

# Design and Assessment of an Anti-lock Braking System Controller

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**Abstract.** The anti-lock braking system is a safety equipment that prevents the vehicle wheels from locking up under emergency, panic, or harsh braking conditions, ensuring steering control during braking and reducing braking distance. This system is studied by automotive engineers for performance comparisons and for determining optimal control methods. For this reason, this paper presents a method to mathematically model the anti-lock braking system. The obtained model is afterwards used inside a Simulink simulation to investigate the results with and without the anti-lock braking system and to propose a three-position regulator instead of the generally used bang-bang controller. The simulation results show the improvement of the vehicle braking time and braking distance.

**Key-words:** Anti-lock braking system; automation and control theory; modelling; simulation.

## 1. Introduction

Autonomous driving represents a research topic of global interest which influences the future of the vehicle manufacturing industry, and which is seen as a combination of complex hardware technology with artificial intelligence with the purpose to fulfil the actual society needs: quality of transportation [1, 2] reduction of traffic risks, safety and security of vehicle data, comfort for drivers and passengers.

The automotive field has experienced intensive automation in recent years using embedded systems with dedicated functions [3, 4]. As a result of this, advanced levels of control over vehicle autonomy have been reached, and the human intervention factor has been greatly diminished. Several countries around the world have already tested in real-life many types of self-driving vehicles: cars, trucks, buses, and subway trains. The most well-known contemporary examples, in this regard, are the car models from Google and Tesla.

In 2014, the *Society for Automotive Engineering* (SAE) defined six levels of automation in the standard from document J3016, levels which range from level 0 (no automation) to level 5 (full automation) in which the system is responsible for driving the vehicle in all conditions. It is estimated that approximately in 2025, cars with level 4 automation in which the system drives the vehicle independently in specific cases and ensures safe operation will be on the market.

Autonomous driving has many advantages but at the same time it brings into question several aspects such as processing large volumes of data, improving hardware technology, high connectivity, and legal requirements. However, the biggest challenge is avoiding collisions and therefore passenger safety. For this reason, vehicles must provide stability and must be able to brake safely in real-time after an obstacle has been detected. For critical situations, the driver assistant systems incorporate vehicle control systems which have been proven to significantly improve the safety perspective, the best-known systems being the Electronic Stability Program and the Automatic Emergency Braking. Both are based on the Anti-lock Braking System (ABS) which allows steering control during braking and reduces braking distance.

ABS technology has been developed by Bosch company since 1930 but production of the first electronically controlled four-wheel anti-lock system for cars began in 1978. Since then, such systems have become progressively more complex and efficient, and ABS has turned into a standard that equips all modern cars. Its purpose is to prevent the wheels from locking during braking maneuvers because when they get in this state the adherence between the wheel tire and the road surface is reduced and it makes the direction of the vehicle uncontrollable, especially on wet or slippery surfaces.

ABS systems usually include an *electronic control unit* (ECU), one speed sensor for each wheel, and a hydraulic unit comprising of a return pump and at least two valves that control the braking pressure on each wheel. The sensors measure and transmit the speed of each wheel to the ECU. If the electronic control unit detects that one of the wheels is spinning slower than the others, condition which can cause a locking state, it will generate a command to the valves to lower the pressure in the braking circuit and to reduce the braking force on that respective wheel. The system must also be able to supply pressure by means of the electric pump from within its composition. After the wheel spins again, the brake pressure on the wheel increases once more. This increase and release of the pressure is performed up to 40 times per second and continues until the driver reduces the force applied to the braking pedal or until the locking tendency is surpassed.

When the ABS is activated, the brake pedal can pulsate, and some drivers may reduce the pedal pressure. This causes the increase of the braking distance and raises the risk of accidents. For this reason, modern braking assistant systems maintain the braking force in such situations.

Depending on the number of individually controllable valves and the number of speed sensors, several types of brakes used in ABS systems are differentiated. The maximum braking force is obtained in the configuration that uses a speed sensor on each wheel and individually controlled valves for the four wheels. Older cars equipped with ABS use individual valves for the front wheels and a single valve for the rear.

The ABS was studied both for comparing the performances of vehicles in different conditions with and without ABS, and for determining an optimal control method. Several studies in this regard are, for example, an extensive review to highlight that ABS performance can be improved and to quantify the benefits of a new generation of wheel slip control systems [5], an optimal scheduler which incorporates the hybrid nature of the ABS and provides a feedback solution with a negligible computational burden in control calculation [6], an ABS coordinated control

scheme to shorten the braking distance while ensuring the vehicle stability during emergency braking under complex driving conditions [7], a coordinated control strategy of the ABS for in-wheel motors driven electric vehicles to recover more braking energy while satisfying the target of slip ratio control [8], a two-phase algorithm where the wheel acceleration is controlled in closed-loop and the longitudinal force measurement is used to fire phase switching [9], a real-time estimation of the wheel slip value corresponding to the peak of the tire-road friction curve to provide the ABS with reliable information [10], a slip control of electric vehicle based on tire-road friction coefficient estimation [11], a method to predict different road surfaces and to control the wheel slip to achieve maximum friction coefficient [12], a wheel slip controller developed and tested in a car equipped with electromechanical brake actuators and a brake-by-wire system [13], a simulation of integrated controller of vehicle ABS which consists of the continuous PID and finite state machine theory [14], an estimation of the uncertainty and disturbances for ABS model [15], ABS modeling and model based control algorithms to improve braking performance [16–18].

Most studies present numerous control strategies and many of them are based on simple on-off controllers which switch on when the error is positive and switch off when the error is zero or negative, without any intermediate states. These controllers, commonly used in commercial vehicles [19, 20], are often called bang-bang controllers. As an alternative control solution, this paper proposes a three-position regulator that is as simple as the bang-bang controller, but which provides better performance results while the ABS is active. This ABS controller type is proposed because it has many advantages: it is a simpler control method compared to other ABS controllers that can be implemented in the actual ECUs and that require a high level of mathematical understanding (*e.g.* MPC, LQR methods), demonstrates better performance and robustness than the PID controller [5], it is not a hardware dependent control method, and it can be easily implemented on a real-time embedded system.

The anti-lock braking system has many advantages and has improved traffic safety as well as vehicle control in almost all conditions. Benefits of using ABS include maintaining steering control during emergency braking, reducing braking distance, improving steering control on surfaces with variable adherence, and preventing damage to the tire during braking.

The structure of the paper is as follows. Section 2 presents the ABS model used for simulations. Section 3 provides in MATLAB the assessment for the ABS. Section 4 presents the paper's conclusions.

## 2. Anti-lock Braking System Model

The ABS is applied during hard braking maneuvers to prevent the wheels from locking. This is achieved by controlling the slip of the wheels to keep the coefficient of friction at a value close to the optimum value. Wheel slip is defined as the relative movement between the wheel and the road surface while the vehicle is moving. Slippage occurs when the angular velocity of the wheel is higher or lower than its free running speed.

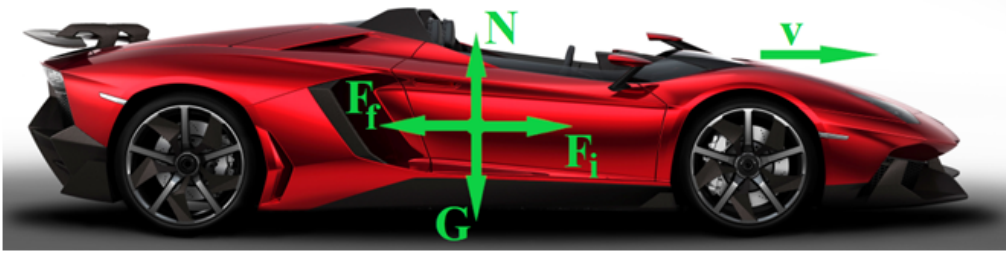
Fig. 1 presents the forces acting on a vehicle moving in a straight direction during braking.

The equations of equilibrium can be written for the horizontal and vertical directions:

$$\begin{cases} F_i = F_f = \mu \cdot N \\ N = G = m_v \cdot g \end{cases} \quad (1)$$

in which:

- $F_f$  [N] is the friction force between the wheel and the road surface.
- $F_i$  [N] is the inertial force of the vehicle.
- $N$  [N] is the normal force.
- $G$  [N] is the weight force of the vehicle.
- $\mu$  [-] is the coefficient of friction between the wheel and the road.
- $m_v$  [kg] is the mass of the vehicle.
- $g$  [m/s<sup>2</sup>] is the gravitational acceleration.



**Fig. 1.** Forces acting on a vehicle during braking.

The inertial force can be expressed according to Newton's second law:

$$F_i = m_v \cdot a_v = m_v \cdot \frac{dv_v}{dt} \quad (2)$$

in which:

- $a_v$  [m/s<sup>2</sup>] is the acceleration of the vehicle.
- $v_v$  [m/s] is the linear speed of the vehicle.

The following expression of the vehicle acceleration is obtained from the above relations and the linear speed of the vehicle can further be obtained through integration:

$$\frac{dv_v}{dt} = \frac{1}{m_v} \cdot (\mu \cdot m_v \cdot g) \quad (3)$$

Fig. 2 presents the forces acting on a vehicle's wheel during braking. The driver applies a braking torque to the wheels via the braking system. The friction force between the wheel and the road surface together with the wheel radius creates a resistive torque. For simplicity, it is considered that the wheel does not add additional torque.

The equation of equilibrium for the wheel is:

$$C_b - F_f \cdot r_r - J_r \cdot \frac{d\omega_r}{dt} = 0 \quad (4)$$

in which:

- $C_b$  [Nm] is the braking torque applied on the wheel.
- $F_f$  [N] is the friction force between the wheel and the road surface.
- $r_r$  [m] is the wheel radius.
- $J_r$  [kg·m<sup>2</sup>] is the moment of inertia of the wheel.
- $\omega_r$  [rad/s] is the angular speed of the wheel.

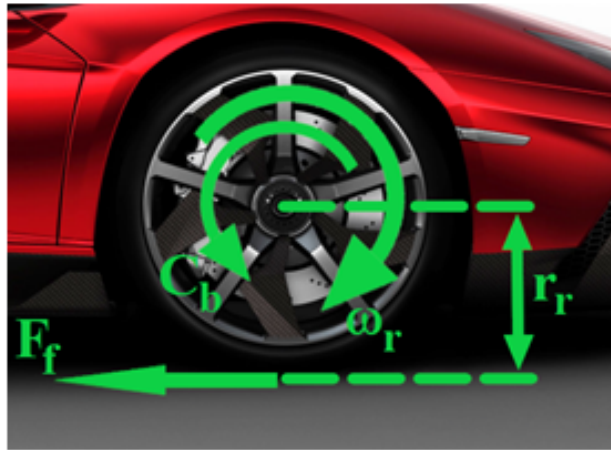
The following expression of the wheel acceleration is obtained from the above relation and the angular speed of the wheel can further be obtained through integration:

$$\frac{d\omega_r}{dt} = \frac{1}{J_r} \cdot (C_b - F_f \cdot r_r) \quad (5)$$

The wheel slip  $s$  [-] can be expressed as:

$$s = 1 - \frac{\omega_r}{\omega_v} \quad (6)$$

in which  $\omega_v = v_v / r_r$  [rad/s] is the equivalent angular velocity of the vehicle.



**Fig. 2.** Forces acting on a vehicle's wheel during braking.

The coefficient of friction  $\mu$  between the wheel and the road depends on several factors such as type of road, humidity and temperature conditions, wheel slip, and vehicle speed. It can be expressed as an empirical function dependent on the slip of the wheel  $s$ :

$$\mu(s) = C_1 \cdot (1 - e^{-C_2 \cdot s}) - C_3 \cdot s \quad (7)$$

in which  $C_1, C_2, C_3$  [-] are coefficients determined empirically.

Table 1 contains the coefficient values for different road surfaces as described in [12]. Fig. 3 shows the dependence of the coefficient of friction to the slip of the wheel simulated with these values. There are two areas which can be observed: the stable area in which  $\mu$  increases as  $s$  increases, and the unstable area in which  $\mu$  decreases as  $s$  increases. The ABS keeps the wheel slip  $s$  close to the optimum value.

**Table 1.** Coefficient values for different road surfaces

| Road Surface | $C_1$  | $C_2$ | $C_3$  |
|--------------|--------|-------|--------|
| Dry          | 1.2801 | 23.99 | 0.52   |
| Wet          | 0.857  | 33.82 | 0.347  |
| Snowy        | 0.1946 | 94.12 | 0.0646 |
| Icy          | 0.05   | 306.3 | 0      |

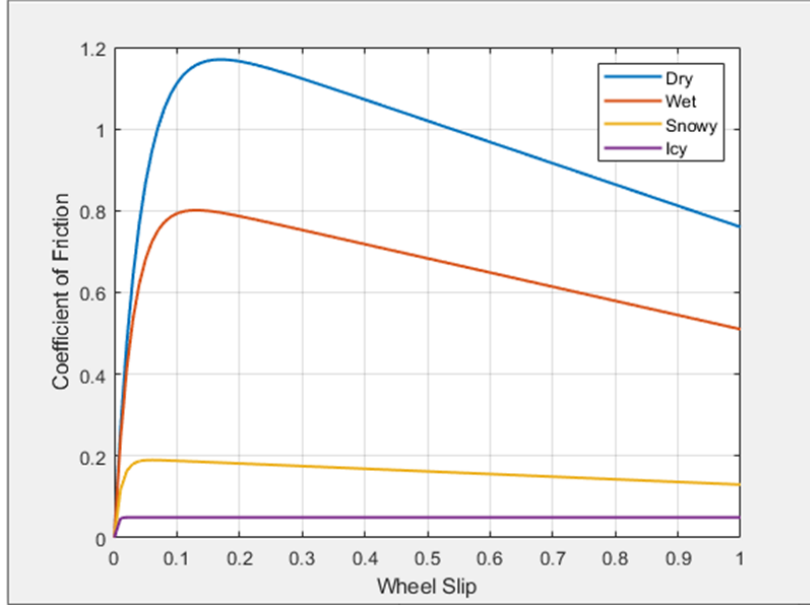


Fig. 3. Simulated dependence of the coefficient of friction to the slip of the wheel.

### 3. Assessment of the Anti-lock Braking System

In order to evaluate the obtained ABS model, a Simulink block diagram which can be seen in Fig. 4 was used for the ABS simulation. The diagram contains the vehicle and the wheel models which were analyzed at a quarter-car level. Therefore, a quarter of the mass of the vehicle with a single wheel is considered. The simulation takes into consideration only the longitudinal dynamics of the vehicle without the impact of the suspension. The following parameter values taken from [12]:

$$J_r = 5\text{kg}\cdot\text{m}^2, m_v = 800\text{kg}, g = 9.81\text{m/s}^2, v_0 = 28\text{m/s}, r_r = 0.28\text{m}, C_{b\max} = 1500\text{Nm} \quad (8)$$

describe the vehicle on a dry road surface in which  $C_{b\max}$  [Nm] is the maximum braking torque applied on the wheel and  $v_0$  [m/s] is the initial speed of the vehicle.

The integrator block used in the wheel model for the angular velocity of the wheel is initialized with the value  $v_0/r_r$  [rad/s] and it is saturated between 0 and 1000 [rad/s]. The linear speed of the wheel is obtained by multiplying the angular wheel velocity with the radius of the wheel. The integrator block used in the quarter-car model for the velocity of the vehicle is initialized with the value  $v_0$  and it is saturated between 0 and 1000 [m/s]. The braking distance is obtained through the integration of the vehicle speed.

The execution element (actuator) represented by the hydraulic system is modelled with a first-order transfer function which has the amplification factor  $K = 500$  and the time constant  $T = 0.01$  s. Its output measure is the braking torque  $C_b$  accumulated by the integrator and limited between 0 and  $C_{b\max}$ .

The wheel slip  $s$  is calculated according to relation (6), but the  $eps$  constant is used as a

denominator to avoid division by 0 when the vehicle speed is 0. The coefficient of friction  $\mu$  is calculated according to relation (7) and the coefficients  $C_1, C_2, C_3$  have the values for the dry road surface as described in Table 1.

The system reference is set to 0.2, which represents the approximation of the optimum slip value for which the maximum coefficient of friction is obtained. The bang-bang regulator was utilized as the controller of the system because it is the most used and simplest control solution for ABS, and it can be used as a benchmark for comparison with other controllers. This regulator reacts to the sliding error  $\varepsilon$ , emulating an ABS controller. It is implemented using a sign block which provides the output value as  $-1$  when  $\varepsilon < 0$ ,  $0$  when  $\varepsilon = 0$ , and  $1$  when  $\varepsilon > 0$ .

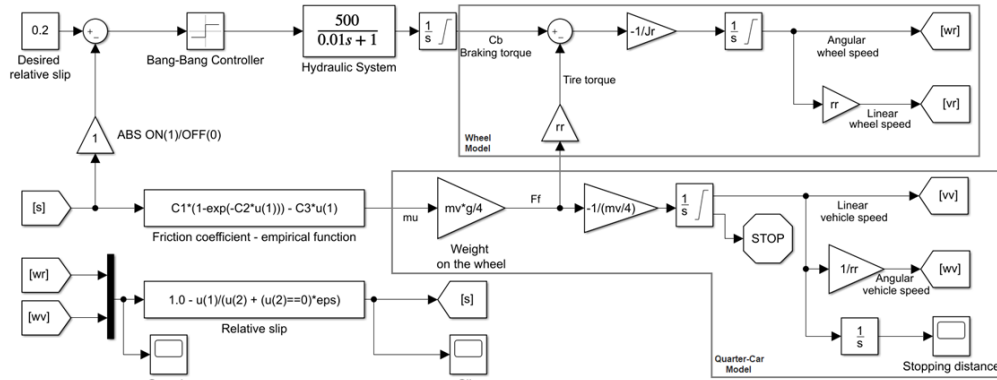


Fig. 4. Block diagram for the simulation of the ABS.

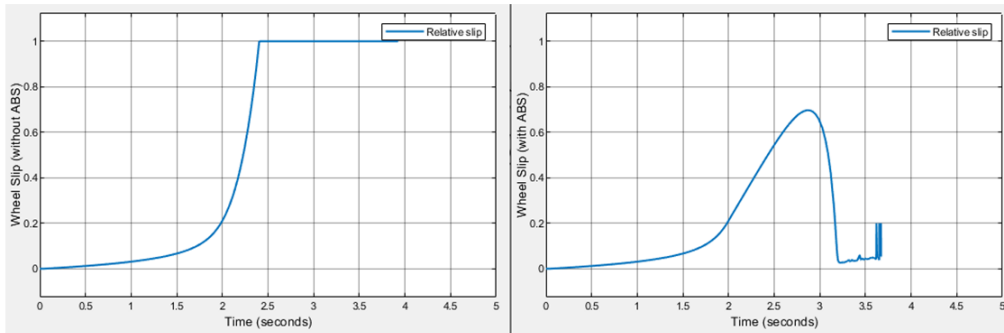


Fig. 5. Comparison of the wheel slip with ABS and without ABS.

Using the Simulink model in Fig. 4, simulations with and without ABS were performed to study the evolution of the vehicle and wheel speed, braking distance, and wheel slip. The simulation considers the initial speed  $v_0 = 28$  m/s, which means that  $\omega_v = 100$  rad/s, and it is executed until the vehicle stops.

Fig. 5 presents the wheel slip with and without ABS.

When the ABS is inactive, the results show that as the braking torque increases the wheel slip also increases rapidly to the value of 1 (slip rate: 100%) which leads to the locking of the wheel.

When the ABS is active, the wheel slip is maintained around 0.2 (slip rate: 20%). The wheel slip reaches value 1 when the vehicle stops.

Fig. 6 presents the vehicle and wheel speed with and without ABS.

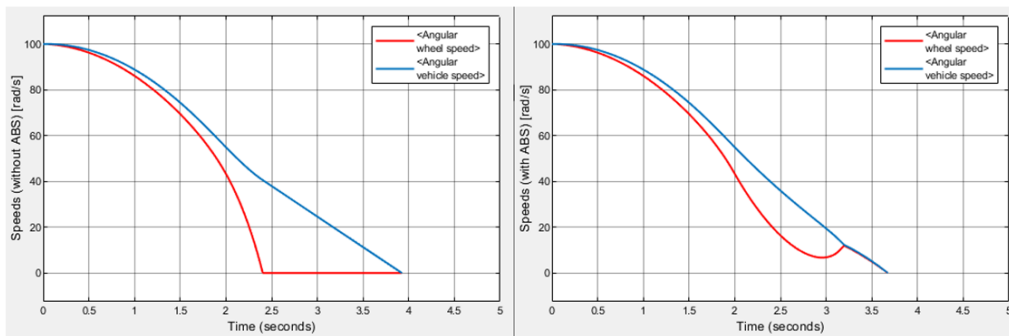
When the ABS is inactive, the results show that the wheel will lock before the vehicle stops and the deceleration slope changes after the wheel locks because the friction force becomes smaller and therefore the braking distance increases (the vehicle stops after 3.92 s).

When the ABS is active, the reduction of the braking distance is observed (vehicle speed reaches 0 after about 3.67 s) because the wheel slip is maintained around the desired value generating a greater frictional force between the wheel and the road.

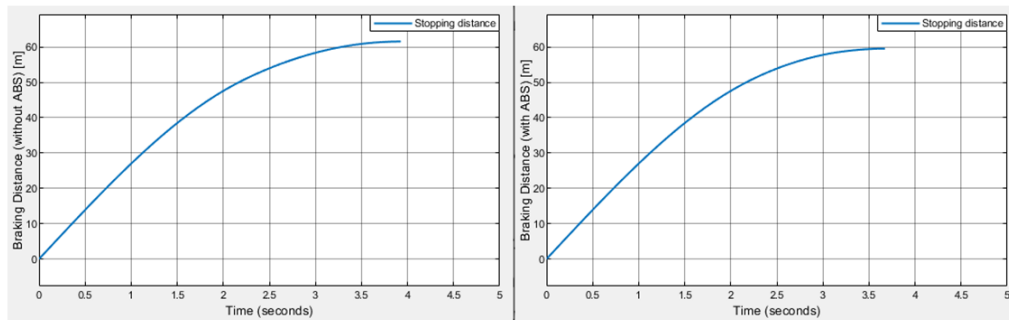
Fig. 7 presents the braking distance with and without ABS.

When the ABS is inactive, the braking distance is approximately 61.55 m.

When the ABS is active, the braking distance is approximately 59.54 m.



**Fig. 6.** Comparison of the vehicle and wheel speed with ABS and without ABS.



**Fig. 7.** Comparison of the braking distance of the vehicle with ABS and without ABS.

It can be observed from the simulation results that the ABS reduces the braking distance of the vehicles, preventing the wheels from locking.

The ABS has been intensively studied with different control strategies leading to optimal performance in real time. Assuming a robust estimation of the longitudinal wheel slip, the wheel control is simpler and has the advantage that the applied braking torque converges to a fixed value. Given the requirements regarding real-time applicability and robustness to road changes and uncertainties, it is difficult to select a single control method as the most appropriate. Current

trends in ABS control include control strategies such as controllers based on logical thresholds, controllers based on fuzzy logic, neural network controllers, PID controllers, LQR controllers, MPC controllers, sliding mode control.

In the above simulation, a control based on a switching action depending on the wheel slip (the bang-bang controller) was used, which is part of the sliding mode control category.

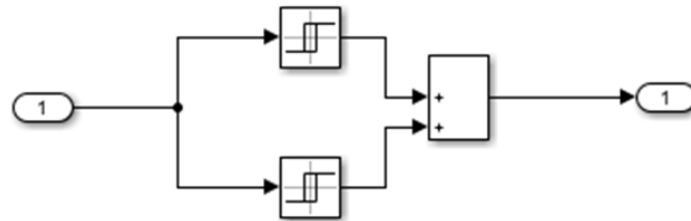


Fig. 8. Proposed three-position controller implemented with two relay blocks.

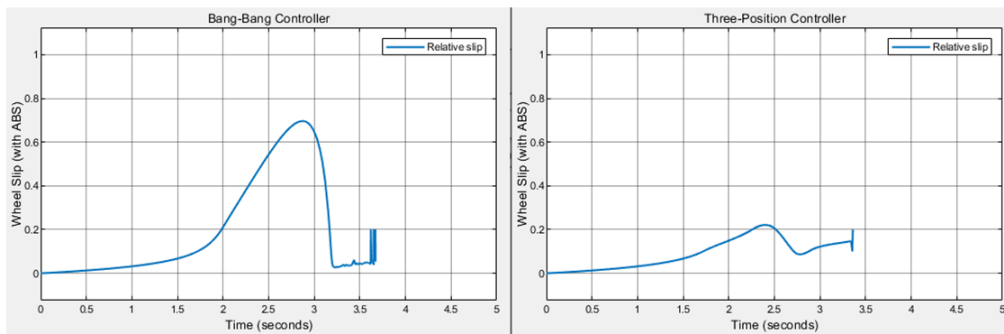


Fig. 9. Comparison of the wheel slip with the bang-bang controller and the three-position controller.

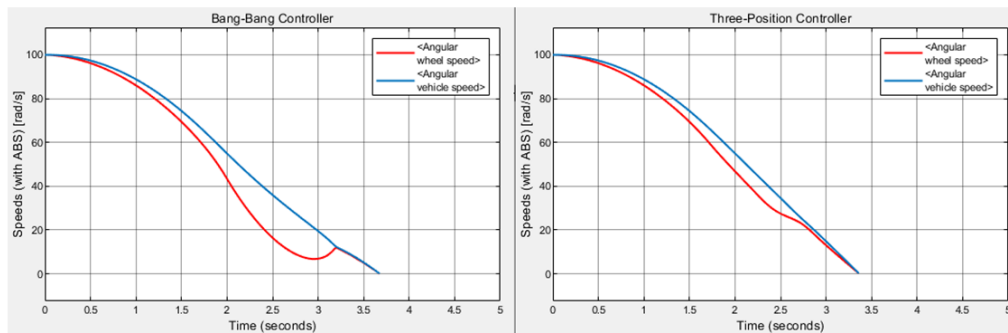
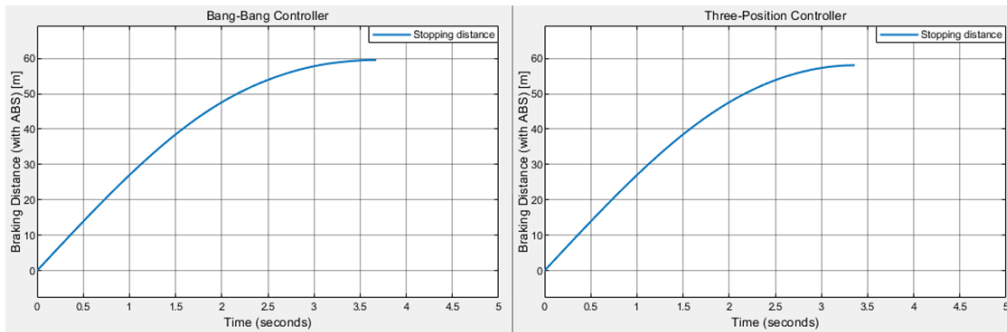


Fig. 10. Comparison of the vehicle and wheel speed with the bang-bang controller and the three-position controller.



**Fig. 11.** Comparison of the braking distance with the bang-bang controller and the three-position controller.

This paper proposes a performance improvement obtained by using a controller from the same category, namely a three-position controller, which provides the output as  $-1$  when  $\varepsilon < 0$ ,  $0$  when  $\varepsilon \in [0, 0.1]$ , and  $1$  when  $\varepsilon > 0.1$ . The proposed controller is implemented in a subsystem block using two relay blocks as seen in Fig. 8, and it replaces the bang-bang controller in the simulation block diagram from Fig. 4. This three-position controller considers a dead zone in the interval  $[0, 0.1]$  providing in this range the value  $0$  at the output, unlike the bang-bang controller where the switching was performed according to the sign in the immediate vicinity of the value  $0$ . The results from Fig. 9, Fig. 10 and Fig. 11 show a braking time reduced to  $3.36$  s and a braking distance reduced by  $1.5$  m.

In order to compare the results obtained with the two controllers, additional use-cases for different road types were analyzed in the simulation. The road types were simulated using the Burckhardt model coefficients values from Table 1.

Table 2 contains some performance criteria represented by the wheel slip average, braking time and braking distance for each road type considering the following simulation scenarios: without the ABS active, with the ABS active using the *bang-bang controller* (BB) and with the ABS active using the *three-position controller* (TP). From the performance criteria it can be observed that better simulation results are obtained using the three-position controller for the wheel slip average considering that the  $100\%$  slip rate value corresponds to the wheel locking.

**Table 2.** Performance criteria of wheel slip average, braking time and braking distance

| Road type | Wheel slip average [%] |       |       | Braking time [s] |       |       | Braking distance [m] |        |        |
|-----------|------------------------|-------|-------|------------------|-------|-------|----------------------|--------|--------|
|           | No ABS                 | BB    | TP    | No ABS           | BB    | TP    | No ABS               | BB     | TP     |
| Dry       | 44.06                  | 15.79 | 13.41 | 3.92             | 3.67  | 3.36  | 61.55                | 59.54  | 58.04  |
| Wet       | 64.86                  | 19.57 | 16.13 | 5.52             | 4.90  | 4.43  | 79.46                | 72.37  | 69.02  |
| Snowy     | 93.16                  | 18.76 | 14.64 | 21.71            | 16.53 | 16.38 | 301.03               | 228.63 | 226.46 |
| Icy       | 97.62                  | 20.24 | 15.34 | 57.18            | 57.29 | 57.36 | 801.96               | 801.98 | 802.03 |

For the braking time and braking distance, the proposed three-position controller provides better simulation results for a dry, wet, or snowy road. In case of an icy road, the ABS prevents the wheels from locking, but the braking results are similar to the ones without ABS.

The proposed control algorithm can be easily implemented on an ECU. The inputs are the

values provided by the wheel speed sensors. The output is represented by the three-values command applied to the hydraulic unit to control the three pressure states: building up pressure, maintaining pressure, and reducing pressure in the brake chamber. The ABS controller is usually implemented on ECUs with real-time operating systems. The main implementation issues can be related to the software configuration for real-time performance since an optimal cycle time for the acquisition of inputs, execution of the control algorithm, and transmission of the command to the actuator is needed to obtain the desired braking results and to have a reasonable actuator switch frequency.

## 4. Conclusions

The anti-lock braking system is a safety technology that equips all modern cars, and which aims to control the dynamics of the wheels to maintain steering control regardless of the road conditions by modulating the applied braking pressure. This paper models the braking behavior of a vehicle for the purpose to study the ABS. The simulation results show the braking performance with and without ABS where the braking distance of the vehicle is significantly improved when the ABS is active, preventing the wheels from locking and ensuring the ability to maintain steering. This paper also proposes a control strategy based on a three-position regulator which is as simple as the bang-bang controller, and less complex than other control algorithms. The simulation results with this controller show better braking performance than the generally used bang-bang regulator.

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