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A SOFT COMPUTING METHODOLOGY APPLIED TO ABS

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1. Introduction

The aim of this paper is to create a new ABS (Antilock Braking System) control system of a Soft-Computing type, on the grounds of the excellent results obtained in the field of automobiles in former studies [4]. Such a system should make it possible to enhance performance in all conditions. The novelty lies in the fact that the system improves not only the physical nature of the hydraulic and electronic components used [6] and [7], but also the functioning of these, by means of a new control strategy based on a fuzzy-type algorithm optimised with genetic algorithms. In this way the performance of the system may be improved or alternatively the control logic may be simplified for the same degree of performance, offering satisfactory results in all possible conditions. The target performance aimed at may be summarised in two points: reduction in braking distance and improved directional control of the vehicle. The study was optimised on a monocorner model, subsequently to be extended to a complete vehicle model.

2. Iter of the research

Starting from the control logic most commonly used in standard vehicles an ABS strategy of a *Soft Computing* type [4] was developed. As a first step, the system already on the market was analysed on the basis of the corresponding control logic found in literature [1], in order to characterise the thresholds of intervention. These thresholds were defined with an optimisation by means of genetic algorithms, on the monocorner model specifically created for the purpose; they were then used to set the logic of intervention of the traditional controll system acting on each of the wheels of the vehicle, which had previously been verified with steering pad manoeuvres. On the basis of experimental findings, related to a panic-stop manoeuvre carried out on a vehicle with such a system, it was possible to check that the model of vehicle tested by means of the above strategy would give results faithful to those of a real vehicle. After carrying out a study of the behaviour of the vehicle during braking and establishing the variables suitable for control, the fuzzy controller was designed.
Subsequently, the control system was perfected by means of training with genetic algorithms, obtaining results worthy of note: the fuzzy control system was able to acquire a correct strategy for using the control variables. This strategy proved to be valid for the entire range of adherences and for every speed of the vehicle. It is therefore not necessary, as it is for other types of ABS control which allow for a variety of strategies according to the operative conditions, to identify specific adherence conditions in order to define the most appropriate strategy for each.
It was possible to see that, for any adherence value, the fuzzy control system is able to make the system run at or near the ideal pressure value. This represents the optimal value which an expert driver would bring the braking system up to in a vehicle without an ABS system.

3. Development of the monocorner and the vehicle model

From an analysis of the working principle [1] on which the anti-lock system is based, it is possible to see that control strategy used is the same for each of the wheels of the vehicle. As a consequence, at a first stage, the implementation of the control was limited to that acting on a single wheel. In this way it was possible to identify, tackle and solve the major problems regarding modelling of the control in the most immediate way (without wasting any time). A model was therefore initially created, developed in *Matlab-Simulink*, consisting of a single wheel and given the name of monocorner or monowheel: it is a model with concentrated parameters, designed to read the most important aspects of behaviour (of the braking mechanism).

For the purposes of this study the hypothesis was formed of a vehicle running on a flat road, at zero gradient, in a straight line, proceeding at a constant speed prior to the application of the braking mechanism. As in most of the studies concerning braking systems, factors such as the aerodynamic resistence, rolling resistence and the passive moment of the rotoidal pin-hub of the wheel were considered negligible. This made it possible to simplify the mathematical calculations while acting in favour of safety. These forces, in fact, lead to a further slowing-down of the vehicle. Not only was the direction of movement taken as a straight line, but the intervention of the driver on the steering wheel was considered non-existent, as also the effect of side-wind and possible transversal interference with the contact between wheel and road surface. This model was created with the aim of studying the dynamics of braking, taking into account the nature of both the tyre and the suspension.

The concentrated-parameter model, related to a single front wheel, consists of two masses, (one suspended, one non-suspended) and a series of physical dimensions suitable to describe the behaviour of the elements present in the real system. It offers five degrees of freedom:

- Vertical translation of the suspended mass zm;
- Vertical translation of the non-suspended mass zr;
- Longitudinal translation of the suspended mass xm;
- Longitudinal translation of the non-suspended mass xr;
- Rotation of the wheel

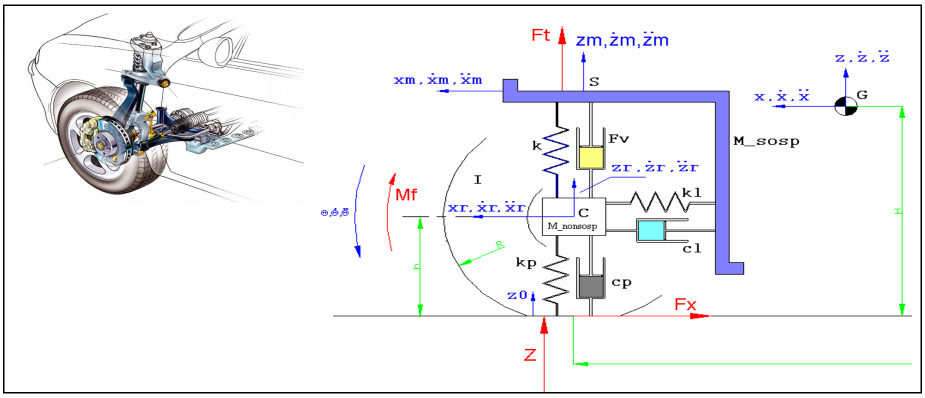

Figure 1. Physical model of the monocorner

In figure 1 the characteristic dimensions are represented with colours: cinematic entities (in blue), dynamic entities (in red), geometric entities (in green) and physical entities (in black). Since it is a concentrated-parameter model, the above masses are understood to be pointed in form and applied to the relative centres of gravity. In the initial moment, the simulation paracmeters are set in such a way as to consider the vehicle subjected only to the force of weight and moving at constant speed. The translations of the masses forming the system are estimated by defining three fixed systems of reference: for the non-suspended mass, for the suspended mass and for their shared centre of gravity G. The origin of these systems is placed respectively in the centre of the wheel C, in a generic point of the suspended mass S and in the centre of gravity G. As well as these three fixed systems of reference a fourth mobile system was used with a non-suspended mass, coinciding, in the initial moment, with the fixed system of reference of the mass itself. The equations of balance given below support the dynamics of the system and are as many as the degrees of freedom; they are given in the following order:

$$\begin{cases} M\_sosp \cdot \ddot{z}_m + F_v(\dot{z}_m - \dot{z}_r) + k \cdot (z_m - z_r) - F_t = 0 \\ M\_nonsosp\,\ddot{z}_r - F_v(\dot{z}_m - \dot{z}_r) - k \cdot (z_m - z_r) + c_p \cdot (\dot{z}_r - \dot{z}_0) + k_p(z_r - z_0) = 0 \\ M\_sosp \cdot \ddot{x}_m + c_l \cdot (\dot{x}_m - \dot{x}_r) + k_l \cdot (x_m - x_r) = 0 \\ M\_nonsosp \cdot \ddot{x}_r - c_l \cdot (\dot{x}_m - \dot{x}_r) - k_l \cdot (x_m - x_r) + F_x = 0 \\ M_f + I \cdot \ddot{\Theta}_r - F_x \cdot h = 0 \end{cases} \tag{1}$$

In particular, the first relation represents the equation of balance to the vertical translation of the suspended mass. In this equation, besides the term of inertia and the elastic-viscous reaction of the suspension, there is also the load transfer F_t due to the force of inertia applied to the centre of gravity G of the entire system. To make the simulation realistic, the force under examination was calculated considering a complete vehicle:

$$F_t = F_x \frac{H}{L} \tag{2}$$

supposing to make the position of the centre of gravity G of the quarter-vehicle coincide with that of the centre of gravity of the complete vehicle. In the same relation, k represents the elastic rigidity of the suspension spring which may, with a reasonable approximation, be considered as constant. On the contrary, the viscous reaction of the shock-absorber is strongly non-linear and its characteristic is introduced into the model with a look up table. In the wheel-turning balance the arm h of the force of adherence F_x appears, which is variable and does not coincide with the rolling radius R0 of the wheel.
The values of the inertial, elastic, damping and geometric parameters are extrapolated directly from the technical details of the vehicle under study and set out in Table 1. The force of longitudinal adherence F_x developed at the contact of the tyre with the road surface, which figures in the last two relations, derives from the effect of the application of the braking moment M_f to the wheel.
The value of the vertical load Z developed from the contact of tyre and road surface is included in the calculation of the braking force. It represents, together with the load transfer F_t, the only relation between the equations of balance to the vertical translation and those to the longitudinal translation, even if this does not become clear from an examination of relation 1.

Table 1. Technical details of vehicle adapted to monocorner

SYMBOL	DEFINITION	VALUE	UN. DI MIS.
M_tot	Total mass	1420	[kg]
M_nonsosp_ant	Non-suspended mass of each front corner	49	[kg]
M_nonsosp_post	Non-suspended mass of each rear corner	35	[kg]
a	Distance center of gravity G front traction	0.963	[m]
b	Distance center of gravity G rear traction	1.587	[m]
H	Height of centre of gravity	0.55	[m]
L	Inter-axes	2.55	[m]
M_sosp	Suspended mass of monocorner	389.6	[kg]
I	Inertia equivalent of wheel	1.04	[kg m^2]
k	Rigidity of suspension spring sospens.	19553	[N/m]
kl	Rigidity of longitudinal suspension	400000	[N/m]
cl	Damping of longitudinal suspension	500	[Ns/m]
kp	Tyre rigidity	186314	[N/m]
cp	Tyre camping	186.314	[Ns/m]
R	Radium of undeformed wheel	0.3124	[m]
h0	Static height of wheel centre	0.2893	[m]

In general, in a study of the dynamics of the vehicle, it is essential to have available mathematical tyre models capable of representing tyre behaviour with sufficient accuracy. Some models are based on the physical nature of the tyre, while others are completely empirical. In any case, both types always refer to partially empirical formulations. Literature shows that the totally empirical models have met with the greatest consensus of approval. The most common of these is the model by Pacejka [2] [12], used by us for the present study; this model is able to give an accurate description of tyre behaviour on the basis of the experimental figures introduced. The aim of Pacejka was to represent a series of curves, which he called "adherence characteristics", to define tyre behaviour, with the use of a minimum number of possible coefficients. Observing that all the adherence characteristics of tyres indicate a sinusoidal trend, he introduced a so-called Magic Formula, reproducing, on only six parameters, the curves of the longitudinal force Fx(σ), the lateral force Fy(θ) and the moment of self-alignment Mz(θ), for given vertical loads and camber angles γ. To calculate the longitudinal force only the effect of the longitudinal slippage σ is considered, while the definition of the lateral force and the moment is made to depend only on the drifting angle θ. Incidentally, the longitudinal slippage is the index of micro-slippage of the tyre and is determined by the following relation:

$$\sigma = \frac{V - V_s}{V} \tag{3}$$

where V is the speed of translation of the wheel while Vs is the equivalent speed of slippage of the centre of the contact tyreprint. With the Magic Formula it is possible, moreover, to obtain curves with different shapes in the opposite quadrants (to consider the difference between the arcs of traction and braking). The six factors are related to the vertical load Z and the angle of inclination by means of polynomial functions. To obtain the coefficients of these functions it is necessary to obtain by experimental means the behaviour of the tyres when there is a variation in the drifting angle θ, (or, for F_x, of the longitudinal slippage σ), of the vertical load and the angle of inclination.

To permit the optimization, verification and perfecting of the control system it was necessary to add to the monocorner model, and subsequently to the vehicle model, a block which could reproduce the functionality of the hydraulic modulator in the ABS system. The delay due to the propagation of the pressure front within the hydraulic circuit and to the commutation times of the activating servovalve (150 ms in the rising phases and 50 ms in the falling phases) was estimated by means of an analysis of experimental readings related to a *panic-stop* manoeuvre.

In particular it was possible to advance the hypothesis that in the falling phase, the instantaneous speed of pressure diminuition depended on the instantaneous value of the same, according to the following law:

$$p = p_0 \cdot e^{-kt} \tag{4}$$

where p_0 is the initial value and k is a constant characteristic of the hydraulic circuit. To test the validity of the ABS control system applied to the monowheel system, a dynamic model of non-linear vehicle was developed, sufficiently detailed to read all the more significant phenomena in behaviour on the road and to reproduce the reactions of the vehicle faithfully, even when involved in near-limit manoeuvres.

This model consists of a rigid body, known as the chassis, characterised by six degrees of freedom with an added warp, and four corners constituting wheels and suspension. The system in all therefore has fifteen degrees of freedom: seven related to the chassis and two to each corner (vertical movement and rotation of each of the wheels).

Moreover, a series of hypotheses was formed which made it possible to uncouple inertially the equations regarding the chassis on the horizontal plane and outside it.

It is necessary to underline that the contact forces (F_{xi}, F_{yi} ed M_{zi}) are obtained by using the interpolating formulation of Pacejka, analogous to that already introduced in the study of the monocorner. Before verifying the antilock control, it was necessary to test that the vehicle model would supply data faithful to that of a real vehicle, that is in line with the dynamic figures obtained by means of experimental readings kindly supplied by the FIAT Research Center (CRF). The dimensions used for the comparison with the simulated results were acquired experimentally during the execution of handling manoeuvres aiming to test the stability of the vehicle in cases of interfering action, whose methods of operation are established by ISO regulations. In Figure 2a in particular, the experimental results refer to a steering-pad with a 40 m radius. A good correspondence was noted, and for the sake of brevity we illustrate here only the lateral acceleration a_y.

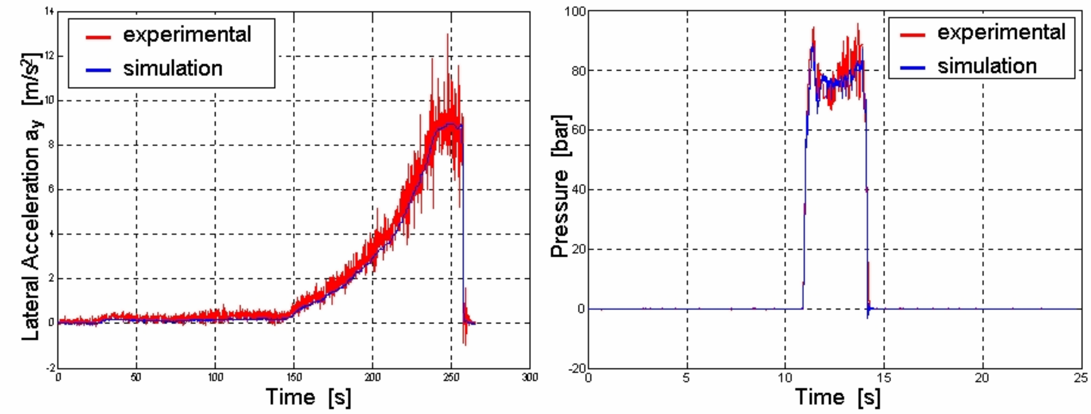

Figure 2. (a) Lateral acceleration a_y in a steering- pad (b) Pressure at front wheels

4. Development of the *Fuzzy* control System

To define the maximum performance of the system without ABS control it was proposed to simulate the behaviour of the so-called expert driver, who limits the braking action as soon as he realises that he is reaching a state of instability.

The classic *Bosch* control strategy was then implemented, its thresholds of intervention optimised by the use of genetic algorithms. After verifying that the control thus obtained gave results faithful to reality, the results of the simulations were compared with those of the model of the complete vehicle, with a panic-stop manoeuvre carried out by the CRF. Figure 2b shows a comparison between the trend of brake-cylinder pressure of the right front tyre obtained through simulation and the reading obtained experimentally. As a result of this comparison it was possible to state that the *Bosch* strategy had been correctly implemented and had determined all the intervention thresholds effectively. The controller intervenes in the system, and more specifically in the hydraulic circuit, after elaborating the signals received by specific measurement by wheel-speed sensor with pulse ring. The simplest variable to monitor consists in the longitudinal slippage, calculated by the exchange by means of readings of the wheel and the vehicle speed. As the force of adherence is influenced by a large number of factors, the link between this and the longitudinal slippage is not univocal: if there is a variation in adherence conditions, the slippage value, corresponding to the maximum value of the longitudinal adherence coefficient, falls within a field between 8% and 30%. As a result of this, it is impossible to fix a single reference threshold and choose slippage as the only control variable.

It is therefore necessary to introduce a second variable: peripheral acceleration of the wheel

$$a_r = \ddot{\theta}_r \cdot R_0 . \tag{5}$$

If this value begins to increase rapidly it is a sign that an unstable field of the adherence curve has been reached, at which point, while the braking moment of a passive system continues to increase, the adherence moment decreases. In these terms, it may be considered as an index of danger to differentiate the behaviour of the wheel. Common antilock systems are set in order to permit intervention as soon as peripheral deceleration passes an established limit value, defining the beginning of the area of instability. This threshold must be established accurately, otherwise there is the risk of permitting the system to intervene too late, in which case wheel locking is possible, or too soon, increasing braking distances. It is clear from the above that the two variables mentioned, slippage and peripheral deceleration, cannot be used singly as control variables, while if they are used synergically it is possible to achieve an almost optimal control of the braking manoeuvre. This is what occurs in the Bosch system strategies, which have been considered as a reference index. From an analysis of the working principles on which antilock systems are based, it may be seen that the control strategy used is the same for each of the wheels of the vehicle. As a result, in an initial phase, also for fuzzy control, the implementation of the control was limited to that acting on a single wheel. After an examination of the Bosch system, but also of what was achieved in [13], the following variables were

chosen for the fuzzy control: ***input variables*** **(**peripheral wheel acceleration: *a_wheel*; longitudinal slippage: *Brake slip*) ***output variables*** **(**control signal of the operator: *sign_contr*).
From an analysis of a number of simulations of the *Bosch Control System*, for a variety of operative conditions (adherence value and speed at start of braking) ranges were established for each variable; these are set out in Table 2.

Table 2. Range of variables of the fuzzy control

Variable	Range
a_wheel [m/s]	[-500, 500]
Brake slip	[0, 1]
sign_contr	{1, 2, 3}

While ranges were determined for the input dimensions, three values were set for the control signal, corresponding to the three possible states of the electrovalve: *1)* increase, *2)* steady, *3)* decrease. The three signals represent the response by modulating the pressure via the solenoid relay values. It is useful to observe that in normal braking manoeuvres, the peripheral acceleration a_wheel remains within the range [-50, 50], while it is only in cases of braking with a change in adherence that it reaches far higher levels as an absolute value. In the passage from high to low adherence, in fact, a sudden locking of the wheel occurs; in the opposite case a sudden acceleration of the wheel is noted.
Each range of the input variables was then subdivided into a series of sub-ranges, to each of which a membership (mf) was associated [5]. The output variable *sign_contr* was assigned a number of mf equal to the minimum number of rules which may be formed from the pairs of input variables: 28 rules were elaborated, with 7 mf for the first input (wheel acceleration) and 4 mf for the second input (brakeslip), defining 28 mf for the control signal. Applying the *fuzzy* inference (rules and logical operators) to all the possibile values included in the range of the input variables, it is possibile to obtain an output map similar to that indicated in figure 3a. It is important to observe that figure 3a represents the values of output from the fuzzy control. They do not, however, represent the values transmitted to the activator. They appear as continuous values in the range between [0;4], in order to give the fuzzy control system the maximum freedom in positioning the output memberships. Nevertheless the activator may receive only the discrete signals {1, 2, 3}. The values are subsequently rounded up to the nearest whole number and saturated between the limits of 1 and 3. Proceeding in this way (figure 3b) a three-colour map is obtained (blue = 1, green = 2 and red = 3). These are the values of the signals transmitted to the operator, corresponding to suitable levels of command tension of the electrovalve. Also the fuzzy controller was implemented in *Matlab-Simulink* and was coupled to the monocorner model.

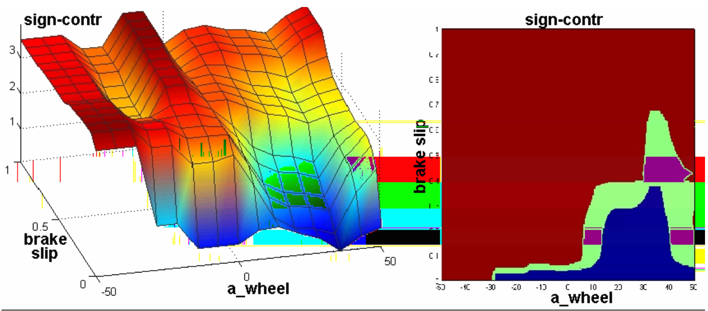

Figure 3. Output map of continuous values (a) and discrete values (b)

The only dimension acquired by the sensors is the angular speed of the wheel. All the other dimensions are derived from this, with the exception of the reference speed *V_rif*, for which the speed of the wheel centre is used. It is assumed that the control system receives the signal *V_rif* from a further module placed previously (ramp function, integral of the deceleration before activation of the mechanism, assessment with *fuzzy* logic, etc.). This assumption makes it possible to analyse performance independently of the errors caused in estimating the reference speed. It is also assumed that all the signals are given without the inevitable measurement noise and therefore that they have been supplied to the controller already suitably filtered by a previously placed pre-processing module.

It is clear that the performance of such a control system is the best that may be obtained by the control itself and that it is subject to deterioration in real application as a result of errors of measurement, interference and erroneous assessments of the dimensions involved.
The following may be found within the control subsystem: input of reference speed: dxr(*V_rif*), input of angular wheel speed: dteta (w_omega), input of braking signal: stop, output of control signal: (*sign_contr*) and the subsystem related to real and effective control: *fuzzy Control.* All the signals were discretised with a sampling interval of 0.01 s.
The *fuzzy control* subsystem is activated if and only if the following conditions occur simultaneously: activation of the brake pedal (stop), reference speed greater than the threshold of disconnection (V_dis) equal to 10 km/h. During the inactive phase the controller supplies the command signal 1 thus placing the activator in an off position (open valve, circuits communicating on either side of it) and permitting the braking circuit to function as if the ABS mechanism were not present. Once the system is activated, if one of the two conditions ceases to exist, it is disconnected and returns to a standby position, until it is re-activated. An initial analysis of the control system immediately reveals its extreme simplicity, since it consists of a reduced number of equally simple blocks. The control force is enclosed in the fuzzy system, which contains data acquired during the simulation (training) phase; this data permits the system to model an extremely flexible control strategy, not rigid or pre-set like the traditional control systems. With the training carried out by means of optimization with genetic algorithms [8] and [9], in fact, the fuzzy system has succeeded, as the final part of this paper will show, in building a control strategy able to operate in all conditions without needing to know the adherence coefficient and the initial braking speed. Traditional strategies based on "states", in fact, give excellent performances in the operative conditions for which they were created, but these performances tend to deteriorate as soon as the real conditions differ from these or if unexpected conditions develop in the synthesis phase.
In such a case it is necessary to consider a large number of combinations of operative conditions, or alternatively to develop a variety of strategies which may be activated on the basis of the prevailing conditions. This type of development is limited by the knowledge of the subject possessed by whoever is planning the control system. Moreover, the existence of a variety of strategies presupposes the presence of a further system supervising these, in order to assess (or recognise) the prevailing conditions and decide which strategy to activate. This is not always easy to achieve because the system is difficult to realise. Once the control model of the monocorner has been developed, the next step is to implement the ABS control model of the complete vehicle. The *Vehicle-Control* complex appears identical to the Monocorner-Control model, but in this case the dimensions exchanged are of a vector type (with the exception of the pedal signal) as the relative information must be transmitted to all four wheels. The Control block proves to be similar to the corresponding block of the monocorner. In this case the Omega input is a vector containing the four angular speeds, one for each wheel, while the four outputs are grouped in the *sign_contr* vector.
Within this block the Control blocks of the monocorner have been repeated, one for each wheel, where the corresponding *Fuzzy Logic Controller* block recalls a file with extension .FIS, identical for the pair of wheels belonging to the same axle, but differentiating the front from the rear axles. This makes it possible to optimize the parameters for the two axles separately, while the wheels belonging to the same axle are optimized together, since the behaviour of wheels on the same axle is fundamentally the same.

5. Optimazation of the control

The maximum performance of the *Bosch* control model, suitably optimised as usual with genetic algorithms, was used as a relative reference, relative that is to another ABS mechanism applied to the same vehicle. The results obtained with the fuzzy system were used only as a term of comparison, and not in the calculation of the objective function. Out of the many membership functions available in the *Matlab-Simulink* environment, it was considered sufficient to use classical trapezoidal and triangular mfs, which make it possible to take into account possible saturations of the membership functions.

Since the operative conditions studied were those of a flat road with braking on the straight, the principle object may be summarised as that of minimizing braking distance while maximising longitudinal adherence force. Maximizing the longitudinal adherence force implies making the system work for values of longitudinal slippage between 0.1 – 0.3, values for which the transversal force still remains quite high and is generally sufficient to govern the vehicle. From the first simulations, it was decided to carry out global optimizations, that is for the entire field of the adherences, identified with the parameter mu. The objective function therefore takes into account all the braking distances x_i corresponding to the i-th adherence defined by mu in the interval [0.2-1.0].
It was considered advisable to normalize each distance xi with respect to a suitable reference distance x_{i_rif} in order to appreciate its percentage variation, preventing the braking distances related to low adherence from masking those related to high values. Each adherence value was assigned a weight p_i, proportional to the distance of its corresponding braking distance from the reference value, to oblige the fuzzy system to improve in the points where intitially its performance was less good, as can be seen in Table 4.

Table 3. Weights p_i for the various adherence values

mu	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
p_i	1.5	1.5	0.978	0.961	0.964	0.997	1.027	1.077	1.5

In synthesis, the objective function fob for each single speed at start of braking is defined thus:

$$f_{ob} = \frac{\sum_i p_i \frac{x_i}{x_{i\_rif}}}{\sum_i p_i} \tag{6}$$

where the meaning of the symbols is known. In cases where more than one speed is present a suitable average weight will be attributed by means of a weight pvj proportional to the importance given to the j-th speed v_j. In the present study, because of the large amount of time necessary for the calculations of each simulation, a maximum of only two speeds was established, 100 and 50 km/h, weighted with equity.

6. Analysis of results

Figure 4 show in red the distances, at 100 km/h, corresponding to the fuzzy system and in blue the distances deriving from the Bosch strategy. These two curves fall between the reference distances, which are those which an expert driver would reach in a system without ABS (below), and the distances obtained when the wheels lock (above). The reference distances were calculated by the passive system, determining, with the use of genetic algorithms, the maximum pressure of the hydraulic circuit at which the pressure increase is to be blocked. This simulates the behaviour of the expert driver, who succeeds in blocking the pressure increase just before reaching the area of instability. From a more detailed analysis it becomes clear that both the control strategies, *Fuzzy* and *Bosch*, reach performances which are substantially similar to those of the expert driver for adherences of over 0.6 (the most favourable conditions) whatever the speed at which braking starts, while both performances always deteriorate at lower adherence values, leaving considerable room for improvement. Moreover, at the lower speed tested, that of 50 km/h, both the strategies examined always assume comparable values, over the entire range of adherences considered, with an average Δ% of about −1.11%, that is the *Fuzzy* controller reaches on the whole slightly better performances than the *Bosch* strategy.
At the higher speed, 100 km/h, the Bosch strategy performs better at very low adherence values, with distances of up to 6.7% more for the Fuzzy strategy at an improbable *mu* of 0.2. This is probably to be attributed to the pressure variation in steps, at present not implemented in the *Fuzzy* control system.

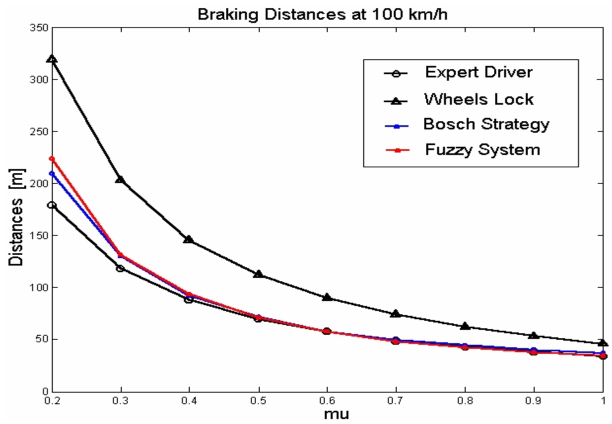

Figure 4. Comparison between braking distances at 100 km/h

For adherence values of over 0.4, on the other hand, the *Fuzzy* system improves its performance and succeeds in compensating, as can be seen in Table 4 which lists the average deteriorations, for the performances observed at very low adherence values.

Table 4. Average Δ% with respect to the ideal system and the *Bosch* strategy

Strategy	**Passive System (Expert driver)**		**Bosch**	
Initial speed	50 km/h	100 km/h	50 km/h	100 km/h
Average Δ%	+4.7 %	+4.6 %	-1.11 %	-1.02 %

In conclusion, it may be affirmed that the principal objective of antilock control, that is the reduction of braking distances, compared to those obtained with blocked wheels in any adherence condition, has been easily reached. Moreover, the Fuzzy strategy, in comparison with the Bosch control strategy, proves to have a good potential, since, even if at very low, and very improbable, adherence values its performance is inferior, it is reasonable to foresee a clear improvement with the implementation of pressure variation by steps. For the sake of brevity, figure 5 shows only the description of the trend of characteristic dimensions for an adherence value equal to *mu*=0.6. Similar trends were obtained for all the other adherence values. The figure shows the speed and acceleration of the wheel, the slippage, the control signal and the pressure, on the basis of the braking time. These diagrams are sufficient to grasp the most important aspects characterising Fuzzy control:

- the slippage values, and the corresponding braking pressure values, oscillate around their respective optimal values;
- at high adherence values, after a certain period of adjustment, the control becomes aware of the optimal pressure value and is even able to maintain it until it is disconnected (under 3 m/s, about 10 km/h), as is confirmed by the steady state at level 2 of the control signal.

Examining the behaviour for a variety of values of *mu*, the frequency of oscillation of the dimensions diminishes proceeding from the most critical conditions of low adherence values towards more favourable values. The most regular trend of all is that of the braking pressure, shown in figure 6a, for *mu*=1. After a few small adjustments, the respective optimal level is reached, which is the level simulating the behaviour of an expert driver. The increase in pressure in the final braking phase is always due to the disconnection of the ABS control system: the value of the pressure follows the pressure before the valve and therefore increases up to the maximum value allowed by the system. The increased irregularity of the wheel speed is expressed by an equally irregular longitudinal slippage, which tends to oscillate at greater widths in the final phases of the braking manoeuvre, indicating that the controller is having difficulty in maintaining it within the optimal limits.
The trends of the peripheral wheel acceleration and of the braking pressure prove similarly irregular. Figure 6b shows the trend of the pressure for mu=0.6. As in the other cases, the Fuzzy control system is able to maintain the values close to optimum, especially in the case of the braking pressure. Although no specific control cycle was introduced into the development of the Fuzzy control strategy, leaving total freedom of action, it is interesting to note how, especially at low adherence levels, the Fuzzy controller tends to build its own control cycle, that is a substantially identical succession of

signals, repeated periodically for almost the entire duration of the braking manoeuvre. The dimensions have a periodic trend, with the exception of the reference speeds, where the oscillations are minimal.
This result is of enormous importance: the training with genetic algorithms has allowed the Fuzzy system to acquire the correct way of functioning and confirms the validity of the methodology developed so far. The control was set for only two possible speeds at the start of braking, but it appears clear that these good performances will be maintained at any speed.

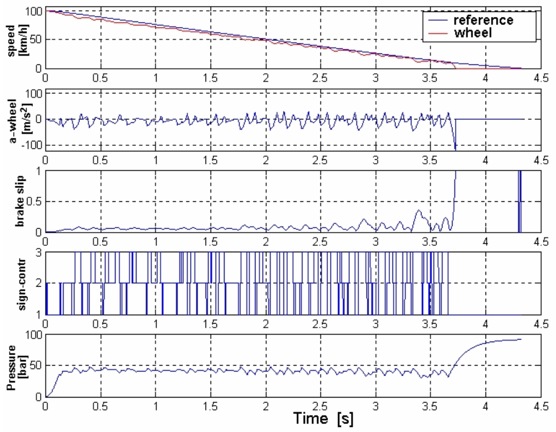

Figure 5. Characteristic dimensions for mu=0.6

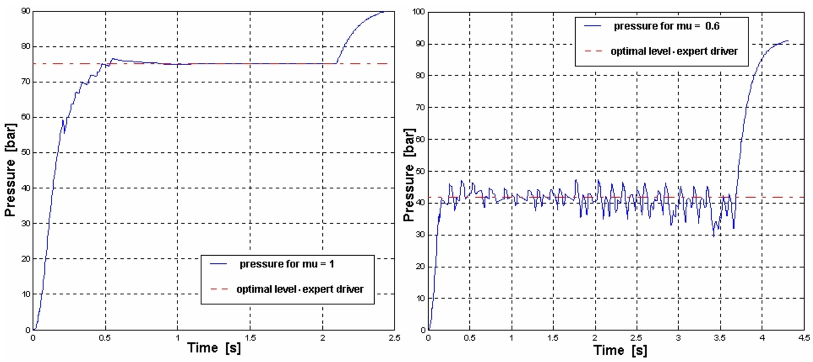

Figure 6. Braking pressure for *mu*=1 (a) and *mu*=0.6 (b)

To check the reliability of the control system, it was tested at different speeds from those used in the training, associated with different adherence conditions. It was thus possibile to confirm that in every case, and regardless of the combination of initial speed and adherence conditions, the Fuzzy controller always performed correctly. An important requisite for an ABS system is that it should maintain a correct functioning also in changing adherence conditions. Substantially two cases may occur:

- sudden transition from a highly adherent surface (such as asphalt) to one of low adherence value (sand, ice) with a tendency to wheel lock;
- sudden transition from low adherence to high, less critical than the preceding case.

Since these conditions were not supplied in any of the training tests carried out on the Fuzzy system, it was necessary to verify its performance. The reliability of the control system in situations of variable adherence was verified by effecting braking manoeuvres with different combinations of changes in adherence and in the instant of variation (delay). For the sake of brevity, only one example is reported here, of the most critical case. Figure 7a indicates a transition from an adherence condition defined by *mu*=0.7 to a condition of *mu*=0.4, with delay of 1 sec. In the first diagram the characteristic change in gradient of the reference speed may be noted (speed of system) corresponding to the change in adherence value: this indicates that the longitudinal deceleration has changed and therefore also the available adherence, in fact:

$$a_x \propto \mu g \qquad (7)$$

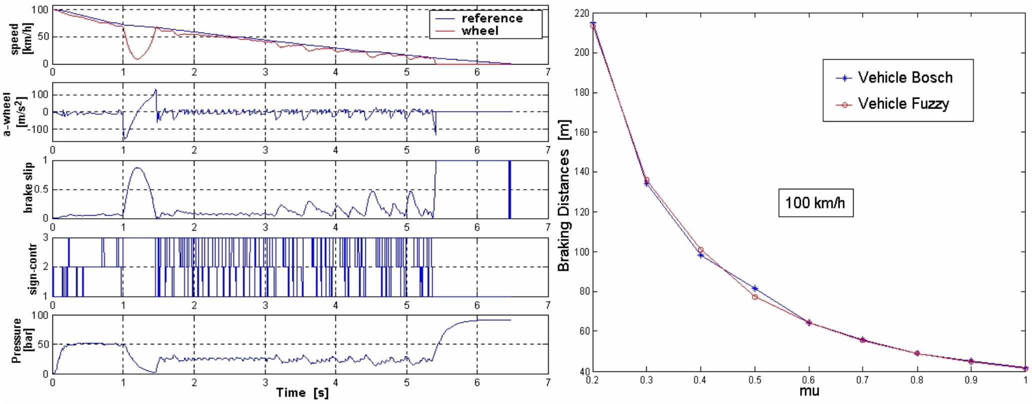

Figure 7. (a) Change in adherence from 0.7 to 0.4, interval 1s, (b) vehicles at 100 km/h

It is possible to note that the Fuzzy controller immediately becomes aware of the change in adherence conditions and correctly sets a signal of pressure decrease, until the slippage comes back to an optimal level. Note also that the value of the pressure drops almost to zero, and then starts to rise again towards the new optimal pressure level corresponding to the new condition of *mu*=0.4. At the same time, the wheel acceleration inverts its tendency and increases steadily up to the instant in which the pressure is made to increase again. In the opposite case, that of an increase in adherence, the trends of the dimensions are more regular, since this type of change in adherence value is less critical. The change in gradient of the reference speed is again present, as well as the change to a new level of pressure. In the instant following the change in adherence value, the wheel acceleration presents a positive peak and a zero slippage (pure rolling) corresponding to it. It is important to underline how, in every case, the Fuzzy controller becomes automatically aware of the change in adherence conditions and reacts in a suitable way, without any need for further information or even of a supervisor to define the new adherence conditions. It may also be noted how the training with genetic algorithms has given the Fuzzy controller the ability to learn a correct control strategy regardless of the prevailing adherence conditions. Once the control system of the monocorner has been defined to a satisfactory degree, the following step was that of implementing the same kind of control in the complete vehicle model, simply by duplicating it. The braking distances obtained are set out in figure 7b, for the most critical case of braking at 100 km/h. Note that the performances of the two control systems are comparable, but that of the Fuzzy system may be improved further. In the optimization of the system, in fact, an front monocorner was used, while in the complete vehicle it is necessary to distinguish between front and rear monocorner because of the opposite load transfer. If the same control system is used for all four wheels, without any modification, it is therefore impossible to obtain excellent results. The Authors are continuing to carry out optimisation activities in order to improve the performance of the complete vehicle. Separate optimisations are being carried out on the rear monocorner and will then be introduced on the complete vehicle so that the performance of this too may be perfected.

7. Conclusions

Starting from the control logic of the Bosch antilock system, a new ABS (Antilock Braking System) strategy was developed, of a fuzzy type, optimised with genetic algorithms. The Fuzzy system was found to have good potential: although at very low adherence values, which are very unlikely to be met with at high speeds, the performance of the Fuzzy system is less effective than that of the Bosch strategy, it is reasonable to foresee an improvement with the implementation of a pressure variation by steps. What immediately becomes clear from an initial analysis of the control system is that it is extremely simple, since it consists of a reduced number of equally simple blocks, with a low burden for computing and a high level of reliability. It was in fact possible to model a control strategy which is very flexible, unlike the rigid and pre-set strategies of traditional control systems. It is important to underline how, in every case, the Fuzzy control system is able to become aware of changed adherence conditions and to react in a suitable way, without any need for further information or even of a supervisor to define prevailing adherence conditions. In the development of the Fuzzy control strategy, although no particular control cycle has been defined, leaving complete freedom of action, it is interesting to note that, especially at low adherence values, the Fuzzy control system tends to build its own control cycle, that is a substantially identical succession of signals, repeated periodically for almost the entire duration of the braking manoeuvre. Moreover, it is very important to underline that the Fuzzy control system, for any adherence value, works at or near the ideal pressure, that is the pressure value that an expert driver would bring a system without ABS up to, to avoid going beyond the stable functioning area. These reference pressure values were obtained, with former simulations of the passive system, by finding the maximum pressure value in each single case, by means of genetic algorithms, in order to minimize braking distances. The Fuzzy control system developed in this study proves simpler to realise than those on the market at present, [1] [3], since it does not need to allow for a further mechanism or a supervisor to decide in real time which strategy to implement. This result is due to the fact that the Fuzzy control system, during its training campaign, has acquired information which enables it to break away from the specific operative conditions and adapt itself suitably, even to situations, within certain limits, not encountered during the training stage.

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