International Journal of Control and Automation
Vol. 13, No. 1s, (2020), pp. 137-153

# Investigation of Anti-Lock Braking System Performance Using Different Control Systems

Ahmad O. Moaaz[1], Ahmed S. Ali[2] and Nouby M. Ghazaly[3]

[1]*Mechanical Eng. Dept., Faculty of Engineering, Beni-suef University, Egypt*

[2]*Mechanical Engineering department, Assiut University, Egypt*

[2]*Mechanical Engineering department, Zarqa University, Jordan*

[3]*Mechanical Eng. Dept., Faculty of Engineering, South Valley University, Qena-83523, Egypt*

**Corresponding Author E-mail: Nouby.Ghazaly@eng.svu.edu.eg,*

***Abstract***

*The modern vehicle uses the mechanism Anti-lock Braking System (ABS) to maintain vehicle safety by controlling the wheel slip in a stable zone during braking process conditions. The main aim of the controller of the ABS braking is to give a controlled torque required to obtain an optimal wheel slip rate. The slip rate is expressed as a function of automobile linear velocity and the angular speed of the wheels. The ABS mechanism and many control ways are applied. Applying the braking force to the braking system, the response is simulated mathematically in Simulink models. Applying control strategies such as (ON-OFF) Bang-Bang control, PD type and PID type, maintaining the required slip rate is evaluated. It is concluded that using the Bang-Bang, PD and PID controllers give good braking performance since the vehicle velocity as well as the wheel angular speed are controlled at the same time which prevents skidding during braking conditions. It is also found that stopping time and distance are reduced in the PID controller to 23.61 m at stopping time is 2.319 seconds compared to without control, Bang-Bang, PD control.*

***Keywords:*** *Anti-lock Braking System; linear control strategies; Bang-Bang control; PD control; PID control.*

## 1. Introduction

The first motor vehicle was built in 1769 and the first road accident appeared in 1770. Due to this accident engineers determined to improve vehicle safety by reducing road accidents [1]. The aim of braking systems design is to reduce accidents. The first anti-lock braking mechanism was in 1930 in the field of aerospace [2, 3]. The ABS mechanism was utilized for the first time in 1945 in a Boeing B-47; it is commonly used in aircraft [4, 5]. In the 1960s, automobiles firstly used the ABS in the rear wheels only, by developing the electronic technology the use of ABS increased in the 1980s. Recently ABS is found on the most recent automotive [6-10].

ABS is considered an important factor for improving road safety as its design keeps a vehicle steering stable and under control during the maximum braking process throughout preventing the wheels from locking. During sudden braking, the wheels will slip and lock, which results in uncontrolled steering and long stopping distance [11-13]. The main ABS

ISSN: 2005-4297 IJCA

target deals with the shortage in the traditional braking systems by controlling the wheel slippage to obtain maximum friction and to maintain the steering system under control [14].

Design of ABS controllers represent is a complex target to the designer because; i) The controller must do its function at the unstable point to achieve optimum performance, ii) Also the controller must be suitable for the various road conditions, iii) Tyre slip measurement signal is important for performance control[15]. A static feedback control algorithm for ABS control has been proposed. The robustness of the controller in the face of the longitudinal force of the tire and the road coefficient was guaranteed thanks to the fulfillment of a set of linear matrix inequalities. The robustness of the controller versus actuator delays as well as the controller gains adjusting was discoursed [16]. A new ABS algorithm with continuous wheel slippage has been proposed. Control based on wheel speed rules is minimized. The rear wheels independently cycle through the modes of applying pressure, holding and emptying, but cycling is done by continuous feedback control [17].

The model of a quarter of a vehicle braking system in MATLAB-SIMULINK was described. The characteristics and dynamic behavior of the tire on a flat and irregular road were proposed using the SWIFT tire model [18]. ABS performance with weight variation, road friction coefficient, road inclination, etc. has been studied. A fuzzy GA PID control was developed to eliminate these problems. The control system tends to reduce the stopping distance and also maintaining the desired range of tire slip rate [19]. Using the feedback controller to the ABS system, there were problems, so they used the adaptive NN to overcome the feedback control systems [20].

An adaptive fuzzy control approach was proposed and used in the anti-lock braking systems in [21]. The modeling of the ABS actuator and the design of the control are described. [22]. the fuzzy model reference learning control (FMRLC) has been illustrated. Braking efficiency in the case of a transition between icy and wet roads is studied [23]. The fuzzy controller controls the hydraulic modulator and therefore the brake pressure was used. The hydraulic controller performance and the modulator are evaluated by the equipment in loop experiments [24]. Recently, the mechanical links connecting the pedal and the actuator of the brake are replaced by electronic signals and control units [25].

In this research paper, the ABS braking system is examined under the influence of different control algorithms. The slip rate as a function of the vehicle speed and the angular wheel speed is examined. The results are induced by using Simulink models and applied the biased braking force system. The effectiveness of holding the required slip rate is assessed by different linear control strategies such as Bang-Bang control, PD type and PID type.

## 2. ABS Dynamic Modelling

### 2.1 Automobile Dynamic

The actual automotive model must contain all characteristics that are too complicated to be used in the design of the braking control system. So, a simple model contains the basic characteristics will be considered for the controller design. The proposed quarter vehicle model used to design the ABS controller is illustrated in Figure 1.

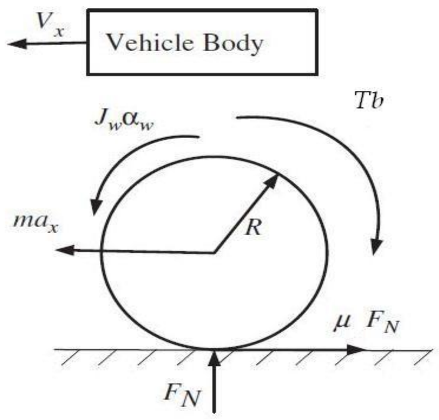



**Fig 1 Quarter car braking model**

The vehicle linear speed and the wheel rotational speed constitute the degrees of freedom for this model. The equations governing of the vehicle movements as following [26] as shown in Eqs 1 to Eq.5:

$$\boldsymbol{m\, a_x = -\mu F_N \rightarrow m\, \frac{dv_x}{dx} = -\mu F_N} \dots\dots\dots\dots\dots\dots.(\mathbf{1})$$

The torque at the wheel center:

$$\boldsymbol{J_\omega \alpha_\omega = \mu R F_N - T_b \rightarrow J_\omega \dot{\omega} = \mu R F_N - T_b} \dots\dots\dots(\mathbf{2})$$

The slip ratio is presented as:

$$\boldsymbol{S = \frac{v_x - \omega R}{v_x}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(\mathbf{3})$$

Differentiating the equation (3) with respect to time (t),

$$\boldsymbol{\dot{S} = \frac{\dot{v}_x(1 - S) - \dot{\omega} R}{v_x}} \dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(\mathbf{4})$$

$\boldsymbol{v_x}$ = linear vehicle speed

$\boldsymbol{a_x}$ = linear vehicle acceleration

ω = wheel angular speed

$\boldsymbol{\alpha_\omega}$ = wheel angular acceleration

$\boldsymbol{T_b}$ = Braking Torque

$\boldsymbol{S}$ = Slip ratio

$\boldsymbol{\mu}$ = Friction Coefficient

$\boldsymbol{R}$ = tire radius

$\boldsymbol{m}$ = quarter vehicle mass

The friction coefficient and the wheel slip ratio relationship shows the ability of the ABS to maintain the steering and stability of the vehicle while reducing the stopping distances. The friction coefficient is considered as a function of the automotive speed and the tire slip rate [5]. The factors, such as; the road condition (dry or wet), slip angle, type of tire, vehicle speed, and the wheel slip ratio cause the friction coefficient to change more.

$$\boldsymbol{\mu(S, v_x) = [c_1(1 - e^{-c_2 S}) - c_3 S)]\, e^{-c_4 v_x}} \quad \ldots\ldots(\mathbf{5}) \quad .$$

Where:-

$\boldsymbol{c_1}$: The friction curve the maximum value

$\boldsymbol{c_2}$ : The friction curve shapes;

$\boldsymbol{c_3}$ : The difference between the maximum value and the value at $\boldsymbol{S}$ = 1 in friction curve

$\boldsymbol{c_4}$ : The road wetness characteristic value.

The parameters for dry asphalt are showed in table 1:

Table 1: The value of C1, C2, C3 and C3 as ref. [5]

| The type of road | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| Dry asphalt road | 1.2801 | 23.99 | 0.52 | 0.03 |
| Wet asphalt road | 0.8570 | 33.822 | 0.347 | 0.04 |
| Snow-covered road | 0.1946 | 94.129 | 0.0646 | 0.04 |

The coefficient of friction between the tire and road optimum value at a certain value at a wheel slip ratio of 1 (when the wheels locked up). So, the ABS controller is designed to control the wheel slip ratio (S) to the optimum value (0.2) to obtain the maximum frictional coefficient (μ) for any road irregularities as shown in Fig.2.

ISSN: 2005-4297 IJCA

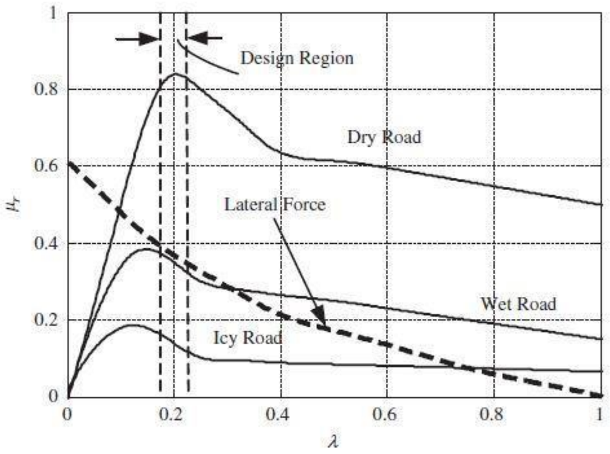



**Fig. 2 Road surface friction coefficient versus wheel slip ratio [5].**

## 3. Braking Control Systems

Closed loop feedback control system is the system in which a sensor measures the output signal and sends it to the controller which regulates the system to obtain the desired input. The feedback control system block diagram is shown in Figure 3. The used controller is:

1. Bang-Bang Control
2. Proportional Derivative (PD) Control
3. Proportional Integral Derivative (PID) Control

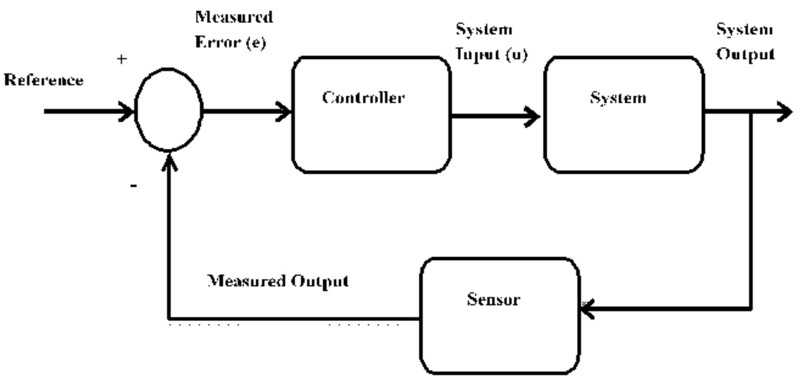



**Fig. 3 Block diagram of control system**

### 3.1 Proportional Derivative Feedback Control (PD-type)

This controller used the error gain (Kp) and the error differentiation gain (Kd) to the system to maintain the output at the desired point as in Eq.6.

$$u = K_p e + K_d \frac{de}{dt} \dots \dots \dots \dots (6)$$

### 3.2 Proportional Integral Derivative Feedback Control (PID-type)

This type of controller, the system input is the summation of error with constant gain (Kp), integral of error with constant gain (Ki), and differential of error with constant gain (Kd) as in Eq.7.

$$\boldsymbol{u = K_p e + K_d \frac{de}{dt} + K_i \int e\ dt} \ldots\ldots\ldots\ldots\ldots..(\mathbf{7})$$

### 3.3 Bang-Bang Control

The ABS braking system that employs the bang-bang control is depending upon the error between actual slip ratio and desired one. Where, the desired value of the slip ratio is considered as the value at which the $\boldsymbol{\mu - S}$ curve gives the maximum value, which is the value that reaches the minimum braking distance.

## 4. Quarter vehicle Simulink model

Fig. 4 shows the quarter vehicle Simulink model during braking process in straight line without control.

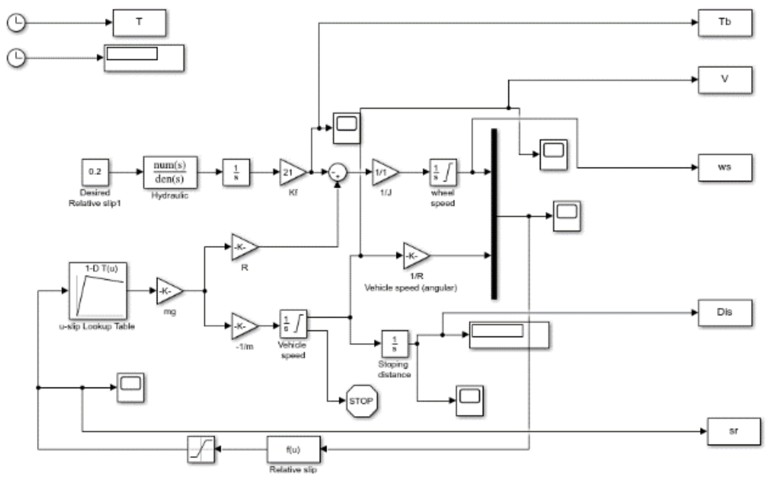
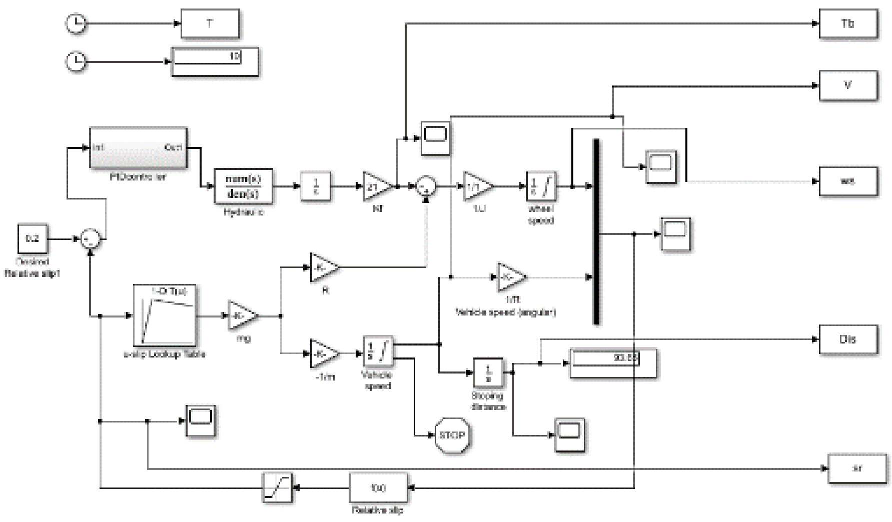



**Fig 4 Quarter vehicle Simulink model without controller**

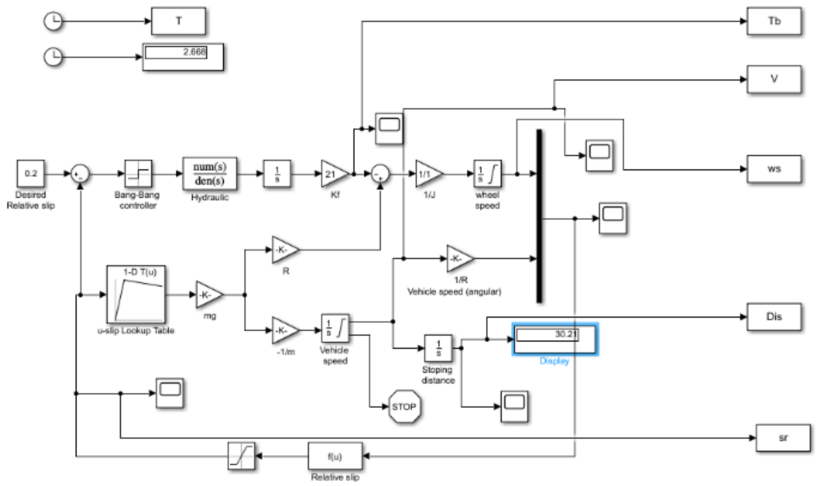
### ABS Simulink model using Control systems

Fig. 5 to represent modelling of controlled ABS system using Bang-Bang and PID control systems.

ISSN: 2005-4297 IJCA




(a)




(b)

**Fig 5 Quarter vehicle model with feedback control (a) PID and (b) Bang-Bang control)**

## 5- RESULTS

The quarter vehicle parameters are indicated in table 2.

Table 2 quarter vehicle parameters

| Symbol | Value |
|---|---|
| R | 0.32 m |
| m | 300 kg |

ISSN: 2005-4297 IJCA

| | |
|---|---|
| Jw | 1 kg m2 |
| Initial linear velocity | 100 km/hr |
| λd | 0.2 |
| Kp | 100 |
| Kd | 5 |
| Ki | 10 |

### 5.1 Vehicle braking without control

The vehicle performance during braking in a straight line without a controller is shown in Fig.6 to Fig.8. The Figures show the braking torque, vehicle velocity, stopping distance, wheel speed, and wheel rotational speed respectively versus time. From Figures [6:8], it is found that the stopping distance is 50 m and the stopping time is at 4.145 seconds.

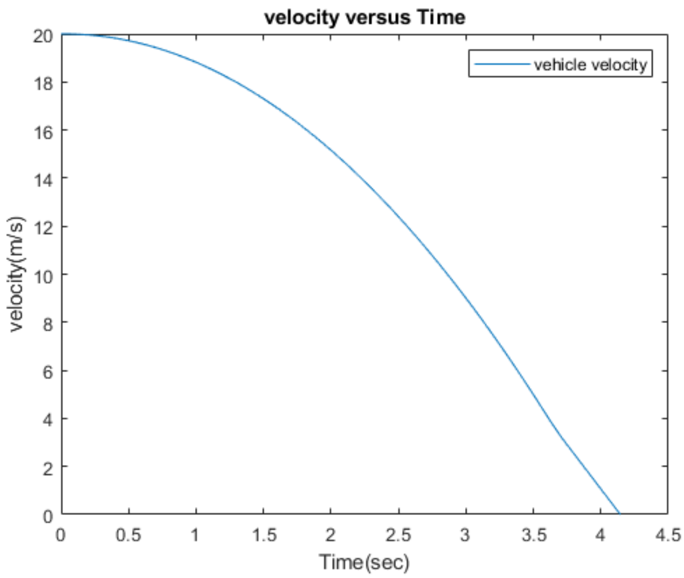



**Fig. 6 Vehicle speed versus time in vehicle braking without controller.**

ISSN: 2005-4297 IJCA

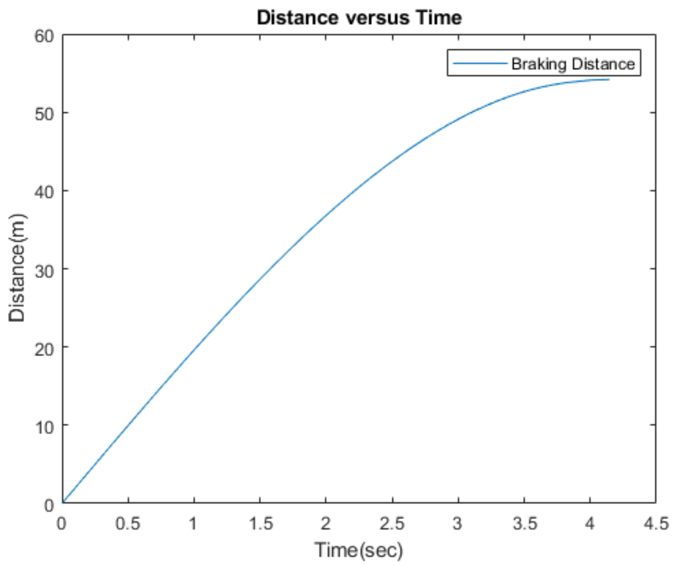



**Fig. 7 Stopping distance versus time in vehicle braking without controller**

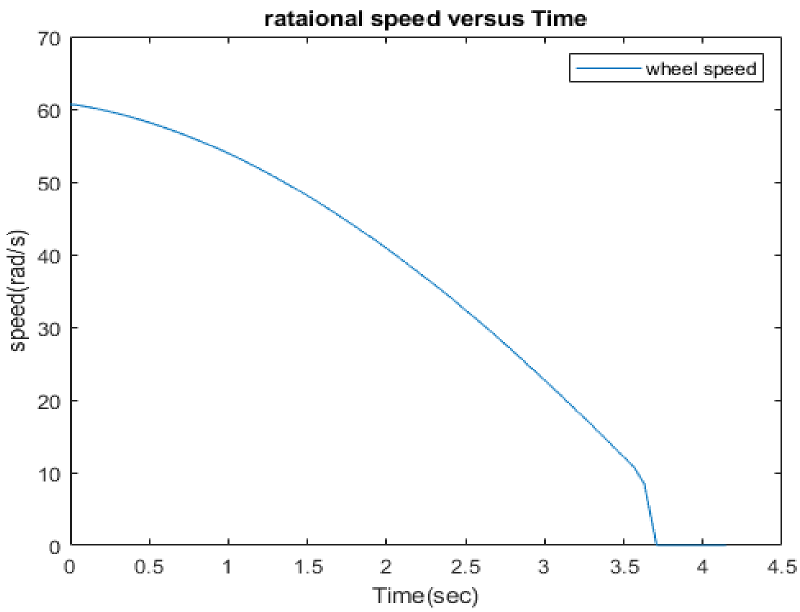



**Fig.8 Wheel rotational speed versus time in vehicle braking without controller.**

### 5.2 Control Systems:

#### 5.2.1 Bang- Bang Control

The vehicle performance during braking in a straight line using the Bang-Bang controller is shown in Fig.9 to Fig.12.The Figures describe and plot of the braking torque, vehicle velocity, stopping distance, wheel speed, and wheel rotational speed respectively versus time. It is found that by using the Bang-Bang controller the stopping distance is reduced to 31 m at 2.6 sec for a straight line braking conditions.

ISSN: 2005-4297 IJCA

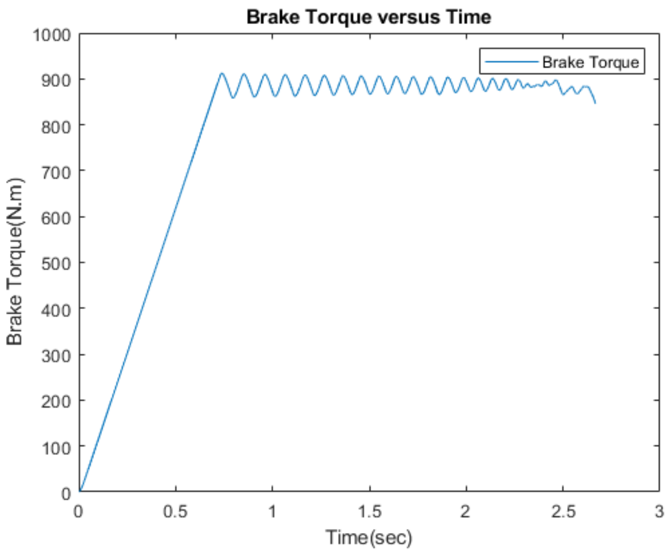



**Fig. 9 Brake torque versus time in vehicle braking using Bang-Bang controller.**

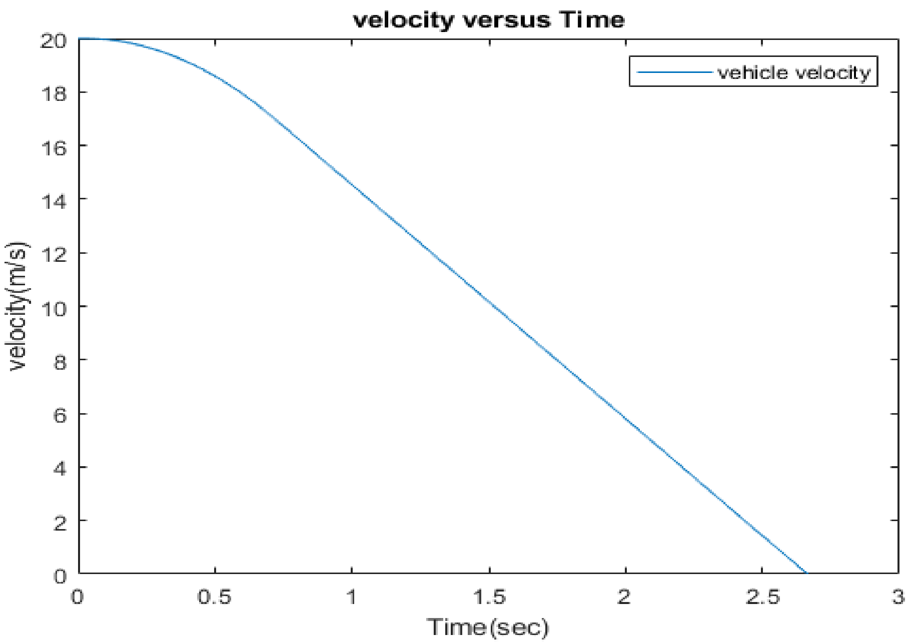



**Fig. 10 Vehicle speed versus time in vehicle braking using Bang-Bang controller.**

ISSN: 2005-4297 IJCA

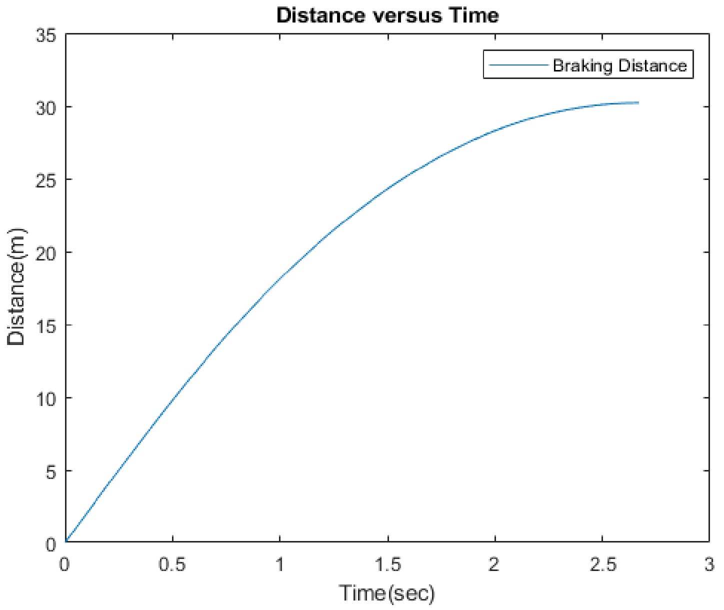



**Fig. 11 Braking distance versus time in vehicle braking using Bang-Bang controller.**

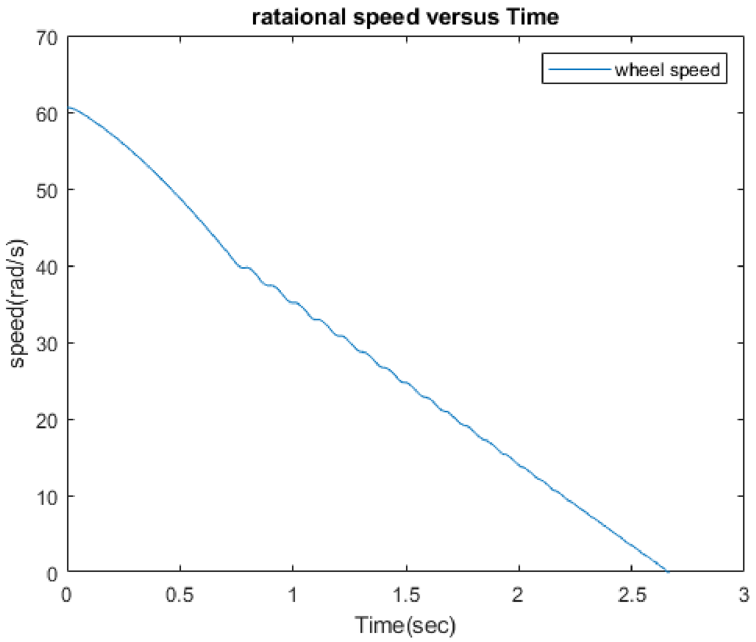



**Fig. 12 Wheel speed versus time in vehicle braking using Bang-Bang controller.**

### 5.2.2 Proportional Derivative Control

The vehicle performance during braking in a straight line using the PD controller is shown in Fig.13 to Fig.16. The Figures describe the plot of braking torque, vehicle velocity, stopping distance, wheel speed, and wheel rotational speed respectively versus time. It is found that by using the PD controller at a straight line braking the stopping distance is reduced to 24 m at 2.4 sec.

ISSN: 2005-4297 IJCA

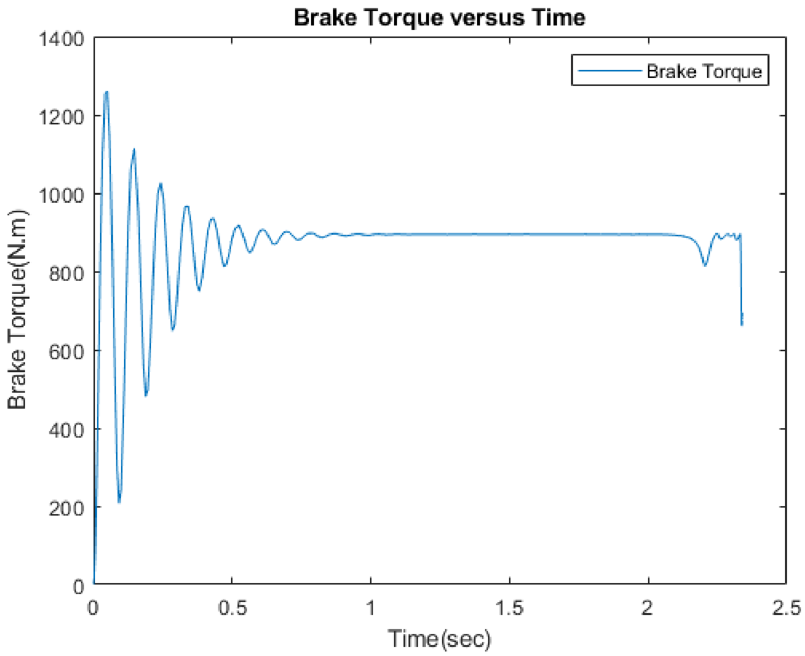



**Fig. 13 Brake torque versus time in vehicle braking using PD controller.**

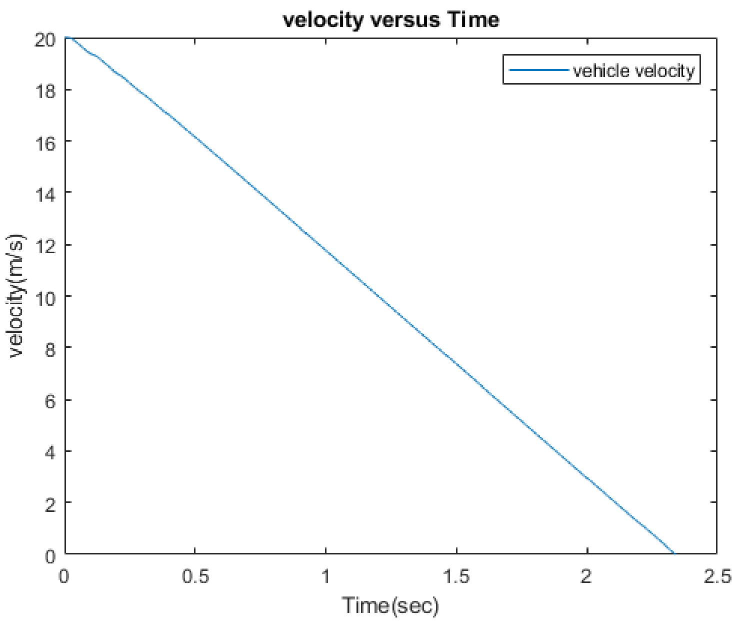



**Fig. 14 Vehicle speed versus time in vehicle braking using PD controller.**

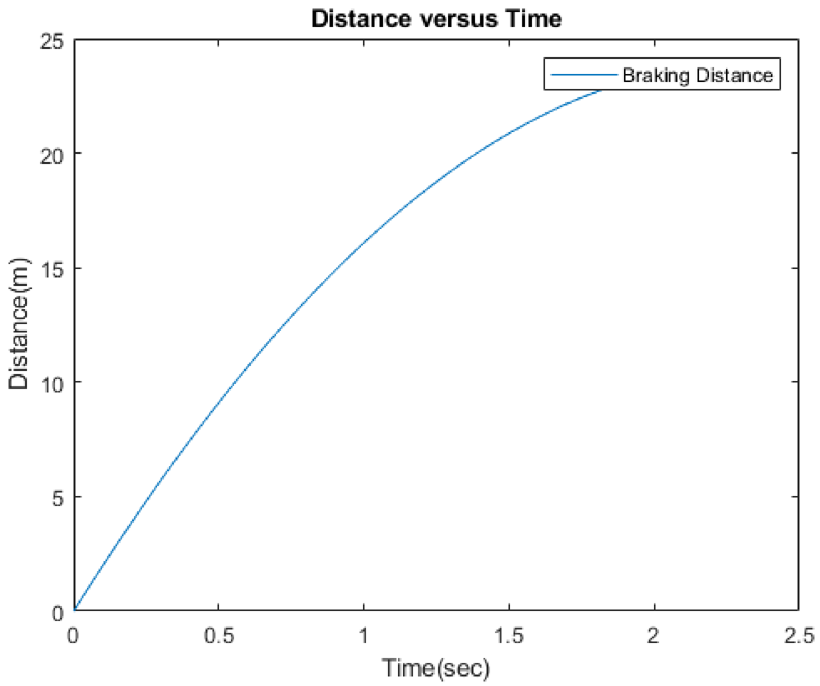



**Fig. 15 Braking distance versus time in vehicle braking using PD controller.**

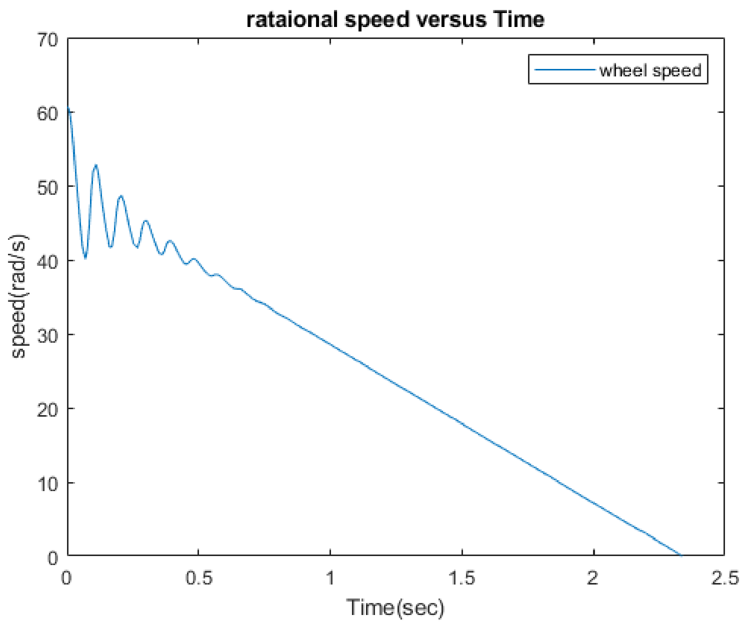



**Fig. 16 Wheel speed versus time in vehicle braking using PD controller.**

### 5.2.3 Proportional Integral Derivative Control

The vehicle performance during braking in a straight line using the PID controller is shown in Fig.17 to Fig.20.The plot of braking torque, vehicle velocity, stopping distance, wheel speed, and wheel rotational speed respectively versus time. It is found that stopping time and stopping distance are reduced in the PID controller compared to

ISSN: 2005-4297 IJCA

without control. It is obtained that the stopping distance is 23.61 m at stopping time is 2.319 seconds.

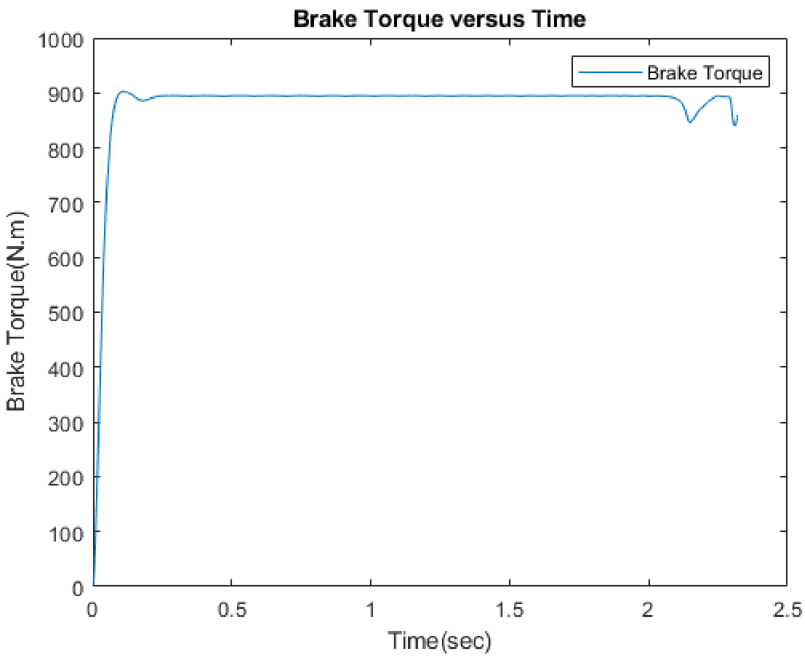



**Fig. 17 Braking torque versus time in vehicle braking using PID controller.**

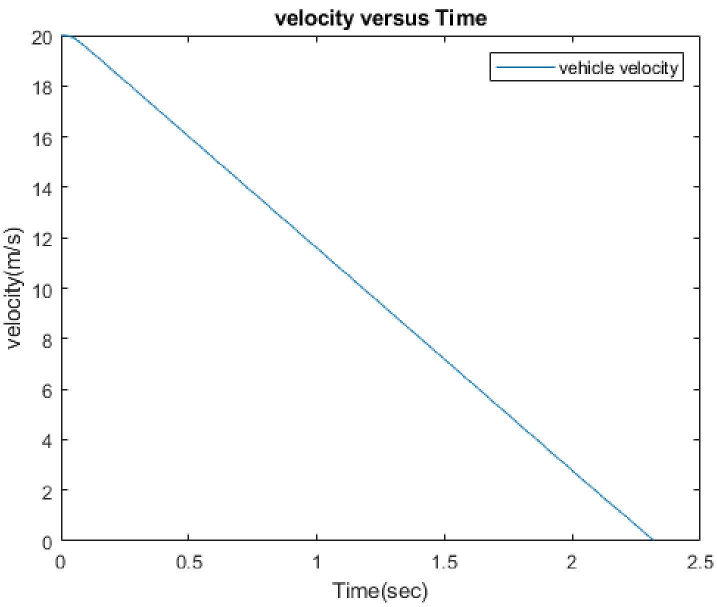



**Fig.18 Vehicle speed versus time in vehicle braking using PID controller.**

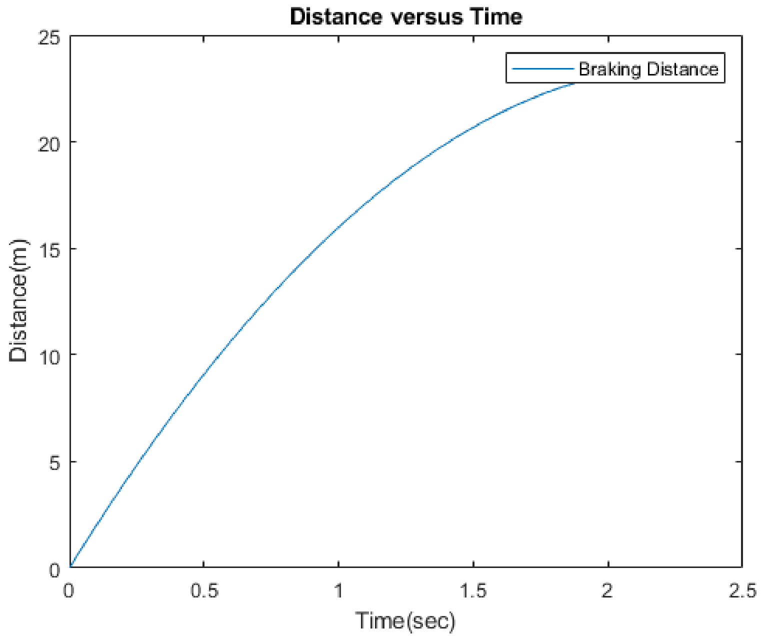



**Fig.19 Braking distance versus time in vehicle braking using PID controller.**

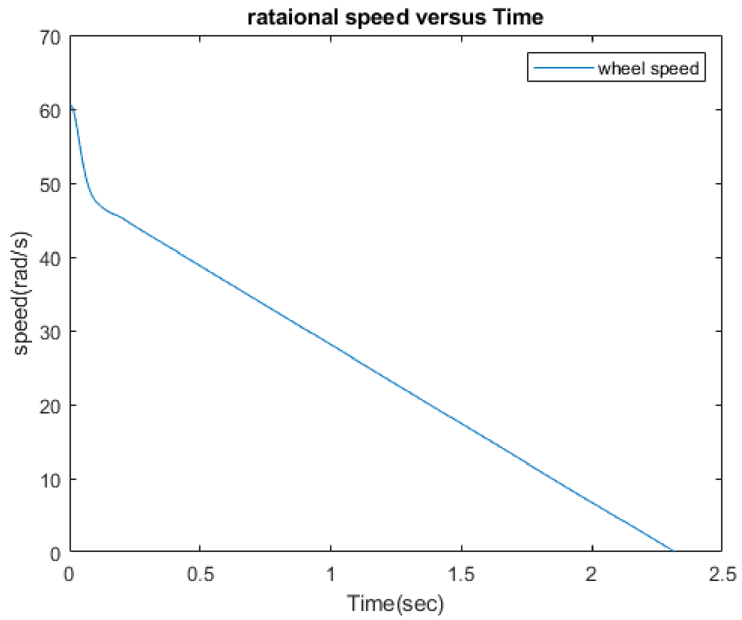



**Fig.20 Wheel rotational speed v/s time in vehicle braking using PID controller.**

## 6. Discussion

From Table 3, it is clear that controlled ABS improves the automobile braking performance compared to the uncontrolled. The stopping distance is 50 m and the stopping time is 4.5 seconds with the ABS without a control system. Applying the bang-bang control system improves the stopping time and distance. The stopping time and distance in the ABS system controlled by bang-bang are 2.668 sec and 31.21. Using the PD and the PID types also improves the braking performances. The stopping time and distance of the abs controlled using PD are 2.4 sec and 24m. The stopping time and distance of the abs controlled using PID are 2.319 sec and 23.61 m.

**Table 3 Braking performance results**

| ABS (Type) | Stopping time | Stopping distance |
|---|---|---|
| Without control systems | 4.5 | 50 |
| Bang-Bang Control | 2.668 | 31.21 |
| PD control Type | 2.4 | 24 |
| PID control type | 2.319 | 23.61 |

## 7. Conclusion

In this paper, the ABS system is modeled using Simulink software. Various types of controllers are applied for controlling the ABS system. The time-domain of the vehicle stopping distance and braking time is plotted. The controller used is Bag-Bang, PD-controller, and PID-controllers. From the simulation results, it can be concluded that the Bang-Bang, PD and PID controllers have better braking performance compared to the uncontrolled system because the wheel speed and the vehicle speed are controlled at the same time in order to avoid the vehicle skidding during the panic braking. It is recorded that the stopping distance is 50 m and the stopping time is 4.5 seconds with the ABS without a control system. Meanwhile, the stopping time and distance in the ABS system controlled by bang-bang are 2.668 sec and 31.21. In addition, the stopping time and distance of the ABS controlled using PD are reduced to 2.4 sec and 24m. It is found that the most reduction values for stopping time and distance of the ABS controlled using the PID are 2.319 sec and 23.61 m.

## Reference

[1] P. M. Hart, "Review of Heavy Vehicle Braking Systems Requirements (PBS Requirements)," Draft Report, 24 April 2003.

[2] M. Maier and K. Muller "The New and Compact ABS Unit for Passenger Cars," SAE Paper No.950757, 1996.

[3] P. E. Wellstead and N. B. O. L. Pettit, "Analysis and Redesign of an Antilock Brake System Controller," IEE Proceedings Control Theory Applications, Vol. 144, No. 5, 1997, pp. 413-426. doi:10.1049/ip-cta:19971441.

[4] A. G. Ulsoy and H. Peng, "Vehicle Control Systems," Lecture Notes, ME 568, 1997.

[5] P. E. Wellstead, "Analysis and Redesign of an Antilock Brake System Controller," IEEE Proceedings Control Theory Applications, Vol. 144, No. 5, September 1997, pp. 413-426. doi: 10.1049/ip-cta:19971441.

[6] R. Fling and R. Fenton, "A Describing-Function Ap-proach to Antiskid Design," IEEE Transactions on Ve-hicular Technology, Vol. VT-30, No. 3, 1981, pp. 134- 144. doi:10.1109/T-VT.1981.23895.

[7] S. Yoneda, Y. Naitoh and H. Kigoshi, "Rear Brake Lock-Up Control System of Mitsubishi Starion," SAE Paper, Washington, 1983.

[8] T. Tabo, N. Ohka, H. Kuraoka and M. Ohba, "Automo-tive Antiskid System Using Modern Control Theory," IEEE Proceedings, San Francisco, 1985, pp. 390-395.

[9] H. Takahashi and Y. Ishikawa, "Anti-Skid Braking Control System Based on Fuzzy Inference," U.S. Patent No. 4842342, 1989.

[10] R. Guntur and H. Ouwerkerk, "Adaptive Brake Control System," Proceedings of the Institution of Mechanical Engineers, Vol. 186, No. 68. 1972, pp. 855-880. doi:10.1243/PIME_PROC_1972_186_102_02.

[11] G. F. Mauer, "A Fuzzy Logic Controller for an ABS Braking System," IEEE Transactions on Fuzzy Systems, Vol. 3, No. 4, 1995, pp. 381-388. doi:10.1109/91.481947.

[12] W. K. Lennon and K. M. Passino, "Intelligent Control for Brake Systems," IEEE Transactions on Control Systems Technology, Vol. 7, No. 2, 1999, pp. 188-202.

[13] B. Lojko and P. Fuchs, "The Control of ASR System in a Car Based on the TMS320F243 DSP," Diploma Thesis, Dept. of Radio & Electronics, Bratislava, 2002.

[14] P. Hart, "ABS Braking Requirements," Hartwood Con-sulting Pty Ltd , Victoria, June 2003.

[15] Q. Ming, "Sliding Mode Controller Design for ABS Sys-tem," MSc Thesis, Virginia Polytechnic Institute and State University, 1997.

[16] S. Ç.baslamisli, I. E. Köse and G Anlas, 'Robust control of anti-lock brake system', Vehicle System Dynamics, vol. 45, no. 3, pp. 217-232, March 2007.

[17] S. B. Choi, 'Antilock Brake System with a Continuous Wheel Slip Control to Maximize the Braking Performance and the Ride Quality', IEEE Transactions on Control Systems Technology, vol. 16, no. 5, September 2008.

[18] K.Z. Rangelov, SIMULINK model of a quarter-vehicle with an anti-lock braking system, Master's Thesis -Eindhoven: Stan Ackermans Instituut, 2004. - Eindverslagen Stan Ackermans Instituut, 2004102.

[19] Ahmad O. Moaaz and Nouby M. Ghazaly "Fuzzy and PID Controlled Active Suspension System and Passive Suspension System Comparison" International Journal of Advanced Science and Technology, 2019, Vol. 28, No. 16, pp. 1721 – 1729.

[20] A. Poursamad,'Adaptive feedback linearization control of antilock braking system using neural networks', Mechatronics, vol. 19, pp. 767-773, 2009.

[21] A. V. Talpov, E. Kayancan, Y. Onit and O. Kaynak, 'Nero-fussy control of ABS using variable structure-system-based algorithm', Int. Conf. On Adaptive & Intelligent System, IEEE Comput Society, DOI 10.1.1109 / ICAIS.2009.35/ pp.166.

[22] C. B. Patil and R. G. Longoria, 'Modular design and testing of antilock brake actuation and control using a scaled vehicle system', Int. J. of vehicle system modelling and testing, vol.2, pp. 411-427, 2007.

[23] J. R. Layne, K. M. Pessino, S. Yurkarith, 'Fuzzy learning control for antiskid braking system', IEEE Trans. Control system tech., vol. 1, pp. 122-131. 1993.

[24] C. K. Huang & H. C. Shih, 'Design of a hydraulic ABS for a motorcycle', J Mech Science Technology, vol. 24, pp. 1141-1149, 2010.

[25] X. Y. Peng, L. He, and Y. B. Lyu, "Fuzzy sliding mode control based on vehicle slip ratio for electro-mechanical braking systems," Journal of Central South University (Science and Technology), vol. 49, no. 2, pp. 360–370, 2018.

[26] Y. He, C. Lu, J. Shen, and C. Yuan, "Design and analysis of output feedback constraint control for antilock braking system with time-varying slip ratio," Mathematical Problems in Engineering, vol. 2019, Article ID 8193134, 11 pages, 2019.