CALIFORNIA STATE UNIVERSITY, NORTHRIDGE
Department of Mechanical Engineering

BRAKE ASSEMBLY DESIGN: MATERIALS, MANUFACTURING, AND COST ANALYSIS

ME 286 - Mechanical Engineering Design II
Fall 2025

Submitted to:
Professor Mohab Shalaby, Ph.D. P.Eng.

Prepared by:
Rodrigo Cervantes
Emily Skipworth
Arturo Orozco
Gavin Dion
Vincent Seip
Jovanny Perez-Giron

December 18, 2025

ABSTRACT

High-performance automotive braking systems operate under extreme mechanical loads and severe thermal conditions, requiring careful integration of geometry, material properties, manufacturing feasibility, and economic constraints. As vehicle speeds, power output, and mass continue to increase, braking systems must safely dissipate large amounts of kinetic energy while maintaining consistent frictional performance and structural reliability. The design of such systems therefore represents a multidisciplinary engineering challenge involving solid mechanics, heat transfer, manufacturing science, and cost optimization.

The focus of this project is on design choices, material selection, manufacturing process selection and cost analysis of a high-performance automotive braking system. Modern braking systems must undergo high mechanical and thermal stresses while providing responsiveness, reliability, and durability. The objective of this project is to design and develop a braking assembly that is capable of withstanding the operating and service conditions of a high-performance automotive.

To accomplish this objective, the braking system was evaluated as an integrated mechanical and thermal energy conversion device. Design considerations included the transfer of hydraulic pressure into clamping force, the transformation of kinetic energy into heat at the rotor–pad interface, and the subsequent dissipation of that heat through conduction and convection. These operating principles guided all design, material, and manufacturing decisions.

The scope of the components considered in this project includes the rotor, brake pads, calipers, pistons and other relevant supporting components of the assembly. Each component was analyzed based on their functionality, anticipated mechanical and thermal loads, and geometry. CAD modeling, calculations, and other general engineering analysis aided us in the reasoning behind each design decision.

Each component was evaluated using fundamental engineering principles including stress analysis, heat transfer behavior, and manufacturability considerations. Tradeoffs between performance and cost were assessed by comparing conventional production materials and methods with higher-performance alternatives typically used in motorsports and premium automotive applications.

The report is broken into four chapters. Chapter 1 is the introduction. Chapter 2 focuses on design choices, such as geometry, assembly design, and cooling features. Chapter 3 discusses material selection. This includes an analysis of each material's mechanical and thermal properties, performance, manufacturability, and cost . Chapter 4 presents the manufacturing techniques and processes selection, with a focus on feasibility, scalability, and product efficiency. Chapter 5 is our final cost analysis estimations based on how each design process selection affected the system c

TABLE OF CONTENTS

INTRODUCTION

1.1 - Historical Development of Automotive Braking Systems

Automotive braking systems are among the most critical safety subsystems in any vehicle, as they directly control vehicle deceleration, stopping distance, and overall stability. However, braking technology did not initially receive the same development priority as propulsion during the earliest stages of automobile design. Early vehicles relied on simple mechanical braking mechanisms adapted from horse-drawn carriage systems, including levers that pressed wooden blocks directly against wheel rims. These early brakes suffered from low friction capability, rapid wear, and extremely limited stopping performance, making them unreliable as vehicle speeds increased.

As pneumatic tires replaced solid wheels and vehicles became faster and heavier, braking mechanisms were moved inside the wheel assembly. This transition led to the development of drum and disc brake concepts in the early 20th century. These early braking systems remained fully mechanical and were limited by inconsistent force transmission and poor controllability. In 1917, the introduction of the hydraulic braking system represented a major technological breakthrough. Hydraulic brakes allowed braking force to be transmitted uniformly using pressurized fluid rather than mechanical linkages, greatly improving braking reliability and consistency. The subsequent development of vacuum-assisted brake boosters further amplified driver input force, enabling higher braking forces with reduced pedal effort.

As vehicle performance continued to increase, engineers began addressing the fundamental thermal limitations of early braking systems. Drum brakes, while effective at low speeds, trapped heat and were highly susceptible to thermal fade during repeated braking. This limitation led to the widespread adoption of hydraulic disc brake systems, which offer superior heat dissipation, improved response time, and more consistent braking behavior. Disc brake technology advanced further with the transition from solid rotors to internally ventilated rotors, significantly improving convective heat transfer and thermal stability during sustained braking events. The later adoption of multi-piston fixed calipers allowed braking forces to be distributed more uniformly across the pad surface, improving braking efficiency and reducing uneven wear.

1.2 - Performance and Thermal Motivation for High-Performance Braking Systems

High-performance automotive braking systems operate under extreme mechanical and thermal conditions that far exceed those encountered in conventional passenger vehicles. During braking, a vehicle's kinetic energy is converted almost entirely into thermal energy at the rotor pad interface. Under aggressive driving, track operation, or extended downhill braking, component temperatures can rise rapidly and exceed several hundred degrees Celsius. If this heat is not effectively dissipated, braking performance degrades due to brake fade, material breakdown, and reduced friction coefficient at the contact interface.

Modern braking systems must therefore balance several competing engineering objectives: rapid heat dissipation, structural rigidity, controlled thermal expansion, and long-term durability. To meet these demands, engineers have introduced ventilated rotors, advanced airflow geometries, ceramic-based friction materials, and high-temperature coatings. These features enhance heat rejection and maintain braking effectiveness during repeated high-energy braking cycles.

The demand for improved braking performance has been especially pronounced in motorsports and premium automotive applications. In these environments, braking efficiency, consistency, and thermal endurance directly influence lap time, safety, and vehicle control. As a result, manufacturers have increasingly adopted lightweight structural materials such as aluminum to reduce unsprung mass and improve suspension response. More recently, advanced materials such as forged aluminum alloys, ceramic-based friction materials, and carbon-ceramic composite rotors have been introduced to further improve thermal resistance, stiffness, and wear performance under extreme operating conditions.

While these advanced materials significantly expand the performance envelope of braking systems, they also introduce substantial increases in manufacturing complexity and system cost. As a result, modern braking system design represents a continuous trade-off between thermal performance, mechanical integrity, manufacturability, and economic feasibility.

1.3 - Design for Manufacturing and Cost Drivers in Brake Systems

As braking systems evolved to meet modern performance demands, engineers were required to balance increased design complexity with the realities of mass production. This balance is governed by the principles of Design for Manufacturing (DFM), which require that components be designed not only for optimal performance but also for consistent, economical production at scale.

Key DFM considerations in braking systems include draft angles and wall thickness for cast components, machinability of caliper bores and piston chambers, tolerance control for hydraulic sealing, and consistent bonding of friction material to backing plates. Manufacturing route selection—such as casting, forging, stamping, and CNC machining—directly affects material utilization, cycle time, tooling costs, and final part quality.

Although the brake system functions as a single integrated assembly, overall system cost is driven by a small number of high-complexity components. Among the most significant cost contributors are the brake calipers, rotors, and master cylinder assembly. High-performance calipers frequently employ multi-piston configurations, which require precise machining and tight dimensional tolerances. This complexity increases both manufacturing time and cost. Likewise, high-performance rotors experience severe thermal loading and are often produced from high-carbon iron or ceramic-based composites, significantly increasing material and processing costs.

Additional cost drivers include advanced friction materials, anti-lock braking system (ABS) integration, and the increased maintenance requirements associated with performance-oriented components. These factors highlight the economic consequences of performance-driven design decisions and motivate the need for careful material and manufacturing process selection.

1.4 - Project Objective

The primary objective of this project is to design, model, and evaluate a high-performance automotive disc brake system and compare it to conventional brake systems with respect to geometric design, material selection, thermal behavior, manufacturing feasibility, and preliminary cost.

This project integrates mechanical design, materials engineering, manufacturing process analysis, and economic evaluation to provide a complete system-level engineering assessment rather than a purely geometric modeling exercise.

1.5 - Project Scope and System Overview

The braking system examined in this project consists of the following primary components:

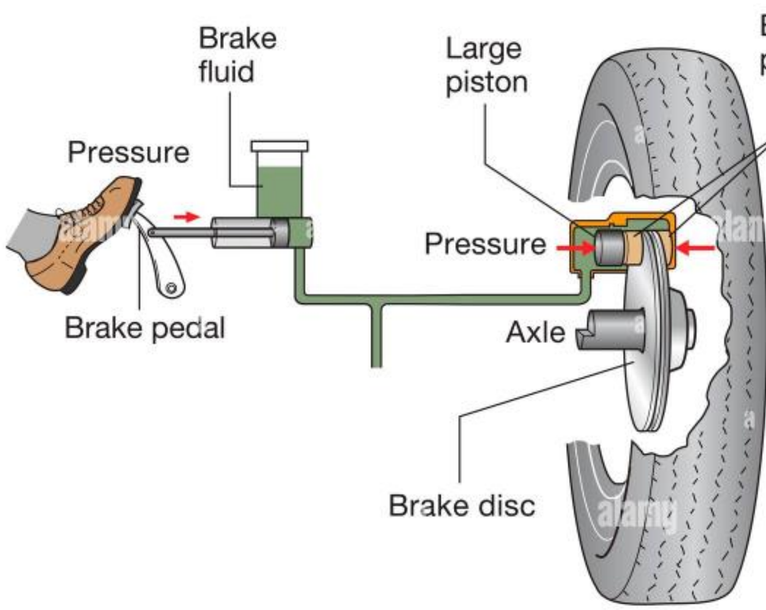
- Brake rotor
- Brake caliper
- Hydraulic pistons
- Brake pads and backing plates

Each component is evaluated based on its functional role within the braking system, anticipated mechanical and thermal loads, geometric constraints, and compatibility with selected manufacturing processes. SolidWorks CAD modeling, analytical calculations, and general engineering analysis were used to guide all major design decisions and to ensure that the system functions as a fully integrated braking assembly.

CHAPTER 2 - DESIGN CHOICES

2.1 - Introduction

When designing and/or manufacturing anything, the key element to how the part or component will operate and perform is the material selection. Another key element is the design of the parts and the assembly as a whole. The materials used when designing something such as a braking system, and the design of the system (what is being analyzed here), must have certain qualities and properties to complete the task in which it is being used for, while also doing it well. Moreover, the design of each component is crucial to the performance and efficiency of a system. In this section, each component will be broken down explaining function, design features, potential issues, and ease of assembly features.



<u>Fig 2.1.1</u> Brake System Visualization.

2.2 - System Level Braking Operations

The braking system starts with the initiation of the driver compressing the brake pedal which uses hydraulic force to compress brake caliper pistons to then push against abrasive brake pads to push against a spinning rotor mated with the wheel in motion, the brake pads then create friction which is an opposing force to the brake rotor in motion thus dissipating energy in motion to reduce speed or shift weight. Hydraulic brake pressure is generated by having a closed pressurized system where the input of the brake pedal is relative to the clamping action/ force of the brake system. It has been a very effective design seen across various models, each model carrying various methods of counteracting drawbacks and limitations of the initial design. One of the drawbacks of this design where friction force is primarily used to reduce speed is heat generation. Excessive heat is generated from the clamping of the pads against the rotors and flows uniformly from the contact patch to the rest of the braking system.

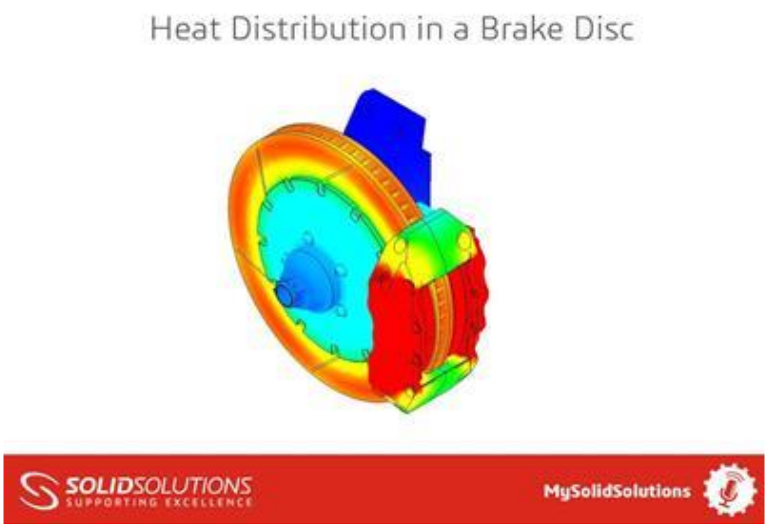


Fig 2.2.1 Heat Distribution.

2.3 - Rotor Design and Geometry

Performance brake systems have the goal of providing superior braking in the form of initial bite, braking over total distance, heat dissipation and longevity. The rotor design features a larger diameter then stock oem to provide more surface area to generate more friction force. The increased diameter helps with total heat absorption taking longer to over heat and the drilled holes allow air to move through the rotor to help with cooling which contributes to overall longevity and short term usage. The rotor also features internal directional vanes to help reject heat absorption by moving air inside the rotor outwards. The cooling from the directional vanes contributes to the overall longevity of the brake system by helping prevent glazing, boiling fluids and warping of the rotor.

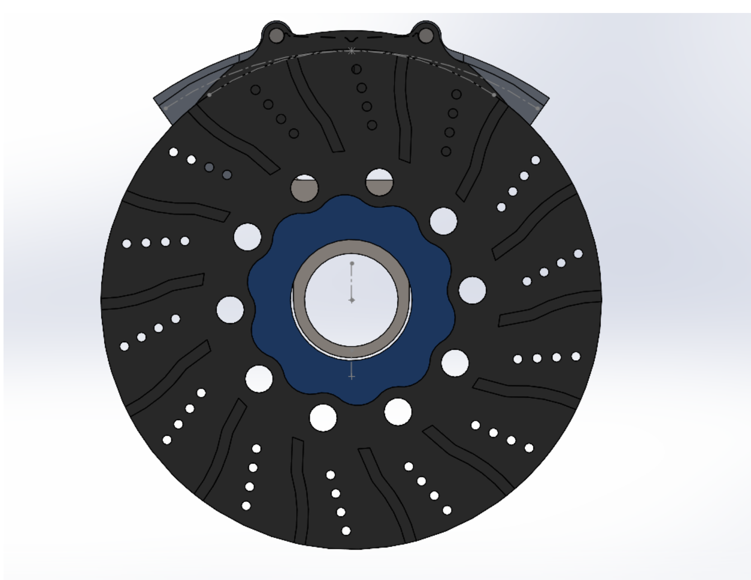


Fig 2.3.1 CAD Design of Rotor.

2.4 - Caliper Configuration and Layout

A floating caliper provides a better layout. A six piston brake caliper design gives better compression of the brake pads against the rotors for superior stopping power. The six piston caliper design more evenly distributes the load against the brake pads which will help ensure even wear, and better modulation at high braking. Larger and wider brake pads are also supported with the usage of more brake pistons, larger brake pads will contribute to more surface area to provide friction force. Configuring more brake pistons will also improve brake pedal feel which is an important feature when driving at the limit.

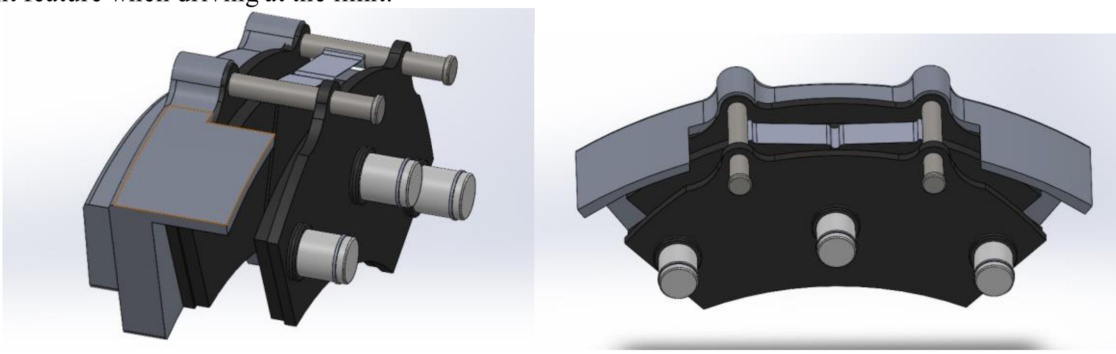


Fig 2.4.1 **CAD Design of Caliper.**

2.5 - Brake Pad and Piston Interaction

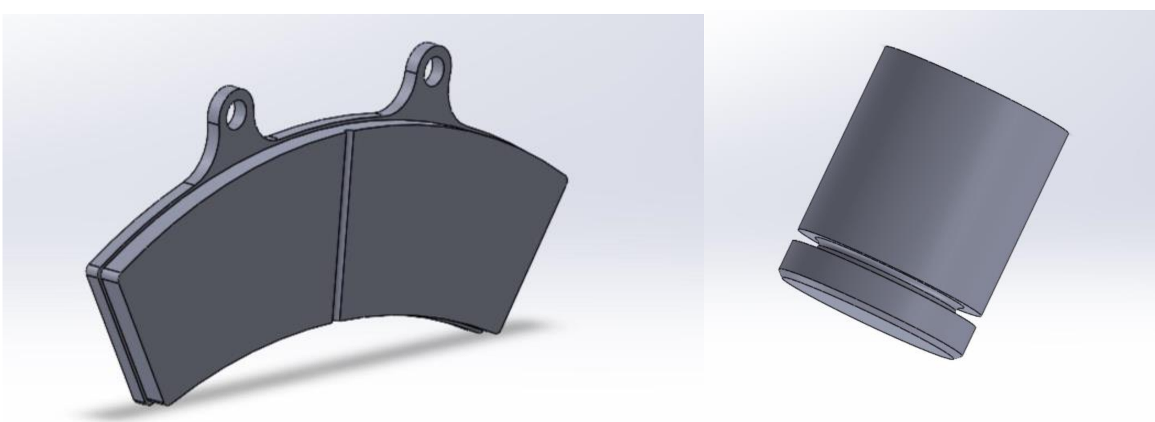
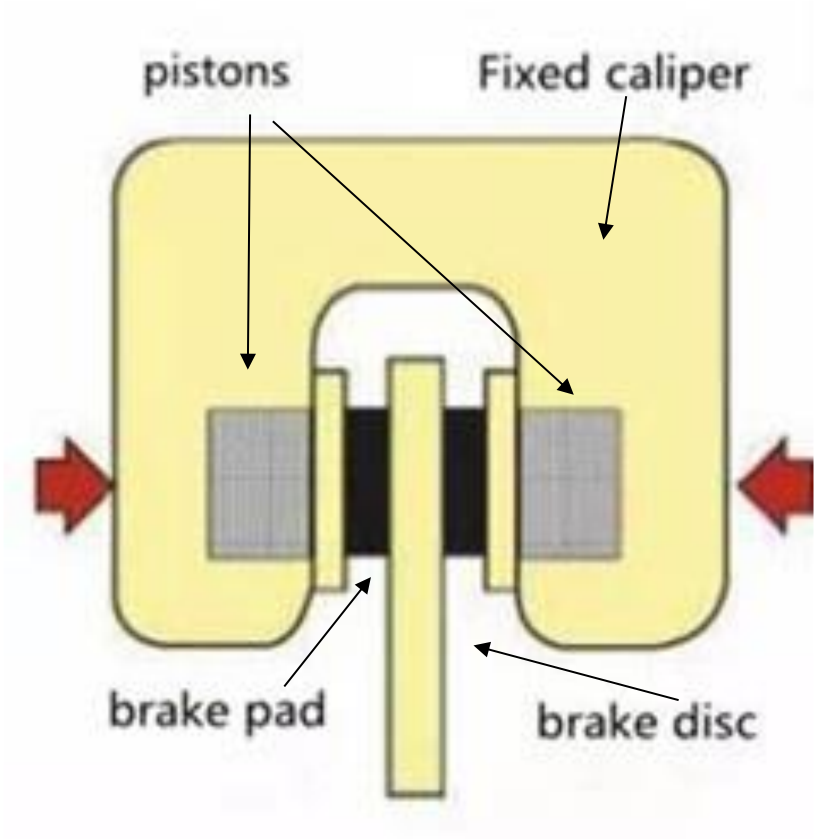


Fig 2.5.1 **CAD Design of Brake Pad (left) and Piston (right).**

In a mechanical braking system, there are many different components that work together to make the car stop. This subsection will focus on the piston to brake pad interaction. First and foremost, the interaction starts from the brake pedal pushed in by the diver. This causes the hydraulic system to push the piston in (through hydraulic pressure) and clamp the brake pad onto the rotor. This is how the system turns hydraulic pressure into friction.



<u>Fig 2.5.2</u> Caliper, Piston, and Brake Pad Configuration & Visualization.

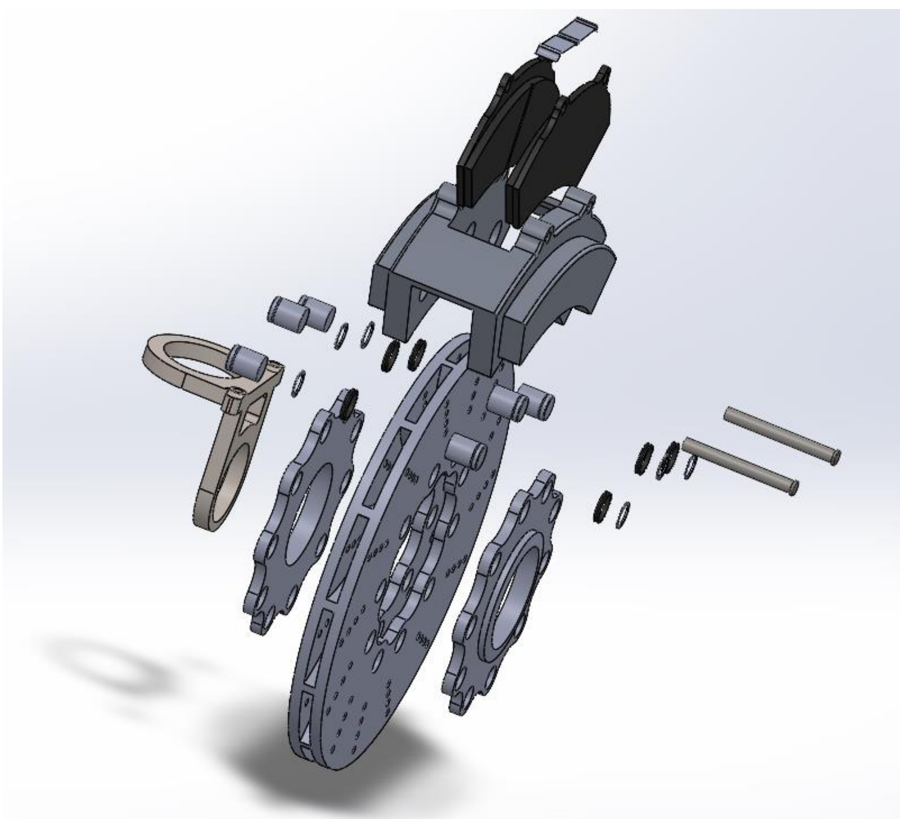
This friction on both sides of the rotor is what will stop the wheel from turning. Something that assists this interaction between the pad and the rotor is the design of the brake pad. Since brake pads are curved, this increases the surface area in which the pads and the rotor are making contact. The most important part of the piston and brake pad interaction is maintaining uniform pressure on the rotor when braking. Which is caused by the caliper, piston, and brake pad configuration. When the pistons activate and press the brake pads against the rotor, the brake pads must be aligned and parallel to the rotor. This forces even pressure along the rotor. However, there are many issues that come from the brake pad, caliper, and slide pins interaction. Issues such as uneven pad wear, rust, warping, etc. These issues come from many different factors. One factor is rust accumulation. Rust and corrosion will be covered more specifically in the next chapter. The next has to do with the slide pins and the caliper configuration. When the slide pins are worn or seized (i.e they are stuck and don't slide), this causes the caliper to not be able to move freely, and causes uneven pressure on the brake pad. Along with this, when the caliper is not configured properly, (i.e misaligned) this also causes uneven pressure on the brake pads.

2.6 - Assembly and Serviceability (DFM/DFA)

The brake assembly is designed for ease of manufacturing, and ease of repair. This means that each component is specifically designed to make manufacturing, the assembly of all the parts together, and the repair of the system easier and more efficient. Each part, although some have different manufacturing processes (which inevitably makes the manufacturing process of the entire assembly less time and cost effective) still has designed components to facilitate ease of assembly. An example of this is the fact that this assembly is designed to allow for disassembly. Parts such as the caliper and slide pins are designed to allow for the caliper to be opened so the brake pads can be changed without removing the entire piece. The slide pins are not permanent fasteners, therefore they allow for removal. Along with this, instead of having permanent fasteners tie the brake pads to the caliper, the brake pads are tied with clips so the pads can be removed with ease as well. Decreasing the amount of permanent fasteners has a couple different attributes. First, it decreases the manufacturing time due to the fasteners not having to be manufactured, and it decreases the assembly time since non-permanent fasteners are easier to install. However, this assembly does require some permanent fasteners, so the parts that do not need to be removed have no chance of moving/shifting which would decrease the reliability of the system. Going along with the reliability of the system, since this assembly is a subassembly of a larger system (the system of the entire whe el/wheelwell and/or the system of the entire car) this is a modular subsystem. To increase the reliability of this modular subsystem, the assembly only requires ___ components (not including the fasteners). Further, the assembly of each component is one directional. This means that the system is not being put together and fastened in multiple directions at the same time. The system is built bottom up, which makes the assembly more efficient and reliable.

2.7 - Design Constraints and Tradeoffs

The biggest design constraint presented was the balance of high performance with cost. The goal was to create a front brake system that provided superior performance while maintaining affordability. Creating a larger brake system was the best course of action to achieve braking performance however the size itself presents drawbacks. Larger braking systems will require more room and as an aftermarket alternative that will eliminate some consumer potential as the braking system can possibly be oversized for some OEM replacements. More parts will also increase the complexity of the manufacturing phase so running more pistons is another drawback. Holding performance as a design criteria meant holding heat dissipation and heat mass as a high standard so improvements were made to the rotor to accommodate that at the cost of structural stiffness.



<u>Fig 2.7.2</u> Brake System Assembly Design (Exploded Top View).

CHAPTER 3 - MATERIAL SELECTION

3.1 - Introduction

A car brake isn't just made out of 1 material, it is made out of many different materials that all have different properties that have to work together in different parts to operate as a brake. Every material has its own advantages and disadvantages that make it suited for a certain part or task in the complete assembly. The material that is used for the rotor wouldn't be the same material as the pistons or the mounting plate. And this would be due to how important a characteristic would be for a part, for example thermal conductivity wouldn't be important for the piston, but would be for the brake pads.
The criteria we chose to determine which material was appropriate for which part were the density, specific heat, modulus of elasticity, yield stress, and thermal conductivity. These criteria aren't all compared the same way, for some criteria bigger is better like for specific heat, while for others lower the better as with density. The criteria that was the most important changed depending on the part, but the criteria that was critical for brakes to work is thermal conductivity. This was due to some parts needing to quickly absorb and release heat like the rotor, while the brake pad needed to have a low thermal conductivity to absorb the heat energy and not let it travel to other parts like the caliper.
We chose several materials as potential candidates for the parts, with different materials having different intended uses. For the rotor, we had cast iron and carbon ceramic as candidates. We had titanium, aluminum, and stainless steel as options for the piston material, while the brake pads were either a semi-metallic compound or a carbon ceramic. Steel is also a common material used in other parts of braking mechanisms like the caliper, the mounting plate, and even as an option for the rotor. Each material has a cost to their use, either in weight or in actual cost, with materials like titanium being more expensive than a material like cast iron, while using steel when you could use aluminum for the same part would have that part be heavier than if we used aluminum.

Table 3.1.1 **Table comparing the main characteristics of all the candidate materials.**

	Density	Specific heat	Modulus of Elasticity	Yield Stress	Thermal Conductivity
Stainless Steel AISI 410	7.7 - 7.8 g/cm^3	460 J/(kg·K)	200 GPa	550 - 1225 MPa	24-25 W/(m*K)
Carbon Ceramic	2 - 2.4 g/cm^3	700-1100 J/(kg*K)	60-400+ GPa	190-240 MPa*	10 - 100+ W/(m*K)
Cast Iron	6.9 - 7.8 g/cm^3	460-590 J/(kg·K)	100- 120 GPa	65.5 - 420 Mpa	20 - 70 W/(m*K)
Cast Aluminum	2.76 g/cm^3	900-960 J/(kg·K)	69-72 GPa	170 MPa	90 - over 150 W/(m*K)
Steel	7.85 g/cm^3	420-500 J/(kg·K)	200 GPa	500+ Mpa	15 - 50 W/(m*K)
Carbon Fiber (high)	1.55 - 1.9 g/cm^3	700-1000 J/(kg·K)	35-600 GPa	3500 - 7000+ Mpa	0.2 - 1200 W/(m*K)
Titanium	4.5 g/cm^3	520 J/(g·K)	80-125 GPa	880 - 1200 Mpa	21.9 W/(mK)
Semi-Metallic	1.8 - 3 g/cm^3	600-1800 J/(kg·K)	0.3 - 5 Gpa	100 - 120 Mpa	0.5 - 5 W/(mK)
	in plane (Exx=Eyy)		2 - 15 GPa		room temp

3.2 - Materials for Rotor & Brake Pads

The materials for the rotor and the brake pads share the same important criteria but for opposite reasons, the brake motor's material has to have high thermal capacity and high thermal conductivity to absorb and spread heat, while the brake pads need to have a low thermal conductivity to not get heated fast to prevent cracking and breaking. The brake pads are used on the rotor to have the car start braking, and that produces a lot of friction heat that only the rotor can take a large amount of since it is designed to absorb and spread that heat out across its surface, while the brake pads' are designed to prevent the heat from transferring from them to the calipers, which would warp the entire brake assembly.

Both of these parts also have the modulus of elasticity be important criteria, again in opposite directions. The rotor has to maintain a high hardness and rigidness that a high modulus of elasticity provides, in order to not deform and warp out of shape from either the heating from friction or the perpendicular force that is pushing on it from the brake pad. If the rotor were to warp, it would mean non functional brakes, or at least lower efficiency brakes. The brake pads on the other hand, need to have a low modulus of elasticity since if the pad is rigid, it might not make complete contact with the rotor, and since it can't absorb heat well it would crack from the friction.

With these characteristics in mind, we made gray cast iron, and a carbon ceramic composite as the candidate materials for the rotor. When comparing the thermal conductivity, the carbon ceramic can go to a higher value of heat transfer with a peak of over 100 Watts per meter Kelvin (W/mK), while the peak for the cast iron was only 70 W/mK. For the modulus of elasticity, the carbon ceramic compound beats better than cast iron since the compound has an upper range of over 400 GPa for the modulus of elasticity, while the cast iron only has up to 120 GPa for its modulus of elasticity. The density for the ceramic compound was lighter than the gray cast iron, but dramatically more expensive so we decided to go with the cast iron rotor.

Meanwhile with the brake pads, we choose a semi metallic material and the high percentage carbon ceramic as potential options for the brake pads. The semi-metallic has the lower heat conductivity of the two with just a max conductivity of 5 W/mk, while the carbon ceramic had a minimum of 10 W/mk and a max of over 100 W/mk. The modulus of elasticity meanwhile follows a similar pattern of the semi-metallic material having a low range of 0.3-5 GPa, while the carbon ceramic compound has a higher range from 60 to over 400 GPa. With those values in mind and knowing that we want a low modulus of elasticity and a low heat conductivity, we determined that the semi metallic material is the best material.

3.3 - Caliper Material

The caliper of a brake needs to handle a large amount of heat due to being in close proximity with the brake pads and rotor, be strong enough to not warp under pressure, and also not draw any heat to it. It needs a low thermal conductivity like the brake pads but also a high modulus of elasticity like the rotor, in order for the caliper to maintain its shape and ensure it can move the brake pads onto the rotor. If the rotor becomes too soft, it won't be able to provide the pressure needed to create friction between the rotor and the brake pads at a high enough scale to stop the car. The specific heat of the caliper doesn't have to be as high as either the brake pads or the rotor, since most of the heat is being pulled into the rotor. It is due to this fact that we don't need a heavy material like cast iron, we can use lighter materials that while having a lower specific heat, it isn't needed as not enough heat would be absorbed.

The materials we chose as candidates were steel, cast aluminum, and also stainless steel. Both of the steels are pretty heavy being 7.9 grams per cubic centimeter, while aluminum is only 2.76 grams per cubic centimeter, and this lower weight is important. Both types of steels share the same 200 GPa for modulus of elasticity, while aluminum is much lower being around only 70 GPa which isn't the best for strength. Both steels had a low heat conductivity of around 25 Watts per meter kelvin, while the aluminum had a higher 120 W/mK, while balancing it out with a specific heat of over 900 Joules per kilogram per kelvin. When taking into account that the heat absorption isn't as critical for the caliper than it is for the brake pads or the rotor, it is aluminum we choose to be the material for the caliper, and the main reason is weight. Weight is important when designing a car in general, as a lighter car can go faster than a heavier car, and the lower weight of aluminum is perfect for that. The lower weight also helps in counteracting the lower modulus of elasticity that aluminum has, as we can have a thicker caliper made out of aluminum than we can out of steel with the same total weight. The strength of the caliper also mainly comes from the shape of it, not the material itself, so the lighter aluminum not only means a thicker caliper can be made, but also more structure in the caliper can be implemented.

3.4 - Pistons and Back Plate

Pistons reside in the caliper, and are what make the brake pads and the rotor touch and begin braking. The pistons push the back plate and the brake pads together on one side of the rotor towards the rotor, while also getting the caliper on the opposite side to move towards the rotor using Newton's 3rd law. The pistons need to not conduct much heat as they are near both the brake pad and the brake fluid lines, while also having a good enough stiffness from both their shape and their modulus of elasticity. They also need to resist corrosion from the brake fluid that is used to operate the pistons. The reasoning for the lower heat conductivity is to prevent the heat from transferring from the brake pad to the back plate to the pistons all the way to the brake fluid.

The back plate of the brake pad, while being right behind the brake pads, has different criteria for its characteristics than the brake pads do. The back plate needs to have high heat conductivity to prevent any heat from going to the brake fluids and the pistons, a high yield stress to prevent breaking, and a high modulus of elasticity to prevent warping. If the back plate snaps or warps, the brake pad will lose its ability to get an even interaction with the rotor, and absorbing the heat that escapes the rotor and the brake pad keeps the brake fluid unheated. If the brake fluid becomes heated, it becomes more compressible leading to worsening braking power until it is heated to the point it becomes a gas, leading to brake failure.

With what we talked about the pistons, we elected stainless steel, aluminum, and titanium as potential candidates for piston materials. Aluminum has the highest heat conductivity with around 120 W/mK, while stainless steel and titanium are below that with 24 and 21.9 W/mK respectively.The stainless steel has a modulus of elasticity of 200 GPa, followed by titanium with an average of 100 GPa and aluminum with 70 GPa. The best two options are stainless steel and titanium, but the light weight of titanium (4.5 grams per cubic centimeter) makes it more useful than stainless steel which weighs 7.7 grams per cubic centimeter, and less weight is good for cars. The lower modulus of elasticity of titanium is good enough for the pistons, despite not being as high as the steel was.

For the back plate, we decided that stainless steel and the regular steel were the best candidates for the back plate material. Both steel and stainless steel are essentially the same for the characteristics that are important here, the same 200 GPa modulus of elasticity, similar yield stress values of over 500 MPa, and stainless steel having slightly worse thermal conductivity than steel for our application. But the main reasons why plain regular steel is better than stainless steel aren't on our table, they are about the costs of stainless steel, and the lack of malleability in manufacturing that make plain steel more preferable to stainless steel.

3.5 - Corrosion

In a braking system, there are three different types of corrosion that occur. The first is chemical corrosion. This is caused by the brake fluid which is a very corrosive substance. When the brake fluid runs through the system, if there is a leak, the system can be corroded quickly by the fluid. Secondly, there is mechanical corrosion. This is the wear and tear on the brake pads and the rotor caused by friction. Since the material we selected for the rotor was cast iron, there is a high chance of corrosion and rust here. Lastly, there is galvanic corrosion, which occurs when there are two dissimilar metals together, which create an electronic charge that passes through the anodic metal and corrodes. All of the material selections put together provide a chance of galvanic corrosion. Due to all of these potential causes of corrosion, some of our selections were made to counteract the corrosion easier. Titanium was one of these material choices due to the fact that titanium has a good corrosion resistance and can't rust like steel.

3.6 - Material Tradeoffs and Final Selection

Table 3.2 **Summary table with chosen materials and reasoning**

Part	Material	Key reason
Rotor	Gray Cast Iron	Price
Brake Pad	Semi-Metallic	low thermal conductivity and flexible
Caliper	Cast Aluminum	Lower density to lower weight
Back plate	High Strength Steel	Cost and ease to manufacture
Piston	Titanium	light and good modulus of Elasticity

For the major parts, we decided to go with titanium for the piston, regular steel for the back plate, aluminum for the caliper, semi metallic compound for the brake pads, and gray cast iron for the rotor. Some materials like stainless steel were rejected for reasons outside of the properties needed for a task like ease of manufacture, while others like aluminum just had better alternatives for the part they were suited for. Some parts like the calipers, we didn't use the material with the absolute best characteristics that part wanted. We decided to use aluminum over the more durable steel that would theoretically be better for calipers because of the amount of weight we could save if we used aluminum instead of steel. A similar situation with the back plate for the brake pads, the stainless steel was essentially on par with regular steel and even had better corrosion resistance, but the difficulties in using stainless steel to manufacture such back plates would be more trouble than just using regular steel since stainless steel has a higher work hardening rate which makes operations harder to do on it.

CHAPTER 4 - MANUFACTURING PROCESSES AND TECHNIQUES

4.1 - Introduction

Manufacturing approaches directly control the results in performance, NVH (noise, vibration, and harshness), safety, and cost of a final disk brake assembly[2]. Design choices and material selections are responsible for creating a theoretical product while manufacturing systems ensure the actual production matches the theory. Microstructure, surface condition, and dimensional accuracy are major components of the final product that are determined primarily by the quality of manufacturing processes. Discrepancies throughout the casting, forging, CNC, sintering, and assembly operations influence general dynamic response, thermal behavior, and friction consistency and reliability, specifically through variations in surface roughness and material homogeneity. Further, slight variations in production and scrap rate as well as machining complexity significantly affect costs and ability to hit regulation requirements related to braking performance and durability. In addition, the manufacturing processes selected for the braking components must all be scalable to high-volume production level while maintaining repeatability, quality control, and economic feasibility. Thus, many issues regarding braking performance, NVH, safety, and final cost stem from the limitations of manufacturing and variability in these processes. The following sections analyze the primary manufacturing techniques used for each component of the assembly and discuss the technical suitability of each option[1,3,4].

4.2 - Rotor Manufacturing

The process of developing rotors must consider the design and end goal of the rotor. To optimize all technical properties the rotor must have proper material selection, primary manufacturing, and secondary operations to ensure a high quality product.

4.2.1 - Material Selection

While **CHAPTER 3** focuses on material decisions for each component of assembly, this section discusses how manufacturing systems directly influence the performance of those materials. Instead of reevaluating the material choices, microstructure formation and composition variability are examined as features involved in the casting process. Cast irons are the standard material choice for most rotor productions; as discussed in **sub-section 4.2.2**. Gray cast iron and high-carbon cast iron are the two material choices selected to analyze for suitability. These materials were chosen based on industry norms for common rotor materials[5]. The primary differences between these materials can be summarised as follows: carbon and silicon content, as well as graphite microstructure formation.

Gray cast iron is the most common material found in modern rotors largely due to its low cost despite its heaviness[5]. Gray cast iron contains 2.5%–4% carbon and 1%–3% silicon which helps with thermal conductivity and improving NVH[6]. Graphite forms in both materials, improving general heat dispersion and damping making it a desirable addition. Furthermore, as seen in **Figure 4.2.1.1**, the graphite morphology can be found as flakes intermixed in an iron matrix as a result of the carbon content.

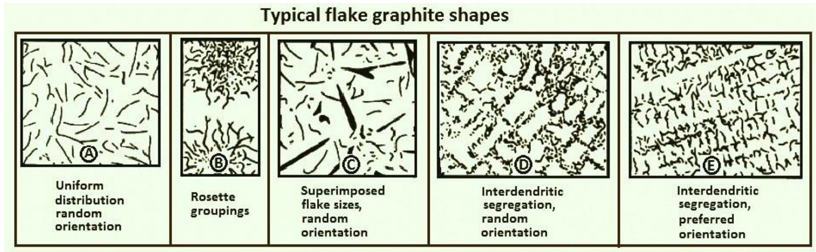


Figure 4.2.1.1 A typical flake graphite shape formation diagram comparing five different morphologies. (A) is representative of the ideal formation in high-carbon cast iron. (D) is representative of what is often found in gray cast iron. (B), (C), and (E) are other possible formations[9].

Graphite flakes are pertinent in absorbing excess vibration energy and reducing noise, enhancing consumer experience. However, the flakes act as local stress concentrations which reduce the overall tensile strength of the material and fracture toughness. The specific cooling rate during casting of gray cast iron dictates the microstructure of these flakes directly influencing performance and NVH. Specifically, flake size is influenced which is the feature that has the largest impact on the rotor results[1,7,9].
High-carbon cast iron is a more expensive rotor material that has greater thermal properties. High-carbon cast iron generally uses a higher carbon and silicon content than is found in gray cast iron, which makes it more sensitive to precise cooling rates requiring tighter control over those rates and the material composition to ensure proper uniform graphite formation; improving thermal distribution and crack resistrance[7]. The following **sub-section 4.2.2**, discusses the casting processes that ensure practical mechanical properties.

4.2.2 - Casting processes

Casting is the process in which a liquid is poured into a mold to create a solid product[1]. Both gray cast iron and high-carbon cast iron are metals that require a casting process to be formed and manufactured. As seen in **CHAPTER 2**, the geometry of the design was chosen specifically with casting considerations in mind such as draft angles, parting lines, and ventilation concerns. The most common form of casting is sand casting, found in **Figure 4.2.2.1**, due to its adaptability and low cost. It also has a high degree of accuracy as seen by its reported ±1.3 mm tolerance when casting cast iron[1]. Therefore the focus of this section is to examine the forms of sand casting and other casting considerations.

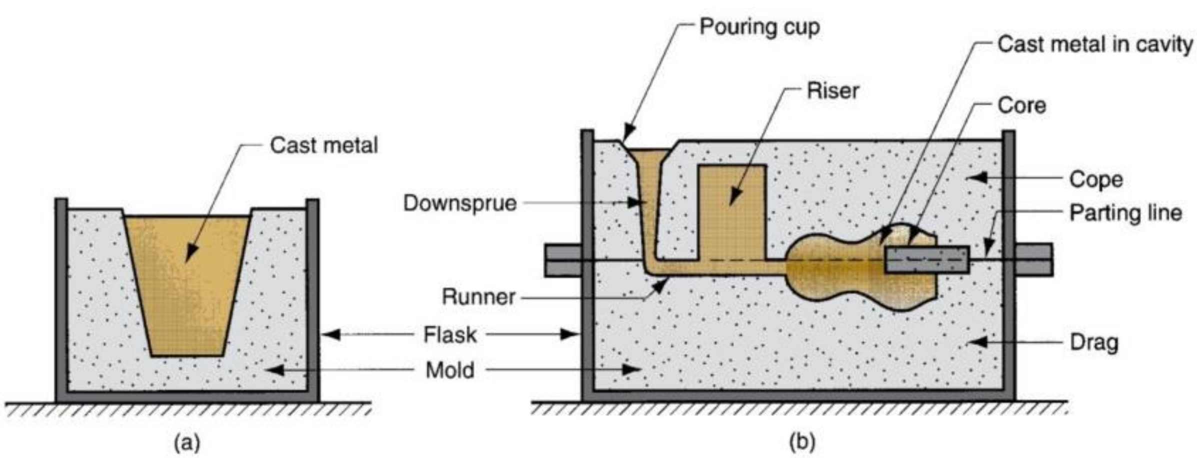


Figure 4.2.2.1: A diagram showing the sand casting process and the components involved. (a) depicts a simplified heads on view of casting. (b) displays a cross-section perspective of sand casting with relevant features labeled[1].

Green-sand casting is a common sand casting technique that utilizes molds formed from sand, clay, and water. This is a very low cost and popular casting method. A large constraint with this method of casting is possible uneven cooling rates. As detailed in **sub-section 4.2.1.**, the cooling rates affect the composition of the cast iron and the graphite flake morphology. Slow cooling rate results in larger graphite particles which improve damping and NVH but reduce thermal crack resistance. Faster cooling creates smaller graphite particles which have less damping effects and more noticeable NVH; but have improved thermal crack resistance. A balance between slow and fast cooling is desired to combine properties of each. Therefore a lack of control over the coolin g rates is a strong negative feature of the green-sand casting approach. Conversely the low tooling cost and minimal scrap rate is a strong positive in favor of green sand casting[1].

Resin-bonded sand casting is another method that combines resin with sand to create a stronger, more dimensionally accurate mold. This form of sand casting has more control over even cooling which allows for more uniform graphite flake size and distribution. This enhances performance, NVH, and safety. Additionally, the greater accuracy reduces secondary machining and scrap costs. A negative feature of this method is that resin-bonded sand molds cost more than green-sand molds to manufacture[1]. Despite this, the greater accuracy and uniformity of graphite flakes validates resin-bonding as the ideal choice for casting the rotor.

The rotor design choices that lended themselves to improve castability were draft angles, parting lines, and ventilation vanes. A slight chamfer was made on any intricate feature on the rotor component to act as a draft angle, or an intentional slope to make the rotor easier to remove from the mold after casting. The rotor has parting lines, or a location where two halves of a mold meet to form the mold, on the outer diameter of the rotor. This location is chosen as to not impact the surface friction on the main contact surface of the rotor. Symmetric ventilation vanes, seen in **Figure 4.2.2.2**, were implemented to improve airflow of the rotor when in service.

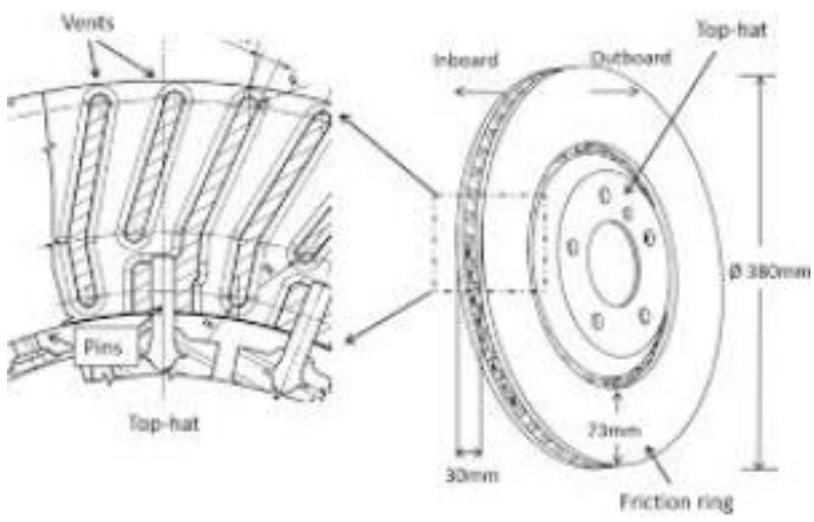


Figure 4.2.2.2 Rotor cross- section with labeled features: ventilation vanes, hats, and friction surfaces[8].

This feature adds slight complexity to the casting process increasing cost but has significant positive results in the heat dissipation process and damping of the rotor improving performance, safety, and NVH[14].

4.2.3 - Secondary Manufacturing Operations

Casting as covered in **sub-section 4.2.2** is the primary manufacturing process in producing a rotor however, it only creates a near-net shape geometrical product. Braking systems have high levels of tolerance which is why secondary operations are needed. Secondary operations ensure that dimensional accuracy is achieved and the surface has the desired level of integrity especially in a surface friction focused design such as this. Furthermore, this focus on improved quality allows the assembly to function as intended, influencing performance, NVH, safety, and cost[1].

4.2.3.1 - Machining Operations

Cast surfaces often have roughness, waviness, and mismatches along parting lines. These features are undesirable as they can impact the performance and safety due to inconsistencies in braking torque required for deceleration. Rough surfaces can also increase the wear on the rotor and the brake pads decreasing service lifetime and long term costs of the assembly. Additionally, surface faults can create vibrations and noise leading to low quality NVH and a poor consumer experience. Features that are most commonly machined consist of the friction faces, outer and inner diameters, and mounting holes. The tolerances machining is focused on improving are flatness, parallelism, concentricity, and runout; **Figure 4.2.3.1.1** depicts runout.

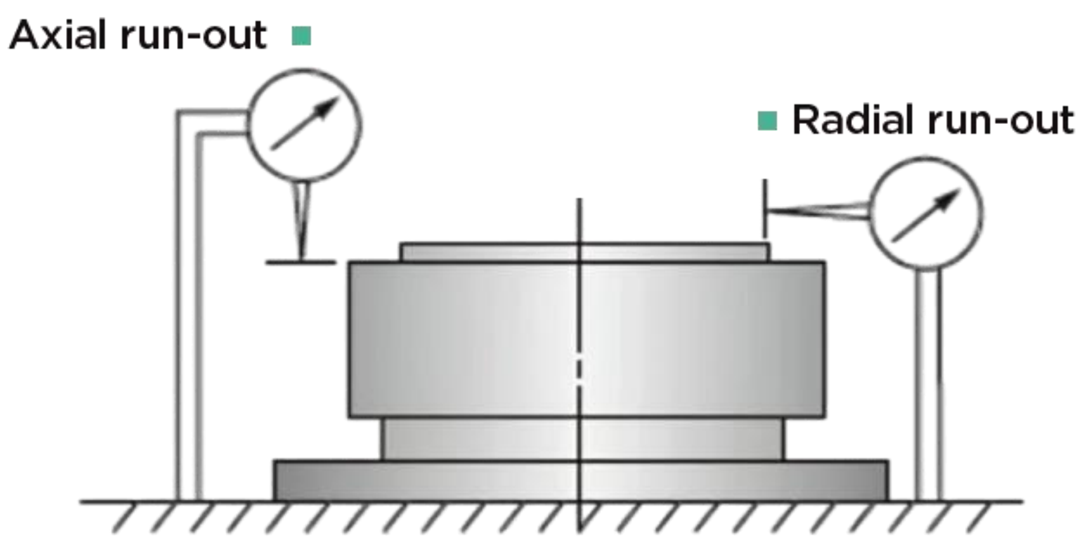


Figure 4.2.3.1.1 Rotary design featuring run outs[10].

Machining has implications on the cost and production time. Each cycle of machining adds total time to production, causes wear on the tooling used, and creates more scrap which is cost inefficient. High casting quality reduces the amount of machining needed mitigating these concerns[1].

4.2.3.2 - Heat Treatment and Surface Conditioning

As a result of non-uniform cooling throughout the rotor during casting and as a byproduct of machining, stress is formed inside the rotor. Stress can lead to early crack initiation and thermal distortion after repeated braking events. A form of heat treatment known as stress relief is effective in redistributing the stresses to improve the service lifetime of the rotor[15].
Surface conditioning can remove oxides and casting defects to improve overall surface uniformity. As brake rotors are intended to generate high amounts of surface friction, processes that improve the reliability of surface quality lead to better results in braking. While adding another layer of production and costs, this process is reported to reduce NVH complaints[16].

4.3 - Brake Pads Manufacturing

Brake pads are made as manufactured composites most often as a semi-metallic material composite. The performance results are often influenced by the uniformity of the composition, density, and surface condition. Manufacturing quality is vital in brake pad formation as pads are very sensitive to manufacturing variabilities. Noise production, wear rate, and most importantly the ability of the surface friction to act as intended are all susceptible to variance from minor defects in process control.

4.3.1 - Brake Pad Material Formulation

Semi-metallic brake pad material composites are made from four main material classes: friction modifiers, binders, fillers, and reinforcement fibers. Friction modifiers are metallic particles such as steel, iron, or other ferrous metals mixed into the composition. This controls the friction coefficient, thermal conductivity, and rate of wear of the material. The quality of mixing is important, as non-uniform distribution of particles leads to thermal stress concentrations, inconsistent surface friction, and poor NVH. Binders are made from organic resin and are often phenolic-based[17]. The resin holds the composite together and is activated during curing. Poor binder distribution causes weak spots to form. Fillers are inert materials that are utilized for density, compressability, and thermal response control. Proper filler application, improves the consistency of stiffness and reduces service wear[18]. Reinforcement fibers are most often steel or synthetic fibers[18]. The fibers improve structural integrity and mechanical strength. If fibers become concentrated in one location, the brake pad could develop anisotropic properties which are not ideal. Semi-metallic brake pads require the proper uniform balance between metallic and non-metallic phases, therefore improper mixing can result in variance in distribution of the particles in the composition causing friction inconsistencies and increased NVH[1,17,18].

4.3.2 - Powder Pressing

Powder pressing is a manufacturing process in which particles are compressed into shape using mechanical or hydraulic presses. Considerations regarding press pressure are that the force must be enough for the material to develop structural integrity but low enough to avoid cracking the pad. The results of this process directly impact pad density, frequency of porosity, and thermal stability. If done at a high quality, performance should be enhanced by good friction quality, NVH should be improved by minimal vibration, safety should be ensured through sufficient structural integrity, and costs minimized through wasted material from minimal cracking[1].

4.3.3 - Sintering Processes

Sintering processes undergo heating particles to a high temperature to fuse them into one cohesive unit. Following the pressing process, the semi-metallic pad is sintered at an elevated temperature. This process activates the binders referenced in **sub-section 4.3.1** to hold the material in place throughout the curing process. If done properly mechanical strength is developed and thermal stability is reinforced. Concerns are over-curing and under-curing. Over-curing can cause brittleness and make the material susceptible to early fracture. Under-curing can result in a weaker composite material that has unstable friction throughout its surface. This process when done well reduces noise, helping NVH, and decelerates the rate of wear increasing service lifetime[1].

4.3.4 - Backing Plate Assembly

The semi-metallic brake pad composite described throughout **section 4.3** requires attachment to a steel backing plate to provide structural support as seen in **Figure 4.3.4.1**.

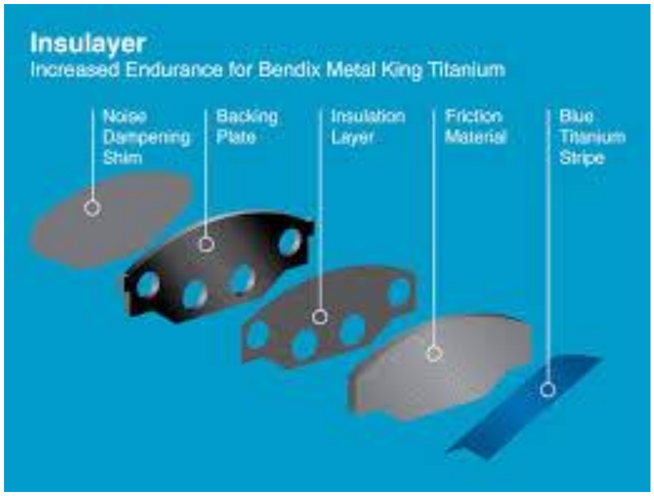


Figure 4.3.4.1 Diagram of a brake pad assembly[11].

These components are often affixed through adhesive bonding or mechanical retention. Adhesive bonding is performed through an adhesive material being placed between the components, given time to harden, and then successfully binding the assembly. Mechanical retention uses hooks to physically interlock the components of assembly. To reduce nuance in the design process from **CHAPTER 2**, adhesive bonding was the chosen process. If bonding were to fail it would cause a very high safety risk. Furthermore, it could cause legal and warranty concerns increasing potential costs of the systems. Poor alignment of the assembly components causes uneven pressure distribution affecting all features of the braking system results. Therefore, it is essential that this step of assembly is done with a high level of attention to detail[19].

4.3.5 - Surface Treatments

Similar to the secondary machining operations for the brake rotor in **sub-section 4.2.3** final processes are required to refine the brake pads to ensure they are ready for service. As pressing and sintering may leave excess material, grinding is needed to achieve final thickness[20]. This is a necessary process despite added costs. Slotting is a process in which grooves are cut into the surface to allow dust and gas to escape, improving overall heat dissipation[20]. This is not a required step however it is utilized as it improves performance of the system. Chamfering is another machining process that cuts angled bevels at 45 degrees into the pads to create a smoother transition of surface contact with the rotor. This reduces harshness and vibration, improving NVH. It can also help with reducing wear[1,16,20].

4.3.6 - Impact on Performance, NVH, Safety, and Cost

Friction repeatability is the most important feature that affects performance, ensuring high quality throughout brake pad formation and assembly allows for this precision. NVH is most affected by inconsistencies in the surface, avoiding those through proper friction surface formation reduces all aspects of NVH. Safety is a primary concern that is satiated when structural integrity, durability, and ideal adhesion are all addressed in this process. Costs are reduced when limited scrap from failed production, excess waste, and minimal warranty and legal issues arise.

4.4 - Caliper, Pistons, and Hardware Manufacturing

The remaining components of assembly require less material microstructure discussion and have more emphasis on geometries, assembly, and tolerances. The components discussed in this section will consist of calipers, pistons, and hardware. Hardware will be defined as any non-discussed minor component that helps with fitting the final assembly. They are as follows: caliper mounting bracket, brake pad backplate, rotor hat, slide pins, bolts, clips, dust boots, and piston rings. A diagram of these components in assembly is seen in **Figure 4.4.0.1**[21].

Figure 4.4.0.1 Exploded disk brake assembly featuring caliper, piston, brake pad, and hardware[12].

4.4.1 - Caliper Manufacturing

The caliper is responsible for the clamping of the disk brake and rotor to engage braking as well as housing these components. The common manufacturing methods used are casting, forging, and machining. Casting is useful in models with complex geometry and large scale production. Forging is restricted by geometrical design and has high costs but increased stiffness. Machining has high accuracy and precision but extreme costs at scale. Industry standard is casting of aluminum or iron with a final CNC Machining finish. The practical nature of casting and the industry norm is why casting was selected.

Cast aluminum and cast iron were the two main materials considered. Cast aluminum has moderate stiffness, moderate mass, moderate thermal stability, and high resistance to corrosion. Cast iron has higher stiffness, greater mass, stronger thermal stability, and moderate susceptibility to corrosion. Calipers are a large component so mass is a leading factor towards decision. Additionally, the environment the assembly is exposed to is highly corrosive; making cast aluminum a more desirable choice[1].

4.4.2 - Piston Manufacturing

Pistons serve to convert hydraulic pressure into braking pad force. It is essential that the surface finish is very smooth, tolerances are met, and high thermal stability. Titanium, steel, aluminum, and phenolic are all common material choices; titanium was selected for this component due its high strength-to-weight ratio and corrosion resistance. Precise machining, grinding and polishing processes, and surface finish and coatings are all vital to effective piston production. Poor manufacturing of pistons leads to uneven wear, NVH, and surface sticking[1].

4.4.3 - Hardware, Pins, and Clips

Additional hardware primarily serves to allow the assembly to fit together properly and guide pad motion. They also help with thermal expansion and reduce vibration and rattle. The variety of components require a variety of manufacturing methods: stamping, wire forming, heat treatment, and surface coatings using elemental zinc and phosphate are all commonly utilized. All of these factors can impact NVH, durability, and corrosion resistance[1].

4.4.4 - Assembly and Tolerances

With the quantity of parts, high precision is needed to ensure all components fit together. As each component is added to the assembly the accuracy of each tolerance matters more. The pad assembly as mentioned in section **sub-section 4.3.4** must be properly aligned. The caliper must be mounted in the proper orientation and with necessary accuracy. The piston must also clear the bore diameter which can be determined through testing. If any component does not meet tolerance it may not fit in the assembly, cause uneven pressure and stress, unintended brake drag for the automotive, increase noise, and reduce service life.
Variability in manufacturing can have negative impacts on disk brake assembly results. High quality manufacturing results in repeatable performance, consistent NVH, a large margin of error to ensure safety, and optimized costs. The quality of manufacturing of each of these components has measurable, direct impacts on reliable braking performance[1].

4.5 - Manufacturing Defects, Tolerances, and Quality Control

Manufacturing defects commonly consist of porosity in casted components, surface finish irregularities on pistons, rotors, and brake pads, and density variation in brake pads. These can lead to an inconsistent friction coefficient, NVH, and increased wear. Due to the critical value safety has in braking systems, all components are disproportionately sensitive to defects.
Strict dimensional tolerances allow for proper fit, pad alignment, uniform pressure distribution, and ideal braking dynamics. Due to the abundance of parts in the assembly, tolerances compound creating very precise windows. If not met small errors can cause NVH and uneven wear.
Industry standards and regulations mitigate aforementioned risks. Common inspections are focused on dimensional accuracy, surface roughness quality, structural testing of casted materials, and statics regarding process control. Quality control is essential when manufacturing assemblies at scale as it helps with repeatability of performance and reduces scrap waste and potential warranty and legal complications.

4.6 - Design-Manufacturing Integration

The design of the braking system is one constraining factor that works in conjunction with the feasible manufacturability and consistency of high quality products. Design must take into account the achievability of tolerances, resulting surface finishes, uncontrollable material variability and the implications those have on braking performance.
With design for manufacturability and assembly in mind, the design must contain simple geometry and reasonable tolerances. Specific considerations can be seen in **sub-section 4.2.2** and **sub-section 4.3.5** which discuss chamfers, draft angles, parting lines, ventilation vanes, and slotting; all intricate design aspects that make a product more and less manufacturable. Further, the manufacturing costs, scale, and quality can all be dictated by the design.
Viewing each component as an isolated part outside of the assembly would result in a poor product. Accordingly, brake system optimization requires coordination across both design and manufacturing levels.

CHAPTER 5 - COST ANALYSIS

5.1 - Introduction

Cost is one of the most critical constraints in the production of all engineered assemblies, particularly in high volume automotive systems. While performance, NVH, and safety are all key guiding factors in designing a braking system, cost has the ultimate control over the feasibility and scalability of the assembly. Thus, all design, material, and manufacturing decisions must be balanced between technical measures of success and economic viability.
As discussed throughout the report, cost is impacted by the interconnected network of system design choices. The geometry chosen in **CHAPTER 2** dictates what level of tooling complexity is needed, machining requirements, and the degree of tolerance used. Materials selection from **CHAPTER 3** directly designates raw material costs, manufacturing operations, and susceptibility to production variability.
Also manufacturing as analyzed in **CHAPTER 4** has a large influence on scrap rate, cycle time, labor, tooling, machinery, and raw material prices. For clarity, the total cost of manufacturing the assembly is categorized into material, labor and overhead costs. Each of these categories is made up of those factors which act as the primary cost drivers for this system[1].
The focus of this section is on the analysis of the relative cost impact of design decisions, materials utilized, and manufacturing methods chosen for all main components of the brake system assembly. The interpretation of these expenses will be based on conceptual breakdowns of cost as well as estimated expenditures as seen in the discussions, figures, tables, and calculations within this chapter. All of this is performed with large scale production in mind, therefore, through an industry standard cost analysis of this brake system, a meaningful evaluation is formulated.

5.2 - Cost Breakdown Approach

In general, there are three main sections that cost is broken down into: materials, labor, and overhead. Material costs can be seen in the price of raw materials purchased from alloy suppliers and industrial founderies[2]. Furthermore, alloying elements such as elemental Carbon are included in this category[3,4,5]. Additionally, consumables such as sand and resin for casting are considered material expenses. This category of expense is denoted as C.
Labor costs are in essence the costs of the employees tied to production. These expenses compound due to wages, salaries, overtime, bonuses, benefits, taxes, and regulations[6]. Engineering firms have strict regulations from companies such as NSPE/ASCE that require annual paid licensing exams and inspections on the basis of employee safety and well being which can be involved with these expenses[7]. Laborers can consist of machine operators, assembly line workers, design engineers, and upper management. This collection of costs are labeled as C_l.
The overhead costs encompass the largest spectrum of manufacturing expenses. The tooling costs, scrap costs, quality control, and energy usage costs are seen as daily expenses. Maintenance and the depreciation of the machinery are seen as long term overhead costs. Machinery provides a strong case for relative value, as the more a machine is used in its service life the greater value it provides. Grouping all of these expenses as, C_o.

Thus, the overall breakdown of costs can be seen in the equation:

$$C_t = C_m + C_l + C_o$$

Where C_t represents total cost[1].

In the remainder of this chapter, this equation will be used to examine each component conceptually and to provide an approximate value for all categories of cost.

5.3 - Material Costs

As introduced in both **section 5.1** and **section 5.2**, material costs are one of the major groups of costs expected in our assembly. Most notably raw material costs make up the bulk of this category. This can only be minimized in the design phase as this is typically a set cost. Similarly, alloying materials follow the same protocol. However, the quantity of scraps due to defects can be mitigated through careful supply purchase. This is valuable to take note of, as in mass production of parts, small increases in costs compound significantly.

5.3.1 - Rotor Material Cost

The two materials analyzed for this component were gray cast iron and high-carbon cast iron. Both metals are cast iron yet they differ in carbon and silicon content. An increase in carbon content yields higher material costs from purchasing more elemental Carbon. Further, since the rate of cooling controls carbon uniformity, with greater carbon percentage this process requires more precision. This process also has a higher inherent risk factor resulting in likely more scrap waste costs. However, the higher carbon percentage produces a greater quality part that has a longer life cycle and is less prone to thermal cracking. A longer service life can often outweigh the initial increased manufacturing costs.

Gray cast iron does not have a high level of carbon meaning it does not need excess elemental Carbon purchases and precise cooling ranges to ensure proper composition. It also has less resulting scrap, making it generally considered the cheapest form of cast iron[3]. High-carbon cast iron has a high carbon percentage indicating it has additional Carbon supply expenses and precise cooling periods that lead to more wasted material in the form of scrap. While being seen as a more expensive alternative, high-carbon cast iron's cost effectiveness is seen over the course of its life cycle. Due to its superior heat distribution, this metal has reduced risk of thermal cracking and can stay in service long enough to justify its heavier initial price.

5.3.2 - Brake Pad Material Cost

Brake pads are manufactured from a semi-metallic composite material. Intermixed into these pads are metallic friction modifiers, resin binders, fillers, and fibers. Each has a raw material cost and an implied cost. Similar to the scrap waste from the rotor described in **sub-section 5.3.1**, the wasted material has the biggest impact on costs relative to revenue from this category. The greater the percentage of yield, the more manageable the costs are despite any size of input mass.

Metallic friction modifiers can be made from multiple materials. Steel is generally cheaper than specialty alloys, while specialty alloys tend to have better mechanical properties. However, unless operating at a high-performance level, steel is sufficient and cost effective for most brake pad designs. More importantly, if friction modifiers are unevenly dispersed the brake pads have undesirable friction variability and are wasted as scrap.

Resin binders have minimal raw material expenses. The main expenditure comes from waste produced by under-curing or over-curing during the sintering phase[2]. Both fillers and fibers have related costs. These materials are seen as the lowest cost in the entire assembly despite their disproportionate value in density control and ensuring friction uniformity across the surface. If dispersed poorly, the pads could develop undesirable anisotropic behavior and be wasted as scrap material, increasing costs.

While the materials involved in the brake pad manufacturing process are not typically considered high cost, if made in poor quality, when manufacturing at scale, can be very pricey due to excess scrap. One of the easiest ways to reduce costs is to ensure as minimal amount of rejected pads as possible.

5.3.3 - Caliper, Pistons, and Hardware Material Cost

Caliper costs are clearly defined by industry standards. Possible materials are cast aluminum and iron. Aluminum has a higher cost per kilogram, or kg, purchased, whereas steel has a lower cost. However, aluminum has a significantly lower mass vs. irons' reported high mass. This property is essential in performance evaluation. Further, aluminum has a high level of natural corrosion resistance, reducing later surface treatment costs, and providing an inherent high life cycle longevity expectation.

The pistons use the priciest material of the entire assembly. This is often seen as undesirable and as an unnecessary cost engineers would likely attempt to avoid. However, pistons have very low production volume and thus low mass regardless of material choice. Thus the total raw material costs are minimal. Furthermore, the benefits in lifetime durability, corrosion resistance, and performance all act as strong justification despite the slight increase in cost. The remaining general hardware consists of small components that each have a very low individual cost despite material choice. However, when needed in high quantities, surface treatments and heat treatment can make costs rise rapidly. To avoid this, hardware components are often purchased as a standardized commodity in bulk. This allows the concept of economies of scale, or an increase in cost efficiency as production increases[8], to take place.

5.4 - Labor Costs

Labor has two main forms of application, direct and indirect labor. Direct labor is made up of those who directly influence the operations in creating each component. These positions require medium to high levels of manual skill and also influence cycle time. The less efficient a manual laborer is, the greater the cycle time of manufacturing; this is time consuming and increases the total relative cost compared to revenue. Casting, pressing, and sintering all require oversight despite their ability to be automated. Nonetheless, automation reduces the total amount of laborers needed, lowering costs. Additionally, CNC machining requires operators that have to load, set, and unload machines adding to cycle times. Assembly of all components also takes time and labor to achieve.
Indirect labor comes in the form of secondary, non-production labor. This can be seen in inspection, supervising, and design that mitigates reworking. None of these forms of labor are directly involved with producing the product yet they are necessary as they help manage and streamline the process to ensure high quality results. These can potentially increase efficiency, reducing costs despite increasing labor costs themselves.

5.5 - Overhead Costs

Overhead costs are the most general and all encompassing cost category. These expenses consist of tooling, equipment, energy, scrap, yield, and final quality operations. Tooling and equipment are upfront costs that justify their value over the course of their service life. Casting molds, CNC machines, presses, and furnaces are all examples of needed equipment. As explained in **section 5.2**, depreciation provides the justification for the relative value of each machine.
Utility costs are driven by the energy needed to operate machinery and furnaces. Machinery for tooling and raw manufacturing have consistent per cycle energy costs. Furnaces are most efficiently used through being held constant at operation temperature due to the high energy needed during the call-to-heat phase of furnace use[9]. Thus, a plethora of furnaces heated to a variety of temperatures allows for most efficient casting and heat treatment of each specific component and material.
Building on waste specific concepts, scrap is an undesirable feature of machining. Any process that optimizes material use through design is a valuable overhead insight. The amount of scrap produced relative to the amount of material input is known as yield[10]. Effective supervision and inspection should reduce scrap rate and improve yield as well.

5.6 - Cost Optimization

The objective of **Table 5.6.1** is to synthesize all relative costs discussed in **sections 5.3. - 5.5**. As specific cost estimates are not easily grasped, a truncated relative sensitivity value provides a clearer understanding of the impact each feature of the design and assembly has on total costs. Further, specific cost drivers are highlighted as key differentiators in driving costs. This analysis is consistent at all levels of production volume and stages.

Table 5.6.1 Relative cost values for each component analyzed in each major category with an additional primary cost driver explicitly denoted.

Component	Material Cost	Labor Cost	Overhead Cost	Primary Cost Driver
Rotor	Medium	Medium	High	Machining and scrap
Brake Pad	Medium	Medium	High	Sintering

Caliper	Medium	Low	Medium	Tooling
Piston	High	Low	Low	Material
Hardware	Low	Low	Medium	High volume

As delineated in **Table 5.6.1**, rotor and brake pad production costs are heavily overhead oriented. The caliper has balanced cost distribution with notably low material costs. Piston costs are dominated by expensive material choice. High volume is the lead cost driver in hardware despite its generally low costs. All components were optimized in early stage design, material, and manufacturing decision making to avoid producing any overly expensive parts. This allows for a technically effective brake system that has a reasonable production cost.

CONCLUSION

Evaluating the design and research of the proposed automotive braking system with performance and affordability in mind has brought about the integration of mechanical design, material selection, manufacturing processes and cost considerations. Great consideration went into heat dissipation, consistent performance, and reliability.

Design choices like the material choice and integrated features proved to contribute to thermal stability, pad wear, and conservation of braking ability. Cast gray iron, directional vanes, semi metallic brake pads and titanium pistons all contributed to achieving these characteristics.

Ultimately these design choices have shown that high performance can be achieved and maintained under intense conditions while being regarded as affordable and more easily manufactured.

REFERENCES

[5]*[9]** Admin, "Graphite morphology: Key insights for material science," Esteem Auto, 2025. Available: https://esteemauto.com/graphite-morphology/

[4]*[7]** "Approximate guide to carbon content in iron," The Home Foundry, 2025. Available: https://forums.thehomefoundry.org/index.php?threads%2Fapproximate-guide-to-carbon-content-in-iron.1953%2F

[6]** BCI Solutions, Inc., "Gray cast iron," 2025. Available: https://www.bcisolutions.com/gray-cast-iron

[3]*[5]** Beck, L., "Brake rotor material differences," Spring Works, 2024. Available: https://springworksauto.com/blogs/auto-truck-trailer-repair/brake-rotor-material-differences-santa-rosa-ca

[11]** "Bendix brake pad compounds: Semi-metallic," The Tyreman Magazine, 2024. Available: https://www.tyremanmagazine.com/bendix-brake-pad-compounds-semi-metallic/

[3]** BREMBO, *1_thegroup.pdf*, 2025.

[4]** BREMBO, *brake_maintenance_en*, 2025.

[12]** "Brake calipers," AA1Car, 2025. Available: https://www.aa1car.com/library/brake_calipers.htm

[2]* "Cast iron manufacturers, suppliers and industry information," Cast Iron Companies | Cast Iron Suppliers, 2025. Available:
https://grey-iron-castings.com/cast-iron/

[10]* Chen, J., "Yields in finance: Formula, types, and what it tells you," Investopedia, 2025. Available: https://www.investopedia.com/terms/y/yield.asp

[7]* Compliance, H., "Information Center & License Library," Harbor Compliance, 2025. Available: https://www.harborcompliance.com/engineering-firm-license-certificate-of-authorization

[2]** Denys, E., "Strategies for combatting brake NVH," The BRAKE Report, 2022. Available: https://thebrakereport.com/strategies-for-combatting-brake-nvh/

[8]* "Economies of scale: Definition, types, and strategies," Harvard Business School Online, 2025. Available: https://online.hbs.edu/blog/post/economies-of-scale

[8]** "Figure 5.1 thickness of the ventilated brake disc and solid brake discs…," ResearchGate, 2025. Available: https://www.researchgate.net/figure/Thickness-of-the-ventilated-brake-disc-and-solid-brake-discs-for-the-parametric-FE-study_fig10_318024455

[1]* Groover, M. P., *Fundamentals of modern manufacturing: Materials, processes, and systems*, 7th ed., Wiley, 2019.

[20]** "Handbook of Precision Engineering," SpringerLink, 2025. Available: https://link.springer.com/book/10.1007/978-1-349-01014-1

* Referenced as [] in Chapter 4
** Referenced as [] in Chapter 5

[18]** Herz, J., Muscat, D., and Strübbe, N., "The influence of fillers on the reinforcement capabilities of polypropylene-based mono-material and core-shell fibers in concrete: A comparison," *Polymers*, 2025. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC12252313/

[19]** Intertronics, "Why use a structural adhesive? Adhesives vs. mechanical fastenings," 2024. Available: https://www.intertronics.co.uk/2024/11/why-use-a-structural-adhesive-adhesives-vs-mechanical-fastenings/

[14]** James, "Maximizing performance: The advantages of a vented brake rotor for your vehicle," R1 Concepts, 2024. Available: https://www.r1concepts.com/blog/brake-rotor-vane-structures-variety/

[10]** Kapoor Enterprises, "Understanding runout in rotating machinery," 2025. Available: https://kapent.com/understanding-runout-in-rotating-machinery/

Limpert, R., *Brake design and safety*, 3rd ed., SAE International, 2011.

[13]** NRS Brakes, "Top 5 causes of brake pads wearing unevenly," 2022. Available: https://nrsbrakes.com/blogs/blog/top-5-causes-of-brake-pads-wearing-unevenly

[6] Paycor, "The biggest cost of doing business: A closer look at labor costs," 2025. Available: https://www.paycor.com/resource-center/articles/closer-look-at-labor-costs/

[17]** Primafond, "Secrets of the foundry binder system: The importance of resins and catalysts," 2025. Available: https://www.primafond.com/blog/foundry-binder-system/

[9] Pros & cons of high efficiency furnaces, PV Heating, Cooling & Plumbing, 2025. Available: https://www.pvhvac.com/blog/pros-and-cons-of-high-efficiency-furnaces/

[16]** Saint-Gobain, "Surface conditioning | surface finishing | solutions," 2025. Available: https://www.surfaceconditioning.saint-gobain.com/

[15]** "Stress relieving: What is stress relieving?," Metallurgy for Dummies, 2025. Available: https://www.metallurgyfordummies.com/what-is-stress-relieving.html

[21]** Tyflopoulos, E., Lien, M., and Steinert, M., "Optimization of brake calipers using topology optimization for additive manufacturing," *Applied Sciences*, 2021. Available: https://www.mdpi.com/2076-3417/11/4/1437

* Referenced as [] in Chapter 4
** Referenced as [] in Chapter 5

APPENDIX

List of Figures

List of Tables

* Referenced as [] in Chapter 4
** Referenced as [] in Chapter 5