MSc Program
Engineering Management

From mechanical to regenerative braking – Implications of the transition towards electric mobility on aspects of deceleration and tribological brake additives

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Em.O.Univ.Prof. Dr.h.c.mult. Dipl.-Ing. Dr.techn. Peter Kopacek

Mag. (FH) David Robitschek

01209199

Vienna, 29.03.2021

Affidavit

I, **MAG. (FH) DAVID ROBITSCHEK**, hereby declare

1. that I am the sole author of the present Master’s Thesis, "FROM MECHANICAL TO REGENERATIVE BRAKING – IMPLICATIONS OF THE TRANSITION TOWARDS ELECTRIC MOBILITY ON ASPECTS OF DECELERATION AND TRIBOLOGICAL BRAKE ADDITIVES", 79 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master’s Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 29.03.2021

Signature

Contents

Abstract

New concepts of mobility, as part of societal change in form of mega trends, are leading to disruption in the automotive industry. Above all the rise of electric mobility is creating changes in structures within the whole sector supply chain. While still only modestly in use up to now, the majority of automotive sector specific forecasts estimate a market share for electric vehicles of 50% and above by 2030. All major automotive manufacturers invest massively in electric driving concepts. In this context, the brakes are one of the most important pieces of safety equipment on a vehicle. Whereas in internal combustion engine vehicles, the braking system is mostly based on creating abrasion resistance thereby inducing the deceleration, brakes in electric vehicles aim at avoiding the latter. Through regeneration, the electric braking system can convert the kinetic energy previously lost and convert it into electric energy subsequently used for acceleration of the vehicle.

This shift in paradigm is causing manufacturers to rethink from the scratch the requirements, possibilities and layout of brake systems. At the same time, the given legislation demands compliance with existing standards that even though presumably outdated, may impede further commercialization of beneficial changes. As a consequence, these developments also have a strong impact on tier 3 suppliers such as producers of additives for friction materials.

Aim of this thesis is to provide an overview over the fundamentals of friction braking, regenerative braking and presumably new necessities and challenges, followed by pointing out subsequent implications on friction materials currently in use.

1 Introduction

The automotive industry is facing indisputably one of its most disruptive moments since its existence. A shift in consumer demand along with ecological and socio-economic necessities is transforming the latter at a fast pace. The influential factors causing the change are broadly incorporated under the term Megatrends. These megatrends are according to Mayr (2018):

- Health & Wellbeing
- Urbanization
- New mobility
- Demographic change
- Individualism
- Digital transformation
- Impact on environment
- Natural resources & energy
- Globalization

While these developments are affecting most areas of society, the automotive sector reacts on them by means of innovation. In short, new concepts mostly revolve around the idea of being smarter, cleaner, safer and lighter (Ibid, 2018). Hybrid vehicles and in particular electric vehicles stand out as consequence of the megatrends for the next years and decades, since they are perceived as incorporating all of the mentioned attributes – arguably with the exception of the debatable subject on safety. The rise of importance of H/EV is demonstrated by the market growth during the recent years, indicating the fast pace at which this transformation is taking place.

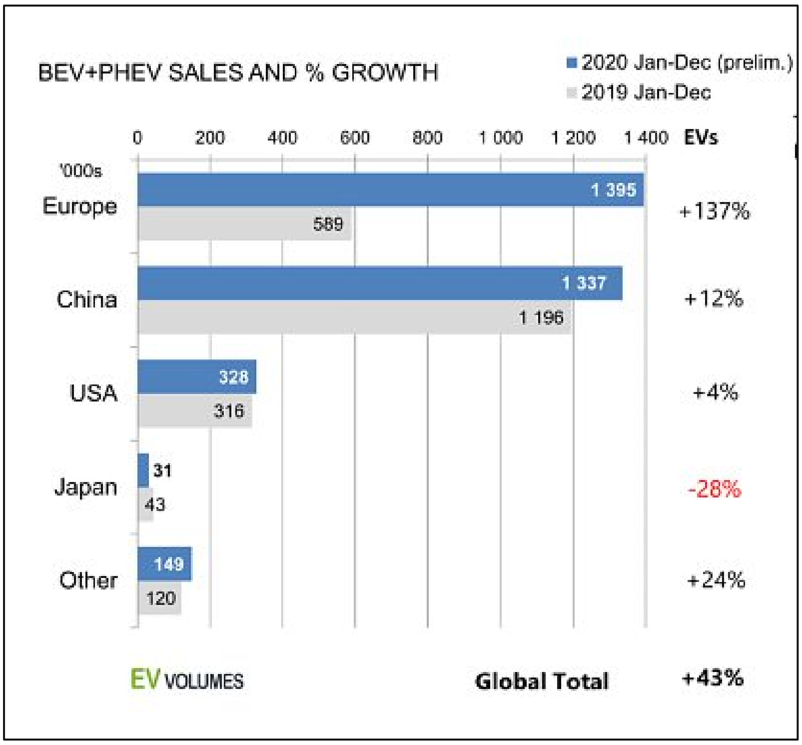


Figure 1: Electric Vehicle (BEV+PHEV) YoY Sales Growth 2019/2020 (Irle,2021)

From 2019 to 2020 the global total growth reached +43%. Above all in Europe new governmental initiatives in combination with a societal mindset inclined towards sustainability, let EV sales soar. Key regions for the market share growth are primarily Europe and China. This striking regional overweight in comparison to other main economic areas – USA, Japan – can be derived from the governmental subsidization for the introduction of environmentally sustainable, emission reducing concepts (Ibid,2021).

Induced by these societal and politically driven developments, the use of electrified drive components increases immensely also due to tightening of the exhaust gas limit values. Here the limitations of CO2 emissions becoming more and more important (Ploetz, et al. 2018). Brake systems occupy here a very central position. Through the recuperation of kinetic energy during the braking process in hybrid vehicles a significant reduction in CO2 emissions possible – depending of course on test conditions, vehicle and drive architecture.

Moreover, the range of electric vehicles remains a clear impediment for an even faster market penetration. Also here, the braking process plays a key role, as recuperation in form of regenerative braking is one of the main elements for making longer ranges possible.

These requirements have substantial implications not only for the concept and design of the existing braking systems, but also for the materials used within the actual and future braking processes.

This paper intends to clarify whether and how the implementation of regenerative braking will change the existing braking systems in place, and furthermore how it will influence the setup and use of state of the art friction materials.

First, fundamentals of braking and friction as well as of materials used for the deceleration process shall be explained. In a second step an introduction into the regenerative braking mechanism, its correlation with the conventional friction brake system as well as how the latter is affected by that change shall be provided. In the ultimate stage the necessities for electric vehicle friction brakes, and the arising requirements for its components will be discussed.

2 Fundamentals of braking

Most broadly, a brake is defined as

"*a mechanical device that inhibits motion by absorbing energy from a moving system. It is used for slowing or stopping a moving vehicle, wheel, axle, or to prevent its motion, most often accomplished by means of friction"* (Bhandari, 2010)

Hence, in its classic setup the brake system is creating kinetic energy in the form of friction. Prior to elaborating on the actual braking systems, basic principles of this force shall be clarified.

2.1 Principles of Friction

The term friction is defined as

"*the force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other."* (Britannica, 2020).The science of friction is referred to as Tribology. According to Hirani (2016), Tribology is etymologically derived from the Greek word *Tribos*, which refers to *"a science that deals with friction, lubrication and wear in all contacting pairs"* Tribology and its scientific research deals with the improvement of parts in motion and reducing the costs of maintenance or change. The optimization of the tribological parts has therefore ultimately an economic benefit, as the lifetime of parts and materials can be positively influenced.

From a physics point of view a conversion of kinetic to thermal energy is occurring. During the contact of surfaces that are moving relative to each other, heat is created. This effect can be observed through simplistic examples, such as wooden pieces catching fire as a consequence of rubbing them against each other. But this effect is not only limited to solids - also liquids change their state by the influence of friction through for example stirring. Obviously, the transformation from kinetic to thermal energy does not necessarily happen on purpose. While on one hand creation of thermal energy, or augmentation of traction of a vehicle on the road may be desired, in other situations the energy conversion might be unwanted. It is very common that the consequences of friction are tried to be avoided, or at least kept within defined limitations. These are most of all wear, degradation or even destruction of parts and components.

In general it has to be differentiated between kinetic friction and static friction. In the case that two surfaces are in contact and moving relative to one another, it is being referred to as kinetic friction. On the other side, static friction involves surfaces which are not in motion relative to each other (Santiago, 2019).

According to Dowson (1979), the main characteristics of friction are:

- Friction is proportional to the normal load
- Friction is independent of the apparent surface area
- Static friction is higher than kinetic friction
- Kinetic friction is independent of the sliding speed
- Static friction increases with rest (or dwell) time of the contact

Following Ruida and Pratap (2002), "*the force on a body A from a body B is decomposed into a part which is tangent to the surface of contact F, with | F| = F, and a part which is normal to the surface N. The relation between these forces depends on the relative slip of the bodies A/B.*"

The extent of the friction power is usually expected to be proportional to the regular force with proportionality constant μ. So the rather unassuming equation for the friction force F throughout the sliding is F = μN in this case N is the part of the interaction force in the inwards regular direction. However, if two parts are in contact but are not in motion, still the friction force can impede the elements from moving. The strength of the friction bond is often assumed to be proportional to the normal force with proportionality constant μ. Therefore should there be no sliding motion it can be assumed that the force is something less than or equal to the strength, |F| ≤ μN. (Ruida and Pratap, 2002)

The here emphasized friction force is mainly referring to two solid surfaces in contact through relative lateral motion. Following Bharat (2013) two main types of friction exist - dry friction and fluid friction. Dry friction, which is also named *Coulomb* friction, depicts the tangential component of the contact force that exists when two dry surfaces move relative to each other. Fluid friction labels the tangential component of the contact force that is in place between the layers in a liquid, and which arethat are in motion relative to each other at different speeds.

Other types of friction are subcategorized as follows:

Lubricated friction, which is linked to fluid friction. Here a lubricant fluid parts two solid surfaces. Generally when speaking about lubricated friction the term boundary lubrication is applied. According to Dorinson and Ludema, (1985), "boundary lubricated friction is not basically different from the friction of what are commonly regarded as unlubricated surfaces. Essentially a boundary lubricant affects frictional behavior by modifying the character of the surfaces and thereby modifying the character of contact during rubbing".

A variation is further skin friction, that refers to the force resisting the motion of a fluid across the surface of a body, and can be therefore categorized as a form of drag friction.

Rolling resistance: In the event of rolling contacts, friction occurs from the resistance to rolling due slight slipping. The extent of the resistance to rolling is typically considerably less than that during a dragging or slipping motion. In addition, energy dissipation happens in this case also as a result of adhesive as well as deformation losses (plastic deformation or elastic hysteresis) during the stress cycling of the surfaces in direct contact (Bharat, 2013).

Key to all these variants of friction is that by the law of conservation of energy, the kinetic energy is transformed to thermal energy, so mechanical energy is not conserved.

2.2 Conventional braking system

For the typical braking system, the intention of friction is first and foremost to decelerate and ultimately stop the vehicle. Through applying the brake pedal, a liquid runs via a tubing system towards the brake appliances surrounding axle, rims and suspension. The system exerts force on a moving counterpart, thereby slowing down the wheels until ultimately halting the vehicle (Reif, 2010).

Most commonly there are two type of braking systems in the vehicle: the disc brakes and the drum brakes. These form part of the service brakes and are operated by a foot pedal, either decelerating or stopping the vehicle. The mechanism is in both cases quite similar, as in the drum brake pressure is put by a brake lining on the rotating drum from the inside. In a drum brake where the friction is caused by a set of brake shoes the drum is connected to a rotating road wheel hub. Drum brake systems most of all can be found on older car and truck models. However,it has to be kept in mind that all brake components are subject to quite fierce price sensitivity, which is why because of their low production cost, drum brake setups are also installed on the rear of some low-cost newer vehicles. Compared to modern disc brakes, drum brakes wear out faster due to their tendency to overheat (ASFSBS, 2020).

In addition, parking brakes form part of the brake system and are either activated by a foot pedal or a hand lever, in order to keep the vehicle stationary and motionless. Usually the automotive services brakes are based on a hydraulic system. The hydraulic setup is compressing a liquid exerting force on the braking parts.

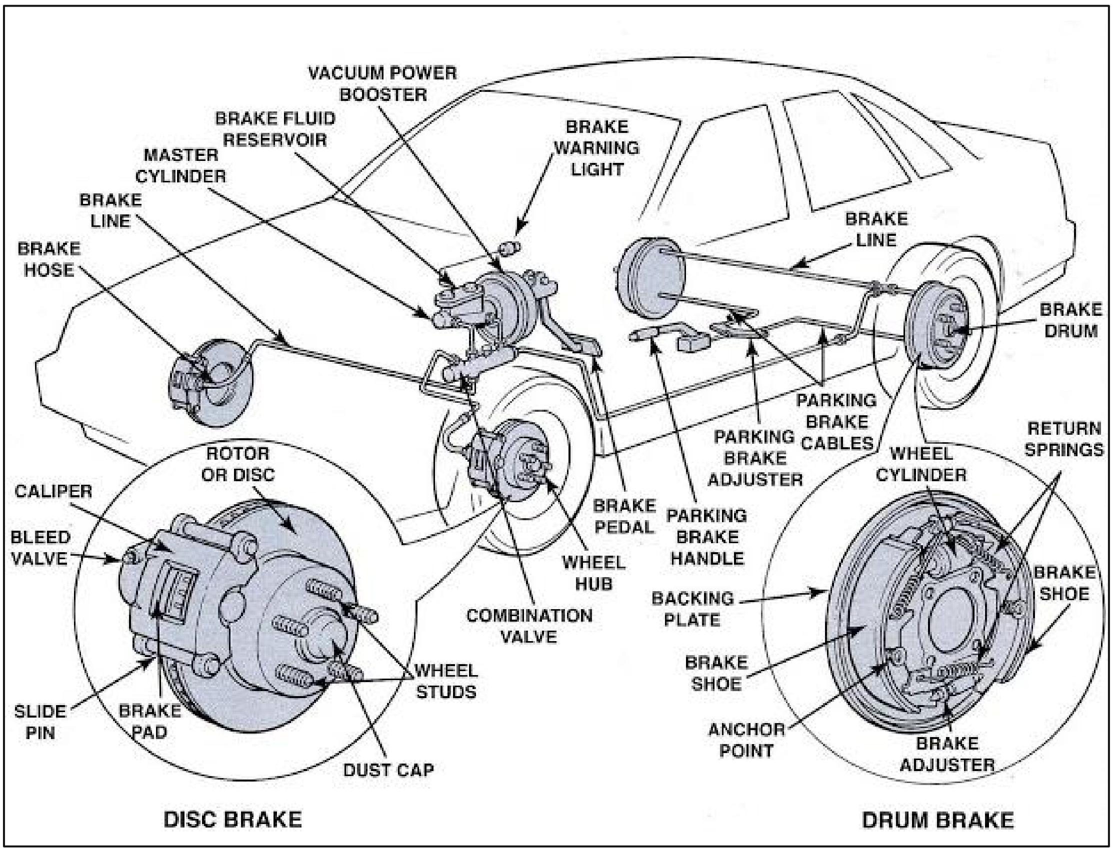


Figure 2 Schematical illustration - Passenger vehicle brake system setup (ASFSBS, 2020)

Alternatively the brake system can be activated by a pneumatic system, mostly to be found in commercial vehicles, buses or heavy duty trucks. These are referred to as air brakes. Key to all braking systems is in this case the dependence on tribological interaction between moving parts as well as stationary parts, in order to decelerate and stop

A brake disc, usually made of cast iron, is connected to the wheel or the axle. To stop the wheel, friction material in the form of brake pads (mounted in a device called a brake caliper) is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop.

The following section will expand on the friction coupling based on disc brake systems, given that in modern passenger and commercial vehicles, disk brakes are installed as they can dissipate more heat and also more stable (Reif, 2012).

2.3 Disc Brake Model

The disc brake system is arranged as a cylinder which is exerting pressure on one or multiple disc brake pads that can interact with the shaft rotor. The compression from the cylinder causes the pads to create friction torque on the shaft. The friction torque in return resists the shaft rotation. The figure below shows the side and front views of a disc brake (Mathworks 2020).

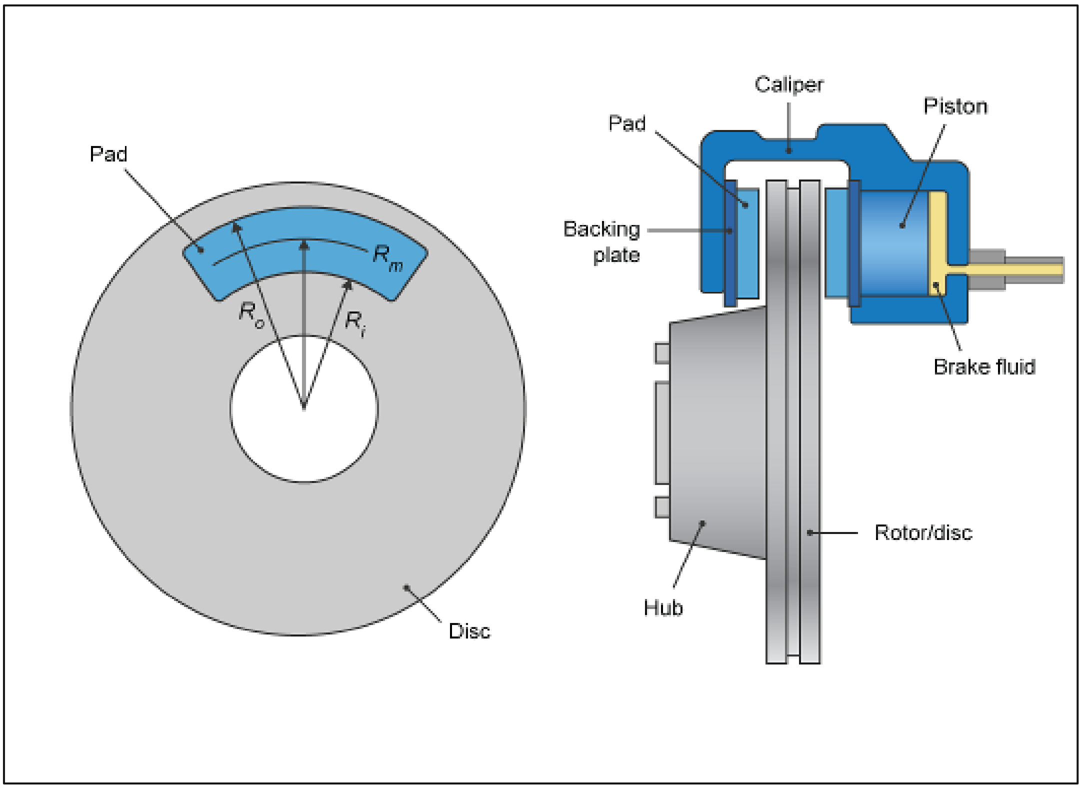


Figure 3: Disc Brake System (Mathworks 2020)

It is visible how the force converted from the brake cylinder is applied at the brake pad mean radius.

The calculation of the brake torque is determined by the rotational speed, *Ω*, such that when Ω≠0,

$$T=\mu^{k}P\pi D^{b^{2}}R^{m}N4.$$

Although if Ω=0, the torque applied by the brake is equal to the torque that is applied externally for wheel rotation. The maximum value of the torque that the brake can apply when Ω=0, is

$$T=\mu^{s}P\pi D^{b}{}^{2}R^{m}N4\cdot$$

In both cases, $Rm=Ro+Ri2.$

The various elements being defined as follows:

- T is the brake torque.
- P is the applied brake pressure.
- Ω is the wheel speed.
- N is the number of brake pads in disc brake assembly.
- μ_s is the disc pad-rotor coefficient of static friction.
- μ_k is the disc pad-rotor coefficient of kinetic friction.
- D_b is the brake actuator bore diameter.
- R_m is the mean radius of brake pad force application on brake rotor.
- R_o is the outer radius of brake pad.
- R_i is the inner radius of brake pad.

2.3.1 Functioning and composition of the Disc Rotor

As previously explained, the actual friction process occurs between the disc rotor and the brake pad where the pairing is referred to as brake coupling. In order to deliver the desired results, the composition of both elements is essential.

During the braking torque and the conversion of kinetic energy into heat, only a small part of the heat shall be absorbed by the rather poor thermally conductive brake pads, in order to protect the brake from wear and damage. By far the largest part of the thermal energy is absorbed from the disc rotor and temporarily stored. However, also the ability of the brake disc to heat up is narrow. Consequently the intention is to have it acting as a heat exchanger, quickly releasing the thermal energy into the ambient air and thus avoiding premature degradation. Since simple solid brake discs can only release heat rather slowly, the use in commercial vehicles and passenger cars is only of limited extent. In this case aerated brake discs will be used. These brake discs are made of two connected friction rings that are designed as fins, knobs or vanes (See Figure 4). Depending on how heavy and how powerfully motorized the vehicle is, the size and design of the aerated discs can be adapted. The aim of these fins or vanes is that through the rotation of the brake disc a ventilation effect is created, which works like a cooling fan for the brake sytem parts. The highest heat transfer is generated when as many air particles as possible come into contact with the brake disc surface.

In addition to the aforementioned requirements with regards to withstanding heat and allowing heat dissipation, the material for brake rotors must also withstand mechanical loads from compressive forces (e.g. for commercial vehicles up to 14N / mm2) as well as tensile and centrifugal forces under high speeds. (Baumgarten et al., 2017)

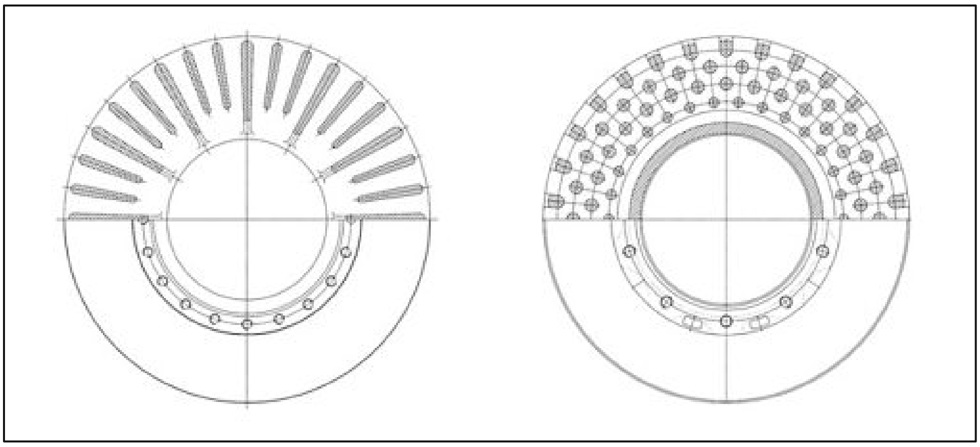


Figure 4 Aerated brake design (Baumgarten et al. 2017)

A disc rotor is typically made of gray iron, being a form of cast iron. The reason for that is mainly driven by economical aspects. In order to fulfil the requirements pointed out, the cast iron is enhanced with pearlitic structured graphite in a lamellar form (corresponding norms are EN 1561 or DIN 1691), which enhances the heat transfer. Also, hardening alloy additives are included in the material composition for reducing wear, and in some cases also Silicon Carbide is being considered for the same purpose.

Special alloy additives such as Chromium, Copper, Molybdenum, or others allow customization for special requirements for brake discs. In this way, material properties such as load mechanics, thermal conductivity, machinability, corrosion and wear behavior can be further improved (Remfrey 2017). These are enhancements which shall be further expanded in the course of this work.

For very high stability requirements to the braking system (e.g. high-performance sports car, Racing) also carbon-ceramic materials can be used. See figure below.

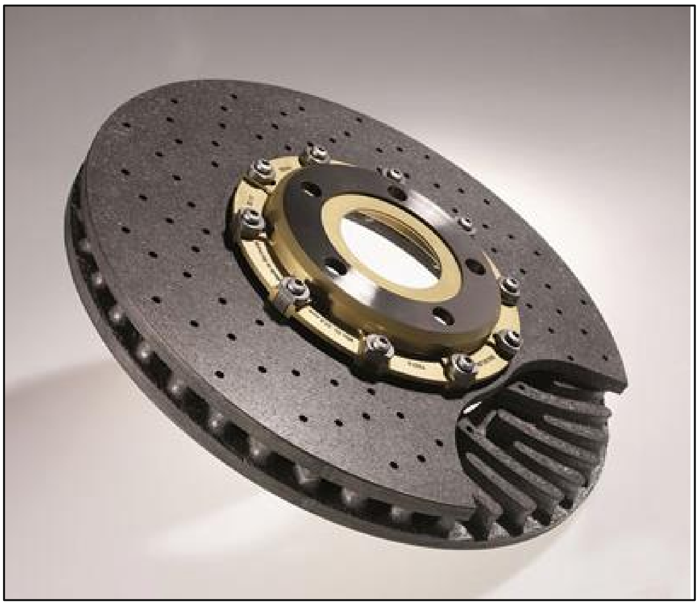


Figure 5: Carbon Ceramic Brake disc (Remfrey et al., 2017)

Such a composite material matrix consists of carbon fibers used for reinformcement silicon alson with carbide and metallic silicon. These C / C-SiC combination results on the one hand in a high mechanical strength, on the other hand also in a high hardness of the material at relatively low weight, which has some distinct advantages over conventional cast iron brake discs.

These advantages are according to Remfrey (2017):

- Very high wear resistance with a long service life up to 300,000km
- Extreme temperature change resistance compared to grey iron discs
- Corrosion resistance, therefore omission of some negative side effects of grey iron, such as brake dust formation or rusting brake pads
- Reduction of the unsprung masses in the chassis

The complex manufacturing process of these products leads to a multiple higher Component price compared to gray cast iron solutions. Still occurrence of heat cracks may lead to an expansion of the brake disc material.

2.3.2 Functioning and Composition brake pads

A typical brake pad is constructed as displayed here below:

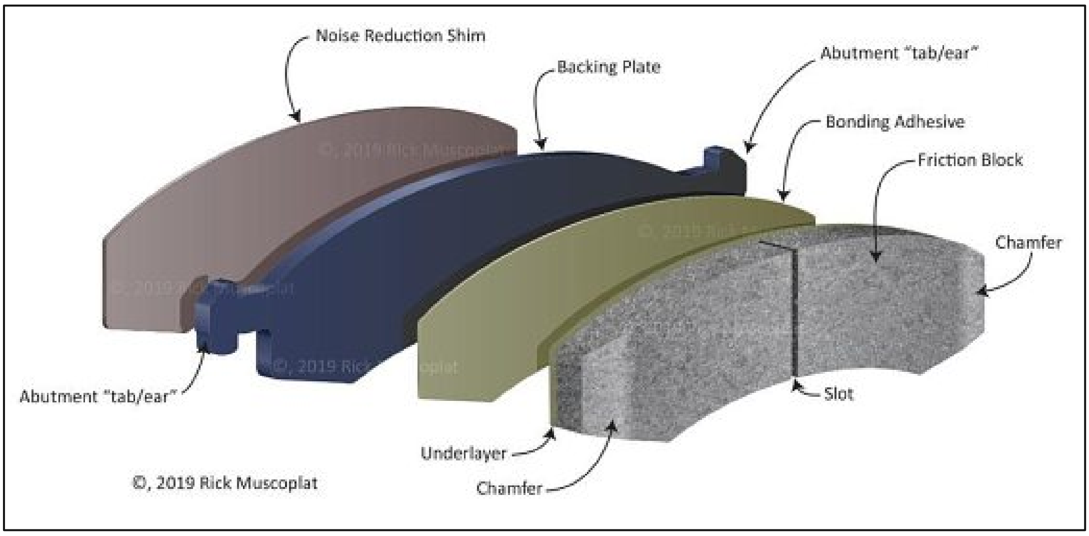


Figure 6: Brake pad standard composition (Muscoplat 2019)

The typical components of a brake pad which are the following (Muscoplat (2019):

Noise reduction shim

The shim is responsible for the insulation from the vibration as well as noise that is being transferred coming from the backing plate and on to the caliper.

Backing plate

The backing plate is most often steel based. It is shaped in a way to reach even clamping pressure over the total dimension of the friction block. The bending of the plate shall not take place. In addition the backing plate has to be designed and composed of materials that hinder corrosion or also the delamination between the friction material land the plate.

Abutment tab/ear

This is the side element, which supports the contact of the backing plate with the caliper bracket with the intention to stop the pad from moving in the case of a forward or reverse stop.

Bonding Adhesive

The bonding adhesive is a glue system specifically formulated to keep the friction block attached to the steel backing plate also under the very hard conditions. Such a case would be e.g. if the ambient temperatures would encompass the full spectrum between beginning with -30°C and up to 200°C in case the deceleration is performed in an emergency stop within a given time frame of merely a few seconds. Here the bonding adhesive still must hold and at the same time assure that the expansion and contraction of the materials do not deteriorate the compound of the components.

Underlayer

Aside from the resin within the friction material formulation, which assures the various raw materials to stick together, ther is an additional layer with high resin concentration located between the plate and the actual friction compound. This is to ensure a suitable connection between the two parts. In the course of usage the friction material wears down until reaching the underlayer which provides less adequate deceleration power. Depending on how sophisticated the system is, there are systems using a squealer sensor, warning the driver to replace the brake pad timely.

Friction material block

This element constitutes actually the active part of the brake pad within the deceleration proces. In general it is made of a specific selection of powders mostly acting as fillers, also fibers, lubricants and abrasives. These components are embedded in a resin matrix, which includes stabilizers, depending on the requirements.

Chamfers

Chamfers are the surfaces that are angled on both sides of the friction material. The intention of having an inclination at theses areas is to reduce noise and absorb the bending of the backing plate under stress.

Slots

The dividing slits that are occasionally visible within the friction material block are frequently coined as *slots.* The intention is to enable the escape of gasses that may arise in the course of the braking process. Another reason for creating these separations is to divide the friction material block into smaller areas in order to limit the natural frequency causing disturbing vibrations.

2.4 Characteristics of brakes

Following the clarification on how a brake system in fact works, the question remains as to how to assess the performance and adequacy of a brake system. Rajmohan (2015) depicts for that purpose the following characteristics:

Peak force –is the maximum decelerating effect that can be obtained. In the case that the peak force is exceeding the traction limit of the tires, the braking causes the wheels to skid.

Continuous power dissipation –as previously described, during the braking the temperature of the system rises. Excessive heat can have a serious negative influence on the brake performance, up to the point of failure. In this context, the continuous power dissipation defines the highest value of energy per unit time that is able to be dissipated through the brake without failure. The value is dependent on various factors, such as for example the composition, speed and temperature of the surrounding air.

Fading – The term fading describes the circumstance at which brakes become less effective under the influence of high temperatures. The fading behavior is influenced by the materials in use. Correlation with heat dissipation as thermal conductive materials may reduce fading, as a result of temperature minimization.

Smoothness – With smoothness the compatibility of the brake bodies is described, with regards to the regularity of the brake force. A brake that is in inconsecutive contact may be defined as grabby or pulsating, which can cause discomfort and affects control, or ultimately even leads to skidding.

Power – Brakes characterized as powerful when it reacts above average to the force applied by the driver. This has commonly more to do with the brake system configuration than with the actual brake parts. Also, a powerful brake does not necessarily imply that its ability for continuous power dissipation or peak force value is superior.

Pedal feel – refers to the subjective feeling of brake power output following the pressing of the gas pedal.

Drag – In the inactive state brake pads tend to drag on brake disc. The extent of the drag depends on the construction of the system.

Durability – Through continuous activation of the brake, the brake partners, and above all the friction material used to absorb large parts of the friction energy are worn out and have to be renewed over time. The amount of wear and resilience of the materials used define the durability.

Weight – While brakes are indispensable for the deceleration, on the contrary they are disadvantageous for the acceleration, and for the omnipresent approach for saving energy, as they represent a significant adding of weight to a vehicle. Not only the brake system itself is heavy, but also the supporting structure in necessitates.

Noise –The shear forces between the braking parts create noise and vibrations. Depending on the materials in use, these have different frequencies and can create unpleasant, annoying squealing or creeping sounds. The attempt is to reduce so called NVH properties (Noise, Vibration, Harshness) to a minimum.

2.5 Requirements for friction materials

The composition variations of friction materials is of a quite sophisticated and diverse nature, with security-related aspects being in the center focus. It has to be kept in mind that the operating conditions to which the brake coupling is exposed are constantly changing. Permanent variation of heat, pressure along with ambient and climatic changes do create a very complex requirement profile. This is also why the composition of friction materials used in brake pads is quite sophisticated, as failure under any of these conditions is not to be tolerated.

In order to better understand friction materials, the subsequent section will discuss on the requirement profile, material concepts, ecological aspects as well as raw materials and their properties, in more detail.

2.5.1 Friction behavior

The friction properties include the coefficient of friction as a function of temperature, pressure, speed and fading (subsequent braking). The braking power force is calculated and determined by setting the coefficient of friction (COF). The COF is referred to by the Greek letter μ. It is defined as:

“a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together.” (Air Brake Association, 1921)

In function of the materials used; the COF can be higher or lower, ranging between 0 and 1. Interestingly an axiom that defines that identical metals such as brass on brass have a higher COF than different metals, such as brass in friction with aluminum or steel. With a few exceptions, such as Polytetrafluoroethylene, dry materials in combination reach a COF between 0.3 and 0.6 (Wiatarek 2017).

It is an axiom of the nature that in case of friction between metals, two surfaces of similar metals than between two surfaces of different metals— hence, brass will have a higher coefficient of friction when moved against brass, but less if moved against steel or aluminum.

There are a variety of tests on inertia dynamometers that both vehicle and brake specific be driven. There are also AMS tests (Auto-Motor-Sport Test) to determine short braking distances, wear programs, endurance run simulations as a function of specific load collectives, disk thickness variation formation and regeneration, wet coefficient of friction, cold coefficient of friction as well as a variety of special programs for use (Ibid, 2017).

2.5.2 Wear behavior

Brake pads are obviously wearing parts. Following the energetic transformation towards thermal energy, the molecules in the friction material used in the brake pad deform or split, forming wear particles. Given that micro hotspots with local high peak temperatures can occur, also the various components of the friction additives can reach their melting point. On a macroscopic level, however, significantly lower peak temperatures over the whole pad are measured.

According to Santiago (2019), wear is defined as

"the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface. As it happens with friction, interaction of at least two bodies is necessary. It can therefore be identified as a joint phenomenon. If there are only two rubbing parts involved in the friction process, the wear is called two body wear. If wear is produced by a particle trapped between the rubbing surfaces, it is called three body wear . Such abrasive actions produce in the micro-level: ploughing, when soft material is not removed but shifted to the sides, cutting, when there is removal of surface material, and cracking, when material cracks in the subsurface regions that surround the wear groove."

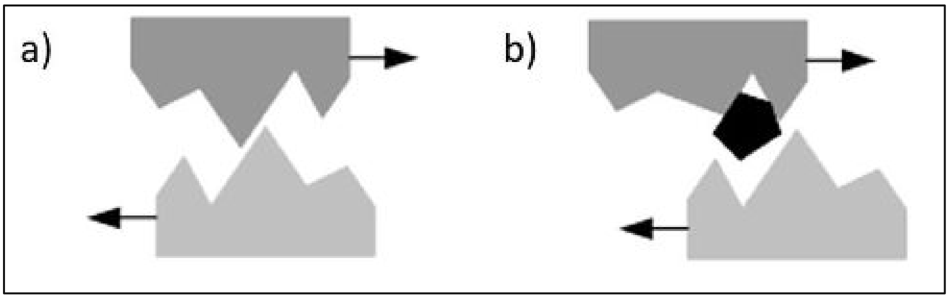


Figure 7: Depiction of two and three body wear (Santiago 2019)

According to Wiatarek (2017), in contrary to typical metal pairings, for example bearings or sliding parts, where low COF and low wear is required, the brake coupling between disc and pad aims at high coefficients of friction with low wear. In this case too, lubrication plays a significant role, albeit not in their supposedly primary function of friction minimization, but rather to increased service life by reducing wear and tear and the counter material abrasion.

Following wear mechanisms are present with brake pads:

- Abrasive wear

Abrasive wear is formed during cutting, grooving and ripping processes. It takes place when a hard material is directly in frictional contact with a softer material. Through the contact motion material removal occurs.

- Adhesive wear

Adhesive wear is present when micro-welds between brake lining and the brake disc, or any other counter material are formed. When these small material junctions are not strongly bonded, the shear forces at the conjunction of the two parts would not cause wear. Contrary when material connections are strong, the shear forces would affect the softer material (Takadoum 2007).

- Oxidative wear

As elucidated by Rowe (2014), *"the presence of oxygen in the environment produces oxides on the surface of many workpiece materials. Even minute quantities of oxygen reduce wear rates. In this sense, oxidative wear can be considered beneficial in the grinding process. The process is accelerated by high interface temperatures and nascent surfaces. The role of oxygen is usually to provide thin films of low shear stress that lubricate the interface and reduce wear on the hard surface. Oxides are also beneficial in reducing adhesion between work material and the abrasive grain. However, in a situation where oxygen produces hard oxides, wear rates may be increased. Hard oxide particles released into the interface will tend to cause increased wear of both surfaces and lead to increased work surface roughness."*

- Ablative wear

According to Kucharczyk (2012), *"the ablation process is the process of exchanging of heat and mass which, due to physical changes and chemical reactions, results in chemical and structural changes of the material with simultaneous heat absorption, which reduces heating up of the material below the front of ablation",* Ablative wear mostly occurs in the degradation of polymers, such as also in tyres during road maneuvering.

2.5.3 Comfort aspects

Also aspects of comfort are being considered in the setup for the material matrix. In studies focusing on such comfort aspects, various operating condition noises like the classic squeak (constant frequency; narrow band; > 1500Hz), but also other noise phenomena like creaking (noise in automatic vehicles when slowly letting go of the brake; variable frequency; broadband; 20–150 Hz), mooing (constant frequency, narrow band; 300-800 Hz), crumple (variable Frequency; broadband; 50–2000Hz) and hum (variable frequency, narrow band; 200–600Hz). The individual noise phenomena will greatly differ depending form the system setup and the materials in use.

The comfort behavior also includes mechanical effects that drivers may experience. Such as steering wheel vibrations, pedal feel and rubbing. Rubbing is used as a very generic term for low-frequency, most of all external vibrations between pad and disc.

In addition, a visual aesthetic effect can also be accounted to the comfort section. In recent years, the issue of rim contamination – also called wheel dust - gained noticeably more importance. The customers, especially in the USA but increasingly also in Europe, become more and more aware of the dust caused by the wear particles of the pad and disc abrasion. The analysis of the dust composition, reveals to a large extent Iron oxide, indicating that disc wear particles are above all the cause.

Over the course of the last decades, the requirements for comfort continuously increased, most of all with regards to NVH properties. In parallel, friction requirements also increased, as a result of vehicles continuously becoming heavier, the engine power continued to grow and also the top speed of vehicles augmented. High-performance cars are constructed for velocities of 250 km / h and way beyond, though these are often electronically limited. Requirements are here for example that brake pads can withstand 5 consecutive full blocking brakes (without ABS control) down from 250 km/h, whereby defined target values shall not be exceeded, and on top comfort characteristics shall not be affected.

The developing of friction material compositions which is able to fulfil all necessary requirements from the outlined categories represents a very complex challenge for the specialized material engineers. The result will in most cases represent a compromise, as unanimously satisfying all elements is most times unattainable for the fact that properties from the various areas can contradict each other easily.

Physical / chemical properties

Aside from the key requirements of brake pads, also the physical and chemical properties are an influential factor which define the functioning of the material matrix. Examples of physical and chemical properties are compressibility (cold and hot), shear values, internal shear strength, flexural strength, compressive strength, modulus of elasticity, damping, density, porosity, Shrinking, waxing, and thermal conductivity, corrosion behavior (Wiatarek, 2017).

2.6 Friction Material Concepts

According to Wang and Chun (2013), “the friction material in a brake system is a multiphase composite containing more than ten ingredients and is considered one of the most complicated material systems. This is because the brake friction material must be developed to sustain brake performance in a wide temperature range and designed to moderate friction-induced excitation at the sliding interface by proper material design.”

The material has to withstand thermal energy peaks of 800°C and above, whereby the braking process is also causing noise and vibration through the absorption of the components and following transmission on other vehicle construction parts. Creating a balanced friction material formulation is a highly complex task to which scientists worldwide are performing extensive, sophisticated research. Moreover, new requirements and regulations represent new challenges to the materials used. Although abundant theoretical research on additive material effects and performance has and still is conducted, the finding and commercialization of suitable friction material setups are mostly relying on trial and error approaches. This is also due to insufficient comprehension of the friction mechanism in the systems, as well as the interactions of the material components amongst them (Wang and Chung, 2013)

Depending on the requirements as previously expanded, there are different approaches for material setups which Wiatarek (2017) segregates in different categories:

2.6.1 Asbestos organic type:

Asbestos-based organic friction materials have proven to be an excellent chemical structure for brake systems. Ubiquitously used until the 1970s, it distinguished through the high thermal stability, outstanding friction behavior and reinforcing properties. The formulation consisted of 30-40% of organic components and above all the use of asbestos fibers. The use of the latter yet was banned in 1989, as studies revealed the undeniable scientific evidence of the causality between asbestos fiber inhalation and cell mutation triggering cancer. Although nowadays the use of asbestos in brake pads is prohibited to in the US, EU, Japan, Korea and most so called developed countries, it is still widely used in other regions, such as South America, Southeast Asia, India or Africa (Wand and Chung, 2013).

2.6.2 Semi-metallic friction pads

The high metal content of over 50%, mostly Fe based materials, like steel wool or iron powder, gave this category its name. It distinguishes through its comparatively longer lifetime and lower pad wear. Yet this is only given under specific conditions. These are limited velocity and vehicle weight. With weight of 6 MT and above and increasing speed, the augmenting temperature is causing overproportioned ablative wear through thermal degradation. This is why for high performance vehicles or also markets with partially no speed restrictions (such as in some areas in Germany), this concept is not advisable. Yet, for markets with moderate speed and vehicle weights, requiring a COF of $\mu < 0.4$, semi metallic pads are a a good fit, due to the very low wear. Given the lower COF this will lead also to higher comfort and less rim dust. In the USA for instance semi met pads are therefore well accepted, even though heavy vehicles are very popular. For these applications the brake pads are designed significantly larger.

Another important advantage of semi met material is their low DTV generation. DTV stands for Disc Thickness Variation. Even when the brake is not activated, the pad tends to be in touch with the disc. This can potentially lead to an uneven profile of the disc, causing vibrations and rubbing. In the worst case holes or dents can occur in the disc affecting brake and steering behavior up to the point where the vehicle becomes difficult to control. This effect is much less present with semi met pad technology.

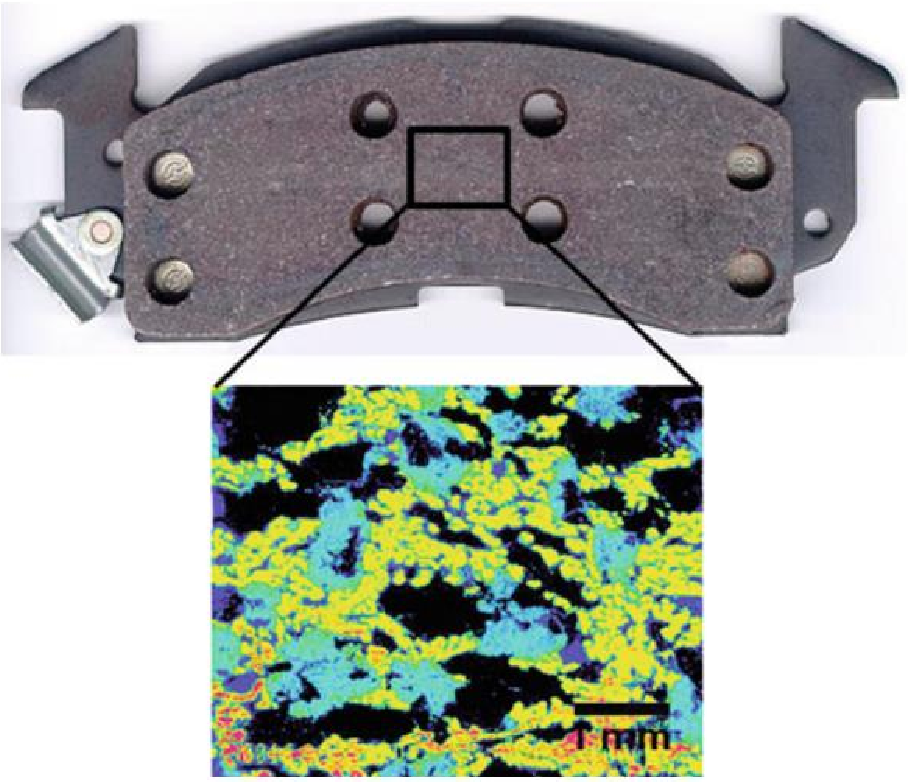


Figure 8: Semi metallic friction material riveted to a steel back plate (Wang and Chung, 2013)

In the picture above displays a typical semi metallic formulation based brake pad and the corresponding micrograph analysis. The bright particles on display reveal the high content of steel fibers and Iron particles, for which the semi metallic formulations are known.

2.6.3 Low Steel Friction Materials

These friction materials are vastly based on a combination of organic and inorganic fibers, combined with further additives, namely abrasives, lubricants and metals of different forms. Low met formulations are above all used in Europe. Over the course of the last years the fiber content has been more and more reduced, as some of them are under the suspicion of being carcinogenic. An interesting development in the field of low steel formulations is the concept of *corrective liners*. The idea here is that although disc thickness variation will occur in the inactive state of the brake, the bad can regenerate variation, through the use of a sophisticated equilibrium of various additives. Another advantage is the possibility of reaching a high COF up ot μ=0.5, in combination of good fading properties.

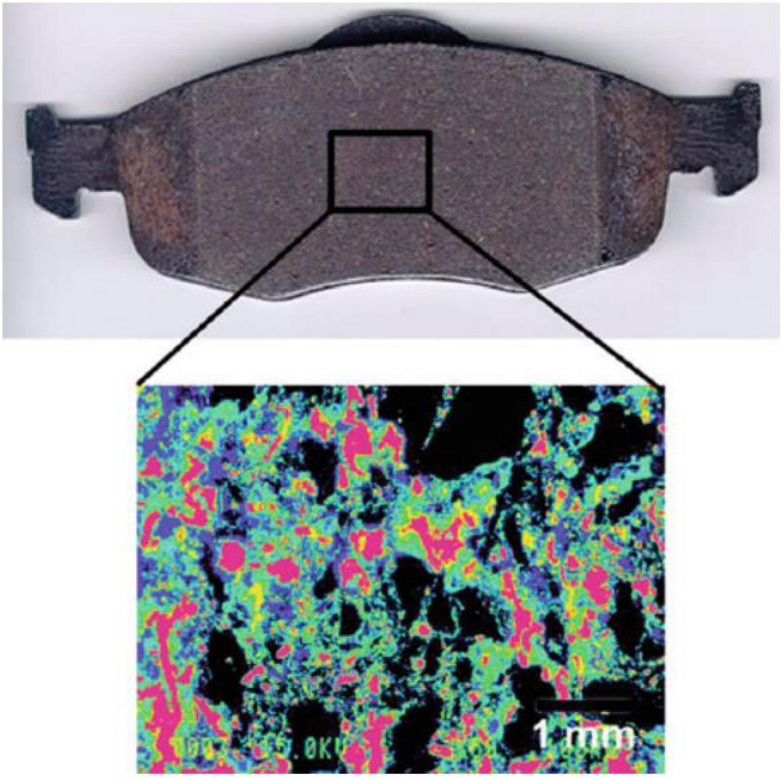


Figure 9: Low steel friction material based brake pad (Wang and Chung, 2013)

In the depicted micrograph analysis above, the steel fibers are shown in grey, along with the high graphite and cashew oil content in black.

2.6.4 NAO Friction Materials

The term NAO stands for “Non-Asbestos Organics”. This friction material technology originates from Japan, where the formerly used Asbestos in brake pads has been substituted with organic materials. Consciously steel wool, iron powder or alike has been avoided in the matrix as these very much in contradiction to the European approach, these are seen in Japan as being responsible for DTV. Also abrasives with higher MOHS hardness tend to be avoided in NAO setups, which results in a rather low COF spectrum of μ=0.3 – 0.4. In this case the friction material has not the ability of DTV regeneration, although the concept is starting to be implemented for achieving longer pad life of 100.000 Km and beyond.

The predominant advantage of NAO is the good comfort behavior with low rim dust rate. Yet for high performance applications and heavy weight vehicles it is less suitable.

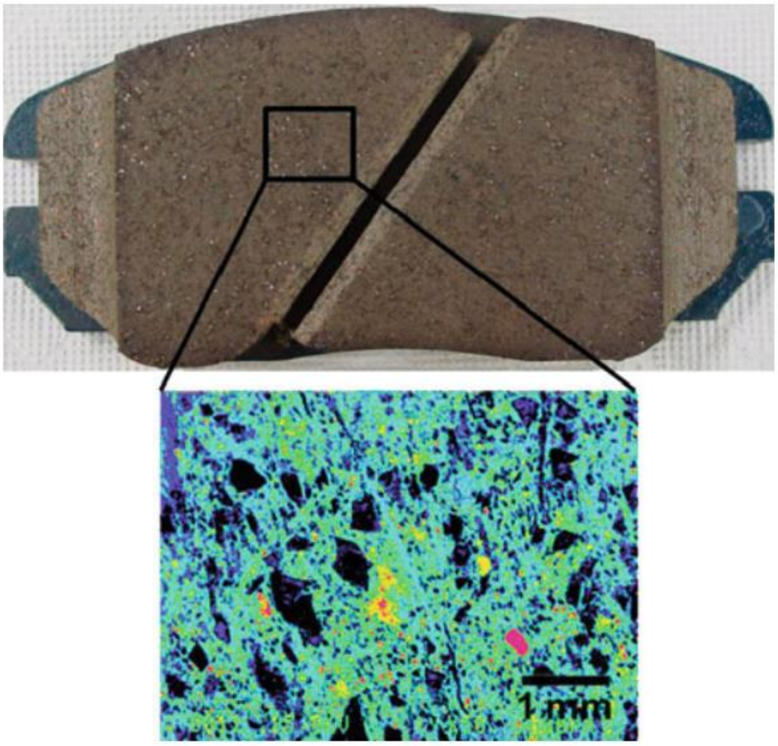


Figure 10: Non asbestos organic friction material based brake pad (Wang and Chung, 2013)

The micrograph analysis above shows clearly the organic components in blueish, grey coloration.

2.6.5 Metal-free Friction Materials

Another basic material concept are metal free friction materials, which in contrast to NAO also do not use any nonferrous metals like copper, bronze or brass. However, these are rather irrelevant for passenger or commercial vehicles, due to the fact that the absence of metals affects the thermal conductivity of the pad. The disc brake tends to excessively heat up and therefore the thermal stress may present a safety risk as all surrounding parts of the brake system might be damaged. Moreover, the mechanical strength of the pad is affected as the metal fibers do have a bonding effect for the friction material. With all these factors taken into account, the use of metal free friction material is limited to the rear axles, which are exposed to less thermal and mechanical stress (Wiatarek, 2017).

2.6.6 Hybrid friction materials

This category approaches the idea of unifying the comfort characteristics of NAO formulations with the high performance suitability of low steel technology. Above all for European conditions this development is attractive. Under these the NAO pads show weaknesses regarding mechanical strength under high temperatures, which is said to be due to the absence of steel wool. In return the Low Met pads are unfavorable especially concerning NVH comfort properties in such a setting. Most of all it is the creep groan noise, which is in the center of attention in hybrid friction materials. Studies have shown that adding steel wool to NAO friction materials will directly influence the creep groan behavior. Up to this point a viable solution to overcoming this problem has yet to be found, as both material concepts remain mutually exclusive.

2.6.7 Composition of friction materials

In function of the properties to be achieved, the composition of the friction materials differ greatly. Fig. 8 below shows the various raw materials that are used within a brake friction compound

Raw Materials	**Semi Met**	**NAO**	**Low Steel**	**Ceramics**
Steel wool	60	0	20	15
Copper		22	16	
Non-ferrous metals				25
Aluminium oxide	3	1	1	5
Zirconia silicate		3		
Silicon carbide				3
Mica		3	7	4
Barite	15	16	10	2
Calciumoxide	5	4		
Ironoxide			10	
Zinc sulfide		5	6	
Sulfide				10
Graphite	10	4	4	4
Pet coke		14	16	12
Potassium titanate		15		
Fibers (PAN)		6	1	2
Rubber	2	2	4	1
Resin	5	7	5	5

Figure 11 Composition of friction materials in weight % (Wiatarek 2017)

There is no clear limitation as to what raw materials shall be used, as long as they are of no toxicological concern. In addition, or perhaps most of all the limitation is that these have to be available and affordable.

The components used can be classified in the following categories (Wiatarek 2017):

- Rubber: used for comfort, damping and compressibility
- Resins: used for stability, consistency of the compound, compressibility and influence on friction
- Abrasives: strong influence on friction behavior, wear, DTV as well as DTV regeneration.
- Lubricants: wear and subsequently pad life, comfort
- Graphite / Coke: Wear, friction behavior, comfort, thermal conductivity
- Fibers: segregation, processing aid, friction behavior, comfort
- Metals: compound consistency, thermal conductivity, wear, comfort, friction behavior

2.7 Qualification of friction materials

Automotive brake friction materials are basically In order to assess the adequacy of brakes and hence also the mixture of raw materials in the friction compound, various tests are made. These are typically subdivided in assessment of physical properties and the performance of the friction material formulation in combination with braking partners (SAE, 2013); (ECE, 2012).

Physical property testing:
For the testing of the physical properties, above all quality control per se, shear strength and compressibility of the friction materials are being assessed.

The testing methods are the following:

SAE J840 - Shear Strength:

While braking under normal service conditions, a shear stress is generated in the disc brake pad lining material. This test standard is simulating these forces of internal shear strength on the friction material (ISO Standards, 2020)

SAE J2468 – Compressibility

This procedure according to this standard examines the deflection of friction materials assemblies and foremost compressibility of friction materials. Compressibility defines as

“the ability of molecules in a fluid to be compacted or compressed (made more dense) and their ability to bounce back to their original density, in other words, their springiness.” (Structural 2020):

SAE J2521 - -NVH Test Procedures and Techniques - Dynamometer tests:

The test procedure consists of high temperature and low temperature cycles. However it does not fully simulate the typical incidents of ambient influences causing brake noise, vibration or harshness. In fact here the term brake squeal stands in the center of the research. Brake squeal is defined as peak noise levels which are reaching 70 dB(A) or higher, between noise frequencies of 1.25 kHz and 16 kHz for tests based on full suspension corners or full axle assemblies, or between 2 kHz and 16 kHz for brakes other than full suspension corner based systems.

SAE J2707 and city driving simulations - -Wear Test Procedures and Techniques - Dynamometer test:

These are typically test runs that measure the degradation of the friction material under specified conditions, mostly temperatures of 100°C and above. The degradation is generally measured by weighing the pad before and after in order to analyze the loss in grams. Although this procedure does not necessarily reflect a so calles normal driving behavior, it allows to draw conclusions regarding the material setuop and qualification to a certain extent.

Other tests include the evaluation of the structural integrity, crack/strength, DTV, hot judder or corrosion removal.

SAE J661/866 - Quality Control

Also known as CHASE test, this procedure is assessing the materials stability under a constant velocity stress test, showing the COF in function of the friction induced rise in temperature. The test is to be categorized under a physical property testing as although it initiates physical stress on brake pads in form of heat and pressure, it does not simulate typical condition environment for a passenger car. The graph below shows a standard test report of this method

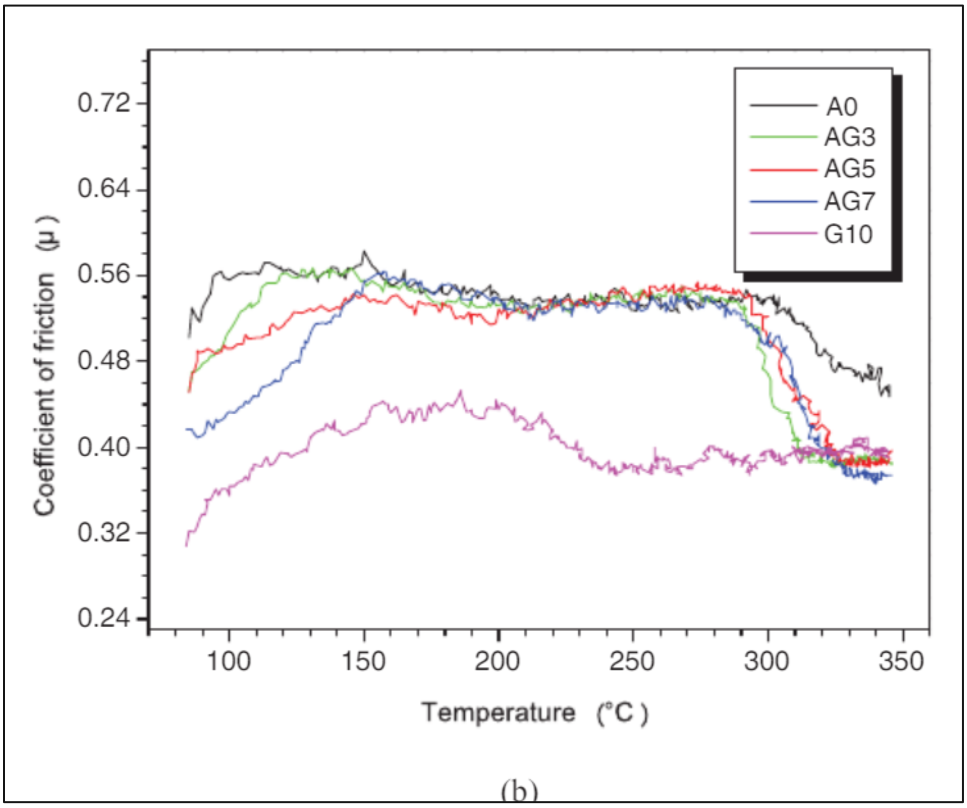


Figure 12 CHASE Test report (Öztürk, 2013)

Although providing accurate results with regards to displaying the material behavior under given temparatures, the CHASE test is frequently criticized when used as performance test. This is because the constant velocity would not represent an adequate simulation of real driving or better braking conditions. For that reason specific performance tests are done by most pad and lining manufacturers.

Performance assessment:

In order to simulate typical real life stress on a brake system in daily use over a long period of time, test cycles with varying conditions are being performed. Here there are several different test standards reenacting different scenarios. The most known ones are SAE J278,SAE J2522 (AK Master), ISO 26867 or the JASO C406.

The SAE J2522 (AK Master) test is considered to be one of the most crucial assessments for brake materials. It has been initiated with the aim of providing a common ground for the development, selection and quality assurance of friction materials on a global scale. Over the course of 15 different blocks, various speed, pressure and temperature settings are being created to test the friction material’s ability to withstand to such burdens.(SAE, 2003)

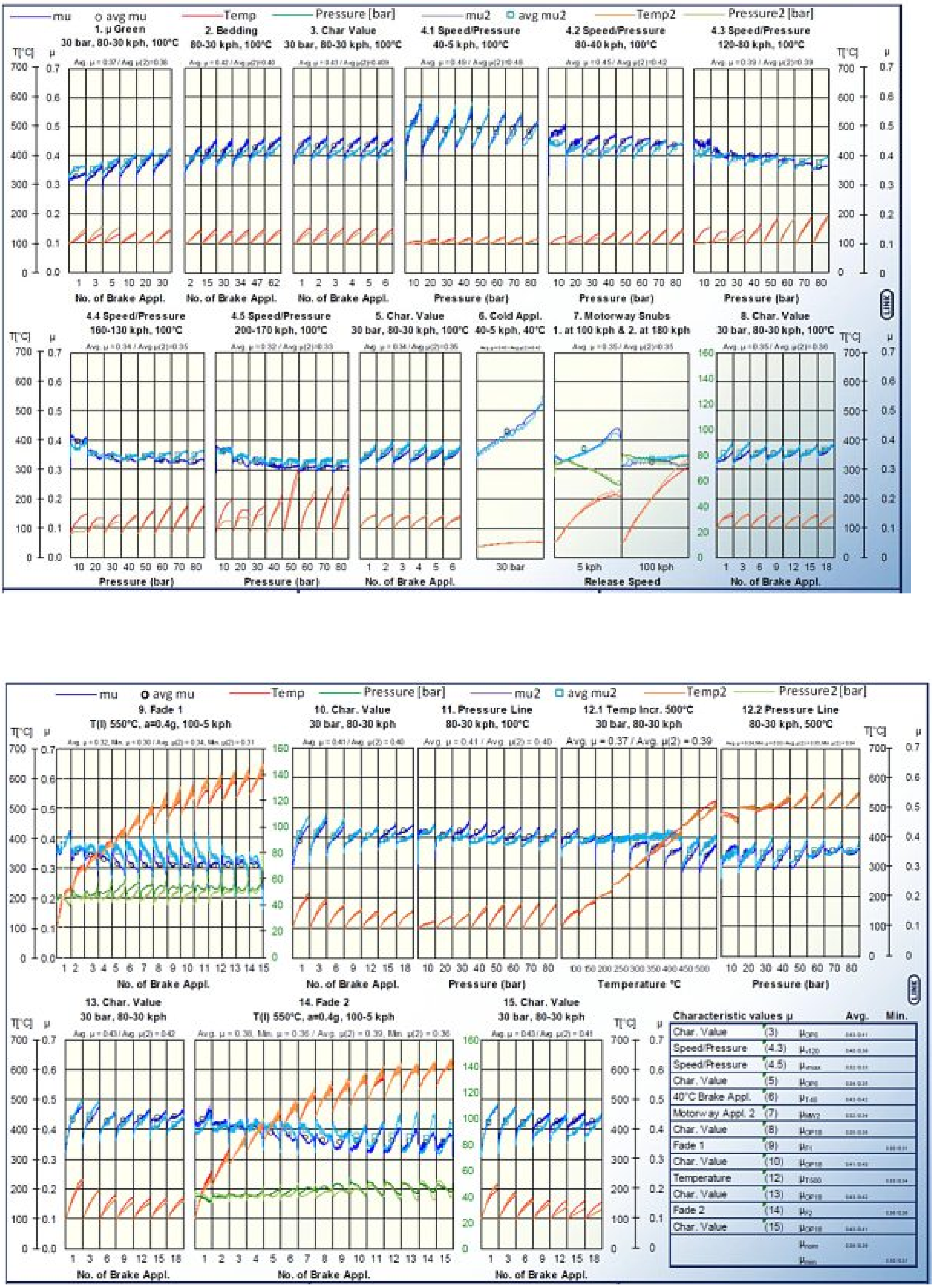


Figure 13: Report example of a SAE J2522 test (Tribotecc, 2014)

One of the main elements are the two fading blocks. Here 15 stops from 100 km/h down to ≤ 5 km/h at a deceleration level of 0.4g and continuously increasing initial temperatures are being performed (SAE, 2003):

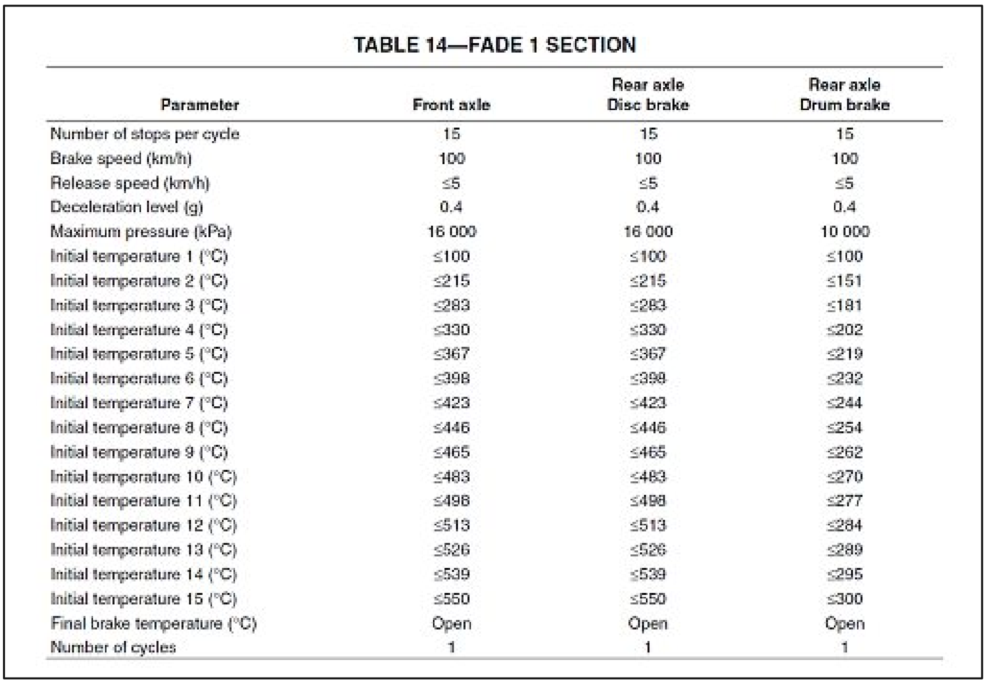


TABLE 14—FADE 1 SECTION

Parameter	Front axle	Rear axle Disc brake	Rear axle Drum brake
Number of stops per cycle	15	15	15
Brake speed (km/h)	100	100	100
Release speed (km/h)	≤5	≤5	≤5
Deceleration level (g)	0.4	0.4	0.4
Maximum pressure (kPa)	16 000	16 000	10 000
Initial temperature 1 (°C)	≤100	≤100	≤100
Initial temperature 2 (°C)	≤215	≤215	≤151
Initial temperature 3 (°C)	≤283	≤283	≤181
Initial temperature 4 (°C)	≤330	≤330	≤202
Initial temperature 5 (°C)	≤367	≤367	≤219
Initial temperature 6 (°C)	≤398	≤398	≤232
Initial temperature 7 (°C)	≤423	≤423	≤244
Initial temperature 8 (°C)	≤446	≤446	≤254
Initial temperature 9 (°C)	≤465	≤465	≤262
Initial temperature 10 (°C)	≤483	≤483	≤270
Initial temperature 11 (°C)	≤498	≤498	≤277
Initial temperature 12 (°C)	≤513	≤513	≤284
Initial temperature 13 (°C)	≤526	≤526	≤289
Initial temperature 14 (°C)	≤539	≤539	≤295
Initial temperature 15 (°C)	≤550	≤550	≤300
Final brake temperature (°C)	Open	Open	Open
Number of cycles	1	1	1

Figure 14: Fading Block SAE J2522 Test (SAE, 2003)

In this section the fundamentals of friction braking systems and the construction of the brake coupling have been depicted, along with the actual tribological processes involved. Ultimately, requirements and possibilities for friction materials have been elucidated. In the subsequent section, fundamentals of regenerative braking and its consequences for the friction braking process will be depicted.

3 Regenerative braking

As mentioned in the introduction of this paper, the automotive industry is strongly relying on the electrification of the drivetrain for the upcoming model series over the next decade. Factually all of these concepts include a regenerative braking system. The European regulations define electric regenerative braking as

"a braking system which, during deceleration, provides for the conversion of vehicle kinetic energy into electrical energy" (Standards, 2017).

3.1 Technical Basics

We recall that with the standard setup, the vehicle decelerates as soon as force on the brake is applied and subsequently the kinetic energy is only transformed into heat and has no further purpose. Now with the regenerative braking, an energy recovery system has been introduced in hybrid or electric vehicles. More precisely the kinetic energy will be converted into electric energy used to recharge the battery supply. The electric energy is then in return used for electric driving, providing for example additional electric drive torque and extend the electric driving range.

The figure shows a simplified graph of the flow of energy in an electric regenerative braking system. The energy in the battery is used to drive the motor connected to the driveshaft.

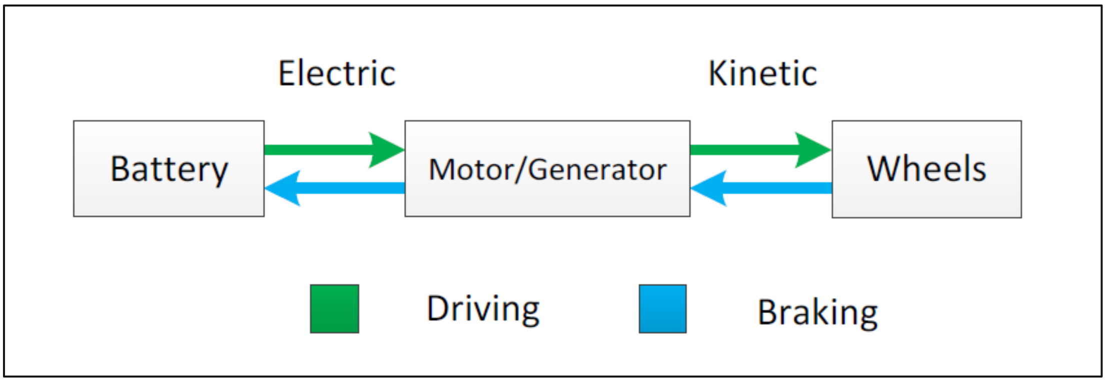


Figure 15 Regenerative Braking Energy Flow (Ehsani, 2010)

There are various types of electric vehicle concepts. These are mainly to be regrouped in the following categories:

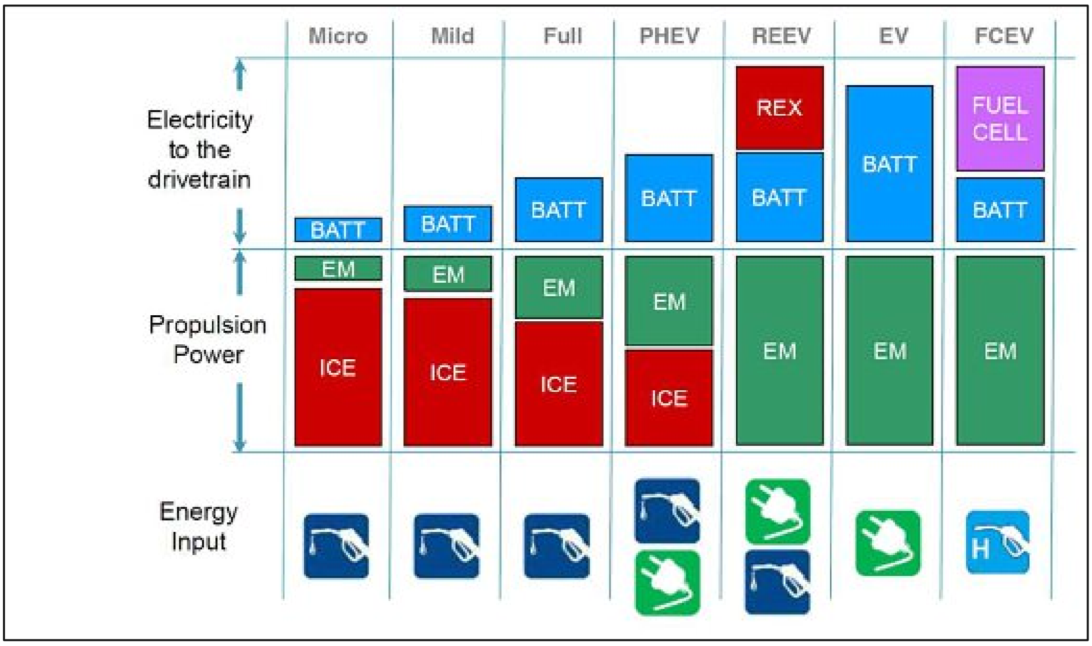


Figure 16: Degrees of electrification in mobility concepts (Mayr, 2018)

The differentiation of the displayed propulsion concepts takes place on various levels. First, the hybrid based vehicles dispose of a battery powered electrical powertrain as well as an internal combustion engine (ICE). Depending on the dimension of the electric drivetrain and at the same time of the electric machine, these are referred to as micro, mild or full hybrid vehicles. The size of the internal combustion engine declines gradually in opposition.The electric machine mostly supports here the ICE, mostly during acceleration up to 50 km/h, and the battery is recharged mainly through the deceleration process. The Plug-in Hybrid Electric Vehicle (PHEV), still includes an ICE, but has next to it a full electric powertrain which is loaded via the electric grid connection, and which has also a larger battery for pure electric driving. A variation of the PHEV is an electric vehicle with a range extender – a small ICE module working as a critical backup system. Ultimately, there is the full electric vehicle with no built-in ICE unit. Technically also the alternative propulsion system based on fuell cell technology has also an electric machine as propulsion mechanism, and does also recuperate kinetic energy for conversion into electric power.

All in all the degrees of electrification may differ in their power capacity and whether they are only relying on electric force or combined with an internal combustion engine (PHEV / HEV). With regards to this paper, the differentiation is of negligible interest, since the braking setup is similar. The intention remains to recuperate a maximum of energy, although cost factors might be a limiting element. Yet it is an economic consideration to use a sophisticated and highly capable regeneration module as it may save battery size, weight and costs.

At this point it is key to emphasize that the regenerative braking system is no substitution for friction brakes, The braking system for H/EV is divided into the classic friction braking system and an electronic braking system with regeneration function. During the braking the electric drivetrain becomes a generator. The potential of the regenerative braking and when this is being surpassed, subsequently causing the switch to the friction brake system, is related to the available braking torque from the engine. The available torque itself is determined by the motion energy in the form of rotational velocity of the motor. The goal is clearly to achieve a maximum of energy recovery from the braking maneuver, and the hydraulic induced friction brake shall only be used when the request for deceleration is higher than the ability for regeneration.

Another limiting factor is the power state of the accumulator in use. Fully loaded batteries will not be able to absorb the electric energy generated through the braking torque. Therefore the friction brake will be activated and this energy will be converted in heat (Kubaisi, 2014).

3.1.1 Regenerative spectrum

The generator’s capability of recuperation is largely dependent on the vehicle’s velocity. At high speeds, the generator can only marginally contribute to the deceleration. Most of the brake torque is absorbed by the friction brake. With decreasing driving speed the ability for conversion in electric energy is augmenting. For assuring a continuous and constant deceleration, the contribution from the friction system has to be progressively adapted.

At low speed the generator's deceleration capacity is at its maximum. Is this maximum greater than or equal to the driver's request, only the electric module brakes and the friction brake is not activated. Shortly before the vehicle comes to a stop, the vehicle deceleration from the generator is reduced to zero. The braking system does this relatively quickly, and the goal is to realize this transition as seamlessly as possible, in order to make the transition hardly noticeable for the driver. Below figure shows the two transitions above the Driving speed (Bletz and Wickenhöfer, 2017).

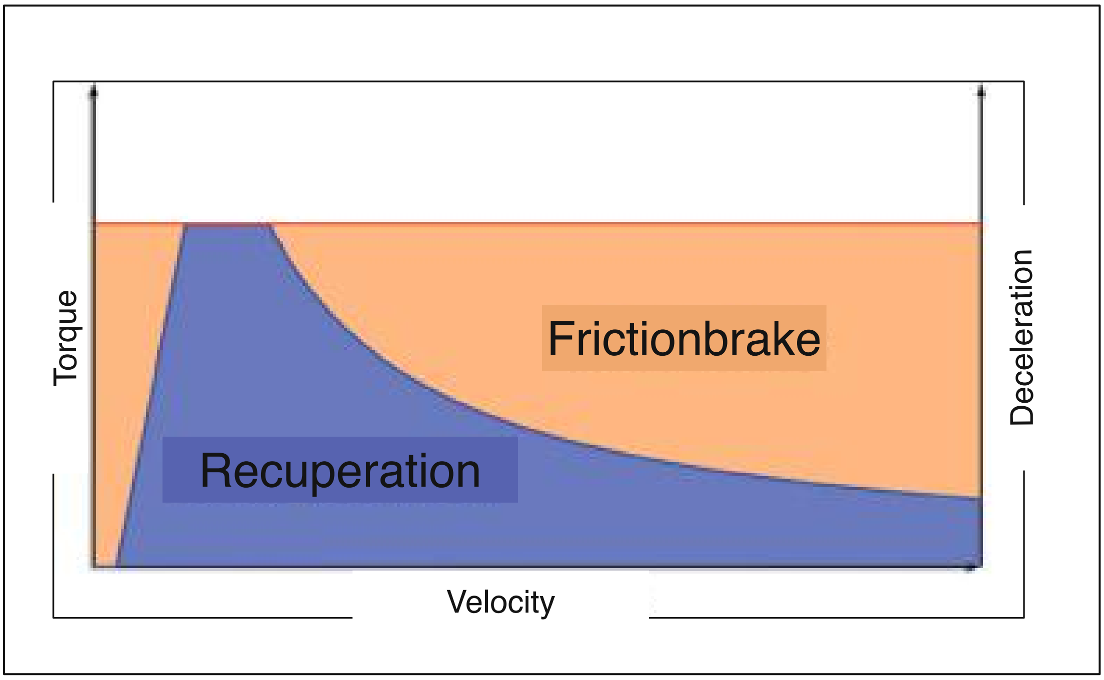


Figure 17: Electric vehicle braking process (Bletz and Wickenhöfer 2017)

3.1.2 Need for adaptation and conditioning the Friction brake

One of the most critical elements in the introduction of regenerative braking systems is the compatibility with the friction brake, meaning when and how each one is engaged. The switch from one to another can create periods of latency or torque deviations, which ultimately could affect the vehicle's stability. The generator can be accurately adapted in function of the available braking torque. Via an electronic communication interface the additionally needed friction brake deceleration is adapted.

However, over a longer time period the brake coupling of disc and pad will be influenced by the continuous manipulation and varying force of use. Influential parameters are here the brake fluid pressure, the friction coefficient and the temperature of the friction surface (see figure 18) In addition, environmental conditions and material ageing processes play a role. This is why periodical adaptions and readjustments will be necessary (Ibid., 2017).

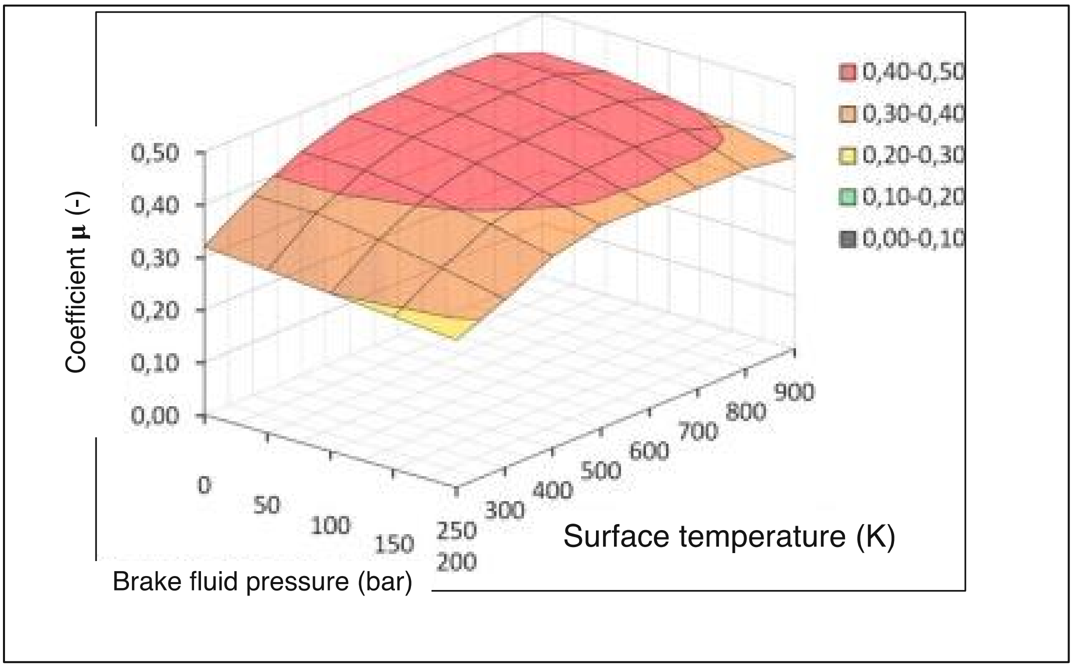


Figure 18: Influences on friction coefficient (Bletz and Wickenhöfer 2017)

Usage of the friction brake

As mentioned before, one of the main goals is the range extension of H/EV vehicles and thus maximizing the energy recuperation. This results in a very different driving behavior. Whereas feisty stopping was an unmindful and omnipresent part of driving behavior in quotidian traffic, H/EV vehicle drivers tend to do exactly the opposite. The act of braking is performed carefully and well timed with the intention to optimize recuperation, or finding the free rolling point, where the velocity is neither caused by active acceleration or deceleration. This state is reached by pressing and holding the accelerator up to a certain point. This driving behavior is characterized as *sailing*. The free rolling point is however not reached by releasing the accelerator pedal, as in that state a negative braking torque is being induced by the motor which is triggering in return the vehicle’s deceleration. This setup is actually simulating the engine brake mechanism also known from internal combustion energy vehicles, where the free rolling point is achieved by decoupling the gear shift. Thus it is referred to as Engine Brake Simulation EBS (Schmitz, 2013).

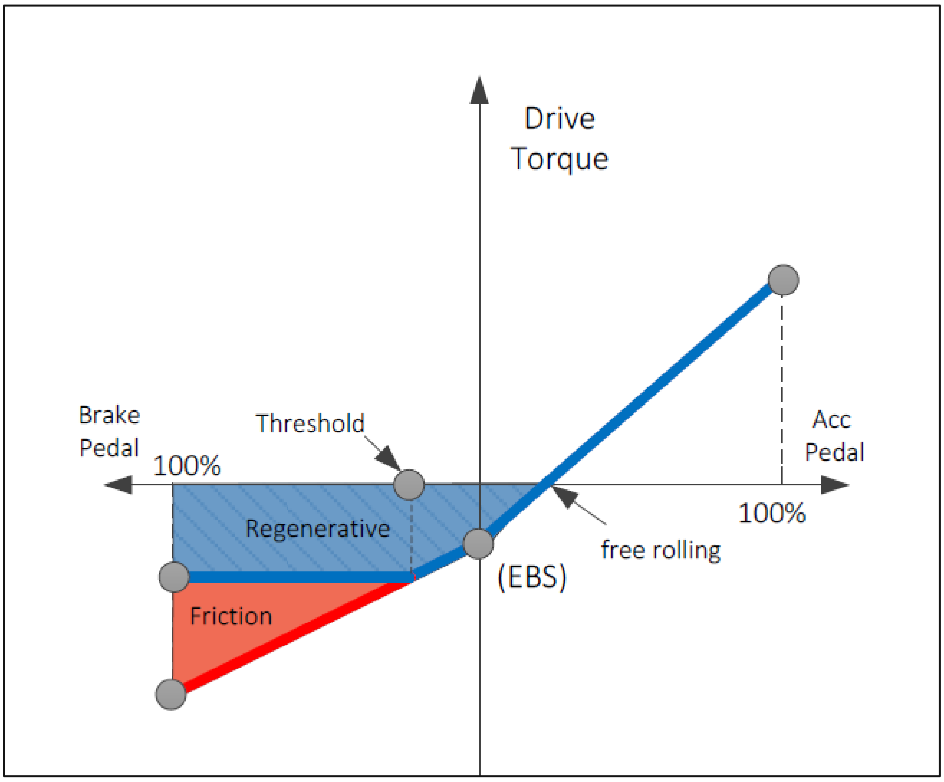


Figure 19: Deceleration free rolling & engine brake simulation point (Kubaisi, 2018)

Requirement Driver perception

Simulating the EBS has to a large extent not only to do with the energy recuperation but also with the perception and expectations of the maneuvering individual. The way in which the vehicle responds to the orders and interactions emitted in the form of pedal pressing is called pedal feel. Every vehicle has usually a different pedal feel, to which the operator is able to adjust rather swiftly, given that the over time internalized parameters of pedal force, pedal travel, damping, etc. are taken into account. The idea is here to simulate the natural analogue feedbacks from conventional braking systems as accurately as possible.

Non-standard deceleration conditions

Especially with low vehicle deceleration, the friction brake will only be partially used if at all. The generator can realize the braking on its own. More than 80% of all braking activities concern a deceleration of < 3m=s2.

In the typical urban vehicle operation, 98% of brake maneuvers will occur between 0.1 and 0.5g. Deceleration levels greater than 0.5g are referred to as emergency braking cases and are obviously rare (less than 2%). in standard, daily vehicle maneuvering (Oleksowicz, 2009).

Depending on the composition and usage of the friction material on the brake pad, it is necessary to regularly intentionally activate the friction brake, so that its function will be guaranteed in unforeseen situations where a high coefficient of friction is necessary – for example strong deceleration or an emergency brake (Kubaisi 2018).

3.1.3 Legal aspects

Regenerative braking systems are subject to much stricter control mechanisms than well-established and understood conventional friction braking systems. Mainly this is caused by the rigorous legal framework for H/EV with a deceleration force above 0.1g.

Aside from complying with legal standards, also the technical complexity in integrating the regenerative braking system smoothly into the standard vehicle concept is challenging. The inclusion has to provide safe and comfortable driving conditions. The deceleration below 0.1g is exempted from the mentioned legal framework, as here the vehicle stability is not affected.

European regulations subdivide regenerative braking systems into two separate categories:

Category A defines an electric regenerative braking system that is not included in the service brake system. It only takes effect by the accelerator control and/or the gear in a neutral position.

Category B: as opposed to the previous category the contrary defines an electric regenerative braking system which is included in the service braking system, with no separate actuator, but which is activated by the brake pedal (Kubaisi, 2018).

3.1.4 Implementation of Regenerative Braking Systems

Aside from the optimization of the recuperation, regenerative systems must above all comply with the existing requirements of conventional braking systems. Therefore the mechanisms of various most of all electronic assistance systems have to be included in the integration. These systems are:

Anti-Lock Braking System (ABS)

ABS is an automated system that helps to avoid skidding of the wheels. Skidding would provoke the vehicle to have less traction, because generally the sliding of the wheels absorb less energy than the friction of the braking system. An ABS regulate the braking process so that the wheels to not lock, with the aim of reducing the stopping distance. At the same time the ABS allows to better control the vehicle, as the steering is still possible with wheels that are not locked.

Electric stability control (ESP)

ESP is a computerized technology, which aims at avoiding control of the vehicle. It actively induces braking on each wheel individually when the front hen ESC detects loss of steering control, it automatically applies the brakes to help countering driving errors such as oversteering or understeering. By that the system contributes to the stability of the vehicle (Liebermann, 2004).

Adaptive cruise control (ACC)

According to Eskandarian (2012) "an ACC system allows drivers to maintain a desired cruise speed as well as a desired following gap with respect to a preceding vehicle if there is no immediate preceding vehicle. The ACC system senses the range (i.e., relative distance) and range rate (i.e., relative speed) to the preceding vehicle with a range sensor (i.e., radar or LIDAR). Such information is used to generate appropriate throttle or brake command to maintain a preset following gap to the preceding vehicle"

Autonomous driving

Autonomous driving, meaning that the vehicle is partially or even fully controlling the acceleration, steering and all other maneuvering including braking. The level of autonomy is categorized in different degrees. The highest level referred to as *Full Automation*, drives without any human supervision. The fully automated vehicle drives by itself without human supervision. As stated by Maurer et. al. (2016), "from a technical point of view, the greatest challenge lies in the complete absence of a human supervisor who knows the system limits, recognizes system faults and, where needed, switches the vehicle into a safe state. Fully automated vehicles must monitor their own state autonomously, spot potential system faults and performance degradations, and then—with a threatened drop in performance—initialize and execute the transition to a safe state." Given that the safety aspect remains here all the more the highest priority, the brake system must be designed with adequate provision. Although, it can be assumed that the quasi elimination of human error through presumably insufficient or also excessive braking activities is likely to result benefical from the perspective angle on safety matters.

3.1.5 Integration of regenerative braking systems

The most straightforward way to integrate a regenerative braking system is by solely including the motor caused deceleration momentum to the actual braking system, which is called a serial regenerative braking system.

Serial Regenerative Braking System (SRBS)

In this case no fundamental alterations to the original brake system have to be made, which is therefore an economically interesting solution. It would classify under the category B system , since the electric and mechanic brake procedures are not intertwined, but do build on each other. First the braking is only electric, up to a defined pedal pressure point, where the master cylinder is being activated, causing the initializing of the friction brake (Duval-Destin, 2011). The torque provided from the hydraulic brake is leveled with the torque not provided electrically.

Especially for low decelerations under regular road circumstances, where a good recuperation rate can be achieved, this system would have its advantage. Yet the braking torque would be influenced by the velocity, which would require clear limitation.

Cooperative Regenerative Braking System (CRBS)

CRBS is capable of combining electric and hydraulic braking simultaneously. The considerable benefit of the CRBS system is its ability to utilize the recuperation potential of the electric brake, irrespective of the velocity – as shown below:

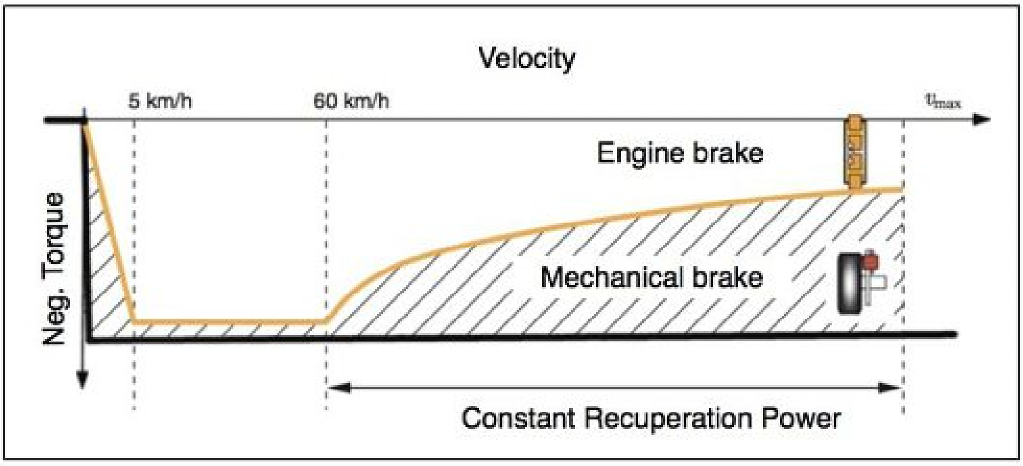


Figure 20: CRBS recuperation and friction / regeneration brake pairing (Reif, 2012)

Aside from depicting the constant recuperation momentum, the graph above reveals that the regenerative braking is inactive at low speeds.

From an economic point of view CRBS involves additional step for adapting the system, such as the installation of a brake by wire system.

Brake-By-Wire

With the coming up of Anti-Lock Braking Systems (ABS) as well as Electronic Stability Programs (ESP), it is essential to include a hydraulic aggregate that can autonomously induce brake pressure. Kubaisi (2018) defines a Brake-By-Wire system (BBW) as a system that

“completely decouples the brake pedal from the brake force. These systems provide all the assistance functions previously mentioned. The decoupling of the brake pedal and the braking force makes it possible to build up higher or lower braking forces at a given brake pedal position than with a comparable conventional system.”

By using a brake by wire system, the vehicle can come to a comfortable stop, given that the braking force is reduced during the last kinetic motion, preventing thereby a rough halting, which may irritate the driver.

Also for the regeneration factor the BBW system is of considerable importance, since it is being applied for separating the deceleration demand from the driver among the various brake actuators, without affecting the pedal feel. The smooth transition between the braking power delivered from the recuperation and the friction brake can be electronically configured, so that the driver hardly takes notice of this change.

3.1.6 Pure electric braking

Up to this point the electric braking is limited as mentioned further above to the extent of use for recuperation. Even though, other parts of the braking system, such as the actuation or transmission device, could also be electrified. This is exactly the case with the previously pointed out brake by wire system, where the pedal is electronically coupled with the rest of the brake system. But still a friction brake would have to be installed.

In other areas of mobility, the transition to fully electric braking has already been realized. Railway vehicles for example are being decelerated with purely electric braking, even up to the total standstill. However, the preconditions for the braking mechanisms in railroad applications are idiosyncratic and cannot be extrapolated to the passenger or commercial vehicle mobility (Hofer,2014).

Still a potential next step could be so called “intelligent corner modules” as developed by SCHEFFLER Group. (see figure 19). In this case the mobility relevant elements are integrated autonomously in every wheel on its own. Not only the suspension and shock absorbers, but an entire electric engine including independent steering system and deceleration mechanism.

Figure 21: Intelligent corner modules (Schaeffler, 2020)

A similar approach has been pursued by Michelin with the „active wheel“ concept, where aside from the generator unit, an active electro mechanic damping unit is balancing road irregularities individually direct in the rotating structure:

“The Active Wheel is essentially a standard wheel that houses a pair of electric motors. One of the motors spins the wheel and transmits power to the ground, while the other acts as an active suspension system to improve comfort, handling and stability. The system is designed for battery or fuel-cell powered electric vehicles, and the technology is such that a vehicle equipped with it will no longer need any gearbox, clutch, transmission shaft, universal joint or anti-roll bar.”(Vijayentiran, 2008)

In the conceptual phase, the Active Wheel fits also a standard brake system as a security backup in each single wheel. A key advantage though is the improvements on passive safety, where the impact absorption is directly absorbed on the wheel (Hofer, 2014).

For a complete elimination of the friction brake, an electrodynamic magnetic field brake could be used – in theory. This brake is also called “Eddy current brake”. In this case, deceleration is effectuated by the force of electromagnetic induction. However, research has shown that the friction brake has a substantial advantage over the Eddy current brake concerning the correlation between braking force and permanent weight. Moreover the Eddy current brake demands an initial momentum before deceleration can take place. Ultimately, commercial aspects may also conclude that the combination of regenerative braking and friction braking is more favorable (Hofer, 2014; Levin, 2006).

In addition there are given situations where deceleration cannot occur through the electronic braking mechanism. Aside from the already mentioned emergency stops and standstill braking, there are also technical predispositions impeding a universal use of the regeneration brake system. Namely the condition of the battery. Depending on various types of batteries and their structure, the state of charge is affecting the possibility of recuperation. In consideration of the accumulators' lifetime the energy recuperation is impeded starting at state of charge levels between 65% and 80% (Hofmann, 2010).

As the excess energy would have to be dissipated, other means of absorption would have to be considered. These could be intermediate energy storage facilities or an adaption of the electric generator (Hofer, 2014).

The reason for this dual setup creating a dichotomy and appearing at first glance anachronistic, will be elucidated further below. In a first step the mechanisms for the regenerative braking will be explained.

4 Key benefits of regenerative braking

The previous chapter has revealed that regenerative braking is reshaping the act of deceleration. In combination with the initially depicted motivations resulting out of the societal megatrends, regenerative braking has substantial benefits supporting that change. Recalling the transposing from the trend drivers into the automotive industry – Smarter, Lighter, Safer, Cleaner – the following elements appeal to these elements.

4.1 Economic benefits

Following a logical deduction, using electric energy replacing the consumption of fossil fuels like petrol or diesel is resulting in an economic benefit. In the same way regaining energy through recuperation consists in a financial saving, all the more as electric vehicles are subsidized by more and more governments in key market regions. In this holistic context that regenerative braking shows its main economic advantage. On a systems level direct comparison, this benefit would at least remain arguable, at least for the time being.

According to Patel (2020) the battery accounts for 25-40% of the total cost of a typical electric vehicle. Therefore it is by far the most costly component. The reason for that is simply that the batteries are expensive in manufacturing. For now price is one of the key factors keeping consumers away from buying electric vehicles. This is expected to change, as it is claimed that by 2022, the average additional cost of producing an electric vehicle versus an ICE based car is estimated with USD 1.900, with further price gap minimization expected. Complete cost parity is expected with 2024. Consumers are likely to opt for electrically powered, instead of ICE based vehicles as soon as price is in equal range. The manufactures yet are reluctant to fully switch to electric powertrains, as long as the battery systems required are either not available in demanded quantity, or at comparable cost structure. The required cost for the battery system in order to reach the tipping point is forecasted at USD 100 per kWh.

Concerning the expectable change with regards to the consumption and demand of friction materials can be foreseen with the example of Toyota's Prius model. The hybrid engine based passenger car has been introduced to the market in 1997. Since then over 8 million vehicles of that type have been sold. Conventional non-recuperating ICE passenger cars in average require a renewal of brake pads every

50.000 to 100.000 km, and every 100.000 to 200.000 new discs. It is estimated that on the Toyota Prius the brake coupling would be able to last ten times longer. As a result, the pads and discs would probably not be changed at all over the course of the vehicle's lifetime. The regenerative brake system has here reduced the use of the friction brake by over 90%. For the BMW i3, only the safety relevant functions as ABS and ESC do require a conventional braking system (EVNews, 2016).

Cost saving as a driving force however may then again be exactly the reason for which the system dualism will be maintained, as keeping the functionality of the ESC would require a complete individual electric motors for each wheel. Disc brakes are in comparison by far cheaper and from today's point of view commercially significantly more advantageous.

4.2 Ecological benefits:

4.2.1 CO2 Emission

Regenerative braking has obviously big advantages regarding the ecological footprint. Recuperating electrical energy which is not being transformed into heat helps reducing the levels of CO2, as the additional electrical energy reduces the consumption of fossil fuels. Hybrid vehicles making use of regenerative braking can enable approximately 30-50% of fuel savings (Kim, 2016). More precisely Clarke et al proposes that the recuperation process would generate an optimization in fuel usage of 29.4% in the rural driving cycle and 51.7% in urban conditions. For road commercial heavy goods vehicles, claimed reduction of fuel consumption and CO2 by 15-25% were communicated (Clarke, 2019; Fleet, 2010).

From an isolated perspective, regenerative braking is undoubtedly beneficial for the attempt to reduce the carbon footprint. Yet, when applying a more holistic scope on electric vehicles, several factors have to be taken into account, which will raise questions. Studies in China have compared the CO2 emissions during the manufacturing process between electric vehicle and state of the art internal combustion engine propulsion car. The outcome was that Chinese EV battery manufacturing is emitting up to 60% more CO2 during the manufacturing than ICE engine fabrication. Even assuming the implementation of US or European advanced, low-emission manufacturing setups would still lead to a slightly higher Carbon Footprint for the EV battery production than for ICE based engines (Qian, 2017).

On a side note, it should be recalled once more that the CO2 emission of H/EV is largely dependent on the source of the electric energy.

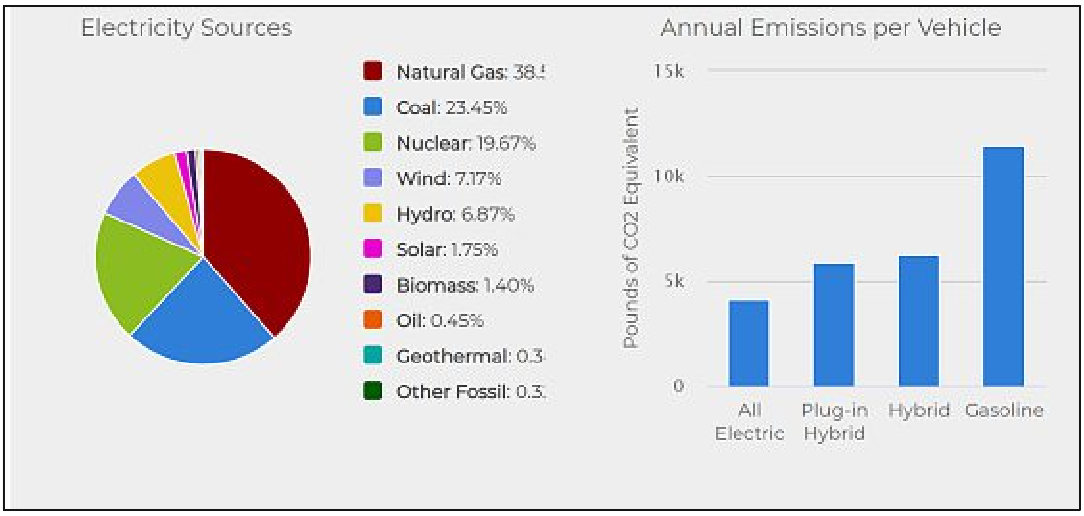


Figure 22: Energy sources and annual emissions per Vehicle in the USA (AFDC, 2021)

In that case, also the indirect emissions resulting from the electric energy generation based on fossil fuel, or also the carbon footprint from the production of regenerative energy facilities (e.g. wind turbines, solar modules) are to be considered.

4.2.2 Particle Emission

An area of research which has drawn much of attention in recent years is the particle emission caused by traffic. In principle these are being differentiated in exhaust traffic related on one hand, and on the other non-exhaust traffic related particle emissions. The latter category is relevant to the subject of this paper, as it relates to automotive braking. Non-exhaust induced processes involving mechanical abrasion and corrosion are seen as cause for particle emission. Abrasion is above all resulting from pad/disc, tyre and road surface wear, which directly produces particulate matter being exposed to the environment. Aside from these, also secondary sources of emissions can be cited such as clutch, engine or any other vehicle component wear.

It has been valued that brake wear is with PM10 emissions ranging between 16-55% by mass, one of the main contributors to particle pollution. With particle emission regulations continuously becoming more restrictive, reduction of this factor is becoming a central factor (Martini, 2014). Relying on a more recent study from Al-Thani et al (2020), quantified brake wear proportionally to the other road particle emissions with 19%.

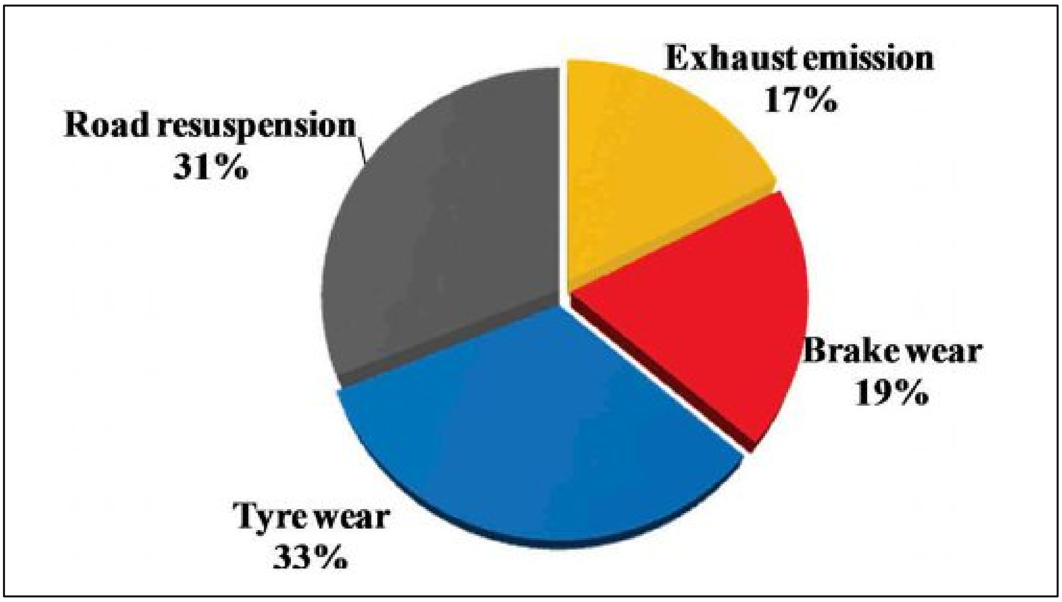


Figure 23: PM_{10} Emission percentage based on mass emission g/year (Al-Thani, 2020)

In order to assess and quantify the effect of regenerative braking on the emission of brake dust particles, a comparative analysis between standard braking system versus a Mild HEV braking system have been performed at the Technische Universität Ilmenau, Germany. The test procedure chosen in this case was the WLTC (Augsburg and Hesse, 2019).

"The Worldwide harmonized Light vehicles Test Cycles (WLTC) are chassis dynamometer tests for the determination of emissions and fuel consumption from light-duty vehicles. The tests have been developed by the UN ECE GRPE (Working Party on Pollution and Energy) group. The WLTC cycles are part of the Worldwide harmonized Light vehicles Test Procedures (WLTP), published as UNECE Global technical regulation No 15 (GTR 15). While the acronyms WLTP and WLTC are sometimes used interchangeably, the WLTP procedures define a number of other procedures—in addition to the WLTC test cycles—that are needed to type approve a vehicle." (DieselNET, 2019)

As shown by Augsburg and Hessel (2019), the effect of regenerative braking on particle emissions cannot be overvalued.

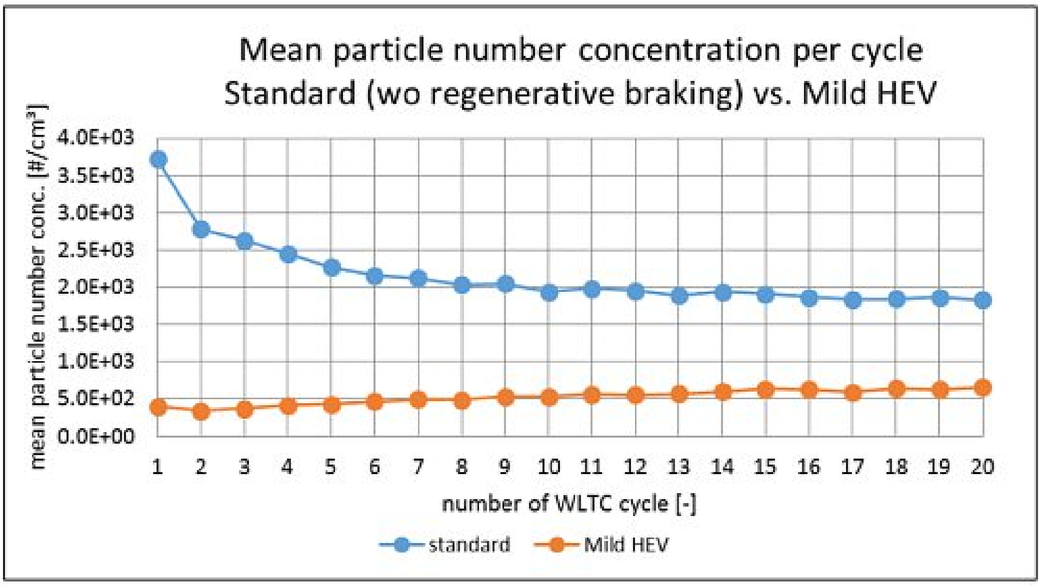


Figure 24: Particle Emission reduction with regenerative braking (Augsburg and Hesse, 2019)

The study has proven that for a mild hybrid electric vehicle, 91% and for plugin or pure electric vehicles even 99% of brake dust reduction was achieved. This reduction is factually due to the obsolescence of the mechanical brake over the main course of the here used testing cycle WLTC.

4.2.3 Toxicology:

Closely related to the particle emission concern, the use of toxic substances in conventional friction bakes would also be positively affected from the integration of recuperation systems, once more caused by less usage. Two main substances of concern have been highlighted in a study from Amato et al. (2011) – Copper and Antimony.

Copper:

Copper is an essential for the basic metabolism of both humans and other animals, including maritime life in a dose of 5-20 micrograms per gram (µg/g). It is indispensable for the creation of heamoglobion and heamocyanin, thus the supply of oxygen within organisms. However, concentrations above 20 µg/g are considered as potentially toxic.(Augsburg and Hesse, 2019)

Copper is used within brake pads for its outstanding thermal conductivity. By dissipating heat, the brake coupling is less exposed to excessive thermal stress, which in return stabilizes the coefficient of friction and minimizes wear. Yet during the braking process, brake dust particles are emitted to the environment and into the ecosystem. Here it may be absorbed in higher concentration by living beings, mostly by maritime life when washed into the sea. Hence, the copper concentration in the brake friction material has been made responsible for the contamination of running water in the environment of metropolitan locations. For that reason a the maximum concentration of Copper in friction materials has been regulated in 2010 within laws of the state of Washington (SB346) and also California (SSB6557).

These laws have been taking effect as of 2021, which limits the Cu concentration in brake applications to 0.5%, forcing friction material producers to seek alternative solutions. (Wang and Chung, 2013)

Antimony:

Antimony (Sb) in its elemental form finds normally use in industrial applications such as semiconductors, infrared detectors, diodes, bearings, or pipe metals. In addition Antimony Trioxide (Sb2O3) acts as a fire retardant in coatings, plastics etc (Augsburg and Hesse, 2019). It is in its from as Antimony Trisulfide where the element finds its application in brake pads. Here Sb2S3 proves to have a substantial effect on high temperature fading stability.

According to Shyam (2010), “there is inadequate evidence for carcinogenicity of antimony trioxide and trisulphide in humans but antimony trioxide and antimony trisulfide have been seen to cause lung tumours in rats. Antimony trioxide is classified as possibly carcinogenic to humans (Group 2B) by the International Agency for Research on Cancer” (Shyam, 2010)

Contrary to Copper, although there is no explicit current ban of Antimony per se for use in brake applications. Nevertheless more and more friction material manufacturers decide to produce Antimony free products, as Sb2S3 transforms into carcinogenic Sb2O3 during exposure to high temperatures of 300°C and above as it happens within brake application (Wang and Chung, 2013).

The study of Amato (2011). primarily aimed at identifying the prime causes of PM10 emissions through measurements in different urban places, namely Zurich, Barcelona and Girona. Aside from correlating the detection of Fe, Cu. Zn, Cr, Sn and Sb as clearly coming from brake dust, Sb and Cu concentrations have been explicitly compared:

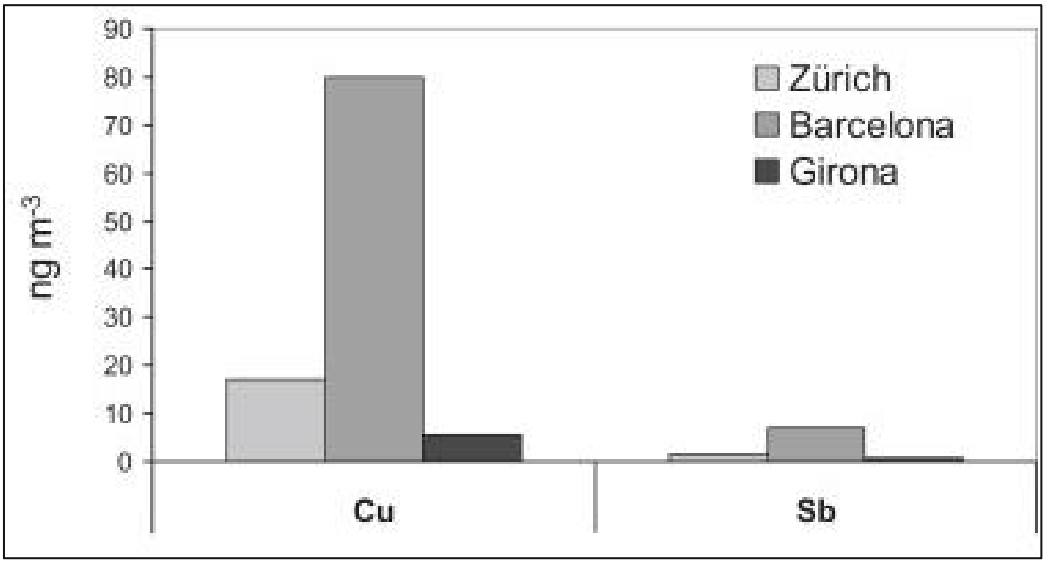


Figure 25 Cu & Sb concentrations in ambient air (Amato, 2011)

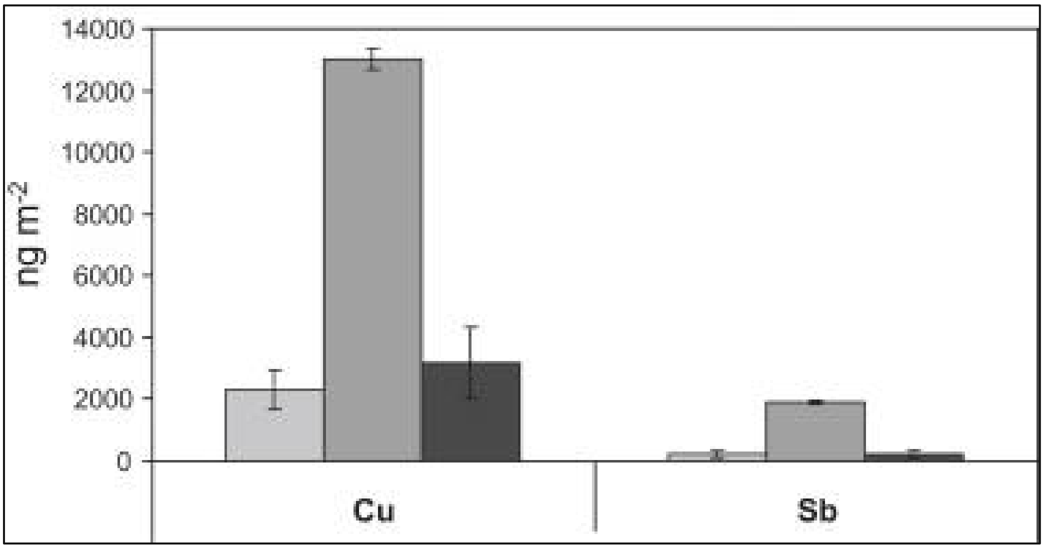


Figure 26: Cu & Sb loadings in road dust < 10 µm (Amato, 2011)

Both the measurements of concentrations in ambient air as well as loadings in road dust indicate higher concentrations with higher traffic. In return it can be deduced that with the implementation of regenerative braking systems the occurrence of particle emissions based on Sb and Cu would be reduced to a fraction, given that the use of the friction brake in such systems is marginal.

Notwithstanding, Augsburg and Hesse also emphasized a new set of technical challenges supposedly arising from the alterations in frequency and kind of usage of the braking system, which shall be elucidated in the subsequent section.

4.3 New application conditions

Reflecting on the technical implications, it invites to recall the AK Master test as one of the most prevalent and realistic simulations of long term stress factors on friction materials. The addition on the regenerative element to the deceleration yet would substantially change the basic correlation to the field use, given that recuperation occurs between 0.1 and 0.5 g. Even the brake fading test blocks considered as being among the toughest ones in the procedure would apply stops from 100km/h to ≤ 0.4. Shall it be the case that the friction brake still is involved in the braking process, one may deduct that the consecutive strong brake stops would not occur to such a strong extent. Therefore there would be far less kinetic energy being converted to heat and hence the temperature raise to 500°C and above would not come about. Typical temperature increments in an AK Master test are shown below:

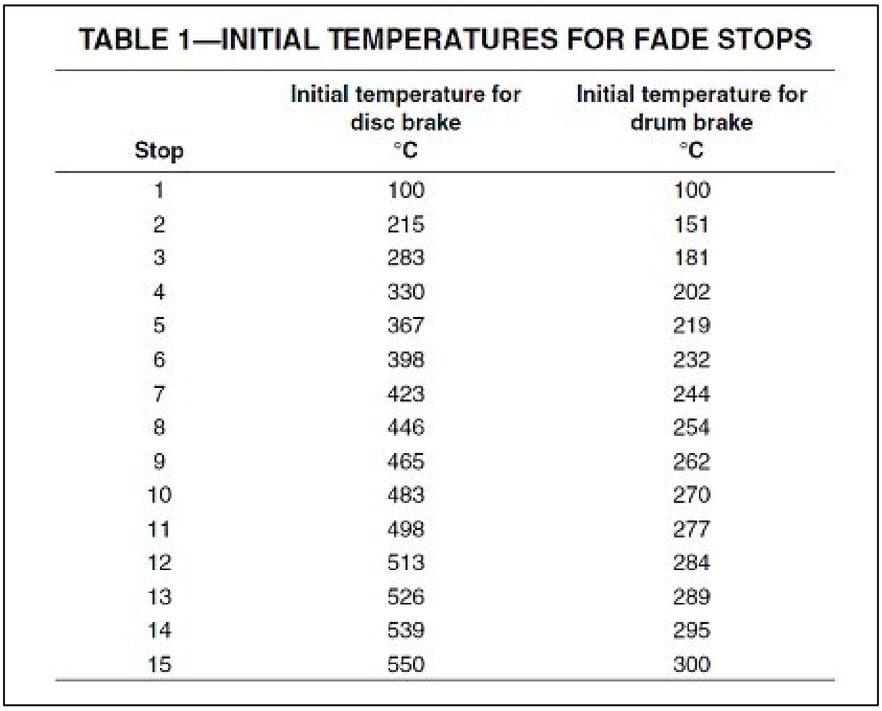


TABLE 1—INITIAL TEMPERATURES FOR FADE STOPS

Stop	Initial temperature for disc brake °C	Initial temperature for drum brake °C
1	100	100
2	215	151
3	283	181
4	330	202
5	367	219
6	398	232
7	423	244
8	446	254
9	465	262
10	483	270
11	498	277
12	513	284
13	526	289
14	539	295
15	550	300

Figure 27 Temprature increase in SAE J 2655 (SAE, 2003)

Less usage of the friction brake and in addition less heat dissipation would also imply substantially less wearing off from the friction material. As already pointed pointed out in 4.1., a pad may last multiple times longer on an H/EV than on a regular ICE based vehicle without recuperation. Consequently, it is being expected that the pads may get noticeably thinner, since usage is simply diminishing. (Tiedemann, 2020)

Thinner pads would mean above all using less of friction material. In addition, the composition of the friction material would also be subject to a reassessment, as the conditions with regards to usage frequency, pressure or temperature have changed.

Another aspect in this context is the use of the friction material additives in use. With temperatures hardly rising to the same levels than under the defined typical testing scenarios, it remains arguable whether some of the prevalent components would become redundant. It is at that point that inevitably a discussion on safety standards, reliability engineering and thereby dual or triple modular redundancies might arise.

As earlier identified do friction brakes take action during fast deceleration, emergency braking, and final halt. Aside from these scenarios, kinetic energy will be converted through recuperation into electric energy. This however presupposes the loading capacity of the H/EV battery system. In case that the accumulators are fully loaded, the kinetic energy would have to be converted into heat due to lack of storage capacity. As a result, the friction brake would have to be used in the same way as in a conventional non-regenerative system. Assuming a continuous deceleration when going downhill, thermal stress on the friction coupling can mount substantially, and may even reach a level of 700°C. Even though the here depicted scenario is unlikely, it does bring up uncertainties requiring risk mitigation. Given that with existing friction brake systems a well-established, proven and reliable solution exists, it remains very questionable whether the latter is to be declared a redundancy.

4.3.1 Weight

It that context, also the weight of H/EV represents an important factor. There is a wide disparity of range for H/EV, mostly depending on the battery system capacity used. For Lithium-ion accumulators, the weight for reaching a range of approximately 100 km is 150 kg and above. For larger ranges of 300km and more, as commonly installed in the high end passenger vehicle segment, the battery load surpasses even 500 kg (Thomas, 2009).

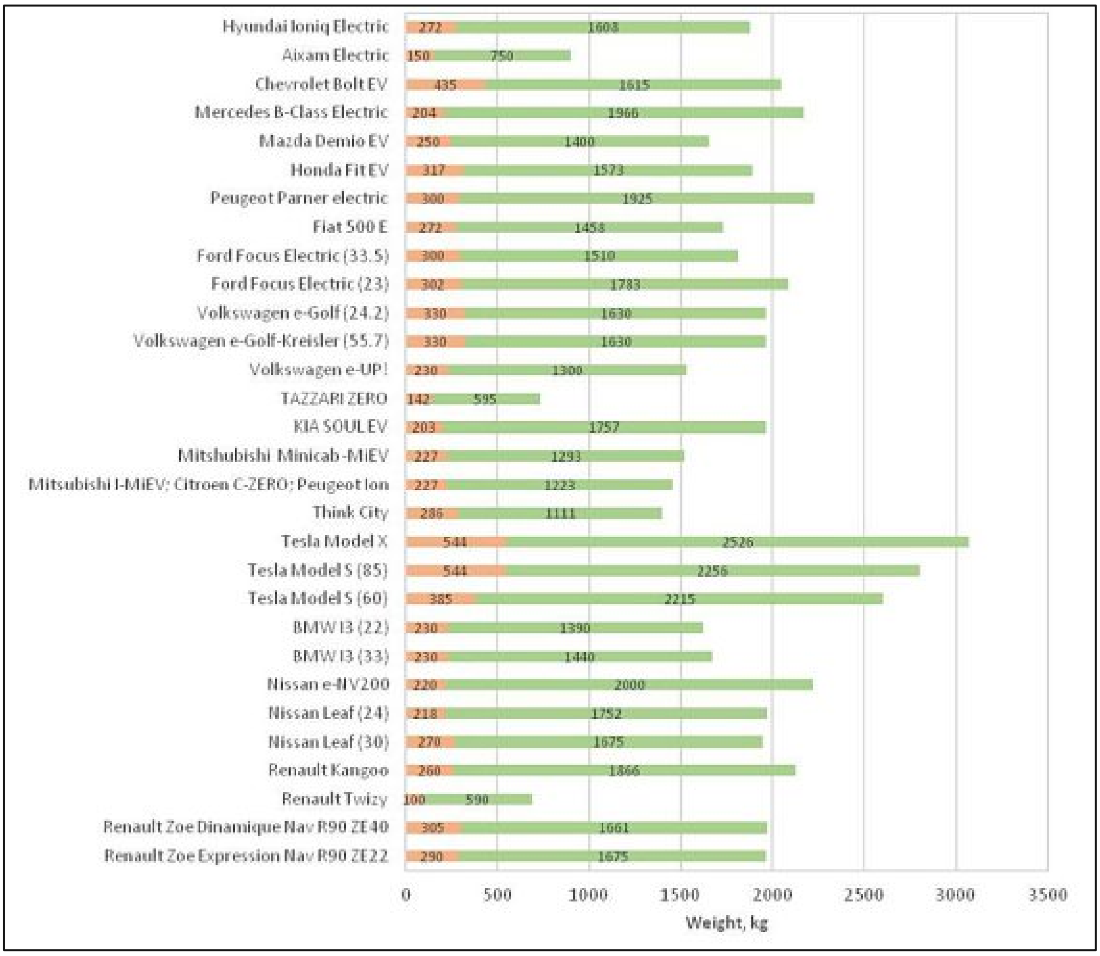


Figure 28: Weight and Range of various H/EV available on the market (Thomas, 2009)

The increase in weight poses a conflict of interest to vehicle manufacturers. On one hand there is the intention to extend the travel range. On the other the additional load will need more power to generate torque for achieving the acceleration. On top, bigger and more efficient battery systems will be more costly. Therefore weight and savings on other parts are being looked for. (Berjoza, 2017)

The brake system in an H/EV with its dual braking mechanism, based both on regenerative and friction braking would represent an interesting possibility for saving weight, as just one disc alone weighs in average 9.5 Kgs. (DBA, 2020)

A complete substitution of the friction brake at first glance would lead to a significant decrease in weight. However as previously pointed out, at the current point in time there is no logical overcoming of the dual system due to safety aspects.

At the same time, the additional weight in electric vehicle, mainly caused by the battery, but also by other components, represents more mass which has to be stopped. Therefore it is being argued that the brake pads of the friction brake would not become obsolete, but right in the contrary these would be dimensioned larger in order to create more surface for faster deceleration. An addition to approximately 20% in size is being evaluated (Tribotecc, 2020).

4.3.2 Corrosion

One of the biggest challenges for only sporadically used friction brakes is corrosion. According to Winston and Uhlig (2009), Corrosion is defined as

„the destructive attack of a metal by chemical or electrochemical reaction with its environment. Deterioration by physical causes is not called corrosion, but is described as erosion, galling, or wear. In some instances, chemical attack accompanies physical deterioration, as described by the following terms: corrosion – erosion, corrosive wear, or fretting corrosion. Nonmetals are not included in this definition of corrosion. Plastics may swell or crack, wood may split or decay, granite may erode, and Portland cement may leach away, but the term corrosion is restricted to chemical attack of metals. Rusting applies to the corrosion of iron or iron - base alloys with formation of corrosion products consisting largely of hydrous ferric oxides. Nonferrous metals, therefore, corrode, but do not rust."

As discussed in Chapter 1, brake discs and brake pads include both ferrous and non ferrous components. In the case of vehicles equipped with regenerative braking system the friction brake system is used only on rather limited occasions, consequently the contact surfaces of disc and brake pad are not in use and therefore worn off on a regular basis. The inactivity leads as described by Augsburg and Hesse (2019) to corrosion.

Figure 29: Effect of corrosion on disc brake pads (Hagman, 2021)

Corrosion is affecting the friction pairing of pad and disc in various ways. The friction material itself eventually become brittle and decomposes, or the adhesion to the backing plate leads to detaching. Ultimately corrosion can have fatal consequences, as the inadequate functionality of the friction material / disc pairing may cause a prolonged deceleration period, not stopping the vehicle timely. (Markel, 2019)

Corrosion prevention

A possible way to avoid corrosion is to use optimized raw materials, such as superior steel alloys that are preselected with the intention to avoid impurities and foreign substances. Depending on the quality of steel components used, oxide formation – being the precursor for corrosion - may be retarded or hindered.

In addition, protection measures in form of coatings and shielding layers may be applied on surfaces exposed to the environment. The aim here is to improve resistance to any mechanical, thermal or chemical impact, which may lead to an entry for oxidation.

Moreover, using non-ferrous materials like ceramic brake concepts would be a possible solution, which however would have to be weighted against potential cost factors. Also the le level of pH is affecting the corrosivity of friction materials. Calcium hydroxide for instance is commonly added as a rust inhibitor since its direct influence on pH values impacts the corrosion resistance of the friction material (Wang and Chung, 2013).

Corrosion testing

To assess the corrosivity and degradation of materials on the brake system, corrosion cycling tests can be performed. The samples, in this case the friction materials or pads, are exposed to different stages of ambient conditions. The conditions are varied in different repetitive cycles, so that real world exposure is reenacted. The goal is to analyze the types and conditions of eventual failure of the materials and part, but under stronger and faster impact, so that predictions on the durability and thereby lifetime of the materials can be made.

Although several automotive companies started their own test cycles, the SAE J 2334 has established as one of the prevalent standards. For these tests generally various application typical exposure scenarios are simulated. Most commonly, the subsequent conditions are set, in a cycle, hence repeating period (LeBozec et. al., 2008):

- Phase 1 - Salt spray pollution: Much like in a traditional salt spray test, the sample is brought in contacted or sometimes even fully immersed in salt solution of different concentration.
- Phase 2 - Air drying: According to the conditions set, the sample is dried either at room temperature or higher thermal conditions, and variations of relative humidity. Generally a regular inflow of fresh air on the specimen is provided, until the latter are visibly dry.
- Phase 3 - Condensation humidity wetting: This phase has the intention to create condensation on the specimen, which is normally performed after a temperature increase and relative humidity level reaching 95% and above
- Phase 4 - Controlled humidity cycling: In that stage the specimen is placed in a regulated climate with clearly set temperature and humidity cycles that can vary over time or remain stable.

In addition other more severe elements to such a testing can be added like for example temperatures below zero degrees.

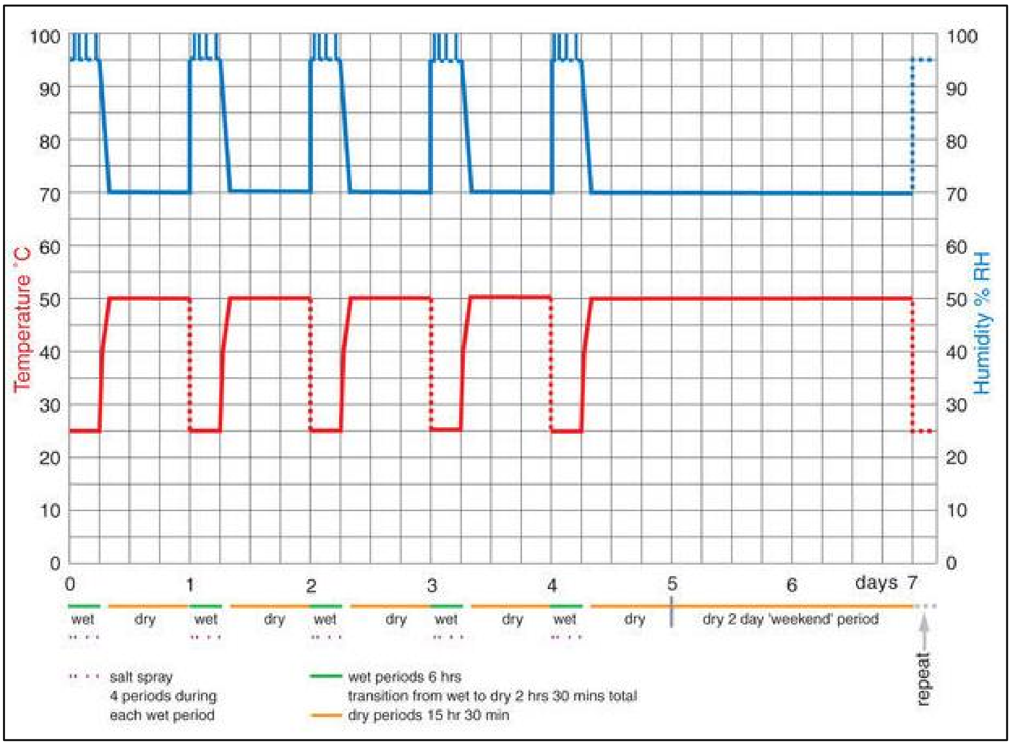


Figure 30: Temperature & humidity steps required during cyclic corrosion test (CETP, 2014)

In the exemplary graph shown, the corrosion test cycle has been set for 7 days, whereby wet and dry periods are alternating. During the wet periods each lasting 6 hours, salt spray will be applied on the sample at 4 different occasions. The following dry period lasts for 15 hours and 30 minutes, during which the temperature will elevate to from 25°C to 50°C. Also the telative humidity augments from 70% to at least 95%

4.3.3 Focus on comfort aspects

In the previous chapter it has been shown that the composition of the friction material largely depends on the brake characteristics requested. Whether selecting a semi metallic, low metallic or NAO formulation would be defined by the needs. We recall that low metallic formulations are used mostly for their high friction coefficient, but then again these do have drawbacks with regards to comfort aspects. NAO formulations in return account for mostly the opposite effect – lower coefficient of friction traded for higher comfort aspects. With regenerative braking in place, the comfort and NVH aspects are gaining significant importance. This is mainly resulting out of new ambient conditions, as the electric power train is not comparable to the soundscape of the internal combustion engine. According to Deng et al. (2020), “whine noise from the electric powertrain system of electric vehicles, including electromagnetic noise and gear-meshing noise, significantly affects vehicle comfort and has been getting growing concern “ Previously some noise may have been simply less detected by the human ear, as other noises, for example from the combustion engine itself were much more present. Since these noises are not present anymore, also brake squealing or groan noises along with vibrations are likely to be more in the focus. By consequence it can be expected that NAO based concepts are likely to be the formulations of choice.

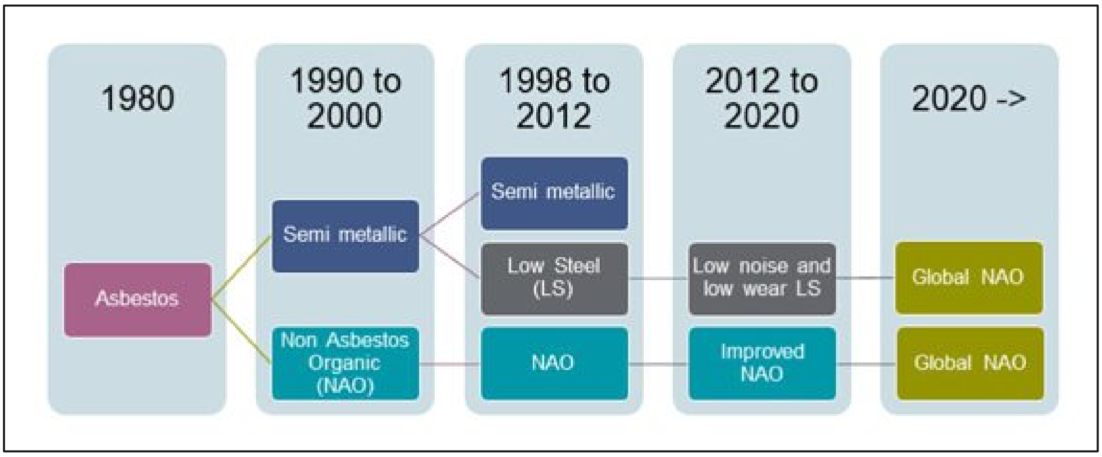


Figure 31: Friction material formulation concepts in use since 1980 (Jansen, 2020)

In the 1990s the main concern was getting a similar performance as the formerly used Asbestos, which began to be banned for use due to its carcinogenic effect. Subsequent alternates first basically assured application adequacy through use of high metal contents, which consecutively began to be reduced given the drawbacks on NVH and comfort aspects. What Jansen (2020) forecasts as Global NAO, can be interpreted as a standardization irrespective of regional idiosyncrasies, given that basic requirements on friction materials are becoming harmonized in their focus on comfort aspects.

4.4 New Material Solutions

The new application conditions would also lead to new material requirements, as the given solutions would cause incompatibilities in terms technology. In the subsequent section, possible alternates for overcoming these impediments shall be discussed.

4.4.1 Toxicological improvements

Particle filtering

It has been shown that particle emission can be radically improved by regenerative braking. Still certain amounts of problematic substances such as Copper and

Antimony are emitted to the environment. This exposure eventually can be minimized by the use of brake dust filtering systems, such as offered by MANN+HUMMEL Gmbh.

"Located close to the brake and therefore the source, the filter retains the particles which are the result of mechanical abrasion on the brake. The filter consists of a robust housing which is positioned directly in continuation to the brake caliper and captures particles created in the braking process. The new development can be fitted to any existing installation space and can be adapted to different brake sizes and concept." (Mann, 2021).

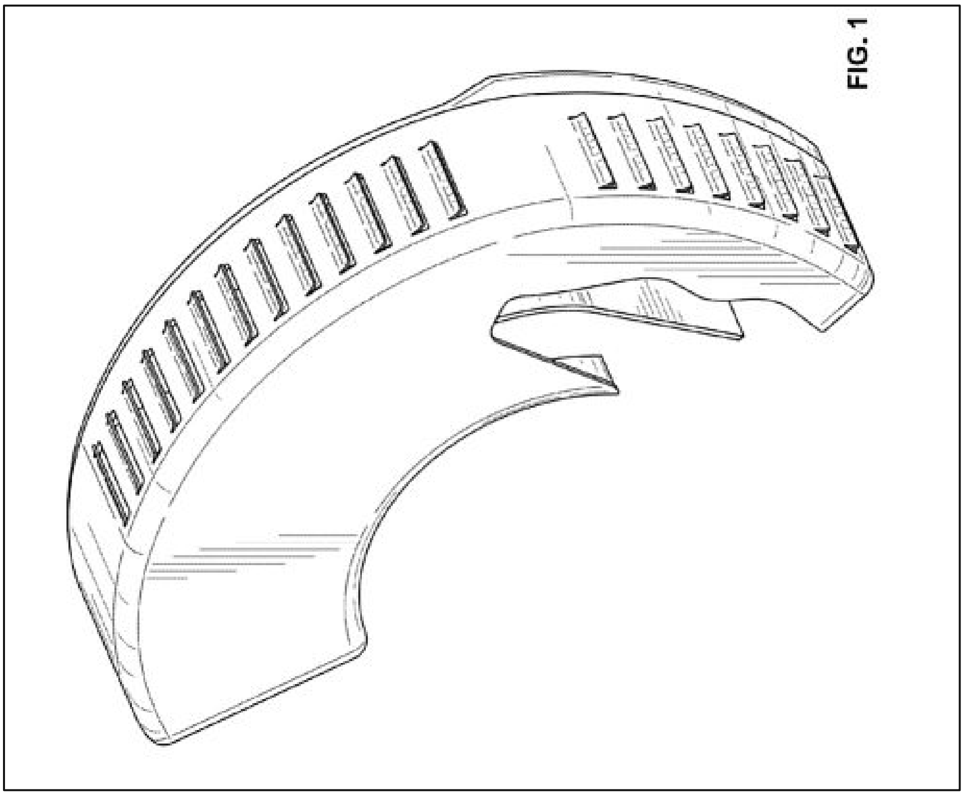


Figure 32 MANN+HUMMEL Brake Dust Filter (Mann and Hummel 2013)

Given that the overall brake dust emergence is significantly low, adding supplementary weight to a system which aims at reducing of the latter would have to be gauged. The filter system however does represent a viable solution for particle emission reduction, also in applications where regenerative braking may not necessarily lead to a major reduction of friction brake usage, and continuous abrasion of friction material is still given.

Copper substitution

Another, or rather additional method of limiting toxicity in the brake system would be the substitution of the toxic substances Sb and Cu. As mentioned one of the key characteristics or Copper is the very high thermal conductivity, which also supports the basic friction stability during braking under high temperatures. The consequence of taking out copper in a standard low-met formulation is depicted in below's figure. Within the high temperature fading blocks, the coefficient of friction drops significantly.

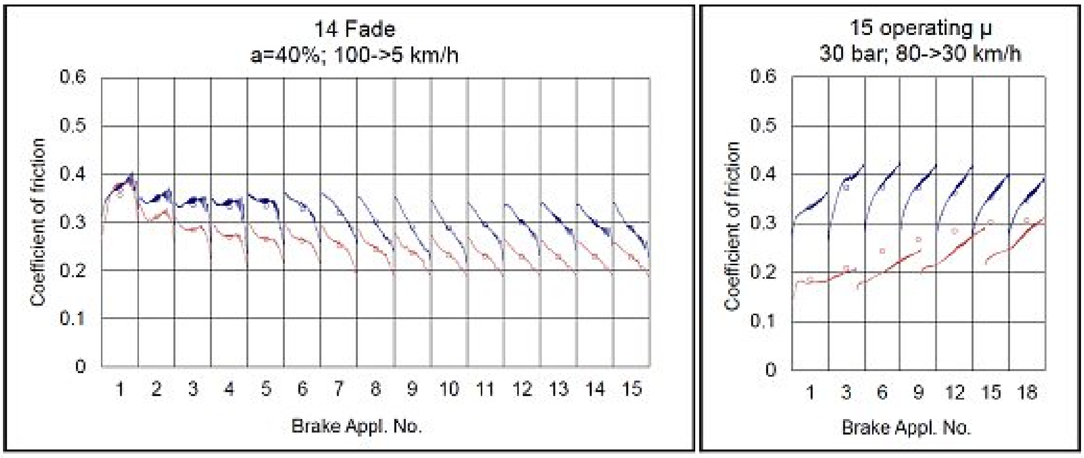


Figure 33: Coefficient of friction of block 14 and 15 SAE J2522

(red curve Cu free formulation; dark blue Cu containing reference)

The test cycle reveals that under the given conditions a mere removal of Cu from the friction material formulation is not an option. A possible substitute are synthetic Iron sulfide based additives, which, although not reaching the same level as Cu, prove a superior thermal conductivity. The following displayed comparison shows FeS based products from Tribotecc – Ferrostar, T100, T201 and T701. The various types of products differ in their volume and combination with other active ingredients, such as Aluminum or synthetic graphite (Tribotecc, 2014).

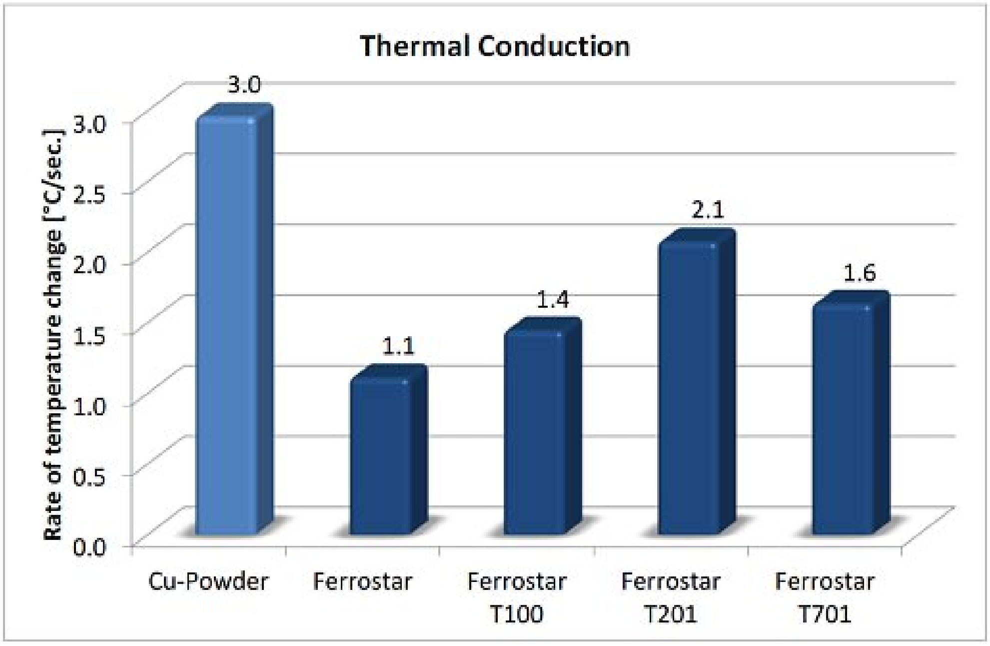


Figure 34: Thermal conduction rate of synthetic FeS based additives to Cu-powder (Tribotecc, 2014)

The measurements show the rate of temperature change over time. While iron sulfide per se has a relatively high thermal conduction, the displayed variations enable further enhancement. The hypothesis of FeS based combinations as an alternate to Cu was in a next step verified in a performance test – SAE J2522. It is here where the previously strong deterioration of the coefficient of friction could be compensated.

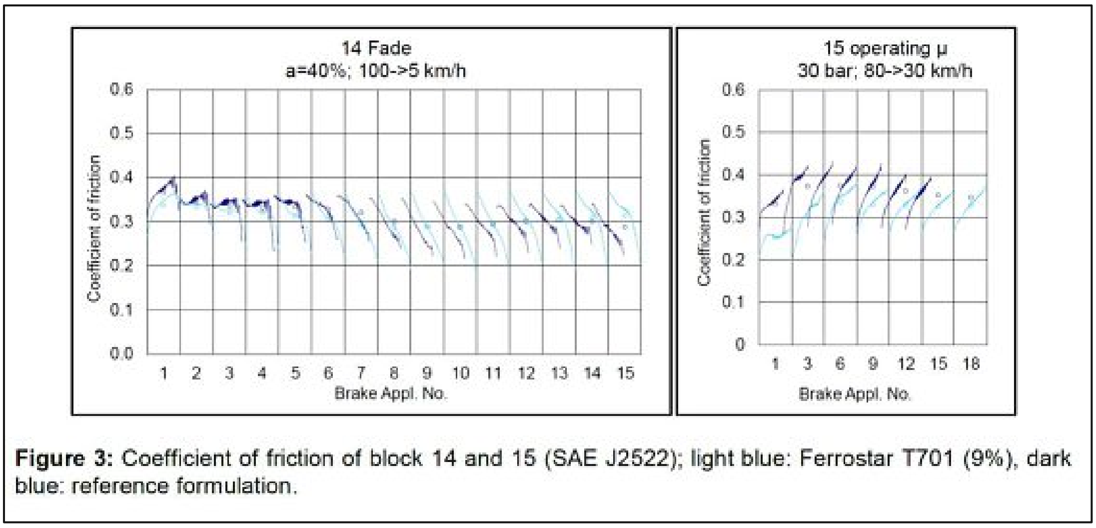


Figure 3: Coefficient of friction of block 14 and 15 (SAE J2522); light blue: Ferrostar T701 (9%), dark blue: reference formulation.

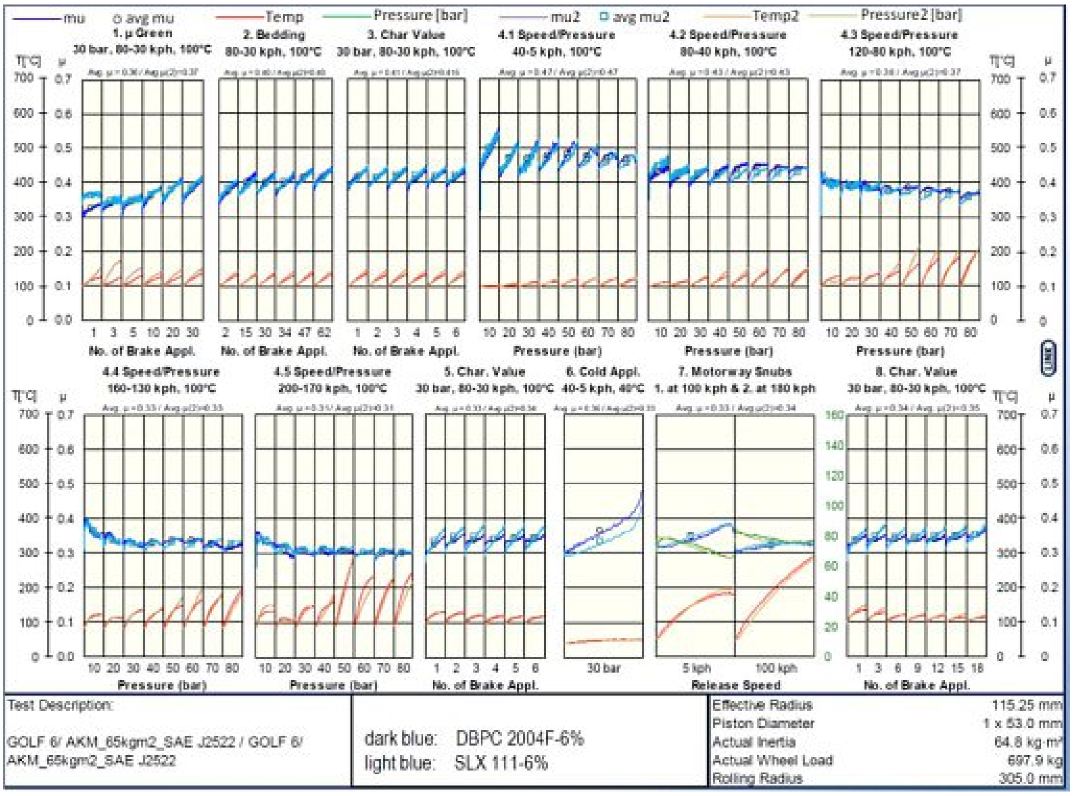
Figure 35: Coefficient of friction of block 14 and 15 SAE J2522 (- bright blue curve: Ferrostar T701; dark blue Cu containing reference formulation (Tribotecc, 2014)

Figure 35 highlights the stabilization effect in this case of Ferrostar T701 under the high temperature fading and high pressure deceleration blocks, and would undermine the suitability of this Cu free formulation under the given conditions.

It has to be kept in mind that due to the broad variety of formulations and additive combinations which may lead to interaction, the effect would have to be verified individually on a formulation.

Antimony substitution

In a similar way as with Copper, also Antimony – mostly present in the form of Antimony Trisulfide - may be substituted by a combination of other metal sulfides which are not subject to a restriction or under suspicion of being carcinogenic. Such substitutes are commonly based on Sn, Bi, Zn, Fe combinations. Direct comparison on the SAE J2522 standard show the viability as a replacement, such as in the case of the proposed replacement Tribotecc SLX 111. Graph here below shows the AK master test completed, whereby the dark blue line indicates the performance of Sb2S3 with 69% Sb content versus Tribotecc SLX 111 shown in light blue. The parallelism in the course of both curves indicates the similarity in performance. Moreover, performance in block 9 (Fade 1) and blocks 12.1 as well as block 12.2 suggest even partially superior performance under the given conditions and formulation setup.

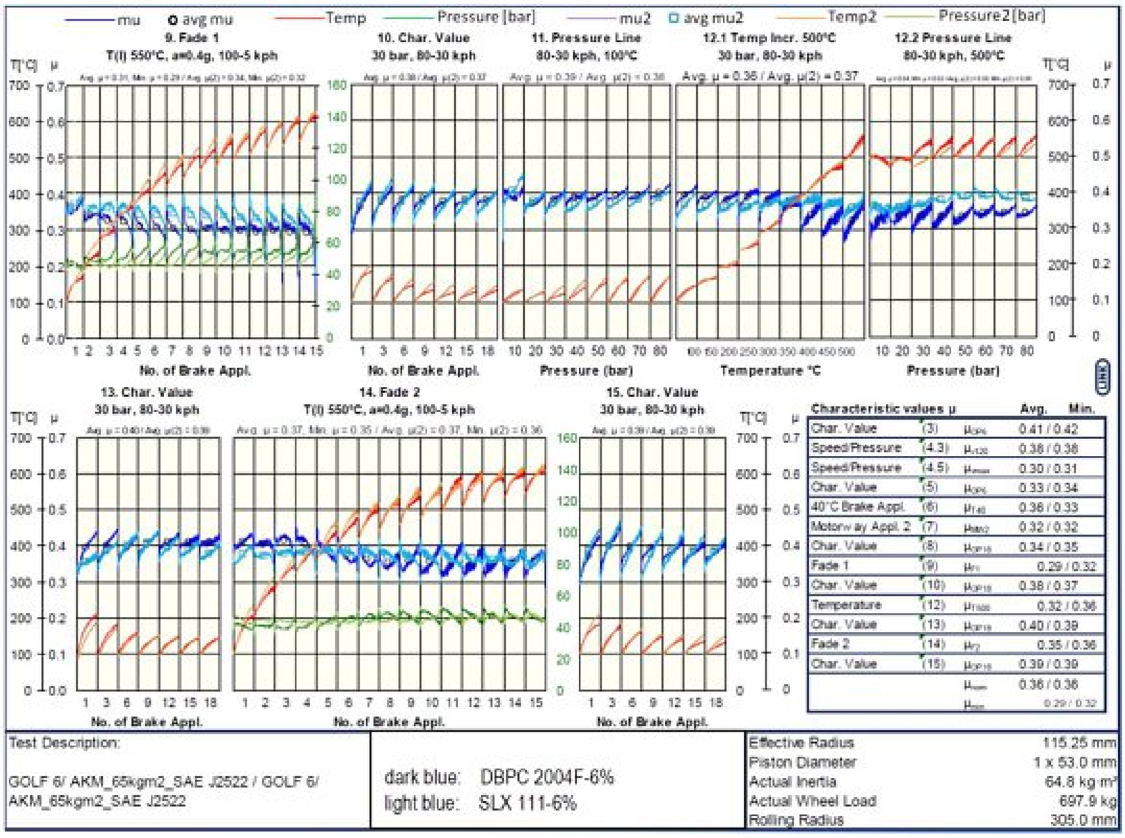


Test Description:

GOLF 6/ AKM_65kgm2_SAE J2522 / GOLF 6/ AKM_65kgm2_SAE J2522

dark blue: DBPC 2004F-6%
light blue: SLX 111-6%

Effective Radius	115.25 mm
Piston Diameter	1 x 53.0 mm
Actual Inertia	64.8 kg·m²
Actual Wheel Load	697.9 kg
Rolling Radius	305.0 mm



Characteristic values μ			Avg. / Min.
Char. Value	(3)	μ [illegible]	0.41 / 0.42
Speed/Pressure	(4.3)	μ [illegible]	0.38 / 0.38
Speed/Pressure	(4.5)	μ [illegible]	0.30 / 0.31
Char. Value	(5)	μ [illegible]	0.33 / 0.34
40°C Brake Appl.	(6)	μ [illegible]	0.36 / 0.33
Motorway Appl. 2	(7)	μ [illegible]	0.32 / 0.32
Char. Value	(8)	μ [illegible]	0.34 / 0.35
Fade 1	(9)	μ [illegible]	0.29 / 0.32
Char. Value	(10)	μ [illegible]	0.38 / 0.37
Temperature	(12)	μ [illegible]	0.32 / 0.36
Char. Value	(13)	μ [illegible]	0.40 / 0.39
Fade 2	(14)	μ [illegible]	0.35 / 0.36
Char. Value	(15)	μ [illegible]	0.39 / 0.39
		μ [illegible]	0.36 / 0.36
		μ [illegible]	0.29 / 0.32

Test Description:

GOLF 6/ AKM_65kgm2_SAE J2522 / GOLF 6/ AKM_65kgm2_SAE J2522

dark blue: DBPC 2004F-6%
light blue: SLX 111-6%

Effective Radius	115.25 mm
Piston Diameter	1 x 53.0 mm
Actual Inertia	64.8 kg·m²
Actual Wheel Load	697.9 kg
Rolling Radius	305.0 mm

Figure 36: SAE J2522 comparison of performance between Sb2S3 and alternate SLX111 (Tribotecc, 2014)

4.4.2 Weight & corrosion improvements

In order to cope with the additional weight that H/EV have, there is the straightforward possibility to use lighter materials. In the case of brake discs, changing from regular cast iron to ceramic or aluminum would be an option. At the same time these would avoid the building of corrosion.

Ceramic brake discs

Ceramic disks essentially consist of carbon fibers, carbon powders and resins, which are pressed into molds under high pressure. In a further production step these moldings are then tempered at approx. 1100 C°, whereby the resins are carbonized. During the carbonization process pores are created, which are infiltrated with pure silicon reacting at approx. 1500 C° with the carbon and forming silicon carbide. Compared to conventional grey iron discs, ceramic discs have impressive advantages. The responsiveness is better, the disc is extremely temperature resistant (up to approx. 1200°C) and the service life is clearly higher than 300.000 km. In addition, ceramic brakes are completely corrosion free, lighter than gray cast iron, has better comfort attributes, better fading properties and enables shorter braking distances. A disadvantage on the other side is the absorption of moisture, which is negatively affecting fading under wet conditions, as well as the possible deformation or even braking under mechanical stress. The biggest disadvantage of all though is the commercial aspect of ceramic discs. The manufacturing costs compared to gray cast iron is many times higher, which explains why the use of this technology is limited to luxury cars, even though a further reduction in costs is expected over the coming years (Wiatarek, 2017).

Aluminum brake discs

The so far discussed friction material concepts are all designed for use with grey iron brake discs as counterpart. Stainless steel and Aluminum discs are other options. Especially the latter would in theory be an interesting alternative to consider, as they are light and do not corrode. But given the low melting point of 450°C of Aluminum, high thermal stress creates other technical problems limiting its use. For that reason, coating the disc surface with silicon carbide, or furthermore Tungsten carbide would be a viable option.

Continental AG came up with a much acclaimed study for future brake solutions based on aluminium discs, yet interpreted in a quite disruptive way. A prototype named *New Wheel Concept* has been presented already in 2017, which was explicitly developed with the intention of optimizing the mechanical braking of electric vehicles. The wheel rim here consists of two aluminum (Al) element - the inner Al carrier star with the Al brake disk and the outer Al rim. In contrast to conventional wheel brakes, the *New Wheel Concept* brake activates the Al disc from the inner side of the wheel. This allows it to have an especially large diameter, which reenforces the braking performance.

Figure 37: New Wheel Concept (Continental, 2021)

All in all, it can be seen that there are indeed several options to overcome the new technical requirements and challenges arising from the switch to regenerative braking systems. The adequate structures and materials are available. It remains however ultimately a commercial decision with regards to which components will be used – much alike the ultimate consideration made by the consumer for switching from ICE based vehicles to H/EV. For most consumers, it must make economically sense to trigger the change. This rationale is in return also applied by the manufacturers, which would explain that as of now, and likely also for the coming years the duality and partial redundancy of the brake concept in H/EV will remain.

5 Conclusion and Outlook

In the course of this work several critical points referring to the transition from solely friction based braking towards the implementation of regenerative braking were broached. In an initial step, the socio-economic factors initiating the actual change from one technology to another have been elucidated. Subsequently a thorough recapitulation of both the concept, mechanisms and construction of both a friction brake and a regenerative brake system have been elucidated in detail. Here, especially the friction material compositions were analyzed, in anticipation of potential new setups under new conditions. In this context, also the relevant test methods for assessing the suitability of material pairings were depicted.

In a next step, it has been shown that the introduction of kinetic energy recuperation does have a disruptive effect on the braking systems and its components. Over 90% of all deceleration activities will lead to recuperation, and only under rather non-standard situations, such as strong deceleration, emergency braking or deceleration to final halting will request the use of the friction brake. These circumstances are provoking the reflection on whether the dualism in systems with a friction brake next to the regenerative brake system is necessary. Notwithstanding it has been deducted that safety standards, security redundancies, risk mitigation and also economic considerations would strongly advocate for keeping the double structures in place. At the same time it is undeniable that the fractional use of the friction brake system compared to its continuous utilization in internal combustion engine based vehicles without electric recuperation will lead to changes not only in technical requirements but also to less demand in friction brake components.

In addition, testing standards as well as the related legal framework for braking systems and friction materials may be subject to reassessment, given that new requirement might be less demanding in terms of performance assessments. An SAE J2522 test cycle represents severe stress on the system, which would most likely not occur in the same way on vehicles equipped with a regenerative brake system, given that the friction brake is used only in marginal cases.

The new conditions for friction brakes in H/EV vehicles however will influence also the setup and composition of the friction brake system. Comfort aspects revolving around factors such as noise, vibration and harshness during the braking process are gaining substantial importance, as the engine related sounds and motion are present to a far lesser degree in H/EV as in internal combustion engines. More comfort oriented NAO formulations are becoming the technology of choice. Also environmental aspects, toxicity concerns and physical changes such as in weight or temperature, lead to the use of new friction additives and material combinations. All in all the use of regenerative braking will have especially a positive influence on the avoidance of particle emissions, which can be considered one of the most challenging and prioritized forms of pollution in urban surrounding. The benefits here are mainly due to the fact that regenerative braking does not produce brake dust which may be problematic partially due to the particle size itself that can affect humans and other organisms.

Based on the findings of this work, it can be concluded that the implementation of regenerative braking constitutes in a change on many levels. It showed an undeniable positive impact from an isolated ecological, economic and technological perspective. Yet these benefits have to be put in a broader context, reflecting on the origin of materials and energy used in the production process. Moreover, new material concepts for further development and in line with performance, regulatory and ecological requirements are available to match the new requirements, though commercial aspects have to be assessed and weighted. Further clarification of material setup optimization along with analysis of commercial rigor is advised.

Ultimately, further investigation for improvements concerning friction characteristics in other parts of H/EV would be of high interest. According to Farfan-Cabrera (2019), although mechanical losses only marginally contribute to the overall efficiency loss of H/EV with 3.53% (electric with 64.1% and magnetic with 26.7% being by far the highest sources for efficiency loss), an optimization would improve significantly the efficiency and durability of the components. Mechanical friction losses are especially caused thermal stress, vibrations and wear occurring from rotor velocity. Here rolling bearings are a key component, given that 40-60% of all electric engine failures are ascribed to the latter. Further optimization on tribological characteristics in form of enhanced lubrication as a prophylactic measure against wear and mechanic losses would be advisable.

List of Figures

Abbreviations

ABS	Anti-Lock Braking System
Al	Aluminum
BEV	Battery Electric Vehicle
BBW	Brake By Wire
CRBS	Cooperative Regenerative Braking System
Cu	Copper
DTV	Disc Thickness Variation
EBS	Engine Brake Simulation
ESP	Electronic Stability Program
H/EV	Hybrid or Electric Vehicle
ICE	Internal Combustion Engine
kWh	Kilo Watt Hour
Low-Met	Low Metallic
NAO	Non Asbestos Organic
NVH	Noise, Vibration, Harshness
Semi-Met	Semi Metallic
PHEV	Plugin Hybrid Electric Vehicle
PM10	Particulate Matter 10µm
Sb	Antimony
Sb2O3	Antimony Trioxide
Sb2S3	Antimony Trisulfide
SRBS	Serial Regenerative Braking System

References

Books:

Baumgartner Hans, Eduard Gerum, Wolfgang Pahle, Alf Siebke, Michael Pehle (2017): Nutzfahrzeugbremsen - Bremsenhandbuch Grundlagen Komponenten Systeme Fahrdynamik; Bert Breuer Karlheinz H. Bill Hrsg., 5th edition, Springer Verlag, pp. 246 – 248.

Beer Ferdinand; P Johnston; E Russel Jr (1996): Vector Mechanics for Engineers, 6th edition, McGraw-Hill, pp. 397 – 399.

Bharat Bhushan (2013): Introduczion to Tribology; second edition, John Wiley & Sons, Ltd., Publication; pp. 253

Bhandari V.B. (2010): Design of machine elements, Tata McGraw-Hill, p.472.

Bletz Marcus, Wickenhöfer Thorsten (2017): Elektrisches Bremsen - Bremsenhandbuch, ATZ/MTZ-Fachbuch, Springer Verlag, pp 811 – 823.

Dorinson A., K.C. Ludema (1985): Mechanics and Chemistry in Lubrication; Volume 9, Elsever, pp. 178 – 179.

Dowson D. (1979): History of Tribology, Longman, New York

Ehsani M, Gao Y, Emadi Y. (2010): Modern electric, hybrid electric, and fuel cell vehicles: Fundamentals, theory and design, 2nd edition, CRC Press. 2010.

Eskandarian Azim (2012): Handbook of Intelligent Vehicles; Volume 2, Springer, DOI 10.1007/978-0-85729-085-4, pp. 192-194.

Gerum E, Baumgartner H, Pahle W (2017): Nutzfahrzeugbremsen, Bremshandbuch -Grundlagen, Komponenten, Systeme, Fahrdynamik, pp. 245 – 248.

Hirani Harish (2016): Introduction in Fundamentals of Engineering Tribology with Applications, Cambridge: Cambridge University Press, pp. 1-51.

Hofmann, P.(2010): Hybridfahrzeuge, Springer-Verlag,.

Maurer Markus, Christian Gerdes, Barbara Lenz, Hermann Winner (2016): Autonomous Driving - Technical, Legal and Social Aspects; Springer, Berlin, Heidelberg; https://doi.org/10.1007/978-3-662-48847-8; pp. 3-6.

Meriam J. L.; Kraige L. G. (2002): Engineering Mechanics (fifth edition). John Wiley & Sons. p. 328.

Reif K. (2012): Kraftfahrzeug-Hybridantriebe: Grundlagen, Komponenten, Systeme, Anwendungen. Wiesbaden: Vieweg + Teubner, pp. 19-21.

Remfrey James; Steffen Gruber; Jan Sendler (2017): Aufbau und Komponenten von Pkw-Bremsanlagen, ATZ/MTZ-Fachbuch.

Rowe Brian W., (2014):Principles of Modern Grinding Technology (Second Edition)2014, pp. 349-379.

Ruina Andy and Rudra Pratap (2002): Introduction to STATICS and DYNAMICS, Oxford University Press, pp. 90-91.

Schmitz M, Hanig, M. Jagiellowicz, C. Maag, Impact of a combined accelerator–brake pedal solution on efficient driving, IET Intelligent Transport Systems, vol. 7, no. 2, pp. 203–209.

Takadoum Jamal (2007): Materials and Surface Engineering in Tribology, ITLE / Wiley, pp. 82 – 83.

Uhlig Herbert Henry, Winston R. Revie (2009): Corrosion and corrosion control: an introduction to corrosion science and engineering, 4th edition, Wiley-Interscience.

Wang Q.J., Chung YW (2013): Encyclopedia of Tribology. Springer, Boston, MA, pp.100 – 123, 269 - 270.

Wiatarek Christian (2017): Reibbeläge – ATZ/MTZ-Fachbuch, Bert Breuer Karlheinz H. Bill Hrsg., 5th edition, Springer Verlag; pp. 572-590.

Wright David A., Welbourn Pamela (2002): Environmental Toxicology, Cambridge Environmental Chemistry Series, Series Number 11, 1st Edition.

Master’s and PhD Theses:

Berjoza Dainis; Inara Jurgena (2017): Influence of batteries weight on electric automobile performance, Latvia University of Agriculture.

Hofer Andreas (2014): Rein elektrisches Bremsen von hybrid- und batterieelektrischen Fahrzeugen, Vienna University of Technology, Fakultät für Maschinenwesen und Betriebswissenschaften.

Rayad Kubaisi (2018): Adaptive Regenerative Braking in Electric Vehicles, Fakultät für Maschinenbau (MACH) Karlsruher Institut für Technologie.

Oleksowicz S. (2009): The modelling of friction process in automotive disc brakes. Cracow University of Technology, Cracow, PhD Thesis.

Santiago Juan Hernandez (2019): Friction and wear reduction of cutting parts via surface patterning; Technische Universität Wien, Fakultät für MAschinenwesen und Betriebswirtschaften, pp 9-10.

Journal Articles:

Al-Thani Hanadi, Muammer Koç, Christos Fountoukis, Rima J. Isaifan (2020): Evaluation of particulate matter emissions from non-passenger diesel vehicles in Qatar, Journal of the Air & Waste Management Association.

Amato F.; M.Pandolfi, T.Morenoa, M.Furger, J.Peya, A.Alastueya, N.Bukowiecki, A.S.H.Prevot, U.Baltensperger, X.Querola (2011): Sources and variability of inhalable road dust particles in three European cities; Atmospheric Environment; Volume 45, Issue 37.

Clarke P, Muneer T., Cullinane K.(2010): Cutting vehicle emissions with regenerative braking. Transp. Res. Part D 2010, 15, pp. 160–167.

Deng Chenghao, Deng Qingpeng, Liu Weiguo, Yu Chen,Hu Jianjun, Li Xiaofeng (2020): Analysis of Vibration and Noise for the Powertrain System of Electric Vehicles under Speed-Varying Operating Conditions, pp 1-2.

Duval-Destin M, Kropf T, Abadie V, Fausten M (2011): Auswirkungen eines Elektroantriebs auf das Bremssystem, ATZ - Automobil-technische Zeitschrift, vol. 113, 2011.

Kim, J.S, Kim, S.M., Jeong, J.H., Jeong, S.C.,Lee, J.W. (2016): Effect of regenerative braking energy on battery current balance in a parallel hybrid gasoline-electric vehicle under ftp-75 driving mode, Int. J. Automot. Technol. 2016, 17, pp. 865–872.

Kucharczyk W (2012): Ablative and abrasive wear of phenolic-formaldehyde glass laminates with powder fillers. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (1): pp. 12–18.

LeBozec Nathalie; Blandin, N.; Thierry, D. (2008): Accelerated corrosion tests in the automotive industry: A comparison of the performance towards cosmetic corrosion. Materials and Corrosion. Wiley. 59. pp. 889–894.

Levin Y; da Silveira F.L.; F.B. Rizzato (2006): Electromagnetic braking: A simple quantitative model, American Journal of Physics 74. pp. 815–817.

Liebermann E.K., Meder M., Schuh J., Nenninger G. (2004); Safety and Performance Enhancement: the Bosch Electronic Stability Control (ESP), SAE 2004-21-0060.

Öztürk B, Öztürk S, Adigüzel A (2013): Effect of Type and Relative Amount of Solid Lubricants and Abrasives on the Tribological Properties of Brake Friction Materials, Tribology Transactions, pp. 428-441.

Ploetz Patrick, Arpad Funke, Patrick Jochem (2018): Empirical Fuel Consumption and CO2 Emissions of Plug-In Hybrid Electric Vehicles; Journal of Industrial Ecology; Volume 22, Number 4, pp 773-774.

Qiao Q, Zhao F, Liu Z, Jiang S, Hao H (2017): Comparative Study on Life Cycle CO2 Emissions from the Production of Electric and Conventional Vehicles in China, Energy Procedia,Volume 105, 2017, pp 3584-3595.

RACV (2004): Effectiveness of ABS and Vehicle Stability Control Systems. Royal Automobile Club of Victoria. April 2004; pp.1-3.

Rajmohan, Arumugam, K. Palanikumar (2015): Brake Characteristics and Cooling Methods – A Review, Applied Mechanics and Materials, Volumes, pp. 813-814.

Selim Oleksowicz, Ruta Mariusz, Curry Eddy, Garces Hector (2013): Legal, Safety and Practical Regenerative Braking Control Challenges, Measurement and Control.

Shyam Sundar and Jaya Chakravarty (2010): Antimony Toxicity, International Journal Environmental Research and Public Health.

Tiedemann M, Kijanski, J.; Otto, J (2020): Vorhersage des Bremsbelagsverschleißes bei Elektrofahrzeugen, ATZ Automobiltech Z 122, 26–31. https://doi.org/10.1007/s35148-020-0254-1.

Thomas C.E. (2009): Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy. 34 (15), pp. 6005-6020.

Laws:

Standards (2017): United Nations Economic Commission For Europe Transport Standards, Uniform provisions concerning the approval of passenger cars with regard to braking, E/ECE/324/Rev.2.

ECE (2012): Rev.3: Uniform Provisions Concerning Replacement Brake Lining Assemblies and Drum Brake Linings for Power-Driven Vehicles and Their Trailers, United Nations Economic Commission for Europe Regulation 90.

SAE (2003): SAE J2522 Surface vehicle recommended practice, SAE International Committee.

Internet Sources:

AFDC (2021): Alternative Fuels Data Center - Electricity Sources and Emissions. https://afdc.energy.gov/vehicles/electric_emissions.html - last retrieved on February 15, 2021.

ASFBS (2020): Disk Brakes. http://automotivesafetybrakingsystem.blogspot.com/ - last retrieved on October 12, 2020.

Commercial Fleet (2019): Kers System for Trucks. https://www.commercialfleet.org/news/trucknews/2015/09/02/kers-system-developed-for-road-freight-trucks - last retrieved on September 4, 2020.

Continental (2021): New Wheel Concept. https://www.continental-automotive.com/en-gl/Passenger-Cars/Technology-Trends/Electrification/Optimized-Wheel/New-Wheel-Concept - last retrieved on January 12, 2020.

DBA (2020): Brake Discs- is lighter better. http://www.dbausa.com/brake-discs-is-lighter-better-3/ - Last retrieved on December 9, 2020

Deloitte (2020): Automotive planning solutions, IHS Markit. https://ihsmarkit.com/index.html; EV-volumes.com: The electric vehicle world sales database, https://www.ev-volumes.com/ - last retrieved on January 4, 2021.

Deloitte Analysis (2020): Electric vehicles Setting a course for 2030. https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/electric-vehicle-trends-2030.html#endnote-sup-17 - last retrieved on January 4, 2021.

DieselNET (2019): Worldwide Harmonized Light Vehicles Test Cycle (WLTC). https://dieselnet.com/standards/cycles/wltp.php#hev – last retrieved on January 20, 2021.

Electric Vehicle News (2016): Are Friction Brakes Redundant on Electric Vehicles & Hybrids?. http://www.electric-vehiclenews.com/2016/03/are-friction-brakes-redundant-on.html – last retrieved on January 28, 2021.

Ellsmoor (2019): Are Electric Vehicles Really Better For The Environment?, Forbes. https://www.forbes.com/sites/jamesellsmoor/2019/05/20/are-electric-vehicles-really-better-for-the-environment/?sh=42607d0876d2 - – last retrieved on January 10, 2021.

Hagman (2021): Brake Wear Enviro Impact - Trends to Combat Them (Part One), https://thebrakereport.com/brake-wear-enviro-impact-trends-to-combat-them/ - – last retrieved on January 20, 2021.

Irle Roland (2021): Global Plug-in Vehicle Sales Reached over 3,2 Million in 2020. https://www.ev-volumes.com/ – last retrieved on December 18, 2020.

ISO Standards (2020): ISO 6311:1980(en) Road vehicles - Brake linings -Internal shear strength of lining material -Test procedure. https://www.iso.org/obp/ui/#iso:std:iso:6311:ed-1:v1:en - last retrieved on January 11, 2021.

Mann and Hummel (2013): Patent US20140054121A1 - Brake Dust Collector for Motor Vehicles; https://patents.google.com/patent/US20140054121A1/en- last retrieved on February 10, 2021.

Mann (2021): Filter solution for the brake. https://www.mann-hummel.com/en/oe-products/stories-en/filter-solution-for-the-brake/ - last retrieved on January 17, 2021.

Markel (2019): Brake Corrosion Science: Why Rust On Brake Lines And Pads Is Not Normal. https://www.tomorrowstechnician.com/brake-corrosion-science-why-rust-on-brake-lines-and-pads-is-not-normal/ - last retrieved on October 13, 2020.

Muscoplat (2019): https://ricksfreeautorepairadvice.com/brake-pad-anatomy/#:~:text=The%20shim%20acts%20as%20an,backing%20plate%20to%20the%20caliper – last reviewed on January 29, 2021.

Nice Karim (2020): Anti-lock brake. https://auto.howstuffworks.com/auto-parts/brakes/brake-types/anti-lock-brake.htm#pt1 last retrieved on January 20, 2021.

Patel Vineeth Joel (2020): EVs Won't Become as Cheap as Regular Cars to Build Until 2024. https://www.futurecar.com/4221/EVs-Wont-Become-as-Cheap-as-Regular-Cars-to-Build-Until-2024 - last retrieved on February 21, 2021.

RFA Advice (2020): Brake Pad Anatomy. https://ricksfreeautorepairadvice.com/brake-pad-anatomy/ - last retrieved on October 12, 2020.

Schaeffler (2020): Full electric brake system. https://schaeffler-events.com/kolloquium/lecture/c1/index.html, last retrieved on January 11, 2021.

Structural (2020): Compressibility. http://structuralgeology.50webs.com/pagec36.htm - last retrieved on October 8, 2020.

Vijayenthiran (2008): Michelin's Active Wheel technology in detail. https://www.motorauthority.com/news/1030025_michelins-active-wheel-technology-in-detail - last retrieved on December 15, 2020.

Studies:

Augsburg Klaus, Hesse David (2019): Investigation of the Potential of Regenerative Brake Systems regarding Brake Particle Emission Reduction, Eurobrake conference 2019, Technische Universität Ilmenau, Germany.

Jansen Roy (2020): Automotive braking trends – the inside track, Lapinus.

Martini Giorgio (2014): Non-exhaust traffic related emissions. Brake and tyre wear PM; doi:10.2790/21481.

Moser Carmen (2014): Innovative Solutions for Copper replacements in Disc Brake Pads, Tribotecc GmbH, Eurobrake Conference 2015, Dresden Germany