Simulation of Electric Truck Brake System Operating in Industrial Plants

Minh Duc Le*, Dinh Nghia Duong, Cong Tin Le

Abstract—This study analyzes the quarter car braking model to determine the effect of the wheel slip ratio (λ) on the friction coefficient (μ) during the braking of the car. The friction coefficient reaches a minimum when the slip ratio $\lambda \sim 1$; maximum friction coefficient at the optimal slip ratio value from 0.18 to 0.2. Dynamic Model of the vehicle in the ABS brake study should consider in detail the dynamic aspects of braking and the interaction between the tire and the road profile. CarSim software is used in this study to simulate the braking system of a vehicle operating in industrial plant; Simulation is performed on both cases of ABS and non-ABS braking systems. The results of braking distance, deceleration, and brake pressure are considered and analyzed to select a suitable braking system for the operating conditions of the designed truck.

Index Terms—ABS, Non-ABS, Slip Ratio, Friction Coefficient, Electric truck

1. Overview

BRAKING is a safety system intended to slow or stop a vehicle [1]. In the past decades, many advanced braking techniques, such as anti-lock braking system ABS, electronic brake force distribution system EBD, emergency brake assist technology BA, etc., have been developed and applied effective use on vehicles participating in traffic [2]. ABS is a pure brake control system, systems such as EBD, BA, etc. are multitasking systems that combine braking, stability and even impact on the vehicle's traction. In which the anti-lock braking system (Anti-lock Braking System: ABS) has been widely applied in cars. ABS helps control wheel slip to maintain the coefficient of friction between the tire and the road at an optimal value, allowing the driver to have better control over the driving process [2].

Slip ratio is an important factor during braking related to vehicle safety and stability. The slip ratio depends on the relationship between the tire and the road surface [3]. Surveys at industrial plants show that, depending on the type and product produced, during production operation, the road surface can adhere to highly viscous wastes, reducing the coefficient of adhesion and increasing the amount of waste. slip ratio. This problem increases the risk of vehicle failure when operating in factory conditions. However, currently, the vehicles operating in industrial plants are almost not equipped with brakes to help control the sliding process. Therefore, the integrated design of an ABS braking system on vehicles operating in industrial plants is necessary in terms of safety factors and operational technical factors.

Slower braking acceleration, braking time, braking distance, braking force are the criteria to evaluate the quality of the braking process. In which the braking distance is the most important criterion to evaluate the braking quality of the vehicle, the braking distance is also a parameter that the driver can perceive visually. National technical regulation QCVN 09:2015/BGTVT clearly states the braking distance requirements for each vehicle under different load conditions [4]. Vehicles operating in industrial plants may not be considered an official vehicle, but to ensure safety, a standard braking distance assessment needs to be performed. Besides the evaluation of the parameters of the speed change during braking, the brake pressure in general needs to be done during the design of a braking system for vehicles in an industrial plant.

The theoretical calculation of the braking distance in a new design for a fully mechanical brake system is possible with high accuracy [1]. Regardless of external factors (i.e., operating conditions), the braking distance depends on the vehicle speed when braking, the total weight of the vehicle, the braking force and the rotational mass factor of the vehicle powertrain system. However, for the brake system with integrated ABS control system, in addition to the above factors, the slip ratio is considered the most important factor in the brake system design. Slip ratio is a function of vehicle speed and wheel speed [3], evaluating the relationship between road surface and wheel conditions to determine wheel speed when braking is very complicated, depending on many factors. factors such as tire material, road surface, tire pressure, etc. The accuracy of the calculated results depends largely on experimental data in many practical conditions.

Numerical modeling and simulation bring many

Minh Duc Le, Dinh Nghia Duong and Cong Tin Le are with the University of Danang - University of Science and Technology, Danang, Vietnam.

**Corresponding author: Minh Duc Le (e-mail: minhducle@dut.udn.vn)*
Manuscript received October 24, 2022; revised February 04, 2023; accepted March 09, 2023.
Digital Object Identifier 10.31130/jst-ud.2023.482ICT

benefits in the automotive field [5]. Numerical simulation software has advantages in calculation with rich experimental data system and suitable for many different external conditions. Therefore, in the design of the brake system with integrated ABS anti-lock control system, the application of simulation helps to understand the braking phenomena and the effects of the coefficients on the braking efficiency of the vehicle.

In this study, the author presents the analysis of the brake system parameters with integrated ABS control system in a specialized truck for transporting goods and materials (i.e., electrical truck). The electrical truck weight is less than 500kg using electric power dynamic system and used in industrial plants. This specialized design of truck requires many factors. In general, if this electric truck wants to be used in industrial zones in Vietnam with the same equipment features as traditional vehicles, it is imperative to have in-depth studies and evaluate the effectiveness of the design. In addition, in Vietnam, the electric car industry has just started and electric trucks have not appeared in the Vietnamese market at all. One of those design factors is breaking system and ABS is obviously used to examine. Consequently, analysis of brake system parameters is performed on the automotive dynamics simulation software CARSIM. The criteria of the brake system with integrated ABS control system are compared and analyzed with the mechanical brake system with the same parameters and working conditions. From there, the appropriate brake system could be determined for the truck operated in industrial plants.

2. ABS simulation theory

2.1. Force analysis model

The quarter model has the necessary characteristics of the entire vehicle dynamics [6]. A force analysis model is shown in Fig. 1.

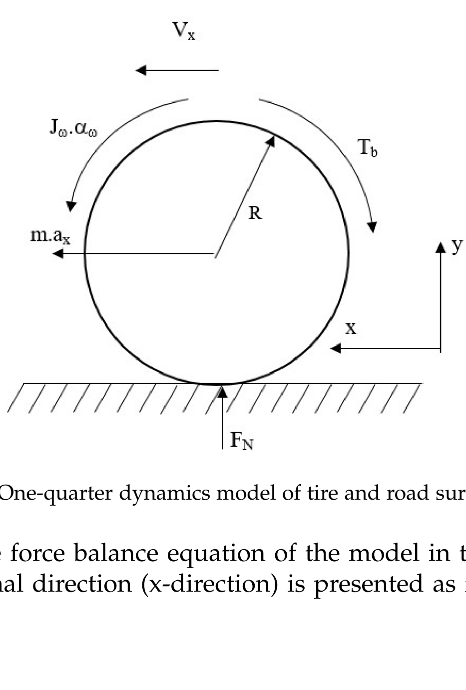

Fig. 1: One-quarter dynamics model of tire and road surface [7]

The force balance equation of the model in the longitudinal direction (x-direction) is presented as follows [6]–[8]:

$$ma_x = -\mu.F_N = m\frac{dV_x}{dt} \quad (1)$$

Torque at wheel center is defined as:

$$J_\omega \alpha_\omega = \mu R F_N - T_b \leftrightarrow J_\omega \dot{\omega} = \mu R F_N - T_b \quad (2)$$

Wheel slip ratio is defined as:

$$\mu = \frac{V_x - \omega R}{V_x} \quad (3)$$

Differentiate Eq. (3) with respect to time:

$$\dot{\mu} = \frac{(1-\lambda)\,\dot{V}_x - R.\dot{\omega}}{V_x} \quad (4)$$

Substitute (1) and (2) into (4):

$$\dot{\lambda} = -\frac{\mu}{V_x}\left[(1-\lambda)\,g + \frac{R^2 mg}{J_\omega}\right] + \frac{RT_b}{V_x J_\omega} \quad (5)$$

TABLE 1: Annotation of mathematical symbols and force model symbols [6]

Parameter	Nomenclature
m	One-quarter of truck weight
V_x	Velocity of truck
m	Friction coefficient
J_w	Moment of inertia of the wheel
R	Working radius of wheel
T_b	Braking torque acting on the wheel
l	Wheel slip ratio
w	Angular speed of the wheel

The relationship between the coefficient of friction and the wheel slip ratio represents the ability of ABS to maintain the driving state and to stabilize the vehicle's motion during braking. The coefficient of friction is a function of the car's speed and the tire's slip rate. In addition, speed factors such as road conditions, tire type, vehicle speed also have an important influence on the coefficient of friction [9]. The mathematical model of tire friction used to simulate the ABS braking system has the form [9]:

$$((\lambda, V_x) = \left[C_1\left(1 - e^{-C_2\lambda}\right) - C_3\lambda\right] e^{C_4 V_x} \quad (6)$$

where:

C_1 – The maximum value of the friction curve; C_2 – The friction curve shapes; C_3 – Difference between the maximum value of friction coefficient and its value at $\lambda = 1$; C_4 – The characteristic value of the wetness of the road. The reference values of C_1, C_2, C_3, and C_4 for different type of road can be found in Table 2 [9].

The coefficient of friction between the tire and the road surface has the smallest value when the slip ratio $\lambda \sim 1$, coefficient of friction reaches its maximum value in the region of optimum sliding ratio value from 0.18 to 0.2 [9], [10]. If the slip ratio is higher than 0.2, the brake pressure should be kept at zero. While if the slip ratio is below 0.18, then the brake pressure is set at maximum value. Therefore, the ABS controller is designed to control the wheel slip ratio λ to the optimal value 0.2 to achieve the maximum value of friction coefficient.

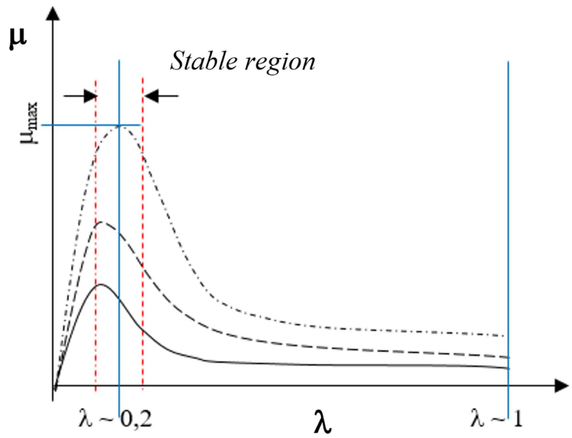

Fig. 2: The coefficient of friction in the domain of slip ratio. [6] [9] [10]

TABLE 2: The value of C_1, C_2, C_3, and C_4 [9]

The type of road	C_1	C_2	C_3	C_4
Dry road	1.2801	23.99	0.52	0.03
Wet road	0.8570	33.822	0.347	0.04

2.2. Kinematic model of brake control

Non-ABS brake system

The brake system consists of a mechanical and hydraulic system that converts the force applied to the pedal F_{bd} into Braking torque Tb. The block diagram of the brake system usually includes the brake pedal, master cylinder, brake circuit, brake pad and brake disc. In the absence of an ABS controller, a block diagram of a brake system can be presented as Fig. 3.

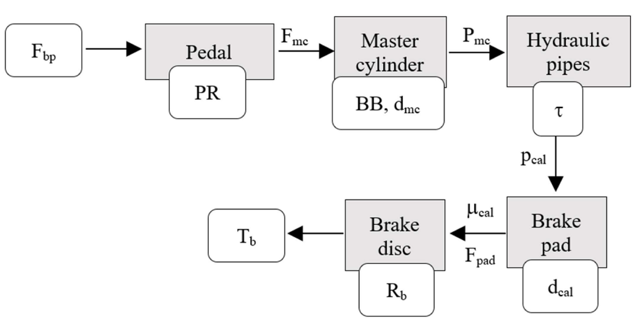

Fig. 3: Non-ABS brake system control block diagram [11]

ABS brake system

The hydraulic modulator is a hydraulic device used to reduce, hold and restore pressure in the hydraulic circuit of the ABS brake system, as shown in Fig. 4.

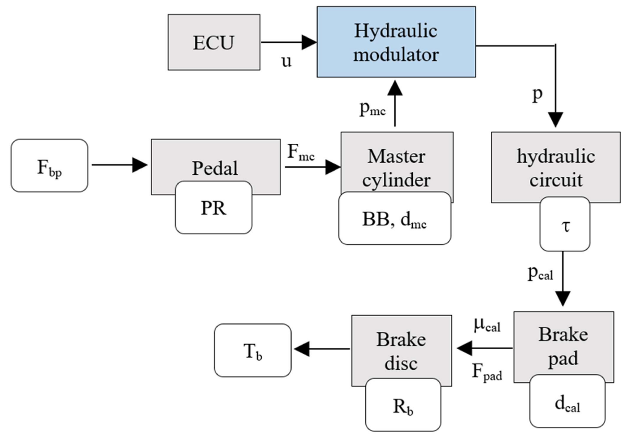

Fig. 4: Block diagram of ABS brake system control [11]

The process of adjusting the pressure of the hydraulic modulator is simply simulated as follows [11]:

$$\begin{cases} u = (0,0) \rightarrow \frac{dp}{dt} = \frac{p_{mc}-p}{p_{mc}} R_{inc} \rightarrow \text{Rising pressure} \\ u = (1,0) \rightarrow \frac{dp}{dt} = 0 \rightarrow \text{Keeping pressure constant} \\ u = (1,1) \rightarrow \frac{dp}{dt} = -R_{dec} \rightarrow \text{Droping pressure} \end{cases} \tag{7}$$

where: u – Binary control signal for inlet and outlet valves; R_{inc} – pressure rise rate;R_{dec} – Pressure drop rate

The overall kinetic model of the vehicle

For ABS system studies, braking dynamics and tire-road interaction are aspects to be considered, a full model is developed consisting of five interdependent submodules. The overall vehicle dynamics model is presented in Fig. 5.

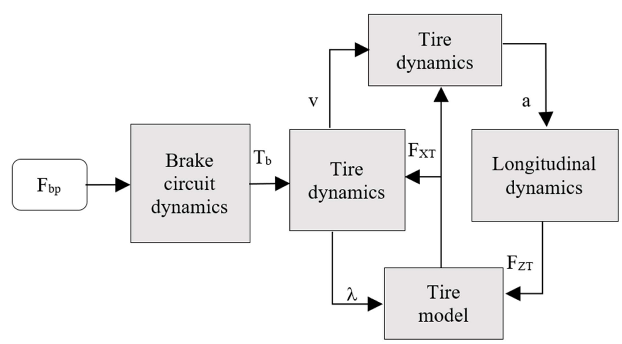

Fig. 5: The overall kinetic model of the vehicle [11]

3. Simulation results and analysis of brake system

3.1. Truck specifications

The main parameters of electric trucks operating in industrial plants are listed in Table 4. The truck model is shown in Fig. 6.

3.2. Simulation model

CARSIM is a numerical software used to simulate the dynamics of cars. The software uses 3D multi-body dynamics models to accurately establish the physical model of the vehicle. Simulating the vehicle's kinematics on Carsim software helps to achieve the design requirements in terms of dynamics of the steering system, special gearshifting of the ABS braking system. The operating conditions including road surface and aerodynamic effects are also considered in the simulation model Carsim [12].

TABLE 3: Annotation of mathematical symbols presented in Figures 3, 4, 5 [11]

Parameter	Nomenclature
a	Longitudinal distance from the vehicle CG to the front axle center line
F_{bp}	Pedal force
PR	Pedal ratio
BB	Brake bias
t	Time constant
T_b	Brake torque
d_{mc}	Diameter of master cylinder
R_b	Diameter of brake disc
F_{mc}	Force applied to master cylinder
p_{mc}	Pressures on the master cylinder
$pcal$	Caliper pressure
d_{cal}	Caliper diameter
v	Vehicle velocity

TABLE 4: The designed truck specifications

Parameters	Symbols	Value	Unit
Total weight	m_g	1350	kg
Transport weight	m_a	500	kg
Mass distribution front axle	m_f	432	kg
Rear axle distribution	m_r	918	kg
Overall length	L	3850	mm
The standard long	L_{cs}	2740	
Distance from center of gravity to front axle	a	1863.2	mm
Distance from center of gravity to rear axle	b	876.8	mm

Fig. 6: Truck model

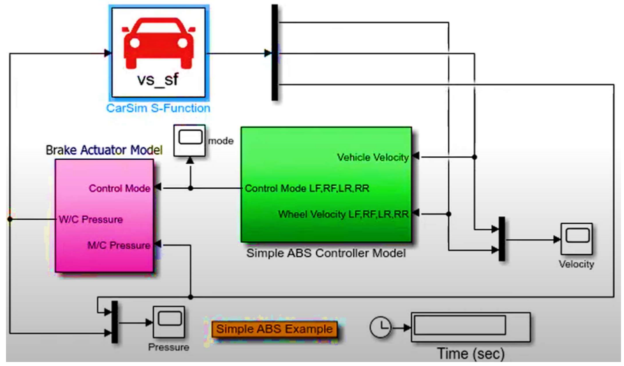

Fig. 7: ABS simulation diagram

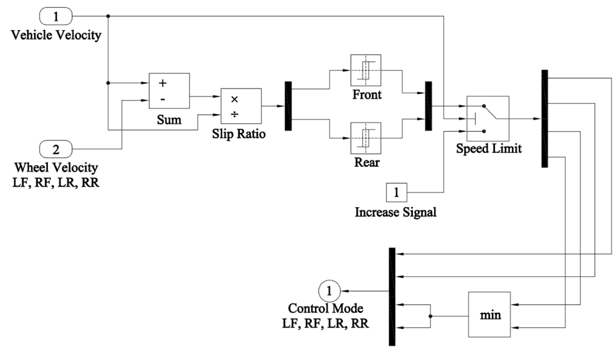

Fig. 8: ABS control block diagram

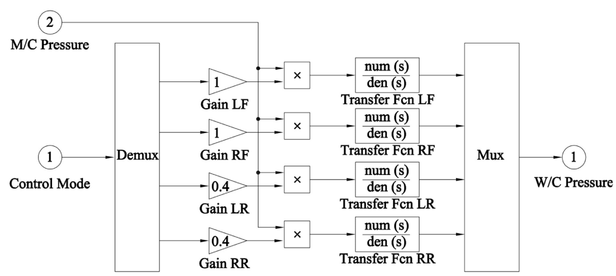

Fig. 9: Block diagram of ABS actuator

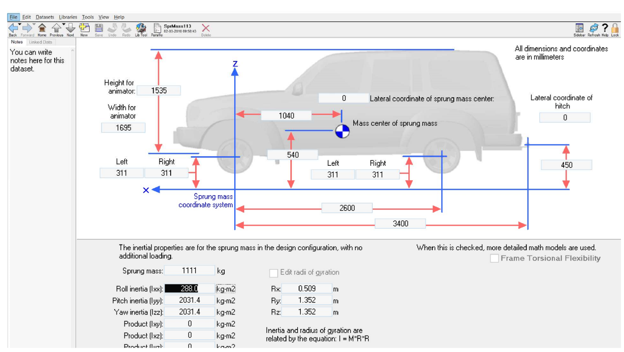

Fig. 10: The interface parameters of the simulated vehicle

Modeling diagram of ABS brake system simulation, ABS control diagram and ABS actuator system diagram in this study is done with the help of Carsim software. The settings are shown in Figures 7, 8, and 9. The interface parameters of Carsim are shown in Fig. 10.

3.3. Results and discussion

Following suggestion of Moaaz et al. [9] and Pedro et al. [10], a constant value of the slip ratio $\lambda = 0.2$ on wet and dry roads is set to perform calculation of the ABS braking system. For the case of non-ABS braking systems, the slip ratio value will vary according to the type of road in which the simulation is performed appropriately. Simulation results are the graphs of braking distance, change of speed, and brake pressure. The case of non-ABS braking system both plays a valid role for the vehicle and tire dynamics model and is used to compare with the case of ABS braking system. Fig. 11 shows typical animated cars during the braking time with and without ABS using Carsim sofware. The blue car keeps going straightforward in the case of using ABS, while the red car rotates and slips in the case of non-ABS.

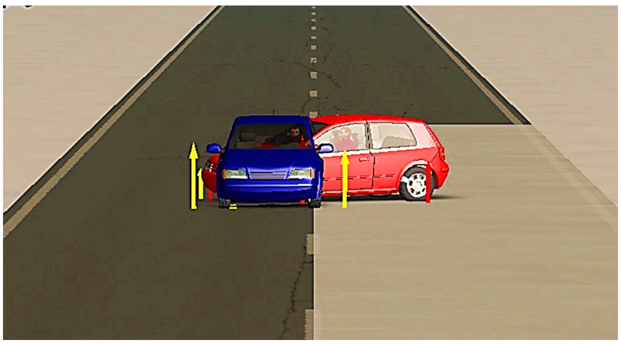

Fig. 11: Animated braking between vehicles with ABS (blue) and without ABS (red) by Carsim

Brake pressure graph

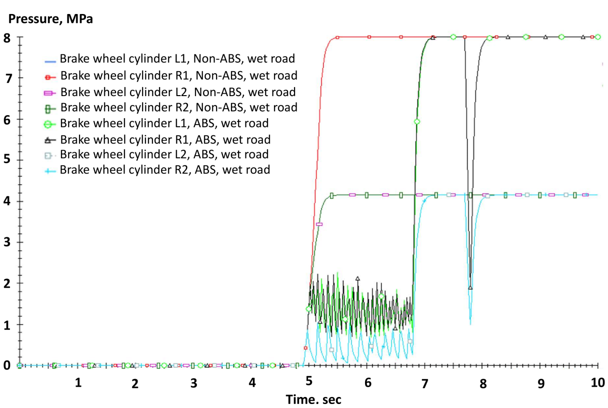

Fig. 12: Brake pressure at wheels on wet road

Comment: For non-ABS braking system, brake pressure increases linearly with braking force; In contrast, for ABS braking system, the brake pressure characteristic curve fluctuates, showing the process of increasing - holding - decreasing the pressure of the ABS control system, the purpose of keeping the slip ratio at a constant value.

Brake longitudinal speed ***Comment:*** The change in speed is a function related to the process of changing brake pressure, so the velocity simulation graph correctly shows the correlation with the process of changing brake pressure. For non-ABS braking systems, the velocity curve decreases linearly and returns to zero; with the ABS brake system, the speed line has oscillating characteristics, showing the control of increasing - decreasing - keeping the pressure of the ABS control system.

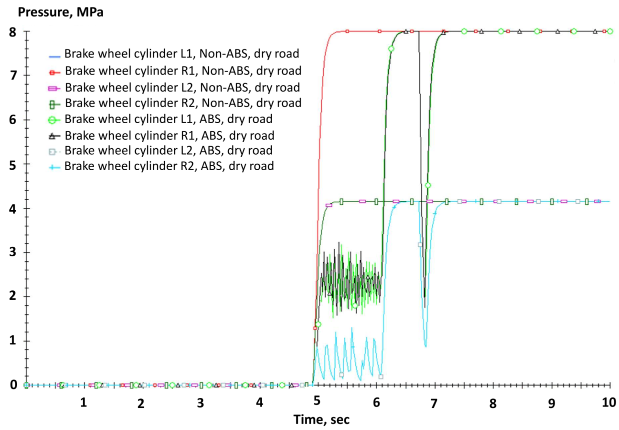

Fig. 13: Brake pressure at wheels on dry road

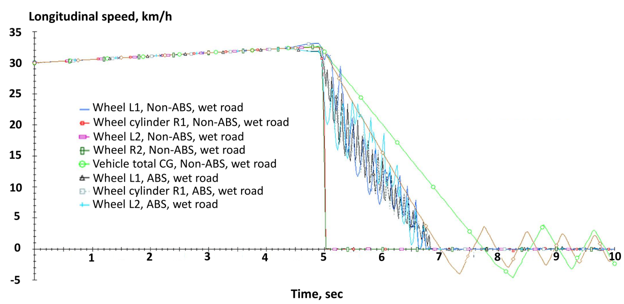

Fig. 14: Longitudinal speed of truck on wet road

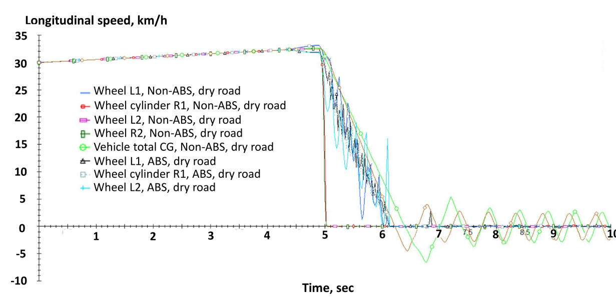

Fig. 15: Longitudinal speed of truck on dry road

Brake distance

Comment:

+ In conditions of wet roads (Fig. 16), with the ABS braking system, the braking time is 1.6s (i.e., the brake start time is 5.2s and the truck stops at 6.8s); The braking distance of the truck is 6.5m (i.e., the position where the truck starts to brake is 45.5m and the truck stops at 52m). With the non-ABS braking system, the resulting braking time is 2.3s (i.e., the brake start time is 5.2s and the truck stops at 7.5s); The braking distance of the car is 10m (i.e., the position where the truck starts to brake is 45.5m and the truck stops at 55.5m).

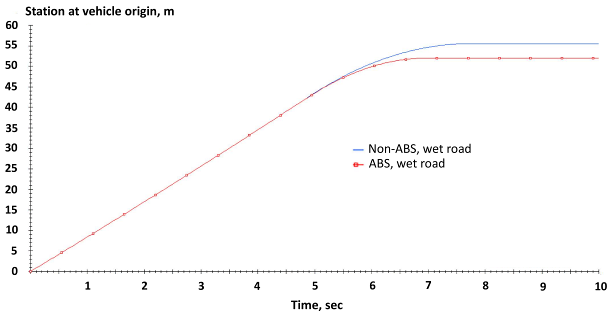

Fig. 16: Braking distance on wet road

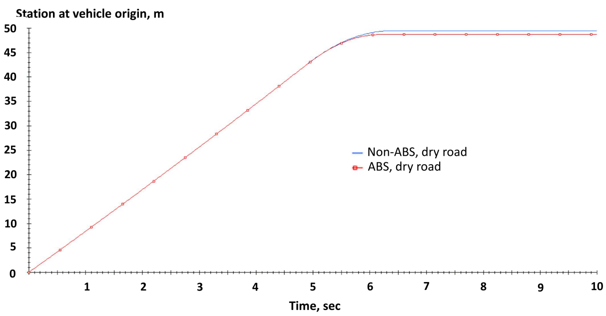

Fig. 17: Braking distance on dry road

+ In conditions of dry road (Fig. 17), with the ABS braking system, the braking time is 0.95s (i.e., the braking start time is 5.2s and the truck stops at 6.1s). The braking distance of the truck is 4m (i.e., the truck starts at 45m and the truck stops at 49m). For the case of without ABS, the resulting braking time is 1.05s (i.e., the brake start time is 5.2s and the truck stops is 6.25s); The braking distance of the truck is 10m (i.e., the position where the truck starts to brake is 45m and the truck stops at 49.5m).

The braking distance is a function that depends on the dynamic system (i.e., the factor taking into account the influence of the rotating mass of the truck δ); truck speed at the start of braking v_1, and coefficient of traction μ [1]:

$$S_{min} = \int_{v_2}^{v_1} \frac{\delta_i}{2\mu g} \tag{8}$$

From Eq. (8), to reduce the braking distance, it is necessary to reduce the coefficient δ, while maintaining the coefficient μ. Thanks to the operation of the ABS brake control system, the skid is maintained at a constant level to ensure the coefficient of traction is valid in the most optimal area, while the coefficient of grip of the non-ABS brake system decreases rapidly with the slip. Therefore, a braking system with ABS will give a shorter braking distance than a conventional mechanical brake system. The simulation results have properly reflected the properties of mathematical analysis [13]–[15].

4. Conclusion

This study focus on the dynamic model of the tire and road surface during braking, and mathematically analyzes the relationship between the coefficient of traction and the slip ratio of an electrical truck. The characteristics of braking distance, braking speed and brake pressure of the traditional mechanical brake system and the brake system with integrated ABS control have been studied and analyzed using CARSIM software. From the analysis results, some important conclusions are drawn as follows:

+ The slip ratio is a function of truck speed and wheel speed; plays a decisive role in the control characteristics of the ABS system. As the ABS controller is designed to control the wheel slip ratio value of λ = 0.2, the friction coefficient can attain highest value consequently.

+ When performing braking simulation on the wet road, the result of the difference in magnitude between the two brake systems is equivalent to 35%; it is about 6.5 [m] for the case with ABS, while it is about 10 [m] for the case without ABS. This means that the safety, drivability, and stability of the truck brake system in the case of with ABS are higher than those in the case of without ABS for the designed model.

+ The brake velocity represents the degree of speed change during braking, with the ABS braking system, the speed of change is a complex oscillation function that depends on the slip ratio; While with non-ABS braking system, the speed decreases linearly with the braking force.

+ The brake pressure shows the increase in pressure during braking. With the ABS braking system, the brake pressure changes according to a complex oscillation function depending on the slip ratio; While with non-ABS braking system, the pressure decreases linearly with braking force.

Acknowledgement

This work was supported by The University of Danang - University of Science and Technology and Murata Project under grant number T2021-02-O2MSF.

References

[1] N. H. Cẫn, D. Q. Thinh, P. M. Thái, N. V. Tài, and L. T. Vàng, "Lý thuyết ôtô máy kéo," *Nhà xuất ban Khoa hoc Kỹ thuât*, 2005.

[2] X. Gong, W. Ge, J. Yan, Y. Zhang, and X. Gongye, "Review on the development, control method and application prospect of brake-by-wire actuator," in *Actuators*, vol. 9, no. 1. MDPI, 2020, p. 15.

[3] C.-K. Huang and M.-C. Shih, "Design of a hydraulic anti-lock braking system (abs) for a motorcycle," *Journal of mechanical science and technology*, vol. 24, pp. 1141–1149, 2010.

[4] "QCVN 09 : 2015/BGTVT," Ministry of Transport, Ha Noi, Tech. Rep., 2015.

[5] R. Machová, L. Fehér, E. Korcsmáros, Z. Gódány, S. T. Kosár, and E. S. Huszárik, "The positive benefits of the practical application of the simulation software," *Journal of Language and Cultural Education*, vol. 9, no. 1, pp. 39–49, 2021.

[6] Y. He, C. Lu, J. Shen, C. Yuan *et al.*, "Design and analysis of output feedback constraint control for antilock braking system with time-varying slip ratio," *Mathematical Problems in Engineering*, vol. 2019, 2019.

[7] A. El-Fatah, A.-N. Sharkawy, N. M. Ghazaly, A. Moaaz *et al.*, "A comparative study of different control methods for anti-lock braking system (abs)," *SVU-International Journal of Engineering Sciences and Applications*, vol. 2, no. 1, pp. 27–34, 2021.

[8] I. Shinko, E. Shurdha, B. Kamo, E. Agastra, and K. Dhoska, "A fuzzy logic-based anti-lock braking systems," *Machines. Technologies. Materials.*, vol. 14, no. 2, pp. 58–60, 2020.

[9] A. O. Moaaz, A. S. Ali, and N. M. Ghazaly, "Investigation of anti-lock braking system performance using different control systems," *International Journal of Control and Automation*, vol. 13, no. 1s, pp. 137–153, 2020.

[10] J. O. Pedro, O. A. Dahunsi, and O. T. Nyandoro, "Direct adaptive neural control of antilock braking systems incorporated with passive suspension dynamics," *Journal of mechanical science and technology*, vol. 26, pp. 4115–4130, 2012.

[11] J. P. Ferro, "Design and simulation of an abs control scheme for a formula student prototype," *Tecnico Lisboa.–2014*, 2014.

[12] M. S. CarSim, "Introduction to carsim," USA, 2021.

[13] T. D. Day and S. G. Roberts, "A simulation model for vehicle braking systems fitted with abs," *SAE Transactions*, vol. 111, pp. 821–839, 2002.

[14] M. H. B. Peeie, H. Ogino, and Y. Oshinoya, "Skid control of a small electric vehicle with two in-wheel motors: simulation model of abs and regenerative brake control," *international journal of crashworthiness*, vol. 21, no. 5, pp. 396–406, 2016.

[15] C. Song, J. Wang, and L. Jin, "Study on the composite abs control of vehicles with four electric wheels." *J. Comput.*, vol. 6, no. 3, pp. 618–626, 2011.

Minh Duc Le is a lecturer in the Department of Transportation Mechanical Engineering at The University of Danang - University of Science and Technology (UD-DUT), Vietnam. He received B.E. in M.E. from UD-DUT in 2008, MSc. and P.D. in M.E. from NTUST, Taiwan in 2013 and 2017, respectively. His current research interests are FEM analysis in automotive structures, combustion engine, and fluid flow, etc.

Dinh Nghia Duong is pursuing his Ph.D. at the department of M.E., Yokohama National University, Japan. He received B.E. in M.E. from UD-DUT in 2011, MSc. in M.E. from NTUT, Taiwan in 2015. His current research focus on the automotive structure and combustion engine.

Cong Tin Le is a lecturer in the Department of Transportation Mechanical Engineering at UD-DUT, Vietnam. He has done his B.E. and MSc. in M.E. from UD-DUT in 2016 and 2019, respectively. His current research interests include Durability Analysis, Noise ad Vibration Analysis, Multibody Dynamic Simulation, Material Microstructure Optimization and Computer-Aided Engineering, etc.