ISSN 2738-9898 (Print) ISSN 2738-9901 (Online)

Design and Analysis of Vehicle Anti-Lock Braking System with Fuzzy Logic, Bang-Bang and PID Controllers

Prashant Lakhemaru[1], Surya Prasad Adhikari[2, *]

[1]Department of Automobile and Mechanical Engineering, Thapathali Campus, Institute of Engineering, Tribhuvan University, Nepal

[2]Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal

E-mail: *surya@tcioe.edu.np*

Received on: 21st Sept., 2022

Accepted for publication: 16th April, 2022

Abstract

In this study, a mathematical model of Anti-Lock Braking System (ABS) has been developed and simulated in MATLAB/Simulink environment using bang-bang, fuzzy logic and PID controllers. The controllers were used to control the braking force to be applied based on various parameters like relative slip, road condition and coefficient of friction between road and tire. The simulated result was compared and analyzed. The simulation result showed that a PID controller would take 9.665 seconds to stop the vehicle at the distance of 434.902 ft at an initial velocity of 88 ft/s. The Fuzzy Logic, Bang-Bang and no controllers offered 935.298 ft at 16.76 seconds, 696.996 ft at 13.751 seconds and 1421.327 ft at 24.217 seconds, respectively for the same initial velocity and road surface. From analysis, it was concluded that the PID controller had better performance compared to fuzzy logic and bang-bang controllers for application of ABS in a vehicle.

Keywords: ABS, optimal slip, relative slip, PID, fuzzy logic, MATLAB/Simulink.

1. Introduction:

Braking system has been one of the most sensitive, essential and significant system in automotive world. It is not only required to cease the motion of any vehicles, but it is also directly linked with safety of the driver and any mishaps. We have seen and heard of many accidents that have occurred due to failure in braking system, and some cases due to inadequate braking time and braking distance.In most of the accidents, an obstacle appears in front of the vehicle and the driver has to take action after recognizing the danger [1]. This action depends on many parameters such as the distance between the vehicle and the obstacle, the state of the other lanes (being occupied or not), the road surface conditions, etc. A vehicle without an Anti-Lock Braking System (ABS) is safe only when there is sufficient clearance before the obstacle, the road is straight, and the friction coefficient is same for the both vehicle sides. If any of these conditions do not apply, single or multiple vehicle crashes may occur. Even with an ABS with only longitudinal motion control capability, single vehicle crashes are not a far risk. The anti-lock braking system (ABS) has been introduced to prevent the locking of vehicles during braking and hence prevent the vehicle from skidding and minimize the stopping distance and stopping time [2]. Most studies and experiments have shown that it is effective for sustaining steerability and stability of vehicle, but the stopping distance and time may not be reduced in all instances. The modern system is controlled electronically for better efficiency and comfort.

The Anti-Lock Braking idea emerges far back since 1930s. In around 1950s, the early examples appear in aerospace applications. During initial 1970s, ABS was experimented on passenger cars. Automobile drivers were assisted with enhanced stability and capability of braking also increased. This made antilock braking a standard system most of the vehicles.

A number of published articles have noticeably shown that skidding of tires during braking or cornering of vehicle has been a major cause of accidents. To overcome and minimize the occurrence of accidents, a braking system has been developed with electronic controls and components that is called Anti-Lock Braking system (ABS) [1, 3, 4].

Anti-Lock Braking System (ABS), also called anti-skid braking system, for preventing the skidding of vehicles, is believed to reduce the braking time, braking distance and sustain the steerability and stability of the vehicle [5–7]. The conventional braking system locks the wheels during braking, due to which the steerability and stability of the vehicles are lost. To prevent the mishaps to occur and sustain the steerability and stability of vehicle, the wheels should be prevented to get locked. The conventional braking system is not flexible for this, however some experienced and skilled drivers apply threshold and cadence braking, that reduces the speed of wheels to some extent but doesn't let them to get locked completely [8, 9].

The key function of ABS is to prevent uncontrollable slip of the wheels during braking and thus avoiding the wheels locking up [10]. The main aim is to keep steerability of the braking vehicle as well as the effective braking process. The effective braking means to achieve the shortest possible braking distance by following optimal value of the friction coefficient without loss of overall maneuverability of a vehicle.

Receiving the low speed signal from the wheel speed sensor provided, the Anti-Lock Braking System (ABS) module commands the brake control unit (BCU) to reduce that braking force on the wheel. This means the pressure acting in the brake line on the wheel is lowered with the help of valves provided in the system. As the braking force reduces, the wheel is free from locking and the steerability of the vehicle remains intact. This means that the vehicle can be controlled by the driver without skidding. Once the vehicle speed is restored to normal condition, the Brake Control Unit raises pressure on the brake line.

In today's motorcycles, cars and other vehicles, the applications of automotive safety have become very common. ABS and electronic stability control types of vehicle stabilization systems are becoming standard in almost all passenger cars [11].The control of wheel slip is a problem that is very challenging [12]. This is because of the model uncertainties, nonlinear dynamics of braking process and a complex behavior of tire-road interaction [13]. Behavior of tire force saturation results in a high degree of nonlinearity. Changing of the vehicle parameters, un-modelled dynamics and coefficient of tire-road friction are additional main sources of uncertainties which exist in vehicle dynamics. Degradation of the control performance is significant due to these uncertainties. While designing the controller for an ABS, key issue is the achievement of robustness.

The uncertainties and high nonlinearities that exist in mathematical model make it difficult to design an ABS. In nonlinear systems control framework, ABS therefore, is becoming an attractive area to research due to these difficulties.

The various controllers or logics adapted for the application of Anti-Lock Braking System has offered different performance and results. Oudghiri *et al.* in 2007 proposed use of Robust Fuzzy Sliding Mode Control for application of ABS in their study [4]. Oniz Y *et al.* proposed a SMC and grey SMC for tracking reference wheel slip in which the grey predictor estimates the forthcoming value of wheel slip and the SMC takes the necessary action to maintain wheel slip at the desired value [14]. Jiang F *et al.* concluded that nonlinear PID controller has shorter stopping distance and lower stopping time than the conventional PID controller [5]. Similarly, Ali H. *et al.* showed the robust stability and better performance for the ABS, and shorter stopping distance with minimum braking torque has been achieved for different types of surface using PI-PD controller [15]. Consequently, Mokarram M. *et al* [16] proposed the application of ABS using FL controller with CMOS circuit. They concluded that the optimised FL controller offered better lateral staility and steerability of a vehicle by keeping slip at minimum value and lessening the oscillations than that of fuzzy logic and PI controller. Shah et al. compared the performances of ABS using FL controller with the ABS that uses Bang-Bang controller [9]. We found that plenty of studies have been conducted on ABS system using various controllers. Yet, the system is still evolving and requires many researches and optimizations. In this study, we intend to compare the performances of an Anti-Lock Braking System that uses various logic controllers at similar braking condition and road surface.

2. Methods and Materials:

2.1. Mathematical Model:

The dynamic equations of ABS are based on Newton's second law of motion applied to wheels and vehicles. The model considers a single wheel (one-fourth of a four-wheeler, with mass m. To further simplify the model, secondary factors are neglected and following assumptions have been considered:

- The tires are rigid.
- The system ignores the influence of lateral wing.
- Aerodynamic drag is ignored.

The dynamic equations for the motion of vehicle are:

$$ma = -\mu(\lambda) * m * g \quad (1)$$

$$J\alpha = r * \mu(\lambda) * m * g - T_b \quad (2)$$

where,

m = mass of vehicle

a = linear acceleration of vehicle

$\mu(\lambda)$ = coefficient of friction between road and tire (nonlinear function of slip ratio and road dynamics)

J = moment of inertia of wheel

α = angular acceleration of wheel

λ = wheel slip ratio

T_b = Braking torque acting on wheel

The slip ratio is defined by:

$$\lambda = 1 - \frac{\omega r}{v} \quad (3)$$

where,

v = linear speed of vehicle

ω = angular speed of wheel

r = radius of wheel

The slip value of λ = 0 characterizes the free motion of wheel and λ = 1 means the wheel is locked (i.e. ω = 0).

2.2. Tire Modeling:

For calculation of friction force of the wheel or tire transferred to the road, Burckhardt's tire modeling has been adapted. This model has been widely used due to its better accuracy in the explanation of friction coefficient [4, 17]. The equation governing this tire model is given by:

$$\mu(\lambda) = C_1\left(1 - e^{-C_2\lambda}\right) - C_3 \quad (4)$$

where,

C_1, C_2 and C_3 are constants which depend on road conditions. The values of the Burckhardt's constants for various road conditions are shown in the following table.

Table 1: Coefficients of Burckhardt Equation

Road Surface Condition	C_1	C_2	C_3
Dry Asphalt	1.2801	23.990	0.52
Dry Concrete	1.1973	25.186	0.5373
Wet Asphalt	0.86	33.82	0.35
Cobblestone	1.37	6.46	0.67
Snow	0.1946	94.129	0.0646
Ice	0.05	306.39	0

The relation between coefficient of friction and slip ratio is shown in the following Fig. 1.

From this figure, we can see that the value of coefficient of friction is highest when the slip is around 0.2 for all road conditions [18]. This value of slip is hence called optimal slip.

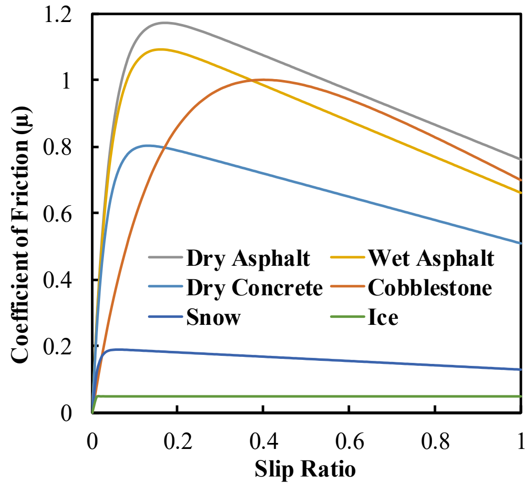

Figure 1: Relation between slip ratio and coefficient of friction for different road conditions

2.3. MATLAB/Simulink Model:

Figs. 2, 3 and 5 illustrate the Simulink models developed for control of ABS. The controllers used for the simulation are Bang-Bang, Fuzzy Logic and PID controllers.

A Bang Bang controller (Fig. 2), also called 2-step or on-off controller, is a feedback controller that takes slip error signal as input and determines the required brake force to be applied to minimize the slip and avoid locking of wheels. Due to the control of vehicle speed and wheel speed at the same time, braking performance with bang-bang controller is better for application of ABS than no use of any controllers [19].

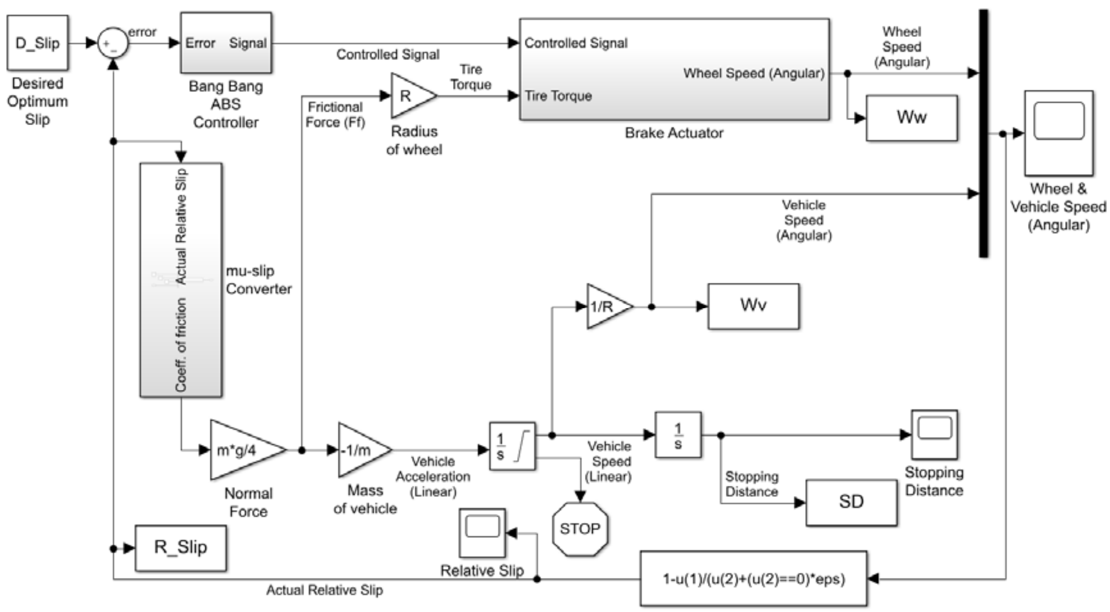

Figure 2: : Block Diagram of ABS Control System using Bang-Bang Controller

Fuzzy Logic (FL) Controller (Fig. 3) has been using as alternative way to solve automatic control problems over the last few decades. FL is a well-recognized perception in mathematics and engineering as it offers unique capabilities to capture nonlinearities and uncertainties that cannot be depicted by particular mathematical model [20]. In real life, situations are often described in linguistic terms. Fuzzy logic is an approach computing based on the degree of truth rather than the usual truth or false. It is similar to human decision making methodology. It is used to solve the real world problems. For example, traditional digital logics are capable of describing only black or white, whereas the fuzzy logic can also describe the vast grey region between the black and white [21]. And this is exactly how the human decision making methodology works.

A PID controller (Fig. 4), also called three-term controller, is a control loop mechanism employing feedback that is widely used in industrial control systems and a variety of other applications that require continuously modulated control. The PID controller's core purpose is to force feedback to match a set point, for instance, a climate control system.

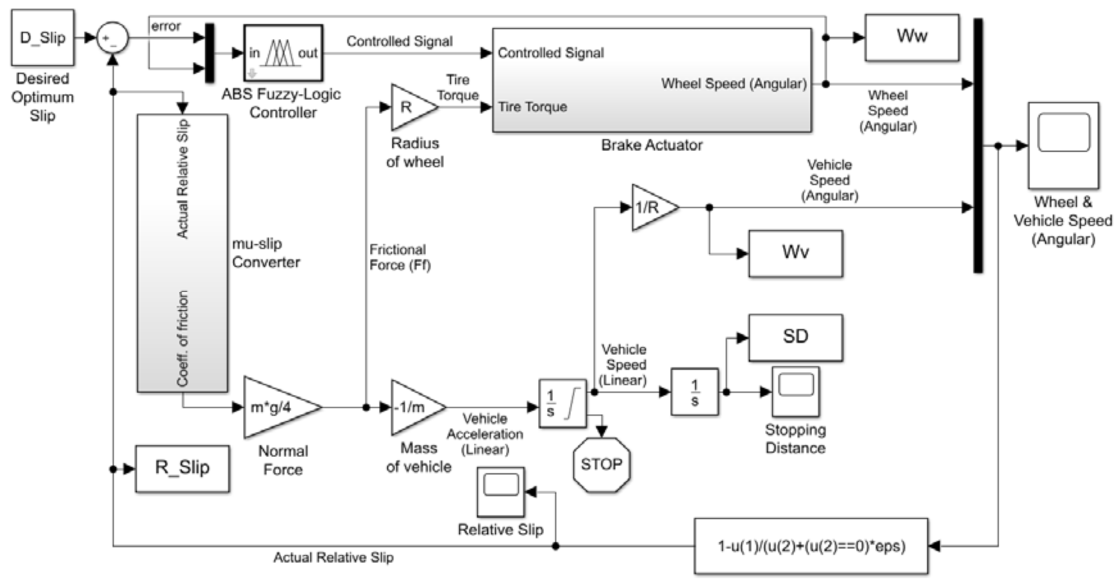

Figure 3: Block Diagram of ABS Control System using Fuzzy Logic Controller

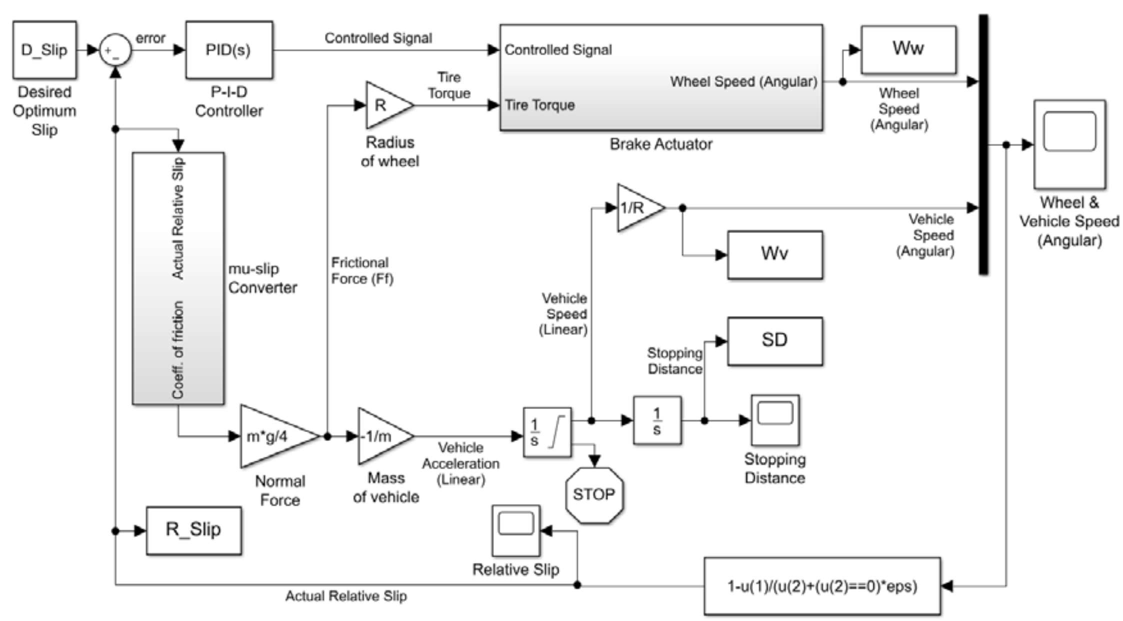

Figure 4: Block Diagram of ABS Control System using PID Controller

a) Brake Actuator:

The function of the brake actuator is to pass the hydraulic pressure through the ABS circuit as per the input signal received from the respective controllers. A schematic model of brake actuator is shown in Fig. 6.

b) Mu-slip Converter:

The mu-slip converter is a subsystem that calculates the coefficient of friction between the tire and the road surface with respect to the relative slip that is calculated from the instantaneous vehicle and wheel speeds. The model of mu-slip converter is shown in Fig. 7.

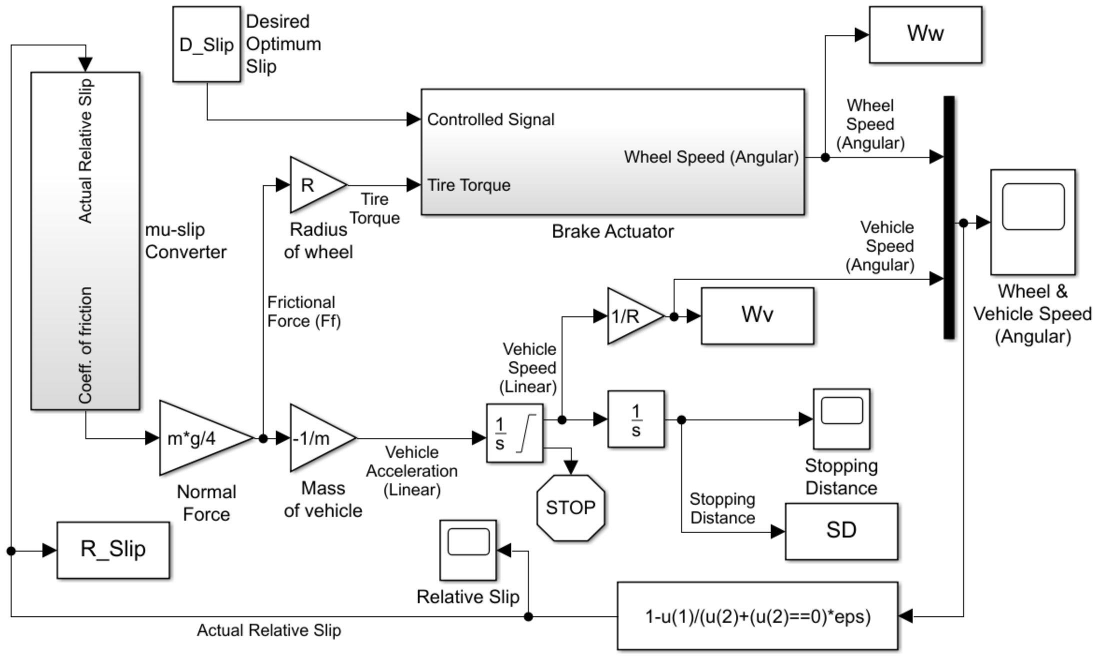

Figure 5: Block Diagram of ABS Control System without any controllers

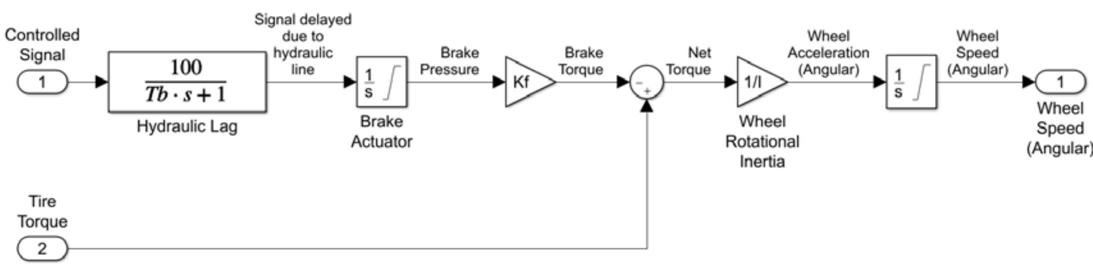

Figure 6: Brake Actuator Subsystem

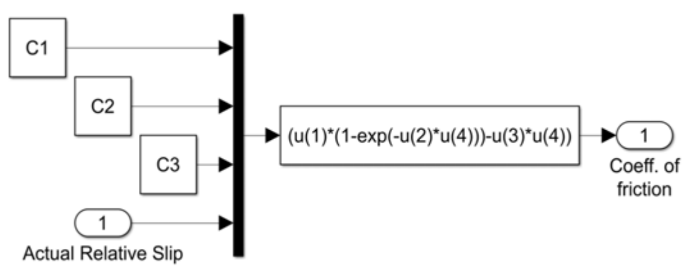

Figure 7: mu-slip converter subsystem

3. Result and Discussion:

The simulation results from the models with fuzzy logic and PID controllers were obtained and compared with the simulation results of a model using BangBang controller and a model without any controllers. The use of controllers delivered better performance of ABS compared to absence of any controllers. The following figures shows the Speed vs Time curve of the simulated models.

From Fig. 8, we can see that there is no fluctuation in the wheel and vehicle speeds during braking when no controllers are used. The steerability and stability of the vehicle is retained and the time taken for the vehicle to cease was found to be 24.217 seconds at a distance of 1431.327 ft.

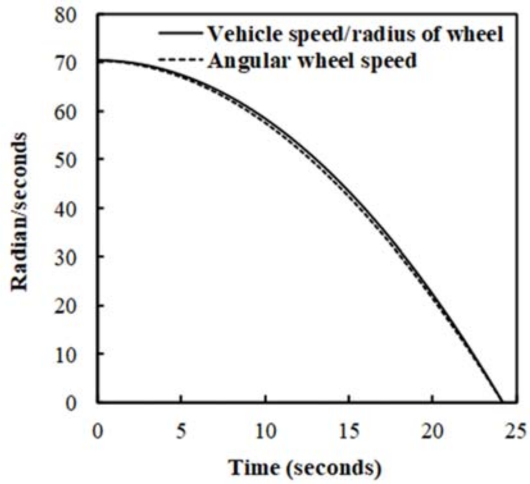

Figure 8: Speed Vs Time for model without any controllers

Using a BangBang Controller, as shown in Fig. 9, we can see that the vehicle comes to stop in reduced time but the fluctuation in the wheel speed has increased which indicates that the controller is repeatedly locking and releasing the wheels. The stopping distance was found to be 696.996 ft at time period of 13.751 seconds. We can hence conclude that use of BangBang Controller can offer better outcome for application of ABS compared to no use of controllers.

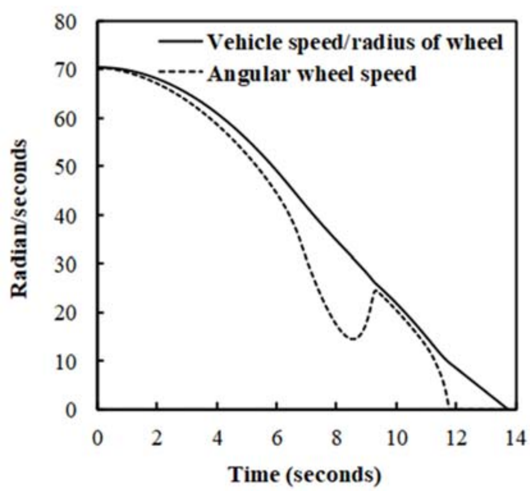

Figure 9: Speed Vs Time for model using Bang-Bang Controller

The stopping time and stopping distance of the vehicle using Fuzzy Logic Controller was found to be 16.76 seconds and 935.298 ft respectively. The relation has been shown in Fig. 10. The vehicle and wheel speed are smooth and there are almost none fluctuations in the speeds. The steerability is better but comparing the distance and time, this controller could not yield better performance than the BangBang controller. The performance of the fuzzy logic controller can further be improvised by changing the input parameters or changing the membership functions of the controllers.

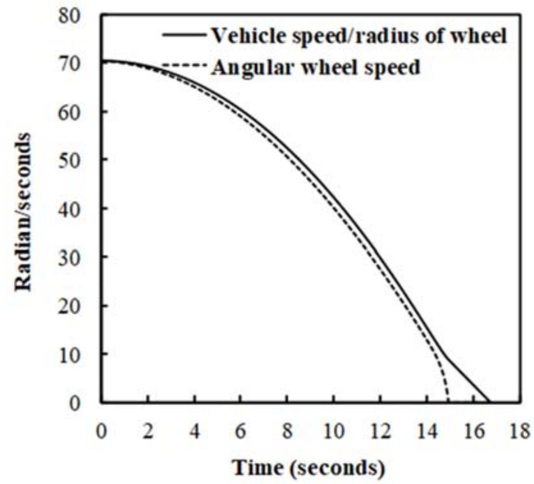

Figure 10: Speed Vs Time for model using Fuzzy Logic Controller

From Fig. 11, we can see that the vehicle comes to stop in lesser time when using PID controller whereas the fluctuation in wheel speed is present. The total distance covered was found to be 434.902 ft in 9.665 seconds. Among all the controllers, the PID controller has been found to offer better performance.

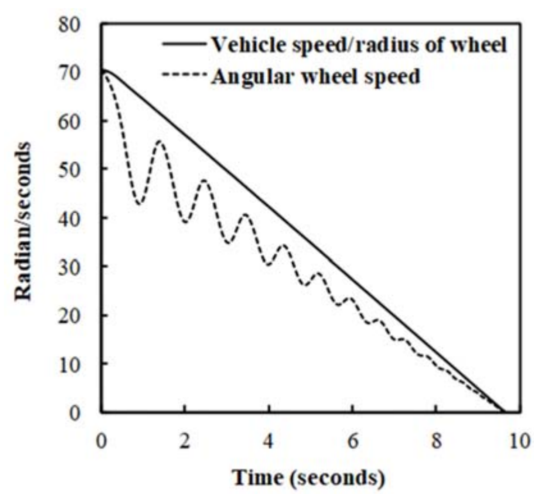

Figure 11: Speed Vs Time for model using PID Controller

The curve of relative slip and stopping distance of different models are illustrate in Figs. 12 and 13, respectively.

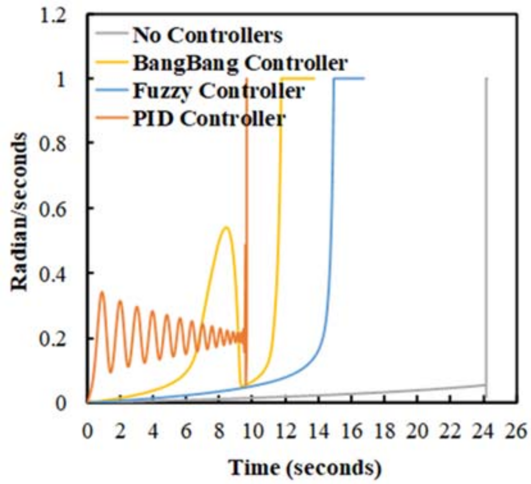

Figure 12: Comparison of Relative slip of different ABS models

Table 2: Performance of different ABS Models

S.N.	Model	Stopping Time (s)	Stopping Distance (ft)
1	No controllers	24.217	1421.327
2	BangBang Controller	13.751	696.996
3	Fuzzy Logic Controller	16.76	935.298
4	PID Controller	9.665	434.902

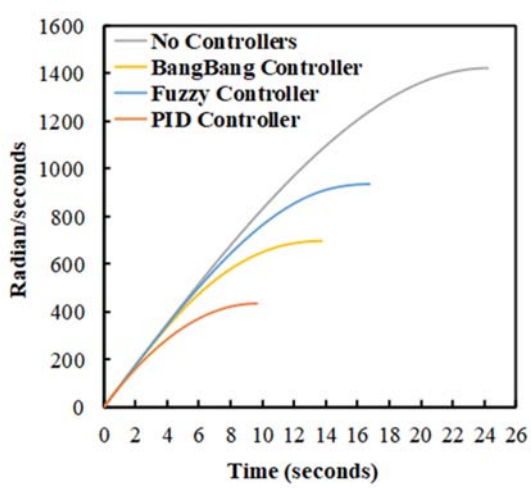

Figure 13: Comparison of Stopping Distance of different ABS models

The curves for relative slip were found to be smoothly rising for no controller and FL controller whereas the curves were fluctuating for BangBang and PID controllers. It can be seen that the control over steerability and stability of the vehicle would be better for FL controller and no use of controllers. In case of BangBang and PID controllers, these parameters would have compromised but they wouldn't be totally absent.

Table 2 given above illustrates the performance of different ABS models.

4. Conclusion:

This paper has intended to study the performance of different controllers in application of ABS. A model of ABS has been developed and the controllers are used to control the braking force to be applied in different instances of time regarding the relative slip and vehicle and wheel speeds as input parameters. Considering the stopping distance and stopping time during braking, we can conclude that PID is the best among the controllers that has been used for simulation of the Anti-Lock Braking System. The stopping distance and stopping time taken by the PID controller are found to be 434.902 ft and 9.665 seconds respectively. For the same initial velocity and road surface, the distance and time taken by a Fuzzy Logic Controller are 935.298 ft and 16.76 seconds. Similarly, a Bang-Bang controller took 13.751 seconds to cover 696.996 ft whereas a model without any controllers took 24.217 seconds. The FL controller showed better control over the relative slip, hence providing better steerability, although the stopping time and distances are higher than that for a PID controller.

This model can further be modified or optimized by adding more input parameters to the controllers and also to the vehicle and wheel subsystems.

Acknowledgements:

This work has been supported by University Grants Commission (UGC), Nepal, Award no. MRS-77/78-Engg-01.

Conflicts of Interest:

The author declare no conflict of interest.

References:

[1] Y. Yazicioglu and Y. Samim Unlusoy, "A fuzzy logic controlled Anti-lock Braking System (ABS) for improved braking performance and directional stability," International Journal of

Vehicle Design, vol. 48, no. 3–4, pp. 299–315, 2008, doi: 10.1504/IJVD.2008.022581.

[2] A. Badie Sharkawy, "Genetic fuzzy self-tuning PID controllers for antilock braking systems," Engineering Applications of Artificial Intelligence, vol. 23, no. 7, pp. 1041–1052, 2010, doi: 10.1016/j.engappai.2010.06.011.

[3] V. R. Aparow, F. Ahmad, K. Hudha, and H. Jamaluddin, "Modelling and PID control of antilock braking system with wheel slip reduction to improve braking performance," International Journal of Vehicle Safety, vol. 6, no. 3, pp. 265–296, 2013, doi: 10.1504/IJVS.2013.055025.

[4] M. Oudghiri, M. Chadli, and A. El Hajjaji, "Robust Fuzzy Sliding Mode Control for Antilock Braking System," International Journal on Sciences and Techniques of Automatic Control, vol. 1, no. June 2007, pp. 13–28, 2007.

[5] F. Jiang and Z. Gao, "An application of nonlinear PID control to a class of truck ABS problems," Proceedings of the IEEE Conference on Decision and Control, vol. 1, pp. 516–521, 2001, doi: 10.1109/CDC.2001.980154.

[6] 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. 1, pp. 137–153, 2020.

[7] M. Maier and K. Müller, "ABS5.3: The New and Compact ABS5 Unit for Passenger Cars," Feb. 1995. doi: 10.4271/950757.

[8] J. Broughton and C. Baughan, "The effectiveness of antilock braking systems in reducing accidents in Great Britain," Accident Analysis and Prevention, vol. 34, no. 3, pp. 347–355, 2002, doi: 10.1016/S0001-4575(01)00032-X.

[9] P. Shah, S. K. Labh, and S. P. Adhikari, "Study on Performance of Vehicle Anti-lock Braking System with Fuzzy Logic controller in Matlab/Simulink," International Journal of Scientific Research and Engineering Development, vol. 3, no. 2, pp. 972–978, 2020, [Online]. Available: www.ijsred.com

[10] A. Harifi, A. Aghagolzadeh, G. Alizadeh, and M. Sadeghi, "Designing a sliding mode controller for slip control of antilock brake systems," Transportation Research Part C: Emerging Technologies, vol. 16, no. 6, pp. 731–741, 2008, doi: 10.1016/j.trc.2008.02.003.

[11] H. R. More, A. A. Digrase, and A. V. Wayse, "Linear PID control technique for single wheel ABS (anti-lock braking system) of motorcycle," 2017 2nd International Conference for Convergence in Technology, I2CT 2017, vol. 2017-Janua, pp. 277–281, 2017, doi: 10.1109/I2CT.2017.8226135.

[12] V. Cirovic and D. Aleksendric, "Adaptive neuro-fuzzy wheel slip control," Expert Systems with Applications, vol. 40, no. 13, pp. 5197–5209, 2013, doi: 10.1016/j.eswa.2013.03.012.

[13] D. Aleksendrić and D. C. Barton, "Neural network prediction of disc brake performance," Tribology International, vol. 42, no. 7, pp. 1074–1080, 2009, doi: 10.1016/j.triboint.2009.03.005.

[14] Y. Oniz, E. Kayacan, and O. Kaynak, "Simulated and experimental study of antilock braking system using grey sliding mode control," Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics, pp. 90–95, 2007, doi: 10.1109/ICSMC.2007.4413975.

[15] H. I. Ali and A. H. Saeed, "Robust Tuning of PI-PD Controller for Antilock Braking System," vol. 20, no. 4, pp. 983–995, 2017.

[16] M. Mokarram, A. Khoei, and K. Hadidi, "A fuzzy Anti-lock braking system (ABS) controller using CMOS circuits," Microprocessors and Microsystems, vol.

70, pp. 47–52, 2019, doi: 10.1016/j.micpro.2019.05.001.

[17] C. ELMAS, U. Guvenc, and M. U. DOGAN, “Tire-Road Friction Coefficient Estimation and Experimental Setup Design of Electric Vehicle,” Balkan Journal of Electrical and Computer Engineering, vol. 3, no. 4, 2015, doi: 10.17694/bajece.88174.

[18] L. Xiao, L. Hongqin, and W. Jianzhen, “Modeling and Simulation of Anti-lock Braking System based on Fuzzy Control,” Iarjset, vol. 3, no. 10, pp. 110–113, 2016, doi: 10.17148/iarjset.2016.31021.

[19] D. V Gowda and R. A. C, “Slip Ratio Control of Anti-Lock Braking System with Bang-Bang Controller,” International Journal of Computer Techniques, vol. 4, no. 1, pp. 97–104, 2017, [Online]. Available: http://www.ijctjournal.org

[20] Y. Jiang, C. Yang, and H. Ma, “A Review of Fuzzy Logic and Neural Network Based Intelligent Control Design for Discrete-Time Systems,” Discrete Dynamics in Nature and Society, vol. 2016, 2016, doi: 10.1155/2016/7217364.

[21] E. H. Mamdani and S. Assilian, “An experiment in linguistic synthesis with a fuzzy logic controller,” International Journal of Man-Machine Studies, vol. 7, no. 1, pp. 1–13, 1975, doi: 10.1016/S0020-7373(75)80002-2.