Adjustable Gain Enhanced Fuzzy Logic Controller for Optimal Wheel Slip Ratio Tracking in Hard Braking Control System

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DOI: 10.15598/aeee.v19i3.4124

Article history: Received Feb 25, 2021; Revised Jul 19, 2021; Accepted Aug 31, 2021; Published Sep 30, 2021.

Abstract. *This paper presents hard braking control system based on Adjustable Gain Enhanced Fuzzy Logic Controller (AGE-FLC) for optimal wheel slip ratio tracking performance. The purpose of the study is to improve slip ratio tracking and eliminate cycling while achieving very much shortened distance during emergency braking. The model of a braking vehicle at speed of 30* $m \cdot s^{-1}$ *subject to wheel locking was developed and implemented in MATLAB/Simulink environment. Simulation was conducted without a controller to study the slip ratio performance of the system on different road surfaces. From the simulation results, it can be observed that the vehicle stopped at a distance of 132.2 m in 5 seconds. The system utilizes a Fuzzy Logic Controller (FLC), which was designed for the purpose of reducing the vehicle stopping distance. The control signal of the FLC was enhanced by adding adjustable gain mechanism to its output. Simulation results showed that the AGE-FLC controller offered optimal tracking of desired wheel slip ratio of 0.1 as fast as possible on all road surface scenarios, while improving the stopping distance by 70.4 % on dry road surface, 63.3 % on wet road surface, 57.5 % on cobblestone road surface and 48.8 % on snow road surface respectively. The stopping time for all scenarios was 2.651 seconds. The proposed system was compared with Proportional Integral and Derivative (PID) controller. The results revealed that the AGE-FLC outperformed PID controller and provided more robust control and faster wheel slip ratio tracking within the same simulation time frame.*

Keywords

Antilock braking system, fuzzy logic controller, hard braking, wheel slip ratio.

1. Introduction

In automobile production, there is an increasing demand to ensure passenger safety, fuel economy and building confidence in company's brand in the highly competitive market. Automobile manufacturers have introduced a technology called Vehicle Traction Control System (VTCS) that offers traction and tracking control in accelerating and braking modes. VTCS offers very important function in Electronic Stability Control (ESC) system. Two forms of vehicle traction control mechanisms are used to improve the traction performance of vehicle on road surfaces with adverse conditions. These are Traction Control System (TCS) and Antilock Braking System (ABS). In TCS, the objective is to maintain an optimal grip of a tyre on road surface while the vehicle accelerates. Contrary, the ABS ensures that an effective grip is realised between a tyre and the road surface during emergency or hard braking.

The ability to maintain optimal grip of tyre on road surface is a measure of wheel slip ratio performance. Wheel slip is the difference between vehicle speed and wheel speed. The occurrence of slip can cause stopping distance to be longer than expected, and in some cases, the steering stability may be lost which can lead to severe accidents. Thus, the control action focuses on maximizing the grip of tyre on road surface, which is called tyre traction, by preventing wheels from locking during emergency braking and from spinning during acceleration. The essence is to guarantee safety during acceleration when the road surface condition is severe or deceleration during hard braking.

This paper proposes an AGE-FLC for optimal wheel slip ratio tracking in vehicles during severe braking in different road surface conditions. The intelligent control based on Mamdani fuzzy inference system whose output is being optimized by an adjustable gain mechanism to enhance the controller performance also aims to eliminate noise effect and provide significantly shortened stopping distance and time.

2. Hard Braking Control System

An important contribution to road safety is the incorporation of hard braking control system called ABS. The ABS technology is designed to guarantee that vehicles are steerable and stable in event of uncertainty leading to emergency braking by preventing wheel lock. During hard braking on severe road surface, wheels slip and lockup and this happens when the rotational or angular speed of the wheel is zero such that the wheel slips on the road by 100 % resulting to prolong stopping distance and loss in steering stability of vehicle in some cases [1] and [2]. This condition is undesirable. A block diagram description of slip control technique in ABS is shown in Fig. 1. The figure lists various components in ABS and data flow.

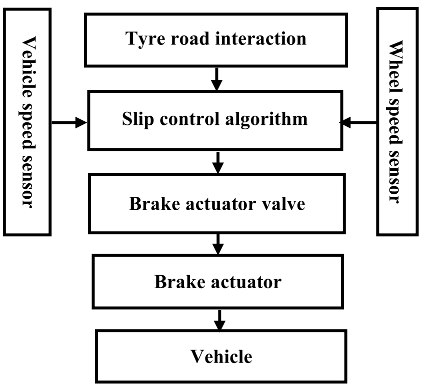


Fig. 1: Description of slip control in ABS.

Several control techniques have been proposed in different studies with the sole objective to track and maintain desired optimal wheel slip ratio. A Grey Sliding Mode Controller (GSMC) for wheel slip control that achieves a faster convergence and better chattering reduction than a conventional Sliding Mode Controller (SMC) was proposed by [3]. However, SMC system are prone to chattering caused by the nonlinear dynamic equations of wheel slip control system that could affect the life span of components of ABS. Hybrid system that uses Feedback Linearization (FBL) and PID controller for slip control during hard braking was proposed by [4]. As a result of the nonlinearity of tyre and road interaction, a nonlinear technique based on input-output feedback linearization was performed and afterward a PID controller was integrated into the linearized slip model. The proposed FBL-PID provided better performance and reduced chattering effect on braking torque compared with conventional FBL system.

In [5] applied a Two Degree of Freedom PID (2-DOFPID) controller in a FBL slip control system for a straight-line braking vehicle on two different road conditions, dry asphalt and wet asphalt. The same technique was used in [6] to investigate slip minimization in vehicles under different drag coefficients. In [7] considers the effect of tyre pressure changes on the optimal slip to design a prediction algorithm whose performance was enhanced by adding a second order factor. The effectiveness of the system was determined in co-simulation environment consisting of MATLAB/Simulink and CarSim. The overall results showed that braking distance and braking time were reduced.

In order to provide anti-lock braking control of wheels over changing road surfaces, in [8] proposed a Sliding Mode Wheel Slip Ratio Controller (SMWSC). In [9] implemented a conventional PID control system for wheel slip reduction during hard braking using a Five Degree of Freedom (5-DOF) longitudinal dynamic model of vehicle. Bang-Bang controller for slip ratio control during severe braking has been implemented by [10] and [11]. In [12] implemented two adaptive nonlinear controllers that use Time Varying Asymmetric Barrier Lyapunov Function (TABLF) to provide optimal slip ratio tracking. An adaptive controller for tracking of desired slip implemented in a laboratory ABS was presented by [13]. FLCs have been implemented for automatic car braking system [14], [15] and [16]. In [17] proposed Fuzzy Sliding Mode Controller (FSMC) to overcome chattering effect of conventional SMC and improve slip performance for ABS.

The literature review provided some of the control algorithms implemented in ABS for wheel slip minimization. However, most of the previous studies did not consider change in road surface conditions or inclusion of some key dynamics of vehicle, such as wheel viscous force and air drag force that may impact on the braking performance of slip ratio controller. Also, the results of almost all the implemented FLC indicated high level of noise in the output responses during emergency braking. Thus, to minimize slip around a steady point of operation, a slip controller is required to track a referenced slip which is necessary for optimal performance.

3. Methods

In this section, the approaches used in achieving the purpose of this study are concisely but clearly detailed in the following subsections.

3.1. Vehicle's Motion Equation

In this paper, single tyre model is used as shown in Fig. 2. The equations of the motion of a straight-line braking car represented by a quarter car model are presented. The following assumptions are made:

- The motion equations are that of a vehicle braking on straight-line.
- There are no vertical and lateral motions.
- The vehicle is braking with an initial straight-line speed of 30 m·s^{-1}.

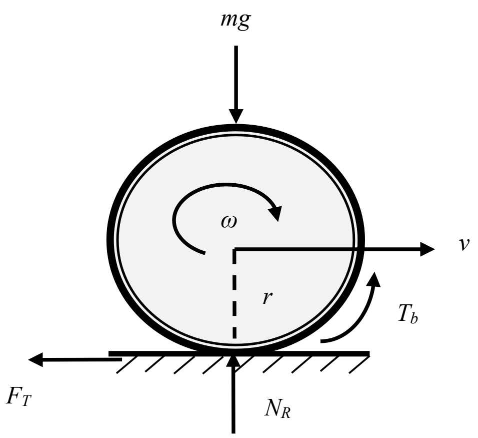


Fig. 2: Single tyre model.

As the car decelerates with a speed $v\,(t)$, the wheels are set into rotation with angular speed $\omega\,(t)$. The motion of the wheel cycles with an arc of length lthat makes an angular displacement θ in radian at the centre. The whole mathematical representation of the motion of the rotating wheel is given by:

$$l = r\theta, \tag{1}$$

where r is the radius of the wheel. In circular motion, the relationship between angular displacement and angular speed is given by:

$$\theta = \omega t. \tag{2}$$

Hence, the tangential forward speed of the wheel to the road surface $v_\omega\,(t)$ can be defined as the rate of change of the length of arc and is given by:

$$\frac{dl}{dt} = v_\omega = r\omega. \tag{3}$$

1) Frictional Force

The frictional or traction force F_T in Newton between the road surface and the rotating tyre is given by:

$$F_T = \mu\,(\lambda)\,N_R, \tag{4}$$

where $\mu\,(\lambda)$ is the coefficient of traction between the tyre and the road surface and a function of the wheel slip, N_R is the normal reaction force in Newton.

2) Vehicle Forward Motion

The forward motion of the braking vehicle is obtained by applying the Newton laws of motion. The resultant force impacting the vehicle is given by:

$$\sum F \geq F_T + F_{drag}. \tag{5}$$

But $\sum F = ma$, where a is the acceleration of the vehicle in m·s^{-2}, mis the mass of the vehicle, and F_{drag} is aerodynamic drag force of air around the vehicle. With the vehicle braking to come to a halt, the acceleration is given by:

$$a = -\frac{1}{m}\left[\mu\,(\lambda)\,N_R + \frac{1}{2}ADCv^2\right], \tag{6}$$

where $\frac{1}{2}ADCv^2$ is the expression for aerodynamic drag force such that A is the projected area of vehicle, D is the density of air, v is the straight-line braking speed of vehicle, C is aerodynamic coefficient of vehicle. Equation (6) can be further expressed in terms of rate of change in speed of the vehicle given by:

$$\dot{v} = -\frac{1}{m}\left[\mu\,(\lambda)\,N_R + \frac{1}{2}ADCv^2\right]. \tag{7}$$

3) Rotational Dynamic

The rotational motion of the wheel is defined by the dynamic equation given by:

$$\dot{\omega} = \frac{1}{J}\left[r\mu\,(\lambda)\,N_R - f_w\omega - T_b\,(sign\,(\omega))\right], \tag{8}$$

where ω is the angular speed of the wheel, J is the moment of inertia of the wheel, r is the radius of the wheel, f_w is the wheel viscous friction and T_b is the braking torque.

4) Actuator Dynamic

The dynamic of hydraulic brake actuator can be modelled as a first order system in transfer function form given by [18]:

$$G(s) = \frac{k}{\tau s + 1}, \tag{9}$$

where k represents the braking gain, which is a function of the brake radius, brake pad friction coefficient, brake temperature and the number of pads [19], and τ stands for the hydraulic torque time constant. Compensating for the fluid lag or delay, a time delay function e^{-sT} is introduced into Eq. (9) and this gives [5]:

$$T_b = e^{-\tau s}\frac{k}{\tau s + 1}T_{ref}. \tag{10}$$

A maximum braking torque limit $T_{\max}$ of 4000 Nm that is constrained to $0 < T_b < T_{b_{\max}}$ has been chosen [20]. The Simulink model of actuator system is shown in Fig. 3.

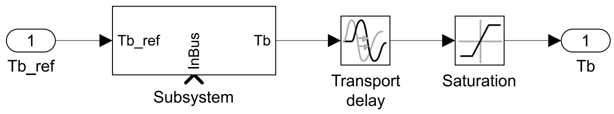


Fig. 3: Actuator dynamic.

5) Tyre-Friction Model

In the representation of tyre-road surface dynamic equation, one of the famously used models is the Pacejka tyre model or Magic Formula, and has proven to suitably match experimental data obtained under certain conditions of constant linear and angular velocity [21]. This friction model is very detailed, and it is the most often used one in commercial vehicle simulators such as CarSim, Adams/Tyre, and BikeSim [22]. The Pacejka friction model is used in this study and given by:

$$\mu_x = a\left(1 - e^{-b\lambda} - c\lambda\right), \tag{11}$$

where a, b, c, are constants of the tyre-friction model respectively.

The friction forces are described by the Pacejka model via static maps that depends on different parameters. Altering the values of the constant parameters in the model brings about the possibility of modelling many different tyre-road frictions. Table 1 shows the values of the constants for different road conditions.

Tab. 1: Pacejka friction model constants [22].

Road condition	$a = \vartheta_{r1}$	$b = \vartheta_{r2}$	$c = \vartheta_{r3}$
Dry asphalt	1.28	23.990	0.52
Wet asphalt	0.86	33.82	0.35
Cobblestone	1.37	6.46	0.67
Snow	0.19	94.13	0.06

6) Slip Model

The wheel slip of the braking vehicle is given by:

$$\lambda = \frac{v - r\omega}{v}. \tag{12}$$

Equation (12) does not contain the input (braking torque) T_b and as such no direct relationship between it and the output (wheel slip) λ. A direct relationship can be established between λ and T_b by applying the first derivative principle to Eq. (12). The details of the derivation can be found in [5] and is given by:

$$\dot{\lambda} = -\frac{1}{v}\left(\frac{\omega}{mv} + \frac{r^2}{J}\right)\mu(\lambda)F_N + \frac{r}{Jv}T_b, \tag{13}$$

where the control input $u = T_b$. The Simulink model of overall vehicle dynamics is shown in Fig. 4.

3.2. Design of Fuzzy Logic Controller

FLC provides realistic and convenient alternative to solving nonlinear problems associated with control systems using heuristic information. Such heuristic information is used as a set of rules to describe the control process. One of the advantages of FLC is that it can be easily implemented on a standard computer [23]. Fuzzy logic emulates human reasoning to provide appropriate control law in a more flexible way than theoretical computations generally done by classical controller. Machines are enabled to understand and respond to vague human thought such as high, medium, low, and so on. Figure 5 shows the components of a fuzzy logic controller in closed loop control system. The components are fuzzifier, defuzzifier, rule base and inference mechanism (the unit responsible for decision making by the FLC). A FLC is usually characterised by at least two inputs and an output. Inputs to output mapping is done by Mamdani fuzzy inference system using Membership Functions (MFs) of the fuzzy sets. A MF is a shape that shows the way by which every point in the input crisp value is connected to a degree of MF (fuzzy value).

The design and implementation of FLC in this paper in MATLAB/Simulink environment is carried out using the Mamdani model and the defuzzification method employed is the centre of gravity (centroid).

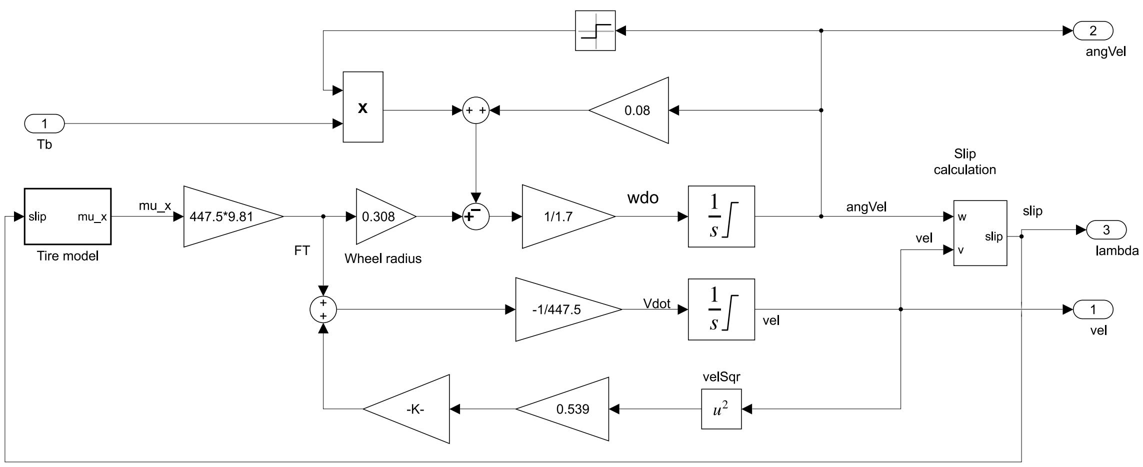


Fig. 4: Simulink model of vehicle dynamic.

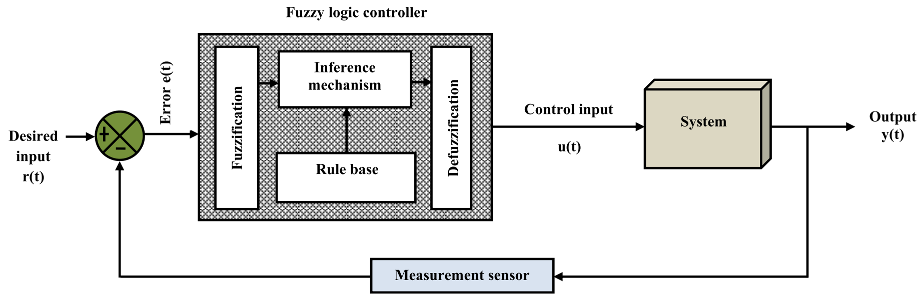


Fig. 5: Fuzzy logic control closed loop control system.

The inputs are the slip error (E) and the change of slip error (CE), while the output is the braking pressure (or torque) T_b that adjusts with corresponding changes in inputs as shown in Tab. 2. The rule base consists of linguistic variables that represent the human thought. The linguistic variables used in this paper are NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small) and PL (Positive Large). The fuzzy rules formulated for this design carried out in MATLAB are 25 and are given in Tab. 2, while the shapes of the MFs used are presented in Fig. 6.

Tab. 2: Fuzzy rule table.

E/CE	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

A triangular MF was used for modelling the inputs, while two MFs (triangular and trapezoidal) were used for the output. A three-dimensional (3-D) plot of the mapping of the inputs to the output called control surface is shown in Fig. 7. The mathematical expressions for the inputs and output variables are given by:

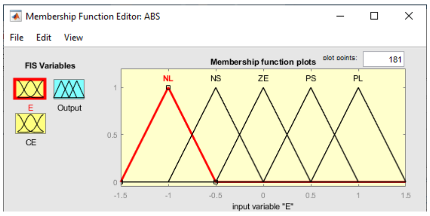
$$\left.\begin{array}{c} E\left(t\right)=\lambda_d\left(t\right)-\lambda_{ac}\left(t\right) \\ CE=E\left(t\right)-E\left(t-1\right) \\ T_b\left(t\right)=T_b\left(t\right)-T_b\left(t-1\right) \end{array}\right\}, \tag{14}$$

where t is the time factor, λ_d is the desired slip, and λ_{ac} is the actual slip.

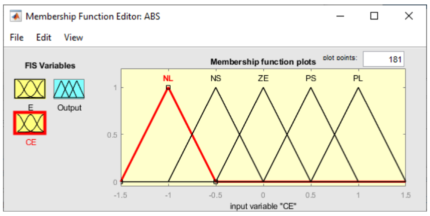
An adjustable gain mechanism was added to the output of the FLC to ensure effective control action is provided to give optimal wheel slip ratio at the output for different road surface conditions. The inequality representing range of gains for the four different road surface conditions is $1.056 \leq \alpha \leq 6.164$, where α represents the adjustable gain whose value is within the range of the inequality. The Simulink model of the proposed system is shown in Fig. 8.

3.3. PID Controller

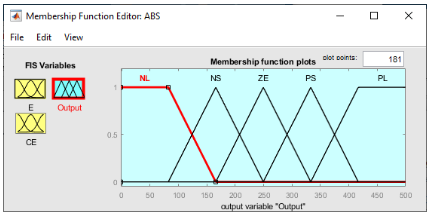
PID controller is a conventional control scheme that combines three mathematical computational operations. The proportional operation involves direct multiplication of error over time, integral operation involves accumulation of errors over time, and derivative operation performs differentiation of error over time until it reduces to zero as quickly as possible [24]. These operations are coordinated simultaneously to execute a correctional action called control command



(a) Error input of FLM.



(b) Change in error input of FLM.



(c) Output variable of FLM.

Fig. 6: Membership functions of the FLC.

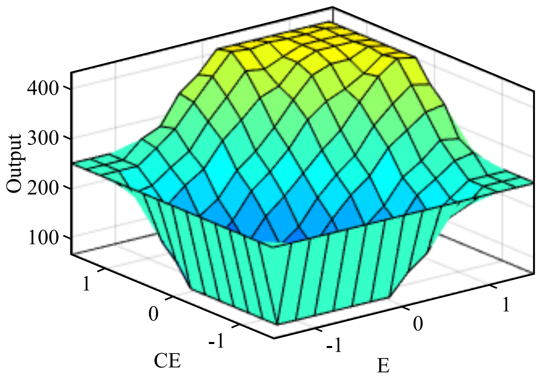


Fig. 7: Nonlinear 3-D fuzzy control surface.

that derives the system into new output state. The PID is a popular controller due to its relatively ease of design and implementation. A PID controller (in discrete time) is implemented in this paper to compare and validate the proposed AGE-FLC effectiveness. The algorithm of the PID scheme is given by:

$$C(z) = 2000 + \frac{500}{z-1} + \frac{10(z-1)}{z-0.9}. \qquad (15)$$

3.4. Simulation Parameters

The definitions and the numerical values of the parameters used for the MATLAB/Simulink simulation analysis carried out in this study are presented in Tab. 3.

Tab. 3: Simulation parameters [4], [11] and [20].

Description	**Symbol**	**Value**
Quarter-car mass	M	450 kg
Moment of inertia	J	1.6 kg·m^2
Wheel radius	R	0.32 m
Wheel friction coefficient	F_w	0.08 Nms·rad^{-1}
Hydraulic time constant	τ	0.0143 s
Gravitational acceleration	g	9.81 m·s^{-2}
Desired slip	λ_r	0.1
Actuator pole	A	70
Hydraulic gain	K	1.0
Initial vehicle speed	v_o	30 m·s^{-1}
Projected area	A	2.04 m^2
Air density	D	1.225 kg·m^{-3}
Drag coefficient	C	0.539

4. Results

This section presents the analysis of the results obtained based on the modelling and simulations of a single tyre model of a braking vehicle with initial straight-line speed of 30 m·s^{-1}. Simulations are carried out for dry asphalt, wet asphalt, cobblestone, and snow road surfaces. The braking torque is limited to 4000 Nm. This is to enable the hard braking control system to disengage at low speeds to allow the vehicle to come to halt as soon as the wheel speed approaches zero. The simulation results are presented for hard braking control without controller, with FLC, and FLC performance comparison with classical PID.

4.1. Results of System without Controller

The simulation plots in Fig. 9, Fig. 10, Fig. 11 and Fig. 12 are the results of slip ratio, stopping distance, braking torque, and braking speed when the system was implemented on different road surfaces without a controller. This is the non-assisted hard braking control system. It can be noticed that the tracking slip (actual slip) obtained for each road surface was off the desired slip of 0.1 by 100 % as shown in Fig. 9. This has resulted to a large stopping distance of 135.2 m in 5 s for all the road surfaces as shown in Fig. 10. The braking torque on the other hand was extremely low (0.1 Nm) in all cases as shown in Fig. 11. The braking speed remains very high with a value of 24.44 m·s^{-1}. Generally, the performance of the system is undesirable; hence a controller is needed to improve system performance. In Tab. 4, the summary of the simulation results is presented.

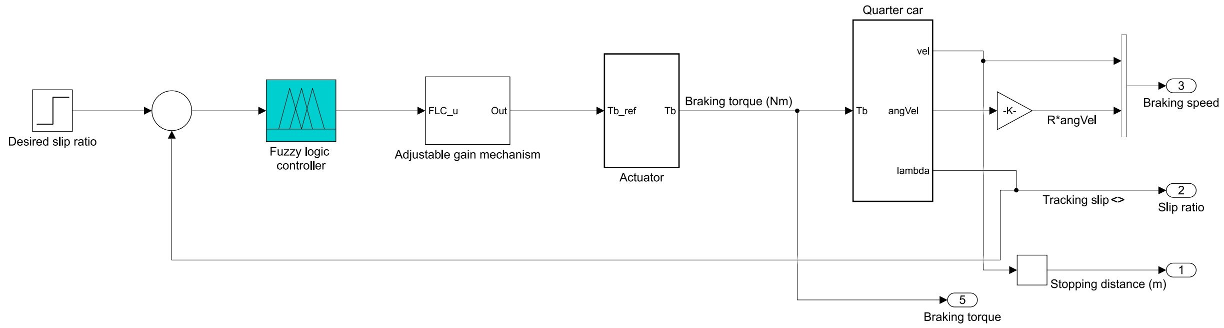


Fig. 8: Simulink model of proposed system.

Tab. 4: Performance of system without controller.

Performance parameter		**Dry road surface**	**Wet road surface**	**Cobblestone road surface**	**Snow road surface**
Slip ratio		D-slip $= 3.517 \cdot 10^{-5}$	W-slip $= 3.671 \cdot 10^{-5}$	C-slip $= 1.331 \cdot 10^{-4}$	S-slip $= 5.924 \cdot 10^{-4}$
Stopping distance (m)		DSD = 135.2	WSD = 135.2	CSD = 135.2	SSD = 135.2
Braking torque (Nm)		DBT = 0.1	WBT = 0.1	CBT = 0.1	SBT = 0.1
Speed	Vehicle speed	DVS = 24.44	WVS = 24.44	CVS = 24.44	SVS = 24.44
($\mathrm{m \cdot s^{-1}}$)	Wheel speed	DWS = 24.44	WWS = 24.44	CWS = 24.44	SWS = 24.44

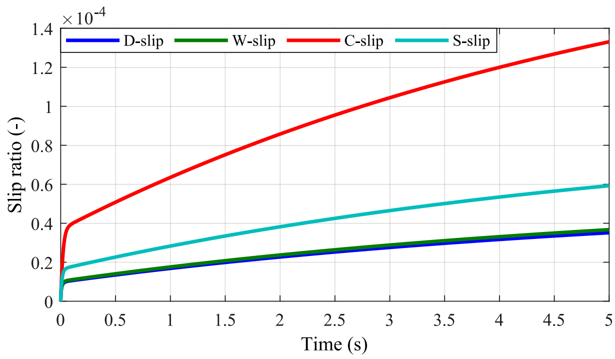


Fig. 9: Slip ratio response (without controller).

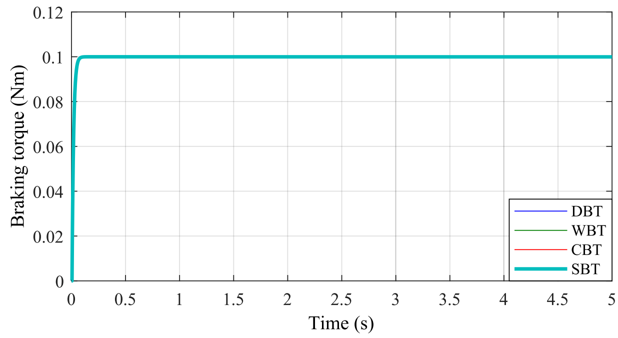


Fig. 11: Braking torque (without controller).

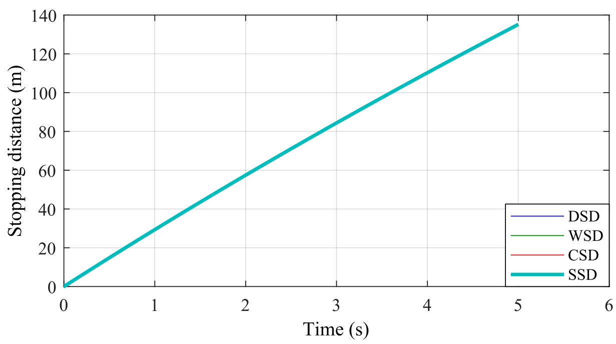


Fig. 10: Stop distance (without controller).

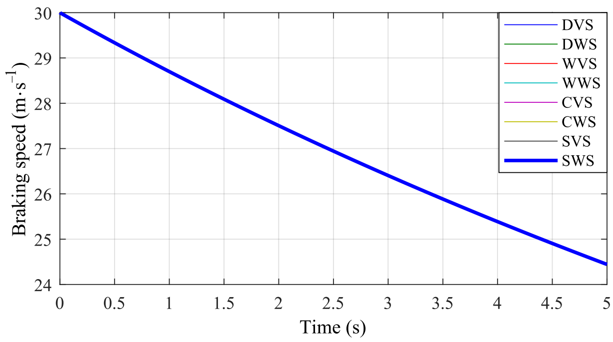


Fig. 12: Braking speed (without controller).

4.2. Results of System with Controller

Figures 13, Fig. 14, Fig. 15 and Fig. 16 are the simulation results for slip ratio, stopping distance, braking torque, and braking speed with an AGE-FLC added to the system. The performance of the system with the AGE-FLC is summarised in Tab. 5 and Tab. 6. Based on the results in Tab. 5, it can be concluded that the controller was able to achieve an optimal slip ratio tracking of 0.1 during emergency braking on all road surfaces.

However, the stopping distances, braking torque, braking speed varies for the road surfaces. The best performance was obtained during braking on dry road surface. In terms of time domain performance characteristics considering Tab. 6, the dry road surface offers the best performance in rise time and settling time.

Tab. 5: Performance of system with adjustable gain enhanced fuzzy logic controller.

Performance parameter		Dry road surface	Wet road surface	Cobblestone road surface	Snow road surface
Slip ratio		Dry-SR = 0.1	Wet-SR = 0.1	Cobblestone-SR = 0.1	Snow-SR = 0.1
Stopping distance (m)		SDD = 39.96	SDW = 49.62	SDC = 57.47	SDS = 69.19
Braking torque (Nm)		BTD = 1537	BTW = 1120	BTC = 782.9	BTS = 263.1
Speed	Vehicle speed	BSD = 0.50	BSW = 7.802	BSC = 13.65	BSS = 22.41
($m \cdot s^{-1}$)	Wheel speed	BSD = 0.45	BSW = 7.022	BSC = 12.28	BSS = 20.16

Tab. 6: Time domain performance of system with adjustable gain enhanced fuzzy logic controller.

Performance parameter	Dry road surface	Wet road surface	Cobblestone road surface	Snow road surface
Rise time (s)	0.081	0.123	0.101	0.513
Settling time (s)	0.102	0.155	0.127	1.8
Peak overshoot (%)	1.8	0.2	0.1	0.3
Final value	0.1	0.1	0.1	0.1

However, the best performance in terms of peak percentage overshoot was obtained during braking on cobblestone surface.

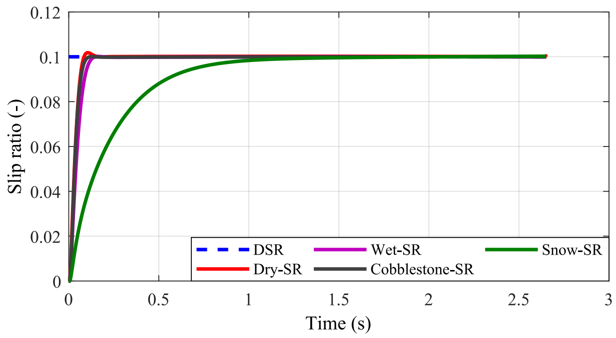


Fig. 13: Slip ratio response with FLC.

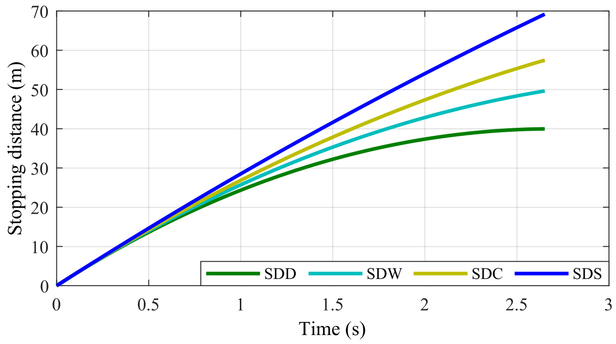


Fig. 14: Stopping distance with FLC.

Generally, the proposed AGE-FLC provided optimal slip tracking of 10 % during braking on all road surfaces considered. The graph in Fig. 14 shows that the vehicle comes to a stop at 2.651 seconds after the application of brake. When both the vehicle speed and wheel speed are the same as shown by the lines, there is no wheel slip. For the dry road surface, a slip of 0.1 is achieved after 0.08 seconds by applying the brakes. In the case of braking on wet, cobblestone and snow road surfaces, a desired optimal slip ratio of 0.1 is achieved after 0.123 second, 0.101 second, and 0.513 second.

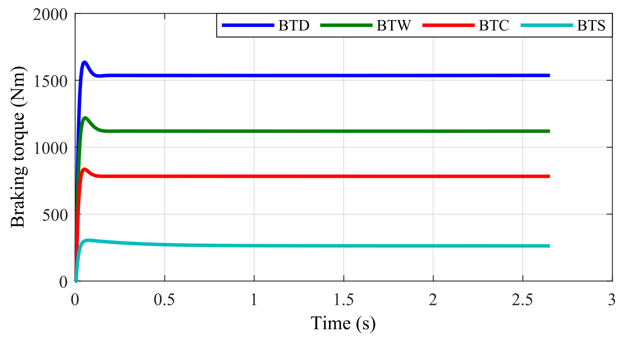


Fig. 15: Braking Torque with FLC.

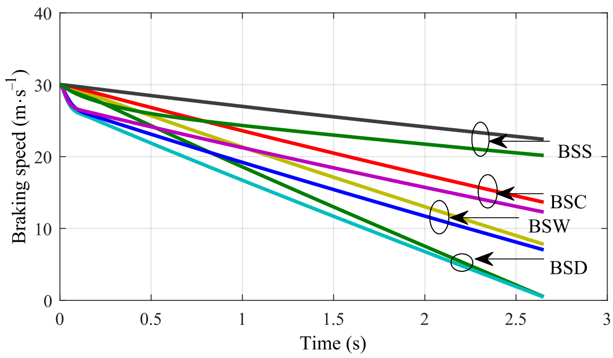


Fig. 16: Braking speed with FL.

4.3. Comparison of AGE-FLC with PID Controller

The performance of the proposed controller is compared with that of PID controller. The simulation graphs for the tracking slip ratio and the stopping distance are presented in Fig. 17 and Fig. 18. The various performances of the AGE-FLC and PID control system in terms of slip ratio, stopping distance, braking torque, and braking speed are shown in Tab. 7. The comparison of the time domain performance responses of AGE-FLC and PID controller are presented in Tab. 8. In order to analyse the percentage improvement in stopping distance, the expression given

Tab. 7: Performance of system with adjustable gain enhanced fuzzy logic controller and with PID controller.

Performance parameter		Dry road surface	Wet road surface	Cobblestone road surface	Snow road surface
AGE-FLC					
Slip ratio		DFS = 0.1	WFS = 0.1	CFS = 0.1	SFS = 0.1
Stopping distance (m)		SDDFuzzy = 39.96	SDWFuzzy = 49.62	SDCFuzzy = 57.47	SDSFuzzy = 69.19
Braking torque (Nm)		BTDFuzzy = 1537	BTWFuzzy = 1120	BTCFuzzy = 782.9	BTS Fuzzy = 263.1
Speed ($m\cdot s^{-1}$)	Vehicle speed	BSDFuzzy = 0.50	BSWFuzzy = 7.802	BSCFuzzy = 13.65	BSSFuzzy = 22.41
	Wheel speed	BSDfuzzy = 0.45	BSWFuzzy = 7.022	BSCFuzzy = 12.28	BSSFuzzy = 20.16
	SDI	70.4 %	63.3 %	57.5 %	48.8 %
PID controller					
Slip ratio		DPIDS = 0.1	WPIDS = 0.1	CPIDS = 0.1	SPIDS = 0.1986
Stopping distance (m)		SDDPID = 44.53	SDWPID = 52.44	SDCPID = 59.19	SDSPID = 70.01
Braking torque (Nm)		BTDPID = 1536	BTWPID = 1120	BTCPID = 782.9	BTSPID = 160
Speed ($m\cdot s^{-1}$)	Vehicle speed	BSDPID = 2.241	BSWPID = 8.853	BSCPID = 14.28	BSSPID = 12.89
	Wheel speed	BSDPID = 2.016	BSWPID = 7.966	BSCPID = 12.86	BSSPID = 18.34
	SDI	67.1 %	61.2 %	56.2 %	48.2 %

Tab. 8: Time domain performance of system with adjustable gain enhanced fuzzy logic controller and with PID controller.

Performance parameter	Dry road surface	Wet road surface	Cobblestone road surface	Snow road surface
AGE-FLC				
Rise time (s)	0.081	0.123	0.101	0.513
Settling time (s)	0.102	0.155	0.127	1.8
Peak overshoot (%)	1.8	0.2	0.1	0.3
Final value	0.1	0.1	0.1	0.1
PID controller				
Rise time (s)	0.208	0.142	0.1140	0.047
Settling time (s)	0.492	1.762	0.270	2.723
Peak overshoot (%)	7.9	34.4	3.7	183.8
Final value	0.1	0.1	0.1	0.1986

in Eq. (16) is used.

$$SDI = \frac{SD_{NC} - SD_{WC}}{SD_{NC}} \cdot 100, \tag{16}$$

where SDI stands for stopping distance improvement, SD_{NC} stopping distance of system with no controller, and SD_{WC} stopping distance of system with controller.

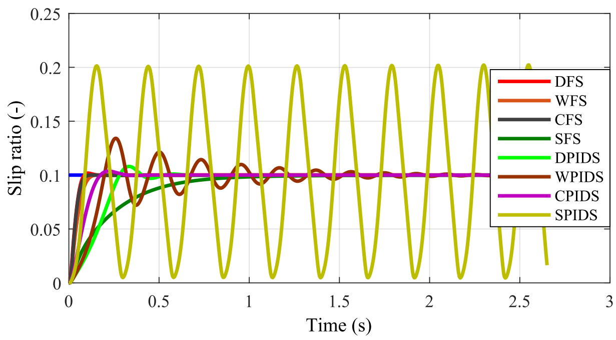


Fig. 17: Slip ratio performance comparison.

It can be deduced from the simulation results in Tab. 7 that the performance of the AGE-FLC outperformed the PID controller in terms of stopping distance, braking torque, and braking speed. When comparing the tracking slip ratio performance of both controllers in Tab. 7 and Tab. 8, it can be noticed that 0.1 optimal slip is achieved faster with the proposed AGE-FLC controller than the PID controller. This is indicated by the reduce rise time for the road surfaces considered. That is to say, the AGE-FLC provided an immediate tracking at the instance of emergency braking than the PID controller. For instance, during braking on dry road surface, the AGE-FLC must have urgently responded and provide slip tracking at 0.08 seconds which is 0.128 seconds head before the PID controller will respond. In terms of settling time, it is obvious looking at Tab. 8 that the AGE-FLC system stabilizes faster than PID controller for all road surfaces while tracking the desired speed. The peak overshoot in percentage is almost zero in the AGE-FLC system compared with PID where the value is outrageously high during braking on wet and snow road surfaces.

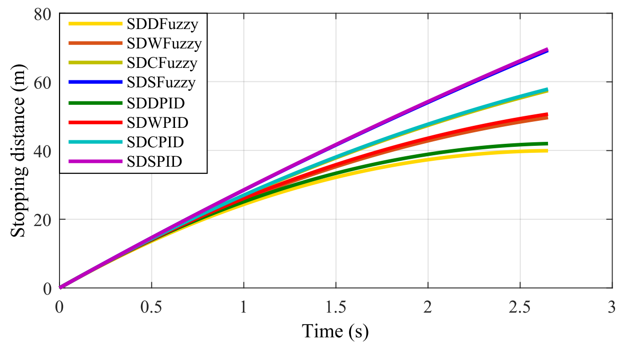


Fig. 18: Stopping distance comparison.

Generally, the introduction of AGE-FLC improved the overall system performance and uses adequate braking torque less than the maximum allowable torque of 4000 Nm to achieve desired optimal tracking slip ratio and stopping distance. For instance, during braking in dry road surface, 70.4 % reduction in stopping distance was achieved with AGE-FLC. Thus, the proposed system outperforms the PID control system.

5. Conclusion

This paper has presented an enhanced FLC for hard braking control system. The use of the FLC addresses the nonlinearity effect of the slip ratio dynamic. The system was modelled with the dynamics of a single tyre of a vehicle decelerating on a straight-line. A desired optimal wheel slip ratio of 0.1 was chosen as a criterion for the control objective. The single tyre model was developed in MATLAB/Simulink environment. Simulation results showed that the AGE-FLC improved the overall performance of the hard braking control system. When compared to conventional PID controller, the proposed controller proved to be faster in providing immediate and urgent response to optimal slip tracking during hard braking on all road surface conditions considered in this paper compared with PID control. The AGE-FLC also showed to be more robust and superior in stabilizing the operation of the braking system without chattering or any form of cycling in all road surface conditions.

The objective of this paper has been achieved. However, the following recommendations are made with respect to improving or applying another approach that will provide more promising slip tracking performance especially for the wet and snow road surfaces.

- An evolutionary optimizing algorithm can be used in place of the adjustable gain to optimize the performance of the FLC.
- Simulation studies can be conducted on the proposed scheme with different parameters of vehicles to ascertain the robustness and effectiveness of AGE-FLC for vehicle braking scenarios. For more practical simulation purpose, the proposed scheme should be implemented via co-simulation involving CarSim/MATLAB.

Author Contributions

P.C.E. carried out the modelling and design of the controller and prepared the manuscript. B.O.E. and N.C.A. wrote the introduction and review of previous studies on antilock braking system. P.C.E. and T.I.O. conducted the simulation and analysis of the results. B.O.E. and N.C.A. also analysed the simulation results and revised the manuscript. All authors read and approved the final paper.

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