Brake discs: A technological review from its analysis and assessment

Discos de freno: Una revisión tecnológica de su análisis y evaluación

Ricardo García-León[1]
Eder Flórez-Solano[2]
Álvaro Suárez-Quiñones[3]

[1] Universidad Francisco de Paula Santander; (Colombia); Instituto Politécnico Nacional; (México); correo: ragarcial@ufpso.edu.co

[2] Universidad Francisco de Paula Santander; (Colombia); correo: enflorezs@ufpso.edu.co

[3] Universidad Francisco de Paula Santander; (Colombia); correo: aesuarezq@ufpso.edu.co

Recibido: 01-10-2018 Aceptado: 19-03-2019

Cómo citar: García-León, Ricardo; Flórez-Solano, Eder; Suárez-Quiñones, Álvaro (2019). Brake discs: A technological review from its analysis and assessment. *Informador Técnico, 83*(2), 000-000.
https://doi.org/10.23850/22565035.1766

Abstract

Braking systems are undoubtedly the most important component for road safety, since it determines the total or partial stop of a vehicle and, therefore, guarantees the physical integrity of passengers. Normally, the front brake discs and the remaining percentage absorb 70% of the kinetic energy produced within a vehicle by the rear brake discs, which tend to have the form of a drum brake. These systems benefit from friction to stop a moving vehicle, under the umbrella of hydraulic pressure that pushes the brake pads against the iron-cast disk. In this document, concepts of famous authors around the world on analysis and evaluation of brake discs are provided, which are carried out using a descriptive methodology and an estimation of the characteristics of the brake disc. The review is carried out in computer assisted design through several existing CAD software in the industry, as the main methodology applied to the development of certain research projects, where different geometric characteristics of the brake discs are considered, as well as problems related to wear and corrosion. This research project has shown that it is vital to incorporate existing computer assisted design software to predict performance, improve components and optimize the functionality of the brake system. In this way, road traffic safety and systems efficiency are achieved, which are a matter of great importance for the industry. It is vital to analyze brake systems through Finite Element Analysis (FEA), with the intention of achieving a broader vision of its performance, since the information collected reveals that the geometric characteristics of the brake and cooling ducts influence the heat dissipation. It depends on the form, the type of material and the application, the heat generated between the pad and the brake. Therefore, the heat is dissipated rapidly according to the analysis performed mathematically by the researchers, which are compared with the made in computer assisted design software.

Keywords: disc brake; Finite Elements Analysis (FEA), friction; temperature; cars.

Resumen

Los sistemas de frenos son, sin duda, el componente más importante para la seguridad vial, dado que determina la detención total o parcial de un vehículo y, por lo tanto, garantiza la integridad física de los pasajeros. Normalmente, el 70 % de la energía cinética producida dentro de un vehículo es absorbida por los discos de freno delanteros, y el porcentaje restante por los discos de freno hacia atrás, que tiende a tener forma de freno de tambor. Estos sistemas se benefician de la fricción para detener un vehículo en movimiento, bajo el paraguas de la presión hidráulica que empuja las pastillas de freno contra el disco fundido con hierro. En el presente documento, se proporcionan conceptos de autores famosos en todo el mundo sobre análisis y evaluación de discos de freno, que se realizan mediante una metodología descriptiva y una estimación de las características del disco de freno. La revisión se lleva a cabo en diseño asistido por computadora a través de varios softwares CAD existentes en la industria, como la principal metodología aplicada al desarrollo de ciertos proyectos de investigación, donde se tienen en cuenta distintas características geométricas de los discos de freno, así como problemas relacionados con el desgaste y la corrosión. Este proyecto de investigación ha demostrado que es vital incorporar el software de diseño asistido por computadora existente para predecir el rendimiento, mejorar los componentes y optimizar la funcionalidad del sistema de frenos. De esta forma, se logran la seguridad del tráfico vial y la eficiencia de los sistemas, que son una cuestión de gran importancia para la industria. Es vital analizar los sistemas de frenos a través del Análisis de Elementos Finitos (AEF), con la intención de alcanzar una visión más amplia de su desempeño, ya que la información recopilada revela que las características geométricas de los conductos de freno y enfriamiento influyen en la disipación del calor. Depende de la forma, el tipo de material y la aplicación, el calor generado entre la almohadilla y el freno. Por lo tanto, el calor se disipa rápidamente de acuerdo con el análisis realizado matemáticamente por los investigadores, que se comparan con los realizados en el software de diseño asistido por computadora.

Palabras clave: freno de disco; Análisis de Elementos Finitos (AEF); fricción; temperatura; automóviles.

Introduction

Worldwide brake context

During the braking process, the heat generated by friction between the brake pads and the disc is not quickly dissipated. This mainly depends on geometrical features and manufacturing material. Consequently, numerous negative effects on the entire brake may arise. Nowadays, pad surface and pad interface wear have been considered throughout all the studies of thermic analysis on brake discs, by implementing Finite Elements Method (García-León; Acosta-Pérez; Flórez-Solano, 2015).

Heat is generated by kinetical energy. When braking, heat might considerably be elevated as friction elevates temperature. Nonetheless, heat is quickly dissipated with surrounding air through convection phenomenon (heat of transfer produced among bodies at a different temperature). This depends on disc geometrical features and manufacturing material (see Figure 1). Environmental factors are also decisive for heat transfer to have place. Additionally, when the temperature reaches elevated values radiation phenomenon appears, which also contributes to dissipate energy in the shape of stored heat within the disc (García-León *et al.*, 2015; Hirasawa; Kawanami; Shirai, 2014; Belhocine; Bouchetara, 2013a). Under these conditions, brake system functionality and safety are jeopardized. It is important to mention that brake disc maintenance is far cheaper than drum-brakes maintenance (Belhocine; Abdullah, 2014; García-León; Flórez-Solano, 2016; García-León; Perez-Rojas, 2017).

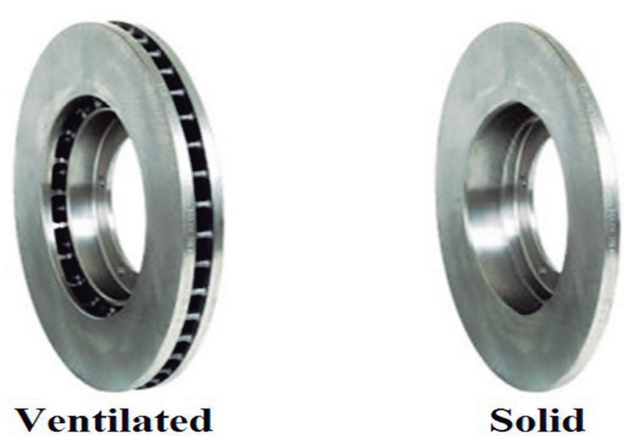


Figure 1. Solid and ventilated disc.
Source: García-León, 2014; García-León; Flórez-Solano; Acevedo-Peñaloza, 2018.

In the same way, elevated temperatures can cause brake fluids evaporation, brake wear, pads breakdown, fading, and vibrations. For this reason, many times system performance is slowed down, which is significant to foretell the distinct types of convection performance that take place during heat dissipation on the environment. This is done with the intent of assessing their efficiency based on their design and their original geometrical features.

Nowadays, ventilated disc brakes are used due to their optimal heat dissipation features, as recent research have proved that this type of brake disc has elevated heat transference rates. This is caused by an elevation of turbulence that stands for an elevated transfer of temperature. Ventilated discs also have a higher resistance to thermic deformation, due to a level distribution of manufacturing material, which reduces thermic stress built-up within the rotor and mainly determines disc geometrical features and an optimal configuration of ventilated ducts (Dhaubhadel,1996; Wurm; Fitl; Gumpesberger; Väisänen; Hochenauer, 2016).

In the main, Computational Fluids Dynamics (CFD) applications in the automobile industry have gone a long way to influence automotive components design, due to continuous breakthroughs in hardware and software, as well as in numerical techniques to solve fluids flow equations. Automotive industry interest in CFD applications stems from its capacity to improve car design and to reduce both manufacturing costs and products useful life (Dhaubhadel,1996; Wurm *et al.*, 2016; Pevec; Potrc; Bombek; Vranesevic, 2012). In view of the foregoing, the study of dynamic effects on brake discs is a major area of research for industry manufacturers and academia.

Considering the above-mentioned, CFD simulations are currently crucial since they constitute a key toolkit to assess the global amount of heat transferred to the environment and its accurate distribution within the systems. Berni's research project proves that two well-developed heat transfer models are effective to foretell heat flow (Berni; Giuseppe; Fontanesi, 2017; Thuresson, 2014). Furthermore, it is important to analyze the physical-chemical features of systems, on the purpose of optimizing mechanical components through Finite Elements analysis, as well as to have a wider vision about their performance under distinct conditions of operation.

Simulations

Determining disc geometrical features depends on load and functioning capacity, which is a key factor at the starting design stage. Under most circumstances, disc design must avoid overheating produced by friction between brakes and pads, considering physical; mechanical and chemical properties. Such overheating is produced because some sorts of materials do not perform correctly, and therefore, have negative effects on braking process efficacy.

At the starting mechanical stage on ventilated disc brakes, it is vital to analyze thermic flows performance where it is possible to observe flow features and operation upon discs' surface, by always guaranteeing braking process effectiveness and heat dissipation through the surface and ventilation ducts. Thermic heat dissipation and ventilated disc brakes performance mainly depend on aerodynamic features of air-flow, through ventilation ducts and disc brake geometrical configurations, which are proved via design software implementation provided by Computational fluid dynamics (CFD) library, such as: SolidWorks Simulation or ANSYS (Chi; He; Naterer, 2009; Klimenda; Soukup; Kampo, 2016).

Simulations are carried out with the intent of analyzing temperature performance between disc surface, ventilation and ducts auto-ventilated disc brakes. This way mathematically obtained results were compared with the ones that were obtained via Finite Elements Analysis (FEA) by relying on the assistance of Software SolidWorks Simulation (García-León, 2017; Jamari; Tauviqirrahman, 2017). This process is carried out with the intent of effectively validating extreme work conditions and of assuring high safety levels.

Heat transfer modeling is achieved under solid or modeled geometry design techniques CAD design software, which allows conducting of the analysis corresponding to computational dynamics. Heat transfer analysis indicates temperature gradients on ventilation ducts linings, as well as on thermic tensions spotted at the stationary lining, which can provoke deformations throughout disc cavity flows. Such effects are key to disc brake designs on the purpose of having into consideration thermic distortions and their effects on performance. Nowadays, the simulation shows that Computational

Fluid Dynamics (CFD) can provide means to understand flows and heat transfer mode, which allows assisting the designing process applied to braking systems components and geometrical features (Wu; Xiong; Hu; Yuan, 2015; Stewart; Singh; Andersen; Wen; Booth, 2016).

Heat transfer problems detected on constant flow of an unfathomable fluid, as is the case of air: temperature effect and Nusselt number; under the parameters of suction and injection at the output of radial and oncoming flows, have come to prove that surrounding fluid recirculation might whether happen or not inside of ventilation ducts, which turns to be necessary for heat dissipation through the environment. Friction and wear digital simulations in disc brake performance have been studied via several approaches, including Multicomponent Cellular Automaton (MCA) approach and Finite Elements Analysis (FEA). In such case, a model meant to digitally calculate body performance can be implemented to understand particles flow at a nanoscopic length scale, with the intent of digitally simulating macroscopic performance of disc brakes. This is carried out by means of a digital method that can handle the contact with microscopic length and time required in scales.

Müller and Ostermayer use a Multicomponent Cellular Automaton (MCA) approach to describe friction in three dimensions and performance wear of disc brakes (Blau; Meyer III, 2003; Shinde; Borkar, 2015; Belhocine; Omar, 2016). Digital simulation applied to geometrical features and to transitory articulate thermic stress is sequentially carried out by means of a structural thermal coupled method, based on ANSYS software, which allows assessing of deformation strength fields that are established on a disc by pads pressure and at hardening disc conditions. In so doing, distribution pressure levels of pads contact are obtained.

By means of Finite Elements Analysis (FEA), it is possible to determine temperature gradient, estimate Von Mises result, which predicts proper design and material, and flow distribution arising during braking. Besides, (FEA) has proved that tensions are mainly situated in the radial direction of friction surface on the edge of cooling holes (Blau; Meyer III, 2003; Kim; Lee; Park; Seok, 2008). Analytic methods have been a great aid in the automobile industry since they contribute to robust design brake systems and to reduce time-consuming experiments (Kim; Ahn; Lee; Jung, 2007; Blau; Jolly; Qu; Peter; Blue, 2007). In the case of materials used to manufacture brakes, such materials must support big thermic changes and resist both environmental and mechanical conditions that might affect tribological properties and safety systems. The main effect that appears on brake discs is corrosion due to the components that are manufactured and to operating conditions. For these reasons, design software-aided simulation strategy, which models transitory temperature within brake discs, was useful to identify disc geometrical design factors on the purpose of setting ventilation systems up on vehicles (Bagnoli; Dolce; Bernabei, 2009).

At the design of a braking system of vehicles, besides mechanical features, it is necessary to take into consideration thermic fails of the system. This is also explained since achieving adequate braking power makes braking systems far more efficient. In this sense, the most important scope is to dissipate heat as quickly as possible through the environment (Milenković *et al.*, 2010). On the purpose of processing brakes geometrical features, nets are tightened to the non-structured solid, through the building of nodes irregularly distributed, as it is shown in the following Figure 2:

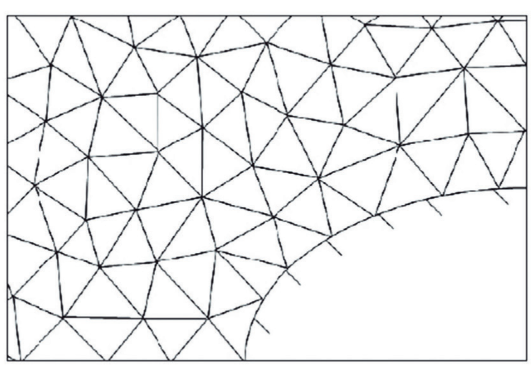


*Figure 2***.** Type of net used on discs.
Source: authors.

In the areas where fluids flow, SolidWorks Flow Simulation software was used, as it resolves Navier Stokes equations, which are formulations stemming from mass conservation law; the amount of motion and energy and the validation of material properties with specialized documents (Sobachkin; Dumnov; Sobachkin, 2014).

Regarding digital analysis study, a considerable number of car brake discs were used, on which cracks were found via specialized software. Macro-fractography revealed that grey cast iron brake discs had several cracks throughout disc rotors' surface radius of approximately 1 to 7.5 cm long. Besides, through an analysis conducted by using an optical microscopic and a Scanning Electron Microscope (SEM), it was possible to find that cracks used to spread following a semielliptical shape, throughout the width of friction surfaces according to thermic fatigue. As well, several areas showing definite signs under the effect of *judder* were noted. Finite Elements Analysis (FEA) was carried out to estimate the temperature gradient within discs and tension distribution during braking. In addition, comparatively elevated temperature levels reached during braking actions were confirmed, which are explained by residual drive tension cyclically caused by thermic repetition. Such process provokes cracks on the discs contact surface (Sakamoto, 2004).

Belhocine; Bouchetara, (2013b), could study thermic-mechanical effects arisen on several discs of different shapes, by implementing Finite Elements Analysis, which has come in handy when assessing discs' performance in terms of temperature levels distribution, pressure, and tensions. The findings prove that analyzed ventilated discs can efficiently be in hard work, which assures high safety quality levels. The thermic-structural analysis is used to a couple established deformation, von Mises coefficient within a disc, and contact pressure distribution within pads (Belhocine; Bouchetara, 2012a; Belhocine; Bouchetara, 2013b).

In other research studies, equations ruling heat within the disc and pads are resolved as transitory heat equations are, based on heat as it depends on time and space. After solving the heat equation, parameters such as: brake duration, vehicle speed, geometrical features, and brake components dimensions, disc brake rotor materials, and contact pad pressure distribution are considered as the key to making calculations on braking systems. Environmental factors are also defining so that heat transfer arises. Besides, when the temperature reaches elevated levels, radiation phenomenon appears, which also contributes to dissipate energy in the shape of stored heat within the disc (Talati; Jalalifar, 2009; Hernández-Mora; Trujillo-Rodríguez; Vallejo-Lozada, 2014; Romero-Millán; Cruz-Domínguez; Sierra-Vargas, 2016).

In recent studies, an explicative model on the contact situation between organic brake pads and grey cast iron discs is introduced. In this model, metallic fibers or other hard materials within the pads create bands, which are located at the main load area (Wahlström, 2011) (see Figure 3):

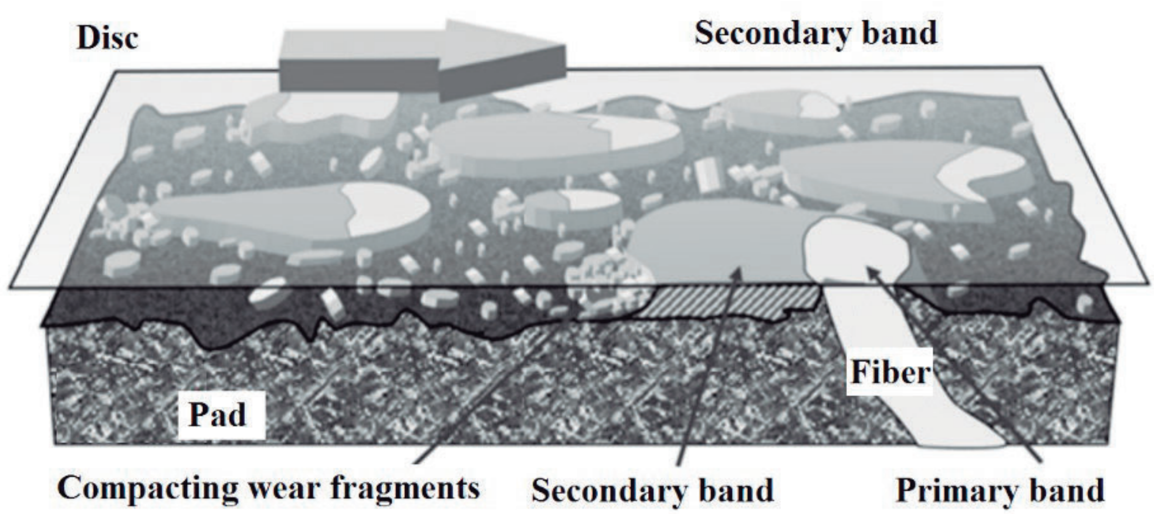


Figure 3. Contact situation between pads and discs.
Source: authors.

In this way, it was concluded that primary and secondary layers or bands' hardness is approximately the same and that the metallic matrix material hardness is 20 times lower. Thus, the most difficult bands to be protected within the matrix material are worn. Considering several measurements, it was found that contact bands can usually exhibit substantially higher hardness values than compound pads middle hardness ones do (for example, comparing 3.000 MPa with 200 MPa). This happens because bands are typically made up of metal fibers surrounded by a softer metallic matrix and compacted components (Söderberg; Andersson, 2009).

Between the disc and pads, the coefficient of friction must relatively be elevated, and moreover stable. A constant level must be kept regardless of temperature, moisture, time, wear level, corrosion, as well as powder and water jets on the road, inter alia. Besides these safety requirements, long useful life and proper comfort are considered, which means vibration; noise and squeaking absence. The technical importance of the friction system and its significant deviations, stemming from tribological situations, constitute contact situations that motivate a study on tribological nature contact within car brakes. Elevated temperature levels on the friction surface with sliding contact on brake setting within the rotor are liable to mechanical-chemical reactions and tribo-chemical reactions that are produced while braking. Due to the complex composition of brake pads, it is difficult to describe all those reactions when produced. A typical phenomenon that occurs at lower temperature levels regards phenolic resin degradation. In this way, phenolic resin degradation starting temperature depends on its nature, modification, and the presence of metals interacting as catalysts of their own degradation.

Baron-Saiz; Ingrassia; Nigrelli and Ricotta (2015), analyzed the thermic-mechanical performance of brake rotors, under extreme work conditions, with the intent of assessing their efficiency and stability. This analysis allowed to identify weaknesses within the structure and was carried out via Finite Elements, by studying thermic-mechanical effects produced within brake discs of different geometrical features. Such a process was as well undertaken to assess discs' performance regarding temperature distribution, pressure, and tensions (Baron-Saiz *et al.*, 2015).

In 2012, Belhocine analyzed the thermic-mechanical performance of contact on the brakes between the latest and pads while getting to braking stage. This simulation strategy is based on ANSYS software, in which transitory temperature field within the brake disc is indeed used to identify the geometrical design of the disc, on the purpose of designing brakes ventilation systems for cars. The thermic-structural analysis is used to a couple established deformation, Von Mises value within the disc and pads contact pressure distribution (Belhocine; Bouchetara, 2012b).

At the design stage of a car braking system, besides mechanical features, it is necessary to consider the thermic fails within the system since a proper and efficient power must be achieved, so that heat is dissipated as quickly as possible into the environment. Under this regard, experimental research of heat transfer process that takes place within cars is resorted, by using lab procedures and standard route tests according to quality regulations imposed by manufacturers. For doing so modern equipment is used, such as: thermic-graphical cameras, thermocouples, transducers, signal amplifiers, speed optical measurement systems and a laptop (Milenković *et al.*, 2010).

In other research studies, equations ruling heat within discs and pads are resolved as transitory heat equations by considering heat attached to time and the surrounding setting. When solving heat equations, parameters such as: braking length; vehicle speed; brakes components geometrical features and dimensions; brake disc rotor materials and contact pads pressure distribution; car speed; brake components geometrical features and dimensions; disc brake rotor materials and contact pad pressure, have been considered. The problem is analytically resolved by implementing several approaches, by which it is concluded that heat is generated since friction between the disc and pads must be properly dissipated into the environment, to avoid the coefficient of friction lessening between the disc and pads, and in such manner, get to avoid temperature levels elevation of every braking system component, and therefore, the evaporation of brake discs caused by an excessive heating.

The main scope of most cases is to provide a broader view on heat flow with the intent of improving heat dissipation into the surrounding setting, via a CFD analysis on several software on the purpose of obtaining numerical predictions and heat transfer to be compared with experimental data available on the corresponding state of art (Manohar-Reddy; Mallikarjuna; Ganesan, 2006; Manohar-Reddy; Mallikarjuna; Ganesan, 2008). The previous processing is carried out with the assistance of fluids dynamics, by using different design software like ANSYS, SolidWorks, inter alia (Rajagopal; Ramachandran; James;

Gatlewar, 2014). In addition, CFD applications in the automobile industry have gone a long way to influence self-propulsion components, due to continuous breakthroughs on hardware and software, as well as on numeric techniques to solve fluid flow equations. Interest in the automobile industry on CFD applications (Computational Fluids Dynamics) stems from their capacity to improve car design and to reduce product expenses and useful lifetime. In view of the foregoing, brake discs cooling is a key research branch for industry manufacturers, as it is for academia.

Likewise, with the assistance of available computer-aided calculus toolkit, such as commercial software meant for mechanical and thermic analysis, computer simulation is the most suitable method to analyze disc brakes, whether during its working or under several conditions of work. However, on any updated design computer-aided calculus toolkit can be used, which must be validated or proved by means of some lab tests and mathematical calculations. These experimental, study and computer analysis methods must be incorporated into any disc brake design methodology if it is expected to be validated.

It is precise to analyze, assess and study the features from all the engineering branches contributing to improving ventilated disc brake conditions and extend their usage (Rashid, 2014). Then, everything contributes to improving several geometrical features with the assistance of several aspects linked to hydraulic machine theory (Abhang; Bhaskar, 2014).

Dynamic system

Brakes systems influence cars' dynamic performance during braking stages, when disc rotor may reach 900 °C. Such a temperature elevation may cause a system loss or breakdown. To reduce these overheating problems within disc rotors, it is necessary to design new geometrical features for cooling ducts allowing to boost air flow, as those are placed between the braking surface of disc brake rotors. Considering research conducted by Aguayo-Ortiz, it is necessary to study several geometrical features of ducts, and therefore, assure a proper brake system functioning (Aguayo-Ortiz, 2016).

To improve brake mechanical and microstructural properties, carbon fibers, with which a lower coefficient of friction and more stable curves under distinct braking conditions can be reached, come in handy. This was mainly caused by major darkness and module on the application of this type of materials, such as brake manufacturing components (Acosta-Alvarez; Pareja-Dangond, 2019; Wu; Yi; Ge; Ran; Peng, 2017). In other research work, polymeric fiber-reinforced compounds show excellent mechanical and tribological properties. For these reasons, they are used in many engineering applications like drive and brakes systems. Considering the above, researchers analyzed wear mechanism in phenolic linen fiber-reinforced compounds within a disc brake under conditions, by implementing electronic microscopy methods. In addition, wear map was correlated to previously taken pictures (Ilanko; Vijayaraghavan, 2017; Palmer; Mishra; Fieldhouse, 2009).

Brake pads and unfunctional discs were used in asphalt mixtures to analyze their properties and features since it has become a type of solid waste, which turns to be a grave environmental problem. Through several tests based on existing regulation, researchers could improve asphalt conditions performance. Furthermore, metallic brake pads made for train wagons have polymeric designs with metallic elements exposed to corrosion, which allows systems treatment to avoid this type of performance. In addition, metallic parts of the pads were used as samples through the study of corrosion speed kinetics (Pavlov; Kudelnikova; Vicharev, 2015). As well, in a research project conducted by Stewart, a similar performance, but in distinct types of brakes were analyzed, such as ventilated; auto-ventilated and ABS brakes, inter alia.

In Mexico, some researchers studied and described wear mechanisms that were implicit within brake pads and shoes. Through this study, the disc brake concerned was subjected to real conditions at service on elevated temperature areas, which allowed to prove that sliding wear was produced and to validate the information gathered through Scanning Electron Microscopy, X-Rays spectroscopy and Atomic Force Microscopy (Laguna-Camacho, 2015).

Nowadays, several researchers considered computer simulations to estimate vibration phenomena on braking systems with the intent of noting angular speed performance (Wei; Ruan; Zhu; Kang, 2016). For the above, bounces of vehicle and distance variation of braking have an impact on braking performance and safety. Researchers of the University of Technology Sydney simulated, in a bank of brake discs' performance tests, to obtain economic and dynamic benefit from system efficiency. This allowed to prove system' efficiency in different operating conditions (Ruan; Walker; Watterson;

Zhang, 2016). Likewise, braking profiles were obtained through computer modeling and analysis of systems components, on the purpose of predicting their performance under several types of usage to which those can be subjected. Besides, Wei studied the effect on longitudinal dynamics on trains that worked with air brakes. The findings showed that it is possible to predict system features through mathematical methods (Wei *et al.*, 2017).

In 2012, scientists used Finite Elements with the assistance of CATIA Software to predict breakthroughs within the brake disc, and in such manner, to identify the most critical areas (Kim; Yim; Jeon; Jung; Han, 2012). On the other hand, researchers of Università Degli Studi di Roma considered the influence of speed regarding friction within brake systems and included a static coefficient, other than kinetical, by applying traditional computer methods (Andreaus; Casini, 2001; Shaw, 1986).

Furthermore, Meng; Zhang & Yu (2016) considered the pedal as amajor component of the braking system to study dynamical calculation conditions. Through this study, mathematical findings under static and dynamic conditions of systems were used to predict their performance. In such manner, Pedal Force (PF), Pedal Tour (PT) and response time are studied with the intent of satisfying customers safety expectations.

Through static and dynamic analysis on distinct types of motor vehicles under several works conditions were of great assistance to apply these toolkits on engineering research (García-León; Flórez-Solano, 2017)Revista Ingeniería e Investigación - Editorial Board. All rights reserved. The braking system of a car must meet several requirements, among which safety is the most important. It is also composed of a set of mechanical parts such as springs, different types of materials (Metallic and Non-Metallic. In addition, surveys and other researchers discussed the influence of loads on braking and pedal force systems, as those directly influence natural components dynamics. Regarding technological resources of braking systems, researchers proposed high-frequency braking by using a magnetic starter, with the intent of solving hydraulic braking problems. The findings were analyzed with the assistance of LabVIEW software and Finite Elements Analysis (FEA).

For the above, it is precise to understand braking systems transitory and non-linear effects, way undulations and vehicle dynamics under the perspective of tires lateral performance, which mainly affects these systems microstructures. To accurately simulate those non-linear effects during vehicle dynamic maneuvers, it is necessary to use fluid dynamics meant for vehicle simulations, which contribute to validate analytical results with those provided by the state of art (Siramdasu; Taheri, 2016).

Methodology

To develop this research project, a review on the state of art is carried out by means of technological analysis methods, under distinct zones linked to ventilated disc brakes in vehicles, by comparing and gathering information, on the purpose of identifying major variables that influence braking process of vehicles, such as: type of material, geometrical features, conducted analysis, and wear. This is done to define more relevant parameters through which future research can be proposed with the intent of improving such automobile industry components.

Besides, hydraulic machines and heat transfer theories are considered to estimate distinct conditions of fluids flowing throughout discs' ducts of several vehicles that are subjected to distinct load-carrying and transport capacity (Mataix, 1986).

Development and discussion

Dissipated power within brake systems that comes from vehicle kinetical and potential energy is transformed into thermic energy. In this direction, the heat generated must be evacuated as quickly as possible, and in this way, getting to avoid elevated temperature levels that might threaten system safety. Vehicle slipping itself allows dissipation of the heat generated via convection and radiation. When there are excessive stops, temperature elevates up to a certain limit (saturation temperature), according to tthe hermic dissipation capacity of a specific brake disc, which is not considered in the case of this analysis.

To make these calculations, the physical and thermic properties of laminar graphite nodular grey cast iron must be considered, since it is the most widely used material to manufacture brakes. This type of material is made up of silicon and manganese. Moreover, speed calculations are made by using radial ventilators, Fluid Mechanics and Hydraulic Machines theories.

Because of elevated thermic conductivity levels, proper resistance to wear, manufacturing facilities and a relatively low cost, the brake disc is generally manufactured based on grey cast iron from the very first stages of car development. Nonetheless, despite these favorable properties, grey cast iron corrosion performance keeps being an issue since it often contributes to an unpleasant situation known as brake judder, which stands for stains onset.

Therefore, few studies have considered size, shape, phenomena of conditions or elemental composition, which cause brake discs to quickly corrode. On these grounds, research projects have been developed on how friction leads to corrosion and wear breakdowns within brakes, as well as to elevated temperature levels that take place in this setting. Thus, there are several projects that analyze: how to improve braking efficiency while evidently staying friendly with the environment based on lighter materials.

To implement an updated material on brake discs manufacturing, the coefficient of friction must relatively be elevated. However, the most important aspect to be considered is stability, regardless of temperature; moisture; usage time; wear rank; corrosion and the presence of powder and water jets on roads. In addition, requisites for long usage life and high comfort stand from vibration, noise, and squeaking.

During regular and relatively soft stops, pads pressure force exerted against the disc is approximate of 5 kN, which turns to be pressure nominal value on pads surface higher than 1.2 MPa. Under extreme situations, the pressure might be close to 10 MPa. During severe stops, power dissipation throughout brake pads is easily exceeded to 30 kW. Such elevated energy density levels result in elevated surface temperature levels, and therefore, special materials meant for friction processes are required. All these remarks make part of a project on squeaking generation within brakes, where squeaks are generally sparked under lower speed and pressure levels. This means that brakes have only been exposed to braking under relatively lower conditions (0-25 km/h). These tests are carried out at a laboratory surrounded by environmental moisture, which is most of the time constant (20-25 °C). When transporting larger loads within vehicles, wear resistant components found in the coefficient of friction that is generated by volume fraction are influenced. Ergo, despite the materials composing brake disc and pads structure, the upper layer of lining volume is affected by wear. Such a situation is caused by a metal-metal contact that arises between both components (Jacobson, 2007; Matějka, 2011).

Newton's law of cooling is a concept of heat transfer stating that an object under a temperature shall cool, if it is exposed to a room temperature , according to the exponential equation established on the references (Kim *et al.,* 2008). The air flow pattern is affected by natural convection caused by distinct temperature levels. Thus, the forced convection flow is reflected on the disc surface, and the rotation flow is prompted to the inside of the disc. The estimated findings show the highest and lowest values of average heat flow in the direction of the disc (He; Ma; Huang, 2005).

In turn, the characterization of all the elements, present in the chemical composition of this type of disc brakes, aims at uncovering the effect exerted on manganese, silicon, and chromium alloy elements, as well as the other components of the metallic matrix that influence the material microstructure.

Parts and Definitions

Brake disc. The brake disc is an element linked to the rim axl or a part of it. Brake discs turn along with the rim, and therefore, constitute braking motion system. Brake pads interact on the brake disc aiming to stop the vehicle. The continuous friction established between the brake pads and discs, due to their heat energy speed, is produced by an elevation of temperature levels within the system. The geometrical constitution of discs, in the shape of dishes with a wide; exposed and ventilated surface, enhances continuous cooling and the whole generated heat evacuation, thanks to friction. Providing this process was not accomplished, the system would collide (Puhn, 1985). Which is made up of the following parts (Gorjan *et al*., 2016) (see Figure 4):

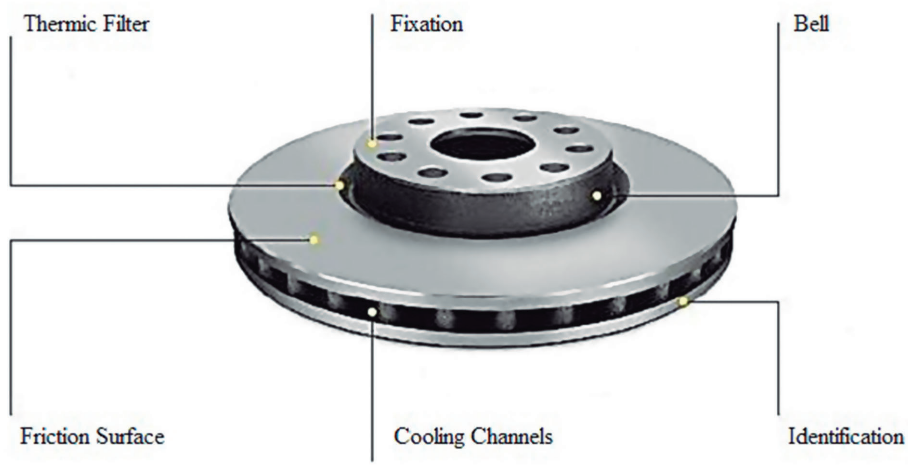


Figure 4. Ventilated structure of a brake disc.
Source: García-León (2014).

Thereafter, every component of the braking system is described in Table 1:

Table1.
Brake components

Components	Description
Vacuum servo	It consists of the system allowing reducing the necessary pressure force on pedals.
Brake booster	It consists of a cylinder whose scope is to the pressurize liquids throughout the hydraulic circuit.
Braking limiter	It consists of a correction or limiting system that reduces pressure exerted on the rear wheel assembly on the purpose of preventing those wheels to be blocked.
Brake caliper	It consists of an element in charge of supporting pads and pushing them against the disc when the system is pressurized. The caliper is a key element of braking systems and is subjected to considerable strength when braking, such as: vibrations, excessive temperature, and other aggressive items.
Brake disc	Brake discs constitute the surface against which pads interact to make a car slow down. Friction between pads and brake discs cause kinetical energy to be turned into heat energy, which makes a car slow down.
Brake pads	Brake pads constitute an element of braking systems, which along with brake discs, produce enough friction to make a car slow down.
Brake ducts and hoses	Brake ducts and hoses oversee driving brake fluids by supporting inner liquids pressure. Besides, they help resist environmental aggression. Brake ducts are usually iron pipes draped in polymers to resist corrosion.
Brake fluids	Brake fluids constitute a hydraulic fluid that drives force exerted on the pedal towards brake cylinders within wheels. It consists of a synthetic fluid prepared out of solvent thinning and additive inhibitor to protect brake hydraulic systems, whether they are disc-like or drum-like, against oxidation and rust.

Source: García-León *et al.*, 2018

***Chemical formula.* The** basic formula of disc material is a nodular grey iron laminar graphite, containing 92 % and 93 % of iron. This ferroalloy generally contains 2.5 % of carbon, more than 1.0 % of manganese, less than 0.5 % of silicon, and others bringing specific properties of braking systems up, as it is shown in the following Figure 5 and 6 (Langhof *et al.,* 2016):

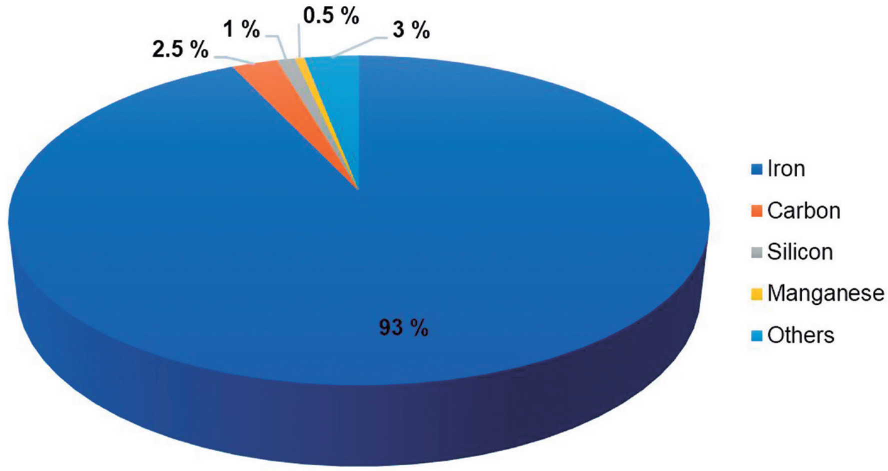


Figure 5. The chemical formula of brake discs.
Source: García-León (2014).

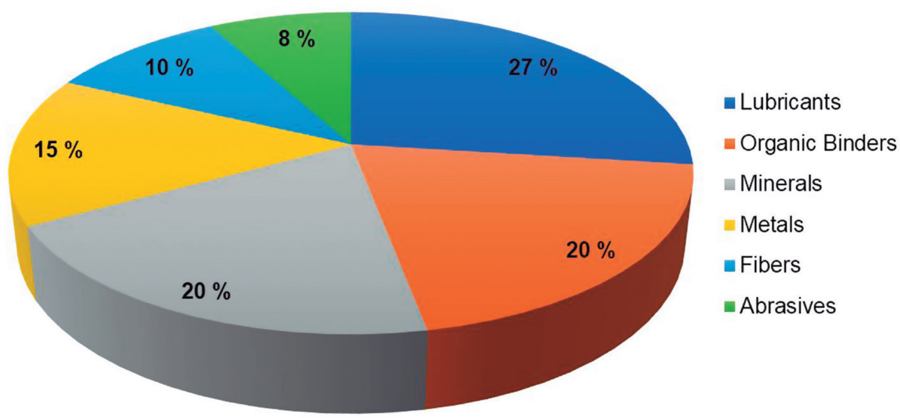


Figure 6. The chemical formula of brake pads.
Source: García-León (2014).

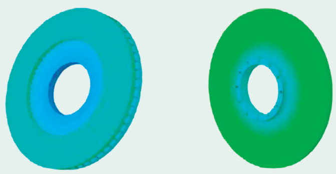
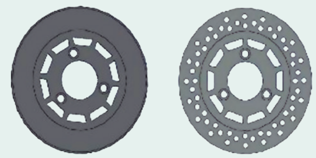
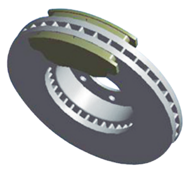
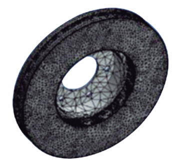
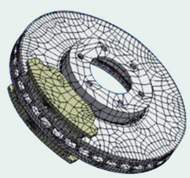
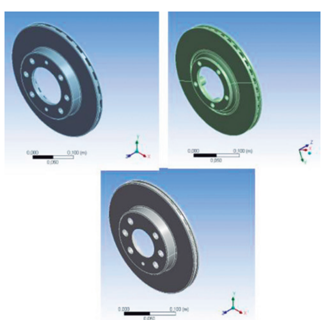
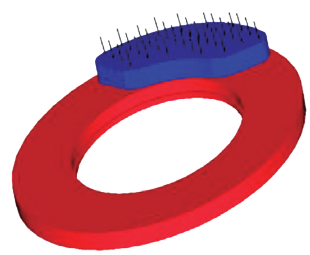
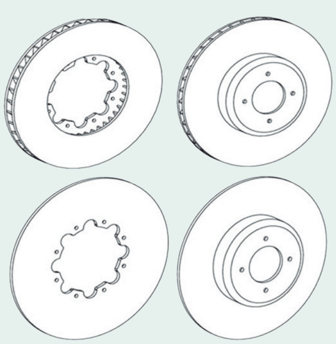
The material used to manufacture brake pads must show an elevated coefficient of friction, so that it gets to slow the speed down within wheels while it interacts with the disc surface. Besides, this coefficient of friction value must keep as stable as possible at any rank of temperature and pressure during its operation, as it may be noted in Figure 6.

Brake formula can be mixed with distinct types of compounds, such as carbon fibers (CF-A and CF-B), according to the research conducted at Central South University, which improved resistance to interlaminar shear stress as a better resistance to wear.

Major problems linked to brake discs. The study of distinct problems in brake discs prove that most of them can be prevented, if hook-up gets more attention and simulations by Finite Elements are conducted, on the purpose of improving systems and their components. Such tasks are not only carried out through quantifiable or measuring controls, but also by means of a strict visual test on the components.

As follows, Table 2 is presented, where geometrical features mainly used while conducting Finite Elements analysis, according to researchers involved in this project, are shown:

Table 2.
Geometrical features used to conduct analysis and assessment of brake discs

Geometrical features	Source	Geometrical features	Source
	(Stewart *et al.*, 2016)		(Jamari; Tauviqirrahman, 2017)
	(Belhocine; Abdullah, 2014)		(Belhocine; Bouchetara, 2013)
	(Belhocine; Omar, 2016)		(Gorjan *et al.*, 2016)
	(García-León, 2017)		(Kim *et al.*, 2008)
	(Rashid, 2014; Bagnoli, *et al.*, 2009)		(Abhang; Bhaskar, 2014; Kim *et al.*, 2012; Echavez-Díaz; Quintero-Orozco, 2017; García-León; Rivera-López; Quintero-Orozco; Gutiérrez-Paredes, 2019; García-León; Echavez-Díaz; Flórez-Solano, 2018)

Source: authors.

Considering (Table 2), several types of geometrical features under disc brakes study, the design software used (ANSYS) (because of its potential in terms of computational fluids dynamics) are presented. It is precise to mention that current brake conditions of brakes can provide heat fluids graphics, speed values, metal-metal contact, type of material, heat loss and fluid turbulence. Such progress evidently contributes to have a broader view on these systems performance, which are key to automobile industry study.

Conclusions

The system, under study and measurement, was the most important of all since nowadays a vast number of vehicles rely on ventilated disc brakes within their four wheels, with the intent of improving the braking process. Failing that, vehicles, that still use drum brakes on their backward axle, have a deficient brake performance since heat generation areas are closed and do not allow heat to be evacuated. Such problems are evidenced when material shows low heat loss, corrosion, and crevice.

It is precise to compare and validate mathematical findings with experimental ones by using specialized design software such as ANSYS, SolidWorks and CATIA, which provide and support mathematical calculations.

By reviewing previous research works on the topic, it was possible to evidence, that according to brakes and ducts geometrical features, rapid heat dissipation is guaranteed. This means there is trustfulness on braking system efficiency, which was validated via design software since it is a powerful tool to validate, assess and experiment with disc brakes.

It is important to keep studying this type of mechanical component since there are plenty of software systems, lab analysis and bibliographical references available, which contribute to easily assess braking systems on the purpose of optimizing and contributing to this important development area of engineering.

References

Abhang, Swapnil; Bhaskar, D. P. (2014). Design and Analysis of Disc Brake. *International Journal of Engineering Trends and Technology*, *8*(4), 165–167. https://doi.org/10.14445/22315381/IJETT-V8P231

Acosta-Alvarez, Iovanny; Pareja-Dangond, Diego (2019). *Construcción de un banco de pruebas para el analisis del comportamiento al desgaste de los sistemas de frenos de disco automotrices* (tesis de pregrado). Universidad Francisco de Paula Santander Ocaña, Colombia.

Aguayo-Ortiz, A.; Cardoso-Sakamoto, H.; Echeverría-Arjonilla, C.; Porta-Zepeda, D.; Stern-Forgach, C.; Monsivais-Galindo G. (2016). Calibration of a Background Oriented Schlieren (BOS). In Klapp, Jaime; Di G, Leonardo; Medina, Abraham; López, Abel; Ruiz-Chavarría, Gerardo (Eds.), *Recent Advances in Fluid Dynamics with Environmental Applications* (pp.103-114). Environmental Science and Engineering. Springer, Cham. https://doi.org/10.1007/978-3-319-27965-7_8

Andreaus, U.; Casini, P. (2001). Dynamics of friction oscillators excited by a moving base and/or driving force. *Journal of Sound and Vibration*, 245(4), 685-699. https://doi.org/10.1006/jsvi.2000.3555

Bagnoli, F.; Dolce, F.; Bernabei, M. (2009). Thermal fatigue cracks of fire fighting vehicles gray iron brake discs. *Engineering Failure Analysis*, *16*(1), 152-163. https://doi.org/10.1016/j.engfailanal.2008.01.009

Baron-Saiz, C.; Ingrassia, T.; Nigrelli, V.; Ricotta, V. (2015). Thermal stress analysis of different full and ventilated disc brakes. *Frattura Ed Integrita Strutturale*, *9*(34), 608–621. doi: 10.3221/IGF-ESIS.34.67

Belhocine, Ali; Abdullah, O. I. (2014). Finite Element Analysis of Automotive Disk Brake and Pad in Frictional Model Contact. *IJMMME*, 5, 32-62. doi: 10.4018/IJMMME.2015100103

Belhocine, A.; Bouchetara, M. (2012a). Thermomechanical Behaviour of Dry Contacts in Disc Brake Rotor with a Grey Cast Iron Composition. *Transactions of the Indian Institute of Metals*, *65*(3), 231-238. https://doi.org/10.1007/s12666-012-0129-6

Belhocine, A.; Bouchetara, M. (2012b). Thermomechanical Behaviour of Dry Contacts in Disc Brake Rotor with a Grey Cast Iron Composition. *Transactions of the Indian Institute of Metals, 65*(3), 231-238. https://doi.org/10.1007/s12666-012-0129-6

Belhocine, A.; Bouchetara, M. (2013a). Temperature and thermal stresses of vehicles gray cast brake. *Journal of applied research and technology, 11*(5), 674–682. https://doi.org/10.1016/S1665-6423(13)71575-X

Belhocine, A.; Bouchetara, M. (2013b). Investigation of temperature and thermal stress in ventilated disc brake based on 3D thermomechanical coupling model. *Ain Shams Engineering Journal, 4*(3), 475-483. https://doi.org/10.1016/j.asej.2012.08.005

Belhocine, Ali; Omar, Wan (2016). A numerical parametric study of mechanical behavior of dry contact slipping on the disc–pads interface. *Alexandria engineering journal, 55*(2), 1127-1141. https://doi.org/10.1016/j.aej.2016.03.025

Berni, Fabio; Cicalese, Giuseppe; Fontanesi, Stefano (2017). A modified thermal wall function for the estimation of gas-to-wall heat fluxes in CFD in-cylinder simulations of high performance spark-ignition engines. *Applied Thermal Engineering, 115*, 1045-1062. https://doi.org/10.1016/j.applthermaleng.2017.01.055

Blau, Peter; Jolly, Brian; Qu, Jun; Peter, William; Blue, Craig (2007). Tribological investigation of titanium-based materials for brakes. Wear, *263*(7-12), 1202-1211. https://doi.org/10.1016/j.wear.2006.12.015

Blau, Peter; Meyer III, Harry (2003). Characteristics of wear particles produced during friction tests of conventional and unconventional disc brake materials. *Wear, 255*(7-12), 1261-1269. https://doi.org/10.1016/S0043-1648(03)00111-X

Chi, Zhongzhe; He, Yuping; Naterer, Greg (2009). Convective heat transfer optimization of automotive brake discs," *SAE Int. J. Passeng. Cars - Mech. Syst.*, *2*(1), 961-969. https://doi.org/10.4271/2009-01-0859

Dhaubhadel, M. N. (1996). CFD applications in the automotive industry (invited keynote presentation). *Journal of fluids engineering, 118*(4), 647-653. https://doi.org/10.1115/1.2835492

Echavez-Díaz, Robert; Quintero-Orozco, Abner (2017). *Estudio experimental del comportamiento dinámico del fluido del aire a través de un disco de freno automotriz con pilares de ventilación tipo NACA 66-209* (tesis de pregrado), Universidad Francisco de Paula Santander, Ocaña, Colombia.

García-León, Ricardo (2014). *Evaluación del comportamiento de los frenos de disco de los vehículos a partir del análisis de la aceleración del proceso de corrosión* (tesis de pregrado). Universidad Francisco de Paula Santander, Santander, Colombia.

García-León, Ricardo (2017). Thermal study in three vented brake discs, using the finite element analysis. *DYNA, 84*(200), 19-27. https://doi.org/10.15446/dyna.v84n200.55663

García-León, Ricardo; Acosta-Pérez, María; Flórez-Solano, Eder (2015). Análisis del comportamiento de los frenos de disco de los vehículos a partir de la aceleración del proceso de corrosión. *Tecnura*, *19*(45), 53–63. https://doi.org/10.14483/udistrital.jour.tecnura.2015.3.a04

García-León, Ricardo; Echavez-Díaz, Robert; Flórez-Solano, Eder (2018). Análisis termodinámico de un disco de freno automotriz con pilares de ventilación tipo NACA 66-209. *INGECUC, 14*(2), 9–18. https://doi.org/10.17981/ingecuc.14.2.2018.01

García-León, Ricardo; Flórez-Solano, Eder (2016). Estudio analítico de la transferencia de calor por convección que afectan los frenos de disco ventilados. *Tecnura*, *20*(1), 15–30.

García-León, Ricardo; Flórez-Solano, Eder (2017). Dynamic analysis of three autoventilated disc brakes. *Ingeniería e Investigación, 37*(3), 102-114. https://doi.org/10.15446/ing.investig.v37n3.63381

García-León, Ricardo; Flórez-Solano, Eder; Acevedo-Peñaloza, C. (2018). *Análisis termodinámico en frenos de disco*. Bogota, Colombia: ECOE Ediciones.

García-León, Ricardo; Perez-Rojas, Eduar (2017). Analysis of the amount of heat flow between cooling channels in three vented brake discs. *Ingeniería y Universidad, 21*(1), 55–70. https://doi.org/10.11144/Javeriana.iyu21-1.aahf

García-León, Ricardo; Rivera-López, Jesús; Quintero-Orozco, Abner; Gutiérrez-Paredes, Guadalupe (2019). Análisis del caudal en un disco de freno automotriz con álabes de ventilación tipo NACA 66-209, utilizando velocimetría por imágenes de partículas. *Informador Técnico, 83*(1), 20-32. https://doi.org/10.23850/22565035.1785

Gorjan, L.; Boretius, M.; Blugan, G.; Gili, F., Mangherini, D.; Lizarralde, X.; Ferrarise, M.; Graulea, T.; Igartua, A.; Mendoza, G.; Kuebler, J. (2016). Ceramic protection plates brazed to aluminum brake discs. *Ceramics International, 42*(14), 15739-15746. https://doi.org/10.1016/j.ceramint.2016.07.035

He, Yan; Ma, Lianxiang; Huang, Suyi (2005). Convection heat and mass transfer from a disk. *Heat and mass transfer, 41*(8), 766-772. https://doi.org/10.1007/s00231-005-0628-7

Hernández-Mora, Johann; Trujillo-Rodríguez, César; Vallejo-Lozada, William (2014). Modelamiento de la irradiancia y la temperatura ambiente utilizando funciones de probabilidad. *Tecnura, 18*(39), 128-137. https://doi.org/10.14483/udistrital.jour.tecnura.2014.1.a09

Hirasawa, Shigeki; Kawanami, Tsuyoshi; Shirai, Katsuaki (2014). Numerical analysis of convection heat transfer on high-temperature rotating disk at bottom surface of air flow duct. In *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, vol. 8A. https://doi.org/10.1115/IMECE2014-36142

Ilanko, Ashok; Vijayaraghavan, Srinivasan (2017). Wear mechanism of flax/basalt fiber-reinforced eco friendly brake friction materials. *Tribology-Materials, Surfaces & Interfaces, 11*(1), 47-53. https://doi.org/10.1080/17515831.2017.1299323

Jacobson, R. (2007). Applications of a new model for the abrasive wear resistance of multiphase materials. *Compos. Coat. Mater.*, *174*, 1459–1463.

Jamari, Jaenudin; Tauviqirrahman, M. (2017). "Thermal analysis of disc brakes using finite element method. *AIP Conference Proceedings 1788*, 30028. https://doi.org/10.1063/1.4968281

Kim, Dae-Jin; Lee, Young-Min; Park, Jae-Sil; Seok, Chang-Sung (2008). Thermal stress analysis for a disk brake of railway vehicles with consideration of the pressure distribution on a frictional surface. *Materials Science and Engineering: A, 483*, 456-459. https://doi.org/10.1016/j.msea.2007.01.170

Kim, J. K.; Yim, E. S.; Jeon, C. H.; Jung, C. S.; Han, B. H. (2012). Cold performance of various biodiesel fuel blends at low temperature. International journal of automotive technology, 13(2), 293-300. https://doi.org/10.1007/s12239-012-0027-2

Kim, M. R.; Ahn, B. J.; Lee, J. M.; Jung, Y. K. (2007). Numerical investigation of thermal behavior. In *brake assembly during the ALPINE braking mode* (No. 2007-01-1021). SAE Technical Paper. https://doi.org/10.4271/2007-01-1021

Klimenda, Frantisek; Soukup, Josef; Kampo, Jan (2016). Heat distribution in disc brake. In *AIP Conference Proceedings*, vol. 1745. https://doi.org/10.1063/1.4953715

Laguna-Camacho, J. R.; Juárez-Morales, G.; Calderón-Ramón, C.; Velázquez-Martínez, V.; Hernández-Romero, I.; Mendez-Mendez, J. V.; Vite-Torres, M. (2015). *A study of the wear mechanisms of disk and shoe brake pads. Engineering Failure Analysis, 56*, 348-359. https://doi.org/10.1016/j.engfailanal.2015.01.004

Langhof, Nico; Rabenstein, Michael; Rosenlöcher, Jens; Hackenschmidt, Reinhard; Krenkel, Walter; Rieg, Frank (2016). Full-ceramic brake systems for high performance friction applications. Journal of the European Ceramic Society, 36(15), 3823-3832. https://doi.org/10.1016/j.jeurceramsoc.2016.04.040

Manohar-Reddy, S.; Mallikarjuna, J. M.; Ganesan, V. (2006). Flow and Heat Transfer Analysis Through a Brake Disc: A CFD Approach. In *ASME 2006 International Mechanical Engineering Congress and Exposition* (pp. 481-485). American Society of Mechanical Engineers. https://doi.org/10.1115/IMECE2006-14317

Manohar-Reddy, S.; Mallikarjuna, J. M.; Ganesan, V. (2008). Flow and heat transfer analysis of a ventilated disc brake rotor using CFD. SAE Technical Paper. (No. 2008-01-0822). *In SAE World Congress & Exhibition.* https://doi.org/10.4271/2008-01-0822

Mataix, Claudio (1986). *Mecánica de Fluidos y Maquinas Hidraulicas. Segunda Edición*, Madrid, España: Ediciones del Castillo S.A.

Matějka, V., Lu, Y., Matějková, P., Smetana, B., Kukutschová, J., Vaculík, M., Tomášek, V., Zlá, S., Fan, Y. (2011). Possible stibnite transformation at the friction surface of the semi-metallic friction composites designed for car brake linings. *Applied surface science, 258*(5), 1862-1868. https://doi.org/10.1016/j.apsusc.2011.10.063

Meng, Dejian; Zhang, Lijun; Yu, Zhuoping (2016). A dynamic model for brake pedal feel analysis in passenger cars. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 230*(7), 955-968. https://doi.org/10.1177/0954407015598030

Milenković, Predrag; Jovanović, Saša; Janković, Aleksandra; Milovanović, Milan; Vitošević, Nenad; Milan, Djordjević; Raičević, Mile (2010). The influence of brake pads thermal conductivity on passanger car brake system efficiency. *Thermal Science, 14*, S221-S230. https://doi.org/10.2298/TSCI100505016M

Palmer, E.; Mishra, R.; Fieldhouse, J. (2009). An optimization study of a multiple-row pin-vented brake disc to promote brake cooling using computational fluid dynamics. *Proceedings of the*

Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 223(7), 865-875. https://doi.org/10.1243/09544070JAUTO1053

Pavlov, A. V.; Kudelnikova, S. P.; Vicharev, A. N. (2015). On the corrosion resistance of half-metallic composite brake pads for railroad cars. *Journal of Friction and Wear, 36*(2), 123-126. https://doi.org/10.3103/S1068366615020130

Pevec, M.; Potrc, I.; Bombek, G.; Vranesevic, D. (2012). Prediction of the cooling factors of a vehicle brake disc and its influence on the results of a thermal numerical simulation. *International Journal of Automotive Technology, 13*(5), 725-733. https://doi.org/10.1007/s12239-012-0071-y

Puhn, Fred (1985). *Brake Handbook.* USA: HP Books.

Rajagopal, Thundil; Ramachandran, Ramsai; James, Mathew; Gatlewar, Soniya (2014). Numerical investigation of fluid flow and heat transfer characteristics on the aerodynamics of ventilated disc brake rotor using CFD. *Thermal Science, 18*(2), 667–675. https://doi.org/10.2298/TSCI111219204R

Rashid, Asim (2014). Overview of disc brakes and related phenomena–a review. *International journal of vehicle noise and vibration, 10*(4), 257-301. https://doi.org/10.1504/IJVNV.2014.065634

Romero-Millán, María; Cruz-Domínguez, María; Sierra-Vargas, Fabio Emiro (2016). Efecto de la temperatura en el potencial de aprovechamiento energético de los productos de la pirólisis del cuesco de palma. *Tecnura, 20*(48), 89-99. http://dx.doi.org/10.14483/udistrital.jour.tecnura.2016.2.a06.

Ruan, Jiageng; Walker, Paul; Watterson, Peter; Zhang, Nong (2016). The dynamic performance and economic benefit of a blended braking system in a multi-speed battery electric vehicle. *Applied energy, 183*, 1240-1258. https://doi.org/10.1016/j.apenergy.2016.09.057

Sakamoto, H. (2004). Heat convection and design of brake discs. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 218*(3), 203-212. https://doi.org/10.1243/0954409042389436

Shaw, S. W. (1986). On the dynamic response of a system with dry friction. *Journal of Sound and Vibration, 108*(2), 305-325. https://doi.org/10.1016/S0022-460X(86)80058-X

Shinde, N. B.; Borkar, B. R. (2015). Literature Review on Fem Analysis Of Disc Brake System. *International Journal Of Engineering And Computer Science, 4*(2), 10554–10558. http://www.ijecs.in/index.php/ijecs/article/view/3422

Siramdasu, Y.; Taheri, S. (2016). Discrete tyre model application for evaluation of vehicle limit handling performance. *Vehicle System Dynamics, 54*(11), 1554-1573. https://doi.org/10.1080/00423114.2016.1220594

Sobachkin, A.; Dumnov, G.; Sobachkin, A. (2014). Base numérica de CFD integrada en CAD (Informe Técnico, SolidWorks, 2014). Recovered from http://www.solidworks.es/sw/docs/Flow_Basis_of_CAD_Embedded_CFD_Whitepaper_ESP.pdf

Söderberg, Anders; Andersson, Sören (2009). Simulation of wear and contact pressure distribution at the pad-to-rotor interface in a disc brake using general purpose finite element analysis software. *Wear, 267*(12), 2243-2251. https://doi.org/10.1016/j.wear.2009.09.004

Stewart, Monique; Singh, Som; Andersen, David; Wen, Rou; Booth, Graydon (2016). Wheel temperature reduction during freight car braking. *2016 Joint Rail Conference, Columbia, South Carolina, USA.* American Society of Mechanical Engineers. pp. 1–11. https://doi.org/10.1115/JRC2016-5819

Talati, F.; Jalalifar, S. (2009). Analysis of heat conduction in a disk brake system. *Heat and mass transfer*, *45*(8), 1047-1059. https://doi.org/10.1007/s00231-009-0476-y

Wahlström, J. (2011). *A study of airborne wear particles from automotive disc brakes* (doctoral dissertation). KTH Royal Institute of Technology.

Wei, Daogao; Ruan, Jingyu; Zhu, Weiwei; Kang, Zuheng (2016). Properties of stability, bifurcation, and chaos of the tangential motion disk brake. *Journal of Sound and Vibration*, *375*, 353-365. https://doi.org/10.1016/j.jsv.2016.04.022

Wei, Wei; Hu, Yang; Wu, Qing; Zhao, Xubao; Zhang, Jun; Zhang, Yuan (2017). An air brake model for longitudinal train dynamics studies. *Vehicle System Dynamics*, *55*(4), 517-533. https://doi.org/10.1080/00423114.2016.1254261

Wu, Shuai; Yi, Maozhong; Ge, Yicheng; Ran, Liping; Peng, Ke (2017). Effect of carbon fiber reinforcement on the tribological performance and behavior of aircraft carbon brake discs. *Carbon*, *117*, 279-292. https://doi.org/10.1016/j.carbon.2017.03.003

Wu, Wei; Xiong, Zhao; Hu, Jibin; Yuan, Shihua (2015). Application of CFD to model oil–air flow in a grooved two-disc system. *International Journal of Heat and Mass Transfer*, *91*, 293-301. https://doi.org/10.1016/j.ijheatmasstransfer.2015.07.092

Wurm, Johannes; Fitl, Matthias; Gumpesberger, Michael; Väisänen, Esa; Hochenauer, Christoph (2016). Novel CFD approach for the thermal analysis of a Continuous Variable Transmission (CVT). *Applied thermal engineering, 103,* 159-169. https://doi.org/10.1016/j.applthermaleng.2016.04.092