 21, the maximum frictional/shear force on each brake pad is half of the required brake force:

$$F_{friction} = F_{shear} = \frac{569.38}{2} = 284.69\ [N]\ per\ brake\ pad$$

The pressure this generates on the calliper body is calculated based on the contact surface area of 44 mm$^2$. This pressure is calculated using the following formula:

$$P_{support} = \frac{F}{A} = \frac{284.69}{4.4 \times 10^{-5}} = 6.47\ MPa$$

### 4.1.2 Brake Pistons

#### *4.1.2.1 Applied load*

The brake pistons are the only component which apply an axial load to the brake pads. The brake pads are required to apply ~ 2300 N of axial force; therefore (in reference to figure 19), the brake pistons must be able to transfer the subsequent fluid pressure to apply this force. The force load is distributed, at the pad/piston interface, over the 170 mm$^2$ surface of the piston in contact with the pad. The pressure/stress experienced by this surface is calculated below:

$$\therefore F_{axial,piston} = F_{piston_z} = 2300\ [N]$$

$$P_{piston_z} = \frac{2300}{170} = 13.53\ MPa$$

#### 4.1.2.2 Cylinder Pressure

The force which is applied to the brake pistons comes from the brake fluid which fills the cylinder where the brake piston sits. The brake pistons must be able to apply ~ 2300 N of force; therefore, the brake fluid pressure was found to find the pressure inside the brake calliper cylinder and the fluid channels. As two pistons are used, the total surface area on which the pressure acts to provide load to the pads is two times the area of a piston (20 mm in dia.).

$$P_{system} = \sigma_{fluid} = \frac{F}{A} = \frac{2300}{2 \times \pi \times 10^2} = 3.66\ MPa$$

Therefore 3.66 MPa of fluid pressure inside the brake calliper cylinder is required to apply 2300 N of force to the brake piston, and subsequently the pads. As such, the material and geometry of the piston must withstand this level of pressure, as will the piston seal (not analysed here due to need for analysis using FEA). In general, the piston seal must be able to seal against this pressure with an appropriate safety factor to be determined later.

### 4.1.3 Calliper Body

#### 4.1.3.1 Applied loads

As this calliper is a two-piston design, there will be 2 reaction forces when the brakes are being used. This force will push the two calliper body halves away from each other, creating a moment about the top support between the two halves. One side of the calliper is fixed to the suspension upright and the other side is bolted to the inboard half. A moment will be induced when a braking force is applied as the centre of pressure of the brake cylinders is 22.5mm away from the bolts. The moment induced is calculated below and shown in figure 27:

$$M = 2299.4 \times 0.0225 = 51.74\ Nm$$

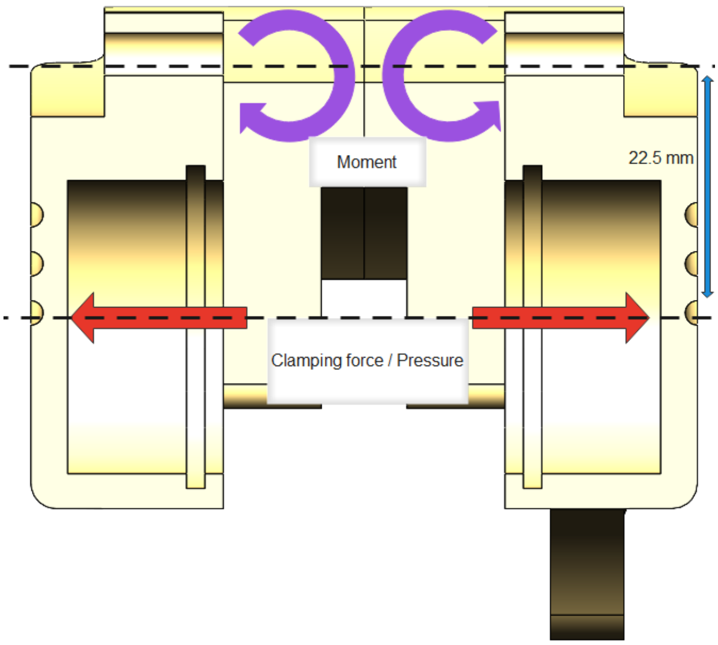



*Figure 27 - FBD showing moment generated on calliper body during brake load.*

#### 4.1.3.2 Reaction forces

Figure 16 shows the two bolt holes where the calliper bolts are inserted. The axial force on these bolts acts to hold the two calliper halves together and resist the moment force generated by the clamping action. Due to sufficient clamping force, a friction support is formed at the interface of the two calliper halves. This means no shear force is carried by the calliper bolts, rather the shear force is carried by static friction this support was analysed. Figure 17 shows the force applied to the joining faces because of friction acting on the brake pads which are supported by the calliper body. The shear force is supported full by the friction force:

$$F_{friction-OH} = F_{pad} = 284.69\ [N]$$

Assuming the static coefficient of friction between the two faces to be 1.2 [12], and excluding (for now) the required tension to resist the moment mentioned previously (2300 N), the required bolt tension was calculated:

$$\frac{F_{friction-OH}}{\mu_s} = TBolt_{axial} = \frac{284.7}{1.2} = 237.25\ N$$

Next, Figure 16 was analysed. If the inboard side of the brake calliper is isolated, the friction force from the outboard side is superimposed on the thrust force generated by the inboard brake pad. The bottom two holes in Figure 16 will be the only bolts which provide a reaction force for the whole calliper, resisting the cumulative brake force and, hence, creating the required braking torque. Therefore, in reference to figure 16:

$$F_{support\_x} = \sum F_{friction} = 569.38\ [N]$$

This is equal to 284.69 N per bolt for an X-axis reaction force. The Y axis reaction will be neglected from analysis as the Y-axis component was considered negligible. Analysis of figure 18 indicated that the pressure forces generated by each piston are ideally equal and opposite, thus, not creating any resultant lateral force. Therefore, it was reasonably assumed that in normal operation no side-to-side (lateral) forces are imposed on the mount.

Again, referring to figure 18. The additional force applied through the bolts is equal to the force applied by the piston, which is 2300 N. The calliper bodies will be held together using two bolts; therefore, these two bolts will experience an axial force of 1150 N through each due to worst-case load. This is superimposed on the 237.25 N initially applied torque to result in a total maximum bolt load of 1387.25 N However, there will be a factor of safety of 1.5 applied to the bolt force to ensure the calliper is held together under extreme circumstances. Therefore, a bolt tension force of 2080.9 N will be applied as the design force. This means the $W_{support}$ load will also be 2080.9 N acting on each calliper body interface.

### 4.1.4 Brake Pad Retaining Pin and Spring Clip

For the purposes of this report, it is assumed these components do not have any considerable force acting upon them as they are merely used to keep the brake pads in position. The brake pads transfer all their force to the calliper body and only transmit load to the pin under failure circumstances. The pin will be selected off-the-shelf.

### 4.1.5 Calliper Mounting Bolts

The two mounting bolts that are to attach the calliper to the upright must be designed with appropriate pre-tension to maintain a frictional support. The same μs value of 1.2 as before was assumed. At maximum brake force of ~ 570 N, the bolt tension must be at least:

$$T_{mountBolt} = \frac{F_{frictionSupport}}{\mu_s} = \frac{570}{1.2} \times 0.5\ (two\ bolts) = 237.5\ N$$

## 4.2 Design for Manufacture Analysis (DFM) (Jacob Garcia-Pavy, N10012478)

Design for Manufacturing (DFM) is a design method used to evaluate manufacturing costs and complexities associated with a design concept. DFM was used to help establish the manufacturing processes which can be analysed in terms of the cycle time, quality, flexibility, material utilisation, and operating costs. Firstly, this allows the team to comprehend the rough cost and practicality of the design. Secondly, enables the team a method to identify potential weaknesses or flaws within the manufacturing procedure or design which can be adapted in further designs. The designated DFM rating for the highlighted aspects is seen in table 2.

*Table 2- DFM Criteria*

| Rating | Cycle Time | Quality | Flexibility | Materials Utilization | Operating Costs |
|---|---|---|---|---|---|
| 5 | > 15 min (production rate low) | Poor quality, average reliability | Changeover extremely difficult | Waste > 100% of finished component | Substantial machine and dedicated tooling costs |
| 4 | 5 min – 15 min | Average quality | Slow changeover | Waste 50% - 100% | Tooling and/or machines costly |
| 3 | 1 min – 5 min | Average – good quality, average reliability | Average changeover and set-up time | Waste 10% - 50% | Tooling and machines relatively inexpensive |
| 2 | 20 s – 1 min | Good – excellent quality, good reliability | Fast changeover | Waste < 10% of finished component | Tooling costs low or little equipment involved |
| 1 | < 20 s (production rate high) | Excellent quality and reliability | No significant changeover of set-up time | No appreciable waste | No appreciable setting-up costs |

The concept design requires the main components to be manufactured in-house. As such, these were considered in DFM. The team has opted to source as many off-the-shelf products possible to reduce manufacturing costs and complexities. The brake pads, retaining pin and clip are presumed to be off-the-shelf products. While the fluid interface components such as the gaskets, O-rings, bleed screws, and banjo are confirmed as off-the-shelf products. The following analysis will determine the specifics and ability to utilise these off-the-shelf products. However, due to the specificity of the concept design the piston, inboard and outboard calliper bodies require manufacturing. Also, the calliper bolts are currently assumed to be manufactured due to the specific constraints and dimensions of the design however, this will be determined in further analysis and design.

Moreover, the concept is likely going to outlast the designated QUTM vehicle. Thus, a one-off production of the assembly is likely sufficient. Therefore, the team has decided to utilise machining rather than casting. As the large initial costs associated with moulds will be underutilised while greater optimisation and quality can be achieved with machining. The calliper bodies were assumed to be CNC machined blocks of 7075 Aluminium which is an expensive alloy due to its quality and production cost at roughly \$20000/m^3. The minimum volume for each calliper body is .001m^3 however, it is most likely to be sourced in standard size billet. Additionally, the piston and brake pad housing sections require greater quality with finer levels of surface roughness to facilitate smooth operation which can be achieved through operations such as grinding and polishing. The pistons can be machined from billets of 7075 Aluminium and require a greater number of surface operations. The calliper bolts will be machined out of heat-treated rods of titanium, lathed and ground. The DFM manufacturing process analysis is seen in table 3 and illustrates the preliminary manufacturing strategy.

*Table 3 - Design for Manufacture (DFM) table.*

| Part | Quantity | Raw Material Costs | Manufacturing Operations | Operation Count (N) | Cycle Time Rating (CT) | Quality Rating (Q) | Flexibility Rating (F) | Material Utilisation (M) | Operating Costs Rating (OC) |
|---|---|---|---|---|---|---|---|---|---|
| Calliper Body Inboard | 2 | $20 (.1m*.1m* .1m* $20000/ m^3) | Operation 1: Machine CNC<br>Operation 2: Grind<br>Operation 3: Polish | 7<br>3<br>3 | 3<br>2<br>2 | 2<br>1<br>1 | 3<br>1<br>1 | 5<br>1<br>1 | 3<br>1<br>1 |
| Calliper Body Outboard | 2 | $20 | Operation 1: Machine CNC<br>Operation 2: Grind<br>Operation 3: Polish | 7<br>3<br>3 | 3<br>2<br>2 | 2<br>1<br>1 | 3<br>1<br>1 | 5<br>1<br>1 | 3<br>1<br>1 |
| Piston | 4 | $10 | Operation 1: Machine<br>Operation 2: Grind<br>Operation 3: Polish | 3<br>2<br>2 | 2<br>2<br>2 | 3<br>1<br>1 | 1<br>1<br>1 | 4<br>1<br>1 | 2<br>1<br>1 |
| Calliper Bolts | 4 | $10 | Operation 1: Machine<br>Operation 2: Lathe<br>Operation 3: Grinding | 1<br>2<br>1 | 2<br>2<br>2 | 3<br>2<br>1 | 1<br>1<br>1 | 4<br>5<br>1 | 2<br>2<br>1 |
| TOTAL COST-$120 | | | Column Rating | | 220 | 162 | 152 | 294 | 176 |
| | | | Overall Design Rating | | 1004 | | | | |

The total cost is $120, and the overall design rating is 1004. With little comparison or reference the results may seem arbitrary; however, it displays the increased manufacturing difficulties associated with CNC due to the number of required operations. However, CNC is the most optimised and practical manufacturing operation available for the calliper bodies. Therefore, the design requires further finalisation to reduce the number of operations required by CNC to reduce manufacturing complexities and costs.

## 4.3 Design for Assembly Analysis (DFA) (Todd Dalgliesh, N6004075)

The calliper seen in Figure 28 below shows the parts as would be ordered for the Design for assembly (DFA). Parts such as the brake seal would be installed onto the pistons before insertion and as a guide this would save time doing these steps prior to overall assembly but as this was for full assembly the order was left so the calliper could be assembled then bolted to the vehicle. Item number 14 omitted from the diagram, but these would be the two bolts that secure the brake assembly to the hub and were included in the overall assembly time. The orientation of each part followed the alpha and beta rotational symmetries outlined by Boothroyd which is seen in Figure 29 below.

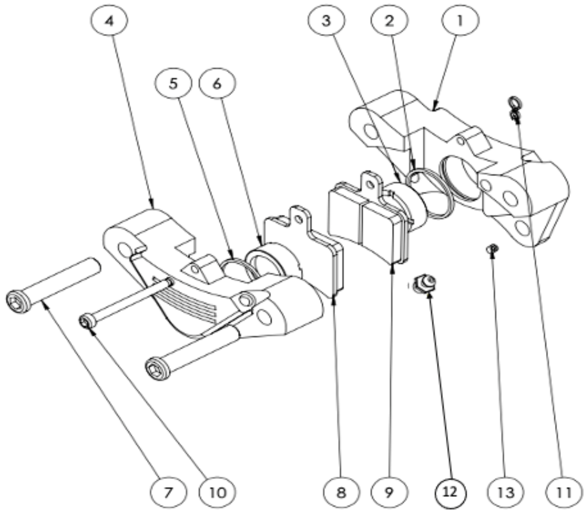
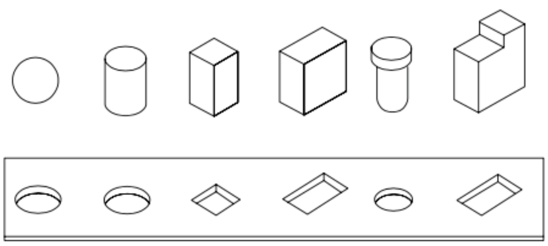



*Figure 28 - Calliper exploded view to show order of installation for DFA.*



| | | | | | | |
|---|---|---|---|---|---|---|
| α | 0 | 180 | 180 | 90 | 360 | 360 |
| β | 0 | 0 | 90 | 180 | 0 | 360 |

*Figure 29 - Rotational symmetries for Alpha and beta of various parts.*

The procedure for the DFA followed the classification system aligned with Boothroyd's handling and insertion table seen in **APPENDIX G** [13] using alpha and beta to determine which category the parts and the manipulation required to be installed. Additionally, a similar procedure was used for the insertion time and all the values can be seen in Table 2 below with the accumulated times for complete assembly as the total. The calliper assembly time was calculated to be around 170 seconds which would be new parts prepared with no interference from debris or cleaning involved in the assembly process with all tools easily accessible. A longer time would be expected if the vehicle would have been in operation as the calliper would need to be cleaned prior to reassembly to prevent ingress of dirt into the system. Tool acquire time (TA) was estimated for a technician who has all the required tools prepared before the job is undertaken and does not have to leave the work station to find the tools. Additionally, this could be the same as having a tool kit for each technician per wheel corner at the racetrack.

*Table 2 - Design for Assembly Analysis (DFA) table*

| | Part ID | alpha | Beta | (Alpha+Beta) | No of items RP | Tool acquire time TA (sec) | Handling code | Handling time TH (sec) | insertion code | insertion time TI (sec) | Total time TM = TA +RP*(TH+TI) (sec) | Operation cost $0.004 *TM ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calliper RH half | 1 | 360 | 360 | 720 | 1 | 0 | 30 | 1.95 | 0 | 1.5 | 3.45 | 0.0138 |
| Piston seal | 2,5 | 180 | 0 | 180 | 2 | 0 | 87 | 5.85 | 0,7 | 6.5 | 24.7 | 0.0988 |
| Piston | 3,6 | 360 | 0 | 360 | 2 | 0 | 88 | 6.35 | 0,7 | 6.5 | 25.7 | 0.1028 |
| Calliper LH half | 4 | 360 | 360 | 720 | 1 | 0 | 30 | 1.95 | 0,8 | 6.5 | 8.45 | 0.0338 |
| Calliper fastener | 7 | 360 | 0 | 360 | 2 | 4 | 11 | 1.8 | 38 | 6 | 19.6 | 0.0784 |
| Pads | 8,9 | 360 | 180 | 540 | 2 | 0 | 25 | 2.57 | 11 | 5 | 15.14 | 0.06056 |
| Clevis pin | 10 | 0 | 360 | 360 | 1 | 0 | 16 | 2.57 | 23 | 7.5 | 10.07 | 0.04028 |
| Retainer clip | 11 | 180 | 180 | 360 | 1 | 0 | 19 | 3.38 | 0,3 | 3.5 | 6.88 | 0.02752 |
| Brake nipple | 12 | 360 | 0 | 360 | 1 | 4 | 18 | 3 | 39 | 8 | 15 | 0.06 |
| grub screw | 13 | 360 | 0 | 360 | 1 | 2 | 18 | 3 | 39 | 8 | 13 | 0.052 |
| Bolt - to hub | 14 | 360 | 0 | 360 | 2 | 4 | 11 | 1.8 | 49 | 10.5 | 28.6 | 0.1144 |
| | | | | | | | | | | Total | **170.59** | **0.68236** |

## 4.4 Failure Modes and Effects Analysis (FMEA) – (William Whigham, N10232869)

The failure modes of the selected brake calliper design were analysed using a failure modes and effects analysis (FMEA) model. Operation of the brake was identified as the primary focus of the FMEA analysis as this is the main functional use case of the brake calliper. It operates under dynamic loads and forms a critical piece of the safety system that is the car's brakes. Each component was considered with respect to its interaction with others in the system and analysed for points of failure. The component breakdown is listed below.

Individual components considered in FMEA, with brief description of function:

- Brake calliper body (inboard and outboard halves) – houses all components and is primary structural member.
- Calliper body bolts – hold the two calliper halves together.
- Pistons – uses fluid pressure to actuate pad movement.
- Piston seals – provides seal between piston and piston bore and retracts piston after brake application.
- Bleed screw/nipple – provides maintenance point to bleed fluid from calliper.
- Brake pads – create friction force when pressed onto rotor.
- Clevis pin (pad retaining pin) – retains brake pads in place within calliper body.
- Retaining clip (for clevis pin) – secondary retention mechanism for clevis pin.
- Grub screw (fluid channel plug screw) – seals off fluid passages drilled into calliper body.
- Attachment bolt (calliper to hub/upright) – bolt that mounts calliper to upright on car.

Complete failure of the brake calliper may be caused by several failure points within the system and could result in catastrophic damage to the car and/or injury or death to the driver. Thus, it is important that FMEA be conducted in full so that dangerous failure points can be remedied in further detailed design. The FMEA analysis in Table 3 details this analysis and the proposed actions that were identified as a result. The FMEA accounts for the components listed only and does not consider components outside the scope of design. The tables in Appendix H were referenced for the establishment of severity, occurrence and detection rankings used in the FMEA table.

*Table 3 - FMEA Table*

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a. Calliper body (both halves) | a. Breakage of mounting bracket | Calliper free from upright causing loss of brake capacity in affected wheel.<br><br>Debris ejected on track or within wheel assembly. | Reduced or total loss of braking performance at rear wheels.<br><br>Binding, jamming or wear caused to wheel-rim by dislodged calliper.<br><br>Damage to vehicle/s or persons due to metallic debris | 7 | Dynamic overloading of calliper body mount bracket | 2 | Nil | 8 | 112 | Material selection and design geometry selection and analysis for worst case load. | Mechanical | Increase support and FOS of >1.5 at mount. | 7 | 1 | 7 | 49 |
| | | | | 7 | Impact from other component or track debris | 1 | Driver feedback due to noise or vibration from impact | 5 | 35 | Heightened safety factor, tough material or added shield. | Mechanical | FOS > 1.5 | 7 | 1 | 5 | 35 |
| | | | | 7 | Crack in bracket material | 2 | Nil | 9 | 126 | Component analysis and design. Inform user of a recommended inspection schedule and add to FFBD | Mechanical | FOS > 1.5 for fatigue | 7 | 2 | 3 | 42 |
| | b. Mounting bracket bends or is distorted | Misalignment of calliper to rotor | Uneven wear of brake pads<br><br>Noise caused by dragging of pads or surface-surface contact<br><br>Reduced brake responsiveness and stopping force | 5 | Impact to calliper causing distortion | 2 | Nil | 4 | 40 | Heightened safety factor, tough material or added shield. | Mechanical | Selection of tough (not brittle) material | 5 | 1 | 4 | 20 |
| | | | | 5 | Incorrect installation | 2 | Driver or maintenance personnel detection from noise | 3 | 30 | Add maintenance step specifying method to ensure calliper is properly aligned with rotor and no damage is present | Mechanical | Nil | 5 | 1 | 1 | 5 |
| | c. Loss of fluid containment | Rapid de-pressurisation of rear brake system<br><br>Contamination of brake pad / rotor surface<br><br>Contamination of motor units and painted surfaces | Loss of brake actuation and ability to use rear brake<br><br>Reduced friction coefficient of pads from contamination<br><br>Damage to motors and painted components as a result of corrosive fluid exposure | 8 | Brake system overpressure due to extreme driver input | 3 | Noticeable loss of brake pedal resistance | 3 | 72 | Increased safety factor of design pressure to account for extreme driver input force.<br><br>Pressure sensor in brake calliper or other location in system with alarm feedback to driver in overpressure event.<br><br>Pressure safety valve venting back to fluid reservoir. | Mechanical & electrical | Design accordingly. Consider PSV in detailed design | 8 | 2 | 1 | 16 |
| | | | | 8 | Defect in material or fit tolerance in piston seal area | 2 | Specified tolerances for manufacturer | 4 | 64 | Establish production & maintenance checks to ensure tolerance | Mechanical | FOS > 1.5 and specify maintenance testing | 8 | 1 | 2 | 16 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | requirements are maintained.<br><br>Increased safety factor in pressure-containing regions. | | | | | | |
| | d. High wear between brake pad and calliper body pad support | Excessive free play between pads and calliper body cavity/support | Increased brake noise<br><br>Reduced brake response feedback to the driver | 3 | Soft calliper material susceptible to wear from concentrated force | 4 | Noise and feedback to driver | 2 | 24 | Design replaceable shim made of hard material to act as barrier between pad backing and calliper body support to reduce wear on support face | Mechanical | Design shim to sit between pads and calliper to spread the load across larger area. | 3 | 1 | 2 | 6 |
| | e. Blockage of fluid passage/s | Reduced or total loss of fluid pressure to the piston/s<br><br>Un-equal distribution of brake load on rear axle | Reduced or total loss of brake force<br><br>Reduced vehicle controllability | 6 | Piston covers fluid passage due to being able to travel too far into the calliper body | 7 | Total loss of brake force | 1 | 42 | Incorporate piston stop within calliper bore to ensure travel is limited and piston cannot cover fluid passage.<br>OR<br>Re-design fluid passage routing to rear of piston rather than bore surface. | Mechanical | Incorporate piston stop in housing | 6 | 1 | 1 | 6 |
| | | | | 6 | Ingress and build-up of solid material in brake calliper | 2 | Proper maintenance of existing brake fluid including periodic replacement.<br><br>Progressive loss of performance | 1 | 12 | Enlarge fluid passages where possible to reduce the risk of small foreign matter from blocking fluid. | Mechanical | Make fluid passages 6 mm where possible | 6 | 1 | 1 | 6 |
| | f. Air ingress to calliper fluid channels | Compressible fluid environment formed inside brake system<br><br>Rapid expansion with heat | Reduced brake force and poor brake pedal feel | 2 | Partial failure of piston seal (wear) | 4 | Regular brake bleeding<br><br>Deterioration of pedal feel noticeable by driver | 2 | 16 | Select appropriate tolerances, material and piston bore design to reduce possibility of wear-induced failure | Mechanical | Select material based on past studies | 2 | 4 | 2 | 16 |
| | | | | 2 | Partial failure or looseness of various hydraulic fittings within brake system | 5 | Regular brake bleeding<br><br>Deterioration of pedal feel noticeable by driver | 2 | 20 | Reduce number of hydraulic fittings (potential ingress points) in the calliper | Mechanical | Nil | 2 | 4 | 2 | 16 |
| | | | | 2 | Improper or insufficient brake bleed maintenance | 5 | Regular brake bleeding<br><br>Deterioration of pedal feel noticeable by driver | 2 | 20 | Orientate fluid channels in such a way that air is not easily trapped in channels while bleeding brake. | Mechanical | Re-evaluate fluid channel orientation. Consider cross-over tube rather | 2 | 3 | 2 | 12 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | than internal passages. | | | | |
| | g. Overheating of calliper body | Expansion of calliper body relative to interfacing components<br><br>Fluid vaporisation<br><br>Weakened structural integrity | Leakage due to openings caused by expansion<br><br>Brake fade from fluid vaporisation<br><br>Loss of brake force due to structural failure | 7 | Inadequate heat management / cooling capacity of calliper with respect to operating environment | 3 | Degraded braking performance noticeable by driver<br><br>Design factors aimed at heat management | 2 | 42 | Incorporate temperature sensor inside brake calliper with alarm to driver when brake overheats.<br><br>Verify design with thermal analysis. Use high FOS | Mechanical & electrical | FOS > 1.5 | 7 | 2 | 1 | 14 |
| | | | | 7 | Use of improper brake fluid | 2 | Degraded braking performance noticeable by driver | 3 | 42 | Clear specification of brake fluid type written on calliper and in maintenance procedure. | Mechanical | Specify brake fluid for design | 7 | 1 | 3 | 21 |
| | | | | 7 | Over-use of brakes (unforeseen) | 2 | Degraded braking performance noticeable by driver | 3 | 42 | Use higher FOS<br><br>Incorporate temperature sensor inside brake calliper with alarm to driver when brake is over-used. | Mechanical & electrical | Temperature sensor. | 7 | 2 | 1 | 14 |
| b. Calliper body bolts | a. Yielding of bolt material | Loss of tension load holding calliper halves together<br><br>Fluid leakage from between calliper halves causing contamination and pressure loss | Reduced brake force due to pressure loss and brake pad contamination<br><br>Poor stopping performance | 7 | Bolt over-tightened | 3 | Degraded braking performance noticeable by driver | 3 | 63 | Specify bolt torque and verify with analysis.<br>Size bolts with higher FOS | Mechanical | Detail bolt specifications | 7 | 1 | 2 | 14 |
| | | | | 7 | Normal force on brake pads too high | 2 | Degraded braking performance noticeable by driver | 3 | 42 | Pressure sensor in brake calliper or other location in system with alarm feedback to driver in overpressure event.<br>Pressure safety valve feeding back to reservoir. | Mechanical & electrical | Consider PSV | 7 | 1 | 1 | 7 |
| | b. Failure of bolt thread or female thread inside calliper body making bolt/s loose | Loss of retention between two calliper halves<br><br>Subsequent fluid leakage and pressure loss | Loss of braking force and degraded pedal feel | 7 | Over-tightening of bolt | 2 | Driver pedal feedback and degraded performance indicating failure | 3 | 42 | Specify appropriate bolt torque with high FOS.<br>Select high tensile material.<br>Size threads appropriate to load.<br>Apply thread-locking compound to stop bolts becoming loose | Mechanical | Size bolts appropriately.<br>Specify torque. | 7 | 1 | 2 | 14 |
| | a. One or both bolts become | Calliper no longer supported | Damage to various | 8 | Bolt under-tightened, | 3 | Driver notices degradation in | 4 | 96 | Specify application of thread locking | Mechanical | Specify thread locking | 8 | 1 | 2 | 16 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| c. Calliper mounting bolts | loose, failing to retain calliper against upright | Calliper becomes jammed in rotating wheel assembly<br><br>Breakage of hydraulic lines | components in wheel assembly<br><br>Loss of brake force on affected wheel | | resulting in it working loose over time. | | performance (if total failure occurs)<br><br>Rattling noise from loose calliper | | | compound to bolts OR use bolts with retaining mechanism such as spring washer, safety wire or Nylon nut.<br>Specify torque to be applied by maintenance personnel.<br>Specify scheduled checks of bolt tightness. | | compound such as Loctite. | | | | |
| | b. Bolt failure (separation or yielding) | Calliper no longer supported<br><br>Calliper becomes jammed in rotating wheel assembly<br><br>Breakage of hydraulic lines | Damage to various components in wheel assembly<br><br>Loss of brake force on affected wheel | 8 | High shear stress on bolt due to under-tightening (no friction support) | 3 | Driver notices degradation in performance (if total failure occurs)<br><br>Rattling noise from loose calliper | 4 | 96 | Specify torque to be applied by maintenance personnel (appropriate torque to induce full friction support.<br>Specify scheduled checks of bolt tightness. | Mechanical | Torque specification. | 8 | 1 | 2 | 16 |
| d. Brake piston | a. Loss of fluid pressure / containment | Rapid de-pressurisation of rear brake system<br><br>Contamination of brake pad / rotor surface<br><br>Contamination of motor units and painted surfaces | Loss of brake actuation and ability to use rear brake<br><br>Reduced friction coefficient of pads from contamination<br><br>Damage to motors and painted components as a result of corrosive fluid exposure | 8 | Brake system overpressure due to extreme driver input | 2 | Noticeable loss of brake pedal resistance (feedback to driver) | 3 | 72 | Increased safety factor of design pressure to account for extreme driver input force.<br><br>Pressure sensor in brake calliper or other location in system with alarm feedback to driver in overpressure event.<br><br>Pressure safety valve venting back to fluid reservoir with set-point lower than MAOP. | Mechanical & electrical | FOS > 1.5. Consider PSV as it has been common suggestion. | | | | |
| | | | | 8 | Improper maintenance causing damage to piston | 2 | Maintenance inspection procedure<br><br>Driver feedback through brake pedal (in complete failure scenario | 2 | 32 | Reduce instances where piston or piston seal (overhaul) maintenance is required.<br>Add dust boot to piston to stop debris ingress which could warrant more frequent seal replacement. | Mechanical | Design dust boot | 8 | 1 | 2 | 16 |
| | b. Inadequate lubrication / excessive wear | Restricted or complete loss of movement within piston bore | Brake is harder to actuate (poor driver feel) | 5 | Fit between piston and calliper body is too tight | 2 | Nil.<br>(Design to be advised later in detailed design) | 5 | 50 | Design tolerance and fit to allow for adequate apace for lubrication to reach piston / seal. | Mechanical | Evaluate tolerance requirements | 5 | 1 | 2 | 10 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Poor seal between piston and calliper | Leaking fluid contaminates braking surfaces, lowering brake force | | | | | | | | | | | | | |
| | | | | 5 | Ingress of dirt and debris and brake dust causing wear and friction | 4 | Poor performance felt by driver | 3 | 60 | Implement dust boot in piston assembly to reduce debris ingress, reducing wear on piston and seal and maintaining low friction. | Mechanical | Design dust boot | 5 | 2 | 2 | 20 |
| | c. Piston overheated | Leakage caused by expansion differential between calliper body and piston<br><br>Heat transfer to brake fluid causing vaporisation | Poor brake performance and brake fade<br><br>Braking surface contamination | 5 | Poor / inadequate heat management for environment and/or driving input severity | 2 | Poor performance felt by driver | 3 | 30 | Design piston with smallest allowable contact patch on pad to slow heat transfer. Increase heat flux to environment via air passages (increase exposed surface area) | Mechanical | Evaluate piston design based on thermal analysis TBA | 5 | 1 | 3 | 15 |
| e. Piston seal | a. Loss of fluid pressure / containment | Depressurisation of rear brake system<br><br>Contamination of brake pad / rotor surface<br><br>Contamination of motor units and painted surfaces | Poor brake performance or major loss of brake capacity | 6 | Wear causing inadequate seal function | 4 | Poor performance felt by driver | 4 | 96 | Implement dust boot in piston assembly to reduce debris ingress, reducing wear on piston and seal and maintaining low friction. | Mechanical | Design dust boot | 6 | 1 | 4 | 24 |
| | | | | 6 | Improper installation or damage during maintenance | 3 | Poor performance felt by driver | 4 | 72 | Design seal and seal groove for maintenance friendly installation and removal. Make seal non-symmetric so that it can only be installed one way (reducing room for error).<br>Design seal to indicate correct seat in groove. | Mechanical | DFA analysis of piston seal. | 6 | 1 | 4 | 24 |
| | b. No or insufficient restoring force imparted to piston | Brake pad dragging on rotor | Inefficient braking performance (wasting energy to heat when not required)<br><br>Increased brake pad wear rate | 4 | Piston seal worn due to debris ingress | 4 | Poor performance felt by driver to indicate problem. | 5 | 80 | Implement dust boot in piston assembly to reduce debris ingress, reducing wear on seal and maintaining restoring elasticity.<br><br>Incorporate brake piston position sensor that detects and alarms driver when retraction fails | Mechanical & electrical | Design dust boot | 4 | 1 | 3 | 12 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f. Brake pad | a. Loss of optimal friction coefficient with rotor | Higher system pressure required to generate given brake torque/force | Driver fatigue due to high force requirement / need to compensate for poor brake force | 4 | Brake pads friction material worn out (no material left) | 4 | Metal-on-metal noise audible to driver and maintenance crew<br><br>Periodic measurement of brake pad thickness included in FFBD plan | 2 | 32 | Include recommendation for pad wear visual check as part of pre-race inspection<br><br>Possibly include audible wear indicator (found on some commercial vehicles) | Mechanical | Specify pre-race pad wear check procedure | 4 | 2 | 1 | 8 |
| | | | | 4 | Contamination from lubrication oil, brake fluid or another friction-reducing agent | 4 | Squealing noise likely audible.<br><br>Poor brake performance noticeable by driver | 2 | 32 | Implement regular cleaning procedure of brake calliper, pads and all surrounding components using suitable solvent | Mechanical | Specify cleaning procedure and inspection | 4 | 2 | 2 | 16 |
| | b. Un-even wear | Premature wear-out of brake pads<br><br>Piston force no-longer perpendicular to brake rotor surface | Poor braking performance<br><br>Short brake pad life requiring more regular replacement | 3 | Calliper or brake pads not in alignment when installed | 3 | Routine maintenance checks | 6 | 54 | Make design non-adjustable with alignment to rotor fixed to reduce maintenance error possibility | Mechanical | Nil | 3 | 1 | 5 | 15 |
| | | | | 3 | Excessive play in hub causing rotor to preference one pad | 2 | Routine maintenance checks | 6 | 36 | Refer to maintenance / inspection procedure of QEV3 to establish adequate measures are in place to avoid cause | Mechanical | Consult QUTMS representative to establish whether this poses an issue | 3 | 2 | 5 | 30 |
| g. Clevis pin | a. Broken pin (structural failure) | Pads no longer retained in housing and are dislodged from calliper | Loss of braking capability at affected wheel | 8 | Impact to pin from external source (incl. during maintenance) | 2 | Sudden loss of brake performance noticeable by driver | 8 | 128 | Specify inspection or replacement of pin with each brake pad replacement | Mechanical | Change pin and clip to split pin design | 8 | 2 | 6 | 96 |
| | b. Pin becomes loose in guide holes / supports | Pad support is compromised | Pads no longer retained in housing and are dislodged from calliper (only if subsequent failure of retaining clip (see below))<br><br>See above row for end effects cont. | 5 | Insufficient tightness on retaining pin threads | 3 | Retaining pin acts as redundancy measure so pin cannot fall out of calliper | 2 | 30 | Replace pin and clip assembly with one-piece split pin which is easily (and cheaply) replaceable and cannot become loose. | Mechanical | Change pin and clip to split pin design | 5 | 1 | 2 | 10 |
| h. Retaining clip | a. Clip failure (breakage) | No redundancy for pad retaining pin / clevis pin | Pad retaining pin dislodged causing complete loss of brake operation at affected wheel **(if** | 3 | Improper installation | 2 | Installation already intuitive to trained maintenance persons (similar to many other designs) | 4 | 24 | Replace pin and clip assembly with one-piece split pin which is easily (and cheaply) | Mechanical | Change pin and clip to split pin design | 3 | 1 | 4 | 12 |

| Subsystem/Module & Function | Potential Failure Mode | Potential Local Effects of Failure | Potential End Effects of Failure | SEV | Potential Causes of Failure | OCC | Current Controls/Fault Detection | DET | RPN | Recommended Action(s) | Responsible Party | Actions Taken | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **pin becomes loose as well)** | | | | Note: However, small part does make it harder to install | | | replaceable and cannot become loose. | | | | | | |
| | b. Clip unseats from recess in clevis pin | No redundancy for pad retaining pin / clevis pin | Pad retaining pin dislodged causing complete loss of brake operation at affected wheel **(if pin becomes loose as well)** | 3 | Improper installation – not installed in recess | 2 | Installation already intuitive to trained maintenance persons (similar to many other designs)<br><br>Note: However, small part does make it harder to install | 4 | 24 | Replace pin and clip assembly with one-piece split pin which is easily (and cheaply) replaceable and cannot become loose. | Mechanical | Change pin and clip to split pin design | 3 | 1 | 4 | 12 |
| | | | | 3 | Clip impacted by debris or another component of the car | 1 | Nil | 8 | 24 | Replace pin and clip assembly with one-piece split pin which is easily (and cheaply) replaceable and cannot become loose. | Mechanical | Change pin and clip to split pin design | 3 | 1 | 4 | 12 |
| i. Bleed screw/ nipple | a. Loss of fluid pressure / containment | Depressurisation of rear brake system<br><br>Contamination of brake pad / rotor surface<br><br>Contamination of motor units and painted surfaces | Poor brake performance or major loss of brake capacity | 6 | Nipple incorrectly installed or not tightened adequately after maintenance | 2 | Poor performance felt by driver; indication of problem | 5 | 60 | Specify required torque so that maintenance personnel check tightness after loosening and re-tightening screw | Mechanical | Design and specify torque. Evaluate effectiveness of open/close mechanism | 6 | 1 | 3 | 18 |
| | b. Bleed screw blockage | Fluid unable to flow out of calliper | Calliper unable to be bled. Air and spent fluid trapped inside system. | 2 | Ingress of dirt and debris through tip of bleed nipple | 4 | Lack of fluid flow is sign of blockage | 1 | 8 | Design rubber dust cover to be retained over bleed nipple stopping debris ingress | Mechanical | Design and incorporate dust cover | 2 | 1 | 1 | 2 |
| j. Grub screw | a. Loss of fluid containment / pressure | Depressurisation of rear brake system<br><br>Contamination of brake pad / rotor surface<br><br>Contamination of motor units and painted surfaces | Loss of braking force at affected wheel | 7 | Screw becomes loose during service (may eject from calliper) | 2 | Poor performance felt by driver; indication of problem | 5 | 70 | Specify application of thread locking compound or sealant to retain screw and ensure egress of fluid past screw threads is mitigated. | Mechanical | Specify thread locking compound or sealant | 7 | 1 | 5 | 35 |

# References


[1] D. Seward, *Race car design*. London: Palgrave, 2014.

[2] M. Usama and G. Singhal, "Design and Analysis of Braking System for FSAE," *IJSRD - International Journal for Scientific Research & Development,* vol. 6, pp. 1877-1881, 2018.

[3] D. Harsh and B. Shyrokau, "Tire Model with Temperature Effects for Formula SAE Vehicle," *Applied Sciences,* vol. 9, p. 5328, 2019.

[4] D. Robertson and G. J. Delagrammatikas, "The Suspension System of the 2009 Cooper Union FSAE Vehicle: A Comprehensive Design Review," *SAE International journal of passenger cars. Mechanical systems,* vol. 3, pp. 366-380, 2010.

[5] AP Racing. *AP Racing CP4226D27 Brake Pad*. (Accessed: 2021, 18 September). Available: https://apracing.com/special-vehicles/motorcycle/brake-pads-ap-racings-calipers/ap-racing-pad-shapes/cp4226d27

[6] M. Ugemuge and S. Das, "Design and Testing of Custom Brake Caliper of a Formula Student Race Car," 2019.

[7] K. Dalal and A. Karnik, "Monoblock Brake Calliper Design and Analysis," *International Research Journal of Engineering and Technology (IRJET),* vol. 7, pp. 2419-2425, 2020.

[8] R. Limpert, *Brake Design and Safety, Third Edition*: SAE International, 2011.

[9] A. Dey, "Thermal Analysis of Disc Brake in order to study the Brake Fluid Vaporisation Phenomenon of a Formula SAE Car," Master of Science in Mechanical Engineering Masters, Faculty of Science and Engineering, University of Texas, 2015.

[10] M. Ouddane and Y. Rancourt, "Sorption and diffusion of a brake fluid in EPDM elastomers," *Journal of Applied Polymer Science,* vol. 79, pp. 1178-1187, 2001.

[11] A. Day, "Brake Design Analysis," ed, 2014, pp. 97-148.

[12] R. C. Hibbeler, *Statics and mechanics of materials*, Fifth edition in SI units. ed. Harlow, United Kingdom: Pearson Education Limited, 2019.

[13] G. Boothroyd, W. A. Knight, and P. Dewhurst, *Product design for manufacture and assembly*, Third edition. ed. Boca Raton, Florida ;: CRC Press, 2011.

# Appendix A – Brake Calliper Piston Sizing Calculations

Formulae from Race Car Design, by Derek Seward [1].

The following table shows input parameters of the vehicle related to section 1.1 of this report. The outputs were considered to be the relevant worst-case load experienced by the brake calliper based on design parameters of the number of pistons and their diameter.

| Parameter Inputs | Value | | Outputs | Value | |
|---|---|---|---|---|---|
| Mass of car and driver [kg] | 305 | 70kg driver | Weight force, W [N] | 2992.05 | |
| Wheelbase, L [mm] | 1510 | | Static axle load front [N] | 1346.42 | |
| COM Height, hm [mm] | 300 | | Static axle load rear [N] | 1645.63 | |
| COM to Front Axle, xm [mm] | 830.5 | | Total braking force, F [N] | 4188.87 | |
| | | | | | |
| Tyre/Road friction coefficient, µs | 1.4 | | Longitudinal weight transfer [N] | 832.23 | |
| Pad/Rotor friction coefficient, µk | 0.32 | | Front wheel load (each) [N] | 1089.32 | 36% |
| | | | Rear wheel load (each) [N] | 406.70 | 14% |
| | | | | | |
| Tyre rolling radius [mm] | 210 | | Rear wheel brake force req. [N] | 569.38 | |
| Rotor outer dia. [mm] | 184 | | Rear wheel brake torque, Tbr [Nm] | 119.57 | |
| Rotor minor dia. [mm] | 141 | | Rear calliper clamp force, Fcf [N] | 2299.42 | |
| Mean radius. [mm] | 81.25 | | Rear system fluid pressure, Pbr [kPa] | 3659.65 | |
| | | | Rear system fluid pressure, Pbr [PSI] | 530.77 | |
| Pedal forcce ratio* | N/A | | | | |
| Master cylinder piston area [mm^2] | N/A | | Front wheel brake force req. [N] | 1525.05 | |
| | | | Front wheel brake torque, Tbr [Nm] | 320.26 | |
| Calliper piston dia. [mm] | 20 | | Front calliper clamp force, Fcf [N] | 6158.87 | |
| Number of pistons per rear, N | 2 | | Front system fluid pressure, Pbr [kPa] | 4901.07 | |
| Number of pistons per front, N | 4 | | Front system fluid pressure, Pbr [PSI] | 710.82 | |
| | | | | | |
| | | | Piston Area [m^2] | 0.000314 | |

Clamp force:

$$Calliper\ clamping\ force, F_{cR} = \frac{Brake\ torque, T_{bR}}{2 \times r_{rotor} \times \mu_{pads}}$$

Static axle loads and total braking force:

$$W_R = (305)(9.81)\left(\frac{830.5}{1510}\right) = 1645\ N$$

$$F_{brakingTotal} = (305)(9.81)(1.4) = 4188.87\ N$$

Dynamic rear axle load:

$$F_{rearWheel} = (W_R - dynamic\ weight\ transfer)/2 = 406.7\ N$$

Rear brake force and torque (max):

$$F_{brake} = F_{rearWheel}\mu_{tyre} = 406.7 \times 1.4 = 569.4\ N$$

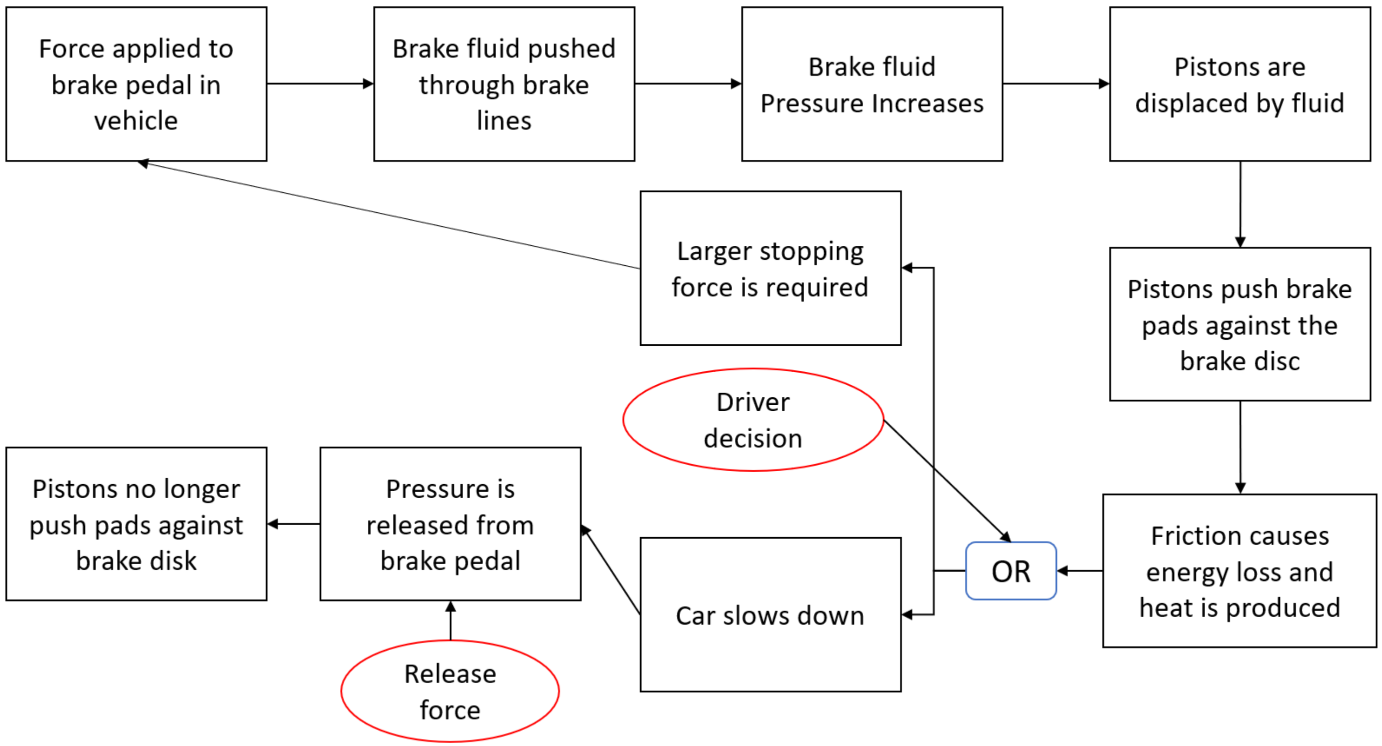
$$T_{brake} = F_{brake} \times r_{rotor} = 119.57\ Nm$$

Rear fluid pressure:

$$P_{bR} = \frac{F_{cR}}{A_{pistons}} = 3659.7\ kPa$$

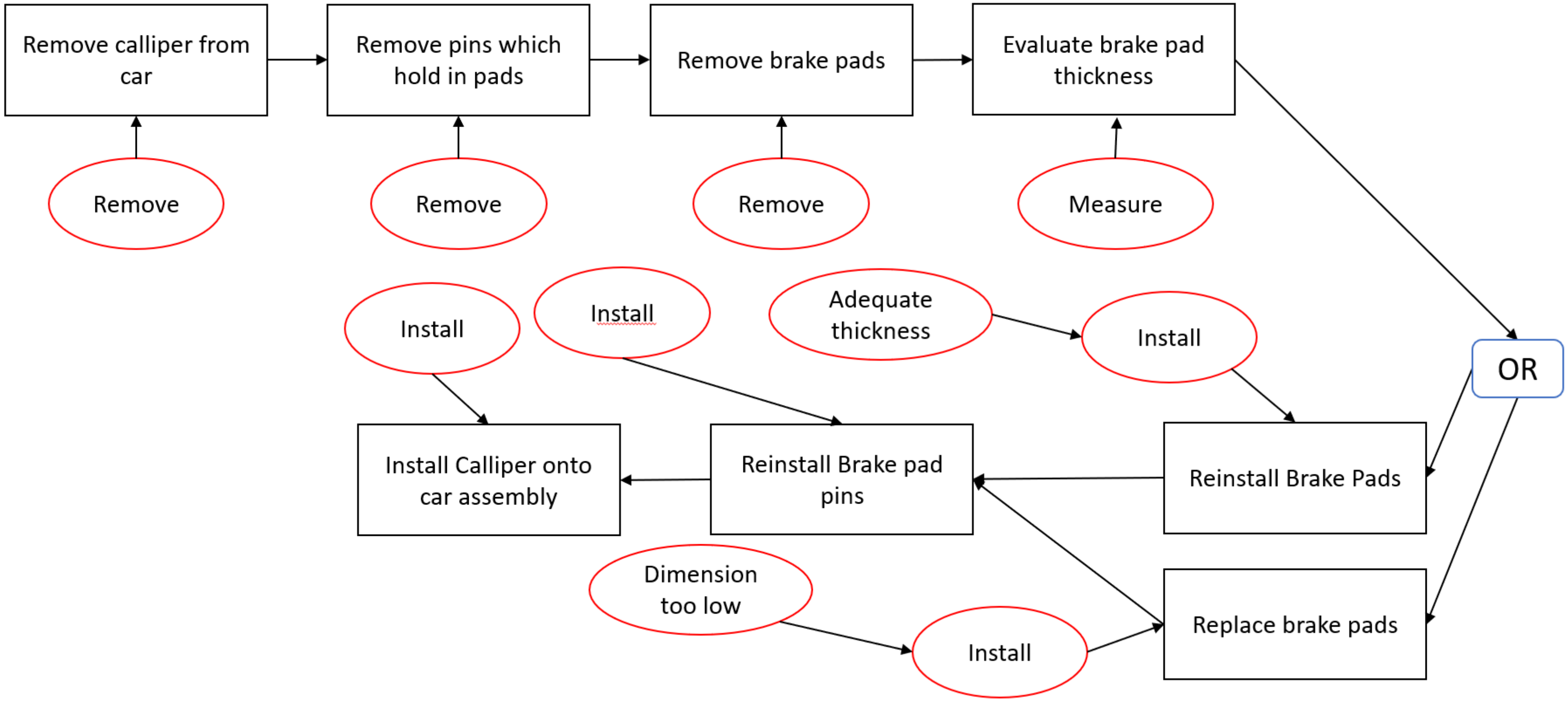
# Appendix B – Concept Design 1 FFBDs

**1 – Brake Operation**



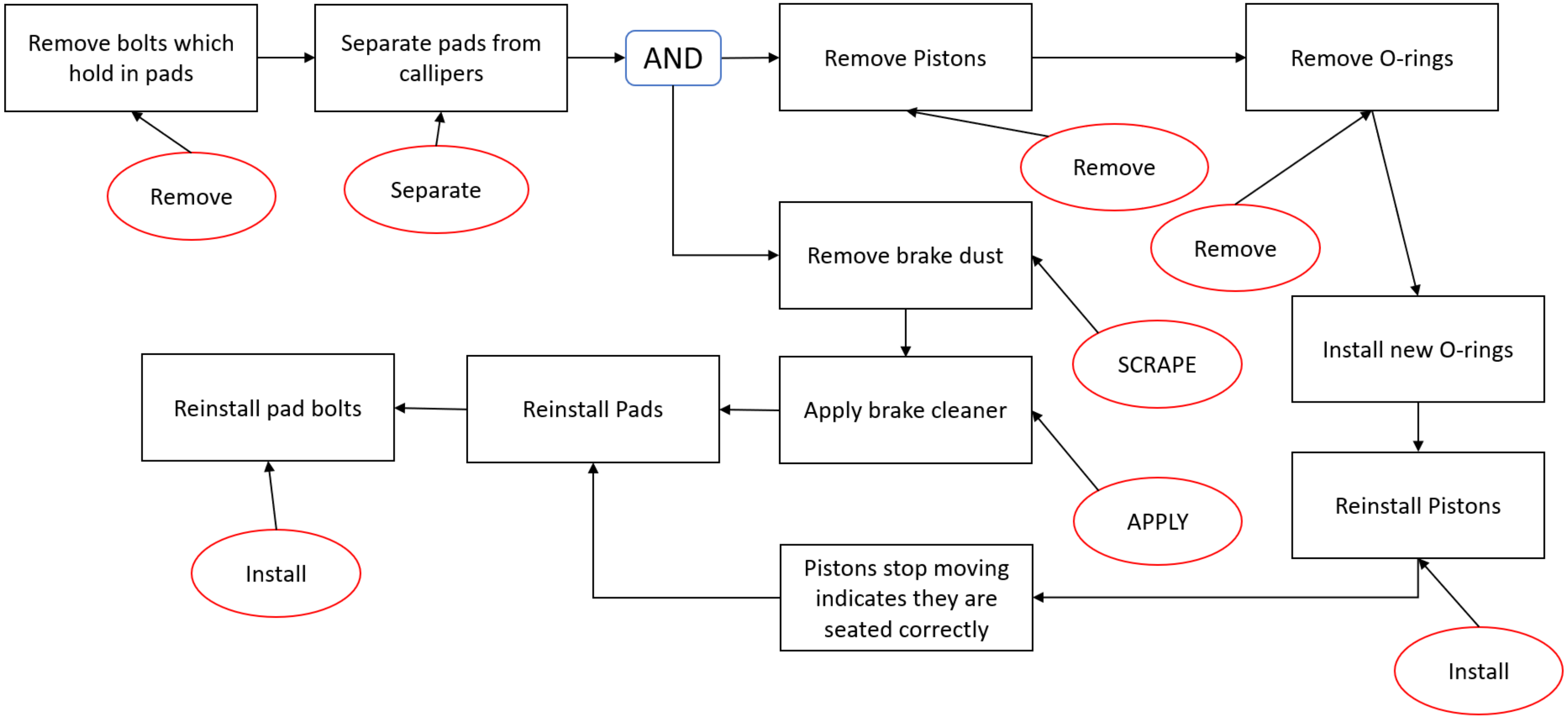

This is the cycle of basic brake operation for the vehicle. As the driver uses their leg to push on the brake pedal, brake fluid will be sent through the brake lines and push against the pistons. The harder the driver presses the brake, the faster they will slow down. During this process, significant amounts of heat will be produced as a result of the friction between brake pads and brake rotors. If the driver presses the brakes too hard, then the pistons will exert enough force to lock the rear wheels as there is no ABS.

**2 – Replacing Brake Pads**




This is the basic process of replacing the brake pads. As the pads must be removed from the inside radius of the calliper, the whole brake assembly must be removed from the car to replace the pads. Once this is done, the pins are removed from which the brake pads will come out. The brake pads must be replaced if there is little to no more material left on them. This is important as if there is no brake pad material then the brakes will not work. Once this is done, the brake calliper assembly can be attached back onto the car.

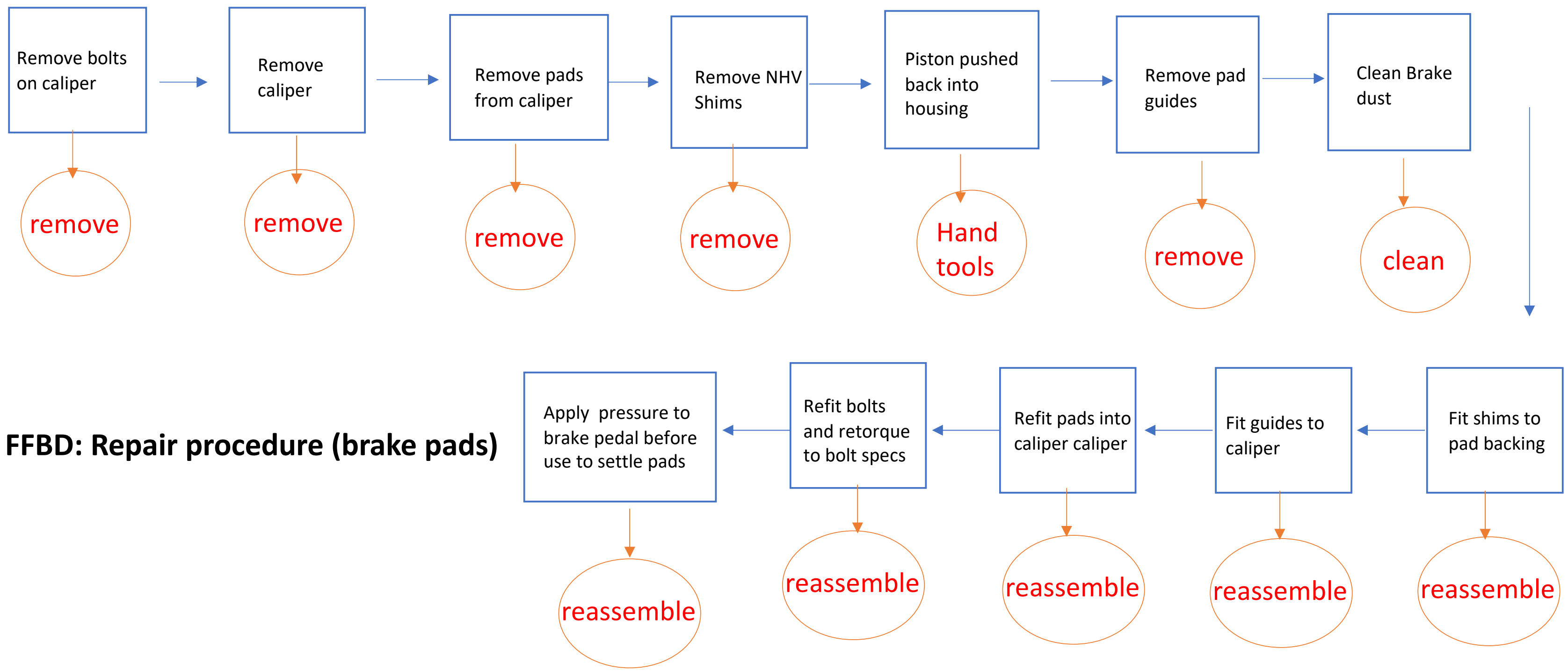
**3 – Calliper Maintance**




This is the process for maintaining the brake calliper. This will be an irregular process however it is done to ensure the best braking performance. Firstly, the entire brake calliper assembly is disassembled. From there the calliper housing is cleaned from any brake dust and other unwanted grime. Secondly the O-rings are replaced as these may deteriorate over time. Then the pistons are seated into the calliper housing. Lastly, the calliper is assembled.

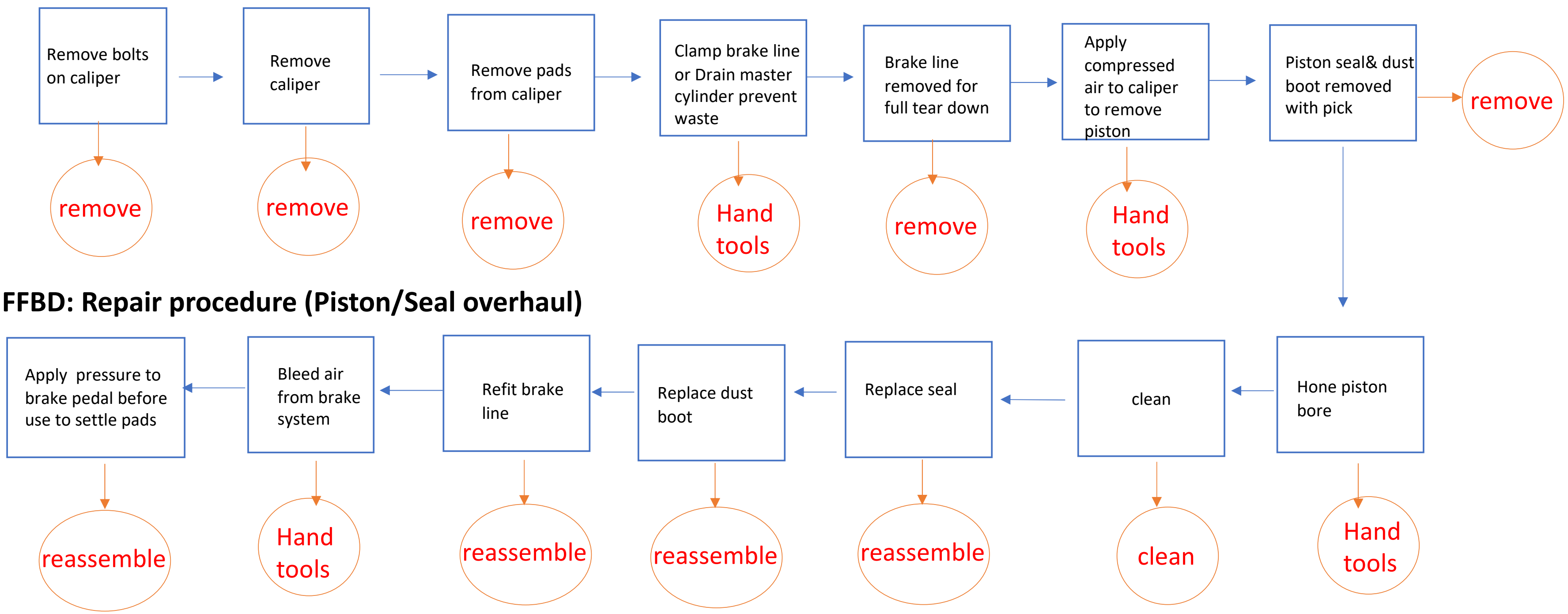
## Appendix C – Concept Design 2 FFBDs

### Design Concept 2.2 Todd – FFBD a.



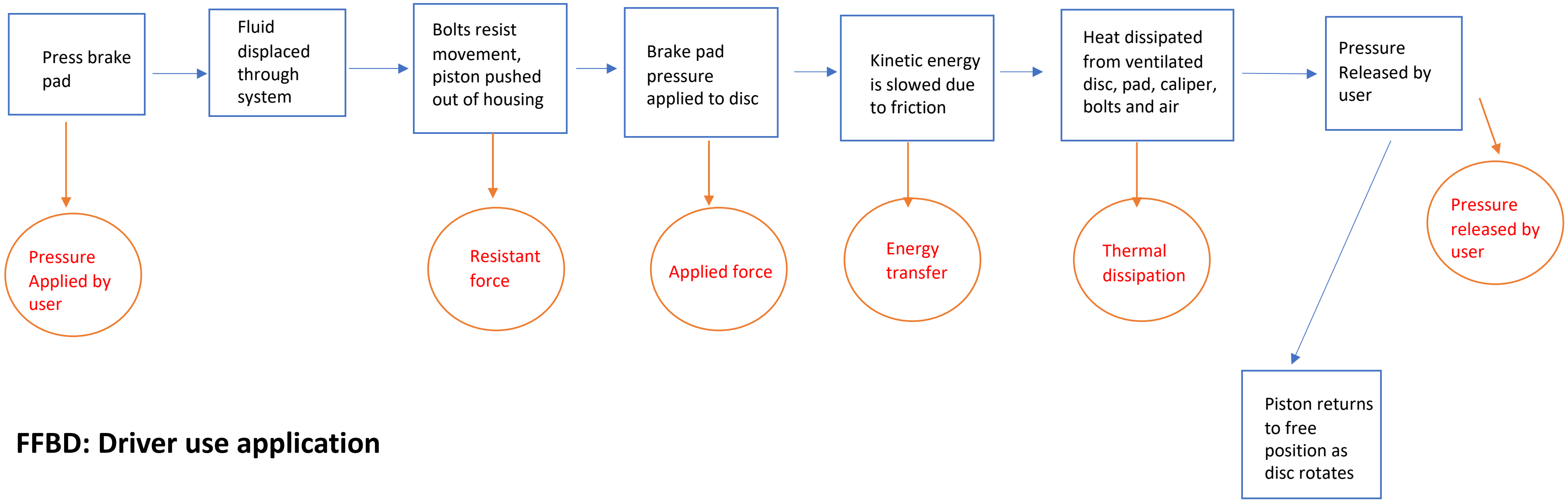

This procedure is for the replacement of the brake pads, operation is completed with wheel removed. Basic hand tools such as 10mm & 12mm spanner and piston compressor are used. Brake caliper can be cleaned and reassembled using the original parts if low amount of use is experienced as is sufficient with an FSAE vehicle. New Pads, shims and pad guides can be replaced at the reassembly stage.

# Design Concept 2.2 Todd – FFBD b.




This procedure is to overhaul the brake caliper if dirty brake fluid or damage has occurred inside the brake piston bore. This could result from rust build up from no piston travel or dirt entering system past the piston seals. Brake cleaner should be used in the cleaning process and care used to address removal of piston seal to reduce scratching of the bore. After honing ensure all excess hone stone is cleaned out. Small amount of brake fluid should be applied on installation to seal to aid reinstallation.

# Design Concept 2.2 Todd – FFBD c.

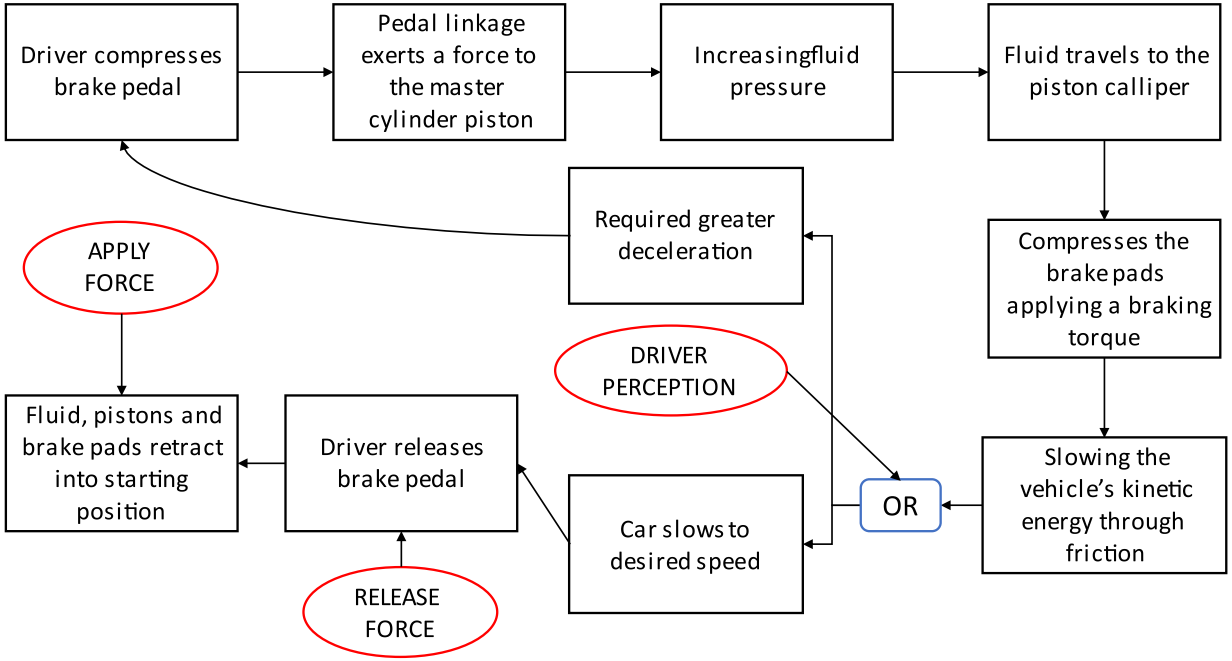



**FFBD: Driver use application**

Procedure follows the main function of the system to stop or decelerate the vehicle with applied force through the user's leg onto brake pedal through to master cylinder, brake lines and applied to each brake caliper. Brake fluid will need to resist the temperature changes in the system as the braking force is changed to thermal energy. Brake efficiency should remain unchanged regardless of number of cycles of the system.

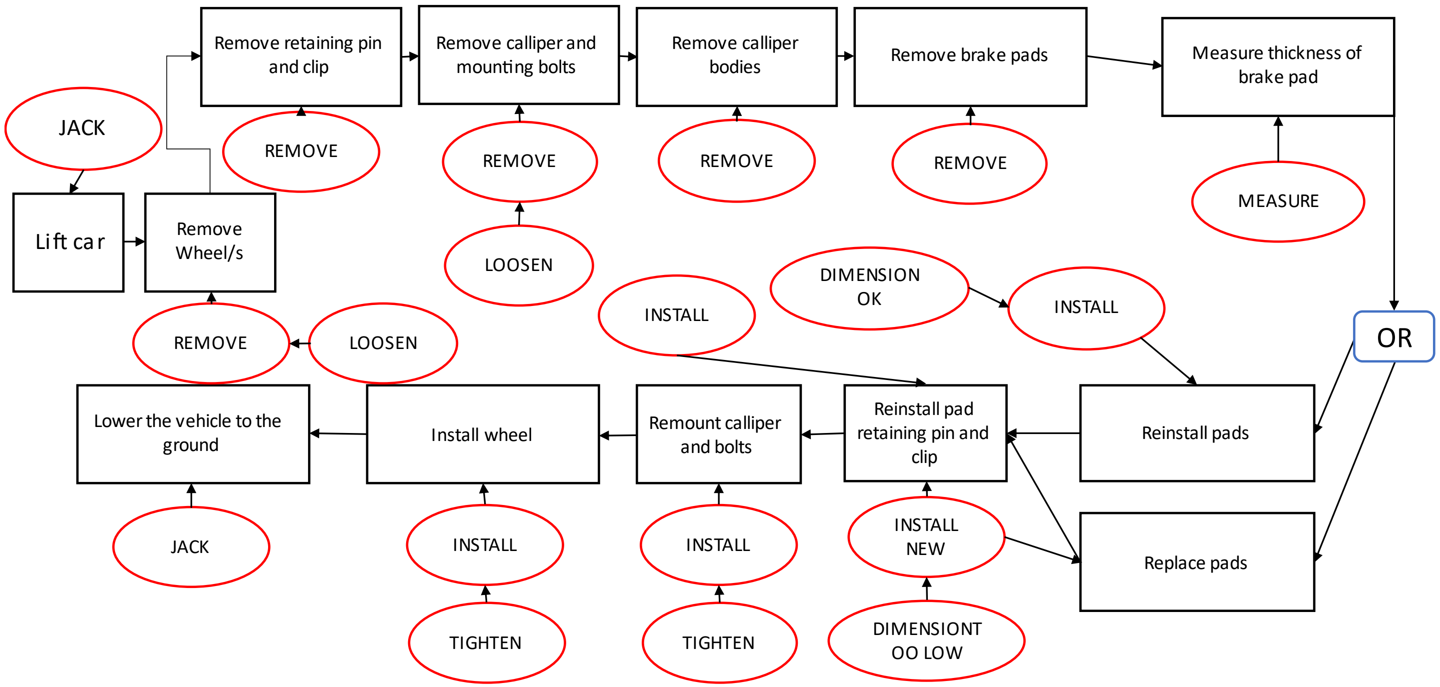
# Appendix D – Concept Design 3 FFBDs

1. Braking



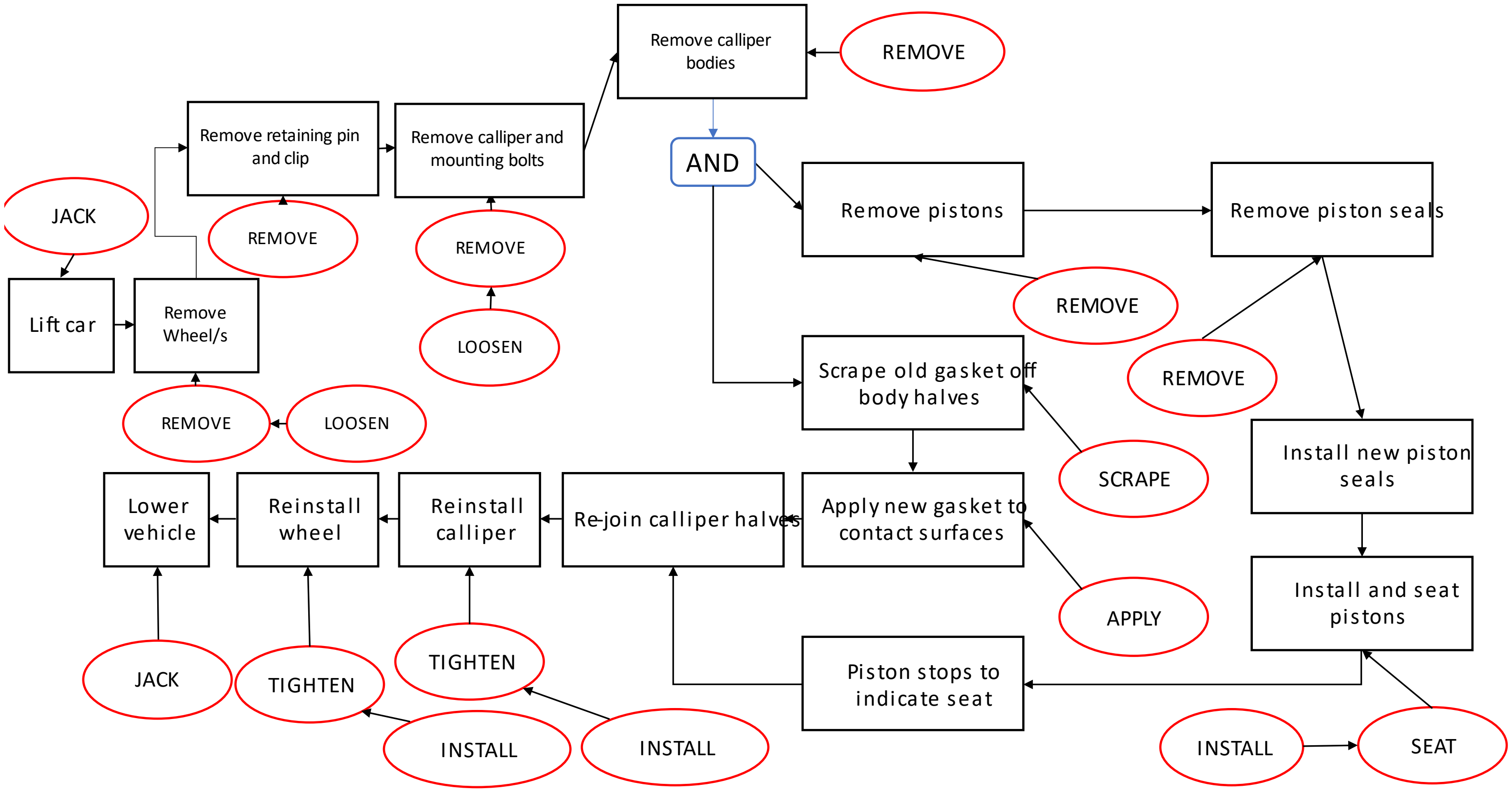

This braking system has limited functions and operation modes. This FFBD encapsulates its braking procedure. The driver exerts a braking force onto the braking pedal which drives a mechanical linkage connected to the master cylinder piston increasing fluid pressure and displacing the pistons which clamps the brake pads together. This generated braking torque slows the kinetic energy of the vehicle through heat dissipation. The initial braking force either generates sufficient braking or the driver compresses the brake pedal further or longer for desired braking. Once braking is complete the fluid, pistons and brake pads retract into the starting position completing the operation cycle.

2. Brake Pad Maintenance




The braking systems includes several service operations. This FFBD displays the maintenance of brake pad wear and damage which is a significant operation required to maintain the safety and performance of the vehicle. Assuming the brake pads have been installed and used, the car must be lifted to remove the wheels which are fastened by a set of bolts. Once the calliper is accessible the retaining pin and clip must be carefully removed as the clip is the most fragile piece of the assembly. The retaining pin holds the brake pad thus the brake pads will be disconnected but housed in the calliper bodies. The calliper bodies must be separated which requires the calliper bolts to be initially loosen but removed after the mounting bolts. Once the calliper bodies are separated the brake pads can be removed and measured. The brake pads must be replaced if the dimensions are too low but can be reused if sufficient. Now, the system can be reassembled, reinstalling the retaining pin and clip, bolts and wheel and lowered back down.

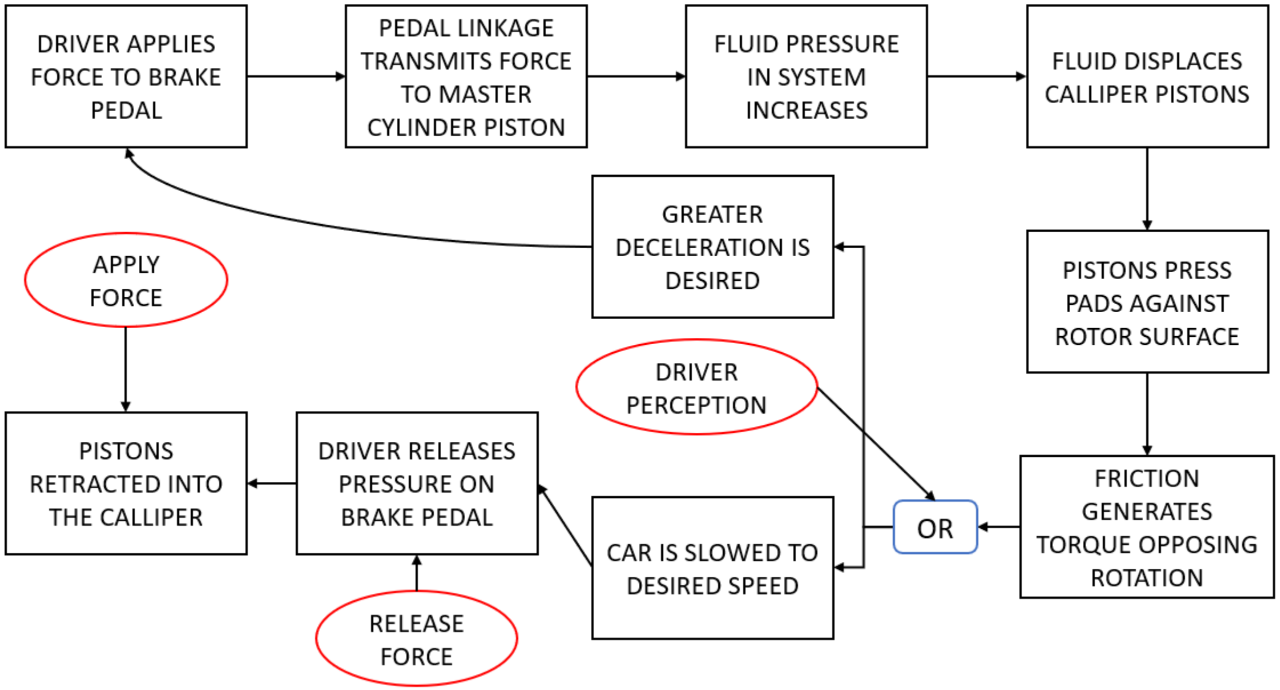
3. Brake System Overhaul




This FFBD displays the procedure required to completely overhaul the brake calliper due to faulty operation or contaminates surrounding the piston. The vehicle must be lifted to removed the rear wheel/s to access the brake callipers. All connecting components must be removed following the brake pad procedure to separate the calliper bodies. This allows accessbility to the internal components of the brake calliper allowing the maintenance and replacement of piston/s, seals and gaskets. Following sufficient maintenance the brake calliper can be reassembled the wheel/s can reinstalled and lowered back down. NOTE, this design doesn't include any fluid interface being a preliminary design, thus operations regarding bleeding are not encapsulated.

# Appendix E – Concept Design 4 FFBDs

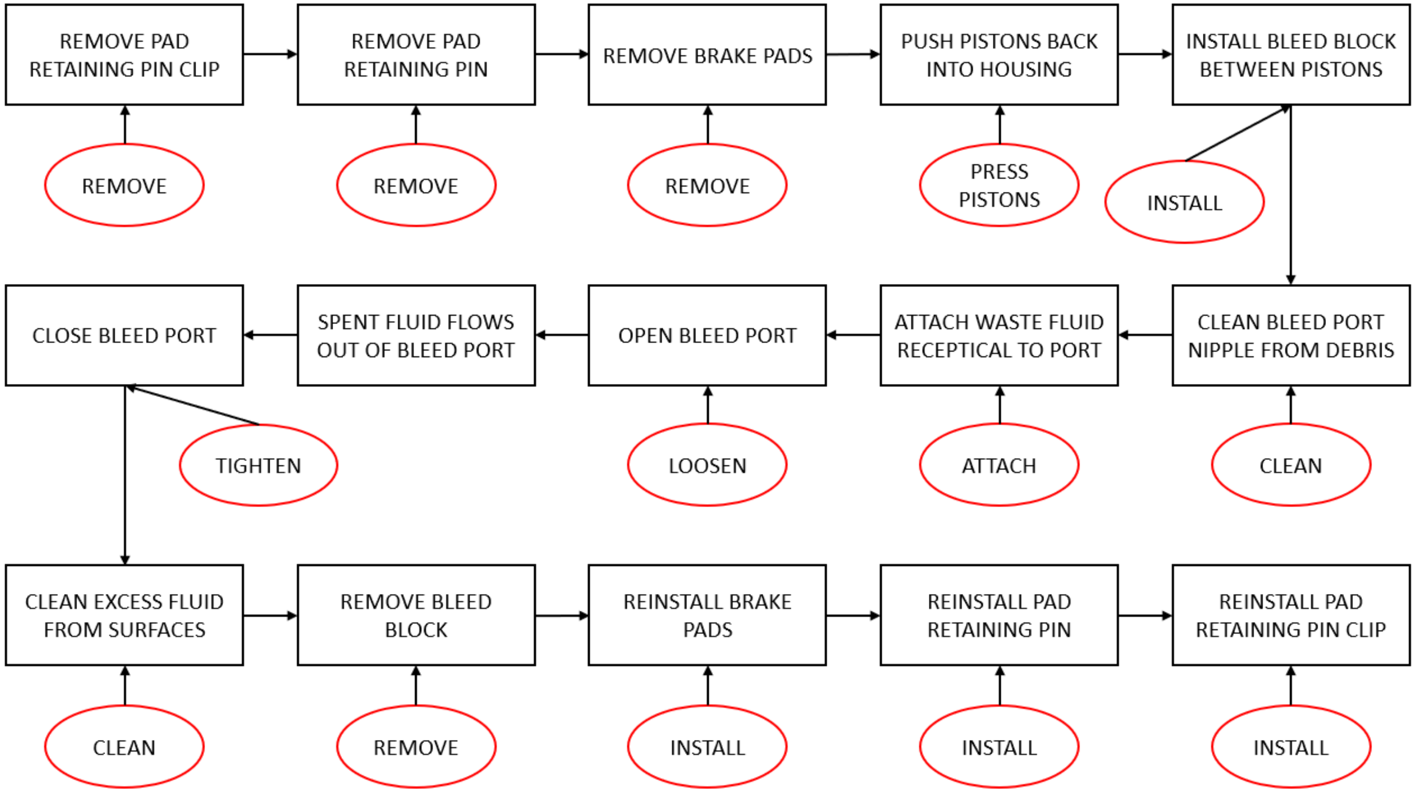
**1 – BRAKE OPERATION BY DRIVER**




Operation of the brake calliper extends beyond the calliper assembly itself as the whole brake system is interfaced with the calliper. Here, the FFBD considers the driver, the brake rotor and all elements of the system in-between as this better illustrates the inputs/outputs involved.

The driver applies force to the brake pedal which in-turn actuates a piston in the master cylinder via a linkage. The linkage incorporates a leverage ratio achieve the desired pressure without using a large piston area. The pressure is transmitted to the calliper via brake lines where it displaces the pistons from the calliper body. As the pads contact the rotor, a normal force is generated, resulting in friction proportional to the pedal force. The driver may increase or decrease pedal pressure based on their perception of the car's deceleration. Once the driver releases pressure on the pedal, the elastic seal in the piston bore applies a restoration force on the piston, retracting it a small enough distance to relieve pressure on the brake pads.

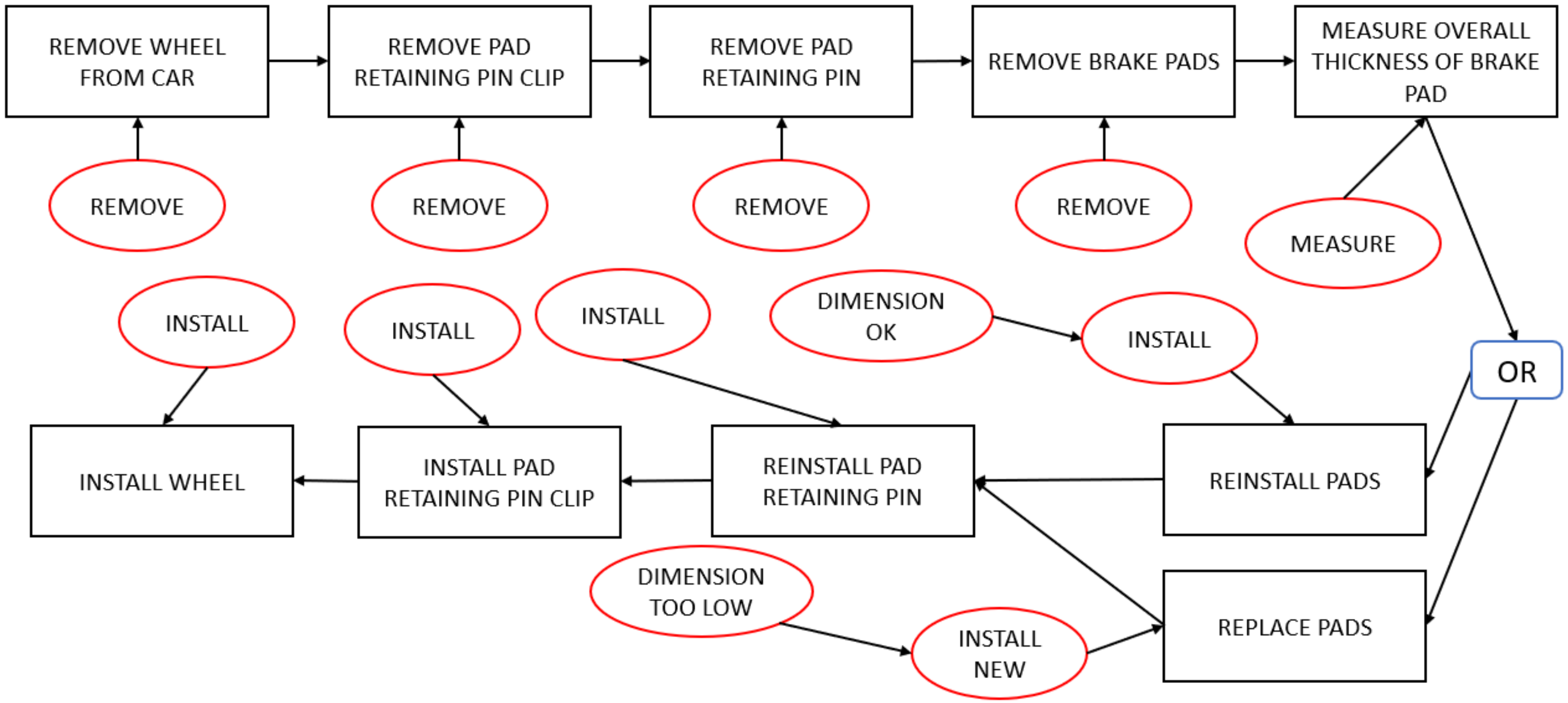
**2 – FLUID BLEED FROM BRAKE CALLIPER**




Bleeding the brake calliper is done to remove air from within the brake fluid channels that would otherwise form a compressible medium and result in poor brake pedal feel and possible failure in extreme cases. Bleeding is also done to replace spent or dirty fluid without introducing air. The process can generally be done with the brake calliper on the car. Standard tools are used other than the “bleed block” which is a device that correctly spaces the pistons within the calliper so that an appropriate fluid volume is maintained in the system. The process begins with the wheel already removed from the hub.

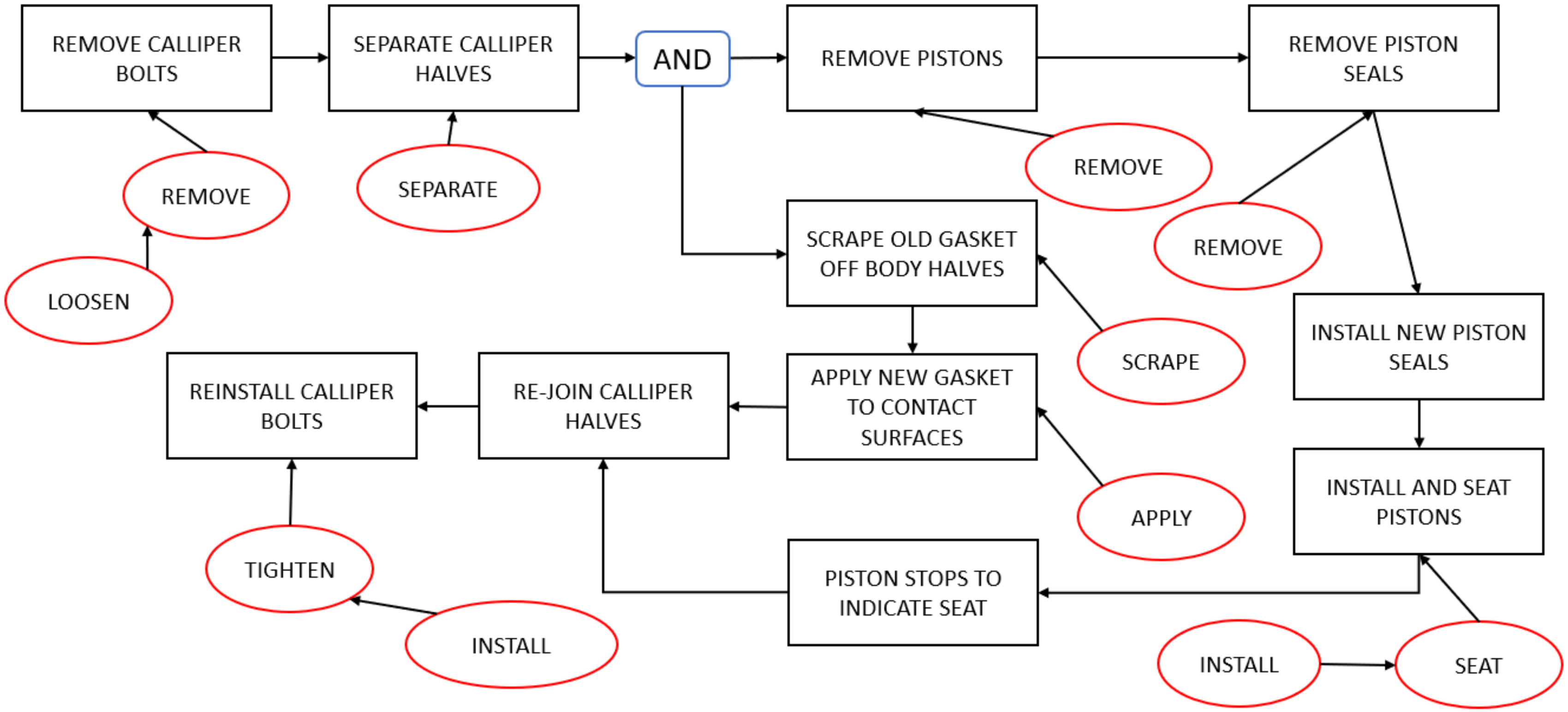
First, the brake pads are removed to avoid contamination. The pistons are then pushed back into the calliper body before the bleed block is installed. A waste fluid receptacle is attached via a rubber tube to the bleed port before the port is opened, allowing fluid and air to escape. It is worth noting that this FFBD does not include processes done at the master cylinder end of the system. Once bleeding is complete, the calliper must be cleaned to avoid contamination of the brake pads. Finally, the bleed block is removed and the pads are reinstalled, ready for operation.

**3 – MAINTAIN BRAKE PAD WEAR AND DAMAGE**




Brake pads wear naturally due to friction and abrasion from the rotor. Periodic inspection of the brake pads is necessary to ensure adequate friction material remains and performance is maintained. Inspection of the brake pads may trigger replacement if the thickness dimension is less than that specified by the pad manufacturer as the minimum allowable. First, the wheel is removed from the car to facilitate access to the brake calliper. The brake pads are removed and measured by the maintenance personnel using vernier callipers. If the thickness is too low, the pads are replaced; otherwise, the pads are reinstalled as there is still useful life in them.

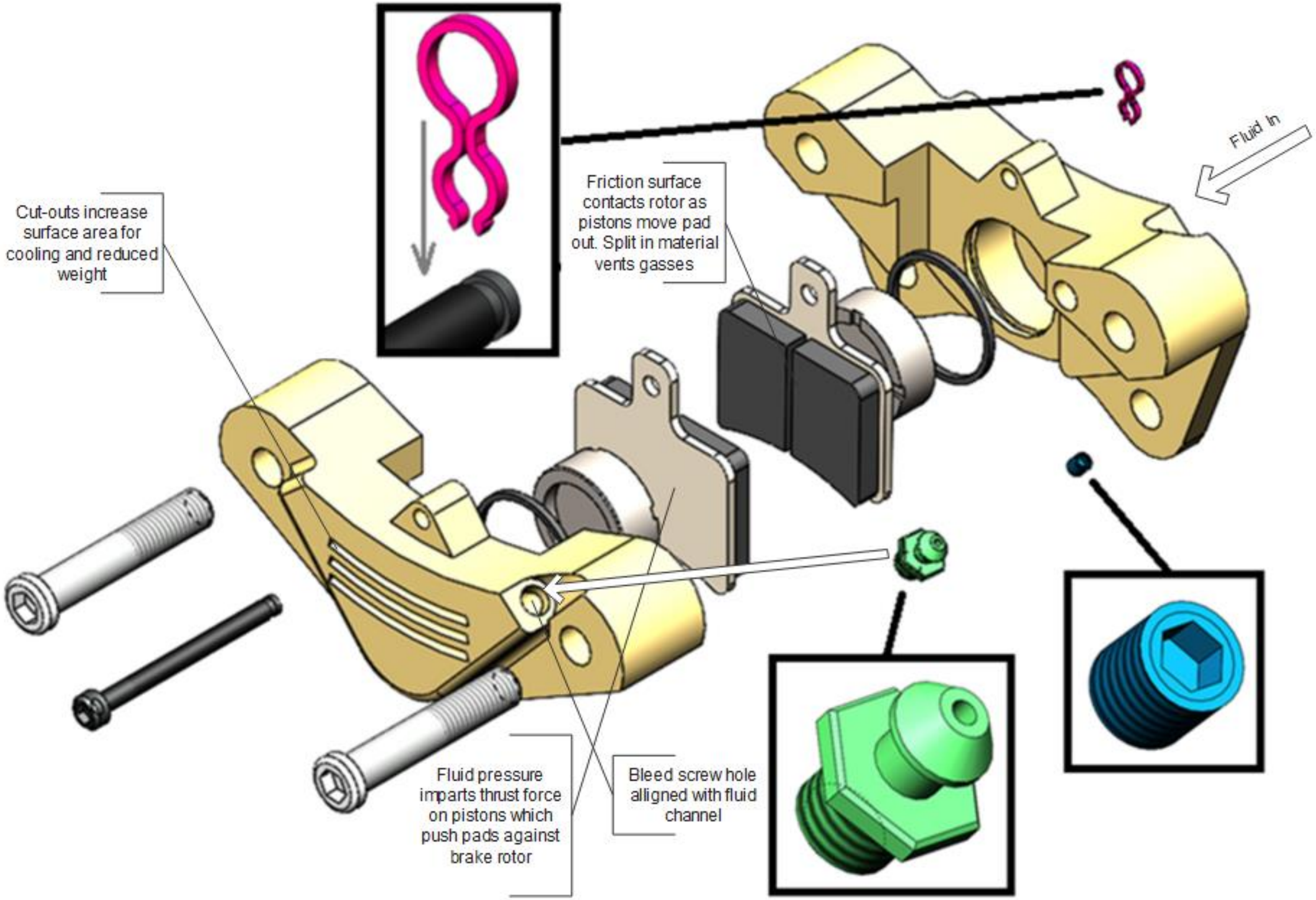
**4 – OVERHAUL BRAKE CALLIPER**




An overhaul of the brake calliper may be done on occasions when calliper performance is reduced by general wear of the piston seals or when a leak has formed. Replacement of a piston due to damage is also considered cause for an overhaul. The need for this function is related to accessibility of the various components within the calliper assembly. If one needs to be replaced, the design must facilitate that. The overhaul process begins with the calliper detached from the upright and drained of fluid.

First, the calliper halves are separated by removing the calliper bolts. In parallel, the pistons are removed from the calliper halves and the gasket seal on the interfaces is replaced to prevent leaks. Removal of the pistons facilitates replacement of the pistons and/or seals but also allows access to the fluid channels which may become blocked on rare occasions if contamination is present. Once replacement parts are installed, the calliper halves are re-joined and sealed by tightening the calliper bolts firmly. Upon completion, the bleeding process must be undertaken (refer to FFBD 2).

# Appendix F – Architectural Exploded View Drawing of Selected Concept Design



# Appendix G – DFA Reference Charts

Manual Handling/insertion time chart (Boothroyd et.al,2010, pp. 83-84)

**MANUAL HANDLING-ESTIMATED TIMES (s)**

Key:

**One hand** — Parts can be grasped and manipulated by one hand without the aid of grasping tools

| | | Parts are easy to grasp and manipulate | | | | | Parts present handling difficulties (1) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Thickness >2 mm | | | Thickness ≤2 mm | | Thickness >2 mm | | | Thickness ≤2 mm | |
| | | Size >15 mm | 6 mm ≤ size ≤15 mm | Size <6 mm | Size >6 mm | Size ≤6 mm | Size >15 mm | 6 mm ≤ size ≤15 mm | Size <6 mm | Size >6 mm | Size ≤6 mm |
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| (α+β) < 360° | 0 | 1.13 | 1.43 | 1.88 | 1.69 | 2.18 | 1.84 | 2.17 | 2.65 | 2.45 | 2.98 |
| 360° ≤ (α+β) < 540° | 1 | 1.5 | 1.8 | 2.25 | 2.06 | 2.55 | 2.25 | 2.57 | 3.06 | 3 | 3.38 |
| 540° ≤ (α+β) < 720° | 2 | 1.8 | 2.1 | 2.55 | 2.36 | 2.85 | 2.57 | 2.9 | 3.38 | 3.18 | 3.7 |
| (α+β) = 720° | 3 | 1.95 | 2.25 | 2.7 | 2.51 | 3 | 2.73 | 3.06 | 3.55 | 3.34 | 4 |

**One hand with grasping aids** — Parts can be grasped and manipulated by one hand but only with the use of grasping tools

| | | | Parts need tweezers for grasping and manipulation | | | | | | | | Parts need standard tools other than tweezers | Parts need special tools for grasping and manipulation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Parts can be manipulated without optical magnification | | | | Parts require optical magnification for manipulation | | | | | |
| | | | Parts are easy to grasp and manipulate | | Parts present handling difficulties (1) | | Parts are easy to grasp and manipulate | | Parts present handling difficulties (1) | | | |
| | | | Thickness >0.25 mm | Thickness ≤0.25 mm | Thickness >0.25 mm | Thickness ≤0.25 mm | Thickness >0.25 mm | Thickness ≤0.25 mm | Thickness >0.25 mm | Thickness ≤0.25 mm | | |
| | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| α ≤ 180° | 0 ≤ β ≤ 180° | 4 | 3.6 | 6.85 | 4.35 | 7.6 | 5.6 | 8.35 | 6.35 | 8.6 | 7 | 7 |
| α ≤ 180° | β = 360° | 5 | 4 | 7.25 | 4.75 | 8 | 6 | 8.75 | 6.75 | 9 | 8 | 8 |
| α = 360° | α ≤ β ≤ 180° | 6 | 4.8 | 8.05 | 5.55 | 8.8 | 6.8 | 9.55 | 7.55 | 9.8 | 8 | 9 |
| α = 360° | β = 360° | 7 | 5.1 | 8.35 | 5.85 | 9.1 | 7.1 | 9.55 | 7.85 | 10.1 | 9 | 10 |

**Two hands for manipulation**

| | | Parts present no additional handling difficulties | | | | | Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | α ≤ 180° | | | α = 360° | | α ≤ 180° | | | α = 360° | |
| | | Size >15 mm | 6 mm≤ size ≤15 mm | Size <6 mm | Size >6 mm | Size ≤6 mm | Size >15 mm | 6 mm≤ size ≤15 mm | Size <6 mm | Size >6 mm | Size ≤6 mm |
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2) | 8 | 4.1 | 4.5 | 5.1 | 5.6 | 6.75 | 5 | 5.25 | 5.85 | 6.35 | 7 |

**Two hands or assistance required for large size**

| | | Parts can be handled by one person without mechanical assistance | | | | | | | | | Two persons or mechanical assistance required for parts manipulation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Parts do not severely nest or tangle and are not flexible | | | | | | | | Parts severely nest or tangle or are flexible (2) | |
| | | Part weight < 10 lb | | | | Parts are heavy (>10 lb) | | | | | |
| | | Parts are easy to grasp and manipulate | | Parts present other handling difficulties (1) | | Parts are easy to grasp and manipulate | | Parts present other handling difficulties (1) | | | |
| | | α ≤ 180° | α = 360° | α ≤ 180° | α = 360° | α ≤ 180° | α = 360° | α ≤ 180° | α = 360° | | |
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Two hands, two persons or mechanical assistance required for grasping and transporting parts | 9 | 2 | 3 | 2 | 3 | 3 | 4 | 4 | 5 | 7 | 9 |

**MANUAL INSERTION-ESTIMATED TIMES (s)**

Key:

Part added but not secured

Addition of any part (1) where neither the part itself not any other part is finally secured immediately

- 0 — Part and associated tool (including hands) can easily reach the desired location
- Part and associated tool (including hands) cannot easily reach the desired location
  - 1 — Due to obstructed access or restricted vision (2)
  - 2 — Due to obstructed access and restricted vision (2)

| | Alter assembly no holding down required to maintain orientation and location (3) | | | | Holding down required during subsequent processes to maintain orientation at location (3) | | | |
|---|---|---|---|---|---|---|---|---|
| | Easy to align and position during assembly (4) | | Not easy to align or position during assembly | | Easy to align and position during assembly (4) | | Not easy to align or position during assembly | |
| | No resistance to insertion | Resistance to insertion (5) | No resistance to insertion | Resistance to insertion (5) | No resistance to insertion | Resistance to insertion (5) | No resistance to insertion | Resistance to insertion (5) |
| | 0 | 1 | 2 | 3 | 6 | 7 | 8 | 9 |
| 0 | 1.5 | 2.5 | 2.5 | 3.5 | 5.5 | 6.5 | 6.5 | 7.5 |
| 1 | 4 | 5 | 5 | 6 | 8 | 9 | 9 | 10 |
| 2 | 5.5 | 6.5 | 6.5 | 7.5 | 9.5 | 10.5 | 10.5 | 11.5 |

Part secured immediately

Addition of any part (1) where the part itself and/or other parts are being finally secured immediately

- 3 — Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily
- Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily
  - 4 — Due to obstructed accessor restricted vision (2)
  - 5 — Due to obstructed access and restricted vision (2)

| | No screwing operation or plastic deformation immediately after insertion (snap/press fits,circlips,spire nuts,etc.) | | Plastic deformation immediately after insertion | | | | | | Screw tightening immediately after insertion | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Plastic bending or torsion | | | Riveting or similar operation | | | | |
| | | | | Not easy to align or position during assembly | | | Not easy to align or position during assembly | | | |
| | Easy to align and position with no resistance to insertion (4) | Not easy to align or position during assembly and/or resistance to insertion (5) | Easy to align and position during assembly (4) | No resistance to insertion | Resistance to insertion (5) | Easy to align and position during assembly (4) | No resistance to insertion | Resistance to insertion (5) | Easy to align and position with no torsional resistance (4) | Not easy to align or position and/or torsional resistance (5) |
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 3 | 2 | 5 | 4 | 5 | 6 | 7 | 8 | 9 | 6 | 8 |
| 4 | 4.5 | 7.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 8.5 | 10.5 |
| 5 | 6 | 9 | 8 | 9 | 10 | 11 | 12 | 13 | 10 | 12 |

Separate operation

9 — Assembly processes where all solid parts are in place

| | Mechanical fastening processes (part(s) already in place but not secured immediately after insertion) | | | | Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion) | | | | Non-fastening processes | |
|---|---|---|---|---|---|---|---|---|---|---|
| | None or localized plastic deformation | | | | Metallurgical processes | | | | | |
| | | | | | | Additional material required | | | | |
| | Bending or similar process | Riveting or similar processes | Screw tightening or other processes | Bulk plastic deformation (large proportion of part is plastically deformed during fastening) | No additional material required (e.g. resistance, friction welding, etc.) | Soldering processes | Weld/braze processes | Chemical processes (e.g. adhesive bonding, etc.) | Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of part(s). etc.) | Other processes (e.g. liquid insertion, etc.) |
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 8 |
| 9 | 4 | 7 | 5 | 12 | 7 | 8 | 12 | 12 | 9 | 12 |

# Appendix H – FMEA Criteria Reference Tables (BS EN 60812:2006)

**Table 4 – Failure mode severity**

| Severity | Criteria | Ranking |
|---|---|---|
| None | No discernible effect. | 1 |
| Very minor | Fit and finish/squeak and rattle item does not conform. Defect noticed by discriminating customers (less than 25 %). | 2 |
| Minor | Fit and finish/squeak and rattle item does not conform. Defect noticed by 50 % of customers. | 3 |
| Very low | Fit and finish/squeak and rattle item does not conform. Defect noticed by most customers (greater than 75 %). | 4 |
| Low | Vehicle/item operable but comfort/convenience item(s) operable at a reduced level of performance. Customer somewhat dissatisfied. | 5 |
| Moderate | Vehicle/item operable but comfort/convenience item(s) inoperable. Customer dissatisfied. | 6 |
| High | Vehicle/item operable but at a reduced level of performance. Customer very dissatisfied. | 7 |
| Very high | Vehicle/item inoperable (loss of primary function) | 8 |
| Hazardous with warning | Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves non-compliance with government regulation with warning. | 9 |
| Hazardous without warning | Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves non-compliance with government regulation without warning. | 10 |

**Table 5 – Failure mode occurrence related to frequency and probability of occurrence**

| Failure mode occurrence | Rating, *O* | Frequency | Probability |
|---|---|---|---|
| Remote: Failure is unlikely | 1 | ≤ 0,010 per thousand vehicles/items | $\leq 1\text{x}10^{-5}$ |
| Low: Relatively few failures | 2 | 0,1 per thousand vehicles/items | $1\text{x}10^{-4}$ |
| | 3 | 0,5 per thousand vehicles/items | $5\text{x}10^{-4}$ |
| Moderate: Occasional failures | 4 | 1 per thousand vehicles/items | $1\text{x}10^{-3}$ |
| | 5 | 2 per thousand vehicles/items | $2\text{x}10^{-3}$ |
| | 6 | 5 per thousand vehicles/items | $5\text{x}10^{-3}$ |
| High: Repeated failures | 7 | 10 per thousand vehicles/items | $1\text{x}10^{-2}$ |
| | 8 | 20 per thousand vehicles/items | $2\text{x}10^{-2}$ |
| Very high: Failure is almost inevitable | 9 | 50 per thousand vehicles/items | $5\text{x}10^{-2}$ |
| | 10 | ≥100 in thousand vehicles/items | $\geq 1\text{x}10^{-1}$ |

**Table 6 – Failure mode detection evaluation criteria**

| Detection | Criteria: Likelihood of detection by Design Control | Ranking |
|---|---|---|
| Almost certain | Design Control will almost certainly detect a potential cause/mechanism and subsequent failure mode | 1 |
| Very high | Very high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 2 |
| High | High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 3 |
| Moderately high | Moderately high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 4 |
| Moderate | Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 5 |
| Low | Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 6 |
| Very low | Very low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 7 |
| Remote | Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 8 |
| Very remote | Very remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode | 9 |
| Absolutely uncertain | Design Control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no Design Control | 10 |

# Appendix I – Gantt Chart Depicting Analysis Timeline

| EGH420 Group 5 | start | end |
|---|---|---|
| **Assessment 3 - due wk 13** | **13/09/21** | **29/10/21** |
| General work towards assessment 3 | 13/09 | 29/10 |
| Report writing and formatting | 21/10 | 29/10 |
| Assessment 3 submission | 29/10 | 29/10 |
| **Design and Analysis** | **13/09/21** | **05/10/21** |
| Calliper body structural and fatigue ... | 13/09 | 24/09 |
| Piston structural and size verification... | 13/09 | 21/09 |
| Piston seal design and analysis (Will) | 21/09 | 27/09 |
| Calliper bolts structural (mounting a... | 13/09 | 21/09 |
| Pad retaining hardware structural (Ja... | 22/09 | 01/10 |
| Brake Pad structural and thermal (To... | 22/09 | 29/09 |
| Bleed nipple and hydraulic fittings d... | 27/09 | 30/09 |
| Fluid passage detail design and pres... | 27/09 | 01/10 |
| Calliper body, piston and pad therma... | 20/09 | 01/10 |
| Fluid channel screws structural (Jaco... | 22/09 | 01/10 |
| Materials selection and justification | 29/09 | 05/10 |
| Design and analysis review meeting | 04/10 | 05/10 |
| **Further Analysis** | **04/10/21** | **14/10/21** |
| HAZOP | 04/10 | 08/10 |
| TBL | 04/10 | 08/10 |
| Report 2 summary and updates to a... | 12/10 | 14/10 |
| **Specification for Production** | **11/10/21** | **29/10/21** |
| Manufacturing drawings | 11/10 | 19/10 |
| Cost list and bill of materials | 11/10 | 22/10 |
| Functional description documentation | 18/10 | 22/10 |
| Design analysis appendix | 11/10 | 29/10 |