https://doi.org/10.21122/2227-1031-2026-25-3-212-221

UDC 629.331.03-83-592.3

Study of Hydraulic ABS Braking Systems under Various Road Friction Coefficients Using Co-Simulation and Experimental Methods

T. H. Nguyen [1], T. K. Nguyen [1]

[1]Dai Nam University (Hanoi, Socialist Republic of Vietnam)

Abstract. The Anti-lock Braking System (ABS) has become an essential safety feature in modern vehicles due to its capability to prevent wheel lock during braking, thereby preserving vehicle stability and steering controllability. As a typical mechatronic system, ABS integrates hydraulic, mechanical, and electronic subsystems governed by an electronic control unit (ECU). This study proposes a multidisciplinary co-simulation framework for investigating the braking performance of a passenger vehicle equipped with ABS. The hydraulic behavior of the system is modeled using AMESim Simcenter, while the vehicle longitudinal dynamics and control strategy are implemented in MATLAB Simulink. In the AMESim environment, a four-channel hydraulic ABS modulator is developed, where the ECU control signal serves as the input and the brake circuit pressure is generated as the output. This pressure signal is subsequently transmitted to the Simulink model, which utilizes it to evaluate wheel slip behavior under braking conditions at a specified tire–road adhesion coefficient, forming a closed-loop simulation architecture. To enhance braking efficiency under varying slip conditions, a hybrid control strategy combining a conventional PID controller with fuzzy logic is introduced. The proposed co-simulation structure enables real-time bidirectional interaction between the physical hydraulic subsystem and the control module: pressure outputs from AMESim are fed into Simulink, while control signals generated in Simulink are used to actuate the solenoid valves within the AMESim model. An experimental test rig was established to validate the proposed model and to assess the effectiveness of the control algorithm under real operating conditions. Experimental results demonstrate that the vehicle can decelerate from an initial speed of 90 km/h to a complete stop without wheel lock in approximately 2.54 seconds, corresponding to a braking distance of 30.48 meters. Compared with a conventional hydraulic ABS, the proposed control strategy reduces braking time and stopping distance by approximately 8.5 % and 6.5 %, respectively. Furthermore, a close agreement between simulation and experimental results is observed, with deviations of 4.4 % in braking time, less than 0.5 % in stopping distance, and 3.9 % in deceleration, confirming the accuracy and reliability of the developed model. The results indicate that the integration of PID control with fuzzy logic significantly enhances ABS performance, ensuring stable and effective braking under emergency conditions across varying road adhesion scenarios.

Keywords: Longitudinal dynamics, ABS; hydraulic modulator, adhesion coefficient, Co-Simulation AMESim/Simulink, PID-Fuzzy controller; braking performance

For citation: Nguyen T. H., Nguyen T. K. (2026) Study of Hydraulic ABS Braking Systems under Various Road Friction Coefficients Using Co-Simulation and Experimental Methods. *Science and Technique*. 25 (3), 212–221. https://doi.org/10.21122/2227-1031-2026-25-3-212-221

Исследование гидравлических антиблокировочных тормозных систем при различных коэффициентах дорожного сцепления на основе комплексного моделирования и экспериментальных данных

Ч. Х. Нгуен[1], Ч. К. Нгуен [1]

[1]Дай Нам Университет (Ханой, Социалистическая Республика Вьетнам)

Реферат. Антиблокировочные тормозные системы (АБС) широко применяются в современных автомобилях благодаря своей способности предотвращать блокировку колес при торможении, тем самым сохраняя управляемость

Адрес для переписки
Нгуен Чунг Кьен
Дай Нам Университет
ул. Сом, 1, Фу Лыонг Район,
100000, г. Ханой, Вьетнам
Тел.: +84 941145058
nguyentrungkien@dainam.edu.vn

Address for correspondence
Nguyen Trung Kien
Dai Nam University
No 1, Xom Street, Phu Luong Ward,
100000, Ha Noi, Viet Nam
Tel.: +84 941145058
nguyentrungkien@dainam.edu.vn

и обеспечивая требуемый уровень активной безопасности транспортного средства. АБС представляет собой сложную мехатронную систему, объединяющую гидравлические, механические и электрические компоненты под управлением отдельного электронного модуля. В данном исследовании представлен мультидисциплинарный подход к комплексному моделированию работы АБС легкового автомобиля с использованием программных пакетов AMESim Simcenter для анализа динамики гидравлических процессов и MATLAB Simulink для оценки продольной динамики автомобиля в тормозном режиме и анализа логики управления исполнительными механизмами. Четырехканальный гидравлический модулятор АБС смоделирован в программном пакете AMESim, где входным сигналом на электромагнитные клапаны является управляющий сигнал электронного блока управления, а выходным – давление в контурах тормозной системы. Субмодель Simulink получает в качестве входных данных информацию о величине давления в тормозных контурах и использует ее для расчета вероятности блокировки и последующего скольжения колес при определенном коэффициенте сцепления, образуя замкнутую систему комплексного моделирования. Для динамического регулирования тормозных сил в зависимости от условий скольжения предложен гибридный алгоритм управления модулятором АБС, сочетающий классический ПИД-регулятор с элементами математического аппарата нечеткой логики. Предложенная структура комплексного моделирования обеспечивает в режиме реального времени взаимодействие между механической частью АБС и ее программно-аппаратным модулем управления, где выходное давление от субмодели AMESim поступает в субмодель Simulink, а управляющий сигнал от Simulink приводит в действие определенную комбинацию электромагнитных клапанов модулятора субмодели AMESim. Для валидации модели и оценки эффективности «нечеткого» контроллера разработана экспериментальная установка и проведен натурный эксперимент. Результаты экспериментальных исследований показали, что система обеспечивает торможение автомобиля со скорости 90 км/ч без блокировки колес за 2,54 с на тормозном пути 30,48 м, что приблизительно на 8,5 и 6,5 % соответственно меньше аналогичных показателей при классической схеме управления гидравлическим модулятором АБС. Результаты моделирования практически совпали с экспериментальными данными, показав погрешность 4,4 % по времени торможения, менее 0,5 % по тормозному пути и 3,9 % по замедлению автомобиля, что свидетельствует о высокой точности математической модели и ее адекватности. Полученные данные подтверждают, что интеграция ПИД-регулятора с нечеткой логикой в цепь управления контроллера значительно улучшает характеристики АБС, обеспечивая эффективное и стабильное торможение в аварийных условиях при различных коэффициентах сцепления с дорогой.

Ключевые слова: продольная динамика автомобиля, АБС, гидравлический модулятор, коэффициент сцепления, комплексное моделирование AMESim/Simulink, цепь управления, нечеткий ПИД-регулятор, эффективность торможения

Для цитирования: Нгуен, Ч. Х. Исследование гидравлических антиблокировочных тормозных систем при различных коэффициентах дорожного сцепления на основе комплексного моделирования и экспериментальных данных / Ч. Х. Нгуен, Ч. К. Нгуен // *Наука и техника.* 2026. Т. 25, № 3. С. 212–221. https://doi.org/10.21122/2227-1031-2026-25-3-212-221

Introduction

The Anti-lock Braking System (ABS) has been researched for over a hundred years, starting in the 1930s [1, 2] by many automotive brands and researchers. Today, ABS has become a crucial feature, adopted by car manufacturers in all vehicles due to its proven effectiveness in enhancing vehicle safety during braking. By keeping wheel slip within an optimal range, ABS helps prevent loss of directional control during braking and reduces stopping distances. Consequently, numerous studies on ABS are still ongoing today. Research on ABS generally focuses on three main areas: modulator hardware design, control algorithms development, and vehicle braking dynamics investigation. Additionally, some studies may integrate these research objectives simultaneously [3–11].

ABS controlling process involves regulating the slip at each wheel to an optimal value. To optimize this control process, various studies have been conducted on different control algorithms[12, 13]. In a study [12], the authors have built the formulas and model block needed for a Nonlinear PID control. Moreover, a cascade structure for the ABS had also been built to help the readers visualize this system. Lastly, the simulation results recorded in this article also show the braking distance, velocity, and time, which proves the reliability of the simulation model. Similarly, in [14, 15], the PID control has also been used to simulate an ABS, but with a more specialized method in which PID control and Fuzzy control [16–18] have been combined. In this method, controlling the ABS is not only based on the pressure in the braking system, but it is also dependent on the wheel slip ratio between the tire and the road surface. This makes the ABS control process more effective and sensitive. In this paper, the authors propose a control algorithm combining PID and Fuzzy logic to achieve optimal performance for the ABS system. The evaluation of this algorithm's effectiveness is carried out through a combination of simulation and real-world experimentation. Matlab Simulink is well-suited for simulating complex control algorithms like the one proposed [19, 20], and thus, this software is used in the paper to develop and assess the performance of the proposed controller.

Another research by the authors' group of [13] has made useful the understanding of one of the most modern simulation software – AMEsim software [9] to build the model for the Hydraulic system and ABS. Each important block in an ABS braking system has been simulated in a very detailed way by the authors, including the brake master cylinder model, the low-voltage accumulator model, the hydraulic pump model, the pressurization, decompression valve, solenoid valve model, the one-way valve model, and wheel brake cylinder model. Then, they compared the simulation results and concluded that the model is effective in studying Vehicle Hydraulic ABS. However, simulating control algorithms in Simcenter can be more challenging and complex compared to Simulink [19, 20]. On the other hand, simulating the operations of systems with complex structures can be more easily performed in Simcenter [9, 13, 21, 22]. So this paper chooses to simulate the operation of the ABS Modulator unit in Simcenter.

After analyzing the simulation effectiveness, the authors have combined both popular simulation software Simulink-Simcenter and the PID-Fuzzy controllers to build a computer model for the ABS hydraulic system. The study has also been based on the physical braking process, the vehicle's longitudinal dynamics model, ABS control algorithm to build the simulation model for the passenger car's hydraulic braking system. The content of the article has three main parts, including building the dynamic model for the car's body and wheels; simulating the working process of the ABS hydraulic brake system with the combination of the two simulation software mentioned, and experiments on the real road to validate simulation results.

Modeling

General Model. The ABS control method sets a desired value for the wheel slip λ, which means controlling the desired value of the relative difference between the wheel speed and the vehicle speed [23, 24]. This issue is referred to as slip control. Among all the braking methods that have been implemented, slip control is considered the most extensively researched method in various theoretical and practical applications [25]. In this study, the structure of the simulation blocks is presented in Fig. 1. The wheel slip controller block (Fig. 1) is constructed using Simulink software, based on equations that calculate wheel slip in practice. The real slip could be estimated [26]. Its task is to assess the current wheel slip λ against a predetermined reference value λ_{ref} and generate a corresponding reference pressure ρ_{ref}. The brake pressure controller block is also primarily built on the Simulink platform but integrates additional components Fuzzy-PID controller and a hydraulic modulator, simulated using Simcenter Amesim software. The brake pressure controller receives the reference pressure ρ_{ref} as an input parameter and sends a control signal to the hydraulic modulator to ensure that the output pressure of the hydraulic modulator equals the reference pressure. While brake torque estimator, wheel dynamics, vehicle dynamics, and wheel slip estimator are all constructed in Simulink based on fundamental calculation equations. They take missing input parameters from the preceding blocks, perform calculations, and provide the necessary parameters to refine the ABS brake system control strategy.

Vehicle Dynamics. Based on the initial objectives of the study, a mathematical model describing the vehicle dynamics (Fig. 2) and wheel dynamics (Fig. 3) was developed.

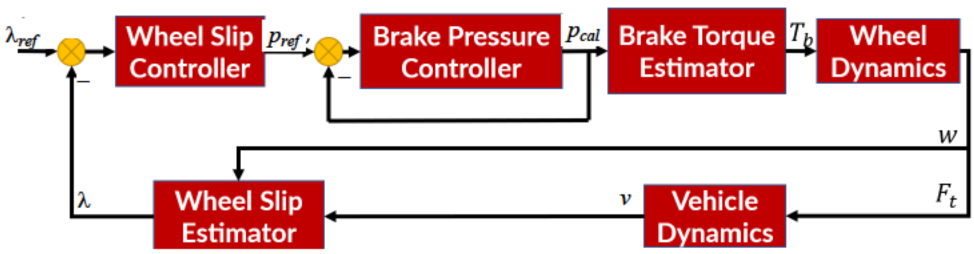

Fig. 1. Brake system control strategy with ABS

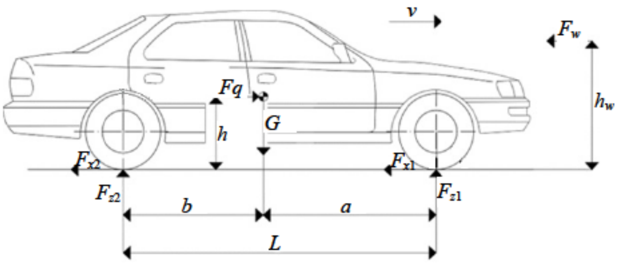

Fig. 2. Forces acting on the vehicle when braking

The equation of the vertical motion of the vehicle can be expressed by using Newton's second law [27–30] and is presented in the equation below. Where a is the vehicle acceleration, F_{ti} is the traction force of each wheel, F_w is an aerodynamic force acting on the vehicle, M_V is the total mass of the vehicle, and M_e is the equivalent mass of rotating parts, $M_e = 0.05\ M_V$.

$$a = \frac{F_{x1} + F_{x2} + F_{x3} + F_{x4} + F_w}{M_v + M_e}. \qquad (1)$$

During braking, the forces acting on the axles will be redistributed, with an increase in force on the front axle and a decrease in force on the rear axle. The aerodynamic force and the forces acting on the axles are determined by the following formulas [29–31]:

$$F_w = 0.5\rho C B v^2; \qquad (2)$$

$$F_{z12} = \frac{pM_V g}{2} + \frac{M_V h_{cg}}{2L}a - \frac{F_w h_w}{2L};$$
$$F_{z34} = \frac{qM_V g}{2} - \frac{M_V h_{cg}}{2L}a + \frac{F_w h_w}{2L}, \qquad (3)$$

where ρ is mass density of the air, C is vehicle drag coefficient, B is vehicle frontal area and v is vehicle speed. While p, q is the weight distribution coefficient on the front and rear axle respectively when the vehicle is in a static state with a full load, g is the acceleration due to gravity, h_{cg} is the height of the vehicle gravity, L is the wheelbase of the vehicle and h_w the height from aerodynamic force to the ground.

Wheel Dynamics. The force diagram acting on the wheel during braking is shown in Fig. 3.

Similarly, when simulating the wheels, the article used the following equations [29]:

$$\omega_i = \frac{\left(F_{xi} + F_{fi}\right)R_w - T_{bi}}{J_{\omega i}}; \qquad (4)$$

$$\lambda_i = \frac{v - \omega_i R_w}{v} = 1 - \frac{\omega_i R_w}{v}; \qquad (5)$$

$$F_{xi} = F_{zi}\mu, \qquad (6)$$

where ω_i is the rotational speed of each wheel, F_{fi} is the rolling resistance force at each wheel, R_w is wheel radius, T_{bi} is the braking torque of each wheel, $J_{\omega i}$ is wheel moment of inertia, μ is the road adhesion coefficient. The road adhesion coefficient depends on the wheel slip ratio λ and can be calculated through the interpolation function between the slip ratio and adhesion coefficient, which is shown in Fig. 4.

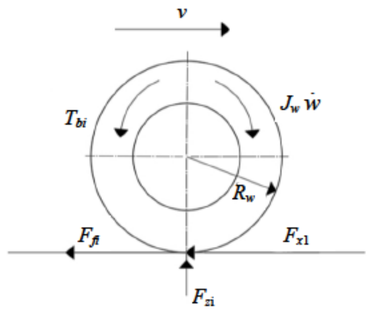

Fig. 3. Forces acting on the wheel when braking

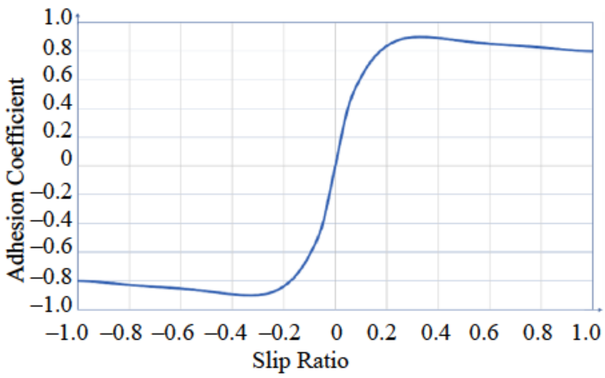

Fig. 4. The function from the sliding degree to the adhesion coefficient

Wheel Slip Controller Block. The objective of this module is to determine the reference pressure based on the wheel slip error, which is the difference between the actual slip and the reference slip (desired slip value). The input variables of the fuzzy controller are the wheel slip error $e_\lambda = \lambda^{ref} - \lambda$ and its change Δe_λ. e_λ particularly is the slip error, which can be determined by the reference slip ratio (λ^{ref}) and the actual slip ratio (λ), while Δe_λ is the change of e_λ within in a time step T. The output variable is the reference pressure p_{ref}.

The paper proposes the use of a PID-type fuzzy controller employing a Takagi-Sugeno-Kang (TSK) fuzzy system to regulate the wheel slip to a desired value because of some outstanding points of this controller mentioned in research [12, 13]. This hybrid control approach combines the intuitive design and computational efficiency of a Fuzzy Inference System (FIS) with the well-established PID control theory. This study also used a PID-type fuzzy controller, which is demonstrated in Fig. 5.

The classification as a PID-type controller is since, before entering the FIS, both input variables are scaled by the gains K_e and $K_{\Delta e}$, which are analogous to the proportional and derivative gains of a PID controller. Conversely, the output of the FIS is scaled by the gain $K_{\Delta p}$ before integration.

Fuzzy sets. The membership functions (MFs) for the input variables are defined using Gaussian curves. The preferences for Gaussian curves, as opposed to triangular or trapezoidal MFs, ensure a smoother transition between fuzzy sets (Table 1).

Table 1

Fuzzy sets and MFs parameters for inputs e_λ and Δe_λ [14]

Fuzzy Set			c	Description
A_1	Negative	$e_\lambda < 0$	–1	$\lambda > \lambda^{ref}$
A_2	Zero	$e_\lambda = 0$	0	$\lambda > \lambda^{ref}$
A_3	Positive	$e_\lambda > 0$	1	$\lambda > \lambda^{ref}$
B_1	Increasing	$\Delta e_\lambda < 0$	–1	λ is increasing
B_2	Steady	$\Delta e_\lambda = 0$	0	λ is steady
B_3	Decreasing	$\Delta e_\lambda > 0$	1	λ is decreasing

This results in a continuous output signal (Table 2). The MFs for each fuzzy set, are evenly distributed within the normalized interval [–1 1]. This choice guarantees that the controller dynamics can be easily adjusted by tuning the PID gains outside the FIS. The input and output gains K_e and $K_{\Delta e}$ were initially adjusted to ensure that the signal values entering the FIS fell within the normalized interval of [–1 1]. Regarding the output gain $K_{\Delta p}$, the initial value for the first iteration was selected based on the modulator limits for pressure increase/decrease rates (Table 3).

Rule Set

Table 2

Consequent function parameters for output Δp_{ref} [16]

y_k	Fuzzy Set	C_k	Description
1	Decrease-fast	–1	Decrease the reference pressure rapidly
2	Decrease-slow	–0.5	Decrease the reference pressure slowly
3	Hold	0	Hold reference pressure
4	Increase-slow	0.5	Increase reference pressure slowly
5	Increase-fast	1	Increase reference pressure rapidly

Table 3

The fuzzy rule for wheel slip control [14, 16]

$e_\lambda \backslash \Delta e_\lambda$	Decreasing	Steady	Increasing
Negative	Hold	Decrease-slow	Decrease-fast
Zero	Increase-slow	Hold	Decrease-slow
Positive	Increase-fast	Increase-slow	Hold

Brake Pressure Controller Block. The brake pressure controller block is tasked with adjusting the command signal u directed to the hydraulic modulator. This adjustment aims to align the pressure on the caliper p_{cal} with the reference pressure p_{ref} established by the wheel slip controller (Fig. 6). Given that there are no highly specific requirements, the preference lies with the design simplicity and familiar principles of a PID-type controller. Using the Tuner tool for automatic tuning further streamlines the design process, enhancing its simplicity and intuitiveness.

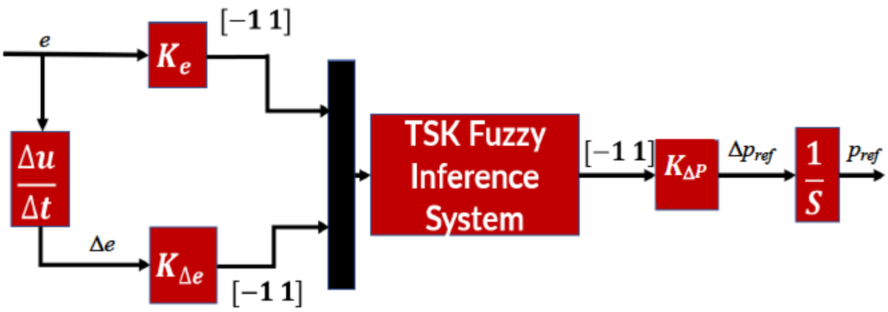

Fig. 5. Control strategy for Fuzzy-PID control

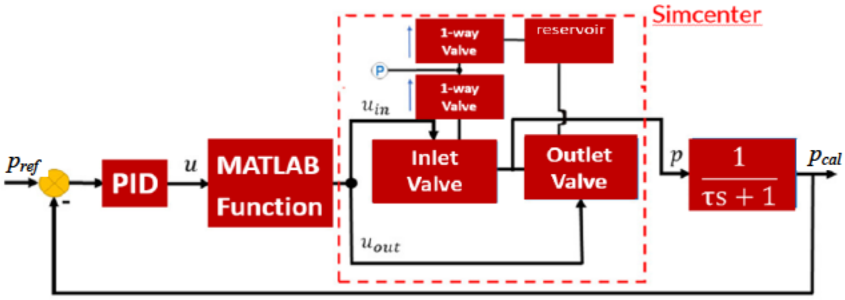

Fig. 6. Pressure control strategy and modulator model

The hydraulic modulator constructed on AMESim (the block is within the red dashed line in Fig. 6) including the master cylinder model (modeled by a stable pressure source, assuming the driver always applies full brake force, low-pressure reservoir model, two solenoid valves controlling pressure increase and decrease, and two one-way spring valve. The hydraulic modulator solely receives binary signals for the inlet and outlet valves, the valve is open when the command signal is 1, while it is closed when the command signal is equal to 0. Therefore, the pressure controller's analog control signal u needs to be transformed into two binary signals denoted as [u_{in} u_{out}]. When the command signal u is positive/negative, the outlet pressure p will correspondingly increase/decrease. This also indicates that the pressure saturates at p_{mc} or 0.

The behavior of the hydraulic modulator is simply modeled as follows:

$u > 1$ (pressure increase): $u_{in} = 1$, $u_{out} = 0$;

$-1 \leq u \leq 1$ (pressure hold): $u_{in} = 0$, $u_{out} = 0$;

$u < -1$ (pressure decrease): $u_{in} = 0$, $u_{out} = 1$.

Based on the theory, set the model parameters, and establish the electrical pulse control signal for the ABS solenoid valve, which is the control signal u derived from a simulation model. The control signal u_{in} is used for the inlet valve, while the control signal u_{out} is used for the outlet valve. The solenoid valve only receives two signals [0 1], corresponding to the open and closed modes of the valve. Initially, the inlet valve is set to open mode while the outlet valve is set to closed mode. The brake torque can be calculated from the pressure p_{cal} as follows. Where μ is the friction coefficient, d is the wheel cylinder diameter, and r_{tb} is the average radius of the brake pad

$$T_b = \mu \frac{\pi d^2}{2} p_{cal} r_{tb}. \quad (7)$$

Experiments on the real road. An experiment was conducted on a Mazda 6 vehicle to obtain input parameters for the simulation process [referencing the vehicle's technical specifications], and to validate both the developed model and control algorithm. The comparison between simulation results and experimental data was carried out to evaluate the model's accuracy and the performance of the controller. Key metrics used to assess braking effectiveness included braking distance, deceleration, and braking time. The Mazda 6, equipped with disc brakes on both front and rear wheels as well as an Anti-lock Braking System (ABS), offers a reliable platform for testing and validation purposes.

The experiment was divided into two parts. Part 1 involved determining the weight distribution on the axles and the coordinates of the vehicle's center of gravity. These are crucial input parameters for the simulation model. To obtain these parameters, a load weight feature of the shock absorber test bench (Fig. 7) was used. After obtaining the parameters for the simulation model, a subsequent experiment was conducted to determine parameters, including vehicle speed, angular velocity of the wheels, and braking distance. These parameters were used to compare with the simulation results to evaluate the accuracy of the simulation model. The equipment and connection diagram are detailed in Fig. 7.

The experimental process was conducted on the route shown in Fig. 8 and included the following steps:

Step 1: The test vehicle moves to location A at a speed of about 40 km/h. The information collector checks the sensor parameters received from the vehicle to ensure the connection is working properly and warms up the brake system.

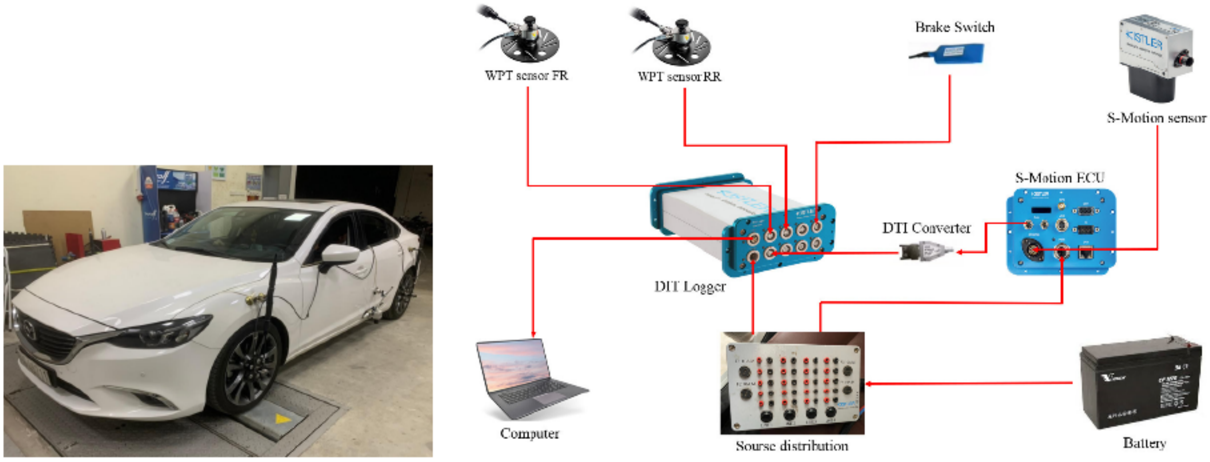

Fig. 7. Experimental vehicle after being equipped with sensors

Fig. 8. Experimental route

Step 2: The test vehicle moves to position *B* at a speed of about 90 km/h (25 m/s) and remains stable. Vehicle speed is observed via the dashboard or vehicle speed parameters displayed on the screen.

Step 3: The test vehicle maintains a constant speed from position *B* to position *C*. When the vehicle reaches position *C*, the driver depresses the brake pedal to perform the braking and stopping process. The Brake Switch sensor will receive the brake pedal signal and begin the process of recording the results on the KiCenter software.

Step 4: When the vehicle stops completely (the experimenter sets $v < 3$ km/h), the software will receive a signal, and the recording process ends.

Step 5: Review the results obtained and examine the wheel skid marks created during braking. Continue repeating the process for the remaining times. The results obtained include: braking distance, length, and braking time.

Step 6: Continue repeating the process for the remaining times to get accurate results.

The experiments were conducted on a dry asphalt road with a measured adhesion coefficient of 0.9. Data from experiments and simulations are presented in the next section.

Results and Discussion

Through survey results in each different road condition, the different slippage and adhesion coefficients between the wheels and the road surface were presented. The relationship between slippage and adhesion coefficient between wheels and road surface can be shown by the interpolation in Fig. 9.

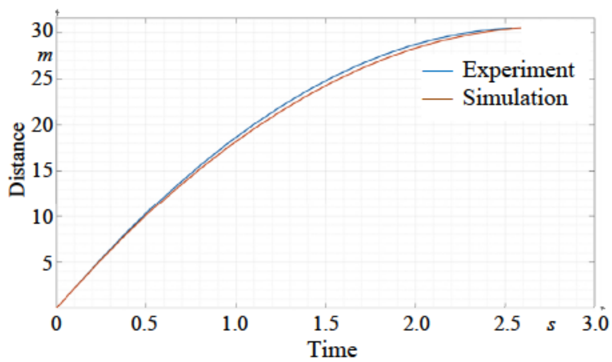

Fig. 9. Braking distance comparison graph

The study also compared and evaluated the effectiveness and accuracy of the built ABS control algorithm in case the vehicle speed was 21,6 m/s (Fig. 10) and the initial pressure measured by the Onboard diagnostics was 15 MPa. The results and evaluations are presented in the Table 4 below.

The table shows that the error of the braking time and braking distance of the simulation results compared to the experimental results above is all less than 5 %. In comparison with the results from some similar research [30], the simulation model combined two simulation software along with the reality experiments was able to give more accurate numbers of the error between the model and the actual, instead of parameters provided by the simulation model and their working as shown in research [6, 7], for example. Thus, the braking efficiency obtained through the simulation process has also been confirmed because the error is relatively small (Fig. 11, 12).

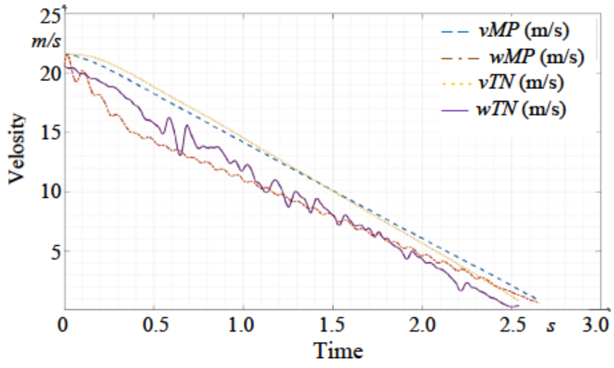

Fig. 10. Comparing the vehicle speed and the converted wheel speed graph *vMP* and *wMP* are the velocities of the vehicle and wheel in the simulation, *vTN*, and *wTN* are the velocities of the vehicle and wheel in the experiment

Table 4

Comparing braking time (t), braking distance (s), and average acceleration (a)

t_{MP} (s)	t_{TN} (s)	Δt (%)	S_{MP} (m)	S_{TN} (m)	ΔS (%)	a_{aveMP} (m/s^2)	a_{aveTN} (m/s^2)	Δa (%)
2.65	2.54	4.41	30.58	30.48	0.33	–7.83	–8.15	3.93
*MP: simulation results; *TN: Experimental data. t: total time of braking process s: brake distance a: acceleration								

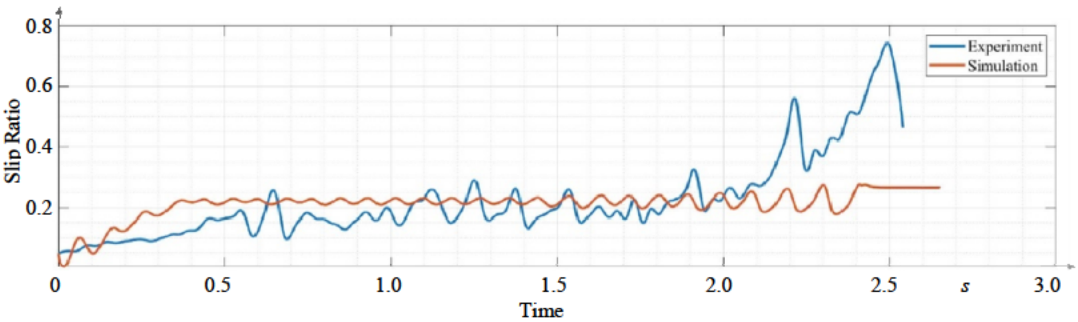

Fig. 11. Slip Ratio of Front Wheel

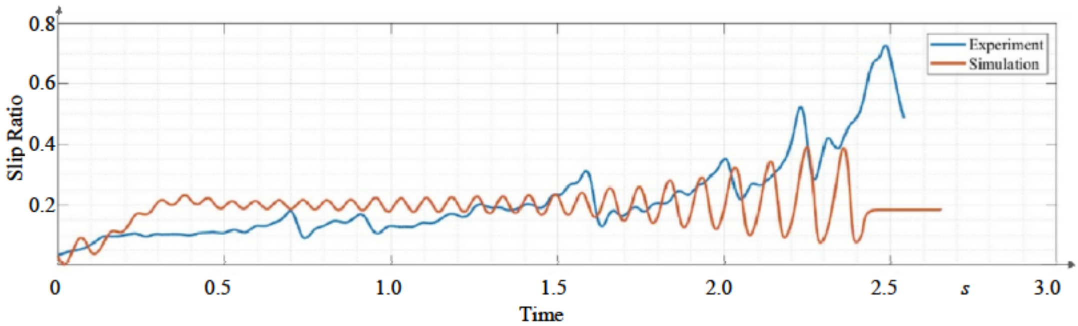

Fig. 12. Slip Ratio of Rear Wheel

In addition, the reliability of the simulation model can be confirmed by combining the Calculation and Simulation software (Simulink and AMESim), which can be shown in the Table 5 below.

Table 5

Error between the simulation and experimental results

Speed when braking	Mean Absolute Error MAE				Root Mean Square Error RMSE			
v_0 (m/s)	A (%)	S (%)	V (%)	w_1 (%)	σ_a (m/s^2)	σ_d (m)	σ_v (m/s)	σ_{w1} (rad/s)
21,6	2,10	0,56	1,90	5,90	0,65	0,21	0,27	2,06
v_0: Initial velocity, a is acceleration, s brake distance, w is the angular velocity of the wheel.								

From the table above, we see that at speed v_0 = 21,6 m/s, the simulation model of the ABS braking system has negligible errors compared to reality; respectively, the braking acceleration parameters, braking distance, and vehicle speed have an average absolute error of less than 3 %, and for wheel angular speed, it is less than 6 %. For root mean square error, the error values of acceleration, distance, and velocity are all so small (less than one), for wheel angular velocity, it is approximately 2 (rad/s). Thus, this proves that the simulation model using simulation software combined with Amesim Simcenter is highly reliable and can be applied to many different conditions. However, the simulation model has not achieved the braking efficiency as the actual experimental results; this needs to be further improved. On the other hand, the slip ratio of wheels in the simulation in Fig. 13 and 14 is similar to the experiment. That demonstrates the proposed control algorithm works effectively in comparison with the classical ABS in 8.5 % of braking time and 6.5 % of stopping distance [32].

The study also conducted simulations of the braking system under road conditions with varying adhesion coefficients to assess the system's effectiveness in real-world scenarios. The results shown in Table 6 indicate that the system operates under different road conditions. A comparison between road conditions with adhesion coefficients of 0.3 and 0.9 reveals a braking efficiency difference of approximately 3.7 times. The system also demonstrates effectiveness in preventing wheel slippage across various road conditions.

Table 6

Parameters assessing the braking efficiency of the system under different road conditions

Friction coefficient	t_{MP} (s)	S_{MP} (m)	a_{aveMP} (m/s^2)
0.3	10.3	112.6	–2.0
0.4	7.8	85.5	–2.7
0.5	5.2	58.1	–4.0
0.6	4.7	51.7	–4.5
0.7	4.4	49.7	–4.7
0.8	3.9	44.1	–5.3
0.9	2.7	30.6	–7.8

CONCLUSION

The experimental results obtained from real-vehicle testing demonstrated that the ABS equipped with a hybrid control algorithm based on PID regulation and Fuzzy logic enables a passenger car to decelerate from an initial speed of 21.6 m/s without wheel lock on a road surface with a adhension coefficient of 0.9, achieving a braking time of 2.54 s and a stopping distance of 30.48 m. These values are 8.5 and 6.5 %, respectively, lower than those obtained with the conventional hydraulic modulator control strategy.

The simulation results are in close agreement with the experimental data, exhibiting a deviation of 4.4 % in braking time, less than 0.5 % in stopping distance, and 3.9 % in vehicle deceleration. This confirms the high accuracy and adequacy of the AMESim/Simulink co-simulation model, demonstrating its suitability for the development and refinement of control algorithms, as well as for the investigation and evaluation of the complete braking process dynamics and system optimization.

REFERENCES

1. Maier M., Müller K. (1996) ABS5.3: The New and Compact ABS5 Unit for Passenger Cars. *International Congress & Exposition, Detroit, Michigan, United States, February 27, 1995. SAE Technical Paper,* No 950757. https://doi.org/10.4271/950757
2. Wellstead P., Pettit N. (1997) Analysis and Redesign of an Antilock Brake System Controller. *IEE Proceedings-Control Theory and Applications*, 144 (5), 413–426. https://doi.org/10.1049/ip-cta:19971441
3. Gajek A., Strzępek P., Dobaj K. (2018) Algorithms for Diagnostics of the Hydraulic Pressure Modulators of ABS/ESP Systems in Stand Conditions. *MATEC Web of Conferences,* 182, 1020. https://doi.org/10.1051/matecconf/201818201020
4. Tao Run Z. H., Dechun F. (2010) The Modeling and Simulation of ABS Hydraulic Brake System Using AMESim. *Journal of Guangdong Communications Polytechnic*, 9 (1), 46 (in Chinese).
5. Choi S. B., Sung K.G., Cho M. S., Lee Y. S. (2007) The Braking Performance of a Vehicle Anti-lock Brake System Featuring an Electro-Rheological Valve Pressure

Modulator. *Smart Materials and Structures*, 16 (4), 1285. https://doi.org/10.1088/0964-1726/16/4/041
6. Zhilevich M., Ermilov S., Kapski D., Vovk Y., Lyashuk O., Vovk I. (2021) Method of Calculating the Design Parameters of a Modulator Anti-Lock Braking System with a High Flow of Working Fluid. *Scientific Journal of Silesian University of Technology. Series Transport,* 110, 199–210. https://doi.org/10.20858/sjsutst.2021.110.16
7. Ferro J. P. (2014) *Design and Simulation of an ABS Control Scheme for a Formula Student Prototype*. Tecnico Lisboa. Available at: http://www.dem.ist.utl.pt/poliveira/Ensino/MSc_2014a.pdf
8. Li X., Zhao L., Zhou C., Li X., Li H. (2020) Pneumatic ABS Modeling and Failure Mode Analysis of Electromagnetic and Control Valves for Commercial Vehicles. *Electronics*, 9 (2), 318. https://doi.org/10.3390/electronics9020318
9. Wang J., Song C., Jin L. (2010) Modeling and Simulation of Automotive Four-Channel Hydraulic ABS Based on AMESIM and Simulink/Stateflow. *2010 2nd International Workshop on Intelligent Systems and Applications*. IEEE, 1–4. https://doi.org/10.1109/iwisa.2010.5473264
10. Abreu R., Botha T. R., Hamersma H. A. (2023) Model-Free Intelligent Control for Antilock Braking Systems on Rough Roads. *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, 7 (03), 269–285. https://doi.org/10.4271/10-07-03-0017
11. Ghanami N., Nikzadfar K., Daniali H. R. M. (2023) A Mid-Fidelity Model in the Loop Feasibility Study for Implementation of Regenerative Antilock Braking System in Electric Vehicles. *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, 7 (03), 343–366. https://doi.org/10.4271/10-07-03-0022
12. Jiang F., Gao Z. (2001) An Application of Nonlinear PID Control to a Class of Truck ABS Problems. *Proceedings of the 40th IEEE Conference on Decision and Control* (Cat. No 01CH37228), 1. IEEE, 516–521. https://doi.org/10.1109/cdc.2001.980154
13. Zhao Q., Duan J. J., Wang C. (2012) Modeling and Simulation of Vehicle Hydraulic ABS Based on AMEsim. *Advanced Materials Research*, 590, 441–445. https://doi.org/10.4028/www.scientific net/amr.590.441
14. Chen C.K., Shih M. C. (2004) PID-Type Fuzzy Control for Anti-Lock Brake Systems with Parameter Adaptation. *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, 47 (2), 675–685. https://doi.org/10.1299/jsmec.47.675
15. Harly M. (2020) Modeling of Hydraulic ABS Plant and Its Control by Using Fuzzy Mamdani with Adaptive Slip Frequency to Improve Stopping Distance and Steering Ability. *Journal of Physics: Conference Series*, 1700 (1), 012044. https://doi.org/10.1088/1742-6596/1700/1/012044
16. Keshmiri R., Shahri A. M. (2007) Intelligent ABS Fuzzy Controller for Diverse Road Surfaces. *World Academy of Science, Engineering and Technology*, 2 (2), 62–67.
17. El-Fatah A., Sharkawy A.-N., Ghazaly N. M., Moaaz A. (2021) A Comparative Study of Different Control Methods for Anti-Lock Braking System (ABS). *SVU-International Journal of Engineering Sciences and Applications*, 2 (1), 27–34. https://doi.org/10.21608/svusrc.2021.65855.1007
18. Mailah M., Al-Mola M. H., Muhaimin A. H., Abdullah M. Y. (2012) Fuzzy-Based PID with Iterative Learning Active Force Controller for an Anti-Lock Brake System. *International Journal of Simulation: Systems, Science and Technology*, 13 (3), 35–41. https://doi.org/10.5013/ijssst.a.13.3a.05
19. Gong T., Yan H., Liu P. F. (2015) Modeling and Simulation for Anti-Lock Braking System (ABS) of Automobiles Based on Simulink. *Applied Mechanics and Materials,* 716–717, 1504–1507. https://doi.org/10.4028/www.scientific.net/amm.716-717.1504
20. Wang X., Wang Q. (2012) Modeling and Simulation of Automobile Anti-Lock Braking System Based on Simulink. *Journal of Advanced Manufacturing Systems*, 11 (02), 99–106. https://doi.org/10.1142/s0219686712500084
21. Cao W. (2021) Modeling and Simulation of the Anti-Lock Braking System Based on MATLAB/Simulink. *Journal of Physics: Conference Series*, 1941 (1), 12075. https://doi.org/10.1088/1742-6596/1941/1/012075
22. Xiao L., Hongqin L., Jianzhen W. (2016) Modeling and Simulation of Anti-Lock Braking System Based on Fuzzy Control. *International Advanced Research Journal in Science, Engineering and Technology*, 3 (10), 110–113. https://doi.org/10.17148/iarjset.2016.31021
23. Liu Y., Sun J. (1995) Target Slip Tracking Using Gain-Scheduling for Anti-Lock Braking Systems. *Proceedings of 1995 American Control Conference-ACC'95*, 2, 1178–1182. https://doi.org/10.1109/acc.1995.520935
24. Mirzaeinejad H., Mirzaei M. (2010) A Novel Method for Non-Linear Control of Wheel Slip in Anti-Lock Braking Systems. *Control Engineering Practice,* 18 (8), 918–926. https://doi.org/10.1016/j.conengprac.2010.03.015
25. Chereji E., Radac M.-B., Szedlak-Stinean A.-I. (2020) Sliding Mode Control Algorithms for Anti-Lock Braking Systems with Performance Comparisons. *Algorithms*, 14 (1), 2. https://doi.org/10.3390/a14010002
26. Vo-Duy T., Ta M. C. (2018) Slip Ratio Estimation for Traction Control of Electric Vehicles. *2018 IEEE Vehicle Power and Propulsion Conference (VPPC)*. IEEE, 1–6. https://doi.org/10.1109/vppc.2018.8604980
27. Hayes J. G., Goodarzi G. A. (2018) *Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles*. John Wiley & Sons Ltd, UK. https://doi.org/10.1002/9781119063681
28. Gao Y., Maghbelli H., Ehsani M., Frazier G., Kajs J., Bayne S. (2003) Investigation of Proper Motor Drive Characteristics for Military Vehicle Propulsion. *SAE Technical Paper Series*, 1, 0148–7191. https://doi.org/10.4271/2003-01-2296
29. Heydrich M., Ivanov V., Bertagna A., Rossi A., Mazzoni M., Bücner F. (2022) Hardware-in-the-Loop Testing of a Hybrid Brake-by-Wire System for Electric Vehicles. *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, 6 (04), 477–487. https://doi.org/10.4271/10-06-04-0031
30. Savitski D., Schleinin D., Ivanov V., Augsburg K. (2018) Robust Continuous Wheel Slip Control with Reference Adaptation: Application to the Brake System with Decoupled Architecture. *IEEE Transactions on Industrial Informatics*, 14 (9), 4212–4223. https://doi.org/10.1109/tii.2018.2817588
31. Heydrich M., Ricciardi V., Ivanov V., Mazzoni M., Rossi A., Buh J., Augsburg K. (2021) Integrated Braking Control for Electric Vehicles with In-Wheel Propulsion and Fully Decoupled Brake-by-Wire System. *Vehicles*, 3 (2), 145–161. https://doi.org/10.3390/vehicles3020009
32. Le V. N., Dam H. P., Nguyen T. T., Trinh M. H., Tran T. D. (2024) Modeling of the Anti-Lock Braking System Employing a Fuzzy Controller. *International Review of Mechanical Engineering*, 18 (10), 525–533. https://doi.org/10.15866/ireme.v18i10.25307

Received: 14.01.2026
Accepted: 19.03.2026
Published online: 29.05.2026