Dissipate energy: the different braking means

As the control devices have been rather improved since Georges Westinghouse invention, in particular for urban vehicles with the introduction of analogic and digital electronic, the means for dissipating energy of a train and slow it down or stop it have really made huge progress only quite recently.

Indeed as the braking control slowly but surely evolved all along the 20th century (brake engineers are cautious guys...), braking technology has not been modified from 1900 to the beginning of the years 1960: the tread brake with cast iron shoes was the only used technology thanks to its interesting performances in terms of brake force, but mainly thanks to two important advantages: a good insensitivity of friction coefficient to wet conditions and a very low purchasing cost.

Anyway, the years 1960 corresponded to the beginning of race for speed, while vehicles weight increased following integration of more and more comfort functions (in particular air conditioning). Cast iron shoes and their very low friction coefficient required brake application forces that where inaccessible with the brake cylinders sizes and amplifications that were used at this time. Moreover, the high energies to be dissipated (+50% when operating at 200 kph instead of 160 kph, and +170% when operating at 200 kph instead of 120 kph) were incompatible with a solicitation of the wheels only, which metallic characteristics could have been severely altered (with resulting consequences that can be imagined!).

Thus new braking technologies had to be developed. The most important innovation has been the application of disc brake to railway vehicles. Also were developed at this time the magnetic track brake (pads applied on the rails) as well as the electrodynamic brake (use of traction motors as generators to produce a retarding force. We will see how these different technologies are born, and how they evolves since today.

The dynamic brake

The friction brake naturally presenting a wear – and thus representing a maintenance cost – the possibility offered by some devices to produce a retarding force without wear has been used for a long time.

The principle of the dynamic brake relies on the use of train inertia to produce a brake force: the train shall thus be in motion for this purpose.

The dynamic brakes in use on railway rolling stocks are:

- The electrodynamic brake, which is associated to an electric or diesel-electric traction chain.
- The hydrodynamic brake, which is associated to a traction chain combining a diesel motor and a turbo-transmission.
- The eddy current brake.

The electrodynamic brake

When a generator draws current into a charge (e.g. a resistor) appears on its drive shaft a resisting force that tends to slow it down. This is true whatever the type of generator is: direct current, synchronous or asynchronous. Only the ways to initiate the process and keep are different.

Thus an electric traction motor, whatever its type is, can naturally be used as a generator in order to produce a brake force which in turn will slow down the cause of its movement, i.e. the axle to which it is mechanically coupled by means of the transmission.
So was born the electrodynamic brake, which can be of two types:

- **Rheostatic** - Traction motors draw current into resistors onboard the vehicle, these resistors then dissipating the energy in form of heat to the atmosphere.

- **Regenerative** - Traction motors draw current into the high voltage power supply line, the energy that is fed back being possibly used by the other trains or fed back to the power supply network by means of the sub-stations.

The rheostatic brake provides the advantage of being able to be implemented independently of any high voltage, thus in particular for a diesel-electric vehicle. However, the braking energy is dissipated in vain.

The regenerative brake provides the advantage to get back the braking energy, thus to significantly improve the economical balance of vehicles operation. Anyway it requires:

- Installation on board the vehicle of motors power supply equipment that is reversible and performing in order to be able to feed back in the power supply line a current which characteristics are very near to the one supplied by the sub-stations, i.e. little polluted by harmonics.

- Presence of consumers at the same time on the power supply line, storing the electric energy being not possible. Thus this type of brake cannot be used during off-peak hours (first and last trains), or requires reversible sub-stations (thus a little bit more expensive) to feed back the energy to the provider (EDF in France). This last topic is not always in use, taking into consideration the constraints of “purity” of fed back current specified by the electric energy providers.

All urban (trams, metros) and suburban (trainsets) rolling stocks are equipped with the regenerative brake, the frequency of braking rendering obvious the economic interest of energy recovery. However it shall be noted that some vehicles (in particular trams) are equipped with both types of brakes – rheostatic and regenerative – in particular when the mechanical brake remains thermally quite under-designed for reasons of available space in the bogies and when the substations are not reversible for cost reasons.

The rheostatic brake also has another advantage: using an appropriate design of power equipment and its control electronics, the rheostatic brake can be considered as fail-safe thus can be taken into consideration for meeting performances required by the signaling system. Without this aspect, the TGV would probably be not developed, as the rheostatic brake makes it possible to address the fact that the reduced number of bogies (articulated architecture of the trainset) and the reduced available space in motor bogies does not allow installing a high mechanical brake power.

Finally it shall be noted that some specific constraints – that are independent of the rolling stock – can highly influence the choice for the type of electrodynamic brake. Thus in France, regenerative braking is possible everywhere with a 25 kV AC power supply although the network is splitted in portions of 50 km (for balancing the connections to the EDF network), sub-stations being systematically reversible. It is the same in Germany, with the advantage that DB Netz supplies all its lines from a unique power network, without a phase shift: thus there are no more systematic splits in the power supply line, which makes it possible to systematically guarantee that a train – thus a consumer – is present in the vicinity. This is the reason why DB vehicles have quite never been equipped with rheostatic brake.

However, regenerative brake is very difficult with the 1500 V DC power supply in France, because of necessity for the driver to be able to detect at any time a disappearance of the high voltage power supply: switching off this power supply is indeed an efficient way to warn him about a danger, and this switching off shall lead to emergency braking initiation by the driver. But if this high voltage power supply disappearance detection during regenerative braking is easy if this power supply is an AC one – by detection of harmonics – it is however very difficult when the power supply is 1500 V DC.
The hydrodynamic brake (or retarder)

The hydrodynamic brake corresponds, for a hydrodynamic transmission, to the electrodynamic brake for an electric traction chain.

It has been developed to enable dynamic braking (thus without wear) on diesel trainsets and locomotives that are equipped with a hydrodynamic transmission (gear box integrating a hydraulic coupler and a hydraulic torque converter).

The principle is very simple: it consists in injecting oil fluid under pressure between two cups that are equipped with radial fans, and turning one in front of the other (the stator is fixed to the gear box carter when the rotor is connected to the drive shaft driven by the axle). The fluid pressure associated to its viscosity generates a retarding force which can be modulated by acting on the fluid pressure. To stop brake force, it is enough to totally drain the brake.

Operating principle of the hydrodynamic retarder (Document VOITH)

The energy is dissipated in form of heat in the hydraulic fluid, which permanently circulates in the brake and is cooled down by means of the oil/water exchanger of the gear box (the water cooling circuit being generally the one of the diesel traction motor). The hydraulic fluid is the one of the transmission, used for coupling or torque converter during traction phases, and in the hydrodynamic brake during braking phases.

A pair of shutters partially closes the brake when not used for braking, in order to avoid overheating due to stirring by rotor fans of the air injected in the brake after it has been drained at the end of braking (and then as a possible consequence the self-ignition of the rests of hydraulic fluid in the brake…). This provision also reduces the resistance of the hydrodynamic brake during traction that could be generated by stirring of air between fans.
This type of brake is particularly efficient over 50 kph, provided that the cooling systems of the gear box and the motor are correctly designed. Thus it is successfully used on several diesel trainsets, such as X 2100, X 72500 and X 73500 series in France.

The eddy current brake

This type of brake exists since the beginning of the years 1970, but its railway history is a sequence of hopes and renunciations in Europe, when it has been implemented at a time on Japanese Shinkansen trainsets in its rotating type, and when it is successfully implemented on several buses and trucks (in form of the famous TELMA brake, of the name of the company that designed it).

The principle is based on the phenomenon wherein a magnet moved in front of a metallic part induces in the latter currents (eddy currents) that, in turn, produce a magnetic force that is opposite to its origin, i.e. to the motion of the magnet (Lenz law).

Two types of eddy current brakes are in use in the world, a third one having been subject to short time tests on the TGV 001.

The SENF brake

First eddy current brake to be used in railway field, the SENF(Sans Entrefer Ni Frottement: without gap nor friction) brake consisted in the generation of eddy currents in the wheels thanks to coil installed around the latter, in the upper part and fixed on the axle boxes. Eddy currents were also induced in the rails due to the relative vicinity of the coils to the rails, generating a complementary force that was independent of the wheel-rail adhesion.

Tests have shown the efficiency of this brake, supposed besides to reinforce available adhesion by magnetic effect at wheel-rail contact. But their main drawback was to notably increase the unsprung weights, which is unfavorable to very high speed applications, and to remain anyway dependent on the wheel-rail adhesion. May be this type of brake was also too much ahead of his time…

The rotating brake

Generalized by Japanese on trailer bogies of some Shinkansen trainsets series since the end of the years 1980, the rotating eddy current brake consists in installing on the axles discs that are similar to those used by the mechanical brake, but in which eddy currents are induced thanks to coils, and that in turn produce a brake force.

Thus it is simply the railway version of the TELMA retarder…
However, its main drawback is to be completely dependent on the wheel-rail adhesion, the portion of this adhesion used by this brake being no more available for the other types of brakes (electrodynamic or mechanical). Moreover, its efficiency quickly decreases with the speed.

Its main advantage is to generate no wear, as there is no friction, to be fully adjustable (the force being proportional to the current in the coils on a wide speed range) and to be able to be supplied from the electrodynamic brake (by the current produced by the traction motors operating as generators).

**The linear brake**

In order to be independent of the wheel-rail adhesion and to fully benefit of the complementary deceleration that can be provided by this type of brake, pads have been installed between the wheels in the bogies, with an integration that is similar to the magnetic track brake.

The principle is here to generate in the rails longitudinal magnetic fields which deformation due to motion produces eddy currents, which in turn produce a brake force. North and South poles are here alternate in the longitudinal direction, contrary to the magnetic track brake.
To operate, pads shall be brought to the vicinity of the rail, the air gap being of ca 8 to 10 mm: this implies that when not in braking, they shall be lifted up, when in braking position they shall be lowered thanks to pneumatic actuators.

Moreover, operation is optimal only if the air gap is kept sensibly constant throughout braking: this requires that pads are clamped on a reference that is under the primary suspension, i.e. on the axle boxes. But in this case they become an unsprung weight, and this heavy weight (ca 1200 kg for the two pads and the associated frame) is hardly compatible with operation at very high speed (which required a strict limitation of unsprung weights). This aspect also explains that it is necessary to lift them up when not in braking and that they require stops devices on axle boxes, which are adjustable, so that a constant air gap can be obtained on the whole wear range of wheels.

Moreover it has another drawback: the brake force quickly decreases with the speed under 200 kph, when the attraction force between the pad and the rail exponentially increases when the speed decreases, which forbids its use under around 150 kph, because of the risk to rip out the rails or(and) to deform the bogie frame (and the pad !). It is then reserved to high speed range.

Anyway this type of brake has the high advantage to be without wear, and perfectly adjustable (as the rotating one).

The first tests have been performed on the TGV001, then this brake has been shelved as its utility for the TGV-SE has not been demonstrated. Anyway, its promoter – the German brake supplier KNORR Bremse – has pushed forwards its optimization as it was one of the brakes planned for ICE1. Its abandonment in Germany for the ICE1 following too frequent disturbances of track circuits on classical lines have put it back on the table in the frame of TGV-NG development in France, for speeds of 350 kph (it will also be tested on a TGV Réseau trainset in two versions, one corresponding to the existing product of KNORR Bremse, the other developed by GEC ALSTHOM). But the TGV-NG project will not have immediate application, and the linear eddy current brake goes back in the drawers… to appear again in Germany, where it is now implemented on ICE3 and VELARO-D series trainsets. Will it have a comeback in France soon ? The future will tell…
The tread brake

The tread brake has been naturally the first type of brake to be used in the railway brake history: it was obvious to slow down a train by simply slow down the rotating movement of the wheel; as this was done for the existing transportation means before grow up of railways (diligences, cabs, etc.).

This braking means remained over more than a hundred years the only means to produce a brake force and dissipate energy. Three technologies have followed one another over the time, all of them still existing today.

The tread brake with wood brake shoe

First railway vehicles have simply been realized by adapting a diligence car body on a railway frame. It was thus of evidence that the brake system should be kept as it was existing on the horse-drawn vehicles, and first railway vehicles have been braked by means of wood shoes.

Wood also has the advantage to be available everywhere, to be cheap and to have correct friction characteristics that are known since a long time.

However its energy dissipation capacities have rapidly shown their limits faced to the increase of vehicles weight and operating speeds of trains, leading to its replacement by cast iron.

But this material came back on the railway scene in the years 1950 with the development of rubber tires metros. Indeed at this time the railway disc brake did not exist, and the only way to brake these vehicles was the auxiliary wheel, a wheel associated to the tire in order to enable:

- Operation in shunting mode of these trainsets on steel rails lines
- Operation in back-up mode in case of flat tire
- Guiding in track switches, the latter remaining classical on lines that have been converted to tire version.

However this auxiliary wheel having energy dissipation capacities and mechanical characteristics lower than a classical railway wheel, it should not be solicited in a too heavy way. But cast iron, in force at this time, has revealed as too aggressive. Thus use of wood turned out to be the most adapted solution, and this is why the rubber tires metros have been equipped with wood brake shoes until the years 1990. And today old series (MP73 in Paris) still use this material.

Wood that is generally used is beech or wild cherry. After machining with the required shape, it is impregnated of oil by soaking during several weeks, so that the heat generated by braking produces in surface a carbonization of the material that enable a stabilization of friction characteristics.

Finally a typical example of recent vehicles delivered with wood brake shoes can be noted: the operator of the Montreal metro has required, for the last series in delivery, to keep this material for which he well knows the characteristics and that he manufactures by himself: thus wood will remain used during tenth of years in the 21st century.
The tread brake with cast iron brake shoe

Railway origins being more or less concomitant with the industrial revolution in Europe, the metallic material quickly replaces the wood as the friction element, and the cast iron, easy to manufacture (and in particular to mold with the required shape) becomes very quickly the ideal friction material solution. One of its main advantages is the insensitivity of the friction coefficient to wet conditions: this characteristic is fundamental for railway braking, for components that are permanently submitted to water, snow, etc. projections. We’ll see further that this characteristic has delayed for a long time the use of composite materials.

However, the cast iron shoe has four major drawbacks:

- Its wear is very rapid,
- Its friction coefficient is very low (ca 0.1 average, which means that the effective brake force obtained to slow down the train is 10 times lower than the one generated by the brake cylinder, or that a very high rigging amplification is necessary to get a significant brake force…),
- Its friction coefficient is not constant as a function of the application force: it decreases when the force increases, even reaching a limit over which the retarding force at wheel rim do not rise any more when the application force increases.
- Its friction coefficient is not constant as a function of the initial braking speed, but also of the instantaneous speed.

This last characteristic is rather disturbing, as it leads to a dramatic increase of this friction coefficient when approaching standstill: the friction coefficient can thus by multiplied by three between 50 kph and 0! As a result, the jerk when coming to the standstill can be very high, which is detrimental to passengers comfort and goods integrity, and requires skills of the driver. Those who frequently used Z 5100 trainsets of the Parisian suburbs necessarily remember of this inconvenience… For some rolling stocks equipped with high power brakes at the end of the years 1960, it was even necessary to install a provision enabling to generate two brake stages as a function of speed (over and under 50 kph) in order to make the best use of available adhesion at high speed without risking axle locking when approaching standstill.
Moreover, the cast iron brake shoe is very noisy on two aspects:

- During braking, it produces unpleasant squealing, in particular for environment.
- It roughens the wheel tread, creating on it micro-flats which in turn generate a rolling noise – thus when not in braking – that is highly increased in comparison with a wheel braked with a composite brake shoes, or with an unbraked wheel. Those using the TGV train station in Le Creusot before renovation of the TGV-SE trainsets certainly remember that it was easy to make a distinction between a non-renovated TGV-SE trainset and TGV Duplex or Réseau trainset when passing at very high speed, and with closed eyes!

This is the reason why the cast iron brake shoe has been almost banned from motorized (locomotives, trainsets) and passengers vehicles, when it remains widely used on wagons (essentially for cost reasons). But it shall be noted that this abandon is recent, as TGV-SE trainsets have used cast iron shoes until end of the years 1990 and that Corail coaches still use it and that some Parisian suburban trainsets are no more equipped since only ca 15 years.

Finally it shall be noted that specific cats iron have been designed, by introduction of phosphorus in a more or less important quantity (1 to 3%). The most current cast iron is the P10 one (1% phosphorus). Aim was to
reduce wear (in particular on urban rolling stocks with frequent braking phases), which has been verified. However, introduction of phosphorus increased the fragility of these shoes to shocks, and some manufacturing provisions (reinforcing frame) had to be met: The cost naturally felt the effects of it.

**The tread brake with composite brake shoe (also known as organic brake shoe)**

First tests of composite materials have been performed in the years 1940, in particular in the USA, based on products used in for automobiles. Even if the dry friction coefficient have been considered as satisfactory, on the other hand the wear remained very heavy due to the natural roughness of wheels treads, which rendered the economic balance unfavorable in comparison with cast iron (cost of composite material being notably higher).

Development of the disc brake in the years 1960 implied to use composite materials for brake pads. Indeed, discs - that are also made of cast iron - would not have resisted very long to aggressiveness of cast iron pads (and provided that weight of the latter would have been necessarily very high). Moreover, materials with high friction coefficient were required, as well as a higher thermal capacity.

Idea was thus naturally to tests again brake shoes made of composite materials. Resistance to wear has been improved by introducing a small amount of abrasive material in order to quickly polish the wheels treads in order to avoid a too quick wear of brake shoes, without wearing notably the wheel.

It shall be noted that the composite brake shoe includes metallic friction materials (cast iron, copper, carbon, metallic oxides, etc.) and an abrasive material (generally silica) aggregated thanks to a binder (synthetic resin). The latter produces a typical burnt rubber smell when braking has been a little bit strong…

International standards have then been issued to standardize the performances of these brake shoes, the composition of each material remaining however specific to each supplier. Three types of bake shoes have been defined:

- The K brake shoe, with high friction coefficient (0.25 average).
- The L brake shoe, with low friction coefficient (0.17 average).
- The LL brake shoe, with very low friction coefficient (0.10 average).

**Brake shoe made of composite material (document KNORR Bremse)**

For a long time, composite brake shoes have been forbidden when used alone, in particular because of their high sensitivity to wet conditions: the friction coefficient could then dramatically drop down during rainy days, and passengers of Montparnasse (Paris) suburban network still keep in mind the two accidents with Z 5100 trainsets equipped for tests with this type of brake shoes in the years 1970 (the last one having ended its run in the station master office…). However, suppliers have made huge progress on this topic, and composite brake shoes have then been widely used on several rolling stocks:
• K brake shoes ➔ Electric locomotives (BB 7200 / BB 22200 / BB 15000 / BB 26000 / BB 36000 and CC 6500) and diesel locomotives (BB 67400 and CC 72000), TGV power cars, suburban vehicles and trainsets (RIB/RIO, Z 5300, Z 6400, Z2N) and regional trainsets (X 72500), and some specific wagons.

• L brake shoes ➔ Suburban rolling stocks.

Moreover, LL brake shoes have been more specifically developed with aim to be able to replace in the future the cast iron shoes on the freight stock, in the frame of a wide project led by UIC with support of the European Community. Target was to dramatically reduce the rolling noise of freight trains, thus participating to modal transfer from road to rail. This project required however several years of work, the base target being to be able to replace the cast iron shoes without modification of the wagons: a challenge, taking into consideration the very specific friction characteristics of cast iron (see above). This project aimed anyway since some years to qualify for operation performing products which started to be mounted on wagons (in particular for container traffic), with spectacular results in terms of emitted noise.

However, it shall be noted that composite brake shoes still have some drawbacks:

• They are subject to metallic inclusions (particles ripped out of the wheel), which render them aggressive to the wheel.

• They polish the wheel tread, which is favorable in terms of rolling noise but unfavorable in terms of adhesion solicitation (see page on adhesion and wheel slide protection): their use is thus reserved, except particular case, to modern vehicles equipped with wheel slide protection devices.

• They have still limited thermal capacities, high temperatures leading to a risk of thermal fading phenomenon (important drop down, eventually to zero, of friction coefficient by thermal transformation of the resin on the surface of the brake shoe due to high temperatures). Their use thus remains limited to applications with average levels of energy.

The tread brake with sintered brake shoe

During the development of the TGV Atlantique, it appeared necessary to develop for motor cars – on which the architecture of the transmission rendered impossible the installation of brake discs on axles and in the wheels – a new type of brake shoe able to withstand the high levels of energies while having a low sensitivity to wet conditions.

The sintered material being under development in parallel for the steel disc brake, decision has been made to use also this type of material for the brake shoes.

These brake shoes combine the advantages of cast iron and composite, i.e.:

• High friction coefficient (0.25 average).

• Low sensitivity to wet conditions and speed.

• Roughening of the wheel tread, which is favorable in terms of adhesion solicitation.

However the sintered brake shoes are very aggressive to wheel, and present the same drawback than cast iron shoes in terms of noise emitted except braking phase: roughening of wheel tread leads to an increase of emitted rolling noise. Moreover, their purchasing cost remains very high.
The production of new composite brake shoes with close performances, but cheaper and especially more performing in terms of emitted rolling noise, have led to abandon the sintered brake shoes (which were mounted originally on TGV power cars, BB 26000 locomotives, XTER trainsets, Z2N motor cars and, in a passing way, some vehicles in the series BB 7200 / BB 22200 / BB 15000 and CC 72000).

**The disc brake**

The years 1960 and 1970 saw the development of the disc brake to accompany the increase of train’s speeds. It was necessary to find the way to increase the onboard thermal dissipation when soliciting the wheels only at reasonable levels. So was born the railway disc brake.

The first brake discs have been naturally manufactured with cast iron, which was a simple and cheap material. Then the era came of steel brake disc, with higher capacities. Waiting then for the emergence of new materials…

Brake discs can essentially be distinguished by:

- Their mounting.
- Their geometry.
- Their material.

**The different types of mounting**

Three types of mounting can be observed for a brake disc:

- The axle mounted disc – By far the most common mounting type, which consists in bolting the friction ring on a hub, which in turn is mounted on a wheel seat machined on the axle. The number of brake discs can be of 1 to 4 per axle (in the last case, friction rings are coupled two by two on a common hub). An important work has been realized on the link between the friction ring and the hub clamped on the axle, in order to enable a good dilatation of the friction ring during braking. The hub can be made either of cast iron or of steel, the friction ring being either molded in one single block with the hub (if same material), or overmolded on it, or bolted on it.
The wheel mounted disc – this type of mounting is more and more frequent because it provides saving in terms of available space in the bogie, in particular when the latter is a motor one. The disc consists in two half friction rings integrated on each side of the wheel flange. The fixation of the friction rings can be done either on the wheel hub or through the wheel flange.

The offset mounted disc – This type of mounting is very frequent for tramcars applications, the integral low floor leaving no space in the middle of the bogie to install brake components. The brake disc is either monoblock of made of a friction ring bolted on a hub. The fixation of the brake disc is done on the wheel hub or flange, the offset of the friction ring enabling the actuator to clamp the disc.
The most common brake disc diameters are:

- 590, 610 and 640 mm for axle mounted discs and for applications on heavy metros / trainsets / passengers coaches, the most common width being 110 mm. Lower widths can be used (80 mm, even 45 mm) according to the disc geometry and the number of discs to install. For wheel mounted discs, the external diameter can go up to 700 mm, even more for locomotive wheels.
- Around 400 mm for tramcars, the width being ca 50 to 60 mm.

**The brake discs geometries**

Two geometries are available for railway applications:

- The ventilated disc – it is made of two friction ring of variable width, between which are inserted cooling fans or studs.
- The non-ventilated disc – it is made of a single monoblock piece, “galette” type.

Ventilated brake discs are adapted to applications with frequent braking, ventilation making it possible to dissipate more quickly between two braking phases the energy stored during the last braking phase. It is useful to recall to mind that frequency of braking phases, except high and very high speed), is between 4 braking per kilometer for a tramcar and one braking every 25 kilometers for a regional trainset (average values).

The non-ventilated brake disc is today only used for very high speed applications, for which the low number of braking (1 stop every 100 km as an average) provides enough time to dissipate energy stored during a stopping or slowing braking.
Ventilation, even if efficient for energy dissipation, has however some drawbacks:

- Traction energy consumption by increase of resistance to motion: originally on a TGV-SE trainset, this consumption corresponded to 1/12 of the traction capacity at max speed (i.e. a complete traction motor was dedicated only to drive the brake discs in rotation!).
- Noise linked to air flow inside the brake disc (« horn » effect).

This is the reason why, if the original design consisted in a ventilation by radial fans, some ventilated discs, in particular for applications over 120 kph, have adopted since about 30 years a ventilation with studs: the laminar flow of the radial fans ventilation has been replaced by a turbulent flow with the studs ventilation, increasing the cooling efficiency (thanks to a higher air volume circulated inside the disc) while reducing the resistance to motion (by a “wall” effect at the disc periphery).
It shall be noted that wheel mounted discs are also equipped with a ventilation on the back side of the friction rings, this ventilation being systematically radial in order to enable air circulation between the disc and the wheel flange.

**The brake discs materials**

Three types of materials are used for railway applications: cast iron, steel and ceramic reinforced aluminum.

**Cast iron**

As already mentioned for the tread brake, cast iron has numerous advantages in terms of braking:

- It is easy to mold, and molding can be mastered by several foundries; this makes it possible to manufacture monoblock of splitted ventilated brake discs, with very different and performing ventilation fans shapes.
- It is a cheap material.
- It is a material with good thermal characteristics: cast iron diffuses very well the heat, which is uniformly distributed in the disc (no hot spot) and is easily dissipated.

This is the reason why cast iron appeared as the best answer, for stopping braking (fast trains up to 200 kph, associated with the tread brake) as well as for frequent braking (urban and suburban operation). Two main types of cast iron are in use:

- The grey cast iron with flaked graphite (GL cast iron): this cast iron is the most commonly used, as it is the cheapest to manufacture and has good mechanical and thermal characteristics.
- The spheroidal graphite cast iron (GS cast iron): more expensive than the previous one, it has however higher thermal performances, in particular in terms of resistance to cracks.

**Steel**

Necessity to ensure braking of trailer bogies of the TGV Atlantique with brake discs only to avoid tread brakes, that generate rolling noise and damages the wheels treads, led to the development of the steel brake disc, called high power brake disc.

Provided that the TGV is a rolling stock that rarely brakes, and that steel is a material that is difficult to mold without defect, design have been originally oriented to non-ventilated brake discs in order to avoid losses by resistance to motion observed with the TGV-SE. It has been then possible to realize the brake disc by forging, a manufacturing process that is easier to master and that avoids manufacturing defects.
The used steel is a high-strength alloy steel, surface treated to have a high hardness. This disc have revealed high energy dissipation capacities, as they are around 2.5 times higher than a cast iron brake discs with equivalent dimensions (up to 25 MJ for this disc in comparison to 8 to 10 MJ for a cast iron brake disc with equivalent dimensions). Energies up to 45 MJ have even been validated during an emergency braking on test bench as a preparation to world speed record in 2007, as well as during a real and unintended emergency braking from a speed over 500 kph during the test campaign before the record. The power that can be injected has also been dramatically increased, from around 150 to 200 kW for a TGV-SE brake disc up to 350 to 500 kW for a steel brake disc of the TGV today.

The success of the TGV steel brake disc and the increase of constraints for some rolling stocks:

- Increase of vehicles weights,
- Generalization of articulated trains architectures that reduce the number of bogies,
- Optimization of the number of brake discs for space and cost reasons,

have driven designers to imagine ventilated steel brake discs, in order to combine braking power and thermal dissipation capacity, which could enable operation at high load level and frequent stops. These brake discs available with axle mounted or wheel mounted geometries.

The problem was particularly raised at the beginning of the years 1990 for V2N passenger coaches, for which braking with disc brake alone (no tread brake) was specified, but also for the Corean TGV then the TGV for Taiwan, which were considered at this time as very high speed metros (stops every 50 km from 300 kph to 0…). The first one was finally evaluated as less critical, and the second one has finally been supplied by Japanese car builders…

However, the ventilated steel brake disc has been developed for the V2N project, and after some difficulties linked to control of the steel molding process, this disc has revealed major advantages which, cabined to performances of recent high temperature composite brake pads, have authorized mounting on some applications with specific constraints, combining high powers (up to 500 kW) and average energies (up to 13/14 MJ). These brake discs also enabled, for the ZTER trainset, to avoid use of tread brake on motor axle (which were still present on XTER) while authorizing braking from 200 kph with a deceleration increased by 30%.

*Ceramic reinforced aluminum*

In the years 1990 appeared brake discs made of ceramic reinforced brake discs. These brake discs, despite a slightly lower thermal capacity than the cast iron brake discs, have thermal conduction factors better than cast iron, which highly reduces the wear of the disc and, mainly, of the brake pads: heat is more quickly transferred from the disc surface to the heart, provided that the brake pad wear increases very quickly with the temperature…

Moreover, these brake discs bring a weight saving of 40% in comparison with a cast iron brake disc with same dimensions. But their still prohibitive cost leads to reserve their use to very specific applications. This is the reason why up to now this type of brake disc has been used only for rare applications (such as Copenhagen metro).

*Disc brake pads*

The disc brake pad forms a friction pair with the brake disc, and the braking as well as the thermal dissipation capacities and thermal behavior of the pair strongly depend on the characteristic of one and the other.

The disc brake pad is characterized by the friction material that is used, but also for some years by its geometry and its interface with the pad holder.

*The material*

Originally, the brake pads associated to the first brake discs have been manufactured with composite material, this material being the only one that could be associated with the cast iron brake discs at this time. These
materials presented the same characteristics – and same drawbacks! – than the composite brake shoes with high friction coefficient:

- Sensitivity to wet conditions.
- Limitation of the maximum surface temperature around 350 to 400 °C, which imposed a quite low limit in terms of energy absorption.

However these disc brake pads have been used during tens of years, before suppliers develop more performing materials that enable to dissipate higher energies. Friction coefficient obtained are very high (0.35 average), and very stable as a function of the speed (initial but also instantaneous).

Disc brake pads made of composite material: UIC type (left, document KNORR Bremse) and for tramcar application (right, document FAIVELEY Transport)

Many progresses have been made since the years 1990, leading to the introduction of composite disc brake pads for high temperatures (that can bear temperatures up to around 500°C) and that are less sensible to wet conditions. These pads have made it possible on one side to install disc brake only or in association with composite brake shoes on some rolling stocks (like XTER), but also to push the thermal limits of the cast iron disc brake to the limits of the disc itself.

However the increase of energies to dissipate has required development of sintered disc brake pads, this development being performed in parallel to the one for the steel brake disc. Sintered materials used for disc brake pads have here also the same characteristics and drawbacks than those used for sintered brake shoes. But they enabled to reach energy levels that are notably higher than those authorized by the cast iron brake disc / composite disc brake pad pair.

Work first carried on the material by itself, then on the pad geometry. Thus appeared the studded pads, providing a better distribution of the thermal flow in the brake disc and a manufacturing of low dimensions studs instead of massive pads.
Studded disc brake pads made of sintered material for TGV (document FAIVELEY Transport)

But the aggressiveness and the hardness of this type of material have rapidly generated problems of hot spots on the brake disc – thus initiation of cracks – leading to imagine a softening of the pad, thus to so called flexible pads: studs are no more rigidly fixed on the back plate, but mounted on elastic links (e.g. spring washers) enabling the pad to better fit with the brake disc surface. This flexibility slightly increased the sensitivity to wet conditions, but enabled to reach notably higher energy levels: from 25 MJ originally, energy that can be dissipated can now reach 35 to 40 MJ per brake disc – tests up to 50 MJ having shown that such energy levels are possible punctually.

Sintered studded disc brake pad flexible type for AGV (document KNORR Bremse)

Finally, some suppliers have worked on the interface between the pad and its pad holder: standing out of the UIC dovetail shape interface, they imagined interfaces that were reputed to enable a more even distribution on the whole pad surface of the application force transferred by the brake cylinder through the rigging. Nevertheless these interface geometries have been during a long time protected by patents, so that their use remained quite confidential.

It shall be noted that for some specific applications like tramcars – not concerned by UIC type interoperability – specific geometries have been developed that are very similar to the ones used for automobiles and trucks.

The future of the disc brake

The race for speed on one side and for more capacitive urban vehicles on the other side, associated with an optimization of costs lead to look for even more performing solutions than the existing ones.

Investigations are continued on solutions like ceramics coated discs with metallic core, associated to specific brake pads, even massive ceramic brake discs. Although very promising in terms of thermal capacities, this type of solution remains for the moment at prototype stage because of its prohibitive costs and the difficulties linked to the control of ceramic coating processes, the steel brake discs having made huge progresses in-between (in particular thanks to specific brake pads geometries).
The carbon solution has also been investigated in the years 1990, but its characteristics proved to be incompatible with railway operation: very low friction coefficient (around 0.10) but mainly very unstable at ambient or average temperature, rendering braking at low energy very difficult. Cost proved also to be detrimental to its use in railway field.

**The magnetic track brake**

The development of high speed in France in the sixties and the generalization of operation at 160 kph in Germany on lines with a signaling system design for 140 kph led to the development, in parallel to the one for the disc brake, of the magnetic track brake.

The latter consists in applying on the surface of each rail a pad made of electromagnets. The latter create a vertical attraction force which, combined with the friction coefficient of the pad on the rail, produces a retarding force. The magnetic field is here transversal: thus each pad element comprises a North pole and a South pole side by side.

They are also equipped with stems which shape makes it possible, in applied position, to cross the tack switches (in particular the switch points) without damaging one or the other. This shape is thus specific to each railway network, thus is different from one country to the other.

The non graduable characteristic of this type of brake leads to use it only in emergency braking, especially because it tends to wear the rail surface (as well as the friction shoe…). However it has two main advantages:

- It is totally independent of the wheel-rail adhesion, and is almost insensible to external conditions and to factors degrading this adhesion: thus it brings an interesting and reliable complement of deceleration.
- It notably improves the wheel-rail adhesion for dynamic and mechanical brakes acting on axles and wheels, by a strong cleaning effect of the rails surface.

This is how it is mounted on almost the totality of DB vehicles operated at speeds over 140 kph (and up to ICE1 and ICE2 trainsets, on which it can be applied from 280 kph!), but also all tramcars in the world and several vehicles in Europe. In France, its use remains limited to specific applications for which the mechanical brake is insufficient to reach the required performances. It can be found on all the modern RER rolling stocks operated by RATP (MI79 and 84, MI2N, MI09), as well as several regional trainsets operated by SNCF (ATER, ZTER, AGC, Regiolis, Regio2N). This type of brake also equipped the first passenger coaches operated at
200 kph for the “Capitole” trains, as well as the “Grand Confort” coaches. It also equips the recent IC trainsets (Coradia Liner and Regio2N).

There are two types of magnetic track brakes, corresponding to two different types of use:

- **Track brakes installed on tramcars, of low hanging type** – They are mounted on the bogie frame by means of springs, these keeping the pads at a distance of 8 to 12 mm above the rail. This distance is sufficiently low so that a simple powering up of the pads leads to their application on the rails by magnetic attraction. This mounting is however applicable only because of the low operating speed of tramcars (100 kph max), which avoids unintended contacts of pads on rails during operation. Moreover, magnetic track brakes for tramcars are generally of the monoblock type, because of their low length (1 meter max). Finally, pads are kept applied down to almost standstill in order to guarantee a complement of deceleration for the longest possible time; the corollary is an important jerk near standstill, the friction coefficient of pads presenting a strong increase when the instantaneous speed decreases.

![Monoblock type magnetic track brake with low hanging, on a CITADIS tramcar bogie](image)

- **The track brakes mounted on suburban and main lines vehicles are of the high hanging type** – They are fixed to the bogie frame by means of pneumatic actuators that keep the pads at a distance of around 10 mm over the rail, this in order to avoid unintended contacts with the latter during operation at high speed. Actuators make it possible, at emergency braking initiation, to lower the pads near to the rails, at a distance sufficiently low so that the powering up of the pads leads to their application by magnetic attraction.
At the end of braking, the electric power supply is switched off and actuators are vented, which leads to lifting up the pads by means of springs integrated in the actuators. Actuators are thus set to exert no force but a simple approach. Pads are, in this type of application, lifted up at low speed (around 15 kph) in order to avoid the jerk phenomenon when coming to a halt: the corresponding loss of deceleration remains insignificant compared to the important braking time. Finally these pads are generally articulated in order to improve their operation on the different track types and switches, as well as due to their length (around 1.3 meters average).

Magnetic track brakes are generally mounted under the longitudinal members of the bogie, between the wheels. But rare cases of cantilever externally mounted small track brakes can be observed.

However the weight of this device (around 800 kg per bogie for a main line or suburban vehicle, track brakes requiring to be linked together by a frame) and the important cost remain quite prohibitive.
It shall be noted that most commonly used magnetic track brakes are using coils supplied by the vehicle battery. However for some years permanent magnets track brakes are in use. The latter have the advantage to be independent of (and to relieve!) the electric power of the vehicle, as well as to be able to be used as parking brake. But they required addition of a complementary mechanism that is pneumatically or hydraulically actuated, and which makes it possible for the magnetic field to be closed into the rails (braking position) or into the pad carter (no braking). This type of track brake is installed in particular on the RE460 locomotives operated by CFF and on the Lausanne rubber tires metro.