Adhesion and Wheel Slide Protection

The railway operation fundamentally relies on the phenomena of adhesion at wheel-rail contact.

This wheel-rail contact is essential, as all traction and brake forces are transferred through this contact. It also influences several parameters linked to railway dynamics, such as stability, derailment, etc.

Theoretical (few!) and experimental (lot of!) studies of physical phenomena at wheel-rail contact level have made it possible to understand factors that can influence the wheel-rail adhesion, and quantify this influence. These studies have led to the development of devices making it possible to limit the effects of the degradation of adhesion, using in all circumstances the maximum of available adhesion at a given time: these are the anti-slip device in traction, the wheel slide protection in braking.

Nevertheless, note that in traction, a loss of performance due to degraded adhesion leads, in the worst case, to require on-line rescue following impossibility to accelerate, but in most cases a slight delay due to more difficulties to transfer traction forces.

On the contrary, during braking, a loss of performances leads to an increase of stopping distances, increase that shall be limited to avoid an accident (crashing into the previous train, derailment due to a too high speed on a tack zone with limited speed). Another factor that can lead to a derailment is the axle locking.

This page proposes an introduction to the problem of adhesion, and it is – unfortunately not perfectly… - addressed.

The wheel-rail contact

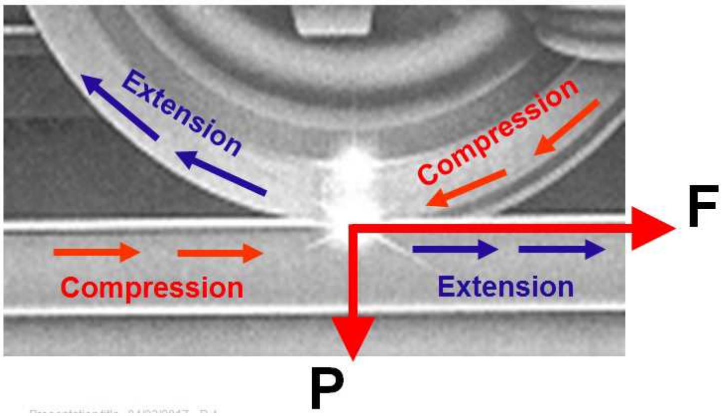
The first studies dedicated to wheel-rail contact are a consequence of studies performed by HERTZ on the modelization of the contact between two metallic cylinders, perpendicular one to the other and rolling one on the other.

HERTZ demonstrated that this contact has an elliptic shape.

This theory is easily applicable to the wheel-rail contact, the rail head having a more or less cylindrical shape and the wheel tread, although it has a conic shape, can be assimilated to a cylinder on the narrow rolling circle.

The average dimensions of this ellipse shall be kept in mind: The main axis (in the direction that is parallel to the rail) is around 1 to 2 cm, when the small axis (in the direction perpendicular to the rail) rarely exceeds 1 cm. Therefore the safety of train operation only relies on few square centimeters!

All traction and brake forces are transferred through the contact ellipse. Following HERTZ studies, and with a more railway oriented target, CARTER demonstrated in the years 1920 that the force applied to the wheel produce compression and traction phenomena in the material of this wheel, as well as in the rail.

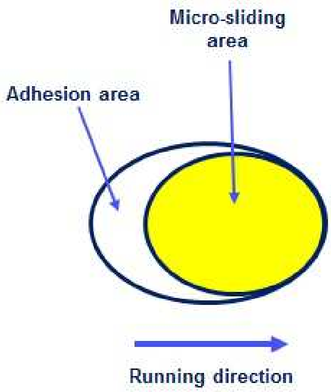


Stresses generated in the wheel during force transmission

The signs are inversed in each constituent (wheel and rail) depending on the fact that we are in traction or in braking.

These traction and compression stresses create elastic micro-deformations (i.e. that are reversible) into the materials of wheel and rail. These deformations limit two areas in the contact ellipse:

- A so called adhesion area, in which the relative speed, at microscopic level, of the wheel in relation to the rail is nil.
- A so called sliding area, in which the relative speed, at microscopic level, of the wheel in relation to the rail is not nil.



Division in two areas of the contact ellipse (braking case)

The slide in question here is not properly speaking a real slide, as it is the image of elastic deformations mentioned above: this is the reason why it is called pseudo-slide, or micro-slide. Thus if the wheel is observed in its whole – i.e. at macroscopic level – no slide can be detected.

The dimension of the pseudo-slide area is increasing when the traction or brake force is increasing.

When the pseudo-slide reaches around 1% relative value (i.e. referring to the translation speed of the vehicle), the pseudo-slide area covers the whole surface of the contact ellipse: the behavior then radically changes, and a macroscopic slide phenomenon can be observed. The moment where the real slide appears corresponds to the maximum instantaneous force that can be transferred to the rail in traction or braking. This force is, more or less, equal to the weight (vertical force) exerted on the wheel (i.e. the mass in kg multiplied by 9.81) multiplied by the adhesion coefficient. The latter corresponds to the adhesion that is physically available on the rail when the force has to be transferred.

Wheel-rail adhesion

The pseudo-slide phenomenon has been perfectly modelized in the last 30 years by a Dutch scientist, Mr KALKER.

On the contrary, concerning the real slide phenomenon – i.e. when this slide exceeds 1% relative value – the theoretical studies were very quickly faced to limitations in terms of modelization, and did not succeed in establishing efficient models.

This is the reason why ORE, UIC Research Office (which is now ERRI), has launched at the very beginning of the years 1980 a working group on the adhesion between wheel and rail in braking. This working group has systematically explored this phenomenon by means of several tests campaigns in several countries, in order to highlight guidelines on the behavior of wheel-rail adhesion versus the different influential parameters that were identified. These campaigns have been the basis of the design of modern wheel slide protection devices, as we'll see further.

We will not detail here the history of these works, but will only provide some understanding lines. For the most curious, the publication "Chemins de Fer" (AFAC) has issued in number 452, written by Michel BOÎTEUX (former manager of Brake design office in SNCF during several years and convenor of the ORE working group on adhesion), a complete and detailed summary of these works.

Definition of adhesion

In fact, two notions of adhesion can be defined:

- Required adhesion, which is the ratio between the traction of brake force and the weight applied on the wheel (the weight being the mass multiplied by the gravity acceleration, i.e. 9.81 m/s²).
- The available adhesion, which is the ratio between the maximum reaction authorized by the rail following effect of traction or brake force and the weight applied on the wheel.

Therefore, the axle does not slip nor slide as long as the required adhesion does not exceed the the available adhesion, the latter being variable as we'll see further.

Just a precision to close this topic: when using the equations of dynamics applied to an axle, and with a certain number of simplification hypothesis, it is easy to demonstrate that the required adhesion is equal to the ratio between the deceleration of the axle and the acceleration of gravity (i.e. 9.81 m/s²). The axle deceleration being the one of train when the axle is in pseudo-slide, the required adhesion is more or less the tenth (as 9.81 is near to 10…) of the train deceleration: therefore, train decelerating at 1 m/s² requires an average adhesion of 0.1 – i.e. 10% - at the level of each axle. Be careful!! This is true only during braking, as all vehicles of a train are braked: in traction, only some of the axles are driven, therefore the required adhesion shall be much higher than 10% to reach an acceleration pf 1 m/s²… (More or less: around 20% for a train with a 50% motorization ratio).

Characterization of adhesion during braking

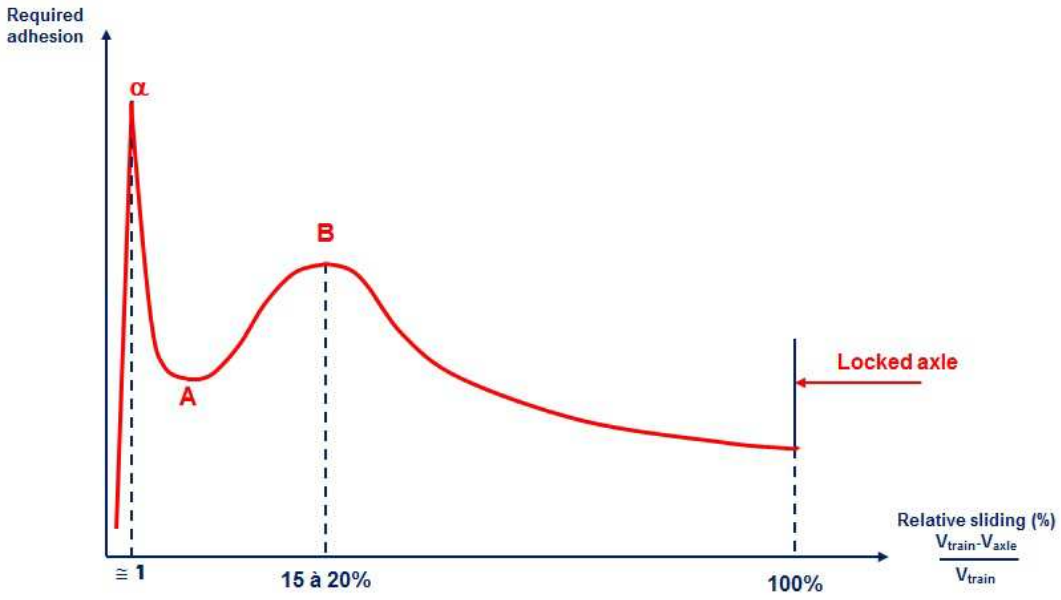
As seen above, adhesion can be characterized by two ranges, in relation to the slide between wheel and rail.

The slide is defined by the difference between the tangential speed of the wheel (linear speed at its circumference) and the translation speed of the vehicle. The relative slide is then defined as the ratio between this difference and the translation speed of the vehicle. This relative slide is given in %. Thus a relative slide of 100% corresponds to axle locking.

When the relative slide is lower than 1%, we have seen that the adhesion is issued from the pseudo-slide. When the slide is greater than 1%, the adhesion is changing differently in relation to the circumstances.

The theoretical study of the pseudo-slide, confirmed by the ORE tests, have demonstrated that in the range of pseudo-slide, the adhesion reaches a maximum called "KALKER's peak", or "α peak". This maximum corresponds in fact to the adhesion that is really available at the level of the rail.

ORE tests have then demonstrated that, when the relative slide increases over 1% (real slide range), the adhesion decreases dramatically. Anyway in some conditions, it can be noted that the adhesion re-increases: it passes through a second maximum value for a slide in the range of 15 to 20% then decreases again until it reaches the friction coefficient of steel on steel when the 100% value (locked axle) is reached.



Adhesion diagram in braking (scales are not correct)

The numerous tests performed by ORE have highlighted the properties of this second maximum value, commonly called “point B”:

- The position of the point B strongly depends on the deceleration of the axle when starting to slide: the faster the axle starts to slide the lower is the adhesion on the point B. The point B does even not exists if the deceleration of the axle when slide is starting exceeds a certain value: we can then observe the dotted line on the diagram above, which can be qualified as the “natural law” of wheel-rail adhesion in braking, and represents the behavior that all railway engineers and technicians have observed during tenth of years.
- The above diagram, and thus the position of the point B – even the existence of the latter – are changing continuously during the time and in the space: when the wheel is rolling on the rail, the diagram changes every second, as well as for every rail centimeter…
- The adhesion on the point B is increasing during braking if the axle is regulated in sliding: this is the

This property – very important for brake engineers – is probably the result of several phenomena, among which:

- A mechanical cleaning effect by wheel slide on the rail at contact level
- A heating effect at the level of this contact, also due to slide.

Therefore, the adhesion on the point B, in relation to the vehicle, can be doubled within a few seconds in sliding, as it remains constant on the rail. This can also explain that when axles of several successive vehicles are regulated in sliding during braking on degraded adhesion conditions, the adhesion “seen” from each vehicle is increasing in direct relation to the position of the vehicle, from front to rear end of the train. It can then be often noted that there is no slide on the last vehicles.

Parameters that can influence the adhesion between wheel and rail

Several parameters can influence the adhesion between wheel and rail. Along these:

- The operating speed: the higher the latter is the lower will be the available adhesion at rail level. Thus a notably increase of adhesion can be observed at low and very low speeds.
- The load per axle: this is due to the fact that, for the same contact ellipse surface, the higher the contact pressure (image of the mass) is the lower is the adhesion. Then, the fact that it is considered that a high mass is required to improve the adhesion required comes from traction, for which the necessity to transfer a given force (e.g. to start a train) implies to increase the mass on motor axles so that the required adhesion remains within the limits of available adhesion (see above).
- The weather conditions: rain, snow, ice, temperature, air hygrometry, etc.
- The atmospheric and industrial pollution: the combustion of fossil energies in particular generates on the surface of the rail the presence of products that, as soon as they are mixed with a small amount of water, will produce on the rail surface a “greasy film” that will dramatically reduce the adhesion in urban and industrialized areas.
- The geographic localization: some areas, in particular the areas with lots of trees in the vicinity of tracks (which leads to the presence of wet dead leaves on the rail during autumn) are reputed as difficult.
- The respective wheel and rail profiles, as well as the wheel diameter: for an equal load, the greater the surface of the contact ellipse is the better will be the adhesion (see above); provided that this surface is linked to the wheel diameter (the greater the latter is the larger will be this surface) as well as to the wheel (conicity) and rail profiles.
- The wheel and rail materials: the contact ellipse surface depends on the deformation (thus on the characteristics) of the materials of the wheel and the rail; but the influence of these parameters remains low.
- The wheel tread surface status: the higher the roughness of the latter is the higher will be the available adhesion. This is the reason why some Operators are very kind of using tread brake, or to require installation of scrubbers. Nevertheless, this phenomenon only exists for cast iron of sintered brake shoes, which roughens the wheel tread, thus produces a rugged state; the composite brake shoes keep a polished state of the wheel tread, similar to the one observed for an axle that is brake only with disc brakes: in this case no improvement of adhesion can be expected.
- The track layout, and in particular the inclination angle of the rails (the latter having a direct impact on the surface of the contact ellipse).

As can be observed, the influential parameters are numerous. Some of them can be managed (load per axle, type and wheel diameter, track layout, rail material, wheel tread surface state, etc.) when some others are random ones (in particular weather conditions and pollution): unfortunately, the latter are the most influential!...

Usual values of adhesion

Speaking about values of adhesion between wheel and rail leads to get quite different opinions depending on the conditions, but also depending on the fact that you are discussing with a traction engineer or a brake engineer.

In the absolute, the adhesion on dry rail is statistically within an interval of 30 to 50% at very low speeds (few kph), then decreases very quickly. It can be estimated that it is around 15 to 20% for speeds comprised between 20 and 100 kph. Then, it decreases in a quite linear and slow way to reach around 9 to 10% at 300 kph.

When the rail is wet, the values do not exceed 10 to 15% at low speeds, to reach 4 to 5% at 300 kph.

On wet dead leaves, the adhesion is quite constant… but around 1 to 2%!

Traction engineers generally try to use the adhesion at the maximum, first because of the low number of motorized axles, secondly because the effects of a slipping do not endanger safety. Brake engineers shall be more careful, and are generally content with the lowest values in each range: the required adhesion in in braking is generally around 10 to 12%, and does not exceed 15% (values at low speeds). These values are now clearly specified in the international standards as well as in the Technical Specifications for Interoperability (TSI) issued at European level, and shall be considered as a basis for the definition of the brake forces.

The Wheel Slide Protection

Why a wheel slide protection ?

Trains operation on a railway line is generally managed thanks to a signaling system based on the principle of track sections: the line is divided into track portions, each of them being protected by a signal.

The length of each section is an intrinsic parameter of the line, and thus defines the maximum speed of trains as well as their braking performances.

Nevertheless, in order to improve the number of trains, the Operators often reduce the length of track sections: this imposes to rolling stocks operated at high speed (160 kph and more) to have more and more hich braking performance levels.

Yet we have seen above that the required adhesion during braking is directly proportional to the brake force. Therefore, increasing the braking performances implies on high speed rolling stock required adhesion levels near to limits authorized on dry rail (around 15%). This observation has, in degraded adhesion conditions, various consequences:

- Important increase of stopping distances
- Wheel flats, consecutive to axle locking, these wheel flats possibly leading, in some circumstances, to a derailment.

This is the reason why the design of high speed rolling stocks (more than 160 kph) required the development of a device making it possible to avoid drawbacks due to degraded adhesion conditions, thus to comply with safety conditions of operation and of rolling stock.

So wheel slide protection was born.

History of wheel slide protection

As specified by their name, the first wheel slide protection devices were designed to avoid slide, and in particular axle locking. Thus these mechanical or electronic (analogic) devices were acting by complete release of brake force as soon as a slide was detected on an axle, then the brake force was restored when the slide was disappeared. This type of device had not necessary a satisfying. It could even be dangerous, leading in some circumstances to great increases of stopping distances: from 60 to 115% observed during tests!

The strong development of digital electronics from the end of the years 1970 and the beginning of the years 1980 has enabled to realize more sophisticated and precise wheel slide protection devices.

In parallel, the theoretical and experimental studies of wheel-rail adhesion in braking has made it possible to better understand this phenomenon and the influential parameters, and in particular to demonstrate that, in some conditions, the adhesion vs slide characteristics has a maximum on which it is possible to regulate (see above).

Therefore, beginning of the years 1980 were developed the slide regulation type wheel slide protection devices, the principle of which being not only to completely release the brake, but to be able to regulate the brake force in real time in order to permanently keep during wheel and rail a constant slide corresponding to the maximum available adhesion (point B of the adhesion vs slide characteristic: see above).

The development of performing and cheap microprocessors and microcontrollers has enable within the last thirty years to develop very high-performing wheel slide protection devices, authorizing high brake force levels while limiting the increase of stopping distances and ensuring the protection of rolling components in degraded adhesion conditions.

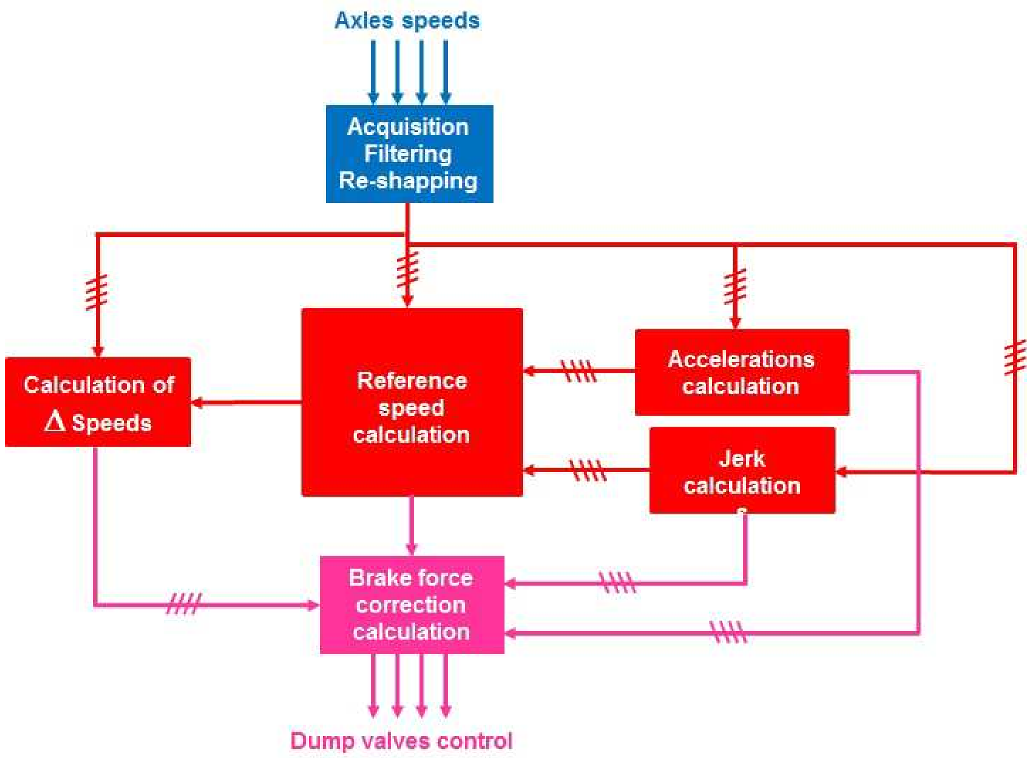
Operating principles of the modern wheel slide protection

The slide regulation type modern wheel slide protection device is the second generation of wheel slide protection, developed from the end of the years 1970.

Of the electronic type, often with a microprocessor, it makes it possible to regulate the slide between wheel and rail in order to permanently adapt the brake force to the maximum available adhesion.

This type of wheel slide protection generally uses a reference speed calculation algorithm (reconstitution of the vehicle speed) and a correction calculation algorithm using criteria of axle speed difference vs this calculated reference speed, of axle acceleration and of axle jerk (derivation of the acceleration).

The slide regulation wheel slide protection calculates a brake force correction, then requires a correction of the brake demand (case of a wheel slide protection integrated in a brake control electronic unit), or directly a correction of the pressure in the brake cylinders. The latter is performed, in the case of a brake with pneumatic actuation, by means of wheel slide protection dump valves (electro-pneumatic valve with two coils, that can provide three states: open, stable downstream pressure that is lower than or equal to the upstream one, exhaust of the downstream pressure).



Operating principle of a slide regulation wheel slide protection (axle per axle regulation configuration)

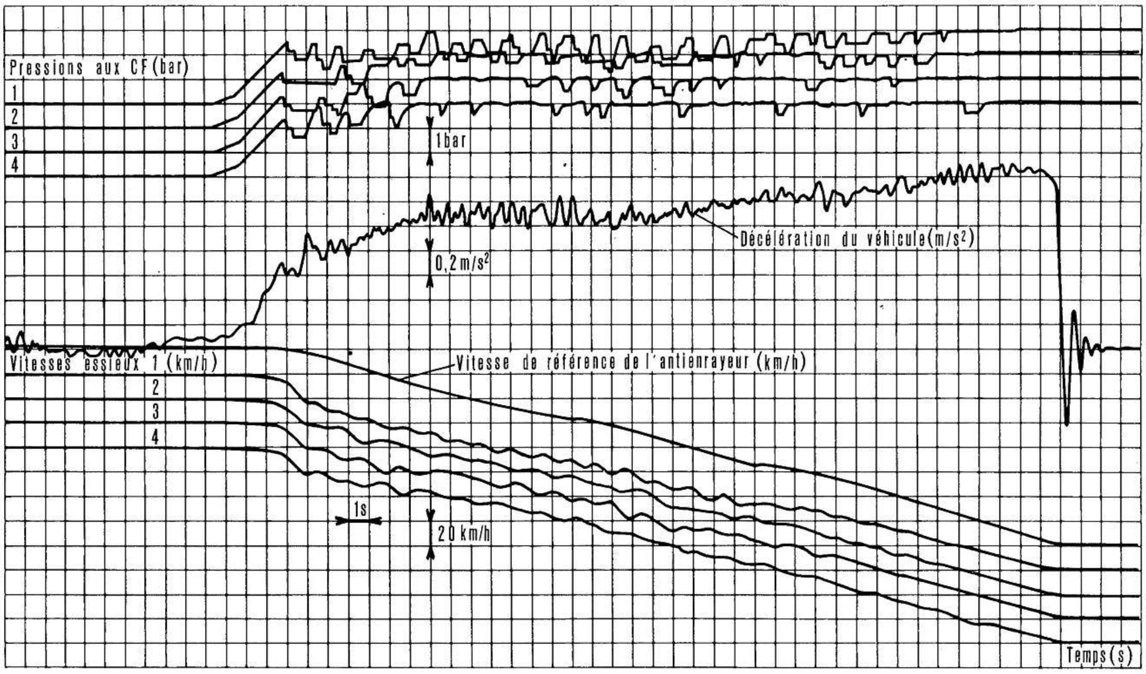
Depending on the type of vehicle, of its braking power and operating speed, the force regulation can be performed bogie per bogie or axle per axle, the speed measurement being in all cases performed on an axle per axle basis (even wheel per wheel for some tramway bogies). It is clear that an axle per axle regulation provides better performances than a bogie per bogie one.

This type of wheel slide protection is nowadays installed on all recent rolling stocks, without exception : TGVs of course, but also locomotives (in France : BB 26000, BB 36000, BB 27000/37000), passenger coaches (most of the Corail cars), electric and diesel multiple units (MI2N, TER2Npg and ng, XTER, ATER, ZTER, AGC, Regiolis, Regio2N), steel wheels metros (the rubber tyre metros do not need it…), tramways (all CITADIS and their foreign counterparts).

Performances of modern wheel slide protection devices

Depending on the cases, wheel slide protection devices make it possible to limit the increase of stopping distance of a train at 10 to 25% versus the stopping distance on dry rail, the adhesion in front of the first axle of the train being in the range of 5 to 8%. The longer the train is the shorter is the increase of stopping distance, as the wheel slide regulation on the first vehicles enable the last ones to brake on a rail that is equivalent to a dry rail (see above).

The following example shows braking of a Corail coach during an uncoupled test, the adhesion being artificially degraded by spraying on the rail in front of the first axle a mixture of water and a soapy product: the increase of stopping distance is around 36%, but it concerns a single vehicle test (so a very unfavorable configuration).



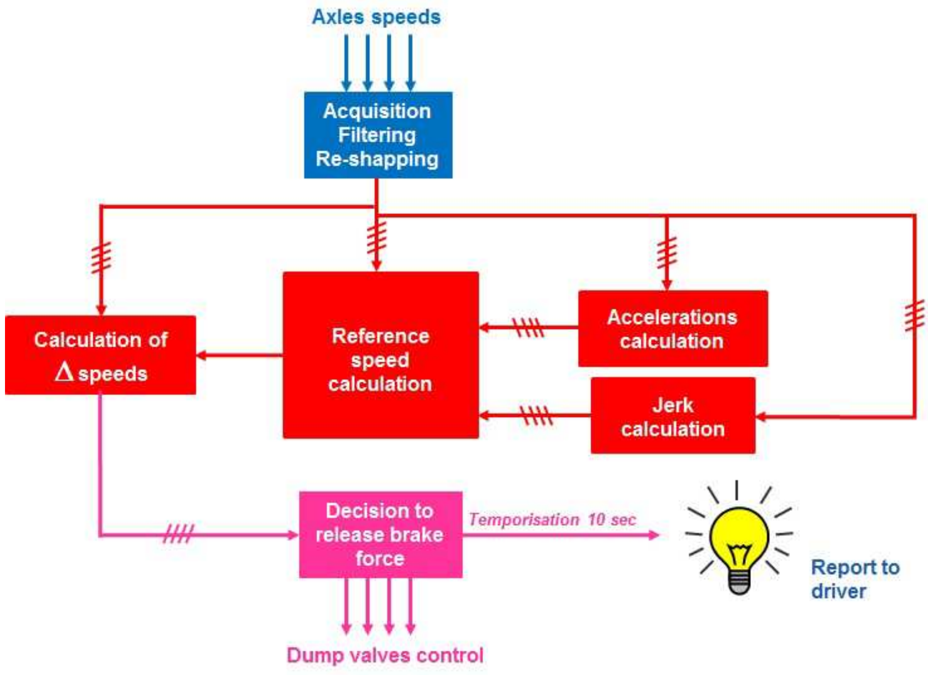
Example of braking on degraded adhesion conditions (uncoupled test)

Wheel rotation monitoring

Also called « detection of locked axle », this device is in fact a redundancy of the wheel slide protection device. Installed only on TGVs at his time, this device shall be physically independent from the wheel slide protection.

The wheel rotation monitoring device detects any great difference of speed between an axle and the train, this difference not having been corrected by the wheel slide protection because of a failure of the latter or because of a particular dynamic phenomenon (great drop of adhesion).

The device requires first a complete release of brake force on the axle or the bogie on which the detection has been performed. If, after some seconds, the axle has not re-accelerated, braking is reapplied (for safety reasons) but information is supplied to the driver: the latter shall then stop the train immediately, in order to take the imperative statutory measures.



Operating principle of the wheel rotation monitoring device (bogie per bogie brake release configuration)

Low slide wheel slide protection

On vehicles equipped with a powerful dynamic brake, it can be interesting to not regulate the slide during drag braking phases using only the dynamic brake, and that last a very long time.

Anyway, in order to avoid axle slide, these vehicles can be equipped with a “low slide” wheel slide protection, the principle of which is to operate like an “inversed” anti-slip device. Indeed its aim is to avoid any slide of wheel on rail that exceeds a few kph.

When a slide is detected, this wheel slide protection completely and very quickly cancels the dynamic brake force, then restores if quickly until a certain percentage of initial force, restoring the full brake force being then slower.

The “low slide” wheel slide protection uses the same resources and input data than the slide regulation wheel slide protection (comparatively called in this case “high slide” wheel slide protection), to which is is generally associated.