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Braking Into The Future

I. Motivation, Reverence, & Background

When it comes to the stats of a car, most OEM manufacturers will advertise horsepower, handling, and luxury features, but rarely do they advertise the braking ability of the car. In today's market with record-fast cars being produced, manufacturers must now focus more on braking technology. Since I was a child, I have been fascinated with the automotive world. I am also incredibly passionate about the engineering and systems involved in the automotive world. The automotive world has a substantial after-market car part industry. Some of these after-market car parts are known as performance parts because they increase the performance of the car. I have a fascination with the high-performance car market. One of the latest advancements in the high-performance market was the option to add carbon ceramic brakes to your car. As someone who loves everything to do with mechanical systems, I became passionate about carbon ceramic brake rotors and the performance benefits they provide.

The car market for new vehicles is projected to reach 83.6 million units in 2023 [1]. Carbon ceramic brakes will not be installed on consumer-level vehicles anytime soon, however, the number of vehicles that offer them as an option continues to grow every year. "The Automotive Carbon Ceramic Brakes Market is expected to exceed more than US$ 650 Million by 2024" [2]. Cars continue to get bigger, heavier, and faster, which requires the OEM manufacturers to install bigger and better braking systems into their cars. If this trend continues, there will be more and more performance consumer cars that will have the option to install these brakes.

Figure 1: BMW M-Performance Carbon Ceramic Brakes [3]

Although the automotive industry is the main industry to use this technology, other industries could benefit from such a system. The railroad industry could potentially benefit from the usage of carbon ceramic brake rotors. Carbon ceramic brakes were originally developed for high-performance aerospace aircraft but found a larger market in the automotive industry. Carbon ceramic brakes can withstand repeated high braking forces without experiencing brake fade. This worked extremely well for planes such as the Concord which required a high amount of braking force upon landing on the runway. This technology soon made it into the automotive industry and was used on high-end racecars such as F1 cars. During races, racecars are constantly applying the brakes at high speeds. Constantly applying maximum braking force to the brakes at high speeds leads to brake failure. Steel brake rotors, the most common form of brake rotors, are not designed to experience these high amounts of braking force: if you were to use the average steel brake rotors on a racecar, the brakes would fail relatively quickly, which could lead to the racecar crashing. Carbon ceramic brakes can withstand high amounts of braking force and have little-to-no brake fade. They can also stop a vehicle at a much faster rate. This could be applied in applications such as landing a plane because aircraft require immense stopping power in a short period of time to fully come to a stop on the runway. Trains have a much longer time to brake and come to a complete stop at the station. Carbon ceramic brakes could be helpful for a train because of the better heat dissipation under load. The better they are at disbanding heat means the chances of the brake rotors warping diminishes.

Carbon ceramic brakes work the same as normal brakes on every car. Instead of steel rotors, carbon ceramic brakes are made of a carbon ceramic composite. Carbon ceramic brakes tend to be bigger and wider than the average brake rotor found on consumer-level cars.

Engineers play a massive role in designing and improving this system. Heat transfer and fluid dynamics are two of the biggest concerns when it comes to braking systems. Brakes have to be specially designed to disband heat at a rate that will be adequate for the application, as well as making sure fresh, cold air can reach the rotors and cool them down. In the case of Brembo's carbon ceramic brake rotors, they have specifically designed the rotor to have fins and slotted holes that promote good fluid dynamics and heat transfer to maximize the performance of the rotors.

II. Historical Evolution

Ever since the first automobile was created, there has been a need for a braking system. Over the years, brakes have taken many shapes and forms, the most popular being steel brake rotors. The first-ever car to use carbon ceramic brakes was the BT49 Brahbam F1 car that debuted in the 1980 F1 season [4]. In 2001, the first commercially available car with carbon ceramic brakes that came to market was the 2001 Porsche GT2. After Porche released the GT2, a precedent was set for the high-performance car industry. Now, most flagship and high-performance cars being released have the option to come with carbon ceramic brakes.

Carbon ceramic brakes are still a new development in the automotive industry. Because the market for these brakes is a lot smaller than the market for steel brakes, the industry has not evolved at a high rate. Carbon ceramic rotors have improved since they debuted in the GT2 over 20 years ago. One of the big developments has been the improvement of heat transfer and cooling systems. Since these brakes are intended for track use, there will always be a demand for brakes that can cool faster and better.

As racecars continue to become faster, the demand for better braking systems continues to grow. In some endurance racing series, the cars' brake rotors can become so hot that they appear to be glowing red hot. Braking system manufacturers are always looking for ways to improve airflow and cooling systems in the rotors. One of the biggest complaints from consumers is that carbon ceramic brakes can be squeaky at low-speed braking. One of the main reasons this happens is because the brakes are designed for high-performance use and when a driver does not use the car/brakes in the way they were designed these issues arise. One easy fix to this problem is to bring the car up to speeds 100+ mph and slam on the brakes. This may seem like an awful idea, however, the brakes are designed for this type of usage. After the high-speed braking is performed, the brakes should not squeak for a while. The carbon ceramic brakes that are currently being made and designed have slightly overcome this issue.

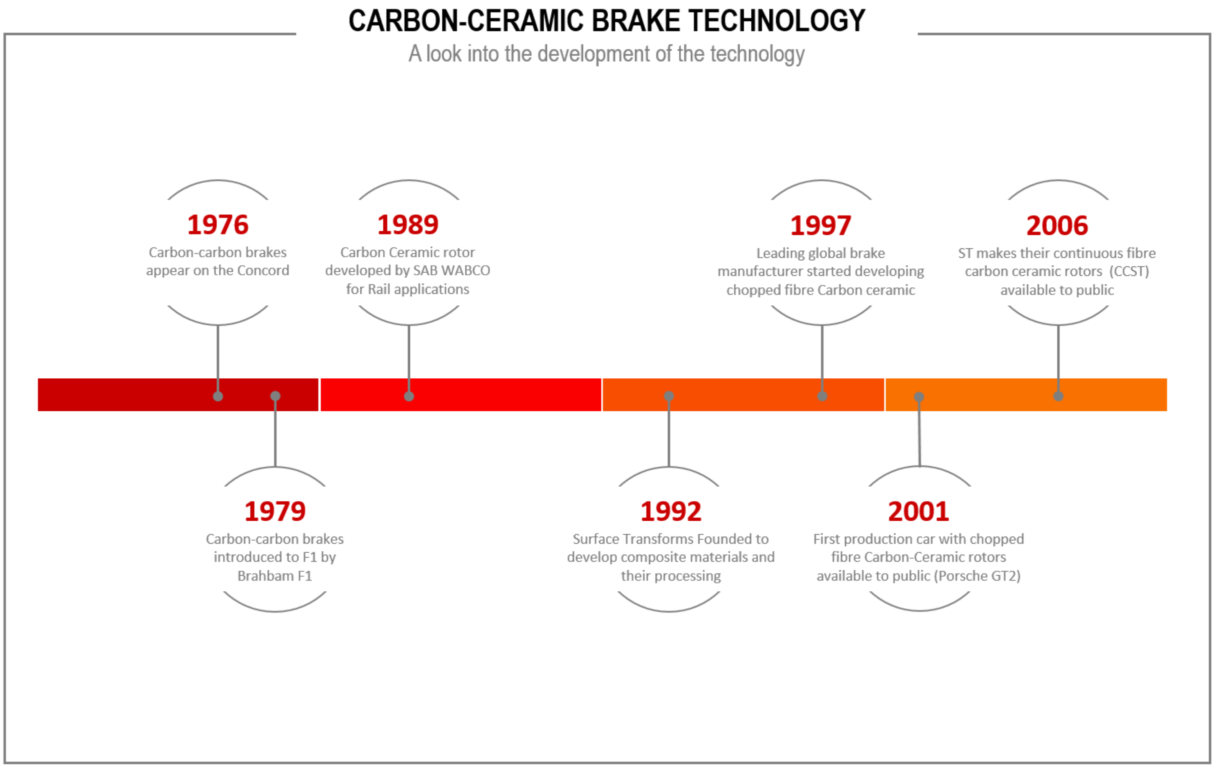

Figure 2: Timeline of the history of Carbon Ceramic brakes [4]

Carbon Ceramic brakes are incredibly relevant in today's world. Since being developed in the 70s, they have slowly made their way into the consumer market. The biggest market is still the automotive-racing industry. The company Brembo Brakes is responsible for the majority of the emerging carbon ceramic brake technologies. They have a patent on a design for carbon ceramics which has a complex design for cooling and heat transfer. In the past, a carbon ceramic braking system was only available as an after-market part. In today's world, these braking systems can come directly from factory from an OEM manufacturer. They are also covered under warranty which speaks to the great strides carbon ceramic brake manufacturers have made in the past two decades.

III. System Architecture and Functional Model

The overall design of carbon ceramic brakes has not dramatically changed over the years. The internals and the way the brakes can cool have significantly changed. On the inside of the rotor, the manufacturers have designed fin-like structures that optimize airflow and cooling within the rotor. The manufacturers also either drill grooves on the surface and/or drill holes straight through the rotor to get even more airflow and surface area. The diameter of the rotors has also increased over time. Carbon ceramic rotors cool down via convection as opposed to steel rotors which cool down through conduction.

	F1 Carbon Ceramic	Ferrari Carbon Ceramic	Range Rover Cast Iron
Size (mm)	278	398	380
Weight (Kg)	1.2	6.7	14
Range of use (°C)	350–1,000	-50–1,000	-50–500
Lifespan (Km)	800	300,000	80,000

Table 1: Comparison between F1 brakes, street-legal carbon ceramics, and traditional brakes [5]

Within a carbon ceramic braking system, there are three main components: the carbon ceramic rotor, the brake piston, and the brake pad. Aside from the rotor being made of a special material, the braking system works exactly like a run-of-the-mill steel rotor braking system. The function of the system is to slow down or completely stop a moving car. This is achieved by

Figure 3: Main components of a carbon ceramic braking system [6]

calipers using hydraulic force and pressing the brake pads onto the surface of the rotor. The friction from the pad making contact with the rotor is what will stop the front and rear axles from continuing to rotate. Because of the carbon ceramic construction of the rotor and its intended uses, the calipers used on carbon ceramic braking systems are extremely large. Steel rotors are usually around 14”, whereas carbon ceramic brake rotors are usually 16”. Unless you see a carbon ceramic brake kit in person, it is hard to comprehend just how big they are.

Figure 4: Size comparison for carbon ceramic brakes [7]

IV. System Performance

Carbon ceramic brake performance is gauged on multiple aspects. The first, stopping force. This measures how much force the calipers can apply on the rotor without the rotor locking up. The next performance gauge is rotor/brake fade. This is where carbon ceramic brakes thrive. When high amounts of braking force are applied repeatedly, brake rotors tend to wear, and this is called brake fade. The final performance gauge is the cooling ability or the rate at which the rotor dissipates heat. Carbon ceramic brakes can dissipate heat at a very high rate due to the mere size of the rotor. There are several ways of testing the performance of these systems. Whether it is a full-speed stress test, or measuring the airflow and temperature dissipation in the rotor.

Most customers who purchase carbon ceramic brakes are familiar with the mechanics/performance of the braking system. Since a set of carbon ceramics can range anywhere from $10,000 to $30,000+, most buyers are aware of what carbon ceramics can do since it is such a costly and niche product. An engineer would describe the performance of the system in a more technical manner, whereas the consumer (the driver) would describe the performance based on the feel and on-road performance. Both the consumer and the engineer would overlap in the way they described the performance, but overall they would describe the performance differently.

The performance of the system aligns directly with the functionality of the system. The performance gauges I mention above all directly align with the overall functionality of the braking system. Stopping force, heat transfer, and brake fade all directly affect the functionality of the system and subsystem. Most stakeholders view performance in the same way engineers and customers view it. Since carbon ceramic brakes are a high-performance oriented system, the more performance development, the better.

V. System Characterization

One of the main selling points of carbon ceramic brakes is that there is little-to-no brake fade. “Brake fade is the loss of braking power under high braking temperatures” [8]. Since racecars and other applications of high-performance braking have to continuously perform high-speed braking, the brake rotors reach incredibly high temperatures from the massive amounts of friction. Carbon ceramic brakes can withstand high temperatures without losing braking ability and performance. Carbon ceramic brakes can get so hot while under load that the rotor can glow from the sheer amount of heat.

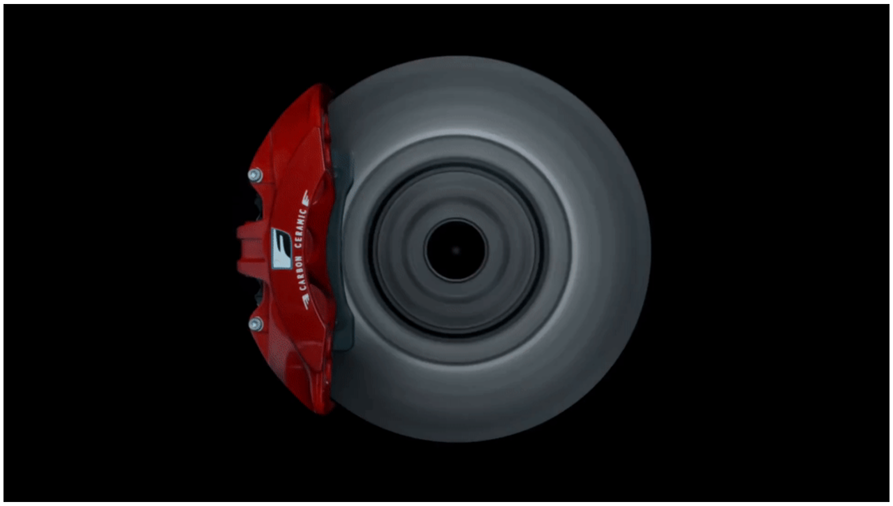

Figure 5: Demonstration of high-speed braking with carbon ceramic brakes [9]

Figure 6: Carbon Ceramic Brakes glowing during heavy braking [10]

These equations are used to quantify the performance of the braking system. The equation for the stopping or "retardation power" is [11]:

$$\dot{W} = -\frac{d}{dt}\,E_c = -\frac{d}{dt}\left(\frac{mV^2}{2}\right) = -mV\frac{dV}{dt}$$

In this equation, *W* stands for work, *m* stands for mass, V stands for velocity, and *t* stands for time. This equation can be used to calculate the stopping power of carbon ceramic brake rotors. This is similar to the work equations we derived in class and used throughout the semester. The next equation that is relevant to carbon ceramic brakes is the heat produced and heat dissipated equations [11]:

$$W_{\text{prod}} = \int_0^{t_0} \dot{q}_{\text{prod}} dt$$

$$W_{\text{diss}} = \int_0^{t_0} \dot{q}_{\text{diss}} dt$$

This equation enables engineers to calculate and understand the brake rotor's heat transfer which is intrinsic to the performance of the braking system. Engineers must be able to calculate the maximum temperatures produced by the brakes in order to design other parts of the car such as brake ducts and vents. Airflow is incredibly important when designing the correct wheel well and housing for the carbon ceramic brakes. As previously mentioned, carbon ceramic brakes rely on surface area to dissipate heat. They need much more airflow to operate as opposed to traditional steel brakes. Carbon ceramic brakes rely on convection to dissipate heat, while steel brakes rely on conduction.

Carbon ceramic braking systems convert the mechanical energy of a foot pressing on the brake pedal into heat due to the friction between the brake pad and the rotor. The total kinetic energy is equal to the total heat energy. The friction between the tire and the road, and the pad and the rotor equal the total kinetic energy of the system.

When redesigning a carbon ceramic braking system, engineers have to account for 3 major components: the maximum heat capacity, the stopping power, and the size/diameter of the rotors. Carbon ceramic brakes "operate at an optimal level of performance at 1,000 degrees Fahrenheit. Even at this temperature and at its upper operating temperature of over 5,000 degrees" [12]. These large temperatures need to be cooled, so engineers must design a system that can achieve a convection heat transfer rate that benefits these rotors.

Carbon ceramic rotors come in all shapes and sizes. When redesigning a system, engineers must keep the size of the rotor in mind as well. The rotor size directly affects the overall heat dissipation. If the rotor is too small, the braking system might not be able to dissipate heat properly leading to undesired performance. If the rotor is too big, it might not be able to fit within the OEM wheel/wheel well.

Carbon ceramic brakes have gone through lots of research and development since their immersion in the 70s. Whether it is Porsche with their in-house R&D, a third-party manufacturer such as Brembo, or an F1 team that spends hundreds of millions per year on their R&D for their cars, carbon ceramic braking systems have been researched, tested, and measured by thousands of engineers. Several machines have been created for the testing of braking systems. The most common machine for testing uses a motor that is mounted to the rotor which spins at high speeds. The engineers can then control the braking force of the brake calipers to test the heat of the rotor from braking at high speeds. Some high-performance cars and racecars have built-in sensors that can output braking power and rotor temperatures to the driver while driving. This is especially important in racecars due to the high amount of heat the carbon ceramic brakes withstand during a race.

VI. Human Organizational System Characterization

Although most humans have never gotten to directly interact with carbon ceramic braking systems, everyone has directly or indirectly experienced a braking system. Whether they rode on a bus, drove a car, flew on a plane, or bought food from the supermarket, braking systems directly affect our day-to-day lives. Planes, trains, cars, buses, 18-wheelers, and trucks are only a few examples of systems that directly rely on braking systems.

Brembo is one of the leading aftermarket manufacturers of carbon ceramic brakes. They have a large team of engineers who have been producing some of the most technologically advanced carbon ceramic brakes on the market. They provide OEM and aftermarket brake kits that are used in all of automotive racing. Whether you go to an F1 race, a GT3 racing series event, or an open track day at your local racecar track, you will see Brembo brake kits being used for their intended purpose.

Figure 7: GT3 Series racecars on track [13]

Brembo is notorious in the automotive industry for making the best quality brakes money can buy. They research, develop, market, and sell the brakes in-house. They are a true powerhouse in the automotive parts industry. Although they have several competitors, none of them come close to the band recognition Brembo has. On top of that, they have a massive social media presence. They sponsor race teams and independent races all over the world. In recent years, they have sponsored Youtubers and content creators who work/buid cars. These videos are immensely popular gaining them even more attention. Brembo Brakes will continue to flourish and develop new and more technologically advanced brakes for the next generation of automotive enthusiasts.

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