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# Simulation of the ABS Braking System Behavior in Critical Faults

**Angel Paleta Blancas[1], Mario Eduardo Leal Lopez[2], Roberto Morales Caporal[3], Rafael Ordoñez Flores[4]**

[1234]Adscritos al Tecnológico Nacional de México/Instituto Tecnológico de Apizaco, División de Estudios de Posgrado e Investigación, Tzompantepec, Tlaxcala, 90300.

**Abstract:** ***This article presents the simulation of critical faults of the anti-lock braking system (ABS) using a mathematical model of a vehicle room, which simulates the dynamics of a car during rough braking with abnormal system operation. For this, 5 scenarios were proposed: system with normal operation, fault in the hydraulic actuator, fault in the ECU, that is, deviation in the system, fault in the vehicle speed sensor and fault in the tire speed sensor. These proposed scenarios identify events and factors that degrade the operation of the system, in this case the ABS system increases the distance and the braking time that can cause the loss of control of the vehicle. Finally, an analysis and comparison of the scenarios is carried out***

**Keywords:** ABS System, fault, fault model, slip, deviation, Friction Coefficient

## 1. Introduction

From the invention of the internal combustion engine to the present, the automotive sector has grown to position itself in one of the most important industrial sectors, so the car has become a primary product in the daily life of the human being.

From the invention of the internal combustion engine to the present, the automotive sector has grown to position itself in one of the most important industrial sectors, so that the automobile has become a primary product for humanity.

ABS braking has become a primary element for cars, so a fault in this system is dangerous. In the event of a fault and braking in an emergency, it can cause overturns and accidents, which in the least case would cause damage to the vehicle, becoming economic losses for the user. In case of malfunction in the system and stopping in an emergency, it can cause overturns and accidents, which in the least case would cause damage to the vehicle, becoming economic losses for the user.

A method to improve the control systems according to [1] is through the fault diagnosis, which will allow to locate a deviation of the system in early stages and avoid by an abnormal state to later take corrective actions in the system. There is research on ABS control systems that seek to reduce the effect of faults, but focus on the design of robust control systems, that is, they are designed to make them immune to certain disturbances or changes in system dynamics, as in [2] that seeks to guarantee the stability of the antilock brakes, applying robust control for two uncertain parameters: the car speed and the coefficient of friction.

In the investigation of [3] Kalman Extended Filter is presented for the estimation of states for the variables of vehicle speed, tire and internal parameters, reducing the appearance of noise in the system.

According to [4] they developed by means of sliding modes a control that estimates and compensates the effects of the uncertainties and disturbances of the ABS for the calculation of the slip rate. In [5] a state observer was developed to estimate the state of the system and the faults in the tire speed sensor ensuring robustness against external disturbances, demonstrating the ability to counteract the effect of the sensor fault.

The investigations on the diagnosis of faults focus on a single deviation of the system, designing robust controllers to reduce the effect of faults or external noise that affect the operation of the ABS system, however, it is of interest to improve these systems through study of multiple faults, since theoretically it facilitates the implementation of conventional methods of detection of faults in addition to improving the sensitivity of detection. This document implements a fault model for the ABS brake system to characterize critical faults and analyze the system's behavior in a fault state. For this, 4 critical system faults are proposed and simulated through Matlab/ Simulink.

This document is organized as follows: in section II the theory of faults in a control system is presented, in section III the dynamic model of an ABS braking system is presented, in section IV a model is proposed of faults through the 4 critical faults of the ABS system, the results of the simulation of the braking system without fault and the fault model are presented in section V.

## 2. Faults in a Control System

A fault in a dynamic system is a deviation from the structure or parameters of the system in a normal operating situation as shown in Figure 1. There are 3 different types of deviations in a control system [6] which are:

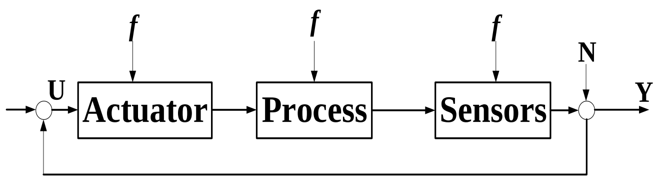


**Figure 1:** Types of fault in a control system.

**Actuators fault:** It is one that can be seen as any deviation from the equipment that drives the system, for example, a fault in the electromechanical actuator for a diesel engine.

**Sensor fault:** Deviations in sensor readings have substantial errors. That is, measurements that no longer correspond to the required physical parameters.

**System fault:** Also called component fault. It is the one that occurs when some changes in the system make the dynamic relationship invalid. That is, basically the variations in the system parameters

To simulate any of the above faults, a mathematical model is determined that will describe a given fault in a system and there are two ways to represent them: additive and multiplicative [7], as shown in Figure 2.

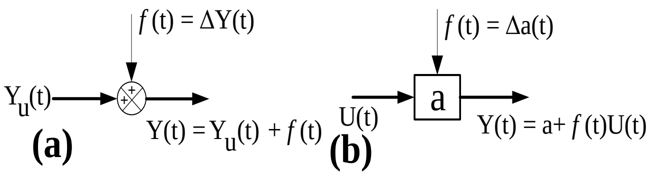


**Figure 2:** Fault modeling a) Additive fault b) Multiplicative fault.

As shown in Fig. 2(a), the signal changes are additive faults, because a variable $Y_u(t)$ is changed by a sum with f(t), that is in (1)

$$Y(t) = Y_u(t) + f(t) \quad \textbf{(1)}$$

The parameter changes are multiplicative faults as shown in Fig. 2(b), the variable U(t) is multiplied by f(t), that is in (2)

$$Y(t) = a + f(t)U(t) \quad \textbf{(2)}$$

Additive faults are adequate to represent sensor fault in the system, while component and actuator faults are multiplicative faults. In practical applications, some faults have the effect of deviations in the dynamic parameters of the system. The behavior of the faults in time, are shown in Figure 3.

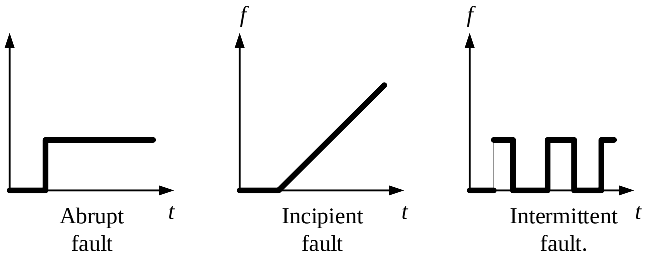


**Figure 3:** Time dependency of faults

**Abrupt fault:** Instantly occur often as a result of hardware damage. These can be dangerous, since they affect the performance and stability of the system.

**Incipient fault:** It is a slow change, as a result of the aging system. These are difficult to detect due to their slow appearance over time, although they are much less severe than abrupt faults.

**Intermittent fault:** These appear and disappear repeatedly in the system, an example is a partially damaged wiring in an electrical panel.

## 3. Dynamic model of ABS System

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.

### 3.1 Vehicle model

The diagram of the model of a vehicle is shown in Figure 4, 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 $W$.

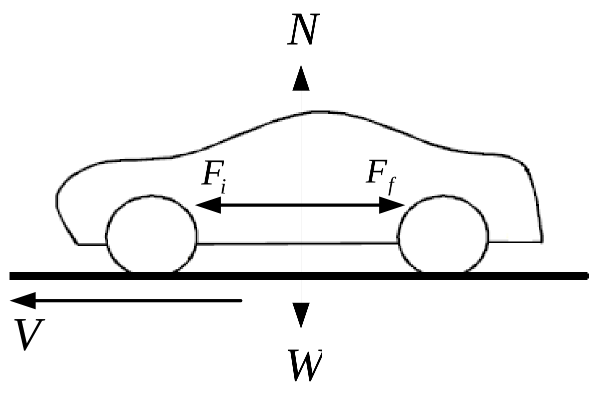


**Figure 4:** Vehicle model

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 (3) and (4).

$$F_f = F_i \tag{3}$$

$$N = W \tag{4}$$

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 (5).

$$F_f = (\mu)(N) \tag{5}$$

Where $\mu$ 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 (6).

$$W = (m_v)(g) \tag{6}$$

Replacing (3) and (6) in (5), (7) is obtained, where the coefficient of friction is $\mu$, the mass of the vehicle is$m_v$ and the force of gravity is $g$.

$$F_f = (\mu)(m_v)(g) \tag{7}$$

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 (8). Acceleration can also be expressed as the derivative of the vehicle with respect to time.

$$F_i = m_v \frac{dv_v}{dt} \tag{8}$$

Substituting (7) and (8) in (3), you get (9), which describes the behavior of the vehicle during the braking process.

$$\frac{dv_v}{dt} = \frac{(\mu)(m_v)(g)}{m_v} \tag{9}$$

The simulation in MATLAB / SIMULINK is shown in Figure 5, by means of (9).

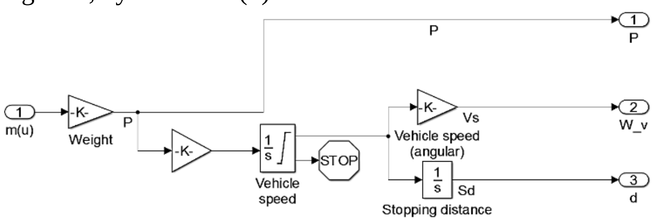


**Figure 5:** MATLAB / SIMULINK simulation of the vehicle model

### 3.2 Tire model

Figure 6 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 $\omega_w$.

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.

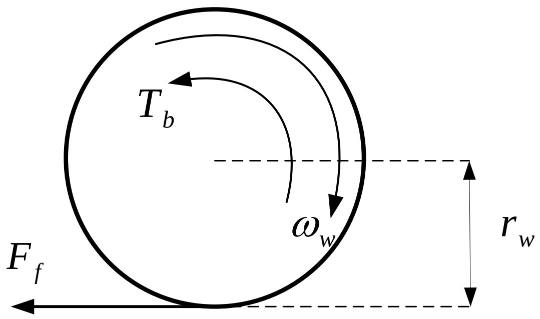


**Figure 6:** Tire model

With these considerations, no additional torque is added that directly affects the system. Therefore, with the above mentioned, the system equation is shown in (10).

$$\frac{d\omega_w}{dt} = \left[\frac{1}{J_w}(F_f)(r_w)\right] - T_b \tag{10}$$

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 $\omega_w$ in rad/s.The MATLAB / SIMULINK simulation of the tire was done through (8) and is shown in Figure 7.

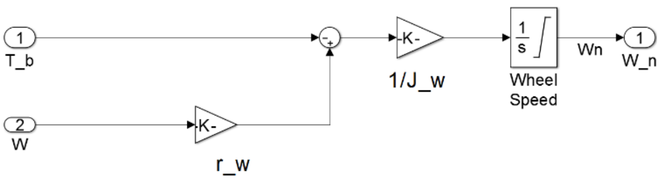


**Figure7:** MATLAB/SIMULINK simulation of the tire model.

### 3.3 Slip model

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 (11).

$$\lambda = 1 - \frac{\omega_w}{\omega_v} \tag{11}$$

where $\omega_v$ is the equivalent angular speed of the vehicle as shown in (12)

$$\omega_w = \frac{v_v}{r_w} \tag{12}$$

Figure 8 shows the simulation of the slip equation in MATLAB / SIMULINK.

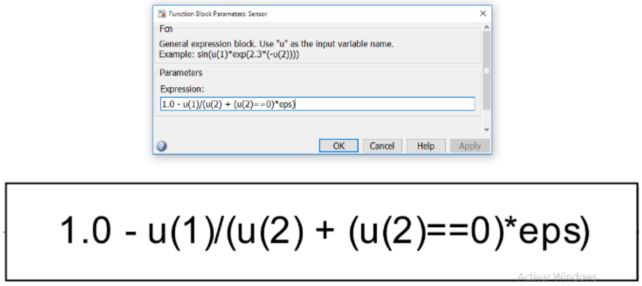


**Figure 8:** Simulation in MATLAB / SIMULINK of the wheel slip

### 1.4 Friction Coefficient

In this case, the model proposed by Burckhardt is used for the coefficient of tire-paver friction which is as shown in (13).

$$\mu = A(B(1 - e^{-C\lambda}) - D\lambda \qquad (13)$$

A, B, C, and Dare coefficients that represent the friction values for different road states, obtained through experimental data, which allowsto 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 (13) 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 9.

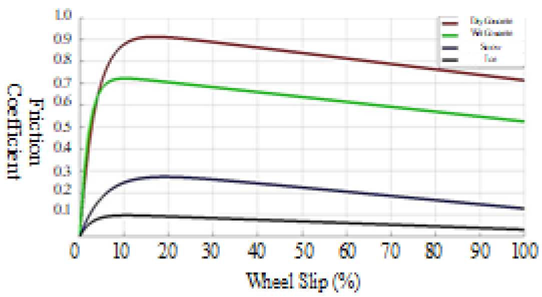


**Figure 9:** Graph of sliding behavior by Burckhardt model for different road.

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 10.

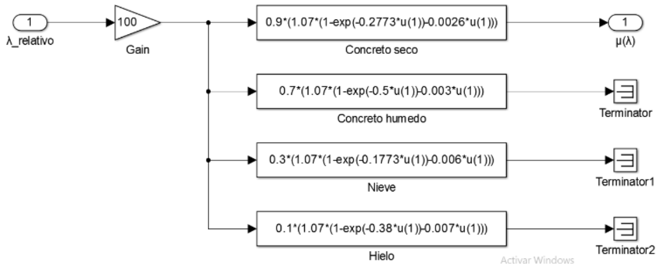


**Figure 10:** MATLAB / SIMULINK simulation of the friction coefficient

### 1.5 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 (14).

$$G(s) = \frac{k}{t_s + 1} \qquad (14)$$

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 11.

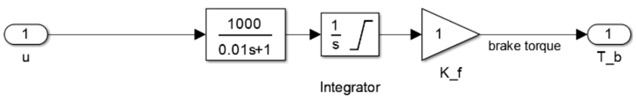


**Figure 11:** Simulation in MATLAB / SIMULINK of the hydraulic actuator.

### 1.6 PID Controller

In this work a PID controller is presented, this is described in Figure 12, which shows a closed-loop controller block diagram.

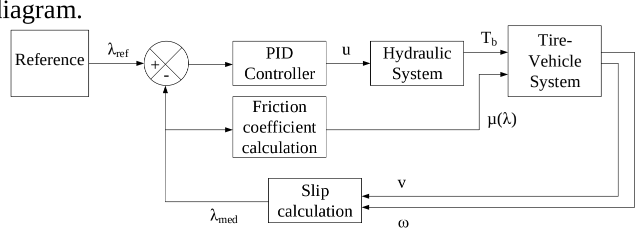


**Figure 12:** Block diagram of ABS system with PID controller.

PID controller is one of the most used strategies atthe 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 $\lambda_{rel}$ and slip measured $\lambda_{med}$, to form the control signal *u(t)* applied to the model of the plant. The description of the PID controller is shown in (15)

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (15)$$

Where u (t) is the control signal for the plant model, the error signal e (t) is defined in (16):

$$e(t) = \lambda_{rel} - \lambda_{med} \qquad (16)$$

The relative slip $\lambda_{rel}$ is the reference input signal and the measured slip $\lambda_{med}$ 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 13.

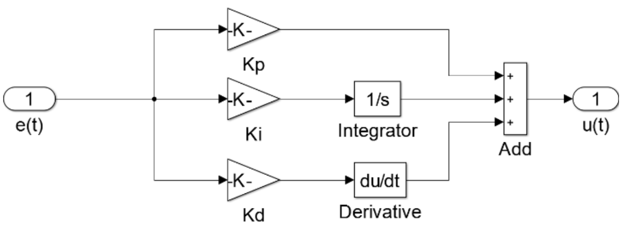


**Figure 13:** MATLAB/SIMULINK simulation of PID controller

## 4. ABS System Fault Model

From [8], [9], [10] and [11] the critical faults in the system were determined, that is, those deviations from the system that, in case of not being isolated and detected, also do not take corrective actions and affect the effectiveness of the system.Among the existing critical faults are: leakage in the hydraulic system, fault to calculate the slip rate/internal error in the electric control unit (i.e. damage or malfunction in the ECU), speed sensor fault of the vehicle and fault in the angular speed sensor of the tire.

Table 2 shows the critical faults and how they have been called in variables each one, since they will later be used to determine the equations of fault of the ABS system.

**Table 2:** Nomenclature Critical Fault in ABS system.

| Critical Fault | Fault Variable |
|---|---|
| Leakage in the hydraulic system | $f_f$ |
| Fault to calculate the slip rate/internal error in the electric control unit | $f_\lambda$ |
| Speed sensor fault of the vehicle | $f_v$ |
| Angular speed sensor fault of the tire. | $f_\omega$ |

Considering the mathematical model of the ABS system presented above and the critical faults of the ABS, the fault model shown in (17), (18), (19) and (20) was established. Another aspect to take into account is that the faults are modeled as additive in the case of sensors and multiplicative for system fault and / or actuator fault. Also when simulating these deviations are simulated as abruptfaults.

The leakage in the hydraulic system was modeled as a fault in the actuator, that is a multiplicative type fault, as shown in (17). The simulation of the fault in Matlab/Simulink is shown in Figure 14.

$$G(s) = \left(\frac{k}{t_s + 1}\right)\left(f_f\right) \qquad (17)$$

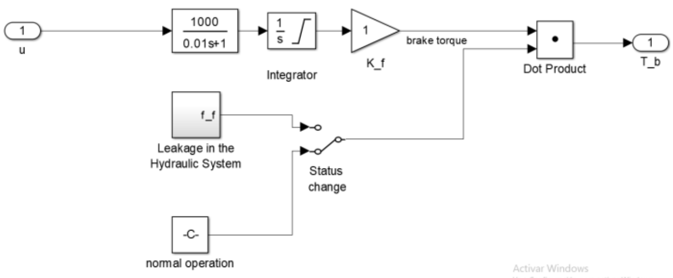


**Figure14:** Simulation in Matlab / Simulink of fault: “leakage in the hydraulic system”

The fault to calculate the slip rate/internal error in the electric control unit was modeled as fault in the system, that is multiplicative type fault, as shown in (18). The simulation of the fault in Matlab/Simulink is shown in Figure 15.

$$\mu = \left(A\left(B\left(1 - e^{-C\lambda}\right) - D\lambda\right)\left(f_\lambda\right) \qquad (18)$$

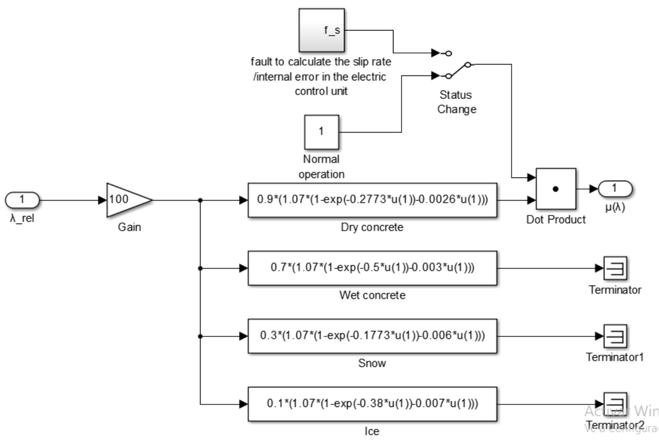


**Figure15:** Simulation in Matlab / Simulink of fault to calculate the slip rate/internal error in the electric control unit

In (19) and (20) we have the equations of fault of the angular speed of the tire and the speed of the vehicle respectively. The variables $y_{v_v}$ and $y_{\omega_w}$correspond to the measured vehicle speed and the measured angular speed of the tire respectively. In both equations they are considered additive, since they are faults in the sensors. The simulation of the faults in Matlab/ Simulink is shown in Figure 16.

$$y_{v_v} = v_v + f_v \qquad (19)$$

$$y_{v_v} = v_v + f_v \qquad (20)$$

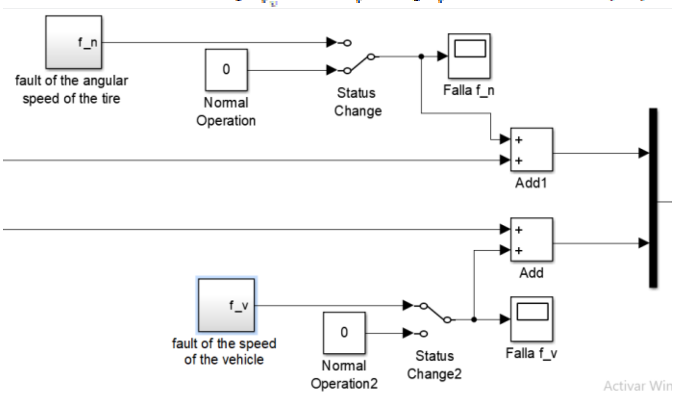


**Figure 16:** Matlab / Simulink simulation of speed sensor faults: tire and vehicle

## 5. Results and Discussion

For ABS modeling in Matlab/Simulink, it is necessary to determine the system parameters as defined in Table 3.

**Table 3:** 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 |
| $\lambda_{rel}$ | Relative slip | 0.2 |
| $K_p$ | Proportional gain | 100 |
| $K_i$ | Integral gain | 0.1 |
| $K_d$ | Derivative gain | 0.001 |

In this work, the results of the simulation of the ABS braking system of 4 different cases are compared: system with normal operation, that is, without faults; fault: leak in the hydraulic unit, fault in the ECU/slip calculation error, fault of the vehicle speed sensor, fault of the tire's angular speed sensor. Another aspect to take into account, is that the simulations presented are in dry terrain, because the results on other types of roads are similar.

In Figure 17 it shows that when the ABS is active, the wheel is prevented from locking. Making the tire have an optimum slip value, that is 0.2, provides greater friction between the wheel and the pavement, therefore, improves operator maneuverability, maintaining vehicle and tire speed in the operating ranges to prevent slippage. Table 4 shows the comparison of the distance and braking time of the ABS system without fault and ABS system with injection of critical faults. The braking time was 13 seconds and the braking distance of 183.2 meters.

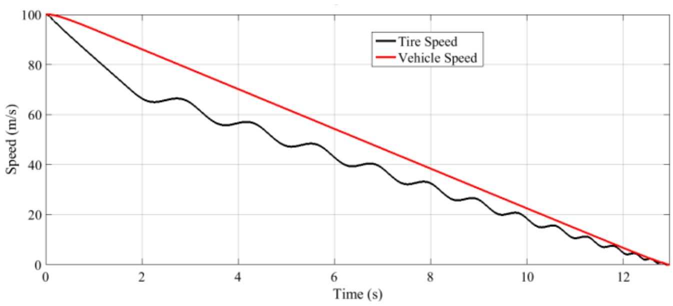


**Figure 17:** Behavior of the vehicle speed and the tire speed of the ABS system without faults

**Table 4:** Comparison of the distance and braking time of the ABS system without fault and ABS system with injection of critical faults

| Parameter | System without fault | Fault $f_f$ | Fault $f_\lambda$ | Fault $f_v$ | Fault $f_\omega$ |
|---|---|---|---|---|---|
| Braking time | 12.97s | 13.3s | 14.08 s | 14.03 s | 13.13 s |
| Stopping distance | 183.2m | 191.6 m | 185.6 m | 206.7 m | 185.3 m |

For the simulation of critical faults, the following parameters are used to model them and are shown in Table 5.

**Table 5:** Parameters of simulation of critical faults

| Fault | Value | Time of injection |
|---|---|---|
| Leakage in the hydraulic system | 0.3 | 1.5s - 4.5s |
| Fault to calculate the slip rate/internal error in the electric control unit | 0.5 | 1s - 4s |
| Speed sensor fault of the vehicle | -10 | 5 - 8s |
| Angular speed sensor fault of the tire. | -25 | 3s - 6s |

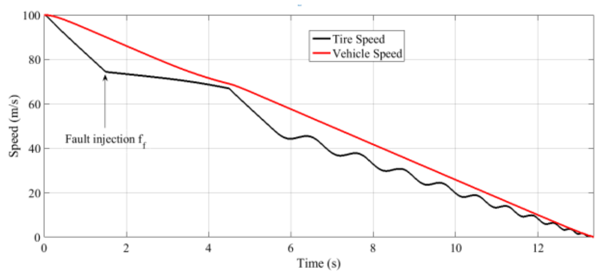


**Figure18:** Behavior of the tire speed and vehicle speed in the event of a leakage in the hydraulic system.

Figure 18 shows the behavior of the tire speed and the speed of the vehicle, during the braking process on a dry concrete contact surface applying the leakage fault in the hydraulic unit ($f_f$). The fault is applied in a time range 1.5 seconds - 4.5 seconds, as a step function. Being a fault in the actuator, the hydraulic unit loses 30% of its nominal performance. As a result of the fault, the braking distance increases from 183.2 meters to 191.6 meters, although on the contrary the braking time does not degrade from the system without faults as shown in the results in Table 4.

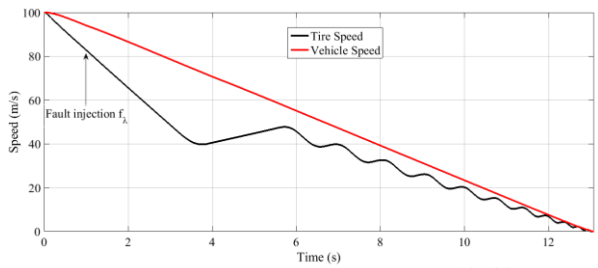


**Figure 19:** Behavior of the tire speed and vehicle speed in the event of fault to calculate the slip rate/internal error in the electric control unit

The fault in the calculation of the slip / Error rate in the ECU, is a fault in the system in which there is a 50% performance loss. The deviation is injected in the time interval of 1 second to 4 seconds, as shown in Figure 19. This fault only deviates the normal behavior of the tire speed, in case of time and braking distance increase due to the fault as shown in Table 4, demonstrating the degradation of the system due to this fault.

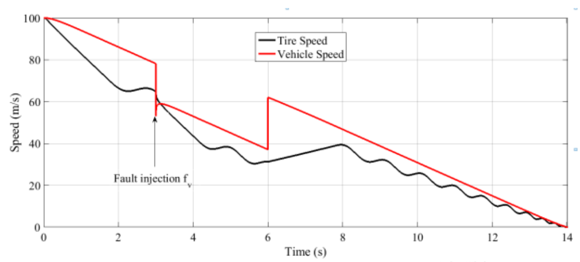


**Figure 20:** Behavior of the tire speed and vehicle speed in the event of speed sensor fault of vehicle

The results of the behavior of the fault in the vehicle speed sensor, are shown in Figure 20, which is applied in the time interval of 1 seconds to 4 seconds, being a fault in the sensors there is a degradation in the reading of -10 m/s that significantly affects the measurement of the speed of the tire and the vehicle, compared to the system without faults. Consequently, as shown in Table 4, the distance and braking time increase compared to the results of the system without faults.

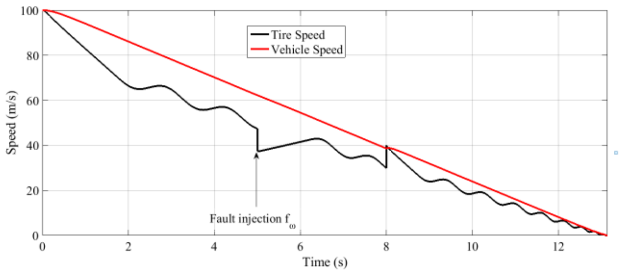


**Figure 21:** Behavior of the tire speed and vehicle speed in the event of speed sensor fault of the tire

The fault of the tire speed sensor is simulated as an additive type fault, so there is a degradation in the sensor reading of -25 m/s during the time interval of 5 seconds to 8 seconds, which affects in measuring the tire speed remarkably, while in the case of vehicle speed it is much lower although there is some deviation in its normal operation, this can be seen in Figure 21. The results of the braking distance and time with the fault are shown Table 4, where due to the fault both parameters increase compared to the system without faults.

## 6. Conclusion

In this article, a model of faults of the ABS braking system was proposed, proposing 4 critical faults: leakage in the hydraulic system, fault to calculate the slip rate/Error in the ECU, fault in the vehicle speed sensor and fault of the tire speed sensor.

For this, they were simulated as additive faults for deviations in the tire and vehicle speed sensors, in case of multiplicative faults for the system fault and the hydraulic actuator fault. For the simulation the 4 critical faults were simulated as abrupt faults.

In order to analyze its behavior, the faults were simulated through Matlab / Simulink and its performance was compared with an ABS braking system without a controlled fault through a PID controller, whose objective is to keep the slip index at 0.2.

With the results obtained by simulating the 4 scenarios proposed on a dry pavement surface, it is shown that the performance of the system is degraded by affecting distance and braking time as they increase depending on the fault presented

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