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An Intelligent Controller Augmented with Variable Zero Lag Compensation for Antilock Braking System

Benjamin C. Agwah, Paulinus C. Eze

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***Abstract*—**Antilock braking system (ABS) is one of the important contributions by the automobile industry, designed to ensure road safety in such way that vehicles are kept steerable and stable when during emergency braking. This paper presents a wheel slip-based intelligent controller with variable zero lag compensation for ABS. It is required to achieve a very fast perfect wheel slip tracking during hard braking condition and eliminate chattering with improved transient and steady state performance, while shortening the stopping distance using effective braking torque less than maximum allowable torque to bring a braking vehicle to a stop. The dynamic of a vehicle braking with a braking velocity of 30 ms^{-1} on a straight line was determined and modelled in MATLAB/Simulink environment to represent a conventional ABS system without a controller. Simulation results indicated that system without a controller was not able to track desired wheel slip and the stopping distance was 135.2 m. Hence, an intelligent control based on fuzzy logic controller (FLC) was designed with a variable zero lag compensator (VZLC) added to enhance the performance of FLC control variable by eliminating steady state error, provide improve bandwidth to eliminate the effect of high frequency noise such as chattering during braking. The simulation results showed that FLC-VZLC provided fast tracking of desired wheel slip, eliminated chattering, and reduced stopping distance by 70.5% (39.92 m), 63.3% (49.59 m), 57.6% (57.35 m) and 50% (69.13 m) on dry, wet, cobblestone and snow road surface conditions respectively. Generally, the proposed system used effective braking torque that is less than the maximum allowable braking torque to achieve efficient wheel slip tracking and overall robust control performance on different road surfaces.

***Keywords*—**ABS, Fuzzy Logic Controller, Variable Zero Lag Compensator, Wheel Slip Tracking

I. Introduction

THE acceleration or deceleration of vehicle can be adversely affected by poor road surface conditions such as sand, ice, snow, or water that can cause emergency braking. In some cases, a vehicle can spin while accelerating or skid while braking due to wheel-lock. Wheel slip is one of the causes of hard or severe braking which can endanger passenger's safety. Slip is the difference between vehicle speed and wheel speed. Maintaining finest grip of tyre or traction on road surface is a function of wheel slip ratio [1].

The stopping distance of a braking vehicle can be extended and in some situations steering stability can be lost when wheel slip occurs, which can result in vehicle crash. This underscores the need for a control system that can drastically minimize such negative consequences of poor road surface conditions and ensure improved directional control [2], [3]. Therefore, the control action is geared towards optimizing the grip of tyre on road surface, which is the tyre traction. The technology for achieving tyre traction is called Vehicle Traction Control (VTC).

In VTC, the control of tyre grip on road surface is designed to achieve desired vehicle motion both in the longitudinal and lateral directions. The tyre traction forces arise from the interaction between the tyre and the road surface and are determined accordingly in longitudinal and lateral directions. Control action is achieved in the lateral direction by the steering angle because the tyre traction force depends on the tyre slip angle. In the longitudinal direction, control action depends on the coefficient of friction between the tyre and the road surface. There are different ways to achieving longitudinal traction force control depending on the control objective. This paper is designed to control wheel slip at any referenced value so as to achieve a desired amount of longitudinal traction force (slip control) in ABS.

ABS is regarded a vital contribution to road safety as it is designed to keep a vehicle steerable and stable during hard braking moments by preventing wheel-lock. In fact, as an active safety mechanism in vehicles plying the road, ABS is activated during severe, hard or emergency braking to maximize the braking pressure (traction force) between tyre and road surface. The goal of slip control in ABS is to manipulate the wheel slip in order that optimal friction is achieved and steering stability is maintained. That is to ensure the stopping of the vehicle in shortest distance possible while keeping the directional control [4]. Meanwhile, various control techniques have been developed to regulate wheel slip within a referenced level that is acceptable for vehicle safety and accident avoidance in ABS. The specific slip for which ABS is designed to guarantee even at maximum braking (that is maximum pressure applied on the brake pedal by the driver) is said to occur when slip is in the range 10%-30% [4].

In this paper, an intelligent control is proposed for wheel slip regulation for ABS. The intelligent control is designed using Mamdani Fuzzy Interference System (FIS) method to realize a FLC whose control action is enhanced by a VZLC so as to achieve optimal wheel slip of 10% during emergency braking on different road surfaces, while improving braking performances with significant shortened stopping distance.

II. Antilock Braking Control Techniques

In the event of uncertainty resulting in emergency braking,

B. C. Agwah is a Senior lecturer at the Federal Polytechnic Nekede, Owerri, Nigeria (e-mail: agwa278@gmail.com).

P. C. Eze is a lecturer at Covenant Polytechnic, Aba, Nigeria; and Research Scholar at the Federal University of Technology, Owerri, Nigeria (corresponding author, e-mail: paulinuseze1@gmail.com).

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the ABS control is activated to ensure that vehicles are stable and steerable [1]. In achieving this, many control techniques have been presented with primary goal to track and maintain a referenced optimal wheel slip. In [5], FLC was used to optimize braking distance of vehicle in critical conditions. Optimal wheel slip and shortened stopping distance was achieved in [1] using adjustable gain enhanced FLC (AGE-FLC). Mamdani FLC has been applied in automatic car braking system performance for obstacle avoidance in terms of distance and velocity [6]. An ABS control with time varying slip ratio has been implemented with output feedback constraint problem using Time-varying Asymmetric Barrier Lyapunov Function (TABLF) to track an optimal slip ratio [7]. Conventional Proportional-Integral-Derivative (PID) controller and two-Degree of Freedom (DOF) PID controller have been implemented to achieve optimal wheel slip tracking on different road surfaces and to investigate the effect of varying aerodynamic coefficients [1], [2], [8], [9]. A nonlinear control based on PID controller with feedback linearization (FBL) has been implemented in [10] to address the problem high nonlinearity associated with the interaction of tyre and road. Bang-bang controller to maintain a wheel slip at desired value has been achieved in [11] and [12]. With three control objectives comprising stopping distance reduction, limiting of slip ratio and improving control system performance, [13] proposed FLC to replace classical PID controller. Considering the influence of tyre pressure changes, a Fuzzy-PID control technique was developed for improved optimal slip ratio prediction in [14]. Adaptive control systems based on Genetic fuzzy self-tuning PID controller and neuro-fuzzy have been proposed [15], [16]. Sliding Mode Control has been implemented [17]-[19]. Fuzzy sliding Mode Controller (FSMC) and Sell-learning FSMC have been implemented to eliminate the effect of chattering associated with conventional SMC in ABS and improve braking performance [20], [21].

Despite the fact that the proposed solutions have improved control performance and achieved promising slip ratio tracking performance, there are certain problems in these control strategies. The classical PID control is prone to system parameter variation. The disadvantage of using FLC only is that it results in steady state error [22]. For bang-bang control system, the output response is not satisfactory [13]. As per the SMC, the control action (bake torque) and wheel slip ratio tracking error are unsatisfactory and suffer from chattering [20]. The neural network algorithm is laden with high data and computational complexity [7]. Moreover, some of the previous studies did not take into account some essential components of braking vehicle dynamics that can influence the braking performance such as wheel viscous friction and aerodynamic drag force [1], [2].

III. System Design

This section presents the dynamics of a car based on single tyre model and the control technique developed in achieving the objective of this paper.

The longitudinal or forward braking dynamics of a vehicle are developed using single tyre model. A quarter mass m of a vehicle moving with forward speed v at time t is carried by a single tyre as shown in Fig. 1. The wheel moves with an angular speed of ω in the direction of the longitudinal motion as the straight line emergency braking of the vehicle goes to a halt. The following assumptions are made [1]:

- The dynamic motion of is that of straight line braking vehicle.
- The vertical and lateral motions are not considered.
- The forward braking speed of the vehicle is assumed to be 30 ms^{-1}.

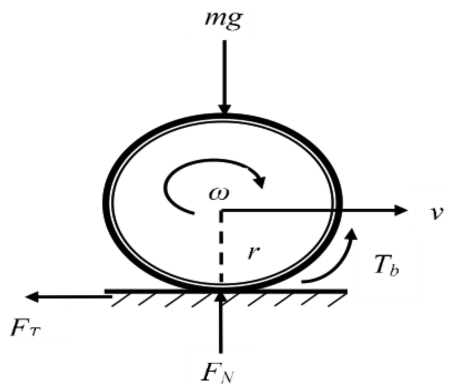

Fig. 1 Single Tyre model

The longitudinal motion of speed v causes the wheel to rotate with angular speed ω. As the wheel rotates, it describes an arc of length l with angular displacement θ at the center. The rotational motion of the wheel is given by:

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

where r is the radius of the wheel in meter. The angular displacement is related to the angular speed by:

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

Therefore, the forward speed of the wheel (or tyre) tangential to road surface v_ω can be defined as the change in l with respect to time t and is given by:

$$v_\omega = r\omega \tag{3}$$

A. Traction Force

The opposition to longitudinal motion of the vehicle tyre caused by friction between the tyre and the road surface is given by:

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

where F_T is the tractive force in Newton, $\mu(\lambda)$ is the coefficient of friction which is a function of the wheel slip λ, and F_N is the normal reaction force in Newton.

B. Longitudinal Motion of Vehicle

The vehicle longitudinal motion can be described based on

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the laws of dynamic motion. The effective force acting on the vehicle is represented by:

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

where $\sum F = ma$ such that a is the retarding acceleration (deceleration) of the vehicle in m.s^{-2}, m is the mass of the vehicle in kg, and F_{drag} is the aerodynamic drag force of air. Therefore, as the vehicle gradually comes to a halt, the acceleration is given by:

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

where $1/2\,ADCv^2$ represents F_{drag} such that A, D, C, v are the vehicle projected area in m^2, the air density in kgm^{-3}, the aerodynamic coefficient, and the straight line velocity in m.s^{-1}. The acceleration of the vehicle can be expressed in terms of time derivative of the straight line (longitudinal) velocity given by:

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

C. Rotational Motion

The braking acceleration of the wheel can be represented in terms of time derivative of the wheel angular speed given by:

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

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

D. Dynamic Model of Actuator

The actuator is a hydraulic brake system is a first order transfer function given by [23]:

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

where k is the braking gain, which is a function of brake radius, brake pad friction coefficient, brake temperature and number of pads [24], τ is the hydraulic torque time constant. The time delay function $e^{-\tau s}$ is introduced into (9) to compensate for the fluid lag or delay and this gives:

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

A maximum braking torque limit $T_{b\_\max}$ of 4000 Nm constrained to $0 < T_b < T_{b\_\max}$ [9] is chosen in this paper.

E. Dynamic Model of Tyre-Friction

Pacejka friction model or Magic Formula is one of the commonly used friction models, which has shown to properly match experimental data acquired under some conditions of given linear and angular velocity [25]. It is very detailed and it is most usually employed model in commercial vehicle simulators like CarSim, Adams/Tyre, and BikeSim [26]. Thus, the Pacejka friction model is given by:

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

where a, b, c are constants. The constant parameters in (11) are varied so that different tyre-road friction conditions can be determined. The definitions of the parameters are defined in Table I.

TABLE I
DEFINITION OF PACEJKA MODEL CONSTANT [26]

Road condition	a	b	c
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

F. Slip Model

The mathematical definition of wheel slip for vehicle braking straight line is given by:

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

From (12), no direct relationship is between the output wheel slip λ and the maximum braking torque T_b (maximum pressure applied to the pedal by the driver). Nevertheless, applying input-out linearization as in [2] gives a direct relationship between λ and T_b defined 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 T_b is the control input u. The model of the proposed system is shown in Fig. 2.

G. Fuzzy Logic Controller

FLC is an intelligent tool that has gain prominence in control systems. Usually, a FLC takes at least two inputs and one output and its operation is characterized by three processes: fuzzification, inference engine and defuzzification [13]. In the FLC implemented in this paper, input to output mapping is performed by Mamdani Fuzzy Inference System (FIS) employing Membership Functions (MFs) of the fuzzy sets [1].

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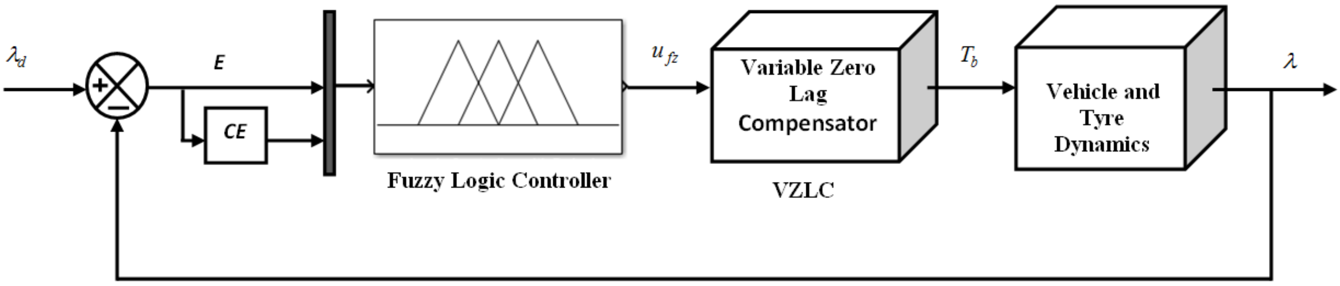

Fig. 2 Proposed intelligent control for ABS

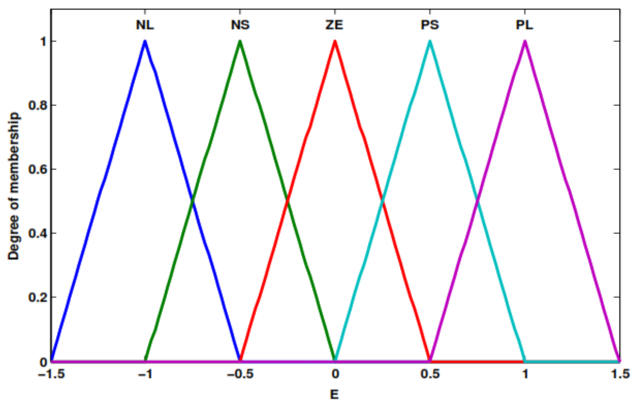

Fig. 3 (a) Error input MF

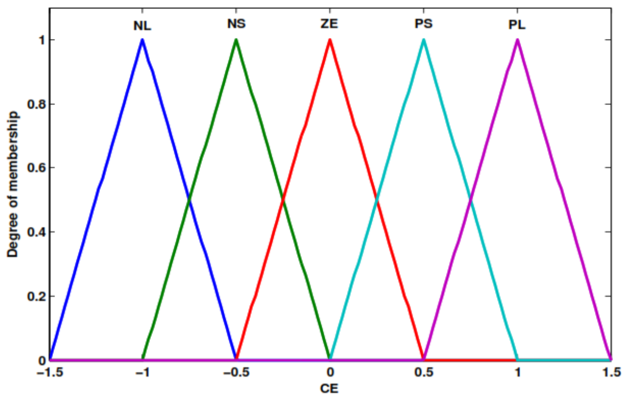

Fig. 3 (b) Change of error input MF

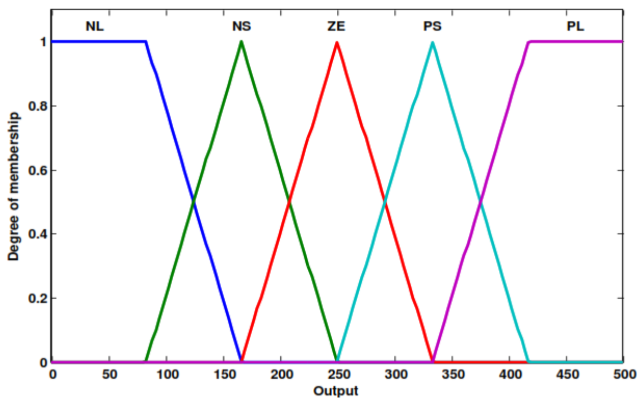

Fig. 3 (c) Output MF

Fig. 3 Membership functions of the FLC

The FLC is designed in MATLAB/Simulink environment using the Mamdani model and employing center of gravity for the defuzzification method. The inputs to the FLC are the slip error (E) and the change of slip error (CE). The output is a variable u_{fz} that adjusts according to changes in inputs as presented in Table II. The rule base comprises linguistic variables that take the form of human reasoning or intelligence. The linguistic variables are: Negative large (NL), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Large (PL). There are 25 fuzzy rules formulated for the FLC design. The shapes of the MFs used are shown in Fig. 3. The rule viewer and the three-dimensional (3-D) graph (called control surface) of the mapping of the E to CE are shown in Figs. 4 and 5.

TABLE II
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

The inputs were modelled using triangular MF, while the output used triangular and trapezoidal MFs. The mathematical equations of the inputs and output variables considering Fig. 2 are given by:

$$\left.\begin{aligned} E(t) &= \lambda_d(t) - \lambda(t) \\ CE(t) &= E(t) - E(t-1) \\ u_{fz}(t) &= u_{fz}(t) - u_{fz}(t-1) \end{aligned}\right\} \tag{14}$$

where t is the time factor λ_d and λ is the output or actual wheel slip.

H. VZLC Design

We consider a lag compensator represented as first-order discrete time system given by:

$$C(Z) = K\frac{(z - z_0)}{(z - z_p)}, \quad K = 1 \tag{15}$$

where K is unity gain, z_0 and z_p are the zero and pole elements of the lag compensator.

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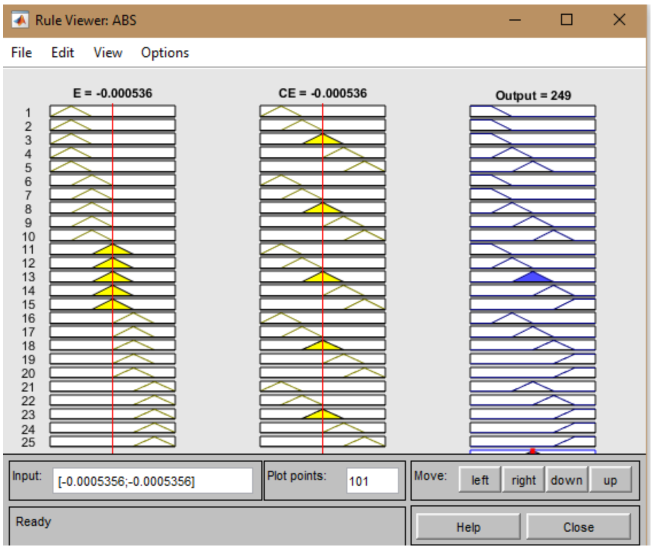

Fig. 4 Fuzzy rule viewer

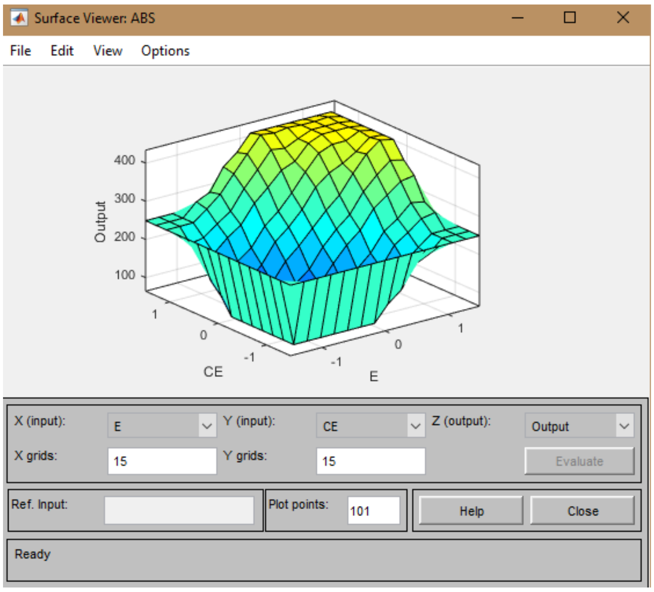

Fig. 5 Fuzzy rule surface viewer

Now, using a Bode method to design the compensator, (15) is first converted to its equivalent form in frequency domain, that is $C(z) \to C(\omega)$, which is achieved using the expression given by:

$$z = \frac{1+(T/2)\omega}{1-(T/2)\omega} \tag{16}$$

where T is the sampling time and it is equal to 1s. Thus, $C(\omega)$ is also a first order system that has transfer function given by:

$$C(\omega) = a_0 \left[\frac{1+\omega/\omega_0}{1+\omega/\omega_p} \right] \tag{17}$$

where ω_0 is the zero location, ω_p is the pole location in the $\omega -$plane such that $|\omega_0| > |\omega_p|$ and a_0 is the dc-gain. Then converting $C(\omega)$ to $C(z)$, the following expressions are used:

$$\left.\begin{aligned} K &= a_0 \left[\frac{\omega_p(\omega_0 + 2/T\ )}{\omega_0(\omega_p + 2/T)} \right] \\ z_0 &= \frac{2/T - \omega_0}{2/T + \omega_0} \\ z_p &= \frac{2/T - \omega_p}{2/T + \omega_p} \end{aligned}\right\} \tag{18}$$

The value of z_p was fixed as 0.95 while the value of z_0 was tuned or adjusted in the range $0.691 \le z_0 \le 0.9472$ according to each road surface condition considered. The addition of the lag compensator was to reduce the effect of steady state error associated with FLC. It was also designed as part of the system to maintain or improve the low frequency characteristics of the ABS. Thus, the introduction of the compensator ensures that during braking when high-frequency noise sets in, the bandwidth of the system response is reduced and thereby eliminating noise effect (chattering), and also offers improved system stability margin. Therefore, as shown in Fig. 2, the expression for the control input (maximum braking torque or pressure) is given in terms of the lag compensator and the FLC output, u_{fz} by:

$$T_b = u_{fz} \frac{(z - z_0)}{(z - z_p)} \tag{19}$$

I. Simulation Parameter

The parameters used for the simulation carried out in MATLAB/Simulink environment are presented in Table III.

TABLE III
SIMULATION PARAMETERS

Description	Symbol	Value
Quarter-car mass	m	450 kg
Moment of inertia	J	1.6 kgm^2
Wheel Radius	R	0.32 m
Wheel friction coefficient	F_w	0.08 Nms/rad
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 kgm^{-3}
Drag coefficient	C	0.539

IV. SIMULATION RESULTS

This section presents the simulation results of the system.

The simulation time was set as 5 s, while assuming that the braking of the vehicle to taking place at braking speed of 30 $m.s^{-1}$ simultaneously on all considered road surfaces (dry, wet, cobblestone and snow). It is expected that the simulations terminate at speed of approximately 1.11 $m.s^{-1}$. This is due to the fact that as the wheel speed tends to zero, slip instability sets in, and thus the ABS must disengage at low speeds to enable the vehicle to come to a halt [10]. The simulation is conducted for two scenarios namely, when the FLC with VZLC has not been introduced (unassisted ABS or uncompensated system) and when FLC with VZLC was introduced (assisted ABS). The simulation plots of the uncompensated system are shown in Figs. 6-9, while that of assisted ABS are shown in Figs. 10-13. The system performances in each case are shown in Tables IV-VI. The performance analysis in terms of stopping distance achieved using the proposed system against the ABS without the developed controller is presented in Table VII.

A. Simulation Results of Unassisted ABS

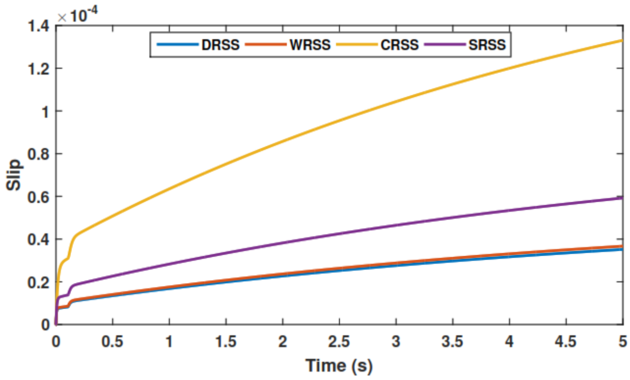

Fig. 6 Wheel slip response (unassisted ABS)

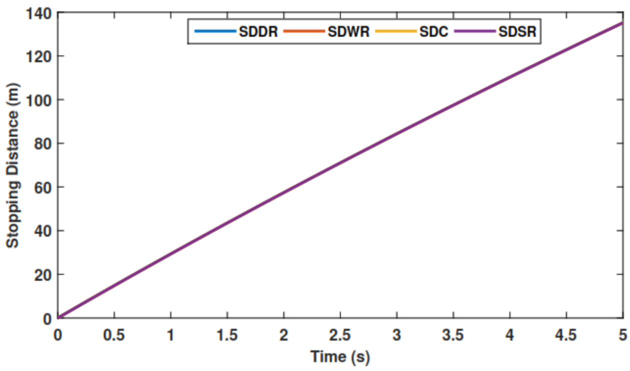

Fig. 7 Stopping distance (unassisted ABS)

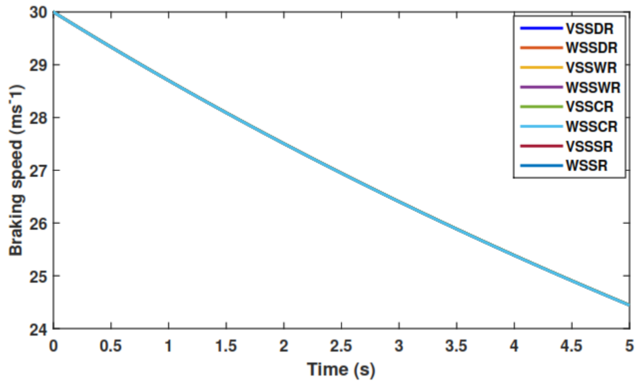

Fig. 8 Braking speed (unassisted ABS)

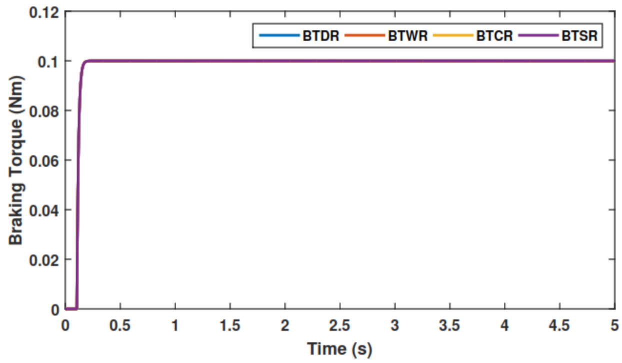

Fig. 9 Braking torque (unassisted ABS)

B. Simulation Results of Assisted ABS

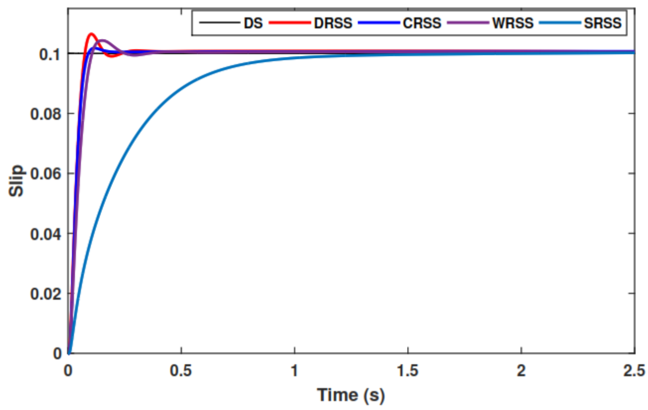

Fig. 10 Wheel slip response (assisted ABS)

TABLE IV
PERFORMANCE OF UNASSISTED ABS

Performance Parameter	Dry Road Surface	Wet Road Surface	Cobblestone Road Surface	Snow Road surface
Slip Ratio	DRSS = 3.517e-05	WRSS = 3.671e-05	CRSS = 1.331e-04	SRSS = 5.924e-04
Stopping Distance (m)	SDDR = 135.2	SDWR = 135.2	SDC = 135.2	SDSR = 135.2
Braking Torque (Nm)	BTDR = 0.1	BTWR = 0.1	BTCR = 0.1	BTSR = 0.1
Vehicle Sped (m/s)	VSSDR = 24.44	VSSWR = 24.44	VSSCR = 24.44	VSSSR = 24.44
Wheel Speed (m/s)	WSSDR = 24.44	WSSWR = 24.44	WSSCR = 24.44	WSSSR = 24.44

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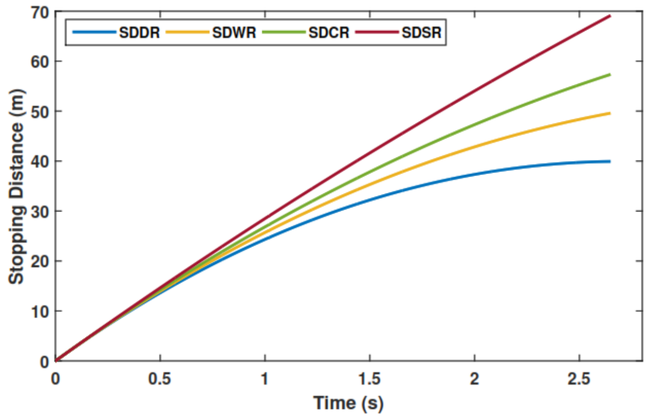

Fig. 11 Stopping distance (assisted ABS)

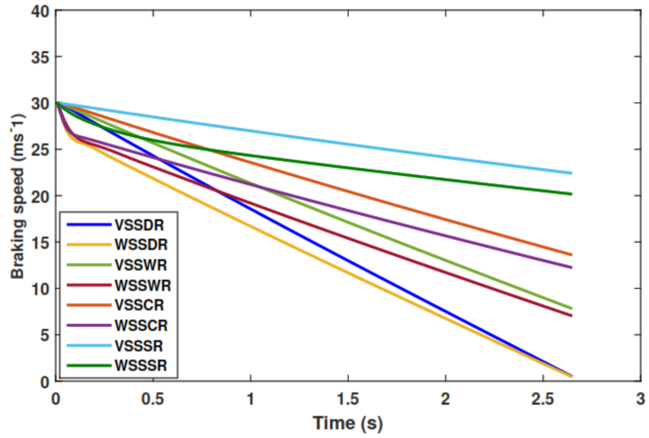

Fig. 12 Braking speed (assisted ABS)

The efficiency performance analysis of the assisted ABS is done in this paper in terms of the improvement of the stopping distance when emergency braking takes. Thus, (20) is used and numerical values are shown in Table VII.

$$SDI = \frac{SD_{unassisted} - SD_{assisted}}{SD_{unassisted}} \times 100 \quad (20)$$

where SDI is means stopping distance improvement, $SD_{unassisted}$ is the stopping distance for unassisted ABS, and $SD_{assisted}$ is the stopping distance when FLC with VZLC control algorithm was introduced.

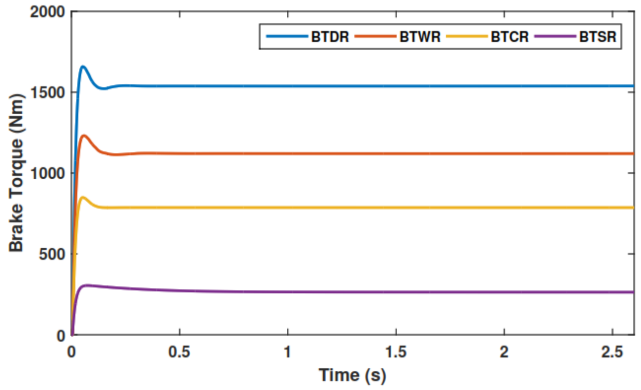

Fig. 13 Braking torque (assisted ABS)

TABLE V
PERFORMANCE OF ASSISTED ABS BASED ON FLC-VZLC

Performance Parameter	Dry Road Surface	Wet Road Surface	Cobblestone Road Surface	Snow Road surface
Slip Ratio	DRSS = 0.1	WRSS = 0.1	CRSS = 0.1	SRSS = 0.1
Stopping Distance (m)	SDDR = 39.92	SDWR = 49.59	SDCR = 57.35	SDSR = 69.13
Braking Torque (Nm)	BTDR = 1538	BTWR = 1121	BTCR = 786.4	BTSR = 263.1
Vehicle Sped (m/s)	VSSDR = 0.50	VSSWR = 7.82	VSSCR = 13.6	VSSSR = 22.41
Wheel Speed (m/s)	WSSDR = 0.45	WSSWR =7.03	WSSCR= 12.23	WSSSR = 20.17

TABLE VI
TIME DOMAIN PERFORMANCE OF SYSTEM WITH FLC-VZLC

Performance Parameter	Dry Road Surface	Wet Road Surface	Cobblestone Road Surface	Snow Road surface
Rise time (s)	0.076	0.134	0.090	0.610
Settling time (s)	0.145	0.178	0.099	2.590
Peak overshoot (%)	5.8	3.9	1.1	0
Final value (actual slip)	0.1	0.1	0.1	0.1

TABLE VII
EFFICIENCY PERFORMANCE ANALYSIS IN TERMS OF STOPPING DISTANCE

Road surface condition	$SD_{unassisted}$ (m)	$SD_{assisted}$ (m)	Improvement (%)
Dry asphalt	135.2	39.92	70.5
Wet asphalt	135.2	49.59	63.3
Cobblestone	135.2	57.35	57.6
Snow	135.2	69.13	50.0

The simulation results presented for ABS assisted hard braking system have shown that the intelligent controller (FLC) with VZLC achieved a perfect tracking of the desired slip (10%) for the different friction surfaces in 2.649 s, which is very much less than the simulation time (5 seconds). The proposed system improved the stopping distance of the vehicle. From Tables V and VII, it is shown that a stopping distance of 39.92 m was achieved on dry road surface, 49.59 m on wet road surface, 57.35 m on cobblestone road surface, and 69.13 m on snow road surface as against 135.2 m for uncompensated system (unassisted ABS). These performances in stopping distance correspond to improvement of 70.5%, 63.3%, 57.6% and 50%

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on dry, wet, cobblestone and snow road surfaces respectively. Also, the FLC-VZLC system equally uses less effective braking pressure (or torque) as compared to maximum allowable braking torque. Thus, as can be seen in Fig. 13 for all the road surface conditions, the effective braking torques were initially high at the start of the braking, but stabilize to effective braking torques of 1538 Nm, 1121 Nm, 786.4 Nm and 263.1 Nm on dry, wet, cobblestone and snow road surfaces respectively.

In terms of time domain performances, the system achieved efficient transient and steady state response performance as shown in Table VI. The rise time and settling time are very low indicating that the proposed system ensures fast response to the application of brake pressure is achieved and attainment of stability, which means settling faster so to reach a steady state as soon as possible. Also, the very low (near zero) percentage overshoot or zero (as in the case of snow road surface) shows that cycling or instability during hard braking on the road surfaces is completely eliminated. Hence, for a vehicle utilizing the proposed system, it will provide significant fast response and stability with zero steady state error and without chattering effect on all the road surface conditions considered in this paper.

V. Conclusion

This paper presented a system based on FLC with VZLC control technique that ensures that effective braking torque is utilized to achieve desired slip tracking with reduced stopping distance on different road surfaces. The dynamics of a vehicle braking at a speed of 30 ms^{-1} on straight line were determined using a quarter car model. An intelligent control using fuzzy logic algorithm whose control variable is compensated with a lag compensator with variable zero was developed and introduced into an ABS. The simulation results obtained showed that the FLC with VZLC effectively improved the overall performance control of the system on various road surface (dry, wet, cobblestone and snow) conditions.

References

[1] P. C. Eze, B. O. Ekengwu, N. C. Asiegbu, and T. I. Ozue, "Adjustable gain enhanced fuzzy logic controller for optimal wheel slip ratio tracking in hard braking control system," *Adv. Electr. Electron. Eng.*, vol. 19, pp. 231–242, Sept. 2021.

[2] P. C. Eze, F. A. Aigbodioh, C. Muoghalu and I. H. Ezeanya, "Linear slip control for improved antilock braking system," *Int. Res. J. Adv. Eng. Sci.*, vol. 3, pp. 198–206, Feb. 2018.

[3] P. C. Eze and I. E. Achumba, "Investigation of slip minimization in vehicles under different drag coefficients," in *2017 IEEE 3rd Int. Conf. on Electro-Technol. for Natl. Dev. (NIGERCON*), 2017 pp. 1–9.

[4] A. A. Aly, E. Zeidan, A., Hamed, and F. Salem, "An antilock-braking systems (ABS) control: A technical review," *Intell. Control Autom.,* vol. 2, pp. 186-195, 2011.

[5] P. Girovský, J. Žilková, and J. Kaňuch, "Optimization of vehicle braking distance using a fuzzy controller," *Energies*, vol. 13, pp. 1–15, 2020.

[6] I. Rizianiza and A. Djafar, "Design car braking system using Mamdani fuzzy logic control," in *2017 4th Int. Conf. on Electr. Veh. Technol. (ICEVT),* Oct. 2017, pp. 129–133.

[7] 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," *Math. Probl. Eng.*, vol. 2019, pp. 1-11, Jan. 2019.

[8] V. R. Aparow, F. Ahmad, K. Hudha and H. Jamaludin, "Modelling and PID control of antilock braking system with wheel slip reduction to improve braking performance," *Int. J. Veh. Saf.*, vol. 6, pp. 265–296, Jan. 2013.

[9] C. Jain, R. Abhishek and A. Dixit, "Linear control technique for anti-lock braking system," *Int. J. Eng. Res. Appl.*, vol. 4, pp. 104–108, Aug. 2014.

[10] S. John and J. O. Pedro, "Hybrid feedback linearization slip control for anti-lock braking system," *Acta Polytech. Hung*., vol. 10, pp. 81–99, 2013.

[11] M. Watany, "Performance of a road vehicle with hydraulic brake system using slip control strategy," *Am. J. Veh. Des*., vol. 2, pp. 7–18, Nov. 2014.

[12] V. D. Gowda and A. C. Ramachandra, "Slip ratio control of anti-lock braking system with bang-bang controller," *Int. J. Comput Tech*., vol. 4, pp. 97–104, Jan-Feb. 2017.

[13] M. Singh, A. Rani and V. Singh, "Wheel slip-based intelligent controller design for anti-lock braking system," *Adv. Res. Electr. Electron. Eng*., vol. 1, pp. 82–88, 2014.

[14] G. Li, T. Wang, R. Zhang, F. Gu and J. Shen, "An improved optimal slip ratio prediction considering tyre inflation pressure changes," *J. Control Sci. Eng.,* vol. 2015, pp. 1–8, Nov. 2015.

[15] A. B. Sharkawy, "Genetic fuzzy self-tuning PID controllers for antilock braking systems," *Eng. Appl. Artif. Intell.,* vol. 23, pp. 1041–1052, 2010.

[16] V. Ćirović and D. Aleksendrić, "Adaptive neutron-fuzzy wheel slip control. *Expert Syst. Appl.*, vol. 40, pp. 5197–5209, 2013.

[17] G. P. Incremona, E. Regolin, A. Mosca, and A. Ferrara, "Sliding mode control algorithms for wheel slip control of road vehicles," in *Proc. of the 2017 Am. Control Conf*., ACC 2017, pp. 4297–4302.

[18] E. Kayacan, Y. Oniz and O. Kaynak, "A grey system modeling approach for sliding mode control of antilock braking system," *IEEE Trans. Industr. Electron.,* vol. 56, pp. 3244–3252, Aug. 2009.

[19] J. Sun, X. Xue and K. W. E. Cheng, "Fuzzy sliding mode wheel slip ratio control for smart vehicle anti-lock braking system," *Energies*, vol. 12, pp. 1–22, Jun. 2019.

[20] S. Latreche and S. Benaggoune, "Robust wheel slip for vehicle antilock braking system with fuzzy sliding mode controller (FSMC)," *Eng. Technol. Appl. Sci. Res.,* vol. 10, pp. 6368–6373, Oct. 2020.

[21] C.-M., Lin and C.-F. Hsu, "Self-learning fuzzy sliding-mode control for antilock braking system," *IEEE Trans. Control Syst. Technol*., vol. 11, pp. 273–278, 2003.

[22] A. Fattah, "Design and analysis of speed control using hybrid PID-Fuzzy controller for induction motors," Master's Theses, Western Michigan University, 2015.

[23] J. Guo, X. Jian, and G. Lin, "Performance evaluation of an anti-lock braking system for electric vehicles with a fuzzy sliding mode controller," *Energies*, vol. 7, pp. 6459–6476, Oct. 2014.

[24] A. Alleyne, "Improved vehicle performance using combined suspension and braking forces," *Int. J. Veh. Mech. Mobility*, vol. 27, pp. 235–265, 1997.

[25] C. Canudas-de-Wit, P. Tsiotras, E. Velenis, M. Basset, and G. Gissinger, "Dynamic friction models for road/tire longitudinal interaction," *Veh. Syst. Dyn*., vol. 39, pp. 189–226, 2003.

[26] S. M. Savaresi and M. Tanelli, "Active braking control systems design for vehicles," 1st ed. London: Springer-Verlag London, 2010.