POLITECNICO DI TORINO

Master of Science in
Mechanical Engineering

Master's Thesis

Investigation of frictionless brake systems analyzing their current and future use for automotive applications

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Abstract

This master's thesis in collaboration with ITT ITALIA SRL concerns with the analysis of innovative braking systems, in particular focusing on frictionless brake systems, in order to define the state of art of these technologies and understand their future trends. The key aspect of this thesis is identified in the combination of technical features, analyzing how braking technologies work, and business aspects whose aim is pointing out risk and chance for braking system companies. This allows to understand where resources will be allocated for research and development.

As first step an overview is given on braking principles and main actuating system. Then, conventional friction brakes such as drum and disk are debated, also discussing an innovative friction-based system which uses a magnetorheological fluid. This represents a possible solution to eliminate particulate matter emissions due to wear. Afterwards, frictionless systems are studied by distinguishing dissipative or regenerative devices. The latter are particularly useful to increase the overall efficiency of the vehicle. Regenerative braking is debated considering the main advantages and drawbacks. Then a comparison is introduced among technologies in terms of braking performance using a simplified dynamic model of a passenger car. Afterward, manufacturing context is considered to give an overview of brake systems market. The analysis is focused on expected evolution of this sector in next years, according to stricter regulations and considering the impact of Covid-19. More detailed examples of patents are analyzed to further understand the pathways that companies are following to achieve competitive advantage. Finally, the effects of pads/linings wear on environment and human health are studied. Coupling regenerative braking and friction brakes is a possible solution to contain these effects. However, also vehicles electrification has an ecological footprint which must be considered.

Sommario

Questa tesi magistrale in collaborazione con ITT ITALIA SRL riguarda l'analisi di sistemi di frenatura innovativi, in particolare concentrandosi sui sistemi senza attrito, allo scopo di definire lo stato dell'arte di queste tecnologie e comprenderne le tendenze future. L'aspetto chiave di questa tesi è individuato nell'unione di aspetti tecnici, analizzando come queste tecnologie operano, e aspetti di carattere aziendale, evidenziando rischi ed opportunità per le compagnie produttrici di sistemi frenanti. Ciò permette di comprendere dove saranno allocate le risorse per ricerca e sviluppo.

Come primo passo viene fornita una panoramica sui principi della frenatura e sui principali sistemi di attuazione. Successivamente vengono trattati i freni convenzionali ad attrito come tamburo e disco, discutendo inoltre di un sistema innovativo ad attrito che sfrutta un fluido magnetoreologico. Ciò rappresenta una possibile soluzione per eliminare l'emissione di particolato dovuta all'usura. In seguito, i sistemi privi di attrito vengono studiati differenziando i dispositivi a dissipazione e a rigenerazione. Questi ultimi sono particolarmente utili per aumentare l'efficienza complessiva del veicolo. La frenata rigenerativa viene trattata considerando i principali vantaggi e svantaggi. Successivamente, viene proposto un confronto tra le tecnologie in termini di prestazioni frenanti utilizzando un modello semplificato di un veicolo passeggeri. Viene inoltre considerato il contesto produttivo per dare una panoramica sul mercato dei sistemi frenanti. L'analisi si concentra sulla prevista evoluzione di questo settore nei prossimi anni, in accordo con normative più stringenti e considerando l'impatto del Covid-19. Esempi più dettagliati di brevetti sono analizzati al fine di comprendere ulteriormente i percorsi intrapresi dalle aziende per ottenere un vantaggio competitivo. Infine, vengono studiati gli effetti dell'usura di pastiglie/ganasce sull'ambiente e sulla salute umana. Accoppiare frenata rigenerativa e freni ad attrito è una possibile soluzione per contenere questi effetti. Tuttavia, anche l'elettrificazione dei veicoli presenta un'impronta ecologica che deve essere considerata.

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Glossary

BBW: Brake By Wire

ECU: Electronic Control Unit

ABS: Antilock Braking System

EBD: Electronic Brake-force Distribution

ESC: Electronic Stability Control

MRF: Magneto Rheological Fluid

DC: Direct Current

AC: Alternating Current

HEV: Hybrid Electric Vehicle

BEV: Battery Electric Vehicle

FCEV: Fuel Cell Electric Vehicle

ICEV: Internal Combustion Engine Vehicle

ECB: Eddy Current Brake

KERS: Kinetic Energy Recovery System

SOC: State Of Charge

NCA: Nickel Cobalt Aluminum

EDLC: Electrochemical Double-Layer Capacitor

CVT: Continuous Variable Transmission

4WD: Four Wheel Drive

CAGR: Compound Annual Growth Rate

EMB: Electro-Mechanical Brake

PM: Particulate Matter

ELT: End of Life Tire

WHO: World Health Organization

COP: Conference Of Parties

GHG: Greenhouse Gas

IEA: International Energy Agency

WTW: Well To Wheel

LCA: Life Cycle Assessment

Introduction

Nowadays, transport sector is going through deep changes thanks to people's environmental awareness. The increasing human need of mobility due to population growth and wealth must deal with global warming, air pollution and resources consumption. Transport policies are getting stricter and represent a big challenge for companies. Manufacturers must develop sustainable products for mobility, integrated in a circular economy.

If you think about vehicles environmental footprint, you may notice this does not affect only powertrain architecture but many vehicle components, including brakes. Even if the commonest devices used nowadays for vehicular application are based on friction, frictionless brakes have been developed since electrification establishment and larger diffusion is expected for future. Indeed, conventional braking systems works dissipating kinetics to heat using friction elements, wasting high amount of energy, and causing abrasive material wear. These two factors lead to high fuel consumption, so CO_2 production, and particulate matter emission affecting the environment and human health. Frictionless braking, especially regenerative braking, is a key solution to limit these issues.

1 Braking Fundamental Principles

1.1 Braking System Introduction

The born of self-propelled vehicles is a fundamental milestone in human history. Joseph Nicolas Cugnot [1] invented the first steam-powered vehicle in 1700s to drag French cannons. However, this invention had a big issue: his inventor forgot to create a braking system. So, during one of his first trials the heavy car knocked down a wall. This event looks funny nowadays because every vehicle has a braking system, but helps you understand its relevance. Every propulsion system must be coupled with an appropriate braking system designed considering vehicle's top speed and mass. Vehicle without brakes would be useless and dangerous.

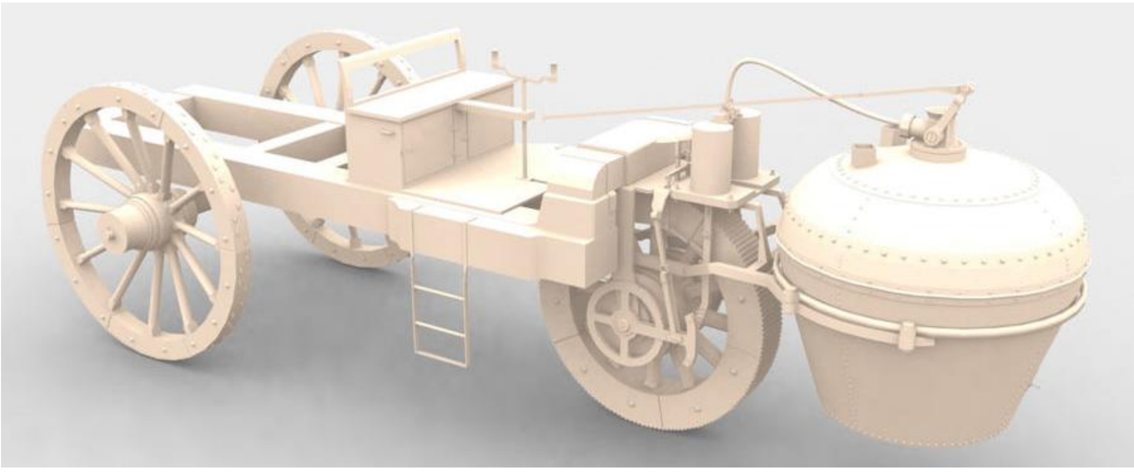

Figure 1.1: 3D render of Cugnot's vehicle

A braking system must be safe, reliable, quiet, light, and cheap. Safety and reliability are the most important characteristics because drivers, passengers and pedestrians' lives depend directly on correct brakes work. Brakes must prevent hazard and be able to respond quickly. Quietness affects driving comfort, and it has more appeal for costumers so cannot be neglected. Lightness is fundamental in automotive application because weight conditions vehicle performance, fuel consumption and braking performance too. Finally yet importantly, braking system must be cheap to reduce vehicle's overall cost for producer.

As the engine convert the chemical energy of the fuel to thermal then to kinetic, or the electric motor convert the electric energy to kinetic, to accelerate vehicle, the basic idea of brake is to convert vehicle kinetic energy to other forms, reducing its speed. The kinetic energy can be converted in thermal, electrical, chemical, or kinetic depending on adopted system. The optimum system provides energy recovery and store, so it can be used later for traction. Unfortunately, this is not always possible or convenient as could seem so needs a specific analysis.

1.2 Kinetic Energy Conversion

Kinetic energy can be converted to thermal due to surface friction, fluid friction, electric resistance, and eddy current. This conversion does not allow energy recovery because heat is all dissipated in air.

1.2.1 Heat Dissipation

Every object's surface presents a roughness due to microscopic edges and valleys. Applying a shear stress to the object to obtain a relative motion, edges move against each other causing obstacle for shift. The movement resistance produced by two objects in contact is named surface friction [2]. Surface friction μ is defined as the ratio between lateral force F_x and normal force F_z applied to an object:

$$\mu = \frac{F_x}{F_z} \ [-] \tag{1.1}$$

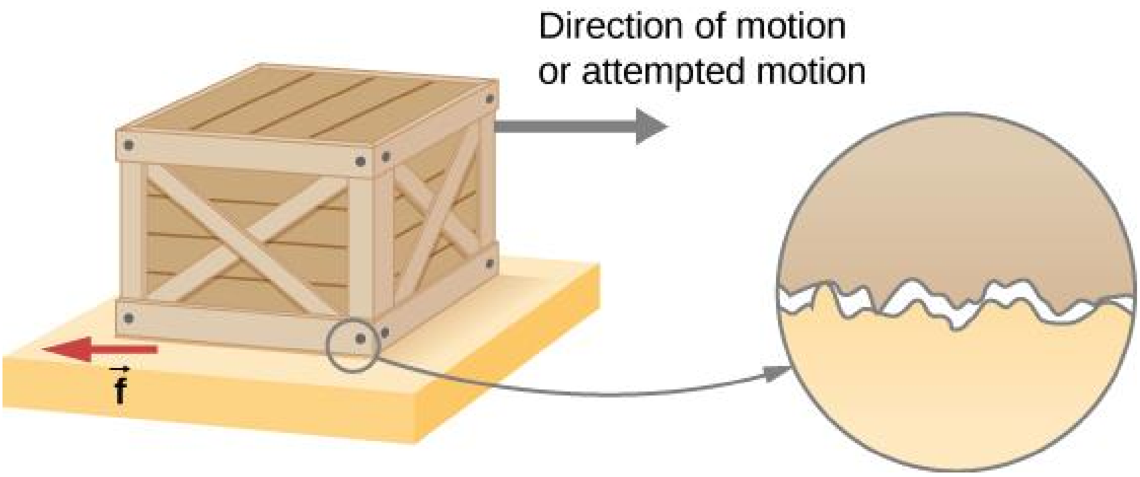

Figure 1.2: Surface friction

Surface friction is proportional to normal force but is independent of the nominal contact area. Indeed, the nominal contact area is not equal to effective one. Actual contact area is very small compared to nominal and its value increases almost linearly raising normal force. Friction causes heat dissipation, so using a friction element made of hard material and pushing it against a moving object causes a speed reduction, depending on force intensity, and convert kinetic energy to heat.

Similarly as surface friction, also fluids restrict object's movement on surface or within them because of molecular friction. The fluid resistance to shear stress is known as dynamic viscosity [3]. This property can be represented as the resistance to flow between horizontal planes. For a wide range of fluids, called Newtonian, viscosity is a constant value and does not depend on strain rate. If viscosity is not constant, fluid is generally indicated as non-Newtonian. Clearly, air is a fluid and has got a very low dynamic viscosity. At room temperature it is equal to $1.983 \cdot 10^{-5}$ Pa·s [3] but generate a lot of aerodynamic drag on a moving object, especially increasing relative speed. This property is used e.g., in landing aircrafts for aerodynamic braking. Consequently, high viscosity fluid could be used to slow down a vehicle.

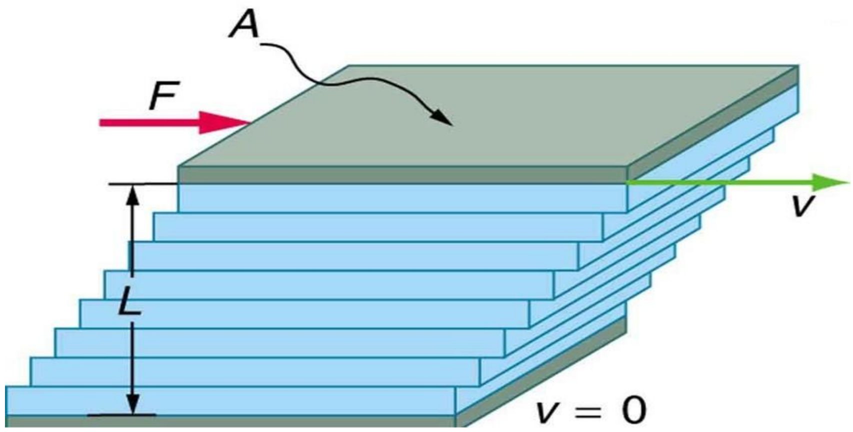

Figure 1.3: Horizontal planes sliding due to viscosity

Electric current flows in circuits made of conductors but they present an opposition to electrons' motion called electrical resistance. Resistance causes power losses due to heat dissipation; this phenomenon is known as Joule effect [4] and it depends on current intensity. The incandescence lamps use Joule effect to heat a filament and produce light. Resistor is an electric element characterized by a specific value of resistance and it is used for many electric or electronic applications. It works as a regulator element or as a heat source for example in appliances. A variable resistor, or rheostat, can change electrical resistance without interruption.

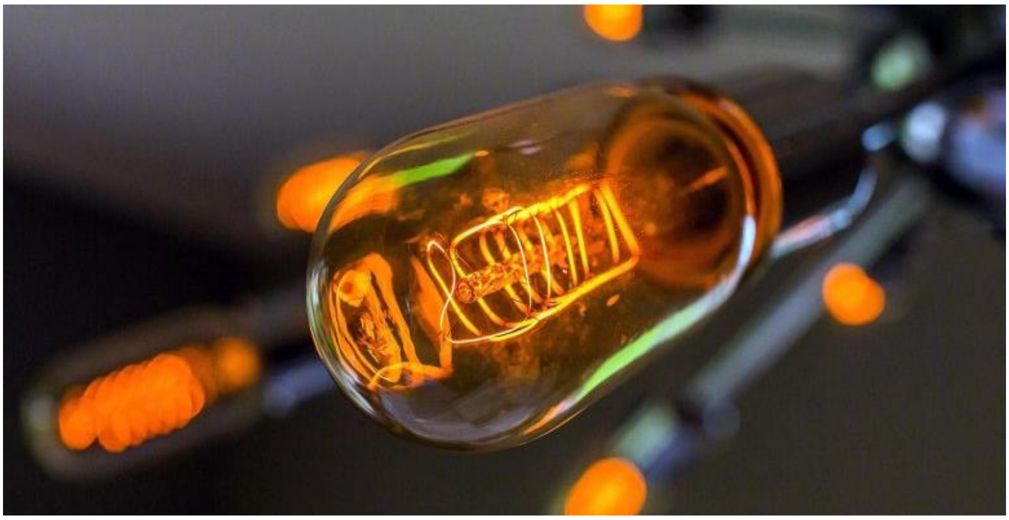

Figure 1.4: Joule effect on incandescence lamp

Faraday-Neumann-Lenz law [4] describes the electromagnetic induction, setting a fundamental link between electric and magnetic fields. A variation in time t of magnetic flux $\Phi_S(\vec{B})$ through a surface S induces an electromotive force emf_i on electric circuit:

$$emf_i = -\frac{\Delta\Phi_S(\vec{B})}{\Delta t} \; [V] \tag{1.2}$$

The produced electric current also generates a magnetic field that opposes to former. The variation of magnetic flux can be obtained also using a constant magnetic field produced by a simple magnet moving relatively to a conductor. Eddy

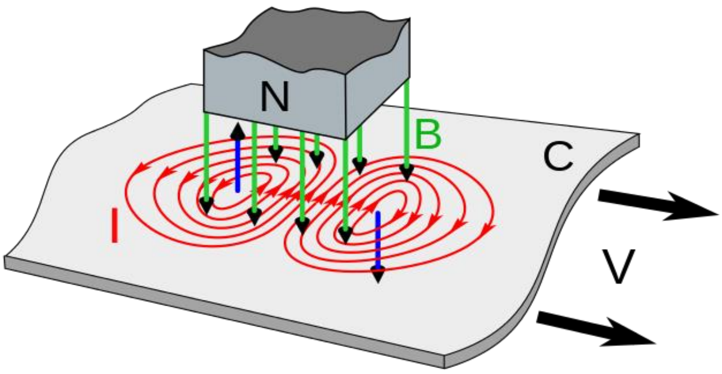

Figure 1.5: Eddy currents

currents [4], or Foucault's currents, generate within the conductor dissipating energy due to Joule effect. The induced magnetic field produces a magnetic force that opposes to relative motion. Induced magnetic field behave as a brake.

1.2.2 Electric Charge

Kinetic energy can be converted to electrical energy (using an electric generator) and stored as electric charge thanks to conductors' capacitance. Electric capacitance C [4] is the ability of a conductor to store electric charge within itself. It is mathematically defined as the ratio between electric charge Q and voltage drop V:

$$C = \frac{Q}{V} \ [F] \tag{1.3}$$

Capacitor is an electric element characterized by a specific value of capacitance. It charges when tension is applied to its clips and discharges when tension drops. Capacitance depends on capacitor's geometry but does not depend on its material.

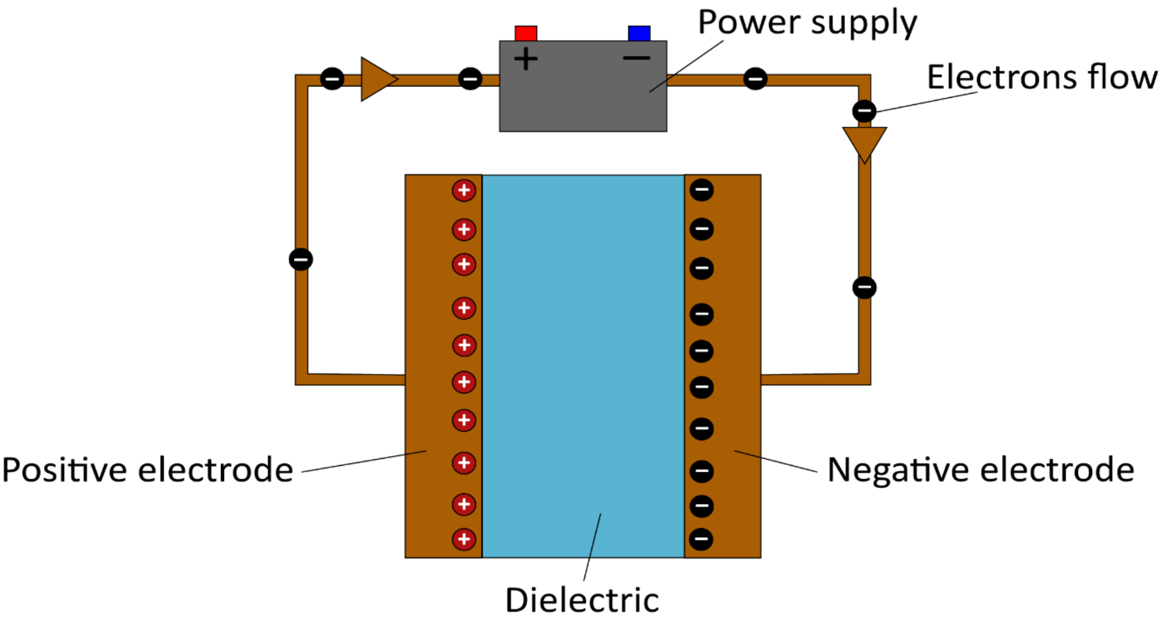

Figure 1.6: Capacitor diagram

1.2.3 Chemical Energy

Kinetic energy can be converted to chemical due to chemical bond variation. The energy of atoms and molecules is in chemical and atomic bonds. For example, during chemical reaction as combustion or nuclear reaction as fission, energy is released, vice versa electrolysis need energy to brake molecular bonds. Thanks to these reactions, energy can be initially absorbed and later released, so chemical bonds act as energy storage. This principle is used in chemical batteries.

Figure 1.7: Fossil fuel energy converted to heat

1.2.4 Kinetic Energy

Kinetic energy can also transfer from an object to another through contact. The motion transmission allows energy to flow without changing its form. The big advantage of this process is the high efficiency. The object's inertia allows using it as a storage, so it stores energy when is provided and releases it when is demanded. For example, this principle is used in car's engine to smooth the torque output. The element is known as flywheel.

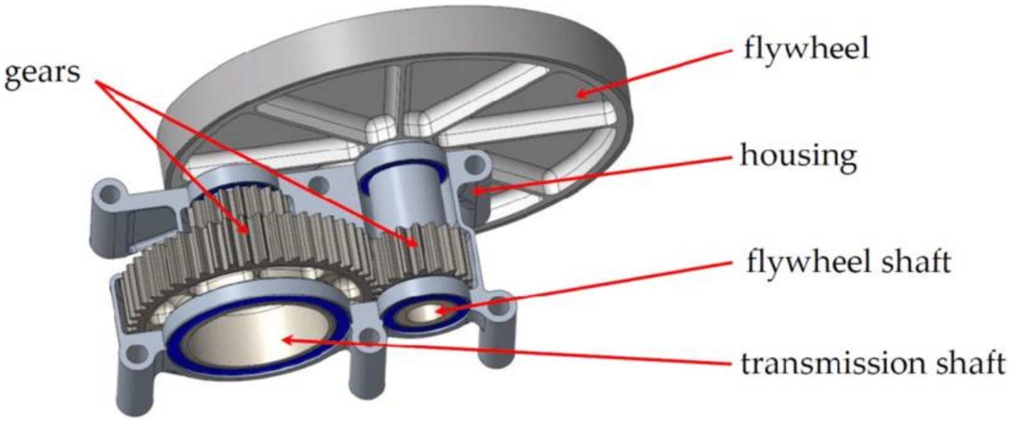

Figure 1.8: Flywheel

1.3 Brake Actuating Systems

The engine needs a transmission system to deliver power and move the vehicle. Similarly, braking force must be transmitted from the driver or from the actuators to the wheels, so vehicle can reduce its speed. In almost every vehicle, brake command is given by the driver, who pushes his foot against a brake pedal. Braking force depends on pedal travel. This pedal is a lever designed to reduce the effort needed to slow down the vehicle. Longer lever increases output force but leads to longer pedal travel, so its length must be a trade-off. The brake pedal is linked to braking devices through a circuit that is different depending on adopted technology.

The most common technology for passenger cars is hydraulic actuation that realizes a hydraulic link between pedal and brakes. It uses brake fluid to push friction element against rubbing surface such as drum or disk. Similarly as hydraulic, compressed air actuation, used on heavy duty vehicles, realizes a pneumatic link. Another system that has been catching on since last years is Brake By Wire (BBW) that realizes electro-mechanic or electro-hydraulic link. In this case, brake pedal and wheels are not directly connected.

1.3.1 Hydraulic System

Liquids are incompressible, so when a liquid is placed inside a closed container and a force is applied on its surface, the fluid pressure is equal on all container's walls. This principle is known as Pascal's law [5]. It is used on hydraulic systems to transmit pedal travel to brakes and amplify driver force. Force F is proportional to fluid pressure p and area A:

$$F = pA \tag{1.4}$$

When the liquid is placed in a pipe, the pressure at initial section A_1 and final section A_2 is equal:

$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2} \tag{1.5}$$

$$F_2 = \frac{A_2}{A_1} F_1 \tag{1.6}$$

Consequently, increasing final section area or reducing initial allows to increase force:

$$A_2 \gg A_1 \rightarrow F_2 \gg F_1 \tag{1.7}$$

The hydralic system [6] uses the brake pedal to move a pushrod connected to a piston inside a bore named master cylinder, in which driver's force is converted into hydraulic pressure. Master cylinder is linked to brake's piston through small diameter pipe in which oil can flow. On the top of master cylinder an oil reservoir is used to avoid air gap in lines when pressurized. Brake's piston moves the friction element to generate braking. From Pascal's Law, since pressure is equal on both, using a bigger diameter on brake's piston compared to master cylinder allows to increase braking force. To further reduce driver effort, vacuum booster is used.

A simplified representation of this system for a vehicle that uses both disk and drum brakes is reported in Figure 1.9.

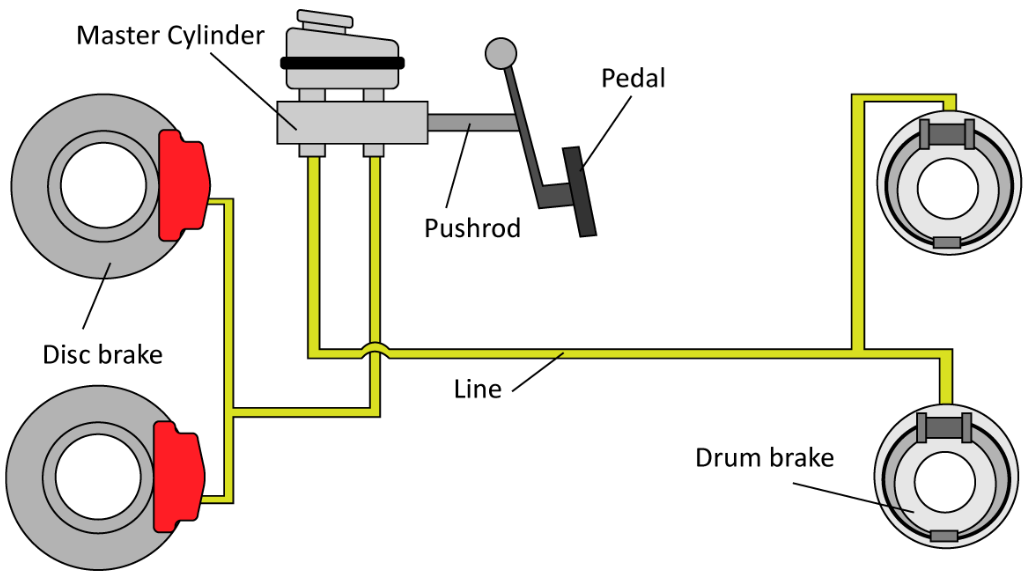

Figure 1.9: Hydraulic actuation system

1.3.2 Pneumatic System

Pneumatic, or air, actuator [7] uses compressed air instead of oil to transmit braking force. Air is compressible so, to carry out its function, a compressor is needed. The compressor is supplied by the engine and pressurizes continuously a reservoir that behave as a buffer. Compressor is controlled to avoid overpressure. Tank must contain enough air to stop the vehicle even if engine is switched off or compressor fails. It is linked to brake chamber that converters pressure energy into mechanical to engage the brake. The brake pedal controls pneumatic valves' opening on air line, so tank can release high pressure air to apply force.

This system is used on heavy duty vehicles mostly coupled with drum brakes thanks to high braking power.

A simplified representation of this system for a vehicle that uses drum brakes is reported in Figure 1.10.

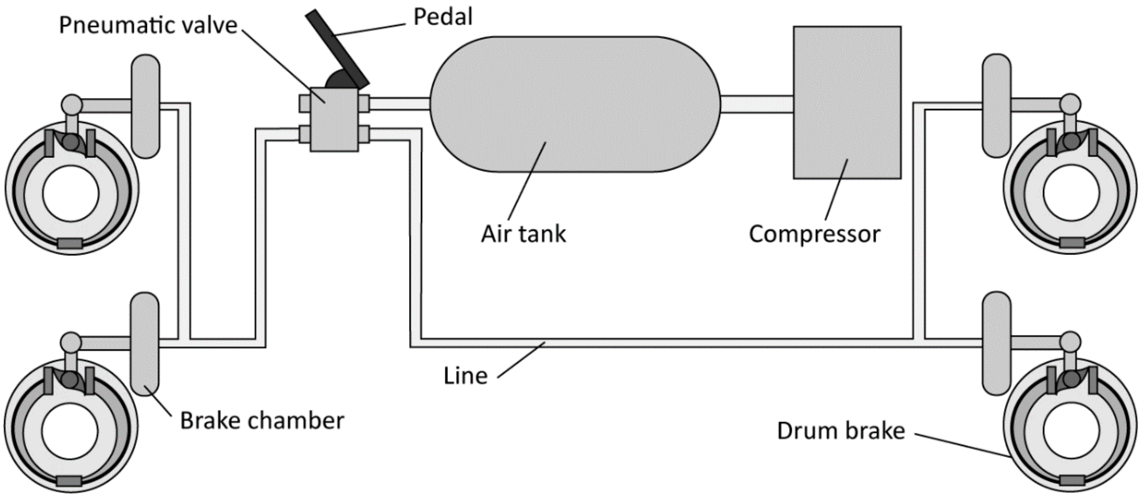

Figure 1.10: Pneumatic actuation system

1.3.3 Brake By Wire

Brake By Wire [8] [9] is a general term referring to a system in which a part of mechanical or hydraulic components are substituted by electronic devices. Consequently, brake pedal does not directly command the brake activation but is used as receiver to collect information about driver's braking demand. Pedal feel and resistance are simulated. The driver input is detected by position sensors to set the needed amount of braking force that must be applied to the wheels. The Electronic Control Unit (ECU) analyzes sensors' signal, produces electronic commands, and relays them on the wheels to the actuators which generate braking force. The actuators can be electro-mechanic or electro-hydraulic.

Brembo Brake By Wire system [10] is presented in Figure 1.11. On front axle electro-hydraulic actuators are used, while on rear axle they are electro-mechanic.

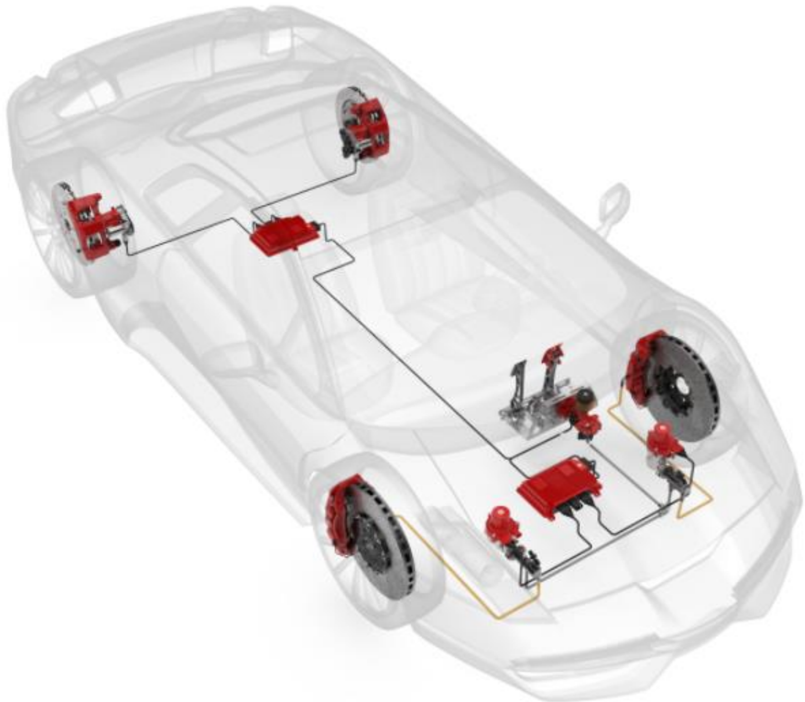

Figure 1.11: Brembo Brake By Wire

This system allows to regulate braking force independently from the driver and for each wheel. It also reduces drastically the delay between when the pedal is pressed, and brake is activated. The delay in hydraulic system is higher because pressure inside a long pipe needs time to equalize. Furthermore, BBW improves stability and safety. Failure odds is low compared to traditional hydraulic system. The electric linkage also allows to reduce weight by eliminating unnecessary components such as vacuum booster.

Several features can be implemented, such as: Antilock Braking System (ABS), Electronic Brake-force Distribution (EBD), Electronic Stability Control (ESC), Autonomous Emergency Braking, etc. In addition, BBW is useful for regenerative braking (see Paragraph 3.1) or if braking device other than disk or drum are used. All this function can be implemented on the vehicle without using any other components, resulting in lower weight and cost. BBW is also the optimum choice for electric vehicles because they cannot use vacuum booster to provide auxiliary braking force.

2 Heat Dissipation Technologies

2.1 Friction Brakes

Friction brakes dissipate kinetic energy to heat pushing friction element against metal surface. This allows to apply high forces to the wheels and decelerate the vehicle quickly. However, friction causes material wear, so service life is reduced. In addition, wear causes particulate matter emissions that increase local air pollution.

The commonest technologies are drum and disk brakes. In other application, band or rim brakes are used. A different friction-based technology adopts magneto-rheological fluid. This brake uses variable fluid viscosity to generate motion resistance avoiding wear debris.

2.1.1 Drum Brake

The main component is the drum [6] that is a cylinder connected to the wheel. Its internal surface rubs on friction material, so must be hard and wear resistant. Indeed, it is usually made of cast-iron. External surface can be finned to promote heat exchange. Inside the drum, abrasive material named lining is settled on brake shoes that are steel rods with T-section. The brake shoe lining material varies but

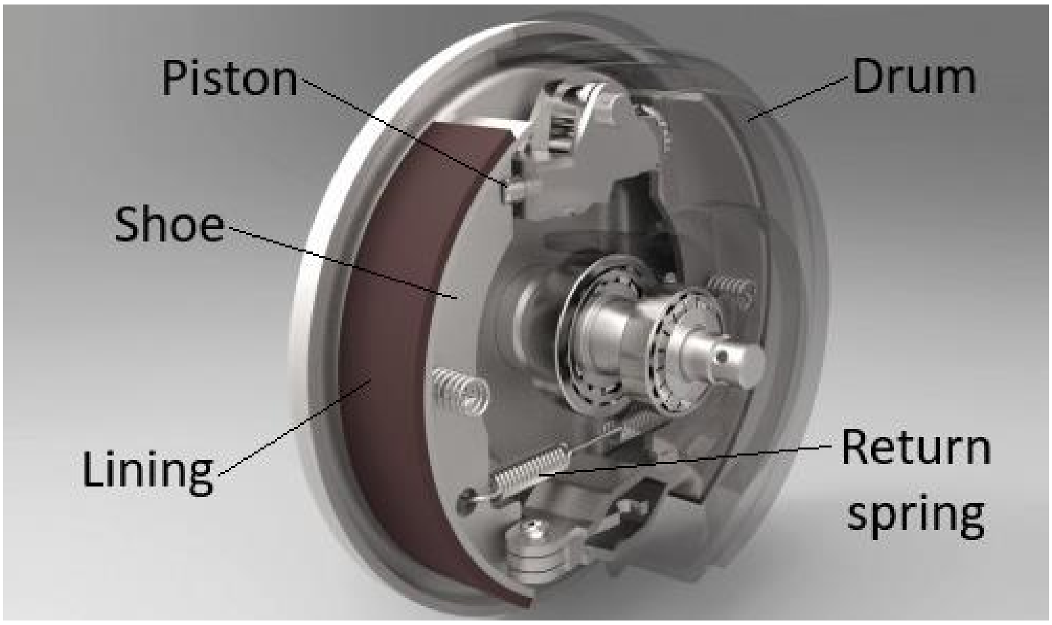

Figure 2.1: Drum brake components

often contains abrasives, such as aluminum, iron and silica, friction modifiers including graphite and ceramic compounds, fillers, and binders. In past, lining contained asbestos to improve wear, but banned due to cancer risks. Drum surface is limited but the contact area with shoes is large. Pistons move brake shoes against drum to generate friction. Return springs allow shoes retraction. To compensate shoe travel distance growth due to lining wear, self-adjuster is used.

Thanks to their geometry, drum brakes generate servo action, so less force on pedal is needed. Leading-trailing shoe refers to two possible behaviors for shoe. This depends on rotation direction compared to shoes pivot. If drum moves from the free end toward pivot end, it is a leading shoe. If drum moves from the pivot end toward free end, it is a trailing shoe. During rotation, friction force pushes leading shoe against drum, creating servo action, but pushes trailing shoe away from drum, reducing braking force. These two effects tend to cancel each other out but a little servo-action is observed. In addition, leading-trailing shoes generate the same braking force in either rotation direction.

Duo-servo shoes are connected by a floating link that transmits force between them. An anchor pin keeps the shoes from rotating with the brake drum. The primary shoe pushes on the secondary shoe through the link and secondary pushes on anchor pin. The force transmitted to secondary shoe generates a servo-action higher than leading-trailing. Changing rotation direction causes primary and secondary role swaps, so servo-action works in either direction.

Figure 2.2: Leading/trailing shoes on left, duo-servo on right

The biggest issue related to drum brake is its structure. Drum does not allow optimal heat exchange for rubbing surfaces and blocks lining sediment inside. Indeed, drum brake is low resistant to fade. Fade occurs when friction material achieves high temperature and releases gases or particles that form a layer on metal surface. This prevents contact between drum and lining, causing friction loss. Thus, drum cannot afford high braking performance compared to disk brake.

Drum brakes were widely used in past years for most vehicles but, after disk brakes diffusion, they have been used mainly for rear wheels. Drum brakes survived on rear axle because of weight transfer. Weight transfer is a dynamic effect due to inertia force that subtracts weight from an axle and adds to the other. During braking, the front axle is loaded more than static condition and rear is loaded less, so additional braking force can be supplied to front avoiding wheels skid. Vice versa, lower braking force can be applied to rear to avoid locking. Typically, rear brakes generate one-thirds of total braking force, so drum brakes can be used.

2.1.2 Disk Brake

Disk brakes [6] by the early 1970s had replaced drum brakes on front wheels thanks to their better performance especially in terms of heat dissipation. The main component is the rotating disk, or rotor, that is a metal plate merged with the wheel.

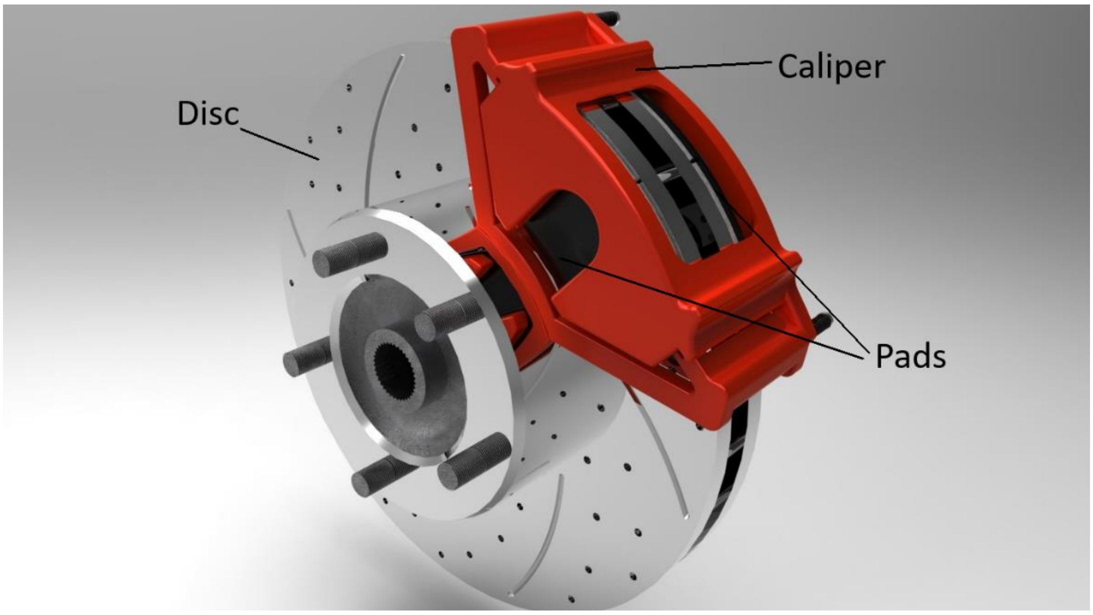

Figure 2.3: Ventilated-drilled brake disk components

Its surface rubs on friction material, so must be hard and wear resistant. As drum, it is usually made of cast-iron. Some high-performance cars use carbon-ceramic rotors and Formula 1 racecars use carbon-carbon disks. The simplest disk is solid but, to increase heat exchange, many geometries are used, such as ventilated or drilled disk. Holes or slots also help to reduce hot gases and dust particles buildup between rotor and brake pad. Brake pad is a backing plate where friction material is fixed, which is a blend of abrasives, binder, lubricant, fillers, metals, and fibers. Pads must be replaced regularly depending on their composition and vehicle usage. Brake pads and hydraulic pistons, that move pads against rotor, are housed on caliper. Caliper is classified as fixed or floating. In fixed caliper, pistons move pads against both side of disk to generate friction. In floating, only one piston on one side is used and it moves caliper away from the disk causing pad contact.

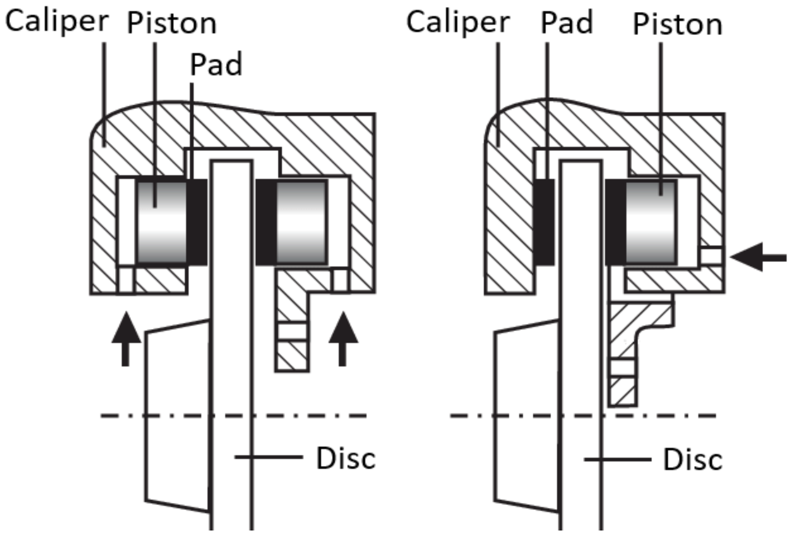

Figure 2.4: Fixed caliper on left, floating caliper on right

Disk brake biggest advantage is the higher resistance to fade. Rubbing surfaces on disk are directly exposed to air so they cool down faster than drum, avoiding fade. Water fade is also avoided thanks to disk rotation. Consequently, disk brakes bear higher stress without losing braking efficiency compared to drums. They are used on almost all front axles of passenger vehicles or both axles for high-performance vehicles that need more braking force. Furthermore, disk brakes are used in many other applications, such as heavy-duty vehicles, motorcycles, bicycle, rail and aircrafts. In addition, drum brakes overheating cause deflection, reducing braking performance, while disk deformation due to heating does not affect its behavior. Finally, pads maintenance and substitution are easier than in drums.

The principal drawback of this technology is its cost, which is higher than drum brakes. This is the other reason for using drum brakes on rear wheels. In addition, disk brakes do not have servo action, so they require vacuum or hydraulic power assist especially on heavy car. Finally, they are nosier.

2.1.3 Band Brake

Band brake [11] is similar to drum brake because drum surface is again used for rubbing of friction material. However, in this case contact occurs between drum's external surface and concentric metallic band lined with abrasive material. Lever movement puts band in tension to touch drum and generates braking force. Thanks to high contact surface and lever, band brakes require low input force to generate braking.

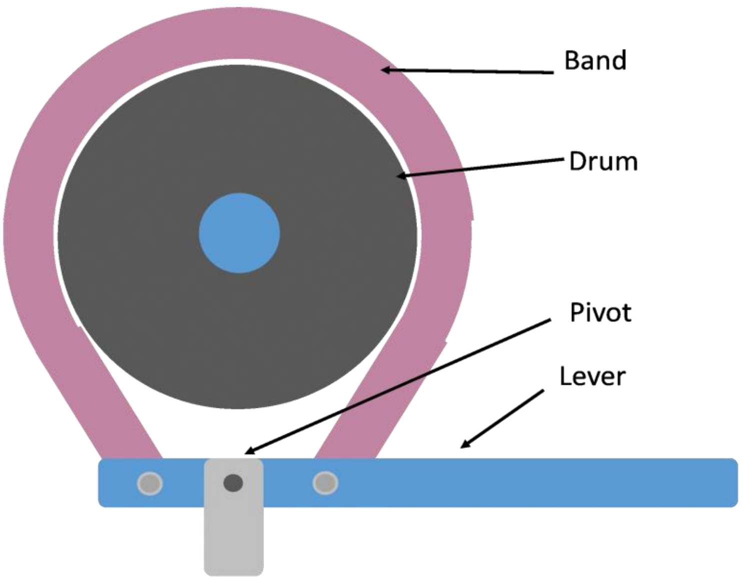

Figure 2.5: Band brake components

Band brakes are simple, cheap, and compact compared to other technologies. However, lining temperature cannot rise above 150°C. In past, they were used as external brake for vehicle, but the increasing braking need compelled producers to switch to internal drum brake. They are now used in automatic transmission to lock ring gear, as backstop, for bucket conveyors and hoist.

2.1.4 Rim Brake

Rim brake [12], as name suggests, uses as contact surface the metallic rim of a rotating wheel. Rubber pads mounted on metal shoes are mostly used as a friction element but sometimes leather or cork could be adopted. Rim is usually made of aluminum. Pads are pushed against wheel using two levers moved by a wire. This wire is linked to the brake lever which is pulled with hand to reduce the speed of the wheel.

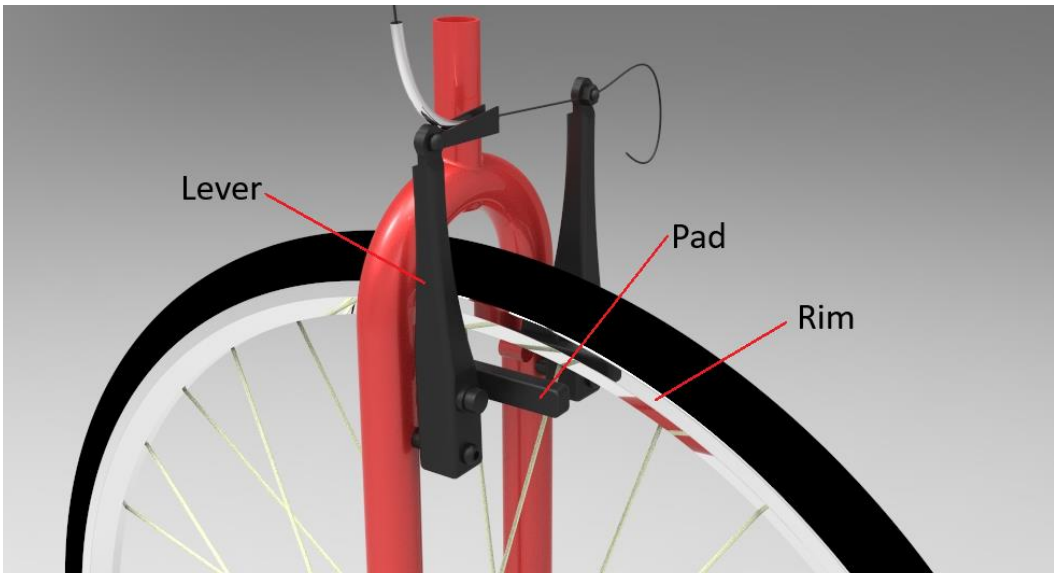

Figure 2.6: Rim brake components

Rim brakes are cheap, light, and simple for assembly, maintenance, and adjustment. Anyway, braking force is lower than disk and drum brakes. Metallic surfaces are more exposed to dust, dirt, and water, especially in off-road. Pads wear is not homogenous because approach to rim is not perfectly horizontal so requires adjustment regularly. In addition, rim brakes do not dissipate heat efficiently, so their temperature increases quickly, and braking force reduces. Consequently, maximum force is low and can be applied for a short time.

These characteristics do not allow vehicle application, but rim brakes are widely diffused for common bicycles where the disadvantages are alleviated by the unchallenging conditions. The low cost allows to reduce overall price for the bike resulting attractive for customers. They are also used on certain racing bicycles because of their lightness.

2.1.5 Magneto Rheological Fluid Brake

As discussed at Paragraph 1.2.1, viscosity is a property of fluids. Its value can change because of chemical composition, temperature or even shear stress (non-Newtonian). These parameters are unmovable or uncontrollable. However, there is a category of fluids known as Magneto Rheological Fluids (MRFs) [13] that modifies its rheological properties when magnetic field is applied. Rheological properties, such as viscosity, measure fluids deformation behavior. MRF's viscosity is controllable varying magnetic field, so motion resistance can easily change to demanded value and restore to original when magnetic field is switched off. MRFs are composed by a basic fluid (oil), metallic particles (iron) and stabilizing additives. Magnetic field application causes metallic particles to align and form a chain that reduce mobility, so its state changes from liquid to semi-solid and viscosity is increased.

The main advantages of these fluids are the fast response to magnetic field (some milliseconds), high controllability of force and no measurable thickening after more than 10 million cycles.

The MR principle allows many applications, such as dampers, clutches, and brakes. The MRF brake [14] [15] concept is similar to a conventional disk brake but uses all the available surface on the rotor as a rubbing surface and a thick fluid instead of pads. A disk made of steel is merged with the rotating shaft and enclosed on a metallic container. The gap between disk and case is filled with fluid. More disks can be used to further increase contact surface with fluid. When braking force is needed, magnetic field is generated, and fluid's viscosity is increased causing friction. The magnetic field is produced by coils supplied by a DC (Direct Current) source such as a battery. The braking pedal movement, thanks to Brake By Wire, results in regulation signal for DC-DC converter, which regulates current value on coils. Thus, fluid resistance can rapidly and precisely be changed varying supply current. When electromagnets are activated, fluid increases viscosity generating friction on disk's surface then reducing vehicle speed.

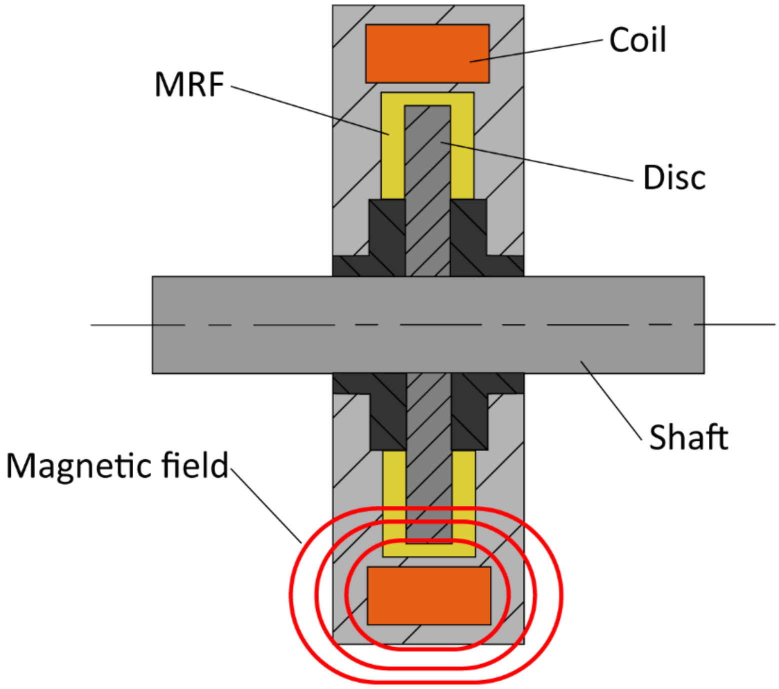

Figure 2.7: Magneto Rheological Fluid Brake components

Edward J. Park et al. [14] developed a finite element model for a MRF brake. They proposed a design optimization and calculated braking force. As result of simulations, they chose a double-disk configuration. The inner radius is 118 mm and outer radius is 168 mm. The overall brake mass is about 29.7 kg. The best performance fluid analyzed by the team was MRF-123AD which shows a maximum yield stress of 44.5 kPa. Its thermal behavior was simulated repeating cycles of pressing and releasing of the brake pedal. They observed a convergence to 100°C after 12 cycles compared to limited operating temperature between -40°C and 130°C. The maximum obtained braking torque is 1013 Nm, revealing good braking performance.

This brake allows to reduce disk consumption and removes lining or pad wear. Braking torque is more controllable and response is faster thanks to BBW. However, the principal drawback of this system is its weight, which is about twice of a conventional braking element, besides if it is used for all wheels. In particular, MRF brakes increase unsprung mass. This issue is partially alleviated considering the reduction of components and weight allowed by Brake By Wire.

2.2 Frictionless Brakes

Kinetic energy can be dissipated to heat also using contactless, so frictionless, technologies. Friction-based technologies cause surface wear, not only for abrasive elements such as pad or lining, but also for disk and drum or any rubbing surface. Consequently, elements consumption reduces their service life requiring periodical maintenance. Particulate matter is generated increasing air pollution. In addition, friction causes vibrations and noise, jeopardizing comfort.

Frictionless technologies based on heat dissipation cancel out these problems. These brakes work converting kinetic energy to electric, then to heat through Joule effect. Unfortunately, energy is still dissipated but principal issues of friction-based technology are removed.

Electric current is obtained using AC (Alternating Current) or DC (Direct Current) machine working as generator. Thanks to AC machine lower purchase and maintenance costs, higher power and accurate voltage control compared to DC machine, it is preferred for most application, especially for traction purpose. The AC generation principle is based on electromagnetic induction. Generating mode for electric machines is discussed at Paragraph 3.1.1.

Kinetic-electric conversion can be obtained using electromagnetic induction without a generator but through eddy currents. These currents flow on a conductor and dissipate energy in form of heat.

2.2.1 Brake Resistor

Electrical energy supplied by generator can be dissipated to heat using brake resistor [16]. When the electric machine operates as a generator it is then connected to a resistor bank. Electric current flow through resistors that act as a load reducing generator speed. This process is also known as rheostatic braking.

Cooling is a fundamental aspect because it limits the maximum energy that can be dissipated. Resistor achieves high temperature which must be limited to avoid failure. So, resistor is usually coupled with cooling system to optimize heat exchange. Resistor unit can be installed outside the vehicle for air cooling, i.e., in railway applications, or can use fans. The most suitable configuration for automotive is probably internal with oil cooling.

A common configuration of resistors bank is wire-wound resistor. This unit includes many resistor strips made of a non-conductive core (usually ceramic material) wrapped by resistive wire and arranged in series. The high resistance of the wire realizes the load for electric machine. These elements are placed in aluminum case filled with oil. As the brake resistor generates heat, oil takes it away, thanks to oil pump, flowing through radiator.

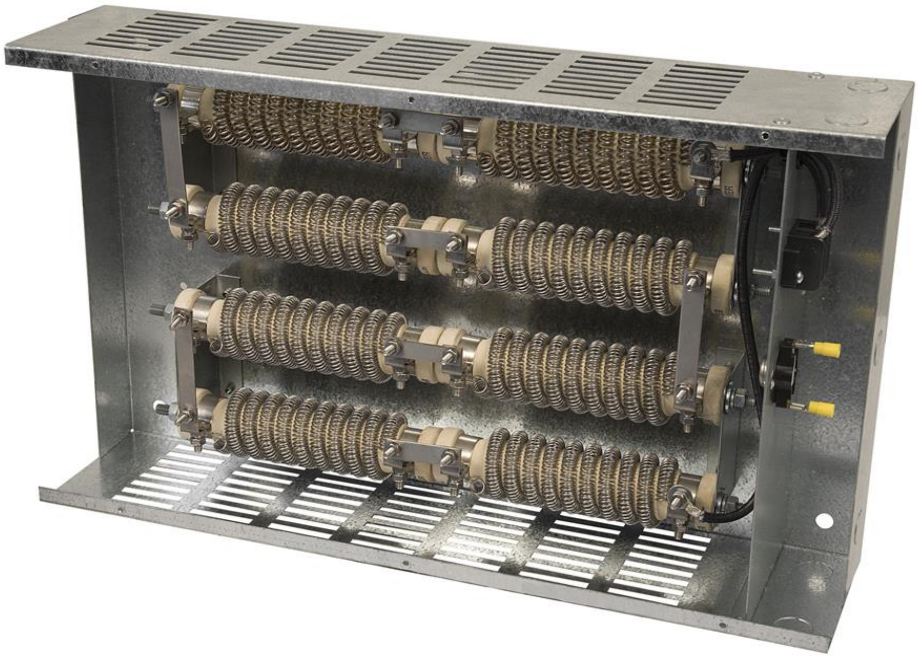

Figure 2.8: Wire-wound resistor (air-cooled)

Brake resistor is a simple and cheap device but cannot be installed on any vehicle because it needs electric machine to generate current. However, it is suitable for Hybrid Electric Vehicle (HEV), Battery Electric Vehicle (BEV) or Fuel Cell Electric Vehicle (FCEV) that uses electric machine for traction purpose. Usually in these vehicles electric energy can be recovered into a battery pack instead of being dissipated, but some limitations and restrictions affect the regeneration process (see Paragraph 3.1.3). So, the surplus energy that cannot be recovered can be dissipated using resistors. The overall efficiency does not increase but more braking torque can be provided by electric machine, reducing demand for conventional brakes.

Brake resistor can dissipate energy to heat with no wear and grants safety and reliability. This allows to reduce friction brakes usage, increasing their service life and decreasing particulate matter emission.

Permanent magnet electric machine could be used as an internal resistive load shorting its terminal. This allows to reduce speed and dissipate energy, but cooling is difficult and the risk of burn the insulating element of the machine increases. This practice cannot be repeated every time the vehicle needs to stop so it is not suitable for traction application.

2.2.2 Eddy Current Brake

The Eddy Current Brake (ECB) [17] [18] is an electromagnetic device that employs induction and eddy current principles. It is also known in vehicular application as electromagnetic retarder. ECB main components are electromagnets, which are excitation windings supplied by Direct Current. These coils generate constant

Figure 2.9: Eddy current brake

magnetic field. Metal disks (rotors) are mounted on both side of electromagnets using small airgap. Rotors are merged with transmission shaft and their design promotes heat exchange. Otherwise, a fan or liquid cooling is used.

As magnetic field is applied, currents are induced on the disks and, thanks to Joule effect, heat is dissipated in air. ECB performance depends on magnetic field density, the airgap between electromagnets and disk, their relative position and disk material. Magnetic flux leakage reduce density, so barriers must be employed.

As said at Paragraph 1.2.1, electromagnetic induction is obtained varying magnetic flux. Eddy currents appear in a stationary conductor that is excited by a changing magnetic field or on moving conductor across a constant magnetic field. The induced currents oppose to the magnetic flux variation generating an inverse magnetic field. This field generates a magnetic force that opposes to conductor motion reducing its speed.

If magnetic field is constant, then current intensity depends on conductor speed, consequently inducted currents at low speed have low intensity and this affects braking force. ECB needs to be integrated with other systems to provide braking force at low speed. For example, it can be coupled with conventional brake. As results, friction brakes increase service life and wear is reduced. Frictionless braking and low maintenance are the biggest advantages of this technology.

Eddy current brake is less sensible to high temperature compared to disk brake, mainly because heat reduce friction coefficient and causes fade. Even if the amount of dissipated energy is the same on both brakes, retarder is more resilient to thermal stress.

Electronic actuation and control allow to reduce delay in braking. The control variable is excitation current. BBW is again used to collect information from the driver and to define the current intensity. Current can be easily varied to needed value using power converters.

Differently from brake resistor, ECB does not need electric machine to convert kinetic energy to electric, so it is suitable for almost all vehicles. However, electromagnet must be supplied by an electric source as seen for MRF brake. If permanent magnet is used, system is simpler and lighter. However, the rare earths used on permanent magnet led to higher costs. Also, maximum temperature must be controlled to avoid demagnetization. A possible solution to this problem is a self-excited induction generator proposed by Jae-Nam Bae et al. [19].

Due to its characteristics, ECB could seem more indicated for high-speed vehicle. However, when rotational speed achieves a critical value, braking force decreases. This phenomenon is caused by the magnetic field generated on rotor that opposes to coil's field. Consequently, the overall effect is a reduction of eddy currents density. Retarder is instead used for heavy duty vehicles or buses to reduce friction brakes wear and overheating especially when driving on downhill roads.

3 Regenerative Braking

3.1 General Aspects of Regeneration

Regenerative braking system [20], also known as Kinetic Energy Recovery System (KERS), is the general term for a system that converts vehicle's kinetic energy to another form exploitable to supply vehicle itself. Recovered energy is stored on accumulators and can be used later for traction or for onboard systems. Regenerative braking allows to recover energy instead of waste it, as happens using heat dissipation technologies. This increases overall efficiency and reduces fuel consumption or battery discharge. However, completely recover all kinetic energy is not possible, so this system is necessarily coupled with conventional brakes, such as drum or disk or anyway dissipated through other devices.

In this case, Brake By Wire actuation can be used. BBW allows to split braking torque in the best way between regenerative braking and friction brakes to optimize regeneration and meet deceleration requirement.

Regeneration can be electrical, so kinetic energy is converted to electric current and then stored on accumulators such as battery or supercapacitors. This is the most common type of regeneration. Also, kinetic energy can be stored without any conversion on a rotating element such as flywheel.

As discussed earlier, converted energy needs to be stored on a device that maintains and releases it when demanded. Many elements can be adopted for this purpose depending on application, so two parameters are used to compare each of them and define the best technology for the application.

Energy storage is characterized by specific energy e that is the maximum energy E per unit of mass m that can be stored in the element:

$$e = \frac{E}{m} \left[\frac{Wh}{kg}\right] \tag{3.1}$$

The higher this value is, the lower mass is necessary to achieve energy demand.

Another important parameter is specific power p that is the maximum power P per unit of mass m that device can effort:

$$p = \frac{P}{m}\left[\frac{W}{kg}\right] \tag{3.2}$$

The higher this value is, the faster energy can flow in or out of the storage.

The Ragone plot [21] is a diagram used for a visual comparison among energy storage systems in terms of power and energy density. The axes use logarithmic scale to better compare device with different characteristics.

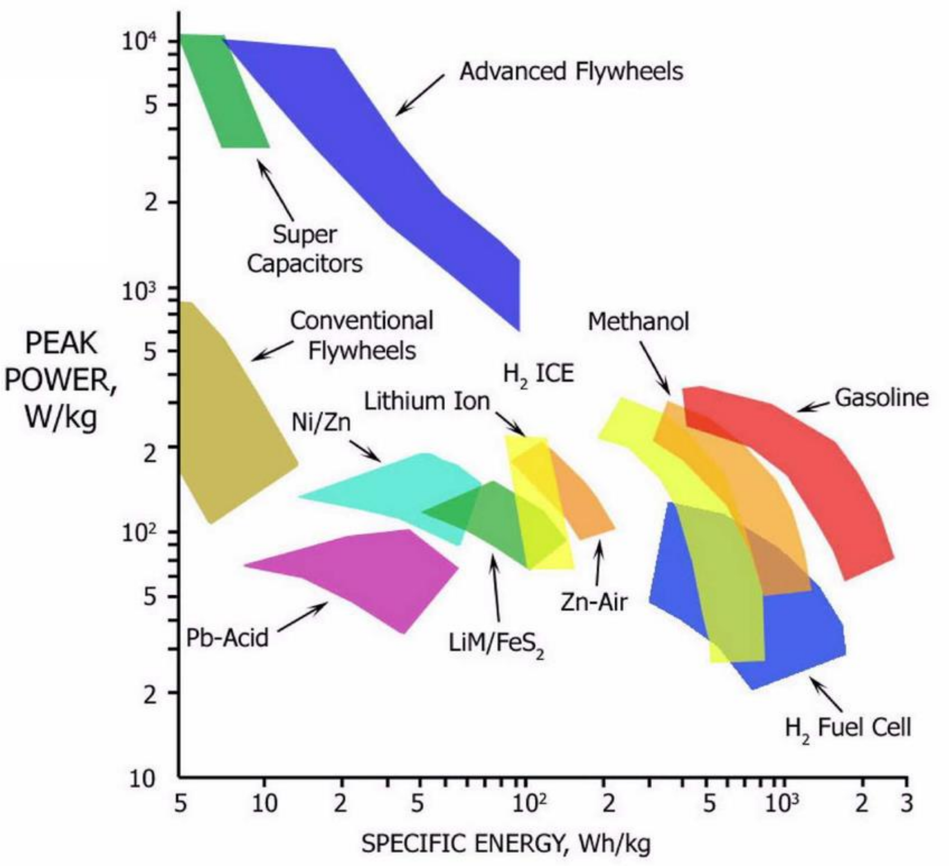

Figure 3.1: Ragone plot

As shown in Figure 3.1, the best storage in terms of energy density is Gasoline. However, it can be only used as a source of power and cannot be regenerated using engine. The batteries, which use different materials combination, have a lower energy density but researchers are working hard to develop new formulation and composition to achieve a comparable performance.

This representation allows to understand energy storage performances, so the best suitable applications for each of them. However, this diagram does not consider important parameters as cost, life cycle, and safety.

3.1.1 Electrical Recovery

The commonest recovery system uses the electric traction motor (often asynchronous motor) as a generator. Induction motor [22] works using a rotating magnetic field that induces electromotive force on the rotor to make it spin. Induction motor's rotor spins slower (rotor speed: ω_r) compared to magnetic field (synchronous speed: ω_s). Synchronous speed is:

$$\omega_s = \frac{2\pi f}{p} \left[\frac{rad}{s}\right] \tag{3.3}$$

Where f is supply frequency and p is pole pair number. When working as a motor, rotor speed is lower than synchronous speed:

$$\omega_r < \omega_s \tag{3.4}$$

When the driver presses the brake pedal, frequency is instantaneously reduced, and synchronous speed becomes lower than rotor speed:

$$\omega_r > \omega_s \tag{3.5}$$

Thanks to this operation, generation mode is obtained. In this case the torque is negative, current and voltage change polarity, but the speed maintains the same direction. AC current flows through AC-DC converter, then to DC-DC converter and is stored in a battery pack or a capacitor bank. Reducing motor speed, frequency must be reduced to maintain (3.5) condition.

Electric machine is reversible, so it can behave as motor or as a generator in both directions of rotation. Consequently, the same output torque values generated while speeding up the vehicle can be applied as resistance to slow it down. More detailed study of induction motor is proposed at Paragraph 4.2.4.

3.1.2 Kinetic Recovery

Flywheel is another system used as energy storage. In this case, no energy conversion is needed. If flywheel is not engaged, it spins at almost constant speed. When wheels are engaged with flywheel, rotational energy transfer from former to latter and vice versa depending on operating conditions.

This element is not well diffused nowadays, especially compared to electrical regeneration which is a standard on electric and hybrid vehicles.

3.1.3 Benefits and Limitations

Regenerative braking allows to save energy instead dissipate it. Consequently, it provides some great advantages:

- Fuel consumption reduces for HEVs, also reducing CO_2 tailpipe emissions
- All electric range of electrified vehicles increases
- The lack of engine brake is filled while driving in electric mode
- Braking is frictionless, so it allows to provide less force from conventional brakes, reducing wear and also particulate matter emission
- Is suitable for continuous stop-go driving condition such as in urban traffic
- Can be included on vehicle maintaining also conventional brakes to preserve safety

However, some limitations and issues do not allow a complete energy regeneration, so a vehicle cannot use this as the only braking source. Many restrictions depend on which storage technology is adopted but others are intrinsically connected to regeneration:

- Braking torque is generally split in two-third on front wheels and one-third on rears. Most of vehicles has front or rear wheel drive so only a part of the energy can be recovered. The electric machine (or flywheel) position should be a trade-off between traction and regenerative braking

- If energy storage has already achieved maximum charge (or speed) and no more energy can be adsorbed, then no regenerative braking could be applied
- Emergency braking requires the maximum braking power, that is limited compared to friction brakes
- Cannot be the only braking system in case of failure
- Regenerative braking efficiency drops at low speed
- When vehicle is switched off, electric machine is not supplied and does not generate braking force so cannot lock the wheel to park the vehicle. Also flywheel cannot apply a static resistance
- Vehicle weight and cost increase because of adding new elements
- Energy management system is complex

3.2 Battery Pack

3.2.1 Lithium-Ion Cells

Nowadays, the most of battery pack in electrical devices uses Lithium-ion technology. Li-ion cell [23] consists of two electrodes (anode and cathode) immersed in electrolyte and divided by a separator to prevent shorting. The electrolyte allows

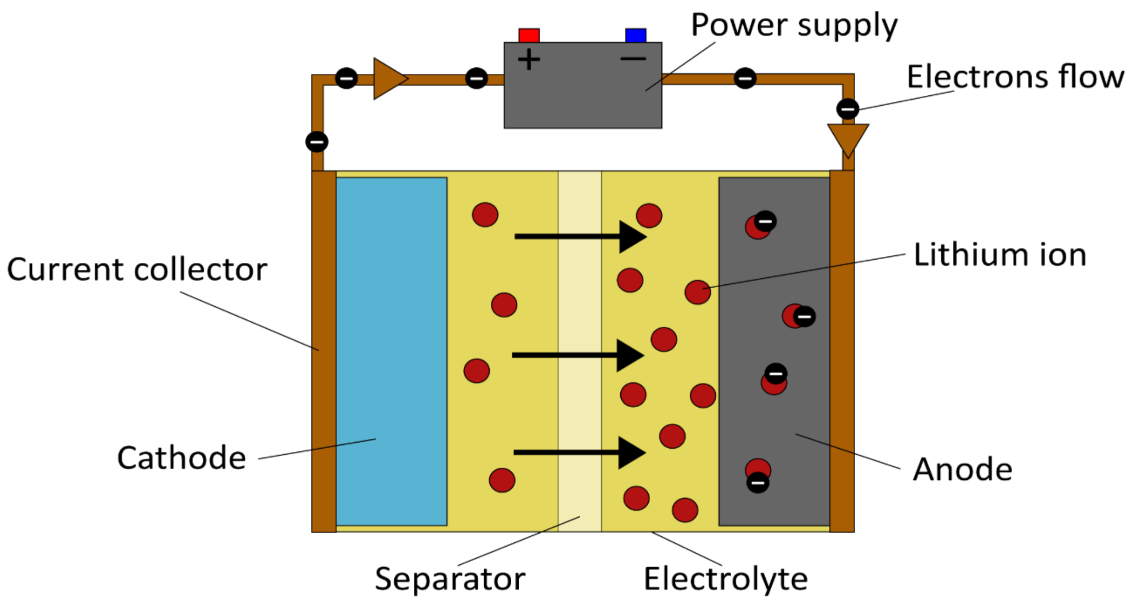

Figure 3.2: Lithium cell charging

ions to move. Electrodes are pasted onto current collector so they can be electrically linked using a conductor wire. These elements are housed in various shape case. If electric current is provided to the cell, electrons transfer from cathode to anode flowing within the wire. Lithium ions move in the same direction but pass through separator to reach electrons. The cell charges. If supply current is removed, ions back to cathode, so free electrons flow within the wire generating electric current. The cell discharges.

The cell voltage is the difference in voltage between electrodes. It decreases while cell is discharging. The cell capacity is the number of ions storable on cathode. The State Of Charge (SOC) is a dimensionless value describing the amount of usable charge in the battery at a given time, and expressed as a percentage of the rated capacity.

Cells are connected in series and parallel in a battery pack to achieve the requested capacity and voltage for the application.

Li-ion batteries feature: good energy density, no memory effect and only a slow loss of charge when not in use. One of the most used and studied system consist of Nickel Cobalt Aluminum (NCA) oxide cathode, graphite anode and an electrolyte composed by lithium salt in organic solvent. Lithium is largely diffused in earth's

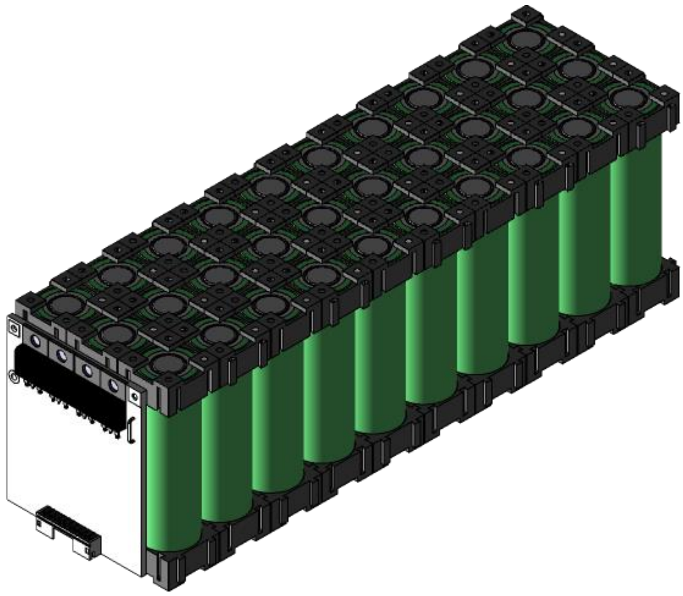

Figure 3.3: Battery pack made of cylindrical cells

crust, especially in South America, so is usable for a lot of application. Polypropylene is used as separator. Cell housing shape can be coin, cylindrical, pouch or prismatic depending on application. Pouch battery provides a good packaging but cylindrical feature better heat dissipation. The service life of this cell has been evaluated to be greater than 15 years if SOC is controlled carefully.

The energy E of a battery can be evaluated as the product of cell voltage V and its capacity C:

$$E = CV \ \ [J] \tag{3.6}$$

Then, to increase cell energy it is possible to increase cell voltage or its capacity. Increasing voltage means increase cathode potential and/or decrease anode potential. Graphite anode can be substituted by silicon. Silicon has higher capacity and potential (3700 mAh/g, 0.5 V) compared to graphite (372 mAh/g, 0.1 V) resulting in increased energy density by 25-35%. However, silicon presents large volume variation during cycle and limited number of charging cycles due to lithium consumption. In addition, at high voltage, side reactions appear within the cell, jeopardizing its correct work, reducing cycle-life, and compromising safety. Voltage window is normally limited to 1-4 V. To overcome such an issue, cells are connected in series, so overall voltage is the sum of each cell voltage. Capacity, instead, can be increased adopting different materials combinations. This allows to properly design the best configuration for considered application and pushes researchers to find out new materials. In addition, to increase capacity, cells are matched in parallel so overall capacity is the sum of each cell capacity.

The parallel/series connection is the easiest way to achieve voltage and capacity values demanded for application. Parallel connection is generally preferred because series reduces the overall voltage.

3.2.2 Temperature effects

A critical parameter for battery is the temperature. When temperature is below 0°C, power capability decreases significantly because of increased resistance in the cell. This is due to increased electrolyte viscosity that hinders ions motion. The choice of solvent can have significant impact on performance at low temperature but leads to higher cost. In addition, it has been observed that at low temperature lithium plates on graphite surface instead of intercalating into it, reducing capacitance. Lithium deposits in dendritic form and could penetrate separator causing short-circuit. A possible solution is using an anode which potential value is much higher than lithium's, allowing bigger thermal window before plating occurs. However, high anode potential leads to low cell voltage so reduces the energy of the battery. Probably, the best solution is to warm up the battery at vehicle start using engine heat on HEV or wait for self-heating on BEV. Consequently, battery cannot be charged until it reaches the correct temperature, so regenerative braking is not allowed.

High temperature is even more critical for battery cause of thermal runaway. If unexpected failure appears, such as short-circuit or overcharge, cells increase temperature. At around 125°C, the passive layer on the anode decomposes generating exothermic reaction that increases the temperature further. As the temperature achieves almost 180°C, oxygen from cathode lattice is released causing heat production. These reaction results in smoke and fires. To solve this issue, reactions must be prevented or retarded. Different materials could be adopted for cathode and anode for this purpose. In addition, it is necessary a protection system for overcharge and a high resistance separator to prevent short-circuit.

3.2.3 Traction Application

As showed on Ragone plot (Figure 3.1), Li-ion batteries are the best compromise for energy and power density compared to other cell technologies. However, fuels energy density is 100 times higher than Li-ion batteries. Conventional vehicle's engine is low efficient compared to electric motor, but fuel energy density allows to drive the car for significantly longer range. BEV instead needs large number of cells to have acceptable autonomy. Consequently, vehicle's weight increases, and a cooling system is mandatory.

Another important battery issue is charging time. It depends on which technology is used for recharge but is extremely high compared to fuel refill. The low charging rate is due to low power density. Indeed, maximum supply voltage and current are limited to prevent aging and fire hazards. This does not affect only charging time, but also regenerative braking. When sudden braking is needed, a big amount of power is generated but only a part of it can be used to recharge the battery. The residual power must be absorbed or dissipated by another braking device.

3.3 Supercapacitors

A capacitor [24] is an electrical device that stores electric charge. It is made of at least two conductive surfaces separated by insulating dielectric material. When voltage is applied to a capacitor, electrons flow in the circuit generating current, but dielectric blocks these particles causing negative charge accumulation on conductor surface. The electrons on the other conductor surface are repulsed and flow in the circuit. The lack of electrons generates a positive charge. Capacitance C is directly proportional to conductor surface area A of each conductor and inversely proportional to the distance d between them:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \ \ [F] \tag{3.7}$$

The character ε_0 is the dielectric constant of free space and ε_r is the dielectric constant of the insulating material. Capacitors have high power density but low energy density for traction application due to geometrical limitation. Then, supercapacitors are used.

Supercapacitors, also known as ultracapacitors, or electrochemical capacitors, utilize conductive materials with high specific surface and thin electrolytic dielectric to achieve significantly higher capacity than conventional capacitor. The higher energy density than capacitors and comparable power density allow to use them as energy recovery system on vehicle. The high power density lead to shorter charging and discharging time compared to chemical battery. In addition, their structure reduces capacitance degradation, so they have longer cycle-life. Supercapacitors can be divided into three classes: electrochemical double-layer capacitors, pseudocapacitors and hybrid capacitors. The former group stores electric charge without chemical interaction between electrode and electrolyte. The latter groups use a chemical mechanism to transfer charge between electrode and electrolyte.

3.3.1 Electrochemical Double-Layer Capacitors

In Electrochemical Double-Layer Capacitors (EDLCs), two carbon-based electrodes are isolated by electrolyte and separator. Electric charge is stored electrostatically on electrodes without chemical interaction. When voltage is applied to supercapacitor, electrons accumulate on electrode's surface generating a negative charge. Positive ions dissolved in electrolyte are attracted and pass through separator to reach negative charge on electrode. On the opposite electrode the lack of electrons generates a positive charge that attract negative ions on electrode surface. A double layer of charge is produced at each electrode.

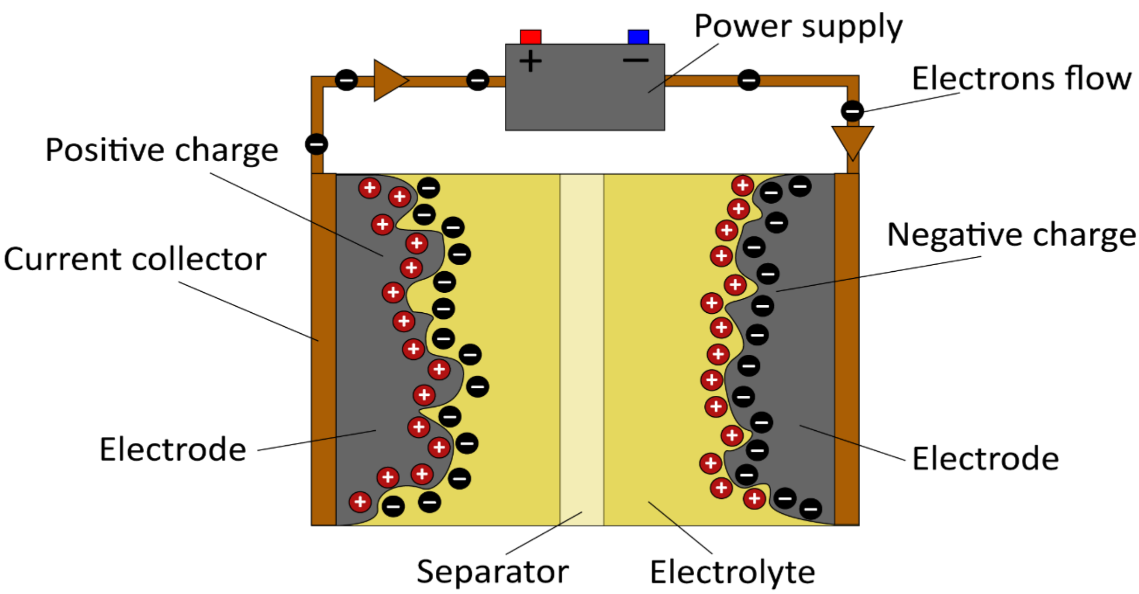

Figure 3.4: Electrochemical double-layer capacitor charging

Thanks to double layer, increased electrode surface and thinner dielectric width, these supercapacitors achieve higher energy density than conventional capacitor, though lower compared to battery. In addition, the lack of chemical reaction leads them to high reversible charge-discharge cycles. It is sometimes observed a life of 10^6 cycles.

The performance of EDLCs is mostly influenced by electrodes and electrolyte's characteristics. Carbon electrodes have the higher surface area, lower cost and more established fabrication techniques than other materials.

3.3.2 Pseudocapacitors

Pseudocapacitors use chemical reactions (electrosorption, reduction-oxidation and intercalation) between electrode and electrolyte to transfer charge. Electrodes are generally conducting polymers or metal oxides and react with the electrolyte. These processes allow pseudocapacitors to achieve higher energy density than EDLCs. However, power density is lower and also cycle-life.

3.3.3 Hybrid Capacitors

Hybrid capacitors combine EDLC and pseudocapacitor's technologies to achieve better performance. Using both electrostatic and electrochemical mechanisms to store electric charge, specific energy increases without sacrificing stability and long cycle-life. Depending on electrode configuration hybrid capacitors can be distinguished in: composite, asymmetric and battery-type.

3.3.4 Traction Application

Supercapacitors can be used for regenerative braking [25] on vehicles when high power density is requested so battery could not be used. It was observed that capacitance is influenced by braking command and initial SOC (then its voltage). In particular, it decreases raising braking command and also decreases reducing initial SOC. Remembering that power is the product of voltage V and current I:

$$P = VI \ \ [W] \tag{3.8}$$

Increasing braking command, power absorption increases so, with equal initial SOC, current increases. Reducing initial SOC, supercapacitor initial voltage reduces so, with equal power, charging current increases. As the current achieves higher value, the electrolyte ions have less time to reach all electrode's porous, reducing the effective capacitance of the capacitor.

However, during regenerative braking operation, as the vehicle slow down, current generated by electric machine reduces allowing electrolyte ions longer time to reach electrode. Consequently, capacitance is slightly dependent of braking command but anyway strongly dependent of initial SOC.

Current maximum value is limited by power electronic converters so, to provide a certain braking power, supercapacitor voltage could not be too low. Consequently, if SOC is below ~10%, the overcurrent must be avoided using a pre-charge resistor. Resistor dissipation jeopardizes charging efficiency at low SOC. These aspects limit the usability of supercapacitors and reduce further the energy density which is already a critical parameter.

3.4 Flywheel

3.4.1 Constructive Aspects

Flywheel-based KERS [26] [27] is a technology firstly designed for motorsport, such as Formula 1. It was used to recover braking energy and reuse it for quick acceleration. Flywheel gave to those vehicles a power boost for a limited amount of time. Indeed, it has really high power density but low energy density.

A flywheel is basically a mass that collect kinetic energy by increasing its rotational speed. Energy, neglecting dissipation, is maintained spinning at almost constant speed and then released to speed up the vehicle. The kinetic energy of this element is calculated as:

$$E_k = \frac{1}{2} I \omega^2 \ \ [J] \tag{3.9}$$

Where I is the moment of inertia of the flywheel (kgm^2) and ω is the angular speed (rad/s). The evaluation of moment of inertia depends on rotating object's geometry, but it is proportional to its mass m and to square value of a characteristic dimension L:

$$I \propto mL^2 \ \ [kgm^2] \tag{3.10}$$

From (3.4) and (3.5) the flywheel energy is proportional to its mass, to the square of its speed and to the square of its dimension:

$$E_k \propto mL^2\omega^2 \tag{3.11}$$

Consequently, the best ways to increase energy is to increase rotor speed or its characteristic dimension. Preferring high speed instead of high mass and limiting the maximum dimension, is convenient for vehicle itself because it does not lead to a significant impact on fuel economy. Then rotor is usually a cylinder made of carbon fiber (up to 60000 rpm) or steel (20000 rpm), depending on maximum rotational speed required and budget. Most of its mass is placed far from rotational axis to increase moment of inertia even limiting its weight. The carbon fiber is generally wounded over a steel hub.

Figure 3.5: Flywheel rotor

The rotor is enclosed in a vacuum chamber made of aluminum or steel to reduce dissipations caused by air friction. This is a key point because energy dissipation increases with speed. Another important source of losses are shaft bearings. In this application magnetic bearings have substituted mechanicals because they guarantee high rotational speed avoiding wear and lubrication. Electromagnets or permanent magnets realize magnetic levitation, so the shaft is supported only by magnetic field and rotates without friction.

Flywheel is connected to transmission system via a Continuous Variable Transmission (CVT). CVT has infinite number of gear ratios, so it is suitable for any speed value and allows high efficiency power transmission. A speed reducer such as epicyclic gearing is also necessary between flywheel and CVT to maintain an acceptable speed range for CVT. Then a clutch is used to separate flywheel and CVT maintaining flywheel at constant speed.

3.4.2 Traction Application

When braking command is applied, clutch is engaged, and the wheels transfer rotational energy through transmission to accelerate flywheel. The rotor stores rotational energy until maximum speed is achieved or vehicle stops, then clutch disengages the elements. At vehicle restart, or whenever it is needed, flywheel is again engaged and releases its energy accelerating the vehicle.

The main advantage of this system is the ability to store energy with high efficiency and with high power density. This because no energy conversion is needed, and friction losses sources are reduced using vacuum chamber and magnetic bearings. Its design allows to have a limited weight and size, so it does not have a significant impact on fuel consumption. In addition, its cost is lower than electrical recovery system because it does not need electric machines.

However, flywheel cannot be used as a permanent storage because its energy density is low, and it loses rotational speed really quicker compared to battery. Moreover, it could cause vibration, noise and gyroscopic effects which cause bad dynamic behavior for the vehicle. In addition, a failure at high speed could causes huge damages on vehicle compromising safety.

Despite of the advantages, nowadays vehicles hardly use this system. Due to flywheel characteristics, it is mainly suitable for high acceleration/deceleration and temporary storage such as in race car. This temporary storage better performs if used whenever achieves maximum speed.

Another important cause is the electric and hybrid-electric vehicles establishment due to current policies. Electric machines, accumulators and power converters are already present on electrified vehicle, so electrical regeneration can be easily implemented.

4 Performance Comparison

4.1 Braking Dynamic

4.1.1 Longitudinal Contact Forces

The most important characteristic of a braking system is its ability to stop the vehicle as fast as possible. However, braking force cannot increase unlimited because of tire-asphalt contact. Analyzing Equation (1.1) the maximum force applicable to the wheel surface in adhesion condition is:

$$F_{max} = \mu F_z \ [N] \tag{4.1}$$

So, it depends on friction coefficient μ and vertical force F_z. Weight transfer during braking operation changes F_z value compared to static condition. The maximum contact force F_{max} increases on the front wheels and decreases on rears.

Supposing:

- Only longitudinal and vertical forces applied to the wheels
- Null slope road
- Rigid suspensions
- Null aerodynamic and rolling contributes

The free-body diagram of a vehicle during braking is presented in Figure 4.1 [28].

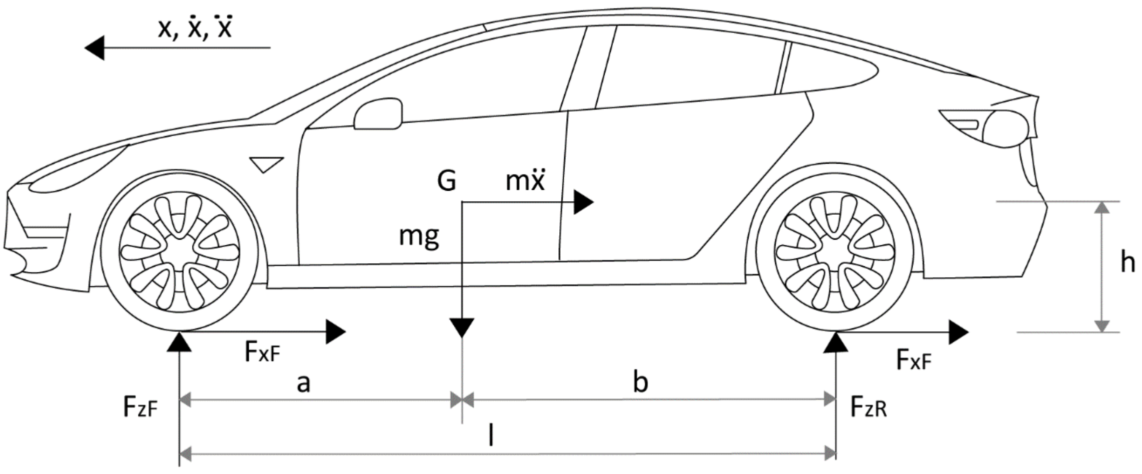

Figure 4.1: Car free-body diagram in braking operation

Vehicle's numerical parameters are listed in Table 4.1 and refers to Tesla Model S Signature Performance [29].

Description	Symbol	Value	Unit
Mass	m	2106	kg
Wheelbase	l	2.960	m
Weight distribution (front)	c_F	0.48	-
Weight distribution (rear)	c_R	0.52	-
Center of gravity height [30]	h	0.460	m
Wheel radius (245/45 R19)	r	0.352	m
Peak motor torque (@ 0-5100 rpm)	$T_{m\,max}$	600	Nm
Peak motor power (@ 5000-8600 rpm)	$P_{m\,max}$	310	kW
Maximum motor speed	$n_{m\,max}$	16000	rpm
Maximum vehicle speed	v_{max}	210	km/h
Final gear ratio	τ	9.73	-
Friction coefficient	μ	1	-
Gravitational acceleration	g	9.81	m/s^2

Table 4.1: Vehicle's parameters

From the weight distribution, a and b can be calculated as:

$$a = \frac{mgc_R}{mg} l = 1.539 \ [m] \tag{4.2}$$

$$b = \frac{mgc_F}{mg} l = 1.421 \ [m] \tag{4.3}$$

The force balance along x coordinate is:

$$F_{xF} + F_{xR} = -m\ddot{x} \tag{4.4}$$

The force balance along z coordinate is:

$$F_{zF} + F_{zR} = mg \tag{4.5}$$

The torque balance around rear wheels is:

$$F_{zF} = \frac{mgb}{l} - \frac{m\ddot{x}h}{l} = \frac{m}{l}(gb - \ddot{x}h) \tag{4.6}$$

So, the vertical force on rear axle is:

$$F_{zR} = mg - F_{zF} = \frac{m}{l}(ga + \ddot{x}h) \tag{4.7}$$

The longitudinal force on front axle at limit condition $F_{xF\,lim}$ (front wheels lock) can be written using Equation (4.1), (4.6) and (4.4):

$$F_{xF\,lim} = \mu F_{zF} = \frac{\mu m}{l}\left(gb + h\frac{F_{xF\,lim} + F_{xR}}{m}\right) \tag{4.8}$$

$$(l - \mu h)\frac{F_{xF\,lim}}{mg} = \mu\left(b + h\frac{F_{xR}}{mg}\right) \tag{4.9}$$

$$\frac{F_{xF\,lim}}{mg} = \mu\frac{b + h\frac{F_{xR}}{mg}}{l - \mu h} \tag{4.10}$$

The limit force on front axle is proportional to the force on the rear axle.

The longitudinal force on rear axle at limit condition $F_{xR\,lim}$ (rear wheels lock) can be written using Equation (4.1), (4.7) and (4.5):

$$F_{xR\,lim} = \mu F_{zR} = \frac{\mu m}{l}\left(ga - \frac{F_{xF} + F_{xR\,lim}}{m}\right) \tag{4.11}$$

$$(l + \mu h)\frac{F_{xR\,lim}}{mg} = \mu\left(a - h\frac{F_{xF}}{mg}\right) \tag{4.12}$$

$$\frac{F_{xR\,lim}}{mg} = \mu\frac{a - h\frac{F_{xF}}{mg}}{l + \mu h} \tag{4.13}$$

The limit force on rear axle is proportional to the force on the front axle.

The intersection of these two lines achieves the maximum deceleration. The maximum acceleration $\ddot{x}_{max}$ is:

$$(F_{xF} + F_{xR})_{max} = \mu(F_{zF} + F_{zR}) \tag{4.14}$$

$$-m\ddot{x}_{max} = \mu mg \tag{4.15}$$

$$\ddot{x}_{max} = -\mu g \tag{4.16}$$

It is important to notice that the maximum theoretical deceleration due to mechanic grip is always $|\ddot{x}_{max}| \leq g$.

Then, the maximum longitudinal forces of Tesla Model S are:

$$F_{xF\,max} = \mu F_{zF\,max} = \frac{\mu mg}{l}(b + \mu h) = 13407\ [N] \tag{4.17}$$

$$F_{xR\,max} = \mu F_{zR\,max} = \frac{\mu mg}{l}(a - \mu h) = 7253\ [N] \tag{4.18}$$

Maintaining constant vehicle's parameters and varying μ, ideal braking parabola is obtained.

All these curves are reported in Figure 4.2.

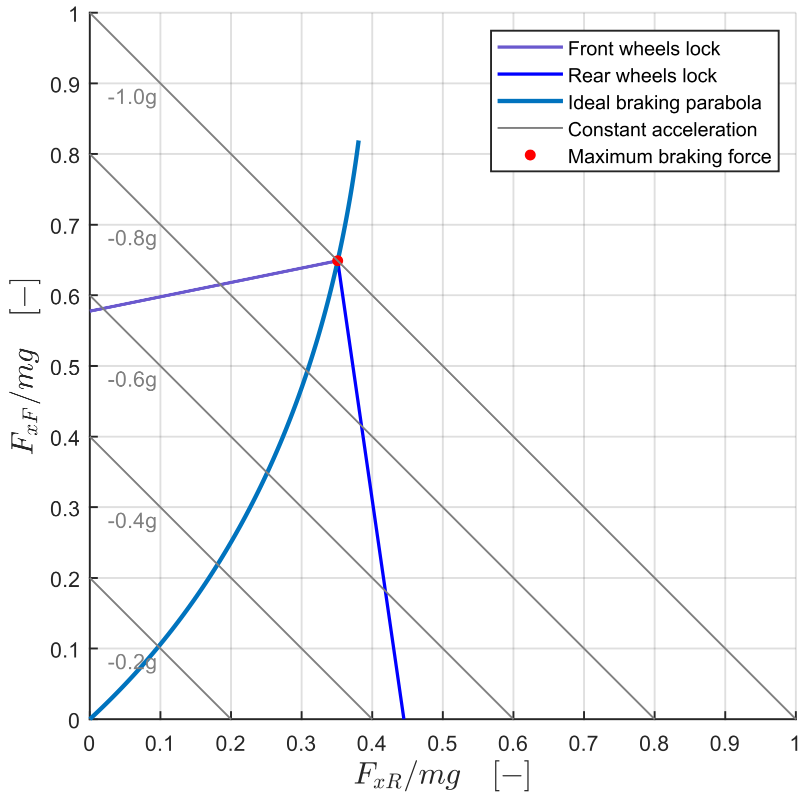

Figure 4.2: Braking curves

4.1.2 Braking Performance

The simplest method to compare braking performance of different technologies is to calculate deceleration achieved by each of them and divide it by $1g$.

F_x is defined as the overall longitudinal force:

$$F_x = F_{xF} + F_{xR} \tag{4.19}$$

The deceleration $|\ddot{x}|$ is calculated from Equation (4.4) as:

$$|\ddot{x}| = \frac{F_x}{m} \left[\frac{m}{s^2}\right] \tag{4.20}$$

Then:

$$\frac{|\ddot{x}|}{g} = \frac{F_x}{mg} \; [-] \tag{4.21}$$

4.2 Braking comparison

4.2.1 Conventional Brakes

Conventional brakes, so drums and disks or a combination of them, allow to apply high forces to the wheels. A proper design of the hydraulic system and the use of a proportioning valve allow to stop the vehicle with a deceleration of μg or more (high performance or race cars) [6]. Indeed, aerodynamic effect produces a downforce on vehicle which increases the overall vertical force, resulting in higher admissible deceleration. The free-body diagram presented in Figure 4.1 does not consider aerodynamic contributes so the maximum deceleration is assumed equal to μg for conventional brakes. Considering $\mu = 1$, deceleration is 1g.

From Equation (4.17) the maximum braking force on front axle on ideal braking parabola is equal to 13407 N. Consequently, the maximum braking torque on a single front wheel is:

$$T_{wF\,max} = \frac{F_{xF\,max}}{2} r = 2360 \; [Nm] \tag{4.22}$$

Similarly, the maximum braking force on rear axle on ideal braking parabola is equal to 7253 N. The single wheel value is:

$$T_{wR\,max} = \frac{F_{xR\,max}}{2} r = 1278\ [Nm] \tag{4.23}$$

4.2.2 Magneto Rheological Fluid Brake

The MRF brake developed by [14] can be used for each of Tesla's wheel instead of conventional brakes. The maximum braking torque T_{mrf} of 1013 Nm is applied to each of them. Then the overall longitudinal force is:

$$F_{x\,mrf} = \frac{4T_{mrf}}{r}\ \ [N] \tag{4.24}$$

Deceleration is calculated using Equation (4.21) and it is equal to about 0.56g. This value is low compared to conventional brake. Also, system's weight is higher. Comparing MRF brake's torque to the value of 1278 Nm, this element is probably suitable only for rear wheels.

The brake performance depends on adopted parameters and optimization. A simplified formulation of braking torque must be introduced to properly compare conventional and MRF brakes. This will help to understand the effective limitations of this technology. In this case, disk brake is considered because of its similarity to MRF brake. According to [14], braking torque for MRF brake T_{mrf} is the sum of two contributes:

$$T_{mrf} = T_r + T_y \tag{4.25}$$

The term T_r is due to fluid viscosity in resting condition and the term T_y appears when magnetic field is applied to the fluid. T_r is usually quite smaller than T_y so can be neglected. Then the formula is:

$$T_{mrf} = T_y = \frac{2\pi}{3} n\tau_y (r_o^3 - r_i^3) \tag{4.26}$$

In Equation (4.26), n is the number of contact surfaces, τ_y is the yield stress of the fluid, r_o is the outer radius of the disk and r_i is the inner radius. Using design parameters in this model, the torque is 1155 Nm, which is overestimated compared to finite element model.

The torque of disk brake can be expressed using two different theories: uniform pressure and uniform wear. The uniform pressure theory asserts that pressure is constant over rubbing surface [31]. The corresponding expression is:

$$T_d = \frac{\theta}{3}\mu_c n p(r_o^3 - r_i^3) \tag{4.27}$$

Where θ is the angular size of the pad, μ_c is friction coefficient, n is the number of contact surfaces and p is the average pressure on the disk.

Considering a single disk with the same dimensions, the ratio between Equation (4.27) and (4.26) is:

$$\frac{T_d}{T_{mrf}} = \frac{\theta}{2\pi}\frac{\mu_c p}{\tau_y} \tag{4.28}$$

This equation shows that even if the dimensions and the number of disks are the same, contact area is higher for MRF brake. This is the main advantage of using a liquid. However, the maximum yield stress of the fluid is quite lower than maximum pressure on pad. The only way to achieve a comparable value of torque, maintaining constant brake geometry, is to increase τ_y.

Using Equation (4.26) the yield stress necessary to have the same performances of a disk brake can be calculated. The value is about 91 kPa. According to A. G. Olabi, and A. Grunwald paper [13], Meng Ji and Yiping Luo's study [32], magnetorheological fluid can reach a yield stress of 50-100 kPa. Then vehicular application seems to be possible but needs researchers to find out new compositions in order to achieve this performance. Even thermal behavior must be considered. It is also important to remember that this model overestimates the braking torque.

4.2.3 Eddy Current Brake

ECBs can be used as a retarder for each Tesla's axle instead of conventional brakes. The eddy current brake model is designed following Alexandre José Rosa Nunes and Francisco Miguel Ribeiro Proença Brojo conference paper [33]. The adopted numerical parameters are the same of the original study except for the number of magnetic poles. In this case, 8 poles are used. The considered material for the disk is iron, as it seems the best compromise in terms of performance. All numerical data are reported in Table 4.2.

Description	Symbol	Value	Unit
Disk width	w	4	mm
Magnetic pole radius	r_p	22.57	mm
Pole radial distance	a	150	mm
Iron core airgap	l_g	7	mm
Iron temperature	t	200	°C
Permeability (iron)	μ_r	5000	-
Permeability (free space)	μ_0	$4\pi \cdot 10^{-7}$	H/m
Resistivity ($t_0 = 20°C$)	ρ_0	$9.7 \cdot 10^{-8}$	Ωm
Thermal expansion coefficient	α	$5 \cdot 10^{-3}$	1/°C
Saturation magnetic field	B_{sat}	1.5	T
Poles number	n_p	8	-
Coil turns	N	3350	-
Coil current	I	3	A

Table 4.2: Eddy Current Brake parameters

Disk temperature is assumed at 200°C. Resistivity is consequently evaluated as:

$$\rho = \rho_0\big(1 + \alpha(t - t_0)\big) \ [\Omega m] \tag{4.29}$$

Then conductivity is:

$$\sigma = \frac{1}{\rho} \ \ [(\Omega m)^{-1}] \tag{4.30}$$

The reluctance of the core is low and can be neglected. Consequently, magnetic reluctance of the airgap and disk is:

$$\Re = \frac{l_g - w}{\mu_0 A} + \frac{w}{\mu_r \mu_0 A} \ \ [H^{-1}] \tag{4.31}$$

Where A is the area of the magnetic pole:

$$A = \pi r_p^2 \ \ [m^2] \tag{4.32}$$

The equation of the equivalent magnetic circuit is:

$$\mathcal{F} - \mathcal{F}_{eddy} - \Phi\Re = 0 \tag{4.33}$$

Where Φ is the magnetic flux and $\mathcal{F}$ is the magnetomotive force, that is:

$$\mathcal{F} = NI \ \ [A] \tag{4.34}$$

Similarly, $\mathcal{F}_{eddy}$ is the inducted magnetomotive force that opposes to $\mathcal{F}$:

$$\mathcal{F}_{eddy} = \sigma a w r_p \frac{\Phi}{A} \omega \ \ [A] \tag{4.35}$$

Where ω is the rotational speed. Rewriting Equation (4.33):

$$NI - \sigma a w r_p \frac{\Phi}{A} \omega - \Phi\Re = 0 \tag{4.36}$$

$$\Phi = \frac{NI}{\Re + \sigma a w r_p \omega / A} \ \ [Wb] \tag{4.37}$$

The magnetic field in the core is consequently calculated as:

$$B = \frac{\Phi}{A} \ [T] \tag{4.38}$$

B must be lower or at least equal to saturation value:

$$B(B > B_{sat}) = B_{sat} \tag{4.39}$$

Current density on the disk (eddy current) is:

$$J_e = \sigma a \omega B \ [A/m^2] \tag{4.40}$$

The torque characteristic curve is calculated and reported in Figure 4.3.

$$T_e = \frac{P_{diss}}{\omega} = \frac{n_p \rho J_e^2 A w}{\omega} \ [Nm] \tag{4.41}$$

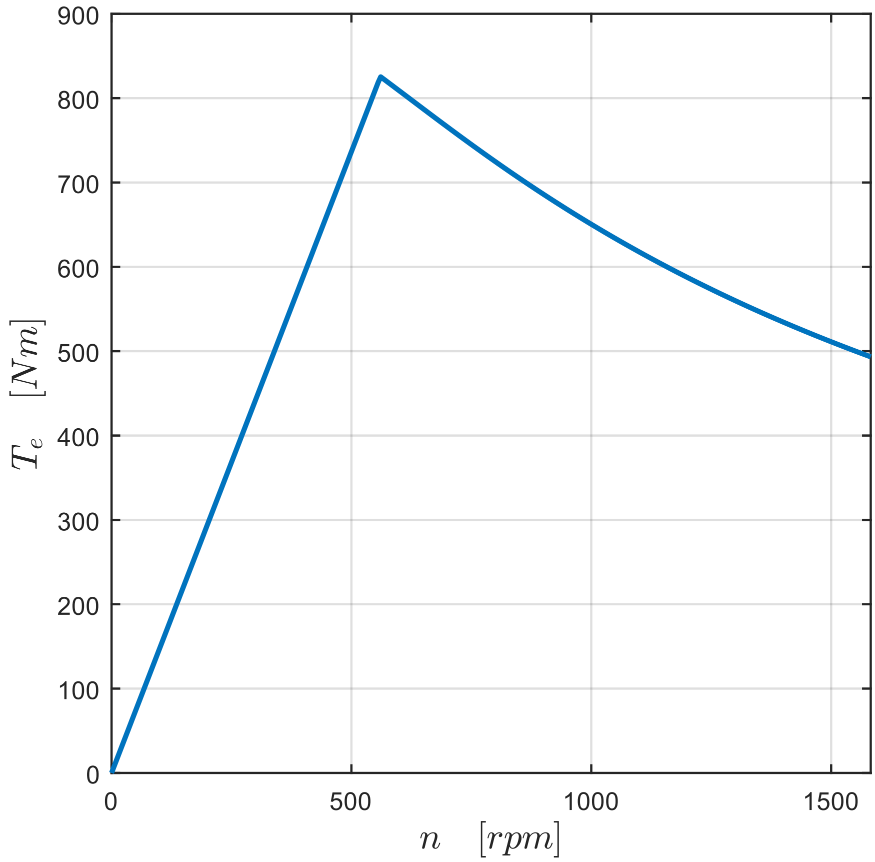

Figure 4.3: ECB torque curve

The curve reported in Figure 4.3 highlights retarder features [18]. At null speed, the torque is zero because magnetic flux is not varying, and no induced current are flowing in the disk. This means that ECB cannot stop and hold the car. At low speed the induced magnetic field is low compared to coil's field, so eddy currents increase linearly and consequently torque. The speed that maximizes torque is known as critical speed. In this case, the critical speed is about 561 rpm, and the peak torque is 825 Nm. Beyond critical speed the torque reduces. At high speed, magnetic field produced by eddy currents is greater than excitation field, reducing the effectiveness of the brake. However, the curve slope is lower than linear domain.

Varying ECB parameters, the peak torque can be adjusted for vehicular applications. For example, reducing airgap, using more magnetic poles, increasing their dimension, and using different materials allows to increase torque. However, these variations cause higher critical speed. Disk can also be finned to promote heat exchange.

Another important aspect is magnetic pole excitation. If permanent magnets are used, energy losses due to coils current are eliminated. In addition, magnets present better performance because of compact design.

Deceleration is:

$$\frac{|\ddot{x}|}{g} = \frac{\frac{2T_e}{r}}{mg} \ [-] \tag{4.42}$$

The maximum deceleration value obtained is about 0.23g at 74 km/h, which is quite low. Braking torque depends on speed and is negligible above zero that is the most important for urban traffic. Indeed, ECB is used as a retarder, so it is coupled with conventional brakes to reduce them effort. Retarders are used on commercial vehicles, trucks, and buses, in which high amount of kinetic energy must be dissipated. This element is especially useful on downhill roads where brake pedal is pressed for long time and lining tends to overheat. Also, if conventional brakes are used at low speed to provide the lack of torque, the overheat and wear is reduced.

At high speed, which is the worst condition for friction brakes, ECBs adsorb part of vehicle's energy.

Even if the obtained results in terms of performance seem not enough for retarder function, there are some manufacturers that produce these devices. For instance, the French company Telma produces a wide range of ECBs. The peak torque of its axial retarders varies from the minimum of 250 Nm to 3600 Nm [34], so they can achieve very good performance. Between these two boundaries, there are a lot of retarders to satisfy the desired request.

4.2.4 Electric Machine

Tesla Model S has a rear-wheel drive 3-phase AC induction motor with 4 poles [29] [35]. Thanks to data provided by manufacturer, torque and power characteristic curves can be represented in Figure 4.4. The peak torque of 600 Nm is provided as

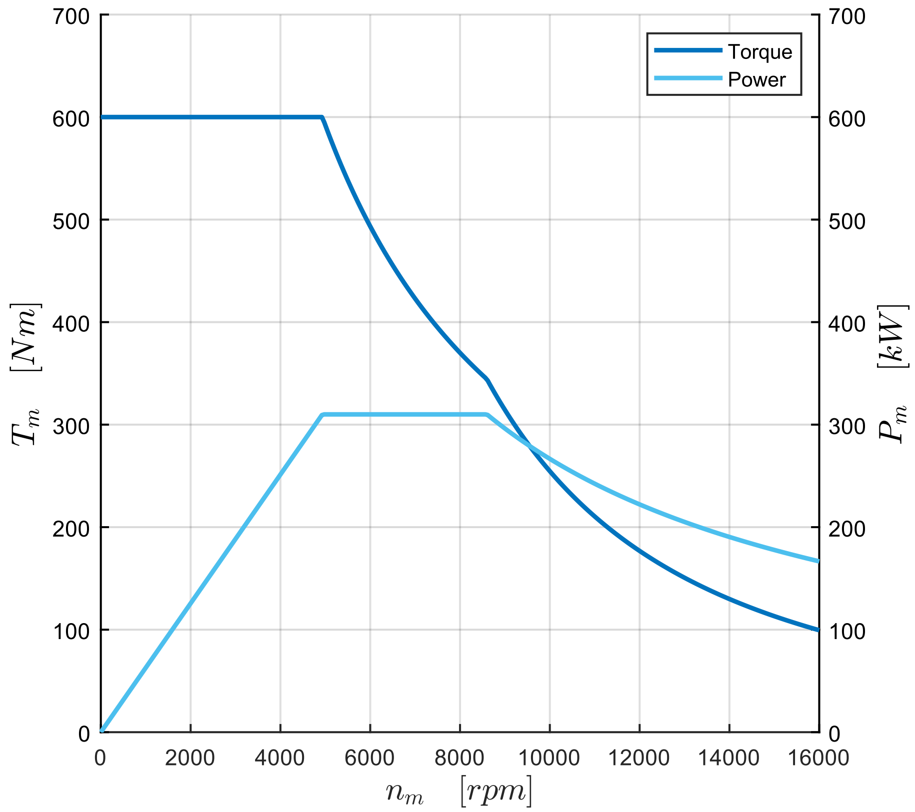

Figure 4.4: Tesla Model S – electric motor curves

constant value from null speed to about 5000 rpm (67 km/h). This value is named base speed. Power increases linearly. Achieved the maximum power of 310 kW, torque T_m decreases inversely proportional to speed n_m:

$$T_m \propto \frac{1}{n_m} \tag{4.43}$$

In this phase, power is constant. Finally, over 8600 rpm (117 km/h) power is reduced, and torque further reduces inversely proportional to square of speed:

$$T_m \propto \frac{1}{n_m^2} \tag{4.44}$$

Maximum motor speed is 16000 rpm (218 km/h), but vehicle speed is however limited to 210 km/h.

In Figure 4.4 only the first quadrant is reported. In this representation the electric machine operates as a forward motor, but induction motor can work in all four quadrants. Torque curve is symmetric with respect to both axes. The four modes are: forward motor ($n_m > 0, T_m > 0$), forward generator ($n_m > 0, T_m < 0$), backward motor ($n_m < 0, T_m > 0$), backward generator ($n_m < 0, T_m < 0$). Consequently, when working as a forward generator, the same torque is applied as a resistance. The car speed decreases, and voltage is applied to the battery pack.

Supposing that all the energy generated is adsorbed thanks to a combination of battery pack, supercapacitors and resistors, deceleration can be evaluated as:

$$\frac{|\ddot{x}|}{g} = \frac{\frac{\tau T_m}{r}}{mg} \ [-] \tag{4.45}$$

The maximum deceleration obtained is about 0.80g, which is a good braking performance. However, this value is not constant but depends on speed. It decreases with speed and drops to 0.13g at vehicle maximum speed (210 km/h). This is not acceptable when driving at high speed. To solve this issue, a two-speed gear transmission can be used. However, this configuration is more complex, and the costs are higher.

Unfortunately, in this case only one motor is used, and it is mounted on rear axle. Considering Figure 4.2, braking torque must be limited to avoid rear wheels locking condition. The maximum torque on rear axle is:

$$T_{R\,max} = 2T_{wR\,max} = 2553\ Nm \tag{4.46}$$

The maximum torque on front axle is instead:

$$T_{F\,max} = 2T_{wF\,max} = 4719\ Nm \tag{4.47}$$

The comparison among the available torque of the motor and the braking limits is reported in Figure 4.5. The available torque at the wheels is high thanks to gear ratio but cannot completely be used. A front-wheel drive machine could apply most

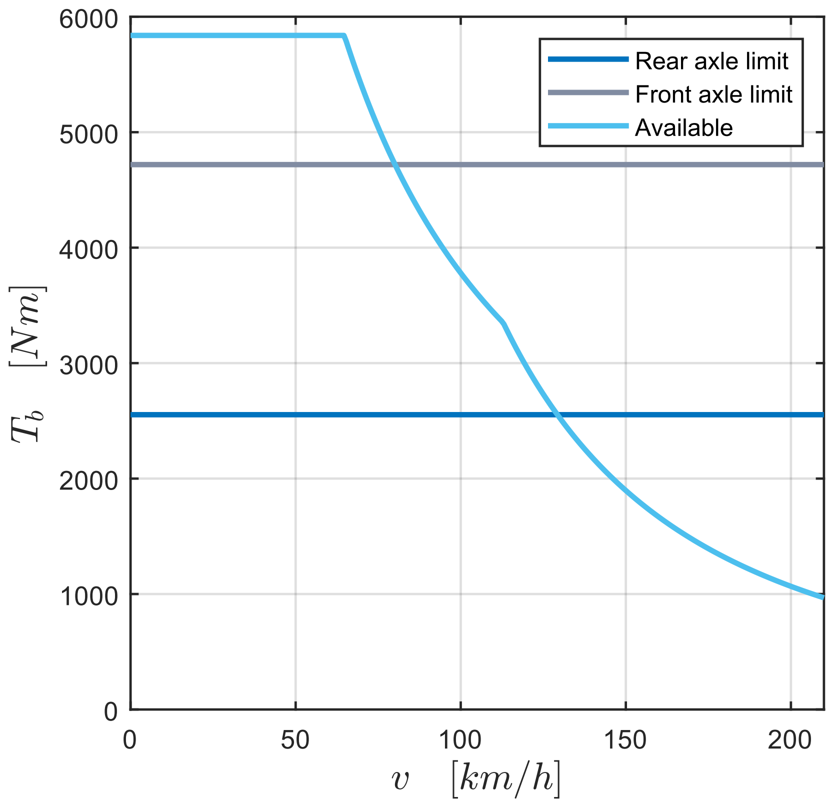

Figure 4.5: Torque comparison – available and limit

of available torque without wheels lock. A rear-wheel drive machine is largely limited because less than half of available torque can be used. Braking limitations also affect regeneration. Even if all energy is recovered in the battery, the benefit is jeopardized by rear-wheel drive configuration.

The obvious solution to achieve better braking performance and recover higher amount of energy could be a front-wheel drive machine. However, this configuration limits vehicle performance in acceleration. Electric machine position must be a compromise between traction and recovery. Another solution well used nowadays to recover more energy avoiding wheel lock is a Four-Wheel Drive (4WD). BEVs use two or more electric machines to drive both axles, and even single wheels. Tesla also adopted this architecture on its more recent models. HEVs use the engine to drive an axle (generally rear axle) and the electric machine for the other. This architecture increases vehicle weight and costs but is more attractive for some customers.

The commonest braking system on BEVs or HEVs combines electric machine used as generator and conventional brakes. This architecture grants the safety of a conventional braking system but increases vehicle efficiency thanks to energy recovery. In case of electric machine failure, the vehicle is always able to stop promptly. This system is also mounted on Tesla Model S which is equipped with four ventilated disk brakes.

5 Manufacture Context Analysis

5.1 Global Market and Main Players

5.1.1 Automotive Brake Market Overview

Increasing wellness and urbanization has been causing a growing need of mobility that results in higher demand of vehicles all around the world. Also, air pollution and climate changes are forcing car manufacturer to develop new technologies and strategies to reduce the human environmental impact. This positive trend is expected to maintain in future years conditioning the automotive sector.

The Covid-19 pandemic partially affected this scenario. Companies and manufacturing ceased production and assembly during the early part of 2020 when most of countries established lockdown. People were not allowed to move from home except for essential needs. These mobility restrictions caused a considerable drop in production and sales. The reduction in vehicle manufacturing is estimated at 19.6% in 2020 [36]. However, the impact of novel coronavirus on automotive industry is expected to be low compared to long term growth for the next years. The restart should give a big input to the market starting from the last month of 2021. An important role in this scenario is played by vaccination campaign and economic recovery.

A vehicle cannot operate without brakes, which are fundamental elements to drive the vehicle and grant safety. Therefore, braking system industry has been growing at the same pace of transport sector. The industry report edited by Mordor Intelligence [37] analyzes the market of automotive brake systems between 2020 and 2026. In this range of time, it is expected to grow, especially in Asia-Pacific. In 2020 this market is valued at 28.81 billion USD, while in 2026 its projected value is 35.71 billion USD. Consequently, the Compound Annual Growth Rate (CAGR) for the global market, which measures the average rate of growth, is evaluated at 3.57%. MarketsandMarkets [36] presented similar results on its trend report. In 2021 the market is estimated at 20.9 billion USD while in 2026 its projected value is 26.5

billion USD. Then the CAGR is 4.9%. A comparison with the previous study evidences a lower market value but a higher growth rate. Regardless of the exact values presented by the two organizations, both expect that the market will grow in the next years.

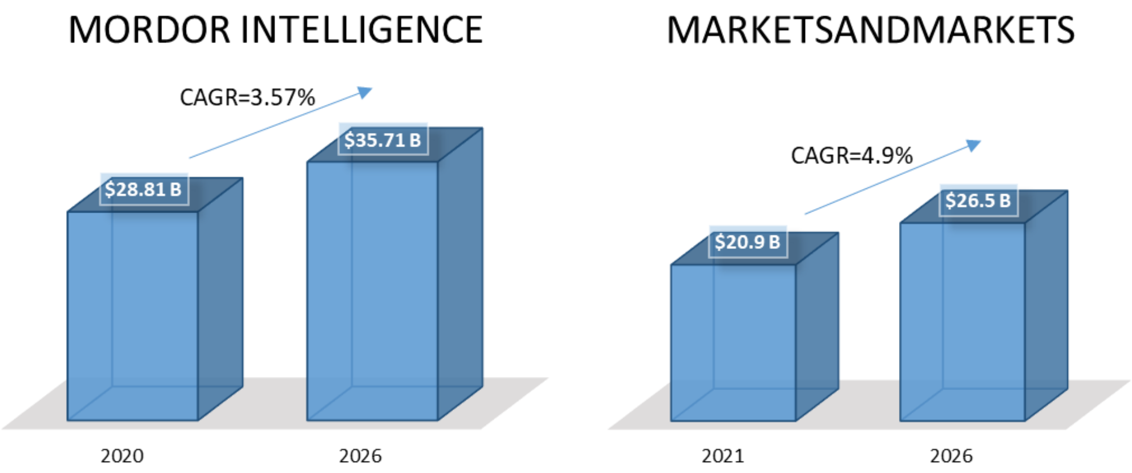

Figure 5.1: Automotive brake market value

Asia-Pacific is the main player of this market. The higher economic growth rate of this region linked to low-cost labor and raw materials allow to cover a large part of global demand. China and India represent almost 34% of overall vehicle production [37]. China is expected to be the major country to support the market of electrified vehicles. India, Japan, and South Korea introduced regulations to avoid accidents obligating the companies to install anti-lock braking system.

Development of new technologies, in order to achieve better performance and safety, is having a positive effect on global market. Anti-lock braking system, electronically stability control, anti-collision and brake by wire are often implemented in new vehicles to prevent accidents. In general, every technological enhancement, new functional element or control strategy represents a driver for the growth of brakes market. Investments in research and development are the main input for this purpose. Obviously, all these additions must deal with higher cost of the vehicle, which is desirable only for a customer who is willing to pay for it. On the other hand, sales of premium and luxury vehicles are expected to grow, therefore boosting the diffusion of these technologies.

5.1.2 Regenerative Braking Market

To better understand the trends of brake industry, a specific focus on automotive regenerative braking market must be adopted. The industry report edited by Global Market Insights [38] analyzes the automotive regenerative braking market between 2021 and 2027. In this range of time, it is expected to grow more quickly compared to total brake market, especially in Asia-Pacific. In 2020 this market is valued at 4.73 billion USD, while in 2027 its projected value is 18.51 billion USD. Consequently, the CAGR for the market is evaluated at 22.4%. This positive trend represents a great business opportunity for companies that operate in this sector. The high growth rate also attracts investors to finance in research and development.

Stricter policies in terms of emissions have been promoting a shift from conventional vehicles to hybrid or electric. The BEV demand is expected to greatly grow in next years. The request in 2027 is set to 45 million units [38]. This is the main driver for the growth of regenerative braking market.

Electrical regeneration is used on every electrified vehicle in wide range of architectures and different prices. In non-rechargeable hybrid vehicles, it is fundamental for battery recharging. The amount of energy that could be regenerated depends on the electrification level (electric machine dimension and battery capacity). Electrical regeneration is a good instrument to increase efficiency, autonomy and reduce power losses. The implementation of this system allows to face newest regulations for tailpipe emissions. It also creates attractiveness for customers, giving a big growth potential to this market.

5.1.3 Major Companies

Some of the biggest companies in the automotive brake system market include Advics Co. Ltd (Japan), Brembo SPA (Italy), Akebono Brake Industry Co. (Japan), Robert Bosch GMBH (Germany), Continental AG (Germany), ZF Friedrichshafen AG (Germany), EBC Brakes (United Kingdom), Aisin Seiki Co, Ltd. (Japan), Knorr-

Bremse AG (Germany), Mando Corporation (South Korea), Hitachi Astemo Ltd. (Japan), Haldex AB (Sweden) etc. These companies form a fragmented network all around the world so many other players operate in the market and could be listed. This causes a highly competitive environment without dominant players and really various products range.

Many companies are involved indirectly in this market. Brake system manufacturers collect raw materials, semi-finished products, and component from external suppliers to obtain a finished product for the vehicles.

5.2 Patents Analysis

Patent [39] is a powerful instrument for a company to grant and preserve the exclusivity of an invention. Invention is the general term that refers to a new device or strategy to solve a problem or fulfil a certain function. Patent's owners control manufacturing, use, distribution, and sale of their invention. This gives to the company a competitive advantage on the market.

Patents analysis offers the possibility to understand researchers focus on current and future technologies. These documents highlight a problem and propose the patented device as solution. Patent characteristics and usage provide useful details on possible evolution or enhancements of analyzed technology.

5.2.1 Magnetorheological Fluid Brake

The MRF brake for vehicular application designed and patented by Wu Xiangfan et al. [40] uses the same principle of MR fluids introduced at Paragraph 2.1.5. The document reports the main issue of existing brakes, which is the fluid gap dimension between disk and case.

Most of brakes adopt a small gap to obtain a larger torque when magnetic field is applied. However, this configuration causes high viscous resistance even when brake is not operating (null magnetic field). Consequently, a big amount of energy is dissipated while driving the vehicle, reducing its efficiency. The viscous friction generates heat that accumulate on the fluid increasing the risk of damaging the system. The possible solution to reduce viscous dissipation is to increase fluid gap dimension but this causes inevitably torque reduction. Fluid gap is then a compromise between these two conditions.

The patented invention is a MRF brake equipped with two disks and three excitation windings. The cavity between disks is filled by the magnetorheological liquid. The most important parts are retractable blades that can move between right and left disks thanks to a gear mechanism and tension springs. The clearance between disks is large so viscous resistance when coils are not excited is low. Energy losses are also low and fluid overheating is avoided. This configuration grants braking stability. Brake blades realizes braking occupying the vane between disks when magnetic field is generated. This allows to reduce fluid gap obtaining high torque only when brake is activated.

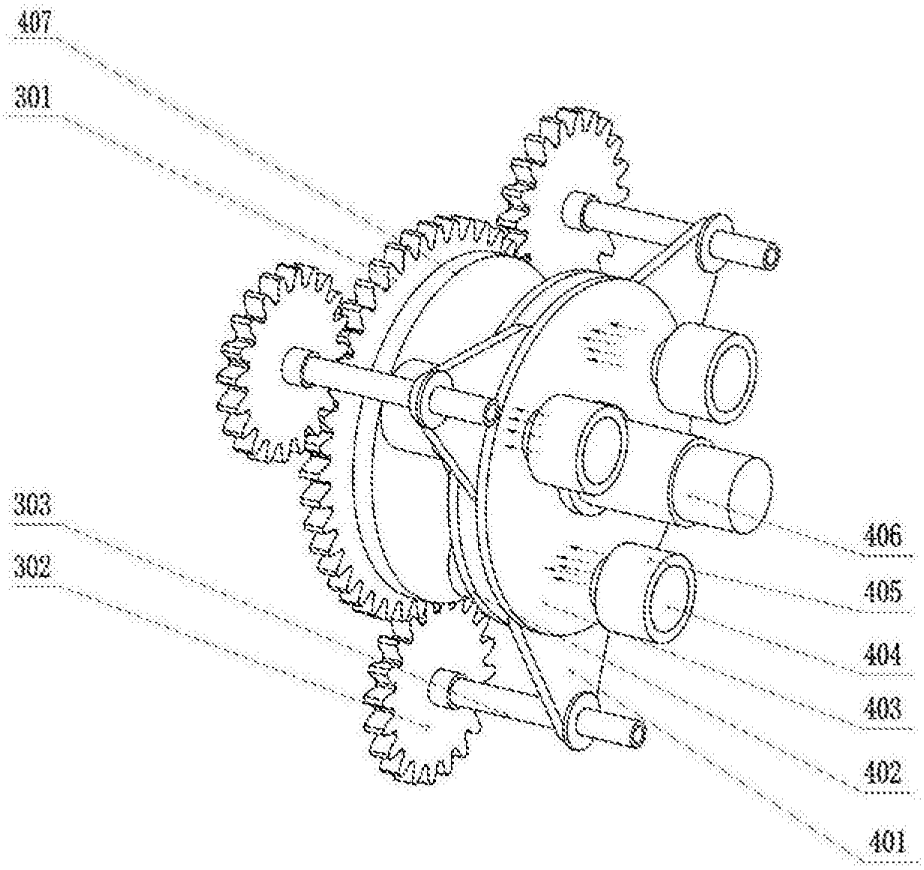

Figure 5.2: Patented MRF brake – structural view

The elements reported in Figure 5.2 are: large gear (301), pinion (302), blade shaft (303), brake blade (401), left brake disk (402), right brake disk (403), iron core (404), electromagnetic coil (405), rotating shaft (406) and magnetic conductive plate (407).

5.2.2 Brake Resistor

The brake resistor patented by Aijun Dai et al. [41] and assigned by the company Nantong Milante Electric Co is a device developed to dissipate the kinetic energy of a moving object to heat. It is suitable for elevators, subway, and vehicles. The purpose of this resistor is to design a simple structure reducing costs.

The outside of the resistor is a metal shell to better dissipate heat. High resistance wire is used to convert electrical energy to heat. Wire is covered using fire-retardant finish to protect it when high temperature is achieved. Resistance wire is wrapped on ceramic core and arranged inside the metal shell. A line is used to connect the resistor with generator.

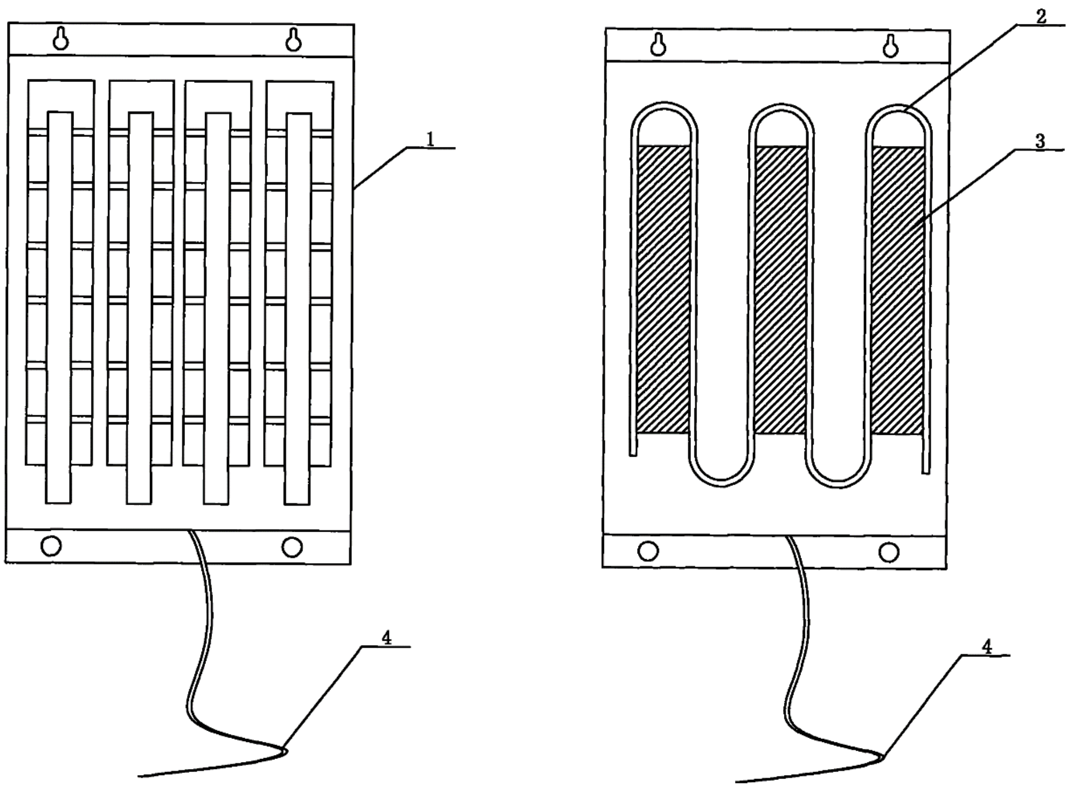

Figure 5.3: Patented brake resistor

The elements reported in Figure 5.3 are: metal shell (1), resistance wire (2), ceramic core (3) and connecting line (4).

This device has really simple architecture and low cost. It helps electric machine to quickly reduce its speed adsorbing energy and avoiding risk of damage. Resistors protect the battery of the vehicle or the electrical grid from voltage ripple or overvoltage.

5.2.3 Eddy Current Brake

The axial electromagnetic retarder patented by Zeng Gang Liu [42] and assigned by the company Telma is a device studied to reduce the speed of a rotating machine. This brake works thanks to eddy currents phenomenon and can be used both for a vehicle or a test bench.

The stator is merged with a hollow shaft. This element is coupled with the second shaft, which is linked to gearbox, and third shaft, which is linked to load. The stator comprises electromagnets formed by coils excited by Direct Current. Two rotating

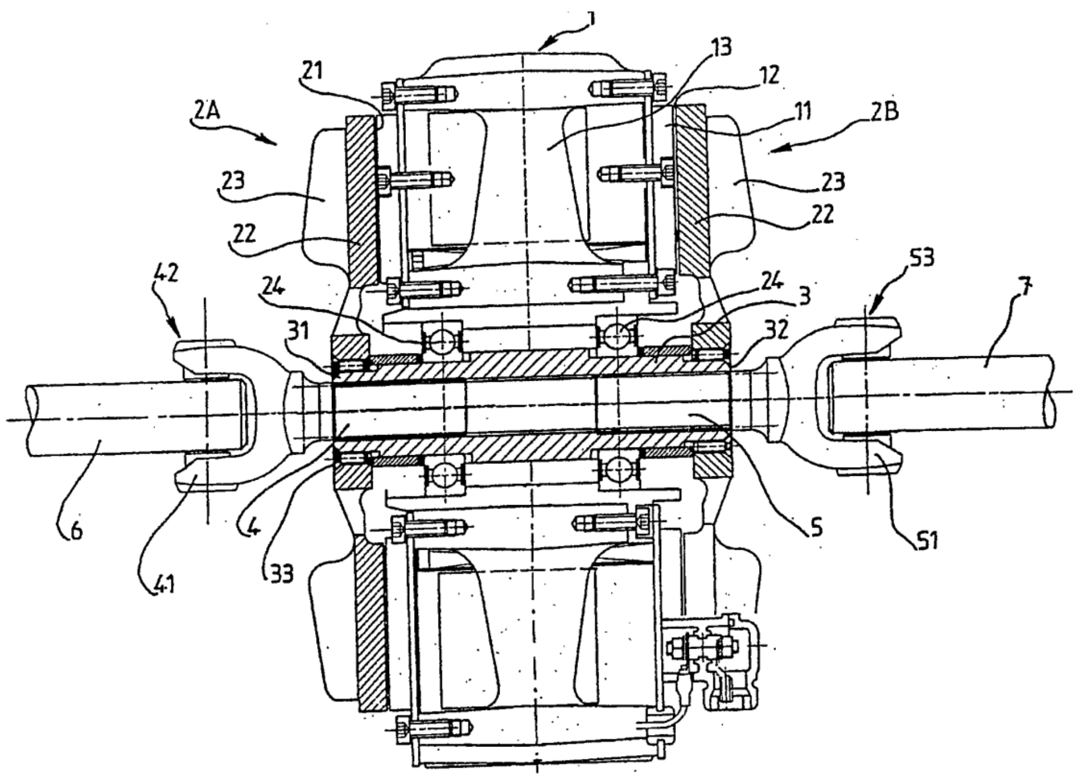

Figure 5.4: Patented electromagnetic retarder

disks are mounted on the shafts each facing the opposite side of the stator. Thin airgap is used between disk and stator. The rotors are finned to promote heat exchange.

The elements reported in Figure 5.4 are: stator (1), external face (11), airgap (12), coils (13), disks (2A-2B), internal face (21), annular ferromagnetic part (22), cooling ribs (23), ball bearings (24), first shaft (3), first shaft ends (31-32), bolts (33), second shaft (4), jaw end (41), cardan joint (42), third shaft (5), jaw end (51), cardan joint (53), motive source (6), load (7).

This ECB can be mounted on the transmission shaft of a truck or bus. The axial sliding of the shaft is integrated in the retarder thanks to three-shaft configuration. Consequently, the use of retarder not only adds a useful feature but also allows to reduce the number of components, so limiting weight. Weight reduction is evaluated around 20 kg. In addition, this layout allows cheaper and faster installation on a conventional vehicle.

5.2.4 Regenerative Braking System – Electric Machine

The regenerative braking system patented by Joo Gon Kim [43] and assigned by the company Mando Corporation relates to a vehicular system that recover energy during braking through electric machine. Braking operation is then obtained using both generator and friction brakes. Priority depends on driving conditions and driver input. The power adsorbed by electric machine and delivered to the battery must be the highest possible to reduce the use of conventional brakes. However, it must be controlled and limited to avoid damages.

The system analyzed in the patent refers to a FCEV. The fuel cell provides the energy to supply the induction motor which drives at least one of the front wheels. Bidirectional inverter is used to convert DC to AC in driving mode and AC to DC in regenerative mode. Recovered energy is stored in a battery pack.

Vehicle is equipped with four disk-brakes. Rear brakes are electro-mechanically actuated (EMB: Electro-Mechanical Brake) and controlled by dedicated EMB ECU. This system also has the function of ABS and ESC. Front brakes are hydraulically actuated by the driver foot and perform as primary brakes. The central ECU controls regenerative braking power and communicates with EMB ECU to engage calipers. The use of regenerative braking must deal with vehicle and driving conditions, driver intention of braking, state of charge of the battery and electric motor characteristics.

When regenerative braking power is determined, central ECU controls inverter and electric machine to recharge the battery. Also, ECU sends the driver intention of braking to EMB ECU, which controls the actuators on rear wheels.

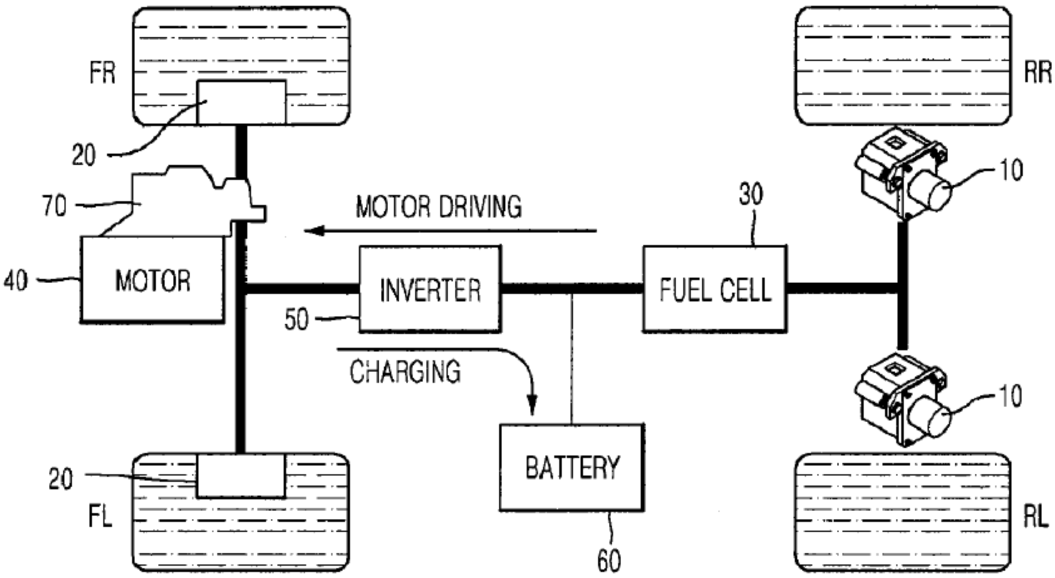

Figure 5.5: Patented regenerative braking system

The elements reported in Figure 5.5 are: EMB actuators (10), hydraulic disk brakes (20), fuel cell (30), driving motor (40), inverter (50), battery (60) and reducer (70).

Another possible configuration is presented in the document. The electro-mechanical brakes can be used in all four wheels. EMB actuators can control more rapidly and precisely the braking force, then the speed of the vehicle.

Jee WooK Huh et al. [44] patented a method for calculating the amount of regenerative braking for an environmentally friendly vehicle. This invention was assigned by Hyundai Motor Co and Kia Corp.

The regenerative braking calculation must consider charging limits, shift level and vehicle load. Charging limits refers mainly to battery restrictions. The state of charge and the temperature are critical parameters during charging, as discussed at Paragraph 3.2.

The method calculates the amount of regenerative braking considering the following steps:

- Identify the need of braking and regeneration
- Define charging limits due to high voltage elements (battery, electric machine, power converters)
- Calculate the base speed of the motor depending on charging limits
- Determine motor operating mode (constant torque, constant power, decreasing power)
- Calculate the amount of regenerative braking using previous results
- Apply braking torque through electric machine

This method allows to properly calculate the amount of regenerative braking. Consequently, recovered energy is maximized referring to a specific driving and environmental conditions.

5.2.5 Regenerative Braking System – Flywheel

The flywheel hybrid system patented by Alexander Serkh and Imtiaz Ali [45], assigned by the company Gates Corp relates to a flywheel used as kinetic energy storage on vehicle. More precisely, it is connected to internal combustion engine through belt system using a dual clutch layout.

Recovering energy allows to improve fuel economy. Differently from most of flywheel KERS, this patented device is used to drive engine's accessories. Recovered energy is used more efficiently compared to drive the vehicle.

A pulley is connected to the crankshaft of the engine. V-belt transmits the rotational motion to another pulley on the shaft, which is linked to three-speed gear transmission. Two clutches are then used to engage only the accessories or both accessories and flywheel. Pulleys and belts are again used to connect all these elements. This configuration allows to vary flywheel speed using the same transmission of accessories.

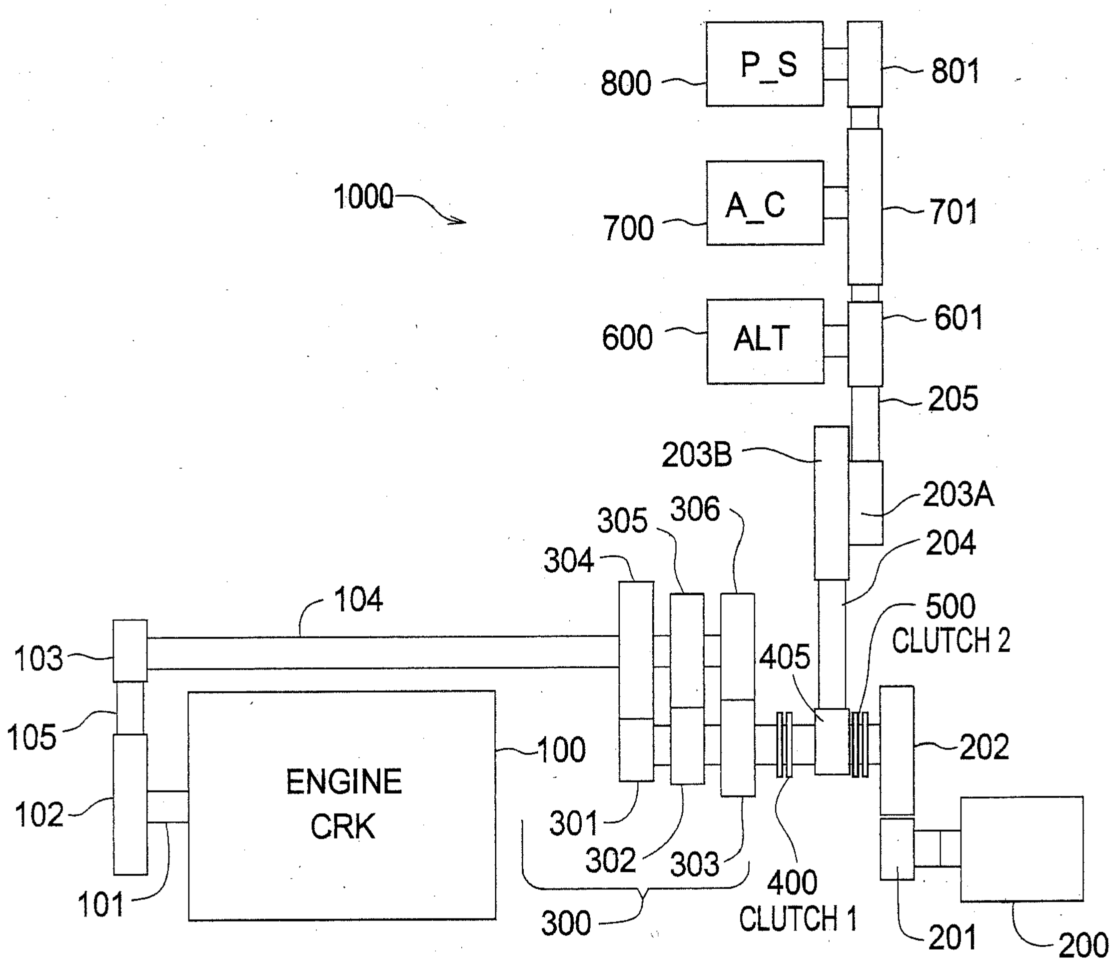

Figure 5.6: Patented flywheel KERS

The elements reported in Figure 5.6 are: invention (100), engine (100), crankshaft (101), pulleys (102-103), shaft (104), belt (105), transmission (300), gears (301-302-303-304-305-306), first clutch (400), pulley (405), flywheel (200), gears (201-202), dual pulleys (203A-203B), belts (204-205), second clutch (500), pulleys (601-701-801), alternator (600), air conditioning compressor (700), power steering pump (800).

Three possible modes are used. In the first mode, first clutch is open, second clutch is engaged, and flywheel supplies the accessories. In the second mode, engine-brake is used to reduce the speed of the vehicle. The clutches are engaged, the flywheel is connected so it charges increasing the resistant torque on crankshaft. In the third mode, second clutch is open, flywheel maintains its speed and engine drives the accessories.

The flywheel is disconnected when maximum speed (60000 rpm) is achieved during braking. When minimum speed (32000 rpm) is achieved while driving the accessories, second clutch is disengaged and first is engaged. Therefore, the engine drives the accessories.

6 Environmental Impact: Friction Brakes and Electrification

6.1 Friction Brakes

6.1.1 Brakes Wear

Conventional friction brakes grant great performances and safety. However, they are not optimal for environmental targets because of particulate matter emissions and energy dissipation. In addition, pad/lining wear involves regular maintenance and replacement causing more costs for the vehicle owner. The service life of rubbing elements depends on driving conditions.

The life of friction elements cannot be measured on vehicles in real driving conditions. The economic and time resources to obtain a statistically significant results would be prohibitive. Thus, wear is evaluated using prediction methods based on collected data in certain conditions [46].

Many methods calculate wear representing the average driving conditions and travel. The covered distance during test must be a tradeoff between costs and accuracy. Usually, the distance is from 4000 km to 16000 km [46].

Other procedures are based on dynamometer tests. Correction factors are used to adjust test results. These factors are obtained empirically comparing wear in driving condition and results of dynamometer test in specific circumstances. Wear maps can be used instead of factors to obtain the wear behavior in dependency of temperature, speed, and pressure.

Several enhancements can be introduced to improve brake sustainability. New materials and formulations allow to reduce wear or at least avoid ultrafine particles emissions. Recycling is also a fundamental aspect for reducing environmental footprint and establishing circular economy. High amount of rubber is used for tires and become waste that must be processed. End of Life Tire (ELT) can be reused for brake pads according to the scientific article written by Aitana Tamayo et al. [47].

Rubber is cryogenic or ambient grinded and particles are introduced at 3% into the composite of pad. This not only represents a good reuse of resources but also enhances adhesion by increasing the coefficient of friction.

6.1.2 Emissions and Air Pollution

Road vehicles emission sources are distinguished in exhaust and non-exhaust [48]. The former state for tailpipe emissions, so they come from the engine combustion process and lubricant vaporization. The latter state for pollutants that come from other sources such as brakes, clutch, tires, and road abrasion. Also deposited dust contributes to non-exhaust emissions because of particles resuspension due to traffic aerodynamic effect. Nowadays, non-exhaust category is not regulated, but largely contributes to PM_{10} (Particulate Matter 10 μm diameter) emissions and lowly contributes to $PM_{2.5}$ (Particulate Matter 2.5 μm diameter) emissions.

The World Health Organization (WHO) [48] reported that these particles represent a risk for human health. Increasing cases of diseases of the respiratory system due to short and extended exposure were observed. Ultrafine particles, which are the most dangerous, settle on air sacs of the lungs causing oxidative stress and inflammation leading to cardiovascular, respiratory diseases and lung cancer. Metallic particles also represent a risk for lung cells which reported tight junction damage after wear particles exposure.

Friction brakes are subjected to pad/lining wear and form airborne particles. The scientific review written by Theodoros Grigoratos and Giorgio Martini [48] reports useful information on this topic. Brake wear can contribute up to 55% by mass to the total non-exhaust traffic related PM_{10} emissions and 21% by mass to both exhaust and non-exhaust. The PM_{10} emissions show a unimodal mass size distribution with a maximum between 2 and 6 μm. Also, particle number must be considered because most of particles has small size, but overall mass is low. Particle number has bimodal distribution with both peaks in fine mode.

Most studies reported that the brake wear composition presents Fe (iron), Cu (copper), Zn (zinc) and Pb (lead) and organic carbon. Other metals were found at contents lower than 0.1%.

Wear debris is emitted engaging disk or drum brakes generating friction and heat. Pad or lining's particles are released in air but only 50% of them have a diameter smaller than 20 µm and almost 40% are PM_{10}. The biggest particles do not scatter in air but stick on the vehicle's wheels or settle on the road. The highest concentration of brake wear is observed next to stop signals, traffic lights, pedestrian crossing, intersections and in general on urban streets. It is instead low on highways where braking operations are usually less frequent.

Figure 6.1: Brake dust sediment

Due to increasing restriction of exhaust emissions, brake wear relative contribute will probably increase in future. This results in the possibility of having new policies for non-exhaust emissions.

The actual absence of regulation causes different approaches for particles evaluation, often obtaining no comparable results. This is a critical point to properly understand the phenomenon. Anyway, many studies [48] found out some parameters that affect emissions. The bulk friction material is clearly a fundamental characteristic, especially related to thermal behavior: particle size reduces increasing temperature. Other important parameters are: braking force, duration of pad engaging, vehicle's speed, vehicle and ambient conditions.

6.2 Vehicles Electrification

6.2.1 Electricity Mix

Nowadays, vehicles electrification is the main solution adopted by manufacturers to face the challenging targets imposed by climate change agreements. The first pursued goal of COP26 (Conference Of Parties) is to obtain global net zero emissions of Greenhouse Gasses (GHGs) by 2050 [49].

Electric machine is more efficient than internal combustion engine, but the effective advantage respect to emissions must be evaluated by using Well To Wheel (WTW) approach. The benefit of electric mobility on environment clearly depends on electricity mix used to charge the batteries. The market report produced by the International Energy Agency (IEA) in late 2020 assesses the energy mix by region. The histogram presented in Figure 6.2 [50] highlights the contributes of nuclear,

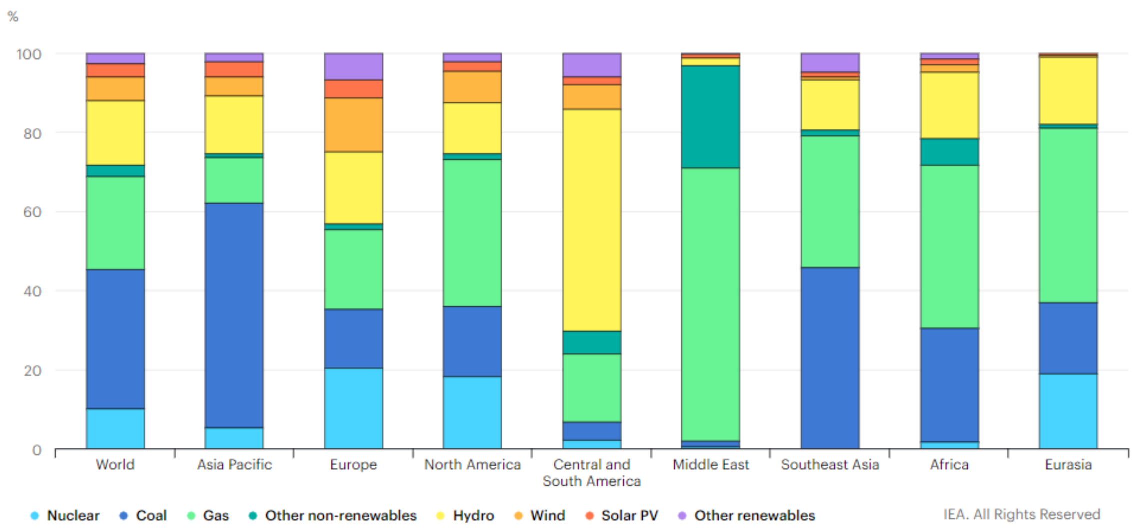

Figure 6.2: IEA electricity supply mix 2020

coal, gas, hydro, wind, solar and others for electricity production. Renewable sources showed large increase while coal, gas and nuclear reduced their production. This is partially due to low energy demand during pandemic period. Unfortunately, the world electricity generation is still based on coal and gas combustion. These sources cover more than 50% of global energy demand.

6.2.2 Battery Pack Weight

The battery pack on electrified vehicles negatively affects vehicle weight. Consequently, electric motor needs more energy to drive the car. As said at Paragraph 3.1, batteries have low energy density compared to fuels. Also, fuel gradually depletes on tank due to engine combustion process. Battery weight instead remain constant even if it is completely out of energy. Casing, management system, and cooling systems add weight and further reduce energy density. The additional weight according to the article written by Ching-Shin Norman Shiau et al. [51] is around 1 kg per kg of battery. This value changes depending on the vehicle type and design.

The additional weight of electrified cars also conditions the brake system. The use of regenerative braking reduces the effort on friction brakes so the effect of overweight could theoretically be compensated. If electric machine size is sufficiently high, even brake downsizing could be possible. However, due to limitations of regenerative braking (see Paragraph 3.1.3) and to grant safety for drivers and passengers, friction brakes must be designed to deliver the maximum torque necessary to stop the vehicle.

6.2.3 Commodities

Metals and rare earths are fundamental assets for automotive industry. This sector is a relevant consumer for many materials and this trend is expected to increase in future. Therefore, materials demand for vehicles must be included to define the Life Cycle Assessment (LCA). The main considered parameters for this count are mass and rarity, which is a measure of energy needed to mine the commodity.

The study written by Marta Iglesias-Émbil et al. [52] considers two C-segment vehicles manufactured by SEAT. One of them is a gasoline-powered Internal Combustion Engine Vehicle (ICEV) and the other is a BEV, which uses a nickel-manganese-cobalt lithium-ion battery. Three combinations of materials in the battery are analyzed, so the contribute of elements is variable.

Almost 50 different metals are used in both vehicles. However, the mass of some elements is quite higher for BEV. Lithium demand is 4 g for ICEV, while is about 6-8 kg for BEV. BEV also requires 23-44 kg of Nickel compared to about 3 kg for ICEV. Cobaltous is about 5-23 kg for BEV, while is 22 g for ICEV. Also iron, aluminum and copper demand is higher for the electric vehicle. The overall vehicle is about 530 kg heavier than ICEV. Nowadays, these metals are largely diffused on earth crust and meet the current demand but could be lacking in the next years due to increasing electrification. Cobaltous is instead a critical asset for automotive industry because of low concentration and high extracting costs. This highlights the relevance of battery design in terms of material choice.

Another aspect connected to environmental impact of materials is recyclability. Often elements are used in form of alloys. Also, some elements are dispersed in most of vehicle parts in low concentration. For example, niobium, molybdenum, and vanadium are used in steel alloys to enhance their structural characteristics. In these cases, recovery is difficult or not possible. Furthermore, even if recycling is feasible in some conditions, higher costs and environmental impact could be prohibitive compared to mining.

6.3 Friction Brakes and Regenerative Braking

The combination of friction brakes and regenerative braking is largely diffused on electrified vehicles. Even if this does not allow brakes downsizing, it reduces the involvement or at least the load on conventional brakes. Wear and particulate matter emissions are consequently limited, and service life is extended.

The positive effect in terms of wear provided by regeneration is calculated using consumption data collected after test drive. The conference paper written by V. A. Rakov [53] considers the hybrid vehicle Toyota Prius ZVW30. Pads and linings wear is evaluated measuring their mass and thickness before and after the experiment.

The starting condition for the test imposes the replacement of all rubbing elements, including brake fluid. The other components are lubricated and checked. The test consists of 50 cycles, in which the vehicle is accelerated from null speed to 40 km/h and decelerated to a complete stop. The first test is completed using only friction brakes, while both electric machine and brakes are used in second test. The total wear using only brakes is 2.1 g, while using recovery is 0.8 g. Wear is reduced by almost 62%. Regeneration allows to adsorb a large part of braking energy and limits pad wear.

6.3.1 Series and Parallel Braking

The best way to maximize energy recovery is to reduce as much as possible the use of brakes. The purpose of control strategy is also to minimize braking distance and optimize recovery. Consequently, a correct repartition of braking torque between friction brakes and electric machine must be adopted. There are two control strategies: series braking or parallel braking [54].

In series braking, if demanded deceleration is low, then all the torque is applied by the electric machine to fully recover the kinetic energy. The resulted behavior is similar to the engine brake on conventional vehicles. When demanded deceleration is high, braking torque is delivered by the generator and friction brakes. In this case, brakes are engaged only if demanded deceleration is greater than electric machine's maximum.

To better understand the process of series braking, a rear-wheel drive electric vehicle is considered. When the driver presses the brake pedal, BBW system analyzes the signals and activates the best control strategy. Braking torque demand is divided between the two axles and most of it is generated by front disk brakes. Thanks to power electronic converters, supply frequency of the motor is changed. The electric machine works as a generator braking rear wheels. Consequently, the vehicle reduces its speed. If the driver presses deeper the pedal and the generator cannot adsorb more energy, ECU controls electro-mechanic or electro-hydraulic actuators to engage disk brakes on rear wheels.

In parallel braking, regenerative braking and friction brakes are used together (in parallel). Electric machine adds a certain amount of braking torque to increase deceleration realized by conventional brakes. However, if deceleration is higher than 0.8g, regeneration is not used to maintain the braking balance of the hydraulic system. Also, if low deceleration is demanded, only generator is used to simulate engine brake as in series braking.

Parallel strategy is simpler compared to series because it uses a conventional hydraulic actuating system. Electric machine is controlled by a pressure signal on the master cylinder. So, this system can be integrated on an existing braking system avoiding design. Instead, for series strategy Brake By Wire is necessary to engage the brakes at the right moment. In this case, a dedicated system must be designed. However, recovered energy is quite lower in parallel compared to series, reducing positive effect of regeneration. Even driver feeling is worse.

Conclusions

This master thesis presented the state of art of brake system, particularly focusing on frictionless technologies. Friction-based brakes are the most used in automotive sector thanks to their reliability and resistance to high stresses. Conventional brakes offer the best performance in term of braking. However, they cause energy dissipation and particulate matter emission, which negatively influence climate change and human health. MRF brakes replace pads with fluid, thus eliminating PM emissions. Nowadays these prototypes can reach lower braking torque values than drums and disks. The biggest challenge for future is to find a fluid that presents high performance in term of yield stress but also good thermal stability.

To solve the issues related to rubbing elements, frictionless system can be adopted. Dissipative and regenerative devices were considered. Both strategies eliminate wear, but recovery also reduces energy losses increasing vehicle efficiency. ECBs performance presents a dependency of speed that prevents the use as the only braking system. The best application is as a retarder, which reduces the effort and usage of conventional brakes. Brake resistors allow to efficiently dissipate the electrical energy generated by electric machine. However, generator is preferably used to recover energy. Electrical recovery is nowadays widespread on many cars thanks to the establishment of electric and hybrid vehicles. Using only regeneration could be theoretically the “silver bullet” for sustainable mobility but is not applicable due to many limitations. One of the main issues is related to the position of electric machine, which is a compromise between traction and recovery. A four-wheel drive partially solves this problem. The braking torque of electric machine is acceptable for urban driving but drops at high speed. In some cases, a two-speed gear transmission is used. Electrical generation is also limited by power converters, battery, and supercapacitors. Flywheel could be adopted for kinetic energy recovery instead of using electric machine and accumulators. Anyway, it is not suitable for passenger cars requirements and does not match with electrification establishment. Consequently, flywheel is hardly used on vehicles.

In order to achieve optimum performance, maintain the vehicle safe and reduce the impact on environment, the best solution seems a combination of regenerative braking, using electric machine, and dissipative braking using both friction and frictionless system. There is a trend in decreasing the use of conventional brakes as much as possible. Frictionless braking is a valid strategy for automotive sector and more common use is expected in the future years. However, the complete abandonment of friction technologies does not seem a viable solution.

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