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Simulation and Comparison of a PID Controller for an Anti-Lock Braking System

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Abstract: ***This paper presents the simulation in MATLAB/SIMULINK of an anti-lock braking system (ABS) by means of a one quarter vehicle mathematical model, which simulate the braking dynamics of a car during a sudden braking, in addition a PID control is implemented to control the slip different road conditions. It also compares performance of the proposed controller with an uncontrolled sliding brake system and hysteresis type controller that shows the ability to significantly reduce braking distance and time in addition to controlling the slipping during a sudden braking.***

Keywords: PID controller, hysteresis controller, anti-lock braking system, slip, friction coefficient, braking torque.

1. Introduction

A car continuously varies in status: that is: accelerates, brakes or turns. These phenomena are produced by various forces and the sum of these are called vehicle dynamics. If the sum of all forces is 0 it means that the vehicle is at rest. Otherwise, that is, if the forces involved in the car are different from 0, it will be moving.

In turn, all these forces vary depending on the acceleration, responsible for modifying the speed and direction. For example, the fact of accelerating the car corresponds to a positive acceleration and in case of braking, there is a negative acceleration or deceleration. In normal driving, the vehicle performs as directed by the operator; this is possible as the physical conditions of the road and the vehicle are not exceeded. When these conditions are exceeded, skids, wheel locks and even road exits occur.

The anti-lock braking system aims to prevent tire blockage during abrupt braking. Modern systems not only prevent the wheels from locking, they also maximize the braking forces generated by the tires to prevent the longitudinal slip ratio from exceeding the optimum value [1]. Locking the wheels reduces the braking forces generated by the tires and as a result the vehicle takes longer to stop. In addition, locking the front wheels prevents the driver from being able to maneuver the vehicle during braking [2].

ABS was initially introduced into aircraft to reduce the braking distance on an airplane. Subsequently, this technology was introduced in the design of ground vehicles, due to the ability to assist the user to improve the maneuverability of the vehicles and make them safer [3]. Therefore, ABS has been recognized as an important contribution to road safety. Although it has been attempted for decades, an accurate mathematical model of ABS has not been obtained. Mainly the deficiencies are due to the controller having to operate at an unstable equilibrium point for optimum performance. A small disturbance of the controller input can cause a drastic change in the output. In addition, there are no sensors that accurately identify the road surface and obtain the data for the ABS controller. As for the system parameters, they depend heavily on road conditions and vary over a wide range, so the ABS performance cannot be satisfactory.

Recently, research on anti-lock braking system has been significantly increased to minimize the above-mentioned difficulties by means of control algorithms such as fuzzy logic [4] [5], neural networks [6] and sliding modes [7] [8]. In the automotive industry, hysteresis control methods are mostly used for slip control [9].

Therefore, a PID controller is proposed in this article with the objective of reducing the set-up time and stationary error, adjusting by means of trial and error, and subsequently compared performance with hysteresis controller and a brake system without sliding control checking that the braking time and distance is reduced.

The paper is organized as follows: in section 2 the model of a vehicle quarter for analysis is presented, the design of the controllers is detailed in section 3, section 4 presents the results of the simulation and analysis comparative and conclusions are presented in section 5.

2. Dynamic model

ABS is designed to control the slip rate of the tire, in order to keep it at the optimum operating value, to avoid skidding and loss of maneuverability. Sliding occurs when the angular velocity is higher compared to the vehicle's speed. For this, it is necessary to monitor the angular speed of the tire and the speed of the vehicle, to determine the braking torque that is applied to the wheel and check that the slip and is at the reference value to avoid to avoid a non-slip rate desired.

To simulate the braking dynamics of a vehicle a one-quarter model of vehicle was implemented, this requires making the following assumptions, for the analysis of the movement of the vehicle during braking.

1) The longitudinal dynamics of the vehicle is considered.
2) Movement in lateral direction are not considered in the

analysis.

3) The analysis assumes that the vehicle during the braking process is on a straight road.

According to these assumptions, the simulation of system behavior was performed in MATLAB/SIMULINK using dynamic model presented below.

2.1 Vehicle model

The diagram of the model of a vehicle is shown in Figure 1, where the vehicle speed V is described, and the inertia force of the car is considered, F_i is the force is provided by the engine and transmitted to the tires to move the vehicle. In case of deceleration the braking force applied by the brake system is described by F_f. In the diagram the reaction of the road is considered; the normal force of the car that is given by N and the weight of the vehicle, that is W.

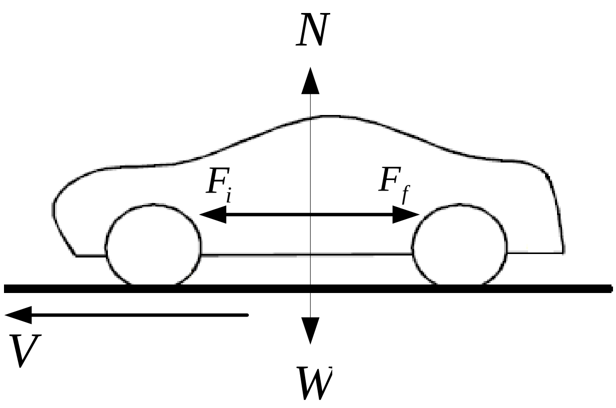

Figure 1: Vehicle model

It is assumed that the vehicle moves in a straight direction in braking conditions, so you can describe the equilibrium equations that govern the system horizontally and vertically, as in (1) and (2).

$$F_f = F_i \tag{1}$$

$$N = W \tag{2}$$

The frictional force between the tire and the road must be equal to the force provided by the engine to stop the vehicle, for longitudinal analysis. The braking force is described in (3).

$$F_f = (\mu)(N) \tag{3}$$

Where μ is the coefficient of friction between the tire and the ground. The normal force, that is, the reaction of the road to the vehicle must be equal to the weight of the vehicle. The weight of the vehicle is described in (4).

$$W = (m_v)(g) \tag{4}$$

Replacing (1) and (4) in (3), (5) is obtained, where the coefficient of friction is μ, the mass of the vehicle is m_v and the force of gravity is g.

$$F_f = (\mu)(m_v)(g) \tag{5}$$

The inertia force F_i, is expressed as the product of the mass of the vehicle m_v and the acceleration of the vehicle as shown in (6). Acceleration can also be expressed as the derivative of the vehicle with respect to time.

$$F_i = m_v \frac{dv_v}{dt} \tag{6}$$

Substituting (5) and (6) in (1), you get (7), which describes the behavior of the vehicle during the braking process.

$$\frac{dv_v}{dt} = \frac{(\mu)(m_v)(g)}{m_v} \tag{7}$$

The simulation in MATLAB / SIMULINK is shown in Figure 2, by means of (7)

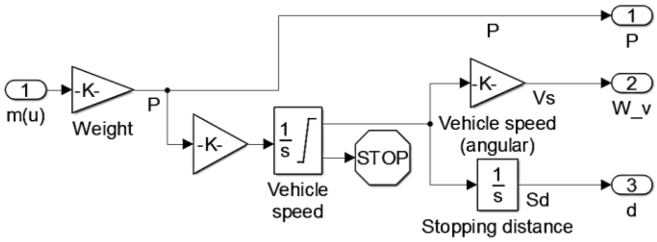

Figure 2: MATLAB / SIMULINK simulation of the vehicle model

2.2 Tire model

Figure 3 shows the tire model during the braking process, the driver applies a pair of torque to the wheels (T_b). The resulting frictional force (F_f) between the wheel and the road generates an opposite torque T_b at the angular velocity of the tire ω_w.

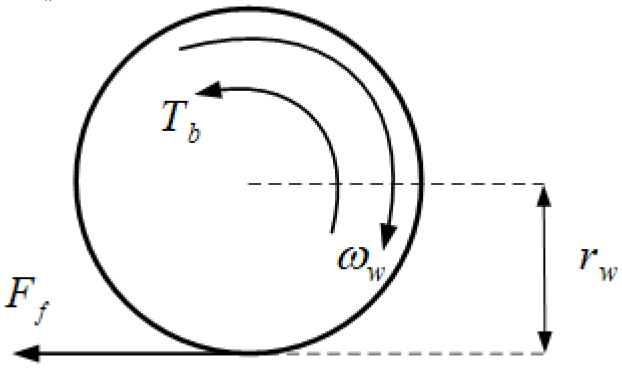

Figure 3: Tire model

To simplify the analysis, the following considerations are taken:

1) The tire is rigid

2) The normal force, that is, the reaction of the road passes through the wheel axis.

With these considerations, no additional torque is added that directly affects the system. Therefore, with the above mentioned, the system equation is shown in (8).

$$\frac{d\omega_w}{dt} = \left[\frac{1}{J_w}(F_f)(r_w)\right] - T_b \tag{8}$$

Where T_b is the torque applied by the braking system in Nm, the braking force is defined by F_f in N, the radius of the tire r_w in m, the moment of inertia J_w in Kgm^2 and the angular velocity of the tire ω_w in rad/s. The MATLAB / SIMULINK simulation of the tire was done through (8) and is shown in Figure 4.

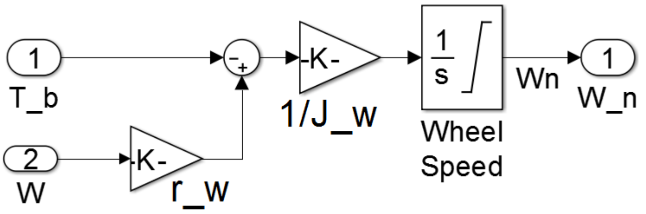

Figure 4: MATLAB/SIMULINK simulation of the tire model

2.3 Wheel Slip

The slip is defined as the difference of the tire speed and the car speed, this variable is important for vehicle braking control, because the higher the slip rate with respect to the reference value, the vehicle will skid on the road, and the user will have a greater chance of losing control over the vehicle, this type of circumstance can be avoided by controlling the slip. The ABS has the main objective of ensuring that the wheel slip is approximately in a range of 20% slip rate, which is suitable for most road conditions. The slip rate during the braking stage can be expressed as shown in (9).

$$\lambda = 1 - \frac{\omega_w}{\omega_v} \tag{9}$$

where ω_v is the equivalent angular speed of the vehicle as shown in (10)

$$\omega_w = \frac{v_v}{r_w} \tag{10}$$

Figure 5 shows the simulation of the slip equation in MATLAB / SIMULINK.

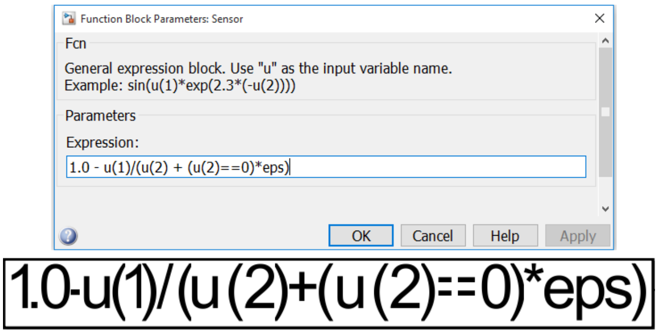

Figure 5: Simulation in MATLAB / SIMULINK of the wheel slip.

2.4 Friction Coefficient

The coefficient of friction between the wheel and the road depends on several factors such as: wheel slippage, vehicle speed, type of road surfaces and the environmental conditions (humidity, temperature). During braking, if the tire slip is 100%, the tire will stop, but it is possible that the vehicle will remain in motion, due to inertia, otherwise, when there is 0% slip ratio, the tire and the vehicle will have exactly the same speed and will stop at the same time. So the optimum friction coefficient, in real situations, is obtained when the wheel slip is around 20%

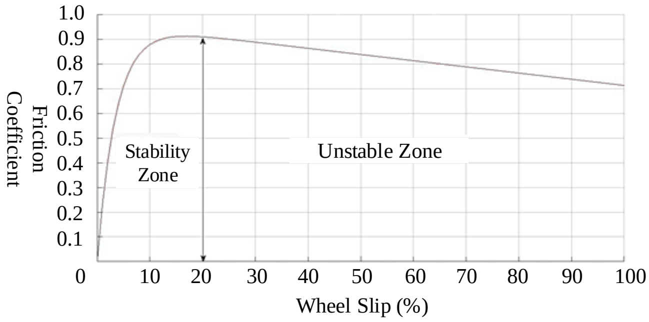

Figure 6: Graph of friction coefficient stability

The variation in the friction coefficient function with respect to the longitudinal sliding of the wheel is shown in Figure 6. The first part of the curve is called the stable zone and the second part is designated the unstable zone.

In the braking and acceleration processes, small sliding values are developed in the stable zone so that an increase in the adhesion to the road can be used. In the unstable zone, an increase in slippage usually causes an adhesion reaction.

When braking, a wheel is locked in a few ms, when accelerating, the moment of excess impulse causes an increase in the revolutions of one or all of the propellant wheels and these are blocked. To model the coefficient of friction there are static friction models that are generally called force-slip models. These models depend on the speed of the vehicle and the changes and characteristics of the pavement.

In this case, the model proposed by Burckhardt is used for the coefficient of tire-paver friction which is as shown in (11)

$$\mu(\lambda) = A(B(1 - e^{-C\lambda}) - D\lambda) \tag{11}$$

A, *B*, *C*, and *D* are coefficients that represent the friction values for different road states, obtained through experimental data, which allows us to know the behavior of the tires in these road conditions. Next, in Table 1, the coefficient values are shown for different types of road.

Table 1: Burckhardt coefficients according to the road type

	Road type			
	Dry Concrete	*Wet Concrete*	*Snow*	*Ice*
A	0.9	0.7	0.3	0.1
B	1.07	1.07	1.07	1.07
C	0.2723	0.5	0.1773	0.83
D	0.0026	0.003	0.006	0.007

By (11) and the values of the Burckhardt coefficients shown in Table 1, the variation in the friction coefficient is determined with respect to the percentage of tire slip, which can be seen in Figure 7.

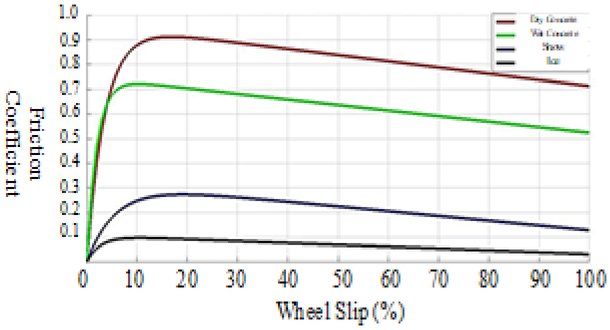

Figure 7: Graph of sliding behavior by Burckhardt model for different road

The maximum value of the coefficient of friction decreases considerably on snow or ice covered surfaces. Even if the value of the coefficient of friction is not significant. For example, in case of a dry road the coefficient values reach their maximum, in intermediate states, on wet asphalt the coefficient is reduced, although this type of condition has the particularity that the coefficient of friction depends largely measured the speed of the vehicle. The MATLAB / Simulink simulation of the friction coefficient model is shown in Figure 8

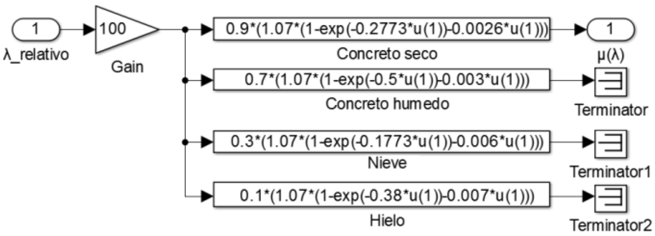

Figure 8: MATLAB / SIMULINK simulation of the friction coefficient

2.5 Actuator Dynamic Model

The hydraulic system is modeled as a first-order transfer function, with an amplification factor *k* and a torque time *t*, as shown in (12).

$$G(s) = \frac{k}{t_s + 1} \qquad (12)$$

The transfer function represents the delay associated with the hydraulic lines of the brake system, in addition to allowing to control the rate of change of the brake pressure that will depend on the difference between the actual slippage of the system and the desired slippage. The simulation in MATLAB/SIMULINK is shown in Figure 9.

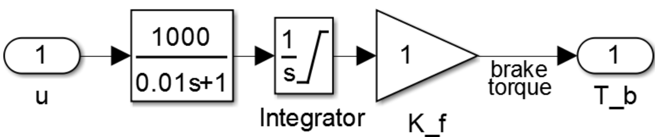

Figure 9: Simulation in MATLAB / SIMULINK of the hydraulic actuator

3. Controller Design

This section presents scenarios for braking system simulation: Open-Loop braking system, ABS brake system with hysteresis controller and ABS brake system with PID controller.

3.1 Brake system with open-loop control.

A braking system without slip control can be defined as an open loop control, because it does not receive any information or feedback on the state of the variable, in this case the slip rate, in Figure 10 the blocks diagram is shown

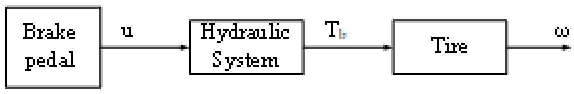

Figure 10: Block diagram of an open loop system of a braking system

The operator, when braking, will press the brake pedal, depending on the force applied *u*, the hydraulic system will act accordingly by applying a braking torque T_b to the tire, decreasing its angular speed ω abruptly. In this case, it does not feedback with information about the slip rate.

3.2 Hysteresis Controller

Figure 11 shows the block diagram of a closed loop control that represents the dynamics of the vehicle during the straight-line braking process. In this case the controller is hysteresis type. The hysteresis controller is based on the calculation of the error between the actual slip and the desired slip and adjusts the desired slip to the slip value of the friction-slip coefficient curve, reaching an optimum value for the minimum braking distance.

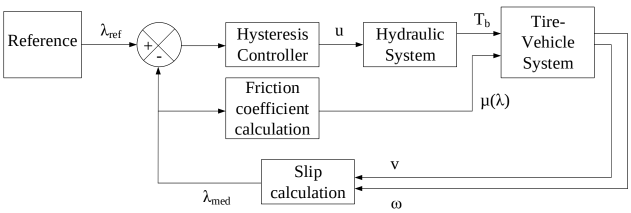

Figure 11: Block diagram of ABS system with hysteresis controller

The control signal, the braking torque, changes between a maximum value and a minimum value as shown in (13), to maintain the slippage in the desired operating region, i.e. λ_{rel}=0.2. Figure 12 shows its design in MATLAB/SIMULINK.

$$u(t) = \begin{cases} u(t)_{max} & if \quad e(t) > 0 \\ u(t)_{min} & if \quad e(t) < 0 \end{cases} \qquad (13)$$

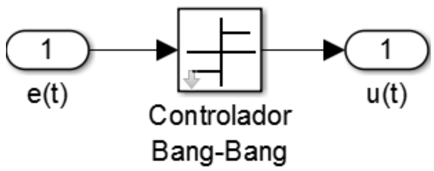

Figure 12: MATLAB/SIMULINK simulation of hysteresis controller

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3.3 PID Controller

The block diagram of a closed loop PID controller for an anti-lock braking system is shown in Figure 13.

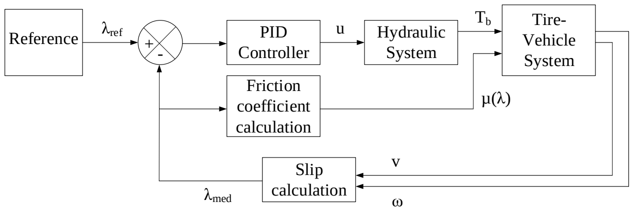

Figure 13: Block diagram of ABS system with PID controller

PID controller is one of the most used strategies at the industrial level. The utility of PID control lies in its general applicability to most control systems.

In the field of process control systems, it is well known that PID control schemes have proven useful in providing satisfactory control, although in many situations they may not provide optimal control.

The error signal *e(t)* is used to generate the proportional, integral and derivative action, with the signals resulting from the difference of slip λ_{rel} and slip measured λ_{med}, to form the control signal *u(t)* applied to the model of the plant. The description of the PID controller is shown in (14)

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (14)$$

Where u (t) is the control signal for the plant model, the error signal e (t) is defined in (15):

$$e(t) = \lambda_{rel} - \lambda_{med} \qquad (15)$$

The relative slip λ_{rel} is the reference input signal and the measured slip λ_{med} is the tire slip monitored during the braking process.

The behavior of the PID controller is determined by the K_p, K_i and K_d values. The process of selecting the gains was carried out to summate it according to the needs of the ABS. Using (15) and (16), the PID controller was simulated in MATLAB/SIMULINK shown in Figure 14.

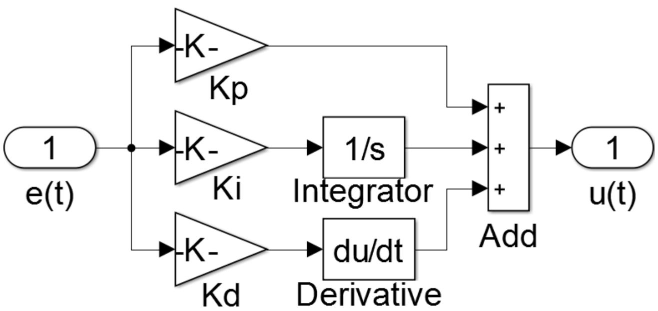

Figure 14: MATLAB/SIMULINK simulation of PID controller

4. Results and Discussion

For ABS modeling in Matlab / Simulink, it is necessary to determine the system parameters as defined in Table 2.

Table 2: ABS system parameters

Parameter	Description	Value
m_v	Vehicle mass	500 Kg
J_w	Moment of inertia	1.2 Kgm^2
r_w	Tire radius	0.28 m
V_0	Initial car speed	28 m/s
g	Gravitational constant	9.81 m/s^2
T_{bmax}	Braking pressure	1500 Nm
K	Amplification factor	1000
T	Constant time	0.01
λ_{rel}	Relative slip	0.2

The results shown are dry asphalt road, so Burckhardt coefficients are for this type of road.

4.1 Simulation results of open loop braking system.

In the braking system with open loop control, the braking torque increases proportionally according to the maximum braking force value T_{bmax} = 1500 Nm, which was reached at 1.5 s and is held until the vehicle stopped at 16 s, as shown in Figure 15.

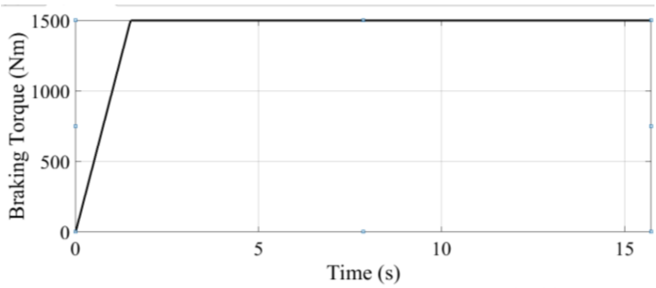

Figure 15: Open loop braking torque performance

As the braking torque increases, until it reaches its maximum value, the slip increases to a 100% rate, the tire will imminently lock at approximately 6.5 s, as shown in Figure 16.

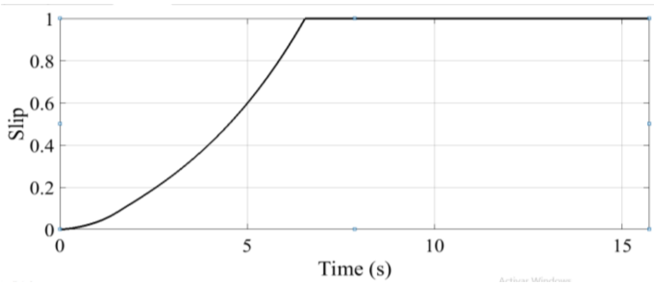

Figure 16: Slip behavior of open loop braking system.

Figure 17 shows the behavior of the friction coefficient without ABS, reaches a maximum point of 0.9 at 2 s, so that the tire speed will decrease sharply until it is blocked when reaching the maximum slip rate because it remains the unstable zone in 0.7 of friction coefficient.

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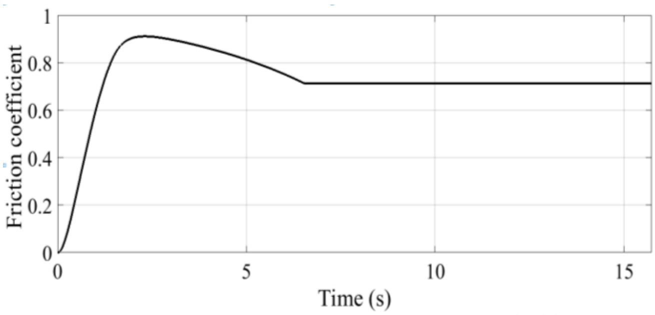

Figure 17: Friction coefficient performance in open loop

When the highest slip rate is reached at 6.5 s, the angular velocity of the tire reaches 0, before the vehicle is at rest. In addition, it is notable that the speed gradient changes after the wheel lock. This occurs because the friction force is reduced and the braking distance increases, as shown in Figure 18.

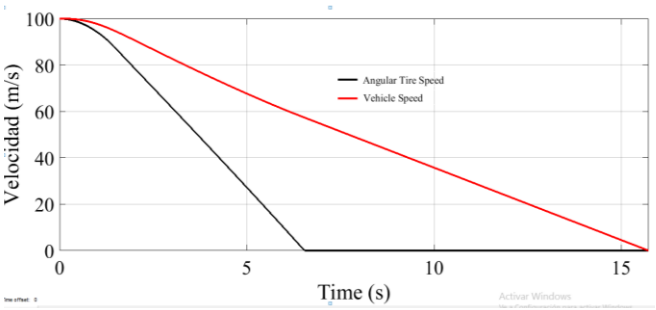

Figure 18: Behavior and comparison of tire and vehicle speeds in open loop brake system

Figure 19 shows the behavior of the braking distance of the vehicle, which enters the beginning of the emergency braking process until the car stops at 17 s, travels a distance of 250 m.

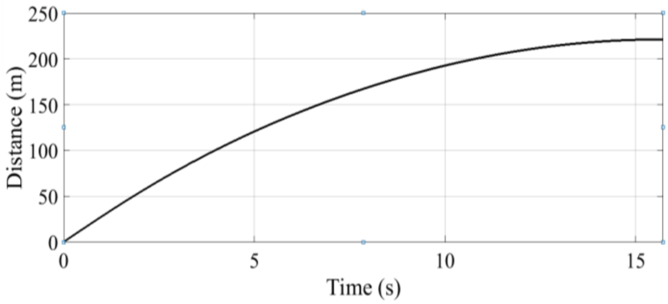

Figure 19: Braking distance with open loop braking system

4.2 Simulation results of ABS system with hysteresis type controller

By controlling the sliding by means of a hysteresis type controller, the braking torque is modulated to maintain the sliding at the recommended reference value (λrel = 0.2). When the tire speed reaches a minimum value, the braking torque is no longer controlled and increases to the maximum value, as shown in Figure 20.

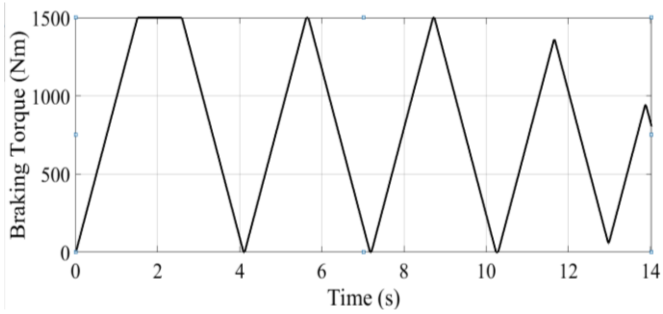

Figure 20: Braking torque behavior with hysteresis type controller

The wheel slip is regulated around 0.2 or 20%, as shown in Figure 21, which keeps it in the optimum operating range, so the braking torque is necessary to prevent the car from skid and maintain maneuverability for the user. When approximately 2 m / s is reached in a time of 14 s, the ABS control is no longer necessary, so the maximum braking torque is applied and consequently the slip is 100%.

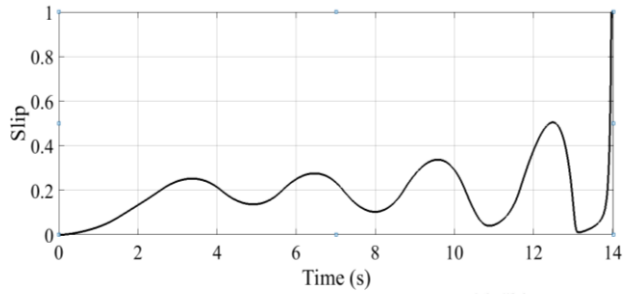

Figure 21: Sliding behavior with hysteresis controller

By controlling the slip as shown in Figure 22 and keeping it at the thresholds of efficient operation, the coefficient of friction is maintained at a maximum value of 0.9, which provides greater frictional force between the wheel and the road, and helps decrease the braking distance in a shorter time. It decreases dramatically, at the time you need less braking force until the vehicle stops.

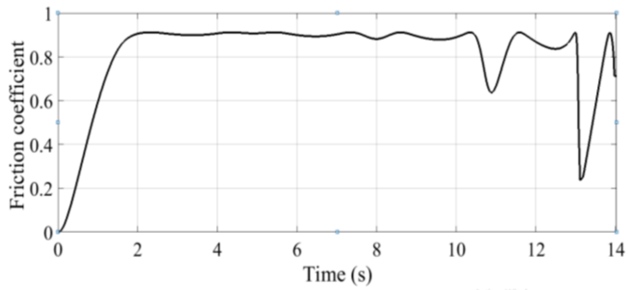

Figure 22: Friction coefficient performance with hysteresis controller

In Figure 23 it shows that when the ABS is active, the wheel is prevented from locking. Making the tire have an optimum slip value provides greater friction between the wheel and the pavement, therefore, it improves the maneuverability of the operator, by maintaining the speed of the vehicle and the tire in the operating ranges to prevent slippage. With the hysteresis controller, the vehicle stops at 14 s.

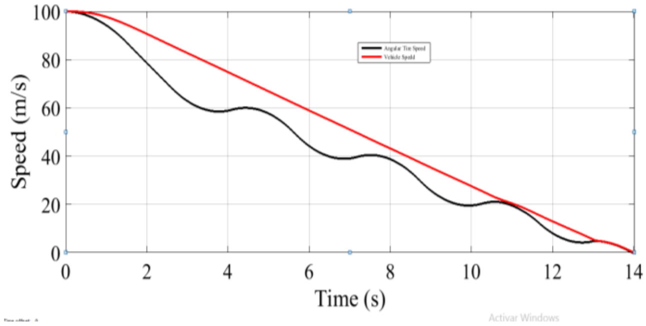

Figure 23: Behavior and comparison of tire and vehicle speeds in the hysteresis type controller brakes

The vehicle stops at 200 m, as shown in Figure 24, prevents the wheels from locking, allowing the unit to reduce the braking distance and avoid vehicle skidding.

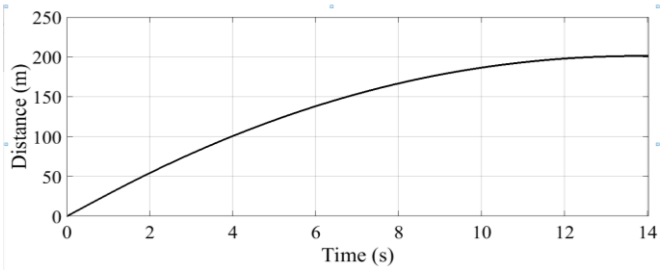

Figure 24: Braking distance with hysteresis controller

4.3 Simulation results of ABS system with PID controller

The design of the PID controller was realized through (13), and its design was shown above in Figure 13, for this it was necessary to determine the values of K_p, K_i and K_d and these are shown in Table 3.

Table 3: Values of the simulation parameters of the PID controller for the ABS braking system

Parameter	Value
K_p	100
K_i	0.1
K_d	0.001

Figure 25, shows the results of a braking torque with a PID controller that limits it to a maximum 1000 Nm and a lower limit of approximately 400 Nm, during the abrupt braking process, which controls the slip rate over a range of 0.2 operation, on a dry asphalt surface.

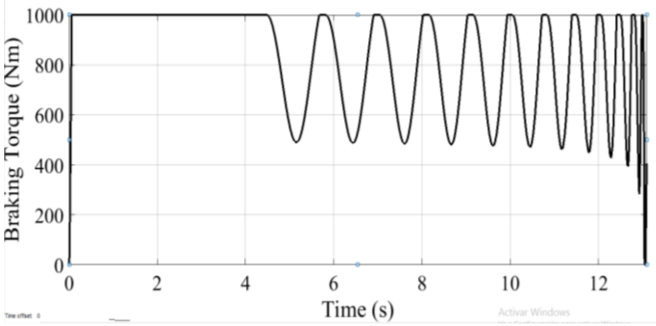

Figure 25: Braking torque behavior with PID controller

The sliding behavior is shown in Figure 26, it remains stable in the reference range set at 0.2, so the tire tends to have less chance of skidding. When the slip index trips at approximately 12.7 s, it is because the tire speed reaches the minimum values, in which the control of the slide is not necessary, so, to stop the tire, all the tire is applied. braking force necessary to stop it since there is no possibility of skidding.

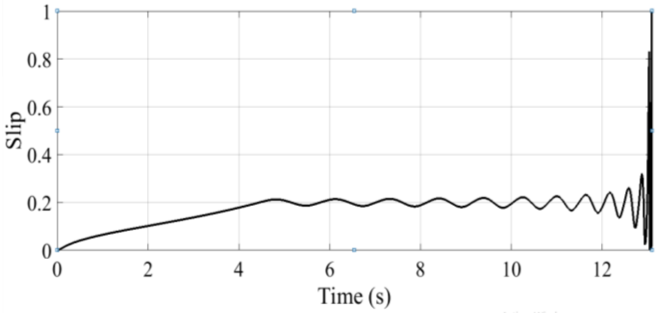

Figure 26: Sliding behavior with PID controller

The coefficient of friction remains at 0.9, but does not vary over time, as it does in hysteresis controller simulations. As shown in Figure 27, it is quite stable, since the measured slip is very close to the reference slip and the friction coefficient very close to the ideal for dry pavement with which it has been designed, so the user will have the vehicle maneuverability despite emergency braking.

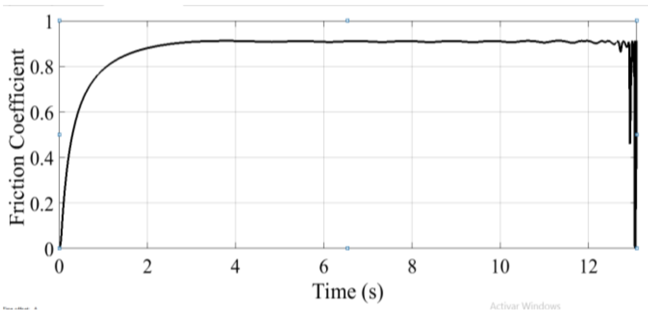

Figure 27: Friction coefficient behavior with PID controller

In the same case of the behavior of the braking torque and the sliding, when the sliding rate does not need to be controlled, because the speeds of the tire and the car reached the operating ranges in which the ABS is not necessary, the braking force will be applied to its maximum.

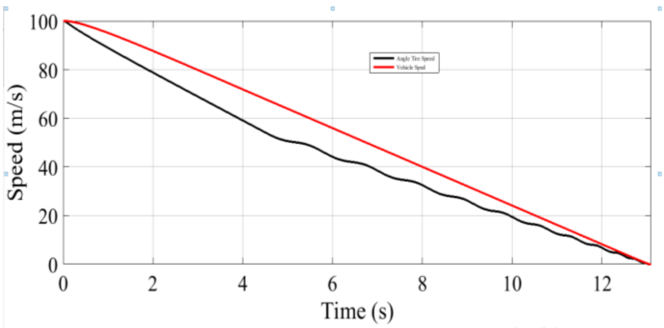

Figure 28: Behavior and comparison of tire and vehicle speeds in brake system with PID controller

The results of Figure 28 show that the braking performance of the ABS system controlled through a PID significantly improved, reduced the braking time to 13 s and consequently also decreased the braking distance to 189 m, as can be seen in the Figure 29.

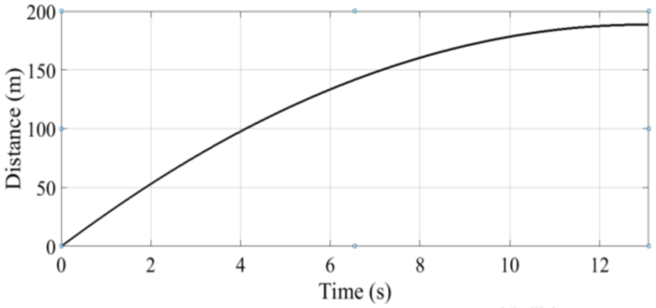

Figure 29: Braking distance behavior with PID controller

4.4 Comparison of control systems

In the open loop control system, the slip rate is not controlled, so, regardless of the type of road, the value of this will be 1, that is, 100%, the main objective of maintaining the rate of 20% slip is not fulfilled because the maximum braking torque is applied, which in the case of study is 1500 Nm, as a consequence the time and the braking distance will be very large.

Table 4 shows the results of the simulations carried out in Matlab in 4 different scenarios: Dry concrete, wet concrete, snow and ice.

With the data obtained, it is analyzed that the road with higher coefficient of friction (dry concrete, wet concrete) reduce their braking time and distance considerably compared to surfaces with lower coefficient of friction (pavement covered with ice or snow), so that the loss of maneuverability is more likely on these surfaces.

Table 4: Simulation results in open loop in different road conditions

	Type of Road			
	Dry concrete	Wet Concrete	Snow	Ice
Slip rate	1	1	1	1
Braking time	15.7 s	21.1 s	86.2 s	350 s
Stopping distance	221 m	289 m	1170 m	4825 m
Braking torque	1500 Nm	1500 Nm	1500 Nm	1500 Nm

In the case of the hysteresis controller, the data obtained are represented in Table 5. The slip rate compared to the open loop system remains in the ideal operating range of 20%, depending on the type of road and the coefficient. The friction range will be controlled over a wider range, on road with a smaller coefficient the oscillation range will be lower, since there is a greater chance that the slip rate will shoot faster than on road with a higher coefficient of friction. The system shows improvement with respect to the system that does not control the sliding, and this can be sustained in the reduction of braking time and distance.

Table 5: Simulation results with hysteresis type controller in different road conditions

	TYPE OF ROAD			
	Dry concrete	Wet Concrete	Snow	Ice
Slip rate	0.27 – 0.1	0.28 – 0.16	0.21 -0.19	0.202 – 0.198
Braking time	4.1 s	2.4 s	1.5 s	0.3 s
Stopping distance	14 s	17.4 s	43 s	126 s
Braking torque	201 m	245.5 m	611 m	1780 m

Finally, the performance of the PID controller is shown in Table 5, where the slip control range is close to 20%, in all types of road.

The distance and the braking time are smaller compared to the previous cases, since the applied braking force is ideal for maintaining a small error, which shows that the performance of the PID controller is superior to the brake systems in open loop and commercial controllers type Bang-Bang.

Table 6: PID controller simulation results in different road conditions

	TYPE OF ROAD			
	Dry concrete	Wet Concrete	Snow	Ice
Slip rate	0.18-0.22	0.17 – 0.23	0.19–0.21	0.197–0.203
Braking time	4.5 s	3.5 s	2.2 s	1.9 s
Stopping distance	13.1 s	16.5	30 s	124 s
Braking torque	189 m	232 m	547 m	1745 m

5. Conclusions

In this article, a PID controller for an ABS braking system was proposed, comparing the results with an open loop braking system and a commercial use controller in the automotive industry such as hysteresis type. This was done by simulating the behavior of the system in MATLAB/ SIMULINK.

With the results obtained by simulating the 3 scenarios proposed in different types of road, the performance of the PID controller, the slip rate in the operating ranges by applying the braking force necessary to avoid skidding of the vehicle during abrupt braking.

It was shown that the distance and braking time was reduced with a PID controller compared to the open loop system and the hysteresis type controller.

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