Politecnico di Torino

Mechatronics Engineering
A.a. 2021/2022
Graduation Session December 2022

Wheel Sliding Protection system for safety in rail transport

System architecture, control and monitoring techniques

Relatori:
Massimo Violante

Candidati:
Maria Caterina Cuzzocrea

A mia madre, un museo pieno d’arte.

A Domenico e Aurora, luci sempre accese nei miei momenti di buio. Presenze certe del mio passato, presente e futuro Il dono più grande fattomi dai miei genitori.

A Marica e Martina, il mio “testa o croce” al telefono. Le sole con cui mi sia spinta a parlare di cose di cui parlavo solo con me, le sole in grado di alleggerirmi il cuore.

Summary

PREMISE

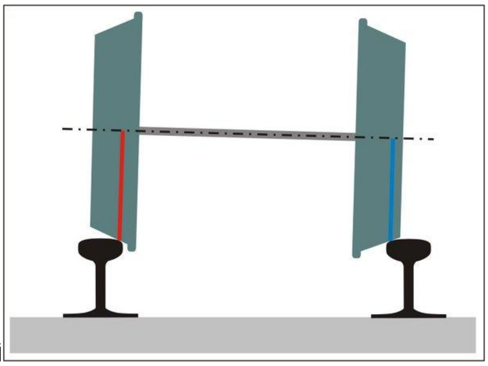
Since the first models, trains have been one of the main forms of transport in the world. In fact, already in 1550, the Germans began to develop wooden railway systems which were followed by more and more developments and innovations that led in 1797, in England, to the invention of the first steam locomotive. Therefore, with this first great step, the Railway as we know it today began to take shape. It goes without saying that, since the train is one of the most used means, not only for the transport of goods but above all for people, the search for safety is one of the main aspects on which more and more attention has been paid. In fact, if on the one hand we have always sought a continuous innovation of efficiency to increase railway technology in terms of speed, energy, power by developing more and more innovations for the engine and all the other mechanical and electronic parts of the train, on the other hand all this must go hand in hand with a continuous attention to maintenance and prevention from any type of risk. The concept that plant safety must go hand in hand with engine excellence is increasingly entrenched. It is precisely from this aspect that the need arises to design devices that guarantee safety in one of the most delicate phases of rail transport: braking. Among them, one of the most important is the wheel sliding protection, WSP, the subject of the paper, thanks to which the slippage and locking of the wheels is avoided.

CHAPTER 1- INTERACTION BETWEEN WHEEL AND RAIL: GEOMETRY AND STRUCTURE

Among the various aspects on which it is possible to pay attention for this continuous development, certainly the wheel-rail axis has an important relevance. It is precisely because of some expedients and characteristics of this combination that it is possible to avoid one of the most unpleasant and risky situations that can occur during any moment in which the train moves or is preparing to move / stop: the derailment. For example, why does a train not derail during a curve since its outer wheel covers a greater distance than its inner wheel? in railway engineering, in fact, the base of a vehicle consists of a wheelset which is in turn formed by the union of two wheels joined by a rigid axle. So, what is there that prevents its derailment? Well, in fact, such a result is achieved through the combination of three mechanisms:

1. The rail and the wheel do not have a flat shape: the rail has a shape called a "mushroom" while the wheels are conical. The figure below represents the explanatory scheme of these geometries and at the same time makes it clear that in the presence of a lateral movement, the rolling involving the outer wheel is higher than that of the inner one. This, therefore, allows both to be able to bend and to be able to maintain the same angular speed avoiding both iron consumption and slips.

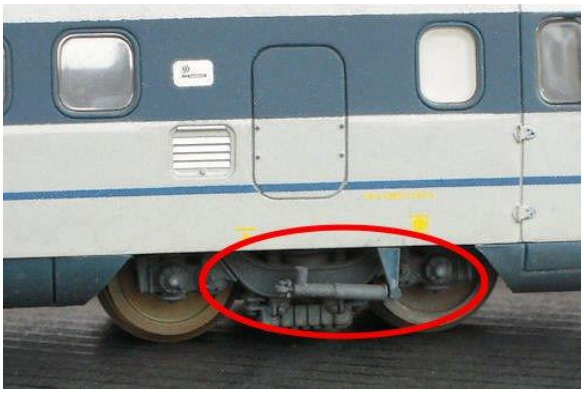
Figure 1.1: Rail-wheel geometry



Source: https://qph.fs.quoracdn.net/main-qimg 79a485c121f883b80bbf69b2577a58c0-lq

2. In addition, to increase the security of this mechanism, in the geometry of the wheel there is an internal rim: the inner edge that can be seen in image 1.1, which is a further way to prevent movement beyond a certain maximum limit. The screech that is felt during some curves is not caused by the brakes or other mechanical parts but arises precisely from the rubbing between the rail and these edges. In addition, since the system is made of at least two axles, to avoid oscillations from the equilibrium position, some elements are mounted on the bogies of railway vehicles between the bogies themselves and the chassis: the dampers visible in figure 2.1 Regarding the edges of the wheels, their presence is also very important for the operation of the switches since between the two switch rails, the moving parts of the switch, the adjacent to the rail pushes the edge of the outer wheel towards the direction for which the switch was controlled, while the switch rail detached from the rail allows the edge of the other wheel, adjacent to the rail itself, to pass undisturbed.

Figure 2.1 Damping between carriage and fixed point of the body



Source: https://qph.fs.quoracdn.net/main-qimg-19046ee0efae60b284073f0ff706a922-pjlq

Figure 3.1 switch

Source: https://qph.fs.quoracdn.net/main-qimg-9797eafe40cf44c84be106138cf3d705-lq

3. Another aspect that contributes is the rise of the rail. With this expedient, when the curve is traveled according to the speed limit imposed by the line and the vehicle, it is possible to keep the system in balance by managing to balance the lateral thrust. In fact, it is dependent on the speed and therefore it is superior externally, but it is compensated by the weight component parallel to the axis of the wheels that is dependent on the inclination and so it is higher internally.

CHAPTER II - The WSP anti-skid system

To prevent the wheels from slipping both during braking and acceleration, a special automatic system is used: the WSP (wheel sliding Protection) equipment which is a real anti-slip protection. In this document the development of this device starting from the first models will be treated, paying attention, subsequently, to its architecture both from a mechanical and electrical point of view. Regarding the innovations that have occurred in the past and in progress in the present, some tests/ simulations (carried out by universities or by teams of engineers recruited by the same production companies who have had the merit of distributing this equipment on the market) will be presented.

2.1 The adhesion between wheel and rail: type of proportionality between the quantities and forces acting

To better understand the issue that is going to be addressed, in the automatic field, the analogue of this mechanism is ABS. The WSP is particularly relevant in slippery railway conditions. One of the aspects considered most in the wheel-rail complex, in fact, is based on the search for a continuous grip that must always be ensured between the two parts. Theoretically, adhesion is proportional to the weight discharged on the wheel and depends on several factors, including speed V, the nature of the wheel-rail contacts and the conditions of humidity and cleanliness of the surfaces in contact, according to the report:

$$A = fa(V) * Pa$$

With:

- fa the coefficient of adhesion.

- Pa the adherent weight (it is the weight weighing on the adherent drive wheel and / or braking wheel)

On the railway the coefficient of adhesion fa (V = 0), at zero speed, has values equal to 0.25 or 0.35 depending on whether you are in the presence of bad or good condition of the surfaces in contact. This value decreases as the speed increases.

In particular, the experimental expression that allows us to quantify the value of the coefficient of adhesion as a function of speed is that of Muller:

$$f_a = \frac{f_a^*}{1 + 0{,}01 * V}$$

Where f_a^* is the coefficient of adhesion at V = 0 and V is expressed in Km/h.

Other elements that intervene to change the conditions of adhesion are:

- state of the surfaces in contact: these are almost never cleaned: there may be dust, oil, moisture, and even a slight film of iron oxide.

- instantaneous load variations: due to the springing of the shock absorbers, large load variations on the wheels can occur. The ratio between the tensile force applied to an axle and the load on it may exceed the grip limit, resulting in slippage. When the conditions of the track are critical in terms of adhesion, the so-called sandblasting is carried out, which consists precisely in the operation of silting the track. In particular, the latter is one of the methods of temporarily providing friction: locomotives carry sand that is pumped through small pipes that release it in front of the wheels, figure 4.1. It is precisely the sand that provides enough friction to allow the motion in grip.

Figure 1.2 Binary sandblasting

Source:https://qph.fs.quoracdn.net/main-qimg-5f7bcff66532fe7603eaf99aaf09b69d-lq

The type of adhesion between wheel and rail changes according to the point of contact that is established between them, there are four different types:

If the longitudinal velocity of the wheel is zero:

- Adherence to the fixed point: in this case the point of contact between the wheel and the surface always remains fixed, plus neither part changes the contact surface. There is neither rotation nor translation (effort of first detachment).
- Pure slippage: the point of contact on the surface remains fixed, however, during its rotation motion, the wheel continuously changes the contact surface (grazing friction). In this case the angular velocity of the wheel is non-zero.

If the longitudinal velocity of the wheel is non- zero:

- Pure skating: in this case the point of contact on the surface (that changes continuously due to the translation of the wheel) varies; therefore, there is a non-zero longitudinal velocity; instead, it does not change the contact surface because in case of pure skidding the wheel is devoid of rotational motion, therefore with a zero angular velocity (grazing friction).

- Rolling: both organs change surfaces in contact with each other. The transmissible force depends on the coefficient of adhesion. Both speeds are non-zero.

According to the equation of motion, to have pure rolling it must happen that:

$$Tmax \leq fa * Pa$$

where fa is the coefficient of adhesion and Pa the adherent weight. It is essential, therefore, to have a certain value of the traction force T to obtain a motion but this is not enough. It must also exceed the sum of the resistances R, namely:

$$T > R$$

The term R is the sum of the planar resistances and resistances due to the altimetric plan trend of the railway line, due to the presence of curves and slopes.

The study of the dynamics of an isolated vehicle is essentially based on the analysis of the forces acting on the vehicle and the links between them. The forces that act are:

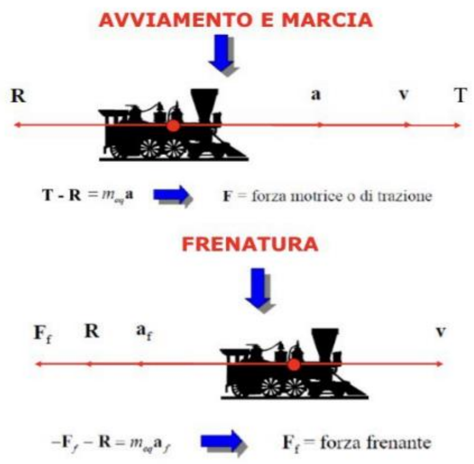
- FORCES DEPENDENT ON THE MASS of the vehicle: weight force, centrifugal force, inertia force.

- PASSIVE FORCES, or resistances, which we will indicate generically with R, which oppose the motion of the vehicle and occur only when the vehicle is in motion.

- ACTIVE FORCES, or traction forces, which we will indicate generically with F, generated by mechanisms on board the vehicle or by other vehicles.

Figure 5.1 represents the dynamics that involve a vehicle in two different phases of its motion.

Figure 2.2 Acting forces



Source:https://www.unirc.it/documentazione/materiale_didattico/1466_2013_341_18919.pdf

The resistance to the advancement is the sum of the ordinary resistances Ro, ie those that always occur in any condition of motion, and of the additional resistances $Radd$, associated with particular plano-altimetric configurations of the track.

$$R = Ro + Radd$$

ORDINARY RESISTANCES Ro:

among these resistances there are: rolling resistance due to pin-bearing torque R_1, rolling resistance due to wheel-rail torque R_2, and air resistance Ra.

ADDITIONAL RESISTANCES $Radd$

Among them, however, there are the Accidental Resistance due to the slope R_{slope}, and the Accidental Resistance in curves R_{curve}

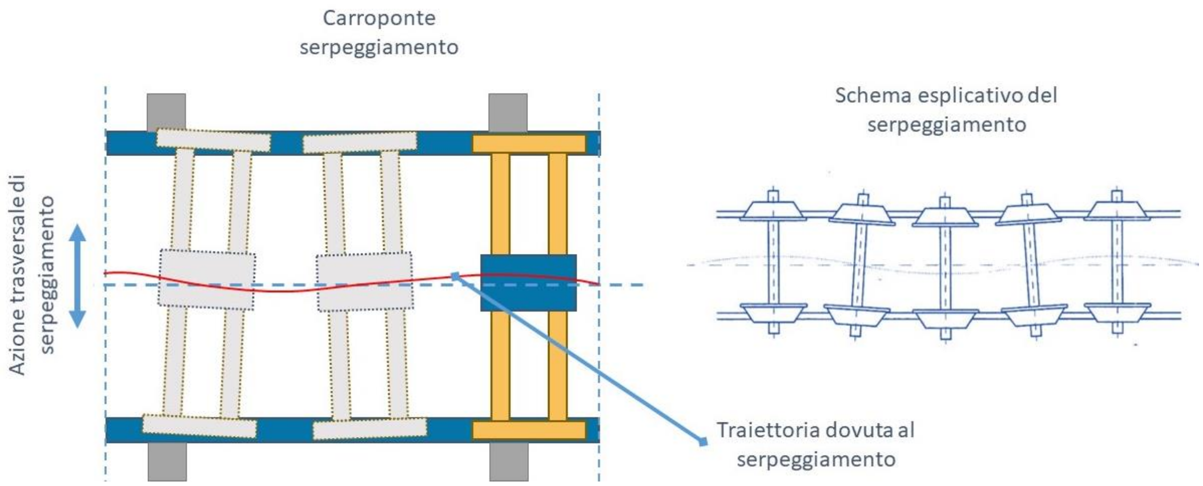
$$R = R_1 + R_2 + R_a + R_{slope} + R_{curve}$$

Additional resistances are determined by:

THE JOINTS OF THE RAILS: in particular, in this case the resistance arises both at the time of the passage of the vehicle on them, (consider the impact of the edge or the impact of the entire bogie in the passage between rails). In addition, this resistance is also due to the elastic flexion of the material used for the manufacture that responds differently to mechanical and climatic stresses.

MEANDERING MOTION: The motion of railway vehicles on the track is not perfectly straight. The vehicles proceed with a meandering motion that causes an alternating impact of the edges against the rails. This is due to the conical geometric shape of the wheels and to the point of contact that is established between wheel and rail.

Figure 3.2 Meandering



Source: https://www.marcodepisapia.com/carroponte-combinazioni-di-carico

The relative resistance also depends on the speed of the vehicle and can be expressed with the relationship:

$$R = f * P * V$$

With:

-f coefficient of friction which takes on the value of about 1.5.

-V speed in km/h.

- P weight expressed in t.

2.2 Derailment: a side effect of loss of adherence

When this adhesion is lost due to these resistances or forces that cannot be balanced during the train in the start or braking phase, the derailment may occur. In the presence of high lateral stresses, the contact of the edge with the rail fungus ensures the correct alignment of the wheel. Under these conditions, high slip occur between surfaces, and relevant forces can be exchanged. These forces may cause the edge to rise on the rail causing the loss of the correct alignment between wheel and rail and therefore the derailment of the train. The total lateral force, a planar component of the total force acting on the wheel (sum of all the forces/resistances mentioned above) causes a friction force that tends to make the wheel "climb" on the rail and therefore to divert the wheel.

the anti-skid system, the subject of study of this work, is used to always maintain a correct value of adherence. In railway technology, this device is mounted on each axle of a railway vehicle with the aim of preventing the locking of the wheels and their slipping on the rails. It is therefore essential during braking since the latter can be applied gradually up to the limit of adhesion.

There are two different cases that create unsafe conditions. The first case occurs when the tensile force is greater than the total adhesion force, thus the difference in power accelerates the wheel and this results in too much strain and stress on the rail. Similarly, when the braking effort exceeds the adhesive weight, the additional braking force prevents the rotation of the wheel with the consequent continuation of the movement in a linear way. In both cases there is the loss of the point of contact between wheel and rail and the geometry of both parts is compromised: the wheel tends to flatten and rub directly on the rail developing deformations such as those in figure 4.2.

Figure 4.2 wheelslip

Source: https://www.iricen.gov.in/ModelRoom/H1_Wheel%20Burnt%20Rails.html

2.3 Internal monitoring of the operating status of the WSP

In addition to the electro-mechanical system installed directly on the wheels, therefore outside the train, through some sensors, there is the possibility of controlling the actual operation of the anti-skid during the train march. As for passenger trains, we must also consider the type of material used to carry out the service, in fact, based on this aspect, there is a different signage on board and in particular the person responsible for controlling its operation also changes. As for trains of ordinary material, therefore those with a locomotive pulling one or more vehicles, the train manager is the guarantor of its correct functioning. According to the rule of Article 12 bis of the MMIEFCA paragraph 5 – Obligations of the train managers– the train manager must check at least once during the journey the absence of fault reports to the anti-skid device. If he finds the alert active, his task is to report the abnormality on the logbook of the carriage, register it on the Train Document and notify the operations room to agree on the intervention of the verification staff for the necessary checks and operations of competence. At the same time, it must avoid any type of rearmament of the anti-skid. In fact, for some types of carriages, for example the Vivalto trains, the displays that highlight the out-of-service condition of the wheel slide protection device report codes known by the verifier based on which he can establish the appropriate interventions. The Verifier, on the other hand, can isolate the carriage from the continuous brake, which corresponds to the type of brake with which railway vehicles are equipped, and determine whether the carriage must be included in the maintenance system for repair work. In the event of a failure of the equipment, a slipping, and a consequent faceting of one or more axes could occur, this would compromise the geometry of the wheel (fig 4.2) with the consequent loss of adhesion.

CHAPTER III - Similarities and differences with the automotive sector: ABS vs WSP

Although the main functions between the WSP system of railway vehicles and the ABS system in motor vehicles are quite similar, there are some crucial differences. As mentioned, there is a principle of operation that unites them since both are systems with the dame goal: preventing the locking of the wheels, especially during braking. Therefore, both are used to modulate in a continuous way the effort of the brakes depending on the slippage of the wheels and the adhesion conditions that are created with the support surface. The first substantial difference lies precisely in the type of brake system that is present in the two different types of vehicles: in the railway braking system there is an electro-pneumatic type of implementation while in the automotive the implementation is of an electro-hydraulic type. At this point, an excursus will be made about the two types of brake, paying more attention to the railway one for obvious reasons.

3.1 The braking system

In vehicles, the braking phase is of considerable importance since it allows speed control during motion and the subsequent stop of the same. Moreover, it is crucial to improve their efficiency and safety in operating conditions. The braking system is responsible for this task, and it assumes different characteristics and architectures depending on the vehicle on which it is located since it must respond to different needs.

What unites all types of braking systems is the conversion of the kinetic energy (that is present during the motion phase) of the vehicle into another form of energy that changes according to the type of brake. There is essentially a pair of braking forces that is generated to hinder the action of a pair of driving forces acting alone until the. In this way, this combination allows the rotary motion of the axes to which the wheels are directly connected.

If the purpose of the braking torque is to completely stop the motion of the vehicle, it is called stop braking. If, on the other hand, the purpose is only to attenuate the speed and to continue the movement, the braking is called holding or slowing down. In addition, there is a distinction into two categories of braking systems based on whether they depend on grip. There are those in which the braking force is exerted on the wheels of the vehicle by means of friction elements (stump or disc brakes) and therefore depend on the grip; and then there are those in which the braking effort acts on the rail as an antagonistic force to the motion (an example is the electromagnetic brakes) and in this case there is no dependence since the force acts directly from the surface. It follows that there are also several systems that allow the control and actuation of the brakes:

• pneumatic brake, in which the braking force is generated by compressed air inside a pneumatic actuator, while the control is mechanical.

• electropneumatic brake, in which the braking force is due to pneumatic actions, but the control is entrusted to electropneumatic elements.

• electro-hydraulic brake, in which the braking force is generated by hydraulic actions, but control is entrusted to electrical or electronic elements.

• electromagnetic brake, in which the braking force is generated by electromagnetic interactions, but the operation of the braking devices is entrusted to electro-pneumatically controlled actuators.

• regenerative brake, in which the braking action is obtained by running the electric motors from generators.

3.2 Car braking system and ABS: development and technology

The acronym ABS comes from the German "Antiblockiersystem" which literally means "System against brake locking". This safety organ was designed by the Volvo company while starting from 1978 German company Bosch put it on the market in Germany on a Mercedes S-class, while in Italy it arrived in 1984, on a Lancia Thema.

When such a system had not yet been designed, if the brake pedal was pressed thoroughly, there was a complete lock of the wheels. Finding yourself in a driving situation with the wheels locked due to this action is very risky because in this case it is not impossible to change direction to avoid any obstacle in line. Moreover, more importantly, with the wheels locked the braking power is lower, because the friction of the tires that slide on the asphalt is lower than that between the brakes and the wheel itself and therefore this causes an increase in the space required to brake. Therefore, its presence allows to obtain the maximum in terms of efficiency during braking especially from the point of view of safety having precisely a greater control of the vehicle.

As for its principle of operation, everything is based on the installation of a sensor on each wheel. Its task is to detect the speed of rotation of a toothed ring (phonic wheel) mounted inside the wheel itself. The rotation value recorded on each wheel is sent to a control unit. The control unit is connected to a hydraulic system (unlike the pneumatic one of trains) which, thanks to electric actuators, can come into action to brake autonomously

Figure 1.3 velocity sensor

Source: https://club.auto-doc.it/magazin/sistema-anti-bloccaggio-abs-cos-e-e-come-funziona

Essentially, the system works as a pressure limiter. If the driver activates the brake with excessive force, braking is controlled and limited by the control unit to prevent the wheels from locking. Therefore, there is an adjustment on the braking that is fragmented into several fractions, thus preventing the total blockage. The ABS sensors at the wheel detect the rotation speed, controlling the braking force to be transmitted based on the data recorded in real time.

During a sudden braking, there is an imbalance of the weight (it is evenly distributed during the normal phase of travel), since it is focused more on the front side; therefore, the vehicle may tend to skid slightly and in addition the steering wheel may begin to vibrate. In the event of emergency braking or deep braking, you must hold the steering wheel firmly and continue to press the brake pedal until the emergency is over. To all this can also be added a vibration directly at the height of the brake pedal, which is completely normal. Indeed, in these situations it is better to also press the clutch pedal, to prevent the engine from turning off. In fact, ABS is a system that is active only if the engine is on and therefore stops working with the engine off leaving the vehicle at the mercy of interrupted emergency braking.

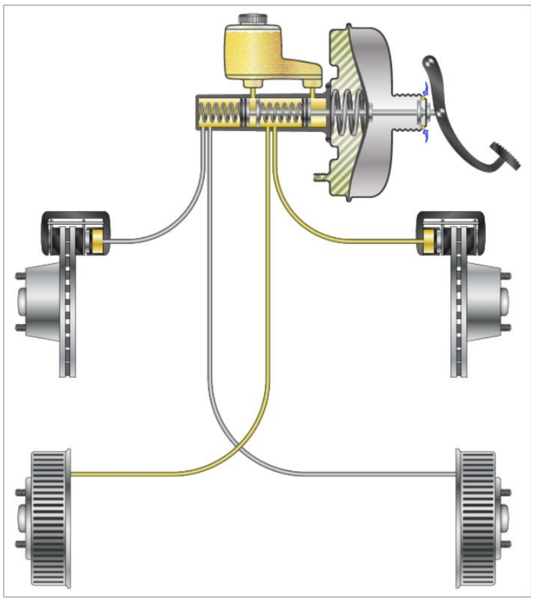
As mentioned above, there is a combination of pressure and oil; in fact, when there is pressure on the brake pedal, this pressure is transmitted directly to a brake system pump that has the task of transforming this pressure into hydraulic energy that is directly used on a technical fluid, the brake fluid (brake oil), which is thus transported to the wheels.

The braking force is distributed unequally between the axles precisely to balance the imbalance of weight that has been created through the braking distribution. Typically, the braking ratio between front and rear wheels is **60**:**40**.

Therefore, ABS prevents the wheels from locking and slipping, to always have control over the trajectory of the machine (for example, on ice or gravel).

As well as any braking system, it has some main components that are consumable both with time and with use. In fact, they tend to deteriorate and must be checked regularly and replaced in time. Among the signs to keep in mind to anticipate a brake check there are: hard pedal, pedal too soft, vehicle that tends to skid under braking, excessive vibrations, tears during braking.

Figure 2.3 architecture of the car breaking system



Source: https://club.auto-doc.it/magazin/sistema-frenante-come-funziona-cosa-consiste

It is necessary to make a clarification: it has been said, in fact, that the circuit of the braking system uses a technical fluid, often called brake oil, but it is not oil in the proper sense. This fluid is responsible for the transmission of pressure, so it is equipped with additives that avoid compression, prevent the formation of rust on the elements of the braking system, prevent the achievement of the boiling point. It therefore has a very important role and for this it is necessary to check that the brake fluid tank is always at the level, with the right amount of fluid. Over time, worn brakes require more fluid, which must be checked periodically. The liquid must be replaced on average every two years, or every 40-60thousand km depending on the registration of the machine.

3.3 The railway brake

This paper will focus on the analysis of the type of system most used in the railway sector, namely the automatic and continuous pneumatic brake. It is known that, by applying the brake, the kinetic and potential energy possessed by the vehicle is converted into thermal energy, by means of the friction that is created during braking between moving surfaces. Subsequently, the thermal energy will be transferred to the surrounding air by convection. A railway brake, in accordance with UIC standards, must comply with the following requirements:

• automatic, to guarantee its effectiveness of action in the event of breakage of the convoy.

• continuous, so that the braking action extends to all vehicles in the train, while allowing it to be operated from any point on the train in an emergency.

• adjustable, i.e., moderate in braking and braking.

• inexhaustible, to ensure its function even after previous braking and braking cycles.

To these main characteristics are added further ones, such as compatibility and interchangeability since different vehicles can circulate on the same line.

3.4 History of the train braking system

the process that has gone through the braking system up to how we know it today, is rich in many examples of architectures and types. It should be noted that the braking phase was not so important compared to that of the actual gear. In fact, the innovation that characterized the search for increasingly efficient propulsion systems certainly did not go hand in hand with research that led to obtaining an increasingly innovative braking system. In fact, in the early days there was no preoccupation with it at all, and this was the main cause of some of the inconveniences of exercise which resulted in fatal disasters and wrecks.

The first real braking system was made by Stephenson. It was a steam brake, in which the latter was brought to a pressure value such as to operate the piston of a brake cylinder. The fundamental problem with this architecture was that it acted only on the locomotive. And in fact, the braking only affected it because the piston, reaching the bottom of the stroke and reaching the adequate operating pressure in the cylinder chamber, came to stop the train tractor as it pushed the stumps on its wheels. However, this system proved insufficient as the number of wagons in the convoy increased. Different types of braking system followed, up to the optimal one that was always on this idea, and that imposed itself as the final solution. It was, in fact, with George Westinghouse, an American inventor, that a pneumatic, automatic, and continuous braking system was arrived.

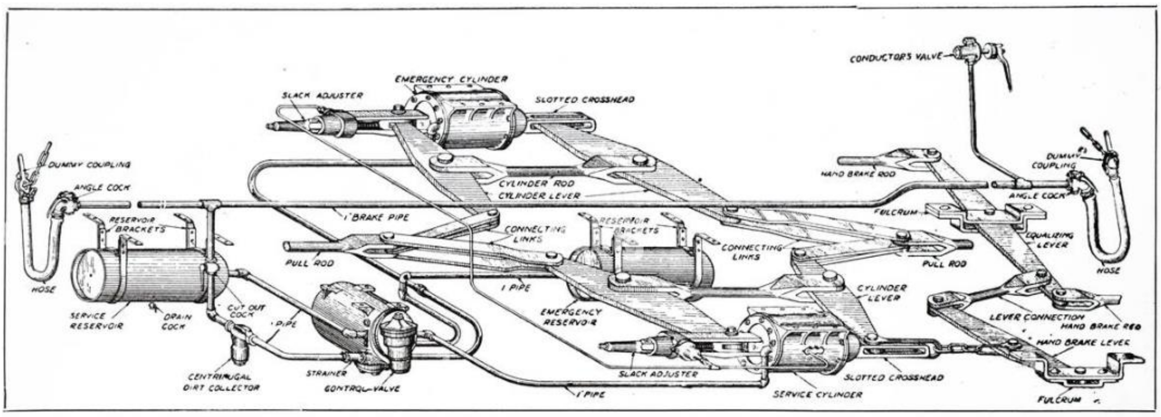
In the first models, the American inventor could not achieve the same effectiveness that he then obtained with the pneumatic brake that was detected, therefore, his final patent. Westinghouse, starting from Stephenson's idea, made up for the lack of the basic model by extending the braking capacity to all the vehicles of the convoy, through a common and continuous conduct, which had, in fact, the task of operating the cylinder-brake of each car pulled by the train tractor (continuous brake).

The connection between the various carriages was ensured thanks to the presence of a flexible hose equipped with insulating taps at each end, to allow the composition of the train with a variable number of vehicles. In fact, it was enough to guarantee everyone the connection to the main system. During the braking session, through the action of a control valve put in the activation position, the pressed steam flowed from the locomotive and through the common duct, reached each cylinder operating the stumps and thus allowing braking starting from every part of the vehicle.

Therefore, the mass in tons of the cars was no longer just a towed mass but also a brake mass. Always through the control valve, the release was performed, discharging the steam into the atmosphere, and rearranging the brakes. The system, however, proved inadequate since the use of steam also led to the danger of condensation along the pipeline. Then, to obtain the pressure necessary for the operation of the system, we moved on to think of other alternatives such as: water, oil, and air.

The choice fell on the compressed air, as it turns out to be an inexpensive and easy solution to supply fluid, with the possibility of being able to disperse it in the environment after its use. In addition, the compressed air system requires a simpler constitution than that based on the use of hydraulic fluids. Therefore, there was an improvement of the efficiency in terms of commitment, cost, and environment. Compared to today's system, there were some changes made to enhance some aspects, but the patent proposed by Westinghouse was always used as a basis.

Figure 3.3 the Westinghouse brake



THE "WESTINGHOUSE" BRAKE

Details of the equipment attached beneath a modern heavy passenger coach to ensure safety in high-speed railway travel.

Source: https://www.alamy.it/schema-del-freno-westinghouse-utilizzato-su-carrozze-ferroviarie-in-data-xx-secolo-image186347294.html?pv=1&stamp=2&imageid=7A16AD00-1D1E-4AE4-

BCF3-AD82B39C8D61&p=75935&n=0&orientation=0&pn=1&searchtype=0&IsFromSearch=1&srch=foo%3db

3.5 Layout of the braking system

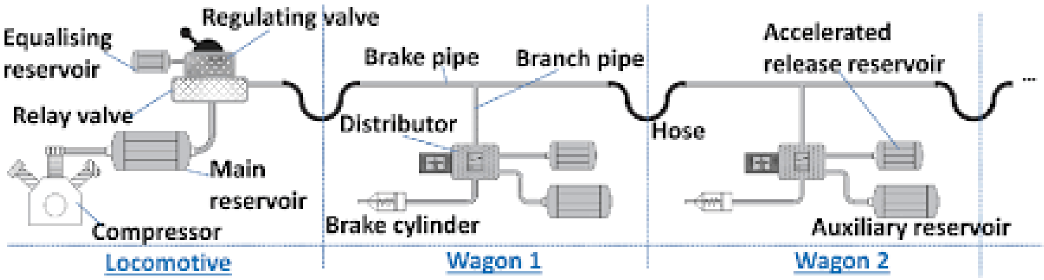
The braking system of a train, unlike that of a car, for example, must consider a particular aspect: its mass. Moreover, in addition to the tons transported at extreme speed on an area that may present critical issues from time to time, it must also be considered that the total complex is not a single block but is formed by several parts that are hooked together by means of couplings able to keep them constrained. These organs change according to the type of vehicle and therefore the type of transport for which it is used (freight or passenger train) but, in principle, these different connection regimes operate according to the same modus operandi.

Precisely for these aspects, the action of the train must be rapid and decisive as several subjects enter the scene, some of which, to have to maneuver simultaneously in different parts of the convoy, and others, instead, subsequently according to a series of appointments in the style of the assembly line. The system is designed in such a way as to fully perform this task and, to perform a correct braking session, it consists of some basic elements.

It is important to point out that the architecture of passenger trains is a little more complex than the installation of freight trains; in fact, in the first mentioned there are some more functions that are guaranteed and controlled by additional elements that would be superfluous in freight trains. Just think, for example, of the pneumatic drives necessary for the correct functioning of the doors; for this reason, in fact, in these trains there is a second pipeline that has the task of loading both the air to power these pneumatic devices and some tanks necessary for braking that will be shown shortly. Therefore, the freight trains aren't equipped with this second pipeline, there is overall a lower braking charge provided by the general pipeline (whose first task is the braking itself) since the tanks take air directly from it. The braking potential that would be able to be provided is therefore limited.

Starting from Figure 4.3 you can proceed with the description of the operation of the system and the function performed by the individual components.

Figure 4.3 train brake model



Source: [PDF] Railway Air Brake Model and Parallel Computing Scheme | Semantic Scholar

The production of the compressed air necessary to put the entire system into operation is entrusted to one or more compressors that are placed in the locomotive. Such compressors can typically be reciprocating or rotary. There is a preliminary treatment that this air undergoes immediately after being generated and before being introduced into the system. It is essential, in fact, that it is deprived of any type of contamination since this would compromise the entire system causing rapid wear. Therefore, it goes through a series of filters and drying stages for the elimination of water vapor which, as we said earlier, would cause condensation.

Once treated, the air is accumulated in a reservoir which is called the main reservoir, whose capacity can reach up to 1200 liters, at a pressure of between 8-10 bar. This tank is the heart of the entire system, in fact it is the organ that has the task of providing the air necessary for the operation of the braking system and of recharging, as happens in passenger trains, secondary systems for additional components.

The air accumulated in the main tank is then conveyed into the entire system through the brake pipe (4). It is a tube that runs through the entire train and connects all the wagons of the train by means of hoses equipped with valves for insulation. It is precisely through the general duct that it is possible to transport the air to the pressure necessary for the braking / braking controls to all vehicles. In particular, the air loads the entire pipeline making it reach a pressure of 5 bar, nominal value of pressure necessary to comply with the task of charging the various elements (according to standard [N1]).

The connection between the air generating organ and the transport pipe is through a regulating valve (3) which has the task of operating the passage mechanism and thus managing the driving, braking, or braking maneuvers. In fact, based on the position assumed by this valve it is possible to manage the value of the pressure along the pipeline and therefore the entry into play of the braking action or not. It is placed in the locomotive and is an element made according to the provisions of the standard [N2].

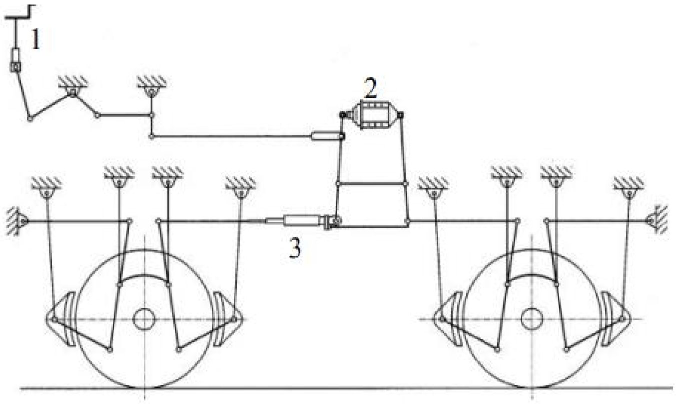
The air conveyed into the general duct flows inside a device that is a fundamental part of the entire operation of the system: the distributor or triple valve (8). It is a pneumatic valve, present on every vehicle, from which there is the actual connection with the mechanical part acting on the brakes placed on the wheels. In fact, this organ connects the brake cylinders with the auxiliary reservoir during the braking phase; vice versa, it isolates such a tank for the unbridled maneuver. The other elements that are part of the entire braking system and are connected to the distributor are:

• equalizing reservoir (6) used as a reference.

• auxiliary reservoir (7): feeds the brake cylinder

• brake cylinder (5) consists of a spring-effect actuator in which the piston transmits the force on the stumps through the wheelhouse distributing the braking action.

Figure 5.3 wheelhouse



Source: [PDF] Railway Air Brake Model and Parallel Computing Scheme | Semantic Scholar

• discharge into the atmosphere.

The distributor is called a triple valve because it performs three functions; in fact, based on the pressure in the pipeline with respect to the equalizing reservoir (always left at 5 bar) it connects:

-auxiliary tank and brake cylinder to achieve braking

-general duct and auxiliary tank to load the braking action

-brake cylinder and atmosphere for braking

3.6 Operation of the braking system

The air, as mentioned above, is generated, and compressed by the compressor in the locomotive, then it is fed into the main tank, ready for its use and conveyed into the general pipeline. The driver, by operating the regulating valve, manages the various phases that can follow. The control valve is characterized by several positions:

• filling position.

• driving position.

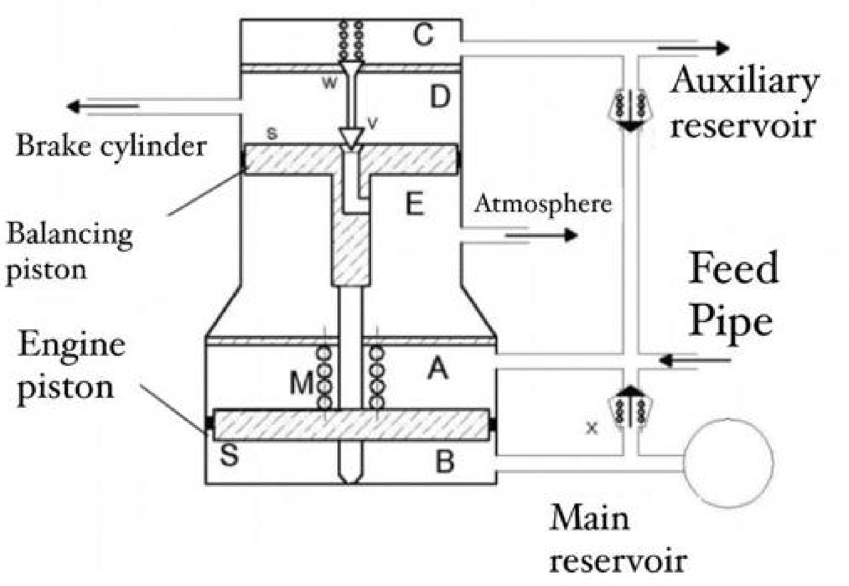
• service braking.

• emergency braking.

There are also gradual applications always managed according to the control of the movement of the control valve or even according to the time spent in each position, depending on how the device was designed.

The heart of the braking system is the distributor. To better understand the operation of this component, an image representing the functional scheme of a cross-section of the valve in question is proposed.

Figure 6.3 distributor valve



Source: https://meccanicaweb.it/analisi-dinamica-freni-treni-merci/

To these elements are added auxiliary devices such as repeating valves or relays, the empty load device, or the variable load one, the discharge aid valves and the WSP anti-skid device that this paper has examined.

After these clarifications, taking up the theme about the difference between the two types of brake on which the two types of anti-lock wheels act, we can add other aspects that enrich the list of similarities / differences taken in charge. Other differences concern accession and stability.

In fact, in the braking system of cars, we try to safeguard lateral stability by minimizing as much as possible the lateral movements along the road surface, but this is obviously a less critical situation compared to a train that is moving along a fixed rail.

As far as accession is concerned, the situation in which a railway vehicle finds itself is also more complicated in this case since in addition to the extra tons at stake, adhesion is particularly limited due to the factor of the very low coefficient of friction between the iron of the train wheel and the iron (steel) of the rail. In addition, the adhesion given by the surface of the railway soil is further deteriorated by the presence of climatic conditions or obstacles that contribute to making slipping more difficult to avoid, even more than what happens on the road surface since for the latter there are more innovative solutions to solve (or decrease) the problem, just think for example of the use of a draining asphalt obtainable from a mix of complex polymers. Precisely because of this greater risk, it goes without saying that the anti-skid system in trains is one of the fundamental devices to avoid the danger of wheel locking that would be risky along with all the other factors.

CHAPTER IV - The anti-skid device in railway vehicles: the WSP

4.1 birth and development of the system

As far as the historical aspect of the anti-lock system of the wheels is concerned, as can be deduced from the name of the system itself, the first devices were designed precisely to avoid slippage situations and in particular axle locking. In the first models proposed, the operation was based on a complete release of the brakes to induce a total reduction of the sliding force at the exact moment when an axial slip start was detected. Only when this phenomenon disappeared, bringing the vehicle back to a linear situation of motion without any alarm, the braking system was restored to its nominal force.

This first type of solution, however, was not very good from the point of view of efficiency especially in terms of safety since this mechanism, based on the total release / restoration of braking force, determined, in some cases, substantial increases in terms of stopping distance. During some tests, in fact, an increase from 60% to 115% of this space was detected. And this aspect was not acceptable considering the tons at stake of the vehicles and the architecture of the railway surface.

More precise and sophisticated WSP models came with the strong development of digital electronics in the late 1970s and early 1980s. In this time axis, in fact, in addition to this progress, in parallel, there were in-depth studies both experimental and theoretical about the wheel-rail adhesion especially during the braking phase. This allowed us to better understand the phenomenon of slippage and some influential parameters to be considered in designs to limit errors.

From the various studies it had come out that to obtain a good WSP system in terms of efficiency it was necessary to always try to guarantee the maximum of the adhesion / sliding binomial. The function representing one magnitude as a function of the other had an overall maximum. Therefore, the task was to adjust the various elements to remain close to that maximum or from the parts of one of the local maximum acceptable.

It is therefore from the beginning of the year 1980 that began to develop new WSP devices that had the task of adjusting the sliding of the wheels and preventing locking with a control technique that went beyond the limit of previous solutions. In fact, as a fundamental aspect, the principle of operation should not be based on a complete release/restoration of the braking system. It was therefore intended to obtain an anti-lock system capable of adjusting the braking force in real time to be able to guarantee, moment by moment, between wheel and rail, the maintenance of a constant sliding during the motion of the vehicle (that in physical / mathematical terms corresponds to the maximum adhesion value obtained).

At the same time, this development was also accompanied by technological growth, especially in the last thirty years, as regards the microcontrollers and microprocessors sector that constitute one of the fundamental parts of the basic elements of the current WSP device. In fact, there was an evolution both in terms of performance and marketing. In fact, valid devices began to be in the market at a revolutionary price compared to the past; and indeed, many production companies focused their sales strategy precisely on the imposition of a price that was competitive with other sellers.

This electronic revolution therefore led to the design of increasingly high-performance devices that, on the one hand, had increasingly high and controlled levels of braking force, and on the other hand were able to go beyond the limits of their predecessors by guaranteeing both shorter stopping distances and protection of rotating components in degraded adhesion condition.

Therefore, this second generation of anti-skid devices based its principle of operation on an adjustment of the braking action that had already begun to take hold since the end of 1970. In a decade, in fact, the main goal of the production companies was to commit themselves to being able to obtain a control system that released and reset the braking action in real time and according to the required quantity. To achieve this adjustment, the turning point was thanks to the previously declared development concerning microprocessors; it was thanks to these new devices that it was possible to begin to adapt the braking force according to what was needed without any excess. The correct sliding between wheel and rail was therefore achieved to permanently adapt the braking force to the maximum achievable adhesion.

After these two generations, in the 2000s, a further development was reached with a third generation of WSP devices designed in Japan. Basically, this new alternative had a basic principle of operation quite like that of the predecessor system with a difference specifically. In fact, this model was designed to use a sort of prevision of adhesion by exploiting the new knowledge in terms of probabilistic calculation and the results obtained from the simulations about the behavior of the system in the various cases. In addition, this new generation also used a continuous individual control system regarding the electro-pneumatic EP valves of multiple position. In this way it allowed each axial brake to be continuously and individually controlled. In this way, it could operate in blocks and in a differentiated manner according to the request.

The system is also capable of maintaining braking at the point corresponding to the saturation of the viscous creep which, as we recall, corresponds to the deformation of a material subjected to constant stress for long periods at a high temperature (the value at which the creep is saturated, also corresponds to a peak value of adhesion, a region that was generally considered unstable by the second generation of WSPs). This ability to reach and maintain certain stress thresholds is a clear demonstration of the high performance in terms of braking especially in snow or ice conditions where grip decreases drastically, and it is therefore essential to have the security of being able to go up to the maximum possible value.

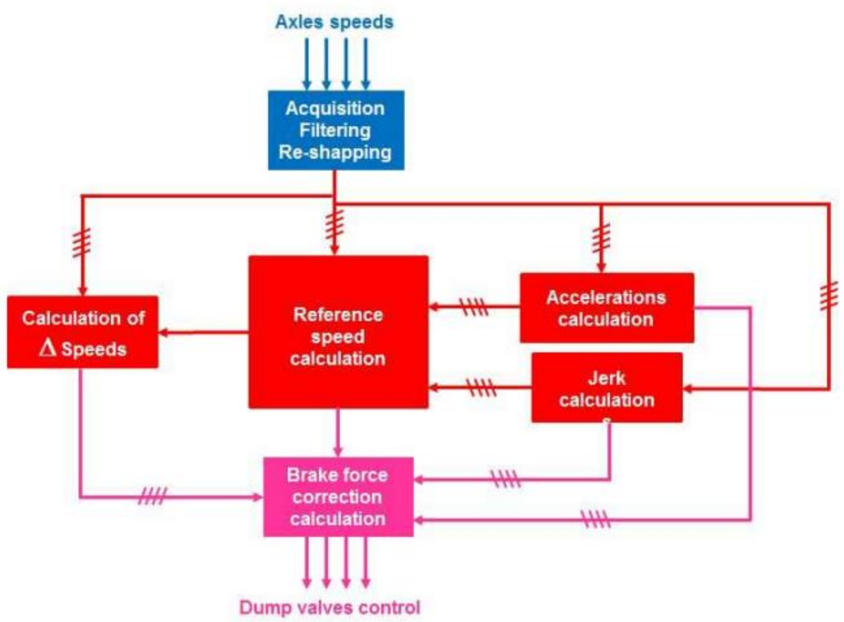
4.2 Calculation algorithms underlying the operation

These types of anti-skid systems based their operation on two calculation algorithms. The first was fundamental to be able to determine the reference speed of the system, it was therefore an algorithm for reconstructing the speed of the entire vehicle; while the second to quantify the difference in terms of speed between the latter and the nominal speed of the single axis to establish whether it was necessary for the anti-lock to come into operation. To have a greater correction of calculation, the algorithm carried out the same steps both for the speed of the axes and for their jerk (magnitude that indicates the derivative of the acceleration) so in this way it is possible to make a check not only on the variation of the speed but also on that of the acceleration. In fact, remembering that acceleration is proportional to the force applied to the body, its derivative indicates the speed with which the force itself is applied. It is therefore in this way that it is possible to have that regulation of the braking force so much required both in terms of quantity and in terms of action times.

For the adjustment of the slide there is therefore a first adjustment through the correction of the braking force to be applied in terms of value; subsequently there is a correction about the request of the brake itself, or in determining whether moment by moment the braking action is necessary. The latter adjustment can also be made by direct correction of the pressure value in the brake cylinders. It is possible to carry it out thanks to the type of implementation of the braking system that is pneumatic and takes place, as already mentioned, through the presence of exhaust valves and their state.

In the figure below there is the schematic representation of the algorithm just described in which the different calculation steps are presented about the kinematic quantities that affect the locking system. As you can see, in fact, everything starts from a level in which in addition to the actual calculation of the quantities there is also the part in which they are compared to determine the difference with respect to the reference ones. After doing this, both based on the delta obtained and based on the real-time values that are obtained from the calculation algorithm, there is the correction and decision of the value of the braking force that will act directly on the control of the exhaust valves in a different way depending on the control system chosen.

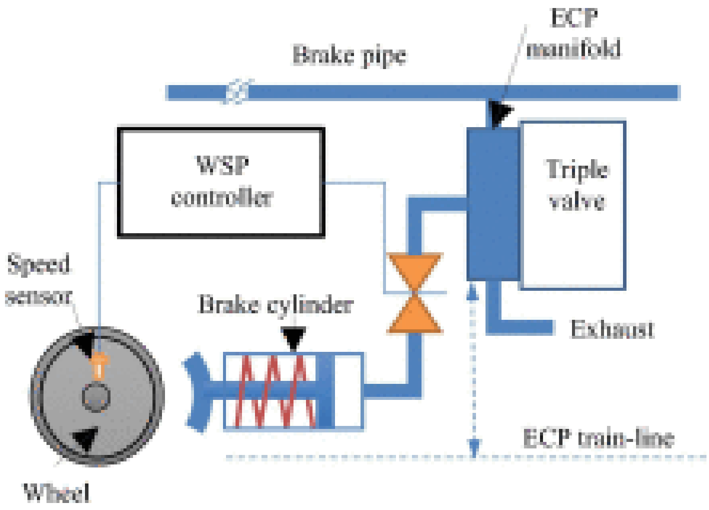
Figure 1.4 schematic representation of the algorithm



Source: https://rail21.pagesperso-orange.fr/Freinage_Adherence_Antienrayeurs_EN.pdf

As for the schematic representation of the entire system, the following image is given in which the entire WSP device is surrounded by the mechanical part of its braking system and the electronic part of its controller.

Figure 2.4 schematic representation entire system



Source: https://www.sciencedirect.com/science/article/abs/pii/S088832701930545X

4.3 Internal architecture of the WSP device

As mentioned above, the WPS system is the guarantor of safety about the dangers that may arise from slipping, sliding, and blocking of the wheels, during both the driving and above all braking, to slow down and to stop the vehicle. In addition, such situations could generate facets of the wheels or in any case compromise in some way the geometry of the wheel-rail combo. Therefore, the safety device is also useful to reduce maintenance costs due to the periodic repair required by these components.

The principle of operation is based on a transmission of signals picked up from speed sensors placed on the wheels that are sent to a processor. They are then processed and analyzed and based on a comparison with the other signals obtained there is the activation or not of dump valves / anti-skid valves that act directly on the brake cylinders. These valves regulate the pressure in the cylinders to avoid locking/skidding of the wheels without interrupting the braking phrase.

One of the most important features in this device is that everything must be instantaneous, and the control values must belong to a certain range since the adhesion to the rail must be maintained. The main parts of the WSP system are:

1. Speed Sensor.

2. Phonic wheel.

3. Microprocessor.

4. Dump valves.

5. Pressure switch.

As for the construction and manufacture of the main devices, among the leading companies, with a more important market position than others, we find: Faiveley Transport, Knorr-Bremse, Wabtec, DAKO, KES & Co GmbH, Mitsubishi, Siemens, Selectron Systems AG and ABB.

Each component will now be analyzed in more detail to better understand the principle of operation of the device, what differentiates one system rather than another according to the production company and also the changes made over the years and planned for the future for continuous innovation.

4.4 Speed Sensor

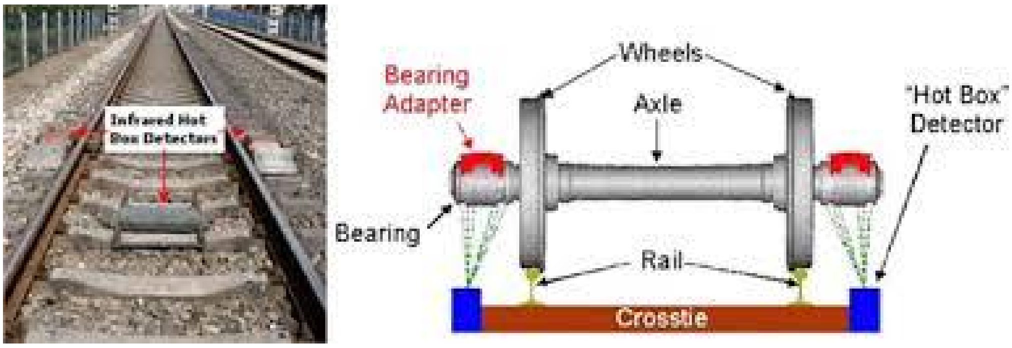
the speed sensors are fixed by means of two bolts at one end of the axle box of the bogie.

Figure 3.4 speed sensor

Source: [Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)]

In particular, the axle box is a mechanical part placed at the end of the axis of each wagon that makes up the train (including the locomotive). It contains bearings to transfer the weight of the wagon, carriage or locomotive to the wheels and tracks. In addition, they allow to minimize the friction due to the rotary motion of the wheel around the axis. For these functions, it is necessary to continuously monitor their lubrication and overload which are among the main causes of their failure thus causing risks to the safety of rail traffic. To overcome this problem there is a control system, namely the ATD axle box temperature detection system that has the function of monitoring the heat released by this element since an increase in heat is an indication of degradation.

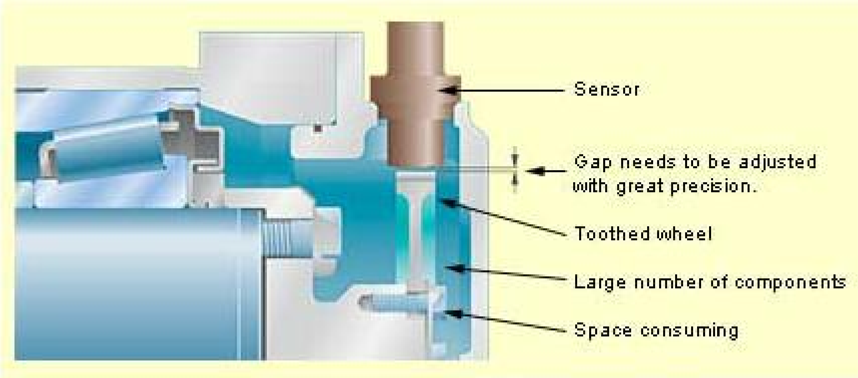
Figure 4.4 hot box detection system



Source: TK-499 infrared hot box detection system (Harbin VEIC Technology Co. Ltd 2008, Southern 2007)

The mounting of the sensor on this element is fundamental given its importance. In fact, in this procedure, the space that is created between the phonic wheel and the sensor probe plays a vital role. However, it is possible to measure this gap through the peephole present in the geometric architecture of the bushing and adjust it using some thicknesses. The air gap between the rotating gears and the probe is also an aspect that differs according to the production house of the element. In fact, for the Knorr Bremse company it is between 0.4 mm and 1.4 mm while for the Faiveley company it is between 1 mm and 2 mm.

Figure 5.4 speed detection design



The conventional speed detection design is based on a sensor mounted into the axlebox housing and a toothed wheel located at the end of the axle.

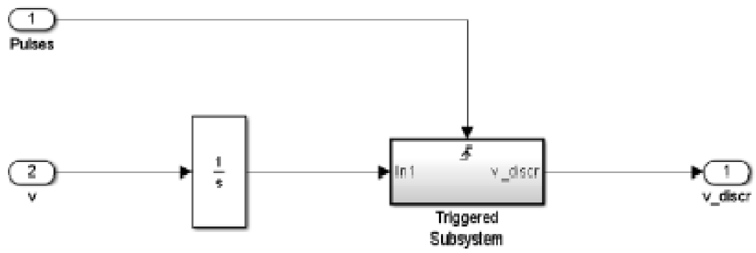
Source: https://evolution.skf.com/us/sensors-for-railway-bearing-units/

As the name already indicates, the main function of the sensor is to collect information about the speed assumed by the phonic wheel and transmit it to the microprocessor for processing. The acquisition of the signal by the sensor therefore takes place without any physical contact due to the presence of the air gap mentioned above.

The sensor, in fact, does nothing but scan the rotary movement of a rotating gear (the phonic wheel). There is a correspondence of direct proportionality between the angular velocity of the wheel and the frequency of the digital signal picked up.

A possible implementation of the speed sensor will be presented through MATLAB Simulink in which is represented a simplified simulation of the sensor that calculates the discrete value of the tangential velocity of the wheel starting from the continuous value of the angular velocity. In addition, a period of 10 ms was chosen as the time interval.

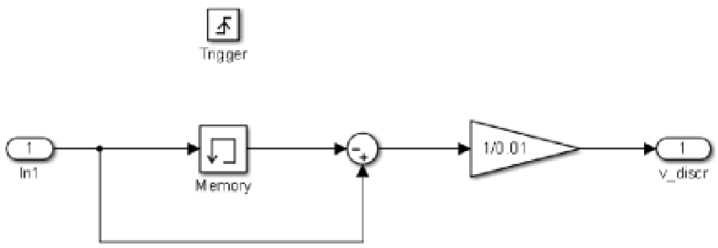
Figure 6.4 simulation model



Source: BarnaG_SimulationModel.pdf

Where the subsystem in turn has such a diagram

Figure 7.4 Simulation model

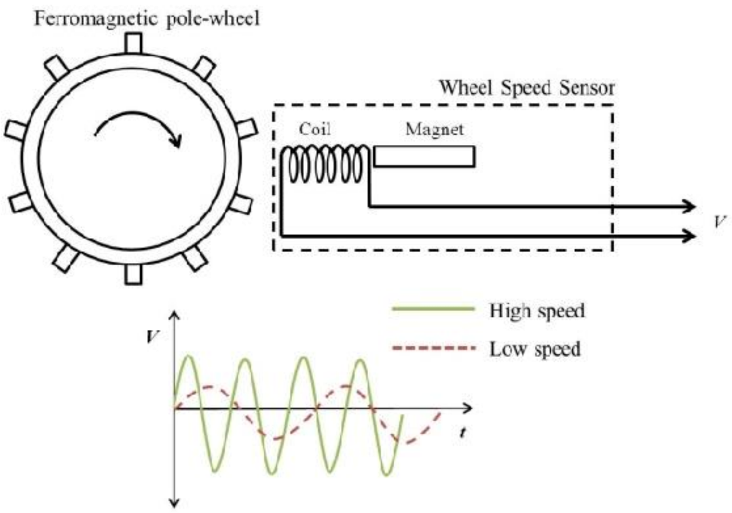


Source: BarnaG_SimulationModel.pdf

4.5 Phonic wheel

The phonic wheel is a mechanical device, installed at the end of each axis, which has the function of altering the internal inductance of the adjacent sensor that must capture its movement. It is a cogwheel, like a gear, and it is important that it is installed correctly to ensure a concentric and non-eccentric movement that would cause an error in the intercepted signals and damage to the sensor probe. As mentioned above, the teeth of the wheel are read by the sensor as they pass in front of it thus generating an oscillating electrical signal. Thanks to it, therefore, it is possible to read in real time the speed of rotation of the wheels.

Figure 8.4 Variable reluctance wheel speed sensor operation



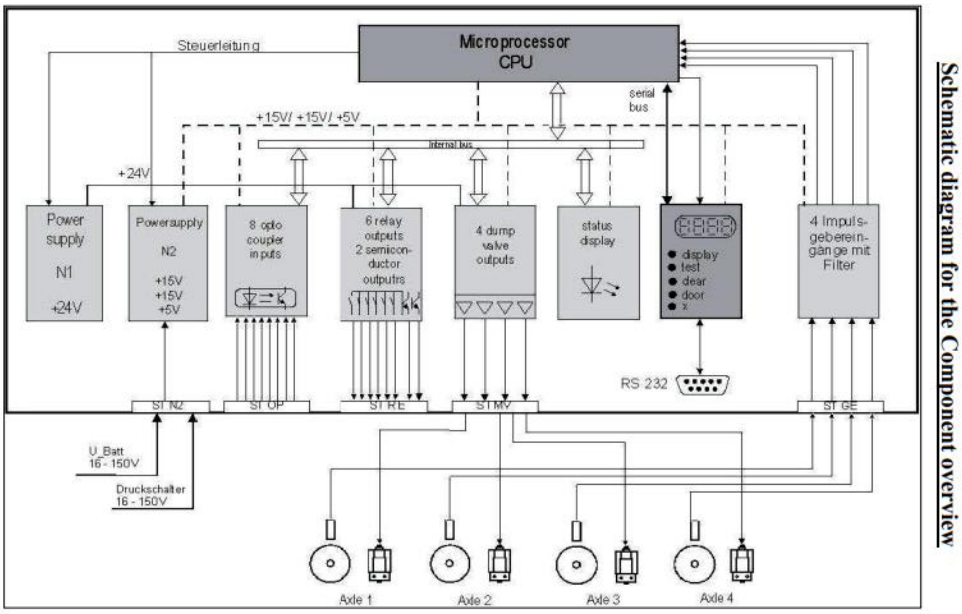
Source: P. Enoksson, R. Johansson Published 1 October 2012 Physics 2012 IEEE International Symposium on Robotic and Sensors Environments Proceedings

4.6 Microprocessor

The microprocessor is the heart of the WSP system. In fact, it receives the signal transmitted by the speed sensor starting from the rotational movement of the phonic wheel and processes it to obtain the speed of the vehicle. In addition, it also has the function of bridging the significant difference in speed that can be created between two axles / wheels in the braking phase which is continuously monitored in this way. To resolve this drop and bring the system back into balance, it operates the exhaust valve to control and regulate the pressure released by the brake cylinders.

As for the architecture, each element consists of LED displays and various test buttons. LEDs, in practice, show certain codes that are transduced via a decoder. In this way it is possible to keep under control the state in which the WSP system is located. As far as manufacturing is concerned, there are commercial contracts shared between several companies, among the main ones with a greater weight on the market are: Knorr Bremse (EP compact, EP2002) Faiveley Transport (EPAC) and POLI Wabtec (ATHENA).

Figure 9.4 Schematic Diagram



Source: https://www.slideshare.net/srguduru/handbook-on-wheel-slide-protection-device-wsp

4.7 Dump valve/Anti-skid valve

At each axle of the vehicle is also placed the exhaust valve that was named earlier. These are solenoid valves, so they are devices that operate electromechanically and are directly connected to the brake cylinders through the air pressure line. Through them all the air available in the brake cylinders is used during braking until it is exhausted, for this reason it is important that they are installed close to them.

They are called anti-slip valves precisely because they allow this depression of the air in the channels connected to the brake cylinders based on the signals that are processed by the WSP microprocessor.

Therefore, this device is the element of the anti-skid system that allows a control of the brake cylinders allowing a continuous rectification based on the signal generated by the microprocessor.

The valve has two doors:

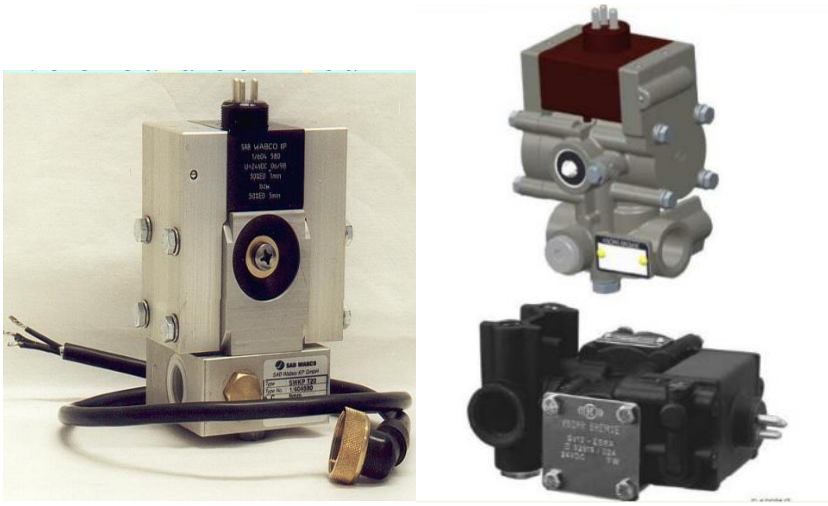
1. Charging port

2. Exhaust port

There is an independence between the two doors and depending on their opening position or not there is a direct control over the brake cylinders. Electrically, the microprocessor sends signals with a supply voltage of 24 V to the ports to change their condition.

In the default position, the charging port is open, and the exhaust door is closed. They vary their condition, exchanging it practically, when the microprocessor generates the signal. Compared to the default position, moreover, there is no need for any intervention by the microprocessor in sending signals in case you want to increase the pressure of the cylinders because this situation also corresponds to the necessary state in which the ports must be for this purpose. Instead, the microprocessor sends the 24 V signal to the cables of both ports to lower the pressure. In this case the charging port closes, and the exhaust port opens. While, to maintain the pressure in the cylinders at the level where it is located, the signal is sent to the cables of the charging ports only to close them and therefore not increase the pressure.

Figure 10.4 dump valve



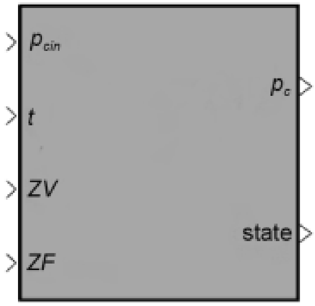
Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

The outlet pressure of the exhaust valve during filling or venting/discharging of the air is given by the following equation:

$$p_c = p_{ch} + (p_{cin} - p_{ch}) * \left(1 - e^{\frac{t - t_{ch}}{T_F}}\right)$$

$$p_c = p_{ch} * e^{\frac{t-t_{ch}}{T_V}}$$

Figure 11.4 Simulink model of dump valve



Source: BarnaG_SimulationModel.pdf

where:

p_c – brake cylinder pressure

p_{ch} – cylinder pressure at the moment of change of the control state

p_{cin} – input pressure of a dump valve

t – time

t_{ch} – time of change of the control state

T_F – brake cylinder time constant at filling

T_V – brake cylinder time constant at filling

ZV, ZF – control signals of respectively venting and filling valves. Control signals of the vent and filling valves respectively.

4.8 Pressure switch

The pressure switch is in the control panel of the braking system. From it the WSP system controls the electrical part of the entire circuit establishing the ON/OFF condition.

It is connected to the braking circuit through the main pipe (FEED PIPE) and based on the value of the pressure present in it is positioned in one of the two options.

When the pressure increases to a value of 1.8 kg/cm^2 there is the automatic closure of the channels through which it is connected to the system. In this way the electrical circuit of the WPS is energized and is in the "in operation" mode. When, on the other hand, there is a drop in pressure in the pipeline to 1.3 kg/ cm^2, the switch takes off mode, thus leading the WPS electrical system not to be powered.

There are various types of switches with different pressure threshold values depending on the production companies. Some values are shown in the table 1.4 below.

Table 1.4 Values from production companies

System makes	Working on pressure		Pressure range
Knorr Bremse	BP Pressure		0.2 Kg/cm2 – 0.5 Kg/cm2
Sat Wabco	FP Pressure	1.5 Kg/cm2 – 1.7 Kg/cm2	

Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

Figure 12.4 Pressure Switch

Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

4.9 Interaction and communication between all parties

Summarizing the principle of operation, it can be said that, starting from a sensor mounted on each set of wheels, a pulse is supplied to the vehicle's electronic unit that is representative of the speed of the axle. There is therefore a comparison between the impulses received from all the wheelsets to be able to make a check of the fact that they work in common agreement.

If there is the deviation of one of these pulses, or the deceleration of one or all of them at a non-compliant speed according to the limits of realization and construction, there is the activation of the electronic unit. This operation leads to a mechanical application such that a signal is sent to the charging or exhaust ports of the exhaust valve to release the brakes until the desired speed is obtained again. After that the brakes are reactivated.

In addition, you must pay attention to the difference between slide and skid. In both cases there is a need for the intervention of the WSP to prevent the wheels from getting stuck, but they take place in two different phases of the march. In fact, the slide is a locking that occurs when you are braking in this case, this occurs as the tangential speed of the wheel takes on a value that is considerably lower than that of the actual speed of the vehicle in motion. In the skid, on the other hand, the wheels assume a speed higher than this actual speed and therefore in this case you are in the acceleration phase.

Figure 13.4 schematic view of the steps

Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

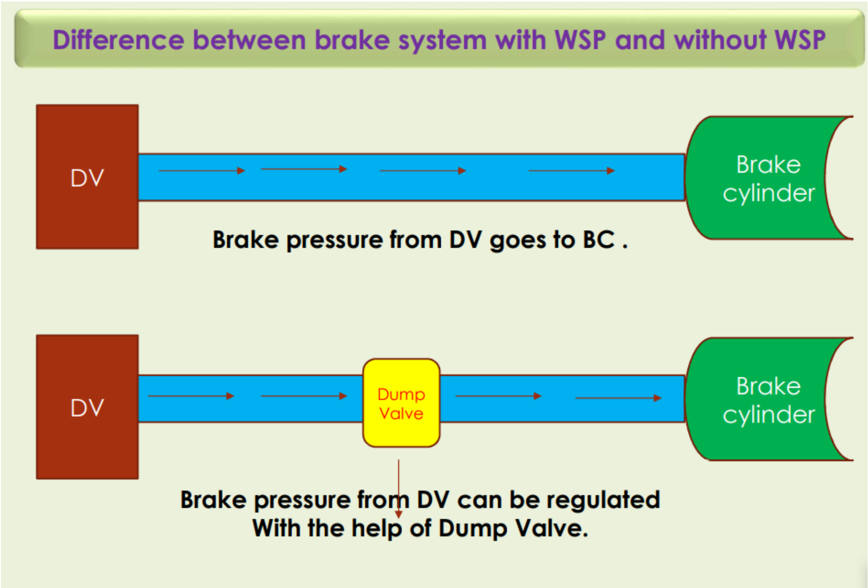
4.10 Features

Through the operations described, the anti-lock device therefore has these characteristics:

- Monitor/reduce wheel slip on rails
- It is activated from a decrease in braking force
- Reduces the distance required for braking
- Does not affect the braking power or its normal operation

The figure below shows that at the connection level along the general pipe, if system is present, the distributor valve (DV=VALVE DISTRIBUTOR) is not directly connected to the cylinders. In this way, thanks to the dump valve between them there is the regularization and modulation of the braking pressure.

Figure 14.4 dump valve for the regulation of the pressure



Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

4.11 Software and logics

To understand the principle of operation through a numerical example you can consider the following:

First, at every moment, the system identifies the axis with the highest speed among all. After a first comparison, therefore, this speed will be the reference speed (V_{ref}). Based on this speed, two virtual threshold speeds are calculated:

-Threshold Speed1= V_{th1}

- Threshold Speed2= V_{th2}

These thresholds are calculated based on complex mathematical formulas used directly by the software. Depending on the model used, therefore, the two speeds can vary between them since the production companies establish different nominal values for the activation or not of the system based on certain internal parameters also depending on the nature of the components used.

To continue this numerical example, for simplicity we assume these two below since, numerically speaking, it has been proven that they are the ones that minimize the gap between all possible alternatives.

$$V_{th1} = V_{ref} - (1.5 + 0.06\ V_{ref})$$

$$V_{th2} = V_{ref} - (2.5 + 0.25\ V_{ref})$$

Therefore, logical instructions are sent to the microprocessor which has the task of carrying out all the required calculations. After their processing by the software, the microprocessor generates the signals with the 24V supply voltage to activate the exhaust valve ports to regulate the pressure in the brake cylinders.

From some logical instructions, their behaviors are determined.

Indicating with V_i the speed of each axis, then V_{th1} will be the high threshold speed of the system while V_{th2} will be the low threshold speed.

Subsequently, if:

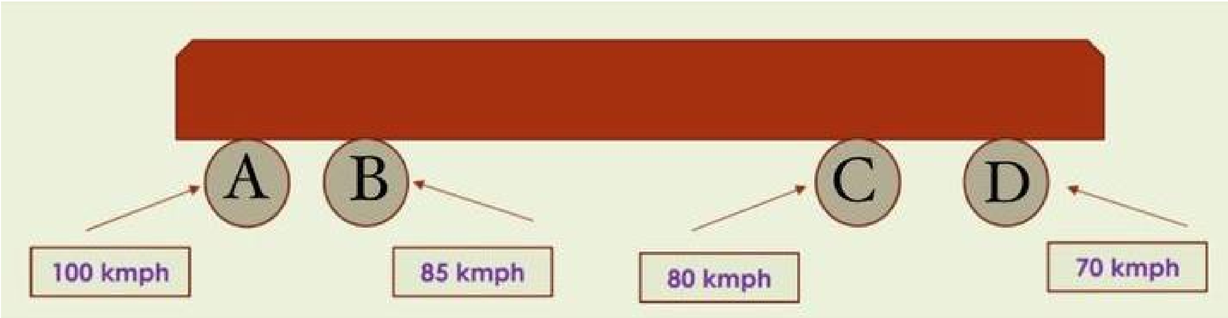
- $V_i \geq V_{th1}$, the pressure on the brake cylinders is increased so the microprocessor does not send any signal to the valve ports to keep them at the default position

- $V_{th2} \leq V_i \leq V_{th1}$, the pressure on the brake cylinders is maintained at the value present at that moment. The microprocessor, therefore, will send a 24V signal to the cables of the charging port to close it and thus keep the pressure constant.

- $V_i \leq V_{th2}$, the pressure on the brake cylinders is lowered. The microprocessor, therefore, will send the 24V power signal to both valve ports to close the charging one and open the exhaust one to allow the required drop of the pressure.

Assuming that you are in the situation shown in the figure during braking

Figure 15.4 Example



Source: Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)

Indicating with V_{ref} the axis with the maximum speed:

V_{ref} = 100 kmph

$V_{th1} = V_{ref} - (1.5 + 0.06\ V_{ref})$

$V_{th2} = V_{ref} - (2.5 + 0.25\ V_{ref})$

Substituting the value of V_{ref} within the formulas

V_{th1}= 100 – (1.5 + 0.06 x 100) = 92.5 kmph

V_{th2}= 100 – (2.5 + 0.25 x 100) = 72.5 kmph

At this point, considering the logical conditions seen above:

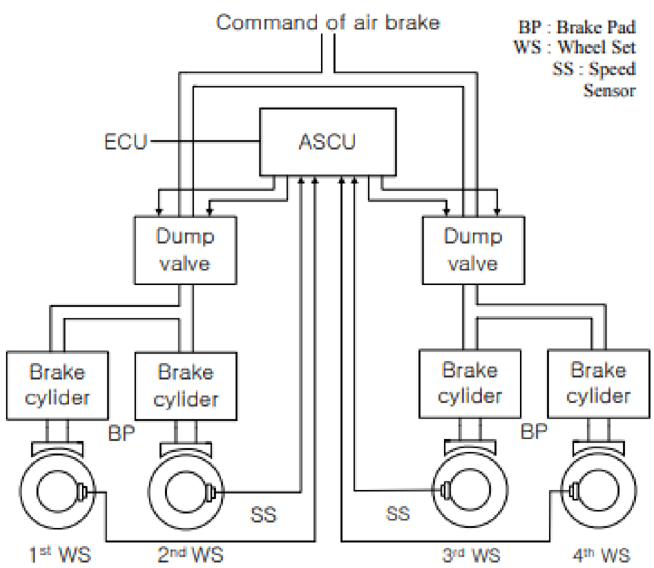
if V_i =100 kmph then $V_i \geq V_{th1}$.

Then the system increases the pressure in the brake cylinders (axes marked with A) if V_i = 85 or 80 Kmph then $V_{th2} \leq V_i \leq V_{th1}$. In this case the system maintains the pressure in the brake cylinders (axes indicated with B and C) at the present value.

If V_i =70 Kmph

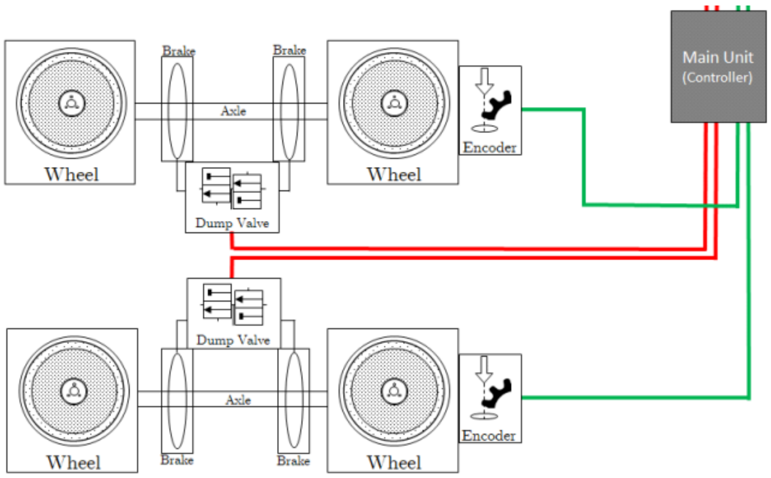
then $V_i \leq V_{th2}$. In this case the system lowers the pressure in the brake cylinders (axis indicated with D).

Figure 16.4 Functional block diagram of the WSP operations



Source:https://folk.ntnu.no/skoge/prost/proceedings/ifac2014/media/files/2106.pdf

Figure 17.4 complete scheme



Source https://rail21.pagesperso-orange.fr/Freinage_Adherence_Antienrayeurs_EN.pdf

4.12 UIC 541-05, 2nd edition standard

The UIC, an international standardization body operating in the railway sector, has defined a standard, the so-called UIC 541-05 "Frein-L'anti-enrayeur", which refers to the method of action on the anti-skid, it establishes the policy to be adopted regarding the speed thresholds and the criteria for which certain tests and simulations are acceptable. Thus, it defines:

• the speed thresholds that determine the insured intervention of the WSP anti-lock / anti-skid device. In particular, the intervention of the device which prevents wheel slip must not in any way lead to a change in either the braking effort or the amount of pressure required by the braking control. On the contrary, the braking effort that you get to have should be such as to make the most of the available grip which, as we remember, is the factor that starting from the second generation of WSP devices we always try to maintain at the highest achievable value

• the criteria for which tests carried out to achieve type-approval of the anti-skid are considered acceptable. In fact, to promote the railway sector, the European policy distributes some directives that have as their scope to increase the guarantee and control of safety. In addition, they also want to encourage type-approval to achieve interoperability through mutual recognition of safety certificates directly issued in the Member States. Simulations are carried out to launch a carriage in which the device has been mounted. First, it is brought to the speed established by the norm through traction by a locomotive; speed is determined and chosen according to the test that wants to be carried out. After the release from the train traction, a rapid braking is activated (braking that is activated because through the release there is the complete discharge of the general pipeline directly into the atmosphere) and the action behavior of the anti-skid system begins to be monitored. The track on which the test takes place has a slope of ± 0.002 m and a length of 1500 m. in addition to these characteristics, there must be a section that precedes this track equal to about 3 km that serves to be sure to bring the carriage to the acceleration necessary to reach the launch speed. In addition to this section, after the test track, another area of about 10 km follows used to allow vehicles to stop safely, even in the case of brake failure or incorrect operation of the device that precisely must be tested so it has no safety of operation.

The standard also has also the goal to present a comparison between the performance obtained in the case of dry track and those instead resulting in the case of dealing with a surface that has a degraded adhesion. The latter case requires that the rail is watered with nozzles placed in the lower part of the carriage and activated with an advance of about 300 meters from the braking start point until the end of the action, then up to the stopping point. Obviously, this situation has the consequence of lengthening the limits of acceptable braking distances, dispersing more compressed air, increasing the error in calculating the relative speed V_{ref}, and finally increasing the maximum permissible flow.

The set of tests includes a program of a succession of simulations that reproduce driving conditions. In addition, according to the standard there are three criteria for the evaluation of the test:

1.the initial adhesion to identify the exact moment in which +the sliding that involves the first axis of the launched carriage is manifested

2. the minimum sliding of the axles of the vehicle.

3. the prescribed stopping space.

4.13 WSP Control System

As has been said above, in the WSP system there is a considerable importance that assumes the control system that determines whether it comes into play depending on the situation in which the vehicle is found. In fact, in addition to the different variants that arise according to the architecture that varies depending on the production company, there are also differences about the control system that determines the quantity of forces that are put into play.

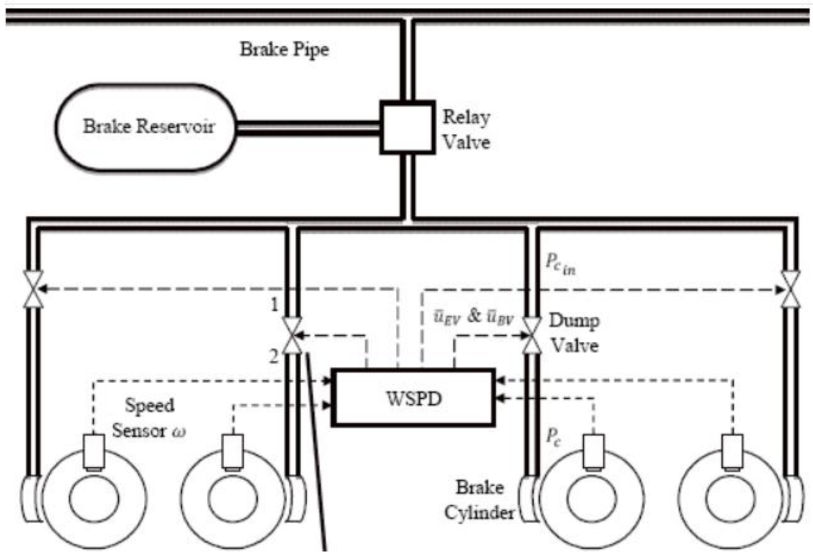
The fact is that, for the calculation of an efficient control system, problems arise due to uncertainties due to quantities that cannot be modeled since, for example, in a certain condition of the rail surface, the friction force is a non-linear function of the slip ratio of the wheel sets.

Therefore, not having the possibility of having a system that acts as a plant exhaustively in the closed circuit for the determination of the control system, it goes without saying that it is not possible to obtain one with 100% accuracy. A study will be proposed such that due to the nonlinear dynamics of the system and the presence of uncertainties, it is shown that the Adaptive Fuzzy Sliding-Mode Control (AFSMC) is used to adjust, towards the desired value, the slip ratio of the wheel sets since the braking friction force is a non-linear function of this ratio.

In particular, the proposed controller uses a PWM (Pulse Width Modulation) technique to generate the braking torque and in this way, unlike other cases where fluctuations in the slip ratio diverge close to the stopping time, simulation studies reveal that with the AFSMC method, the stop time of the locomotive and the fluctuation amplitude of the slip ratios are reduced.

In addition, common methods of control techniques for the WSP of companies such as Trenitalia, Knorr-Bremse and Mitsubishi are introduced for comparison. Comparing the results of these implementations, it was shown how, using the AFSMC control system, it was possible to optimize the anti-lock system managing to minimize the errors and uncertainties that are part regardless of the model. In fact, the results of the simulation show that, compared to the techniques of Trenitalia, Knorr-Bremse and Mitsubishi, the AFSMC method can improve the robustness of the WSP device regarding the various railway conditions.

Figure 18.4 Schematic view of the electropneumatic braking system in a railway wagon



Source:https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Among the proposed techniques, the application technique by Trenitalia will be presented since it bases its control on speed and acceleration values for the activation of the WSP, therefore an implementation of the numerical example reported above.

In the method presented by Trenitalia, the input of the wheel slip protection system indicated in the figure with "u" is determined based on the speed and acceleration values of each set of wheels. In this algorithm by specifying two ranges for the speed and acceleration of wheel sets, the WSP can be adjusted in states of pressure increase, pressure maintenance and pressure reduction.

The algorithm is represented in the image below; where: *i*, *ACC* and *DEC* indicate respectively the number of wheel sets, the maximum and minimum accelerations of the wheel sets. On the other hand, the maximum variable speed V_{Max} and minimum speed V_{Min} of the wheel sets are determined as follows:

V_{Min} = 0.78v and V_{Max} =0.9v,

with v equal to the longitudinal speed of the vehicle. These thresholds are due to the limits imposed using certain mechanical components compared to others; while as regards the values, experimentally they were the most recurrent and that minimize uncertainties. Same motivation also found previously in the numerical example for the choice of mathematical formulas for the calculation of V_{th1} and V_{th2}.

Table 2.4 Trenitalia's control algorithm

$\frac{d(r * w_i)}{dt}$	$(r * w_i) > V_{MAX}$	$(r * w_i) < V_{MIN}$	$V_{MAX} < (r * w_i) < V_{MIN}$
$\frac{d(r * w_i)}{dt} > ACC$	$P_{Ci}\uparrow(u_i = 0)$	$P_{Ci}\downarrow(u_i = 2)$	$P_{Ci}\uparrow(u_i = 0)$
$\frac{d(r * w_i)}{dt} < DEC$	$P_{Ci}\uparrow(u_i = 0)$	$P_{Ci}\downarrow(u_i = 2)$	$P_{Ci}\downarrow(u_i = 2)$
$ACC < \frac{d(r * w_i)}{dt} < DEC$	$P_{Ci}\uparrow(u_i = 0)$	$P_{Ci}\downarrow(u_i = 2)$	P_{Ci} Hold $(u_i = 1)$

In this case, on the part of Trenitalia, there is the output value that indicates the opening or closing of the dump valve door starting from the need or not to raise or lower the pressure in the brake cylinders depending on the comparison of speeds and accelerations with respect to the threshold values.

Thus, the calculation of u has a dependence due to these quantities and is modeled as a first-order linear control system with linear equations. For this reason, it is normal that already a priori it should be known that this method of control is impossible to represent the optimal choice since, in the closed loop for the calculation of u, many variables are not considered. Despite this, from the simulations, a certain efficiency was still found if we are dealing with less complex situations in which the variables at stake represented by the uncertainties are zero.

The figure shows the algorithm established by Trenitalia for the control of the WSP. According to this solution, starting from the range in which the vehicle's wheel set is located, there will be a 24V supply intervention of the charging or exhaust port of the WSP valve depending on what you want to achieve about the pressure of the brake cylinders. You may notice how:

- In the event that the angular velocity of the wheel sets causes their linear acceleration greater than the maximum permissible acceleration value (typical case that can cause SKID during the acceleration phase), if the linear speed is higher than V_{Max} , then the pressure in the brake cylinders must be raised to increase the braking force; if the speed instead it is less than V_{Min} then it is necessary to lower the pressure on the cylinders to decrease the braking force; if instead the speed is internal to the interval between V_{Max} and V_{Min} you still need to raise the pressure in the cylinders because the longitudinal acceleration is higher than the maximum allowed so it is necessary to decelerate the system.

- If, on the other hand, you are dealing with a deceleration less than the minimum threshold allowed (in this case we are in the presence of the SLID phenomenon during braking), if the linear speed is higher than V_{Max} then you have to raise the pressure in the brake cylinders to increase the braking force; if the speed is lower than V_{Min} then you need to lower the pressure on the cylinders to decrease the braking force. These last two behaviors are like the previous case in terms of solution about the increase or reduction of pressure, but it is the context to be different as in the first case we are in the presence of an acceleration while in this second case there is a deceleration. In addition, always in this sub-case examined, if instead the speed is internal to the interval between V_{Max} and V_{Min} there is still a need to lower the pressure in the cylinders because the longitudinal deceleration is lower than the maximum allowed so it is necessary to accelerate the system.

- Finally, if the sets of wheels are found to rotate with an acceleration value between the upper limit and the lower limit mentioned above, there is a similar behavior for the first two cases. This is because, in that case, the system is traveling with such acceleration that it is not actually in the acceleration phase or in the braking phase. If you exceed the maximum speed, then you fall into the first case of SKID and therefore you want to raise the pressure to increase the braking force; while in the case where the speed is lower than the minimum you fall into the case of SLID and therefore you want to lower the pressure to decrease braking force. A different behavior, however, occurs in the case in which it is also the speed to fall within the range imposed by the two thresholds, because, since the acceleration has no critical value to alarm a possible locking wheel, there is no need to act in any way on the brake cylinders since the braking force in place at that moment is suitable to keep the motion constant. For this reason, therefore, the pressure is kept constant, leaving the dump valve to the default conformation.

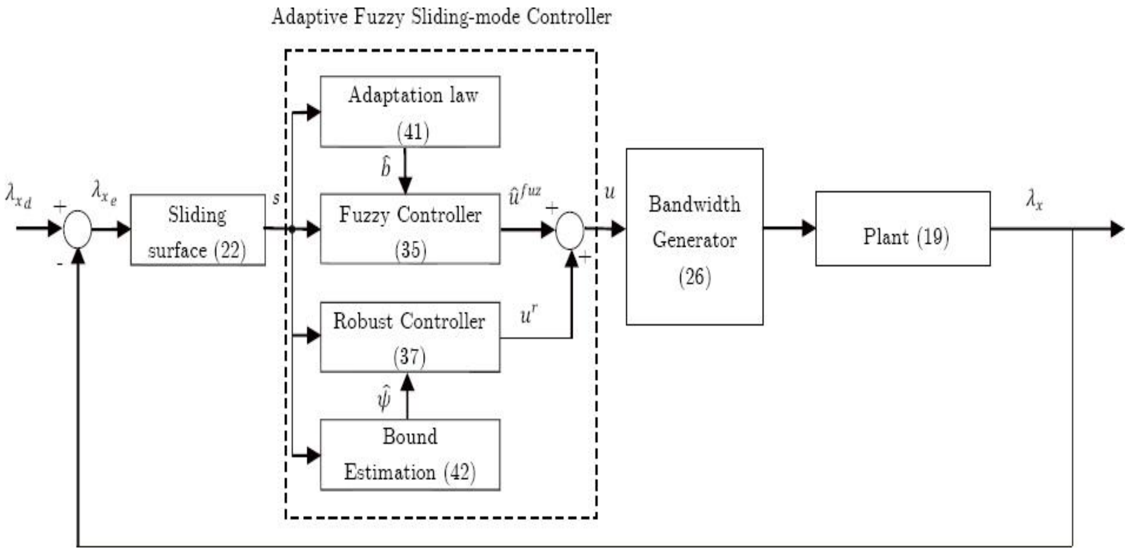
For the value of u indicated in the table, the valve port is considered active in case it is fed via the 24V signal to change its position from the default one where the charging port u_c is open and the exhaust port u_e is close. Thus, in the default position $u_c = 0$ and $u_e = 0$, so u=0. To show all the states of the valves during the phases of increase, lowering and maintenance of the pressure, the table below is shown.

Table 3.4 Status of the charging and exhaust post according to pressure status

Pressure status	Charging port u_c	Exhaust port u_e
Increased pressure	Inactive, u_c= 0	Inactive, u_e= 0
Pressure reduction	Active, u_c=1	Active, u_e=1
Pressure maintenance	Active, u_c=1	Inactive, u_e=0

In the case of Fuzzy control, for the ideal calculation of u there is a much more complex procedure that winds between differential equations and approximations to Gaussian functions (to be able to obtain a limited approximation error) that will be omitted in this paper. It should be emphasized, however, that through these formulas there is a modulation of the ideal value of u obtained through several components constituting the complete controller. To demonstrate this, the closed-loop scheme for its calculation is presented in this implementation.

Figure 19.4 Adaptive controller structure in fuzzy sliding mode.



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

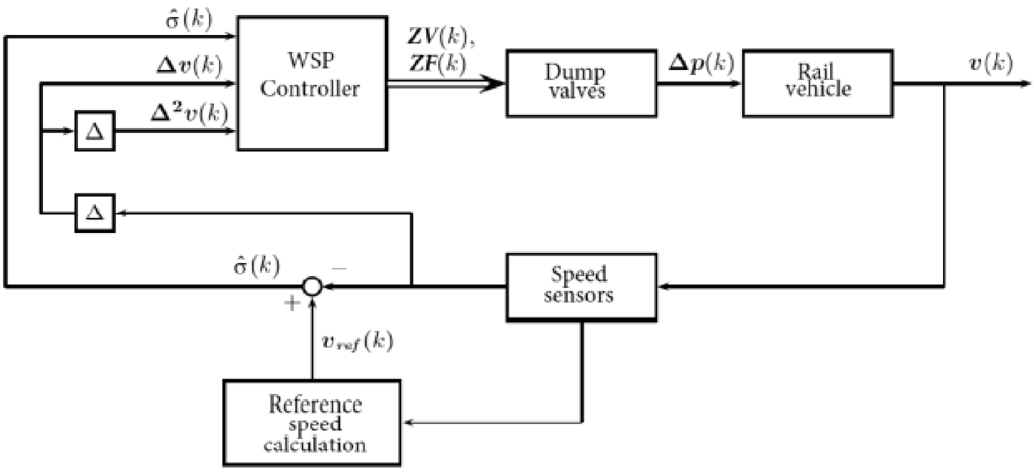
In addition, a practical block diagram through implementation on MATLAB Simulink is provided by the article "SIMULATION MODEL OF WHEEL SLIP AND SLIDE PROTECTION SYSTEMS FOR RAIL VEHICLES"

In the figure below there is a practical representation of a possible implementation of the WSP control system. In this case, as inputs of the controller of the anti-skid system are considered estimates of the speeds of the wheels.

This is because, as mentioned above several times, you do not have the possibility of having a precise value confidently representing the actual value of the speed, and in fact the value of the reference speed is an estimate of the real speed of the vehicle. The same transition from the calculation from angular to tangential velocity implies in the calculations an addition of various uncertainties.

Other inputs, in addition to velocity, are both its first order and second-order derivative. The derivative of the first order indicates the instantaneous acceleration of the wheels and therefore the change in speed over time. The second derivative, on the other hand, indicates the jerk, or the variation of acceleration over time in each instant. Precisely because of the uncertainties present, the classic control systems are almost never used for the WSP system. For this reason, even in this representation it was decided to use the Fuzzy controller rather than others that from the simulations did not give better results than those given by this controller.

Figure 20.4 Schematic representation of Barna's WSP



Source: Barna, 2012b

ZV, ZF – control signals of respectively venting and filling valves. Control signals of the vent and filling valves respectively.

4.14 Comparison by the result of the simulations

the result of the simulations will then be presented to understand why the AFSMC is the best control system to adopt.

For the simulations, being impossible to model many aspects especially being part of the contour / background in which the phenomenon to be studied takes place, it was chosen to use the multibody system, or the study of the dynamics of the system taken all as a single rigid body in which all the parts are interconnected with each other and move respecting the degrees of freedom and kinematic constraints. Through this modeling system, in essence, the movement of the body is described through its kinematics.

These simulations are made by examining the model with 82 degrees of freedom of the ER24PC locomotive during the braking phase starting from an initial speed of 120 km/h. This type of locomotive, also known as Iran Runner, is a single-cabin passenger type diesel electric locomotive manufactured by the Mapna Locomotive Engineering and Manufacturing Company and Siemens.

Figure 21.4 Iran Runner locomotive ER24PC

Source: https://en.wikipedia.org/wiki/IranRunner

The various uncertainties are modeled by random irregularities of the binaries generated from the measurement data using the Power Spectrum, a method used to represent a signal as a vector in complex space at infinite dimensions.

In particular, the PSD (power spectral density) method is used which consists in measuring the signal strength with respect to its frequency.

Another quantity commonly considered in the study of the schemes related to the anti-skid system is the ratio of sliding of the wheels (corresponding to the relative speed between the wheel examined and the train). In other cases, in addition to the control of this coefficient, there is also an attention regarding the values reached by the angular acceleration of the wheel that must always be monitored as there is a threshold that must not be exceeded.

Often, in fact, there may be controllers that operate in a hybrid way since they do not have a single quantity used like input that determines if the anti-skid system must operate or not but provide an approach based on a multiple input with three monitored quantities: the sliding ratio, the speed and wheel acceleration.

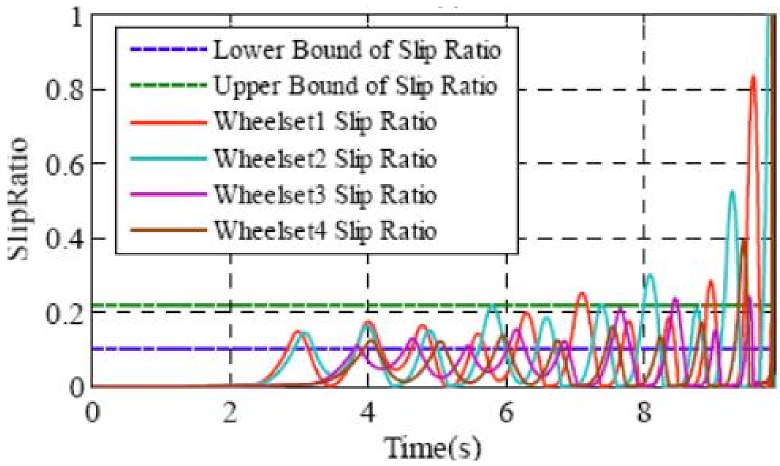
Based on the value assumed by these quantities with respect to the validity thresholds, the control system makes the WSP system come into action to bring the quantity, which operated the mechanism, back to an adequate nominal value that does not involve any risk of wheel locking. However, these multiple controllers are very difficult to design and often do not allow to obtain good performance of the entire system as too many variables come into play that are difficult to keep under control.

For this reason, in this study it was decided to study control systems activated by a single quantity as input and to see how they act on the other quantities to keep the entire system under control.

The first simulation had as case study objects the sliding ratio of the wheel sets and the speed values both in case of dry and wet track surface.

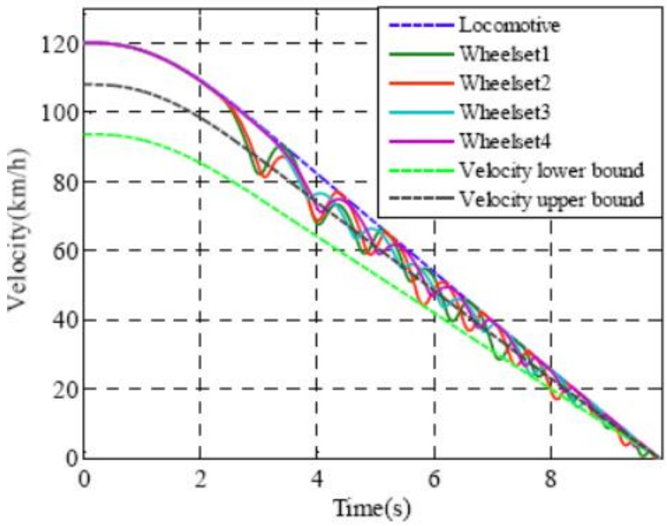
The comparison between the controller proposed by Trenitalia and the Fuzzy one in the case of dry tracks is as follows:

Figure 12.4 values of slip ratio with the Trenitalia control system in the case of dry tracks



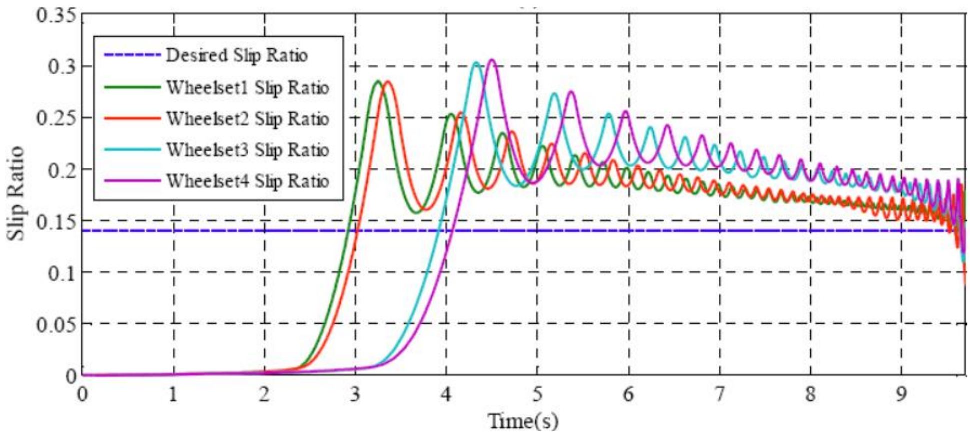
Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 23.4 values of velocity with the Trenitalia control system in the case of dry tracks



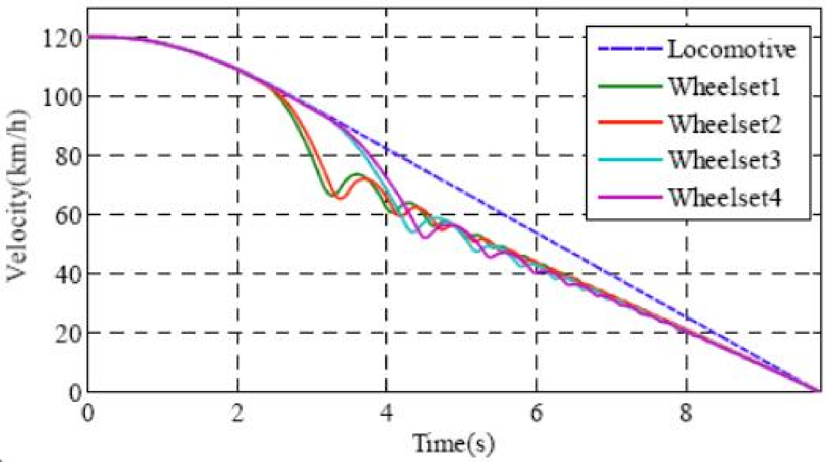
Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 24.4 values of slip ratio with the Fuzzy control system in the case of dry tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 25.4 values of velocity with the Fuzzy control system in the case of dry tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

As can be clearly seen from the diagrams obtained from the data obtained from the various simulations, using the Trenitalia method both the sliding coefficient and the speed tend to assume unacceptable values as they go beyond the values imposed by the upper and lower limit of the validity range.

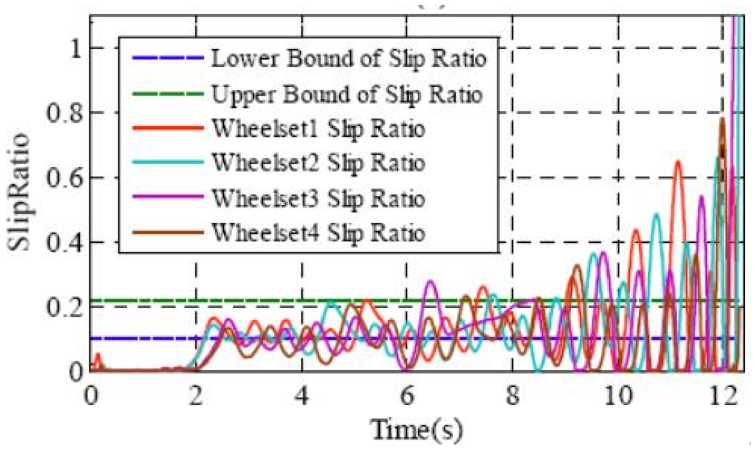
It can be noted that, in the case of the Trenitalia controller, due to a decrease in the speed of the locomotive, the sliding coefficient of the various sets of wheels comes to diverge close to the stopping time unlike what happens in the case of the ASFM controller.

In addition, all the various fluctuations perceived and represented in the speed diagram are elements that worsen the efficiency of the friction part involved in the motion and grip between wheel and rail. In fact, in the braking phase, there should be a progressive reduction in speed that globally occurs in both cases of course. The problem is that in this constant descent, in the case study of the Trenitalia controller, for example, you can see how there are local points where this value exceeds the track that represents the upper bound representing the maximum permissible speed.

The coefficient of adhesion is closely linked to the value of the velocity by means of an inverse correspondence. It is in fact maximum when the speed is zero and is reduced as the speed increases. The peaks in the oscillations that go beyond this limit therefore decrease the efficiency of friction as they trigger sudden increases in the energy at stake that tends to lose the grip between the wheel and the rail. And in fact, all this is confirmed by the diagram of the sliding coefficient that in the case of Trenitalia presents a final divergence with respect to the desired value to which instead converges the diagram of the sliding ratio that is obtained by simulating the system with the ASFM controller.

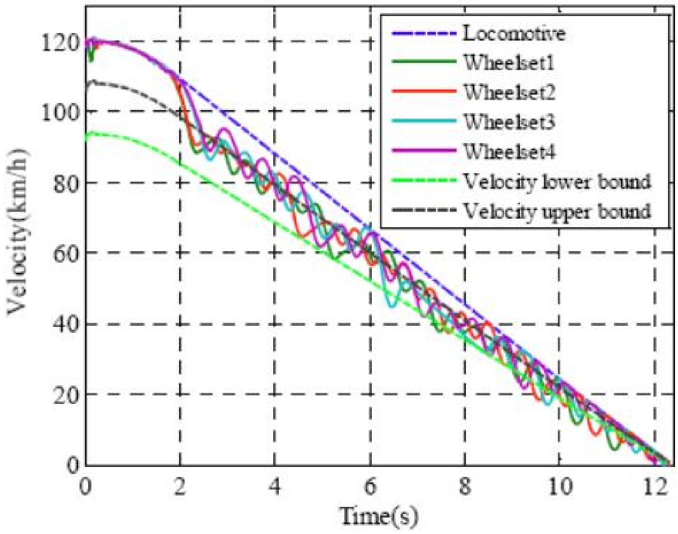
In the case of wet tracks instead:

Figure 26.4 values of slip ratio with the Trenitalia control system in the case of wet tracks



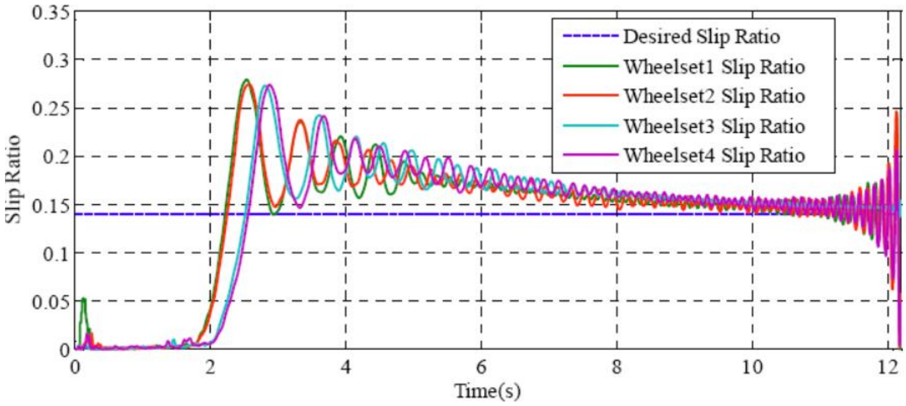
Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 27.4 values of velocity with the Trenitalia control system in the case of wet tracks



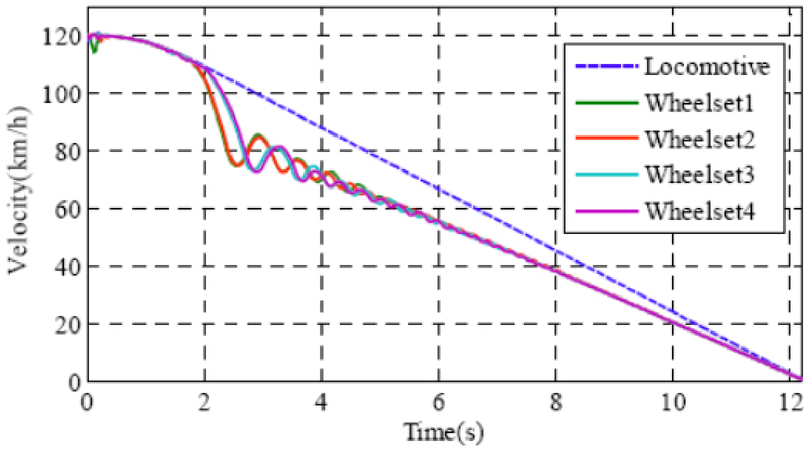
Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 28.4 values of slip ratio with the Fuzzy control system in the case of wet tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 29.4 values of velocity with the Fuzzy control system in the case of wet tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

In both situations of friction conditions, the sliding coefficient of the wheel sets fluctuates around the desired value of 0.14. Obviously, at the end of the braking procedure there is an increase in the amplitude of the sliding coefficient caused by the reduction of the speed of the locomotive to precisely allow the stop of the vehicle. In fact, due to braking, the speed of the entire system (which has an inverse correspondence with the value of the sliding ratio) decreases.

It is also particular, as in the case of braking on the wet surface, there is the reduction of the settling time of the sliding coefficient precisely because in the case of the wet surface there are higher speeds and lower sliding coefficients; therefore, the system's response to convergence towards the desired value is faster. Let us remember, in fact, that this time interval corresponds to the time necessary for the signal, taken into consideration, to be definitively close to the regime value. More precisely, it corresponds to the time necessary for the signal to enter the band, delimited by the upper and lower limit, without then coming out because of some overhang/oscillation that would take it outside.

If, in fact, there was in the meantime of the measurement some phenomenon / event causing the escape from this interval, it would increase the settling time considering the moment in which the signal returns definitively in the band. This value is one of the most important parameters when choosing a particular control system rather than another. in fact, often, in the specifications of the controller to be designed there is indicated a value of settling time to be respected.

As can be seen from the diagram relating to the speed, using the AFSM controller, the amplitude of the various oscillations around the speed value is much lower compared to the magnitude of the oscillations that are observed by monitoring the response of the speed signal with the use of the controller proposed by Trenitalia.

In substance, therefore, the results of such simulations show how the AFSM method is clearly better than the contender. In fact, this method manages to overcome the various divergences of the sliding ratio of the sets of wheels close to the stopping time that are instead evident in the diagram of the controller that is less efficient.

For the second simulation, the torque of braking forces (acting on the same pair of wheels during braking) was examined. Also, in this case it was decided to simulate the behavior of the two controllers both in dry and wet conditions.

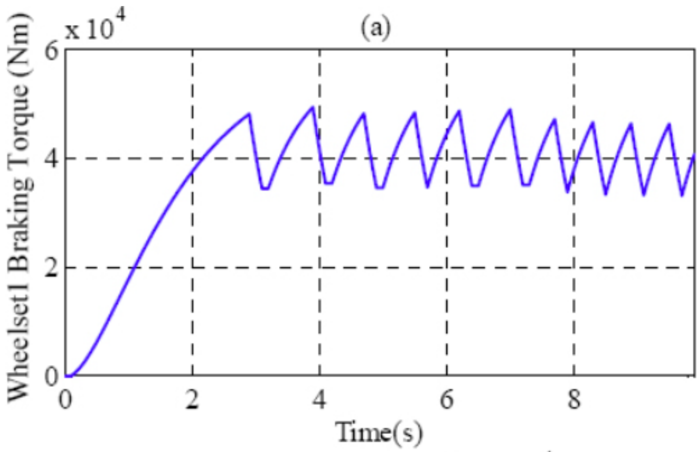
As you can see in the figure below, in the case of braking on wet surfaces, the frequency of fluctuations of the input examined (the braking force torque) is much higher than what can be observed in the diagram representing the simulation on the dry track. This is because, obviously, in this situation there is a greater degradation, and a more frequent intervention of the braking action is necessary with a continuous release / restoration which results in a need for gradual and real-time adjustment. As for the comparison between the two control systems, the difference that immediately stands out to the eye is the switching frequency and the maximum and minimum values that it reaches during the operation of the system; especially when the braking torque comes into play or to increase the degree of braking or to release the brake cylinders and allow the braking.

In the case of the controller proposed by Trenitalia, there are the two peaks, both the highest and the lowest, which touch values that go beyond the allowed range going to exceed the maximum and minimum acceptable values. On the other hand, as far as Fuzzy is concerned, the switching frequency of the examined signal remains within the permissible range. Everything is scanned according to a sampling time interval of 100 ms.

Even from this simulation, therefore, the AFSMC controller is certainly more efficient than the contenders. Inf act, focusing on the clock frequency and the values that it can assume, while on the one hand a higher frequency leads to advantages such as the use of smaller components, a transient time of response of the load faster and an output with a lower ripple; on the other hand, it has as disadvantages a reduction in efficiency, an increase in power losses and an increase in RF and EMI noises.

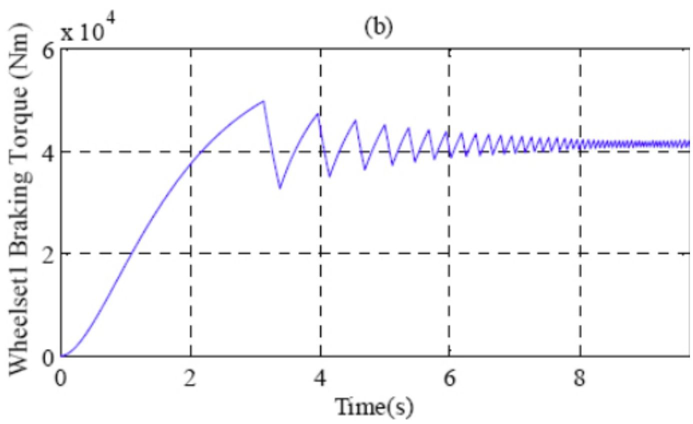
In dry track conditions:

Figure 20.4 braking torque using Trenitalia control system in the case of dry tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

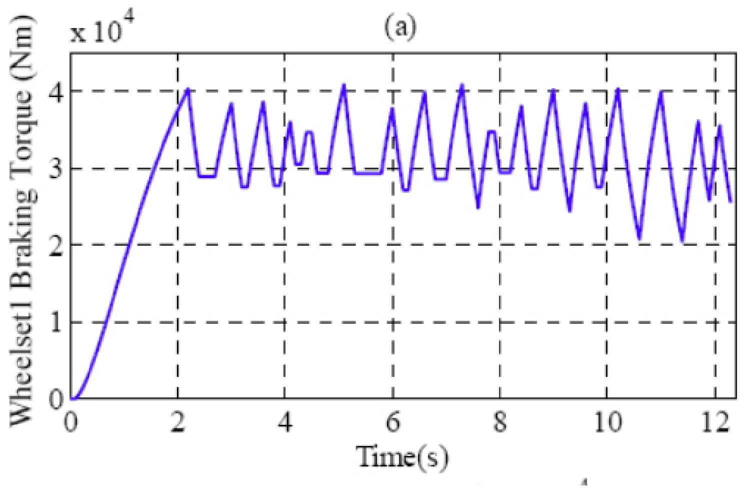
Figure 31.4 braking torque using Fuzzy control system in the case of dry tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

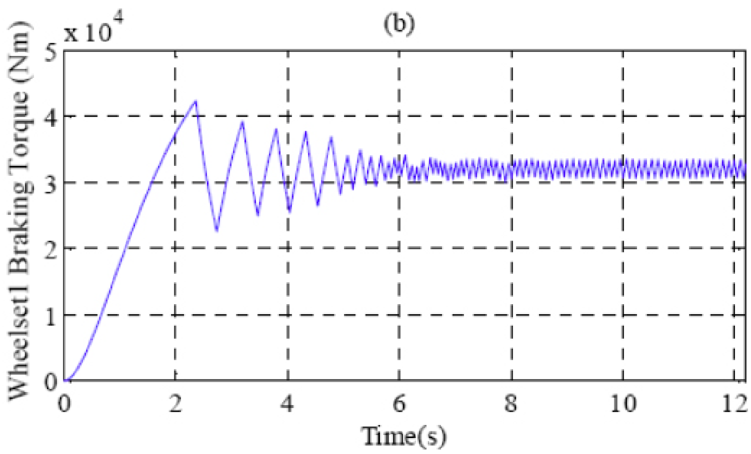
In the case of wet track:

Figure 32.4 braking torque using Trenitalia control system in the case of wet tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

Figure 33.4 braking torque using Fuzzy control system in the case of wet tracks



Source: https://www.scielo.br/j/lajss/a/CL6sKmsQm39PvTyxNsKxFKh/?format=html&lang=en#

By applying the AFSMC method, there is a decrease in both the braking distance and the stopping time of the locomotive. Both, in fact, undergo a sharp reduction in both conditions in which the track is located depending on the presence of atmospheric precipitation or not.

From the simulations carried out, in fact, these values are grouped in the table below. It should be noted that in these data there are certainly uncertainties due to several factors that do not allow the system to be tested exhaustively. You can be sure that these errors are of a fixed nature since they always occur in the same way because they are due to imperfections in the instruments used or to incorrect measurement methods.

In addition, even the random ones due to random events that cannot be governed, affect in the same way the two systems that are simulated simultaneously precisely to prevent one of the two from suffering a catastrophic event rather than another or with a different behavior.

In this way, the data presented can be taken for correct in the sense that certainly we must not rely on the proposed numerical value but rather on the trend that shows how the reduction of time and braking distance are superior in the AFSMC method.

Table 4.4 Values of braking distance according to applied control method

Control method	Braking distance(m)	
	Dry track	Wet rail
Trenitalia	184,63	221,15
AFSMC	184,03	220,60

Table 5.4 Values of shutdown time according to applied control method

Control method	Shutdown time	
	Dry track	Wet rail
Trenitalia	9,9	12,3
AFSMC	9,8	12,2

In addition, to understand even better how the AFSMC method comes to have better reductions in the two quantities taken into consideration, the braking power that the system generates to allow braking has also been calculated. As you can see, you have a lower value for the Trenitalia controller precisely because it is less efficient than the Fuzzy.

Table 6.4 Values of braking power according to applied control method

Control method	Braking power(K*N*m/s)	
	Dry track	Wet rail
Trenitalia	1572,48	1,564.66
AFSMC	1578,03	1,565.84

CHAPTER V - Problems and Solutions to Prevent WSP from Working Incorrectly

5.1Common problems of the speed sensor and related components

- The distance between the phonic wheel and the speed sensor may be an unacceptable value as it does not belong to the range of 0.9 mm to 1.4 mm.

- The phonic wheel is poorly hooked to the total system. This compromises all the data that the sensor tries to capture to analyze the system.

- The use of non-standard fasteners to anchor the phonic wheel to the ends of the axis.

- speed sensors are missing/open circuit, so there is a construction error at the level of the electronic architecture. To avoid such defects, it would be advisable to test the sensor circuit before the fixing. For example, if measuring the values of voltage and current circulating in the test circuit results in an infinite resistance, then you are certainly faced with an open circuit error.

- The sensor and cables are not properly connected. One of the most likely consequences due to this defect is a dissipation of the signals to be measured that inevitably leads to an error in the processing of data starting from the acquisition.

- sensor cable fixing systems are anchored with a weak or loose connection. This means that, even if at the beginning the system works correctly, it is compromised during the journey due to a hook that fails at some point. It is necessary, in fact, that the connections are well established to have the certainty that the entire system does not have any problems during its operation.

- The Junction box, containing all the connection wires that provide part of the electrical operation of the system, is broken or in damaged conditions.

- Presence of water infiltration in the joints of the bushings. This problem would compromise the system both mechanically and electrically. For this reason, the whole complex is properly coated with oil and lubricating grease suitable for protection and preservation.

- The speed sensor itself is defective regardless of the connections and anchors to the rest of the components.

5.2 Care and precautions to be taken for the proper functioning of the WSP

therefore, listed the main problems that can compromise the entire system, to safeguard the operation of the WPS device there are some precautions to be considered:

- Never use non-standard components and cables for anchoring the phonic wheel to the axis. This is because the guarantee of security and adherence that these standards guarantee would be lacking. To obtain this certification, in fact, the components are subjected to multiple verification tests to check their quality and efficiency that they subsequently claim to provide to the buyer. It is also starting from the stress tests and other types of verification that some of the previously declared validity ranges arise, for example.

- Do not use speed sensors whose circuit is open or missing for the reason explained above.

- Do not have the connections properly connected between the sensors and the cables.

- Be careful not to have sensor cables mounted with loose wires. Therefore, always check the perfect adhesion.

- Be sure that you do not have any leaks from the dump valve during the braking phase

- Make sure that the connection box is in proper condition, so with no kind of damage given its fragility

- Do not use water for cleaning the bushing and in particular its joints.
- Be careful not to make inappropriate connections regarding the dump valve and the components connected to it.

CHAPTER VI - Performance of Modern WSPs

Depending on the different cases, in general, the anti-lock wheel devices allow to limit the increase in the stopping distance of a train from 10% to 25%. This increase in terms of efficiency was found in the case when the vehicle moved on a dry track and in addition the grip of its first axle was in a range of values between 5% and 8%.

If a situation of locking or skidding occurred on a wheel, action was taken immediately to bring the adhesion value back to the most favorable area of the characteristic grip-skid. This was done in the shortest possible time by acting directly on the brake cylinders and by intervening on the solenoid valves to increase, reduce, and maintain the pressure. The objective, as mentioned above, was to maintain a range of adhesion values able to allow both a rotation of the wheel on the track and an adequate intervention with a corresponding reduced stopping distance in case of very significant braking.

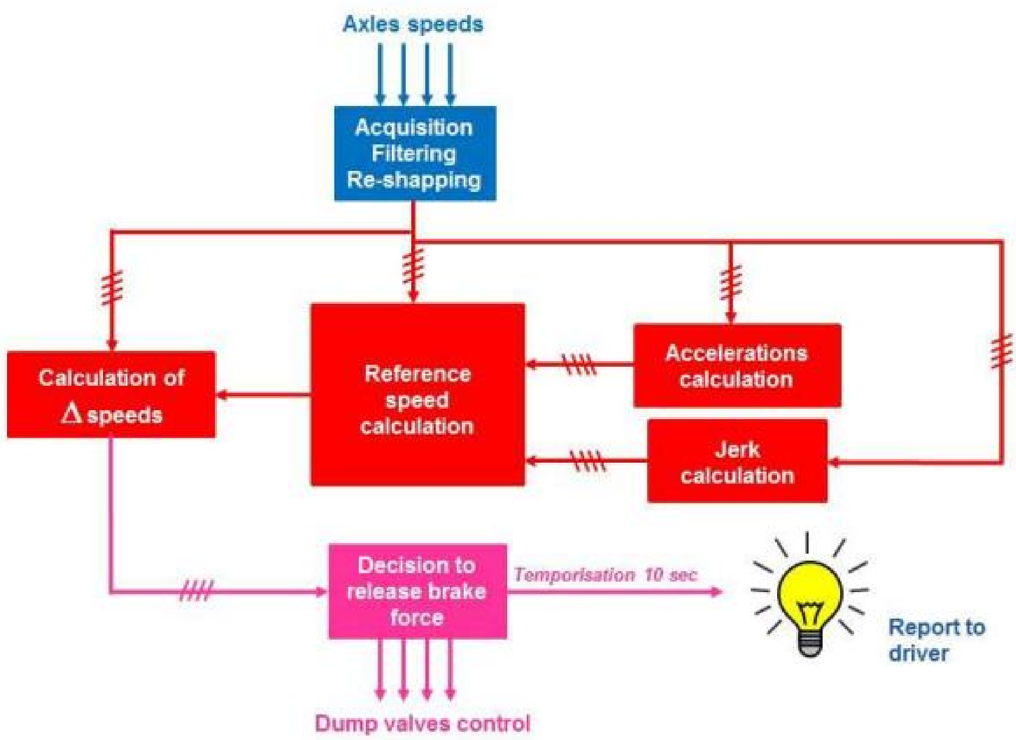
6.1 Supplementary devices of the WSP: the blocked axis detector

Often, in addition to the WSP anti-skid system, there is a device that has the task of monitoring the rotation of the wheels. It represents a redundancy of the anti-blocking system that already operates this control through the integrated sensors. This device, called "locked axis detector" is integrated and mounted completely independently of the wheel anti-lock system.

It intervenes when a large difference in speed is detected between the monitored axis and the speed of the train. In this case the speed delta wasn't detected by the sensor of the anti-skid system due to its failure or due to some dynamic phenomenon (a very large drop of grip). In fact, if one of these two problems arises, the WSP is not activated because for the processed data there is no need for any intervention which would only lead it to distance the system from a situation in which, in theory for it, it is completely efficient.

As regards the principle of operation, it is in close contact with the driver's work. This is because the detector, as a first step, requires a complete release of the braking force on the axis in which the detection and monitoring was carried out. At this point, if after a few seconds, despite the drop of the braking force acting, there is no re-acceleration of the axle, the braking system is rearmed as it was before (for safety reasons), but this problem is directly notified to the train driver through an acustic and visual signal. At the exact moment when this indicator light is activated, the driver is obliged to stop the train immediately and act in accordance with the regulated measures.

Figure 1.6 operating principle of the wheel rotation monitoring device (bogie per bogie brake release configuration)



Source https://rail21.pagesperso-orange.fr/Freinage_Adherence_Antienrayeurs_EN.pdf

6.2 WSP integrative devices: low slide wheel slide protection

Some vehicles equipped with the recent braking systems, which excel in terms of efficiency for braking force and minimum energy dissipation, may present an additional anti-skid device in addition to the system that has been widely discussed. Reference is made to those types of vehicles that are equipped with a very powerful dynamic braking system in which the need and the desire arise not to adjust the braking phase from time to time. In fact, using only the type of dynamic brake would increase the time required to perform full braking. For this reason, in such vehicles a device is mounted that has the task, as well as the classic WSP, to avoid the possibility of incurring a slip of the axis. This device is called "low slide" wheel slide protection.

As for the method of operation, it uses as data resources the same that were used by the general anti-slip system (it is defined as high side to distinguish it from this 'low side'). However, the principle of activation and action is different since this system operates as an anti-lock system of the reverse type. In fact, its purpose is to immediately avoid any type of slippage of the wheel on the rail when it slightly exceeds the kilometers per hour set as a threshold limit.

Practically, the difference lies in the fact that when the slippage of any axis is perceived, this device doesn't work gradually on the brake but rather completely and quickly cancels the dynamic braking force and then quickly restores it up to a particular percentage value compared to the initial force. It is therefore this force that operates on the entire mechanism, while the complete braking force will be reached and recovered very slowly and only later when its intervention will no longer be required.

It is therefore a type of anti-skid that operates not by fully exploiting the braking potential but aiming to lower and avoid energy dissipation to a minimum, since it does not act in stages according to a gradual process as in modern second and third generation WSPs. In essence, it leads to a certain percentage value (corresponding to the amount of braking required by the event) which obviously can only be useful in certain cases. This low side device, in fact, as mentioned at the beginning, comes into action only when there is a small exceeding of the limit threshold with a minimum delay in the intervention. This wait is due precisely to the time required to reach the chosen braking power value.

CHAPTER VII - Simulations to test the operation of the WSP and ideas for the future

7.1 Westinghouse Brakes (U.K.) Ltd. Production: A Realistic Simulation of the Braking Session

Among the various manufacturers, certainly, one of those with greater importance is Westinghouse Brakes (U.K.) Ltd that has contributed greatly to the development of the anti-skid system as it stands today. Indeed, it is one of the companies that in recent years has invested a lot in research to always have a continuous growth in this field.

In one of these research work took part an Italian engineer, Emanuele Guglielmino, graduated in electronic engineering at the University of Genoa and PhD in fluid power systems and control from the University of Bath. at Westinghouse Brakes Ltd he worked as a control engineer, specifically about the braking system in the railway world. Since joining the GE Energy company in Florence, Italy, he has also been involved in research. Dr. Guglielmino, in fact, now, boasts several publications, of which he was the author, of more than 15 works related to the field of robust control and fluid power. In addition, in 2001, it won the ASME Best Paper Award in the Fluid Power Systems and Technology Division.

The Westinghouse' s study aimed to generate a flexible wave that would represent and simulate a braking session as realistically as possible. One of the main problems about the necessary tests to be carried out, as mentioned, is in fact the difficulty to guarantee a discrete truthful simulation of the system and therefore of everything that derives from it. In fact, having already a great margin of error in the representation of the event, it was impossible to consider the data obtained in the various sessions of the tests carried out.

The main goal was to achieve a development of the current WSPs that could certainly be achieved thanks to valid data to be able to study. In addition, these studies certainly had a very relevant importance since already in the automotive field ABS had become a critical element for safety, and this had alarmed the railway sector since in this world, an event of blocked wheels would certainly have caused more impressive and serious damage (dealing with tons of material between trains and rails).

Westinghouse Brakes (U.K.) is a world leader among developers in the field of railway system automation. Right from the start it was the protagonist in the search for new models and devices that would increase the braking action of trains and metros both in terms of efficiency and safety. It was founded more than a century ago by George Westinghouse.

It is currently part of the Knorr-Bremse Group, another player in this sector. At Westinghouse there are many innovations that have led to the development of many of the Wheel Slide Protection (WSP) systems of the last generations that achieved the main goal of minimizing the braking distance and of reducing and preventing various damages both to railway vehicles and to the surface of the tracks.

To achieve the objective of the simulations through the various tests to be carried out, it was necessary for the Westinghouse Brakes engineers, a fairly flexible and at the same time precise method to generate signals for the hardware in the loop test system. In this way, in fact, it would have been possible to create a realistic study context to study and improve as much as possible the WSP device that was the main case study.

The manufacturing company, together with the chosen study team, which included the engineer Guglielmino, decided to solve this research by relying on the PCI analog output (AO) cards from United Electronic Industries (UEI) which was able to simultaneously generate multiple independent signals at a frequency of 100 kHz for each channel.

As has been previously mentioned, for a WSP system to be said to have been well designed, it must not only minimize the stopping distance being able to use the available adhesion to its maximum potential but must also prevent any type of excessive slippage of the wheels on the rails. This last aspect is fundamental because a slippage would lead to an alarming rise in the temperatures at stake which, as is well known, could cause chemical changes since the material with which you are dealing is metal. You could get to have a deformation of the shape of the wheels themselves with flat points or alterations on the sliding surface, both these aspects are among the elements capable of causing a derailment.

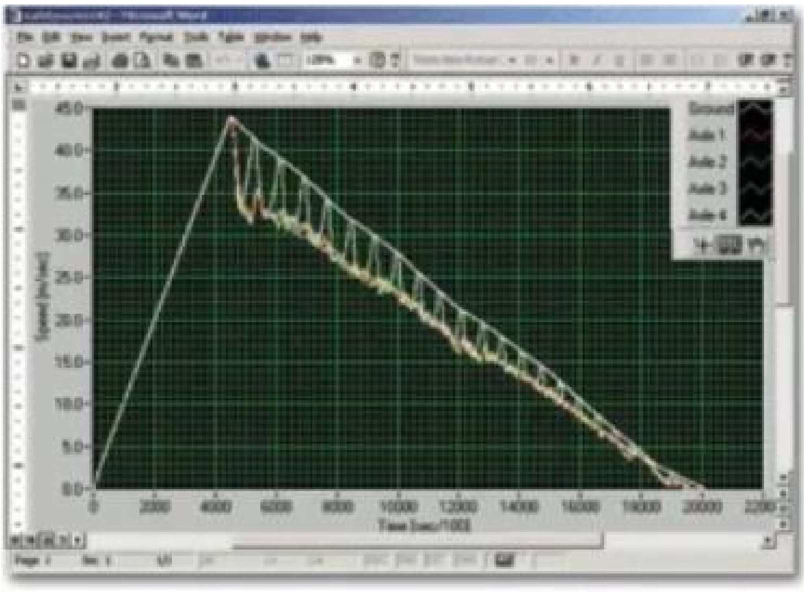
These deformations therefore produce mechanical damage both on the sets of wheels and on the tracks which cannot in any way be considered and whose arrangement must take place as soon as possible to prevent a significant increase in costs and expenses. For this reason, it is essential and fundamental to be able to design a very precise anti-skid system able to accurately control the amount of slippage.

The control system used for the railway braking system is closed loop and acts, as already explained, according to a principle of electropneumatic action. This system uses a speedometer mounted on an axle to measure the speed of the wheels connected to it.

Depending on the slip/slide value (which corresponds to the relative difference between the train and axle speeds), a control belonging to the braking system of an electropneumatic valve is activated or not. This valve is electrically and mechanically connected to some elements that modulate the pressure in the brake cylinders. All this is done according to a control algorithm operating in closed loop so that you can more safely monitor any errors or deviations from the values set as targets. If any part of the control feedback chain collapses, the system must intervene more quickly and efficiently to bring itself into a state of security.

A braking session is shown in the figure

Figura 1.7 braking session



Source: https://ueidaq.wordpress.com/tag/wheel-slide-protection/

In the figure there are three axes showing a controlled amount of slip relative to the ground speed while the fourth axis is released periodically to allow the calculation of the current speed of the train.

From the point of view of safety, railway brakes guarantee a long service life/durability since there are, over the years and periodically, multiple maintenance cycles. In addition to the various checks of the actual functioning of the braking system made daily (brake tests that the train driver and train manager must carry out during the accessories during their work shift); the material, periodically, receives a check by the workshop and the maintenance group to detect any problems, incipit of deformations that it would be advisable to note in time so as not to get to the actual damage of the element.

The working environment of the device is hostile since it is a position below all the rolling stock, therefore full of strong vibration levels and highly variable environmental conditions. These are, in fact, among the main factors that prevent the creation of a realistic simulation context precisely because they are already changing and uncertain, so the replication is practically impossible. It is for these reasons that the two key words of the design of an anti-skid device are: safety and robustness.

It would therefore be a favorable aspect to be able to replicate the operating response of each device in all the possible conditions in which it could find itself exercising. Simulating the way, they fail would also be of great help to understand, for example, the point at which the device stops working (or does not intervene at all) and the nature of the failure that occurs. It is in fact from these studies that it would be possible to obtain a development based on safety and efficiency. But, as mentioned, generating tests including such needs with current trains is impractical.

First, there is to keep in mind an element not considered much up to this point: the cost. The carrying out of tests of this type would certainly be very expensive, moreover it would come to spend exorbitant amounts without being able to repeat the real context in a sufficiently exhaustive way, just think of the unrepeatability due for example to the different adhesion present since its continuous variation along the track.

In addition, there is such a high number of possible electrical and mechanical failures in which the anti-lock device can meet, that it is practically useless to use by the designers an equipment that already has some damage. In fact, a first idea was to test the response of the WSP mounted on the axis of a wheel with some known defects, but there were too many combinations of possible causes of failure that could intervene.

One of the most important aspects to consider during a laboratory test regarding the brakes is certainly to be able to have a really accurate simulation of the control signal that represents the speed of the axis. As mentioned in the chapter on the mechanical parts that make up the device, the task of measuring this speed value is entrusted to a gear wheel mounted directly on the axis, the phonic wheel. For this task, it is connected directly to a magnetic sensor generating a tachymeter signal characterized by pulses at a frequency proportional to that of the rotational speed.

One of the first errors that can occur is precisely from the generation of this signal as a set of several unwanted external factors could easily corrupt the process. Just think of some of them such as: electromagnetic interference, wear or loss of a wheel tooth, vibrations and shock that can occur in contact with the track and during sliding on it, misalignments due to loss of adhesion.

To take into account and avoid these risks during the performance of the various tests, the engineers of Westinghouse Brakes have developed a hardware-in-the-loop simulator, called Safety+ which is able to test the brakes both in normal conditions and in conditions of failure because through an internal generator suitably calibrated, has the property of injecting a tachymeter signal generated by the software that is corrupt faithfully representing others real signals. The braking signal seen above is just one of them.

The system is characterized by the WSP device that works together with a software simulator that has the task of modeling the motion of the train. There is a close connection between these two elements that communicate via signals. In fact, the pressure signals that are instantly measured are sent by the anti-lock device directly to the software that in response will send to the WSP the tachymeter signal directly generated by it and simulating the motion. In this way there is practically a reaction by the system to all the various braking situations that may appear as if they were real, but which instead are simulated starting from the pressure values necessary to obtain the desired behavior. All responses and failures in performance are recorded and a very stringent and precise criterion of success / failure of the various results that you want to monitor, and control is also used.

One of the main challenges to be accomplished for the success of these tests was certainly to obtain a simulation of the tachymeter signal as realistic as possible. Ideally the best thing would have been to have a rectangular wave with variable frequency and constant amplitude; something that could have been achieved quite easily with a digital input/output generator specialized in the realization of data from timeline specifications. However, a signal fully reflecting the reality of the facts would not have been obtained, since the true feedback signal differed in many respects and was closer to an arbitrary analog wave rather than a rectangular one. In addition, engineers had to increase a pure square wave to obtain corrupt signals that simulated the following conditions:

- electrical interference
- power source variations
- rupture of a tooth of the phonic wheel or presence of any eccentricity and deformation of its
- mechanical vibrations
- electromagnetic interference
- failure in electronic control or damage in the tachymeter magnetic circuit.

In some cases, the frequency of the output tachymeter signal can undergo a change of factor 0.5x, 2x, or 3x; in these cases, it is necessary that there is the ability of the control system to detect this jump and to change the value of the frequency to the current one.

In particular, the team of engineers used advanced signal-processing techniques to allow an adequate design of the generated signal that had to be able to simulate in the most realistic way all the existing conditions of failure and mechanical or electrical failure in which there was a risk of running towards it. The resulting analog wave is quite complex.

Generating a high-resolution wave with a range from the nearest DC direct current value (0 Hz) to a larger value of 20 kHz is beyond the capabilities of most analog output cards (AO cards). However, there are devices capable of generating such signals and thus having the required specifications. among them, the team chose to use PD2-AO-8/16. In practice, four waves of variable frequency and amplitude are continuously generated from the test, which essentially represent the corrupted tachymeter signals. Each wave corresponds to each axis of the train so you can monitor the whole vehicle and not the single wheel.

At this point, one of the most complex parts of the entire project/case study was to write a software that could simulate all the possible error variations that could arise and be part of the feedback signal of the tachymeter signal.

The complication was that each type of error came to modify in a critical, way the signal under consideration and therefore the engineers had the task of having to find a software capable of faithfully duplicating these effects. To fulfill this request, the team decided to use a particular driver mounted in the analog output board offered by Universal Electronics incorporated UEI.

Specifically, the board-mounted DSP digital signal processor played a crucial role in meeting the requirements. In fact, through the analog/digital converters, data can flow from the onboard memory of the DSP in a circular way without any kind of external intervention. But during the loading of the dataset, it is possible that in the data flow a slight gap of some samples may appear.

But what the team was looking for at Westinghouse Brakes was instead a continuous transmission of data that at the time consisted of many segments of small waves. This continuity was needed because if the tachymetric or simulated feedback signal had presented gaps or delays, not real but caused by the software generating the signal, the control system would have responded in such a way as to solve these false failures according to the most appropriate methodology for solving the problem. In practice, in addition to a waste of time in trying to solve the problems that would never have arisen, there was also the risk of choosing a control system with incorrect characteristics because it was designed and chosen based on unreal requests for intervention.

A resolution intervention was therefore needed starting from the formation of the data. Then, to achieve this, UEI engineers devised a method to replace part of the data within the DSP's memory with a pointer that was used to continuously transmit the output data that was all saved in the remaining part of the unmodified memory. In addition, the team was able to design a special driver capable of supporting the algorithm to operate this new specification. Moreover, they elaborated an example in C to be able to possibly make use of the algorithm in other systems according to the appropriate adaptation changes.

Unfortunately, the engineers had to give up the potential of the AO board. In fact, even if it is equipped with a series of sixteen analog output pins, the designers were forced to give up fifteen of them and use only one per board for each individual axis of the signal to be generated. A great reduction in efficiency since very little of the possible potential was used but this move was necessary as it was necessary to have independent clocks for each converter. In practice, the 16 pins of the card are channels that use a global clock, the clock of the card itself and the same for all converters. The WSP, on the other hand, needs to have an isolated and unique clock for each converter in it.

Another aspect to be considered in these simulations was the time factor. Specifically, the single WSP test took only a few minutes, unlike what was necessary for a complete test that took up to even hours. However, this was inevitable because to cause this time dilation were precisely all the combinations of the variables. Just think of the different types of weather, the load of the train that could vary both totally and in the individual wagons, the various adhesion profile present due to dry or wet track, the initial speed at the time when the braking started, all the various types of noise (for example white noise or jitter that consists of in the variation and modulation of the amplitude of the tachymeter signal in the different axes). Having to test and consider all the combos of these factors (already difficult to reproduce constantly from one test to another) led to a substantial increase in the tests to be carried out to obtain a complete check.

In the end, the designed software runs its entire protocol routine automatically and at the end of the execution of each individual instruction and the entire test, the Westinghouse engineering team was then able to present a detailed recap in which the set of all the overcoming/failure results was summarized so that it could be made known to the customer. In addition, it was established that the release to the customer would only take place when the entire WSP system and its entire equipment would be approved for release on the market. One of the conditions required to obtain such a permit was to have to win the Safety+ logo.

7.2 Simplifications made in some tests

As mentioned above, one of the main objectives of the simulations carried out to test the action of the WSP device was to be able to obtain a clear image of its effects on the forces at play in cases of low adhesion between wheel and rail.

For some tests, to minimize the calculations, some constraints and some simplifications were considered to reduce both the field of interest to be tested and studied and the calculation times with a consequent reduction in costs. This decision was taken since some aspects could be set aside because there was almost certainty that there could be no event in which they could occur; while other elements could be simplified to be able to make a global study and therefore be able to represent more events rather than the single specific case.

Among the simplifications made, some of the most relevant are the following: short passenger trains consisting of four identical cars equipped with disc brakes; use of tight screw joints; emergency braking on the train performed at 160 km/h on a straight track with no elevation gain; the achievement of the low adhesion zone takes place sequentially by the wagons, in fact the moment of implementation of the WSPD in each of them depends both on the speed of travel and on the position of each individual car in the composition of the train; brake cylinders have the same filling characteristics since they respond to the valves directly connected to the general pipe along the train; same response of the WSPD in each wagon after its implementation since it is activated when global thresholds are exceeded and the chosen device is the same in each car.

The table below shows the main data of the test.

Table 1.7 General data used for the test

Vehicle weight [t]	50
Vehicle length [m]	25
Maximum braking force of the vehicle [kN]	58,65
Maximum air pressure in brake cylinders [bar]	3,837
Filling time of brake cylinders [s]	3,4

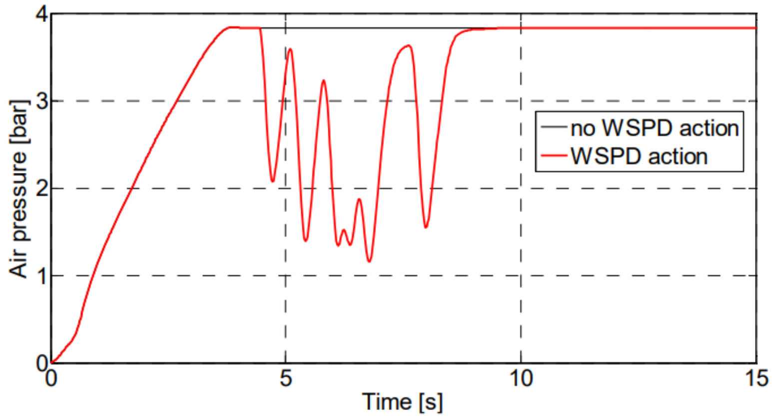
Source: https://www.matec-conferences.org/articles/matecconf/pdf/2017/26/matecconf_imane2017_07012.pdf

7.3 Verification of the operation of the WSP by monitoring the pressure signal in the brake cylinders and study of the forces in the train

The test carried out on the study on the evolution of the pressure inside the brake cylinders when an emergency braking was carried out, was determined experimentally directly using a computerized system mounted directly on the brakes. This step was carried out both in the case of implementation of the WSPD and if it did not activate.

these pressure values collected certainly led to a development of the simulation program designed to better study the anti-skid device. Specifically, the pressure oscillation in a stretch of about 205 meters in length was calculated after reaching the maximum pressure value

Figure 2.7 evolution of the pressure in the brake cylinders experimentally calculated during emergency braking



Source: https://www.matec-conferences.org/articles/matecconf/pdf/2017/26/matecconf_imane2017_07012.pdf

Among the results obtained from the simulations, there are also the maximum values recorded about the compressive forces (buff) and traction (draft) between the couplers, these values are reported in the table below depending on whether or not the WSPD device is activated in one of the four carriages that make up the train. The diagrams, on the other hand, represent the evolution over time of the in-train forces.

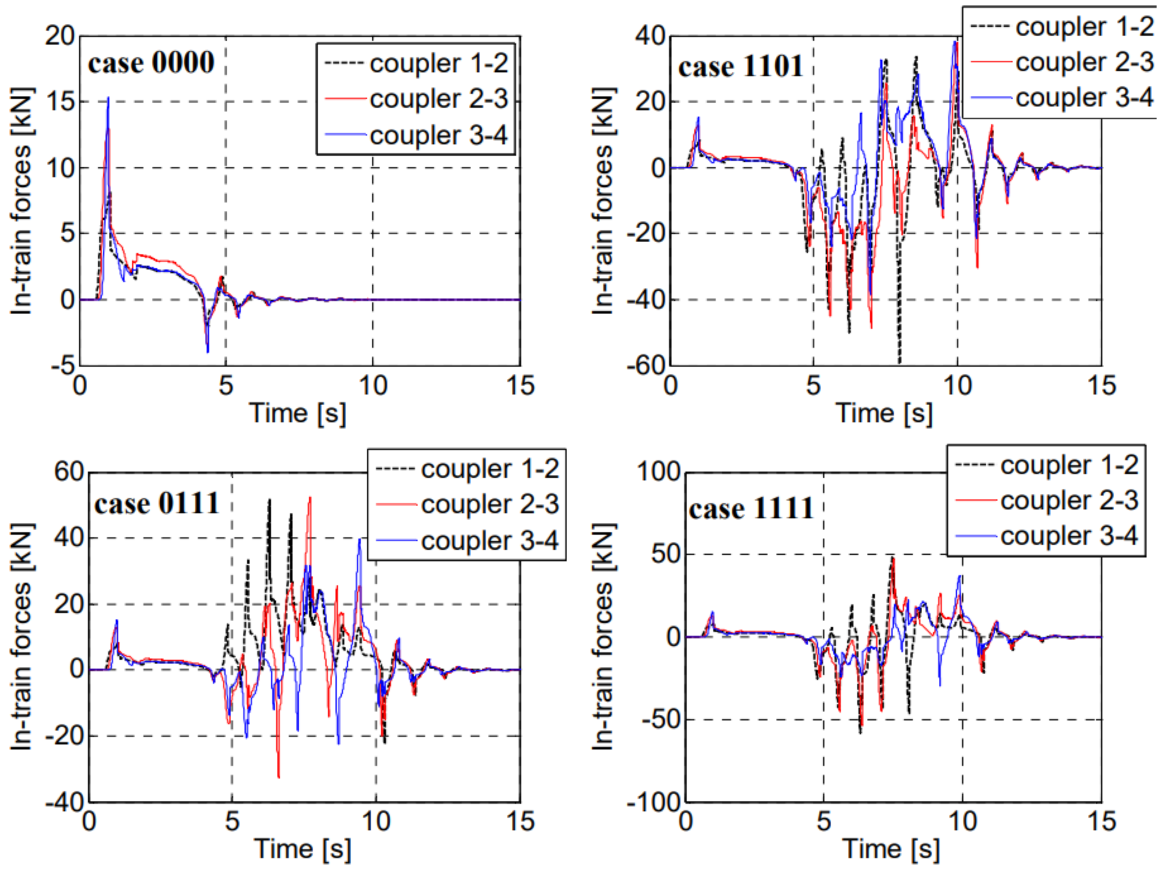
Among the most particular cases and on which to place a point of attention are:

- the case 0000 (no action of the WSPD) which would be the starting point / the basis from which you start for the simulation.
- Cases 1101 and 0111 (cases where the maximum tensile and compression value between the couplers of two of the four adjacent wagons is reached, respectively)
- Case 1111 (case where there is the least adhesion in all wagons since the WSPD is active in all four cars).

Table 2.7 Values of forces in all the possible cases of WSP's activation

	Maximum buff forces [kN]			Maximum draft forces [kN]		
case*/coupler	1-2	2-3	3-4	1-1	2-3	3-4
0000	*8.2*	*13.0*	*15.3*	*-2.0*	*-3.7*	*-4.1*
1000	14.1	13.0	15.5	-39.1	-38.9	-35.2
0100	19.1	13.0	15.3	-7.4	-26.5	-23.5
0010	18.0	23.2	15.3	-10.4	-12.1	-20.1
0001	29.0	36.0	32.1	-14.3	-26.8	-24.8
1100	23.6	13.0	15.3	-50.0	-45.1	-23.9
1010	25.4	35.2	15.3	-46.4	-40.5	-37.2
1001	32.7	44.0	44.4	-44.6	-36.8	-29.3
0110	35.2	34.7	15.3	-16.7	-36.0	-33.2
0101	37.5	36.5	38.8	-20.8	-29.4	-30.6
0011	24.2	49.1	38.8	-17.5	-17.9	-39.1
1110	27.6	19.8	15.3	-57.9	-54.9	-27.3
1101	33.4	37.9	38.3	**-59.7**	-48.8	-38.6
1011	42.6	51.9	31.9	-45.1	-40.5	-33.6
0111	52.1	**52.6**	39.7	-22.3	-32.6	-22.5
1111	48.7	47.4	37.1	-57.9	-53.7	-29.6
* 0 – vehicle with no WSPD action during braking; 1 – vehicle with WSPD actuation						

Figure 3.7 Time history of in-train forces evolution (buff forces positives, draft forces negatives)



Source: https://www.matec-conferences.org/articles/matecconf/pdf/2017/26/matecconf_imane2017_07012.pdf

From the diagrams you can see how until you reach 4.44 seconds (instant of time in which the train reaches the sector of minimum adhesion) the trend of the curve of forces, recorded during braking, is the same in all four cases.

Beyond this moment, there is an increase in in-train forces. Specifically, when there is the implementation of the WSPD, then an increase in modulus of both the compressive and tensile force occurs. These growths can reach values much higher than those recorded. in the case of origin 0000 in which there is no implementation of the WSPD in any wagon (its activation always leads to a reduction of the forces to allow the rotary movement of the wheel). However, the substantial increase in these forces does not exceed thresholds so there is no safety hazard as regards rail traffic.

Another relevant aspect to note is that the point at which the maximum in modulus is reached, both in the traction and compression force, does not correspond to the case in which all the "1111" anti-skid devices are active but to the one in which are active only three of the 4 devices. The activation in all the wagons therefore leads to greater control of the forces in place.

As for the structural aspect of the test, it was decided to use a type of mechanical WSPD that had the ability both to operate in a simultaneously way on the axes of all four wagons and to generate large pressure variations in the brake cylinders. You could also make use of an electric anti-lock device but in that case, you would have lower compressive and tensile forces under the same adhesion conditions.

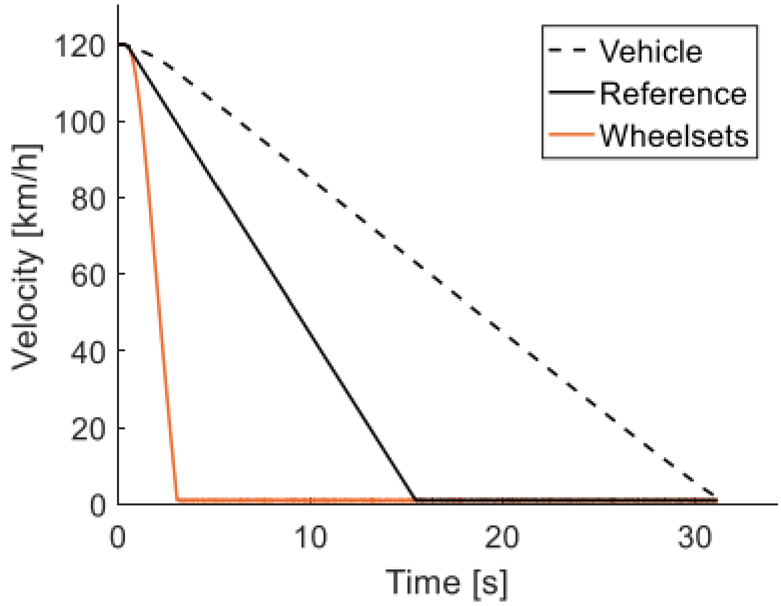
In conclusion, the study carried out at the Polytechnic University of Bucharest through the "Excellence Research Grants" program confirmed that the presence of the WSPD, especially in passenger trains, is fundamental and practically mandatory for safety in the field of rail traffic. Obviously, even in these research works, the team found itself having to face all those problems that have the consequence of increasing the complexity of the braking process. Problems such as the increase in the braking distance in conditions of low adhesion due to the implementation of the WSPD during the braking action, the increase in in-train forces, the changes in the longitudinal dynamics of the train that are encountered when the safety mechanisms are activated in response to external stresses that are not at all predictable.

7.4 Testing to determine the difference in performance of a vehicle with active WSP or not

Another test carried out to be able to understand the importance of the WSP was to carry out several runs on a track with degraded conditions in terms of grip. These tests were carried out under the same conditions, or at least they tried to have them as equal as possible, changing the initial braking speed from time to time. (50, 80,120 and 160 km/h). Obviously, the vehicle has been tested both with the WSP deactivated and with its activation.

Figure 4.7 shows the speed trend if the initial speed is 120 km/h

Figura 3.7 Velocity Plot (initial speed: 120Km/h, no WSP)



Source: CEN. (2011). EN 15595, Railway applications - Braking -Wheel Slide Protection

It is interesting to observe how in this graph there is the lack of an unstable zone; therefore, the simulation ends without any uncertainty about the speeds in play: the vehicle was traveling at 0.5m/s and the axles of the wheels were completely blocked (0m/s).

About three seconds after the activation of the braking system, there is the locking of the wheels that will remain in this situation until the end of the simulation since there is no controller that can adjust the torque of braking force in action according to the value of the adhesion. The value that the latter assumes is not in fact such as to be able to support the counterpart given by the braking force and therefore the wheel sets begin to slip. In addition, another interesting point is given by the fact that the slippage of the wheels leads to an increase in adhesion and in this case the value assumed by the coefficient of friction of the wheels that is indicated in the table.

This effect can be given by two different factors.

The first option is that the slip increases the removal of foreign elements that affect/modify the characteristics of the railway surface, the second is due to the case in which there are mounted on the train the sands that remain active until the vehicle stops. Each of these two events leads to an increase in available membership.

In the case of the first option, for example, you get to have an adhesion coefficient that increases more than twice as much as at the beginning, from 0.05 to 0.11. Despite this, however, the value that reaches the adhesion is still not enough to meet the demand for braking action and therefore the wheels continue to remain locked. Braking times and distances and wear index for the tested speeds (degraded conditions, no WSP)

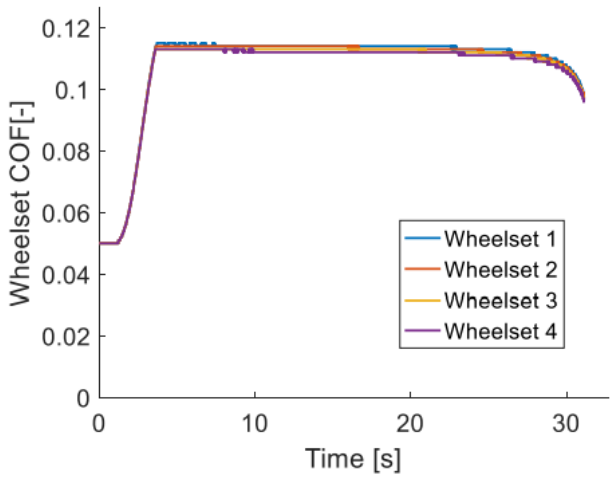
Table 3.7 Results of the test

Initial Speed [km/h]	Braking time [s]	Braking distance [m]	Wear Index [s^{-1}]
50	13.316 (+14%)	100 (+19%)	415.8352
80	20.973 (+12%)	247 (+20%)	443.3833
120	31.1335 (+5%)	541 (+9%)	461.0958
160	41.268 (-2%)	950 (+3%)	470.8941

The table also shows the difference in percentage, both in the distance and in the braking time, which is obtained in the various tests by activating the WSP. As you can read, there is always a difference in positive percentage as the presence of such a system always leads to a performance improvement. As for the braking distance there is an improvement ranging from a minimum of 3% to a maximum of 19%.

Only in one case this trend is not respected: the braking time in the test in which the initial speed is equal to 160Km/h, as can be seen, in fact, there is a worsening of the performance by a factor of 2. This feature indicates that there is a need to adjust the properties of the device as larger speeds come into play. As for the wear index, the absence of the WSP increases the index from 3 to 19 times. It is clear, therefore, how the use and presence of WSP can only lead to benefits in all situations.

Figura 4.7 Coefficient of Friction of the wheelsets Plot (initial speed: 120Km/h, no WSP)



Source: CEN. (2011). EN 15595, Railway applications - Braking -Wheel Slide Protection

CHAPTER VIII - Conclusions and future research

As for the future, there are many fields on which it is possible to focus to be able to improve the quality of the device compared to that of today. In the various tests carried out, one of the most used systems is the one designed and put on the market by the company Knorr Bremse since the 90s of the last centuries. It is therefore one of the WSPs belonging to the last generation but there are many ideas that could be introduced to get to a fourth generation or in any case to a development of the current one. For example, there are already ideas on the use of other types of implementable controllers (machine learning or neural networks). In fact, now anti-lock systems are used that are about twenty years old so there is a wide range of more recent elements to replace those belonging to a past technology thanks to the continuous recent development.

With these new technologies it would be possible to achieve greater flexibility for the control system present in the device and already this aspect would give several advantages in overcoming most of the constraints and limitations present in the types of controllers of the past years.

Another idea that is becoming increasingly popular is that of automatic braking (active braking). There are already proposals for its implementation and design, in fact from the tests, result an evolution regarding braking distances. However, such an improvement is achieved at the cost of greater damage to the infrastructure and therefore such innovation is not a good engineering solution. The task of the engineers will be to derive innovative methods that lead to minimizing damage to railway elements while always keeping in mind the most important aspect: the well-being and safety of passengers. Only by guaranteeing this combination can the railway system be considered by more and more users and face the challenges that the future holds for it.

Bibliography

1. About the influence of wheel slide protection devices action on longitudinal dynamic of trains Cătălin Cruceanu*, Mădălina Dumitriu, and Camil Crăciun University Politehnica of Bucharest, Department of Railway Vehicles, 313 Splaiul Independenţei, 060042, Bucharest, Romania
2. Adaptive Fuzzy Sliding-Mode Control of Wheel Slide Protection Device for ER24PC Locomotive. Alireza MousaviAmir H. D. MarkaziSaleh Masoudi
3. Adhesion During Braking and Anti-skid Devices, ORE B 164, RP 1, Synthesis of Current Knowledge Concerning Adhesion, Office for Research and Experiments of the International Union of Railways, U
4. Art. 12 bis of MMIEFCA "Manual of trade: instruction for the operation of the automatic continuous brake" section 5 – Obligations of train escort staff
5. Article by Emanuele Guglielmino on a method for generating arbitrary signals for a hardware-in-the-loop test system with the aim of simulating braking session and on a development of simulator Safety+ to test brakes in the lab.
6. Article: "Prototype energy harvesting wheel speed sensor for anti-lock braking" Dhasarathy Parthasarathy and Peter Enoksson and Roy Johansson from 2012 IEEE International Symposium on Robotic and Sensors Environments Proceedings, pages 115-120
7. Barna G., Theoretical analysis of Wheel Slide Protection controllers for rail vehicles, Proceedings of 16th International Conference on Methods and Models in Automation and Robotics, Międzyzdroje, August 2011.
8. Barna, G. (2012b). MATLAB Simulink® Model of a Braked Rail Vehicle and Its Applications. In Prof. Subhas Chakravarty (Ed.), Technology and Engineering Applications of Simulink (First edit, pp. 189–218). Intech.
9. Barna, G., (2012). MATLAB Simulink(r) Model of a Braked Rail Vehicle and Its Applications. Technology and Engineering Applications of Simulink. P. S. Chakravarty, intech.

10. C. Crăciun, C. Cruceanu, Brakes for railway vehicles – Applications (in Romanian), Matrixrom (2011)

11. Cabrera, J.A., Ortiz, A., Castillo, J.J., Sim'on, A., (2005). A Fuzzy Logic Control for Antilock Braking System Integrated in the imma Tire Test Bench. IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY 54(6): 1937-1949.

12. CEN, (2011). EN 15595, Railway Applications-Braking - Wheel slide protection.

13. D. Parthasarathy, P. Enoksson, R. Johansson Published 1 October 2012 Physics 2012 IEEE International Symposium on Robotic and Sensors Environments Proceedings

14. Design and preliminary performance evaluation of a four wheeled vehicle with degraded adhesion conditions. Luca Pugi, Francesco Grasso, Marco Pratesi, Marco Cipriani and Argeo Bartolomei

15. Freinage_Adhérence_Antienrayeurs_EN (pagesperso-orange.fr) Adhesion and Wheel Slide Protection.

16. Gholami, A., Markazi, A.H.D., (2012). A new adaptive fuzzy sliding mode observer for a class of MIMO nonlinear systems. Nonlinear Dynamics 70(3): 2095-2105.

17. Govt. Of India, Ministry of Railways, Handbook on Wheel Slide Protection Device (WSP)

18. Grażyna Barna, Miroslaw Lewandowski. Simulation model of wheel slip and slide protection systems for rail vehicles

19. Hardware-in-the-Loop Simulation for a Wheel Slide Protection System of a Railway Train Ho-Yeon Kim *, Nam-Jin Lee**, Dong-Chan Lee*** and Chul-Goo Kang. Preprints of the 19th World Congress the International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014

20. Https://www.marcodepisapia.com/carroponte-combinazioni-di-carico/ Article by civil engineer Marco depisapia about "elements for structural calculation and theory of meandering motion"

21. Https://www.sciencedirect.com/science/article/pii/S088832701930545X

22. *Infrared hot box detection system (Harbin VEIC Technology Co. Ltd 2008, Southern 2007)*

23. "Instruction on the operation of the automatic continuous brake" document by RFI Edition 1966

24. J. Harušinec, A. Suchánek, P. Šťastniak, P. Strážovec, "Brake actuator optimization of the brake test stand as a tool for improvement railway safety", 2018

25. Kawaguchi 1997 "generation of WSP"

26. Kuka, N., Verardi, R., Ariaudo, C., & Dolcini, A. (2016). Railway Vehicle Driveline Modelling and cosimulations in SIMPACK-Simulink

27. Meli, E., Pugi, L. & Ridolfi, A. An innovative degraded adhesion model for multibody applications in the railway field. *Multibody Syst Dyn* **32**, 133–157 (2014).

28. Meli, E., Ridolfi, A. An innovative wheel–rail contact model for railway vehicles under degraded adhesion conditions. *Multibody Syst Dyn* **33**, 285–313 (2015)

29. *Ministry of Transport, "Description of the automatic continuous brake system «Breda» and general requirements on its use", 1964*

30. [N1] – International Union of Railways UIC 540 "Brakes – Air Brakes for freight train and passengers train"

31. [N2] – International Union of Railways UIC 541-3 "Brakes – Regulations concerning manufacture of the different brake parts" 103

32. [N3] – International Union of Railways UIC 544-1 "Brakes – Braking power"

33. [PDF] Railway Air Brake Model and Parallel Computing Scheme | Semantic Scholar

34. Research project title: Research on developing mechanical and numerical models for the virtual evaluation of the dynamic performances in the railway vehicles (in Romanian).

35. Standard EN 15595:2009+A1 May 2011, Railway applications – Brakes – Wheel slide protection.

36. Stuetzle, T., Engelhardt, T., Enning, M., and Abel, D. (2008). Wheelslide and wheelskid protection for a single-wheel drive and brake module for rail vehicles. Proc. Of the 17th World Congress, IFAC, pp. 16051-16056, Seoul, Korea

37. Sundar Shrestha, Maksym Spiryagin, Qing Wu, "Friction condition characterization for rail vehicle advanced braking system, Mechanical Systems and Signal Processing" Volume 134,2019

38. UIC 541-05 "Frein-L'anti-enrayeur"

39. Yamazaki, H., Karino, Y., Kamada, T., Nagai, M., and Kimura, T. (2008). Effect of wheel-slip prevention based on sliding mode control theory for railway vehicles. Vehicle System Dynamics, vol. 46, pp. 255-270.

40. Yoo, B., Ham, W., (1998). Adaptive Fuzzy Sliding Mode Control of Nonlinear System. IEEE TRANSACTIONS ON FUZZY SYSTEMS 6: 315-321.

41. Yujin Electric Ltd. (2004). Anti-Skid Control Unit.

Sitography

1. [PDF] Railway Air Brake Model and Parallel Computing Scheme | Semantic Scholar
2. Freinage_Adhérence_Antienrayeurs_EN (pagesperso-orange.fr) Adhesion and Wheel Slide Protection.
3. https://club.auto-doc.it/magazin/sistema-anti-bloccaggio-abs-cos-e-e-come-funziona
4. https://club.auto-doc.it/magazin/sistema-frenante-come-funziona-cosa-consiste
5. https://en.wikipedia.org/wiki/IranRunner
6. https://evolution.skf.com/us/sensors-for-railway-bearing-units/

7. https://www.iricen.gov.in/ModelRoom/H1_Wheel%20Burnt%20Rails.html
8. https://it.quora.com/ about geometry of the wheel and rail. Type of adhesion between them and railway elements that contribute to maintaining it.
9. https://meccanicaweb.it/analisi-dinamica-freni-treni-merci/
10. https://rdso.indianrailways.gov.in/works/uploads/File/Handbook%20on%20Wheel%20Slide%20Protection%20Device%20(WSP).pdf
11. https://www.alamy.it/schema-del-freno-westinghouse-utilizzato-su-carrozze-ferroviarie-in-data-xx-secolo-
12. https://www.sciencedirect.com/science/article/pii/S088832701930545X
13. https://www.slideshare.net/srguduru/handbook-on-wheel-slide-protection-device-wsp
14. lecture 3F- meccanica della locomozione (unirc.it) from the railway infrastructure course held by the engineer Marinella Giunta at the "mediterranea" university of reggio calabria. Lecture about the mechanics of locomotion
15. *Microsoft PowerPoint - Wheel Slide Protection system (WSP) (indianrailways.gov.in)*
16. *Source: https://folk.ntnu.no/skoge/prost/proceedings/ifac2014/media/files/2106.pdf*