# Evolution of Fuzzy Logic in Anti-Lock Braking System: A Technical Review

**Rahul Pandey[1], Romit Kanabar[1], Rahul Padmakumar[1], Venugopal P[2], Ankamma Rao[3]**

[1]*Student, Embedded Systems, School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India.*

[2]*Associate Professor, School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India.*

[3]*Assistant Professor, Electrical and Computer Engineering Dept, Samara University, Samara, Afar, Ethiopia.*

*Corresponding Author: Rahul1997pandey@gmail.com*

**Abstract:** Over the past decade there have been so many technological advancements and developments in the automotive sector, especially in the field of safety systems and automobile design. Many new systems have been developed that mainly focus on improving the safety and reliability of vehicles. This paper is a review paper that briefs about the journey of braking systems in automobiles and how the systems have become smarter, intelligent, robust and reliable. Each section of the paper focuses on a decade of braking system journey. Anti-lock braking systems, or ABS for short, are a popular safety feature that is becoming increasingly common. Bosch invented anti-lock brakes in the 1930s, and they have been standard on most cars since the 1970s. Anti-lock brakes operate by applying hydraulic pressure to your car's wheels to prevent them from locking up while braking, which can cause skidding and loss of control. The antilock braking system (ABS) which revolutionized the braking industry has been focused upon, different techniques after the development of ABS which further improvised the ABS by enhancing its performance has been focused upon. Different test benches and simulation methods used in the past have been covered that lead to the development of modern-day ABS systems. Over 3 decades of the journey from braking systems which was later transformed into anti-lock braking systems and modern-day fuzzy logic-based ABS and neural optimizer based braking systems have been described along with the results of each paper.

**Key Words: —** ***ABS, fuzzy logic, neural optimizers, test benches, road conditions, Genetic Algorithms.***

## I. INTRODUCTION

The modern-day braking systems used in automobiles are referred to as antilock braking systems or ABS. Antilock braking systems (ABS) are based on concept of closed-loop control systems and form a feedback device that prevent the vehicle brakes from getting locked up and also prevents skidding of vehicle while braking. An electronic control unit (ECU) in the ABS system receives feedback signals from each wheel sensor and performs comparison on them. ABS systems manage the amount of brake pressure applied to the tyres upon which it is acting.

Wireless accelerometers, advances in control software that account for tyre and suspension dynamics, estimation of parameters such as sideways acceleration and wheel slip, and the application of adaptive control and fuzzy logic are just a few of the recent developments. In the recent years these systems have been incorporated as a part of safety systems in vehicles that include four-wheel steering and active suspension. The employment of intelligent elements for sensor development and the usage of roadside-to-vehicle control are predicted to be the upcoming future advancements in technology.

Maximum effective braking occurs only when the wheel brake retarding force meets the grip imposed between the tyre and the road surface [1]. Road grip is determined by the downwards weight on the wheel and the frictional resistance formed between the tyre tread and the road surface. The weight on the wheel will not be enough to keep it rolling if the braking force is too great. The wheel will lock and slide as a result. The wheel will be retarded far less than its maximum achievable if the retarding force is less than the maximum

Manuscript revised June 10, 2022; accepted June 11, 2022.
Date of publication June 12, 2022.

This paper available online at www.ijprse.com

ISSN (Online): 2582-7898; SJIF: 5.59

required to bring the wheel to the point of lock. As a result, it increases the vehicle's minimum stopping distance.

Aside from braking, additional events that cause traction loss include acceleration, cornering, and starting on an uphill incline. The lateral adhesion of spinning or locked wheels is restricted. They lead to significant wear rates in tires and drivetrain components (such as the differential), especially when a freely spinning wheel unexpectedly acquires grip [2]. It is required to manage the forces being applied to the wheel during both braking and accelerating, which is why the antilock braking system (ABS) was invented.

Since their invitation, ABS have been developed for a variety of vehicles throughout the previous two decades [3].

The ABS design's goal is to keep an automobiles wheel from locking and to create maximum braking force so that the vehicle may still be handled while the braking distance is reduced in case of an urgent stop. During an emergency braking maneuver, the distance is reduced. In order to achieve directional stability and considerable braking force, ABS is designed to function within or close to the ideal wheel slip-ratio (or optimal friction force) range. The inherent relation between the force of friction and wheel slip-ratio, which play a critical role in ABS system design, are nonlinear curves derived from experimental data as stated in reference [4] and analytical approaches for various types of road surfaces mentioned in work [5]. ABS is a non-linear system that solves a difficult mechanization problem. Mass of vehicle, change in moment of inertia, weather factors (rain, snow, etc.) and conditions of road surface all interact to aggravate this control challenge.

Sliding mode control [6], adaptive control, and other control techniques based on nonlinear robust control theory have been developed for ABS controller [7]. combined control and feedback linearization with gain-scheduling [8].The effectiveness of these techniques is tested. Over the last decade, precise mathematical models and data have been more readily available. Many nonlinear controllers make use of linearization techniques which use feedback in order for the system to obtain a linear behavior.

ABS control problems have recently seen the use of fuzzy logic controllers (FLCs) [9]. Heuristic reasoning that depends on the learning of the individual and opinions of the expert is used by a fuzzy logic controller.

As a result, FLC is advanced than traditional controllers because it does not need an exact mathematical model, can function with imprecise inputs, can take care of nonlinearity, and is more efficient. Traditional controllers are less reliable. The fuzzy based control rules, on the other hand, are experience-based, and appropriate parameters, such as membership functions or normalization factors, are used. Many times, a time-consuming trial-and-error approach is used. In addition, when the system parameters change dramatically, the fuzzy logic controller must be tuned further more. It's possible that the system parameters aren't familiar to new operators. In order for FLC to be suitable for general cases, a self-learning approach is required. The FLC can be self-tuned using the Genetic Algorithm (GA), an optimization technique. It's been used in adaptable FLC design with great success [10].

## II. OPERATING PRINCIPLE

### *2.1 Surface of road and tire friction.*

When it comes to antilock brakes, friction abrasion present between the tyre and the surface of the road is crucial. When the vehicle accelerates or brakes, there is a force of friction that exists between the tire surface and the road surface. Because of the elasticity of tires, a sophisticated transfer function is required to link the road's retarding force with the braking force applied at the tire. As a result, the term "slip" is used to characterize the tire's and road's interaction. The braking slip is defined as the percentage of the difference in vehicle and wheel speeds divided by the vehicle speed:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{v_f} - \boldsymbol{v_0}}{\boldsymbol{v_f}} * 100$$

The force of braking $F_B = \mu_B G$ is measured in a direction in which the wheel is turning and is affected by a variety of parameters such as the road surface, tire material, pressure, and tread characteristics (depth, pattern, etc.).

The driver pushes the brake pedal to increase the hydraulic pressure in the brake system during initial braking. One or more wheels may lock if the brakes are applied with enough effort. This happens when the brake slip, λ, exceeds the adhesion-slip curve's maximum point and shifts from the stable to the unstable range (Figure 1) [11]. The braking force used and the

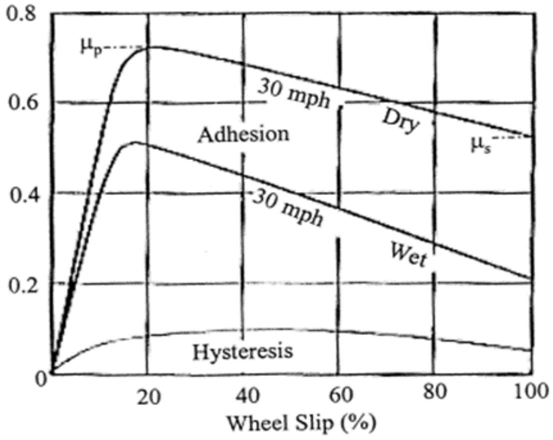


Fig.1. Curve of Adhesion and Slip

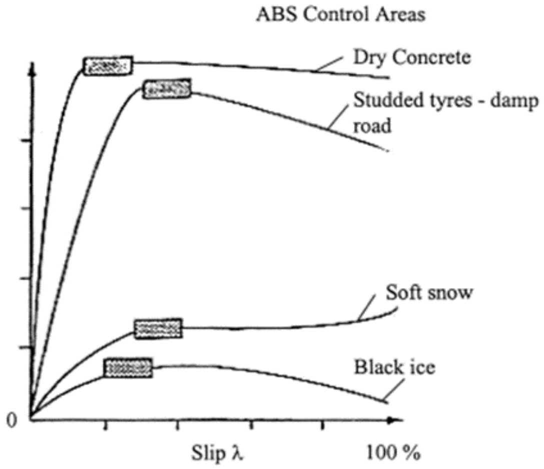


Fig.2. Curve of Adhesion and slip for different road surfaces conditions

adhesion of the road surface is balanced in the stable zone. As a result, braking is possible without slip. Unless the braking effort is lessened in the zone where vehicle is unstable then as the critical slip reaches, the wheel will lock.

Depending on the tires and road condition, critical slip might range between 8% and 30%. Figure 2 [11] depicts the differences in road surface conditions and demonstrates why using a fixed slip threshold as a reference point for when ABS should be used is ineffective. The vehicle's sideway slip is also significant. A lateral sideway force on a rolling pneumatic tire causes the tire to drift to the side. The slip angle, α, is the angle formed between the direction along the plane of the wheel and the direction of travel. The connection between the slip angle and the lateral force is used to determine the vehicle's directional movement.

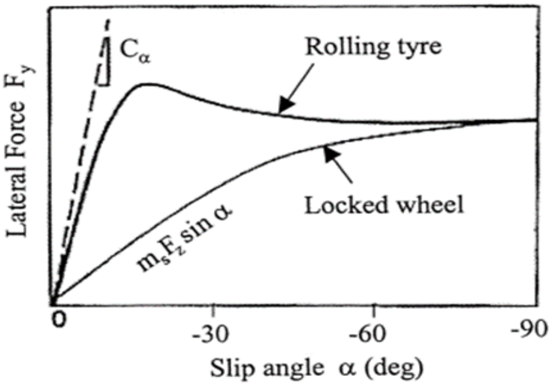


Fig.3. Tire lateral force properties

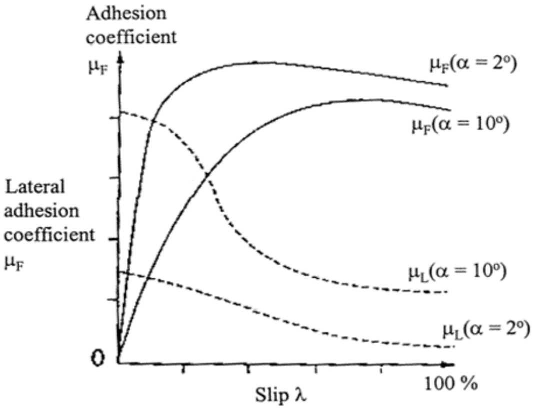


Fig.4. Combination of adhesion coefficient $\mu_B$ and lateral adhesion coefficient $\mu_L$ against brake slip λ.

Figure 3 [11] depicts the lateral force in relation to the slip angle. The crucial slip angle is typically 12 to 15 degrees. Figure 4 [11] depicts the braking force coefficient, $\mu_B$, and lateral adhesion coefficient, $\mu_L$, in relation to braking slip, λ. On a dry road, the slip angle is displayed at 2 and 10 degrees. When the braking slip λ grows, the lateral adhesion $\mu_L$ decreases significantly. The value of $\mu_L$ is a function of the steered angle of the wheel when $\lambda = 100\%$: $\mu_L (\min) = \mu_B \sin \alpha$, as shown in Fig. 3. This shows how a wheel which is locked has no influence on steering. ABS control should be expanded for larger slip angles, as shown in Fig. 4. When a vehicle is fully braking while suffering considerable sideway acceleration, ABS must activate early and gradually allow more slip as the vehicle speed declines.

### *2.2 ABS Description*

When you apply the brakes suddenly, the wheels may lock up virtually instantly. The car becomes unstable as a result of this. When driving on fresh unattached snow the fastening of the wheels causes a little elevation to form in front of the wheel. This aids the vehicle's stopping. The only time wheels may be locked can be beneficial is in this case. It is undesirable in all other circumstances. Brakes are applied to prevent wheels from locking, and they are released before the wheels lock. The identical procedure is followed in multiple events. Drivers had to do the same thing back in the day. This is now done by the braking system on its own, thanks to the introduction of anti-lock brakes. When you press the brake pedal, you're accumulating pressure, and when you let go, you're dissipating it. This is called as Pressure modulation. It can be accomplished up to 15 times per second using the anti-lock brake system. The pressure modulation keeps the friction between the tyre and the surface of the road and keeps the vehicle stable. Because the wheel does not slide, the steering control is not lost, and the car continues to go straight. The vehicle's agility is affected by locking the front wheels, while its stability is affected by locking the back wheels.

The best results are deduced when the wheels are allowed to slip between braking applications. At zero percent slip, the wheel spins freely, but at 100 percent slip, it is completely locked. It also suggests that the wheel's momentum is the same as the vehicles at zero percent slip, and that the wheel's velocity is zero at 100 percent slip, and the vehicle is moving at its own speed. An ABS system's proper slip rate should be between 10 to 30 percent. Anti-lock braking systems come in a variety of configurations. These systems might or might not be necessary. The master cylinder, hydraulic booster, and accompanying circuitry are all combined into a single unit in integral systems. In non-integral systems, there is a pneumatically booster and master cylinder. There is also a standalone control unit available. A hydraulic device with its own pump, motor, and accumulator is available. Solenoid valves can control the hydraulic pressure to the tyres.

Single-channel and multi-channel anti-lock braking systems are the two types of anti-lock braking systems. A single-channel system is a system with 2 wheels in which pressure is adjusted concurrently on both rear wheels instead of the front wheels. A single-speed sensor in the centre provides input to the system. The differential unit could be used to mount the sensor. Two, three, or even four channels could be used in a multi-channel system. In a two-channel system, each channel only applies pressure modulation to two rear wheels. Two speed sensors are installed on each wheel. Three-channel setups are also available. Separate circuits are used each of the frontal wheels, and a single circuit is used for both rear wheels in these systems.

### 2.3 ABS Components

The design of an ABS system varies from automobile to automobile. Hydraulic and electrical/electronic parts and components make up the modem system. Aside from the components found in standard brakes, the anti-lock brake system contains additional components.

#### 2.3.1 Accumulator:

It holds fluid and keeps the system at a high pressure. It also ensures that power-assisted brakes have the necessary pressure. Nitrogen gas is pumped into it. The two compartments are separated by a diaphragm. One compartment holds high-pressure brake fluid, while others hold high-pressure nitrogen. Figure 5 [12] illustrates the accumulator.

#### 2.3.2 Hydraulic valve for control:

It allows for modulation of pressure. When the brakes are engaged, pressure is built in the system, which is then released when the brake is lifted. While applying the brakes, this happens multiple times. This valve can be used in conjunction with a master cylinder or put on its own. In the 1st case, it's called the integral type, while in the 2nd, it's called the non-integral type. Controls are provided through solenoid valves. Figure 6 depicts the block diagram of a hydraulic control valve. [12]

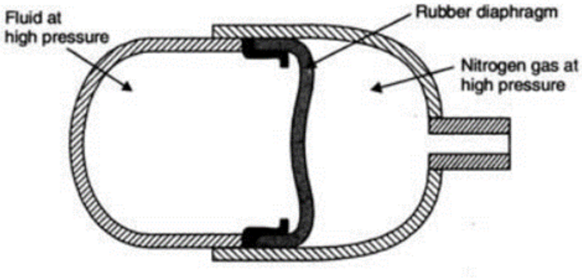


Fig.5. Accumulator [12]

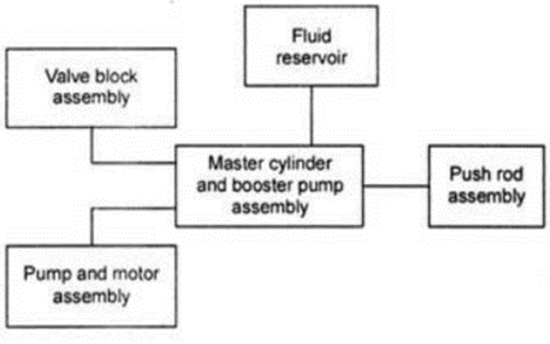


Fig.6. Block diagram of components in a hydraulic control valve. [12]

### *2.3.3 Booster pump:*

It feeds the anti-lock braking system with high-pressure fluid. Because it is composed of a pump and an electric motor, it also goes by the name of electric pump and motor assembly.

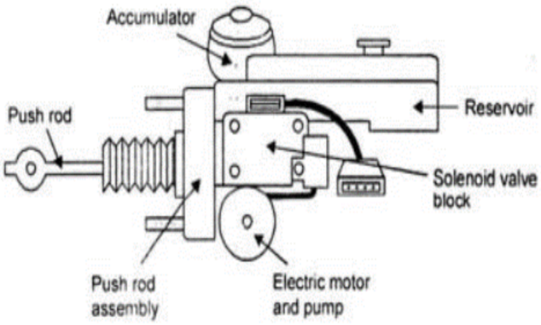


Fig.7. Hydraulic Pump [12]

### *2.3.4 Hydraulic pump:*

It's a booster and master cylinder assembly. It uses valves and pistons to change the hydraulic pressure in the system. For power braking applications, the hydraulic pump also provides high-pressure fluid. Figure 7 depicts the hydraulic unit. [12].

### *2.3.5 Fluid Accumulators*:

The wheel cylinder's hydraulic fluid is temporarily kept here. This oil is for boosting the pressure in the brakes' hydraulic system. It has twin accumulators, one for the primary hydraulic circuit and the other for the secondary.

### *2.3.6 Valve:*

The antilock brake system module is in charge of this valve. The booster circuit sends high-pressure braking fluid into the master cylinder when the switch is in the open position.

### *2.3.7 Modulator*

This machine is used for controlling the flow of fluid to individual wheel cylinders. It has a solenoid valve that regulates fluid flow and controls numerous additional valves. Relays that govern the operation of solenoid valves are also activated by the control module.

### *2.3.8 Solenoid valves*

The modulator is where you'll find these. These valves receive signals from the control module. These are used to adjust the hydraulic pressure in various wheels by activating and deactivating them. A cluster which is connected to the side of the master cylinder houses the solenoid valves for the individual wheels. The block is linked to the control module of the anti-lock braking system.

### *2.3.9 Wheel circuit valves*

The 2 circuits are controlled separately by solenoid valves. One is used to control the inlet valves, while the other is used to control the outlet valves. Using the inlet and outlet valves, the pressure in the circuit can be increased, decreased, or maintained at a constant level. The individual valve's operation is determined by the control module. The anti-lock brake system control module provides a 12 volt electric supply that powers the solenoid. During normal driving, the circuits are not activated. Aside from these components, the system also includes some otheer components. These components make the system more reliable, but they also make it more complex and expensive.

### *2.3.10 Control module*

It is a tiny portable device that contains a microprocessor which is programmed and follows the instructions in the program. It's a tiny unit that attaches to a master cylinder or hydraulic control unit. It receives input from sensors that monitor wheel speed as well as the hydraulic unit. It is capable of diagnosing and correcting problems on its own. It monitors the anti-lock braking system's operation.

### *2.3.11 Brake pedal sensor:*

This sensor functions as a switch. When the brakes are applied past a certain point, the switch opens and the pushing will continue until the switch is closed back. This turns off the motor and causes the pedal to stop moving pump motor starts. The hydraulic reservoir is filled with high-pressure fluid, and the brake pedal is depressed.

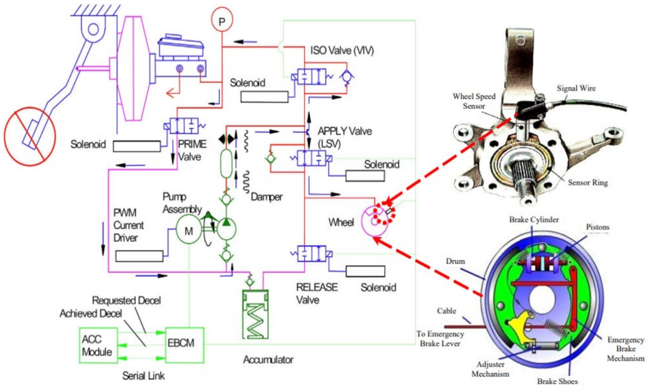


Fig.8. An Anti-lock braking system [7]

### *2.3.12 Pressure switch:*

It displays a low-pressure indicator light on the dashboard. When the pressure falls below the set point, the pump motor is activated by the switch. When the desired pressure is reached, the switch is reset and the pump motor is turned off.

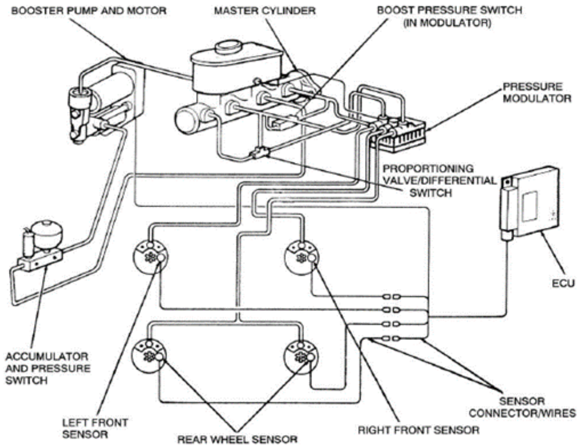


Fig.9. ABS system schematic [13]

### *2.3.13 Pressure differential switch*

When a pressure difference greater than the designed value occurs in the system, this switch sends a signal to the control module. The modulator contains the switch.

### *2.3.14 Relays*

This is used to turn on the motors and solenoids. These require a current signal which is very low for function, which is supplied by the control module. These are electrical devices.

### *2.3.15 Ring with Tooths*

The wheel has teeth that are detected by the wheel speed sensor. An AC signal is generated because of this. As the tooth moves away, the signal fades. The signal is generated by the next tooth that passes by the sensor. The pulsing signal is created in this manner. This is forwarded to the control module. It is converted into wheel speed by the control module. The ring can be found on the axle shaft.

### *2.3.16 Wheel speed sensor*

This sensor is shaped like PMMC (Permanent magnet moving coil) in the middle. The control module receives a pulsating AC signal generated by a toothed wheel. There are also indicator lights on the system. These lights serve as warning signals if the ABS malfunctions. There could also be one more warning light indicating a problem with the fundamental brake system. Aside from the above components, the system includes a Data Link Connector that provides access to operational conditions, vehicle information, and diagnostic data. Numeric identities are assigned to various defects in order to diagnose them. The control module receives these error codes.

## III. CONTROL METHODS FOR ABS

Designers of ABS brake controllers face a particular set of challenges: The maximum braking torque might vary from low to high depending on the driving conditions. c) The tyre slippage measurement signal, which is critical for controller performance, is unreliable as well as loud. d) Due to tyre bouncing, tyre slip ratio fluctuates widely and rapidly on bumpy roads, e) brake pad coefficient of friction varies, and f) braking system transportation delays limit the control system's bandwidth. [14].. ABS is made up of a hydraulic braking system and antilock elements that alter the ABS's control characteristics. Because of the complicated link between friction and slide, ABS control is a highly nonlinear control challenge. Another stumbling hurdle with this control problem is that the linear velocity of the wheel cannot be measured immediately and must be computed. The friction between the road and the tyre is difficult to quantify and may necessitate the use of sophisticated sensors. Researchers have tried a range of control strategies to address this issue. Figure 10 shows a sampling of the study that was done for different control approaches.

One of the techniques that has been used in various aspects of ABS control is soft computing. The following is a quick rundown of soft computing concepts and how they're applied to ABS control. The system has limits, and the ABS's response may be limited, due to the complexity of ABS, the vast number of variables, and the comparatively low quantification data. Improved ABS response may be achieved by enhancing the precision of the transform function, including intelligent feedback loops, selecting relevant variables, or incorporating fuzzy logic mathematics.

The impact of the proposed sliding mode controller (SMC) based Antilock Braking System on longitudinal wheel dynamics, brake torque actuation, brake pressure modulation, and angular wheel speed is investigated by Dankan Gowda et al [15]. The Lugre Friction model and the Burckhardt Friction model are used to describe the antilock braking system mathematically. In addition, a bang-bang control law is used to achieve wheel slip within a set range in an antilock braking system. The suggested controller's performance development in terms of brake pressure modulation, vehicle velocity, wheel slip, and stopping distance is compared to bang-bang controllers, ABS with Lugre Friction Model (LFM), and ABS with Burckhardt Friction Model in the absence of a wheel speed controller (BFM).

### 3.1 Classical Control Methods Based on PID Control

The famous PID has been employed to increase the ABS' performance out of all control types. Song, et al. [16] provided a mathematical approach for analyzing and improving a vehicle's dynamic performance. The purpose of a PID controller in case of rear wheel steering is to improve the vehicle's stability, steerability, and driving ability during transient manoeuvres. Controller braking and steering performance is assessed in a variety of driving scenarios, including straight and J shaped turn movements. The simulation results suggest that the entire car model proposed is enough for reliably predicting vehicle reactions. Both two- and four-wheel steering vehicles benefit from the developed ABS, which minimizes stopping distance and improves longitudinal and lateral stability.

Although the PID controller is simple in design, its performance is clearly limited. It is insufficiently robust for actual deployment. Jiang [17] applied a new Nonlinear PID (NPID) control technique to a class of ABS problems for trucks to solve this problem. The NPID algorithm combines the benefits of reliable control with simple adjustment. The NPID controller has a shorter stopping distance and greater velocity performance as compared to traditional PID controller and a loop-shaping controller, according to simulation results using TruckSim. A nonlinear control system that incorporates a sliding mode-based optimizer and a proportional-plus-integral-plus-derivative (PID) controller has been described in reference [18]

It's challenging to find a control logic that meets real-time requirements while still being flexible enough to adjust to diverse vehicles and road conditions. Fuzzy logic controllers are frequently utilized in ABS controls because they feature a concurrent structure that decreases lags without requiring the execution of an adaptive control law or costly mathematics based computations. The use of fuzzy logic in conjunction with other controllers is a viable option for ABS control implementation. PID [19], [20], SMC [21], adaptive control [22], and adaptative SMC [23] [24] [25] have all been presented as controllers. However, these systems do not take use of fuzzy logic controllers' inherent parallelism and simplicity (FLC). Unlike neural networks [26], [27] where a black box is obtained even after training, it also allows flexibility without sacrificing comprehension.

Because most often used tire models [29] [30] are usually static, a transient term should be added to simulate the tires dynamic behavior.

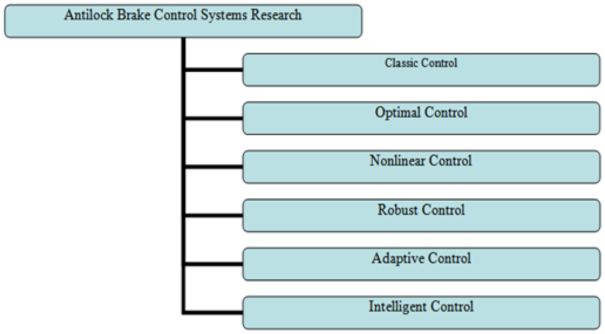


Fig.10. Sampling of ABS Control [28]

### 3.2 Lyapunov Approach based Optimal Control Method

The most difficult areas in control theory are optimum control of nonlinear systems like ABS. For active brake control systems, Tanelli et al. [31] suggested a nonlinear output feedback control law which ensures limited control action and can handle input restrictions as well. Furthermore, the closed loop system features are such that the control algorithm can determine whether the region of operation of the closed loop system is in the unstable region of the friction curve without the use of a friction estimator, allowing for enhanced braking performance and safety. The design is carried out using Lyapunov based approaches, and the efficiency of the design is evaluated using simulations. Changes in road conditions necessitate continual controller parameter adjustments.

R. R. Freeman [32] proposes an adaptive control Lyapunov technique to handle this problem, and related concept are pursued in [33] [34]. The adaptive control Lyapunov approach [35], which deals with scheduling of gain on vehicle speed and experimental testing, employs Sontag's formula. Liu and Sun [36] propose feedback linearization in conjunction with gain scheduling. [37] [38] [39] [40] [41] considers PID based approaches to control wheel slip. A gain planned control design based on LQ approach with related analysis is the only one that includes extensive experimental evaluation utilising a test vehicle, with the exception of [35], and [41] Using sliding modes, [42] uses an optimal searching strategy to determine the highest friction [43] [44] also considers sliding mode control.

Ünsal and Kachroo [45] proposed another nonlinear adjustment for observer-based design for managing traction of vehicle, which is vital in ensuring safety and achieving desired linear vehicle motion. The nonlinear observers substitute the direct state feedback to predict the velocity of vehicle from the wheel velocity. Simulations are used to show the effects and limitations of extended Kalman filters and sliding observers.

Due to unforeseen changes in road conditions, the sliding observer is found to be promising, whereas the extended Kalman filter is determined to be unsatisfactory.

### *3.3 Backstepping Control Design based Nonlinear Control*

Due to the complexity of ABS, feedback control is required to achieve the desired system behaviour, resulting in dynamical systems. Ting and Lin [46] created an anti-lock brake control system with active suspensions for a quarter vehicle model using nonlinear backstepping design methodologies. Although the control torque provided by disk/drum brakes can reduce braking distance in an emergency, the braking time and distance can be reduced even further if the normal force generated by active suspension systems is also included. Each subsystem has its own controller, and these two subsystems are coordinated using an integrated algorithm. The integration of anti-lock brakes and active suspension systems improves system performance by reducing braking time and distance.

Wang et al. [47] used multiple model adaptive control (MMAC) controllers to compare the design process of backstepping approach ABS. In MMAC, four models were used: a high adhesion fixed model, a medium adhesion fixed model, a low adhesion fixed model, and an adaptive model. Different model controller switching rules were also demonstrated. The ABS control system was simulated utilizing the MMAC method using a quarter car model. The results reveal that this method is more accurate and robust in controlling wheel slip ratio, and hence improves ABS performance efficiently.

Research on nonlinear adaptive backstepping with multiple observers and estimator resetting was contributed by Tor Arne Johansen [48].A multiple model-based observer/estimator was used to reset the parameter estimate in a standard Lyapunov based nonlinear adaptive controller for parameter estimation. Transient performance can be improved without increasing the controller or estimator's gain. This enables performance to be modified without losing robustness or sensitivity to noise and disturbances. The scheme's advantages are demonstrated in an automotive wheel slip controller.

Unlike traditional fuzzy logic control systems, a Genetic Algorithm based fuzzy logic controller is proposed by Fu-Wei Chen et al. [49] to tackle the same problem without the need for explicit knowledge of membership function parameters. Numerical simulations show how the suggested control schemes function under various road conditions, as well as in the presence of system parameter fluctuations and a bounded control input. When compared to the feedback linearizing controller and the traditional fuzzy logic controller, the results show that the GA-based fuzzy logic controller provides greater performance.

Andrei Aksjonov et.al [50] introduces a regenerative anti-lock braking system control method with road detection capability. The longitudinal deceleration of vehicle body is used to estimate a road surface - including dry, wet and icy. Based on the estimation results, the fuzzy logic controller generates a suitable braking torque to maintain an ideal wheel slip for various road conditions and to recover the maximum amount of energy for a given motor during vehicle deceleration. A 10 DOF SUV EV mathematical model was used to test the control technique, which was parametrized according to the car manufacturer's specifications and simulations were done using MATLAB/Simulink. The simulation tested decoupled regeneration, pure friction, and locked wheels braking performance on various road surfaces. The suggested technique successfully maintains the optimum wheel slip value for various road surfaces and recovers an average of 8% of power per wheel, with lower energy usage on wet and snowy roads. Other findings include that it manages to reduce the use of friction brakes.

### *3.4 Sliding Mode Control Based Robust Control Method*

Sliding mode control is a significant technique for robust controlling. The controller design gives a systematic solution to the problem of ensuring stability and consistent performance where it is applied. On the other hand, it can enlighten the entire design process by allowing the tradeoffs between modelling and performance to be quantified in a simple manner.

Several results involving the ABS problem and the VSS design technique have been reported [51] [52]. The design of sliding-mode controllers was introduced in these studies under the assumption that the ideal value of the goal slip was known already. The lack of direct slip measurements is a source of worry here. The separation strategy has been employed in all previous investigations. The challenge was split into two parts: estimating the ideal slip and tracking the predicted optimal value. J.K. Hedrick et al. [53] [54] designed a variation of the sliding mode control technique. It was chosen for its modelling error resistance and disturbance rejection characteristics. The simulation results show how a vehicle equipped with this controller can follow a chosen speed path while keeping constant spacing between cars. As a result, for this application, a sliding mode control technique was implemented. Kayacan [55] developed a grey sliding-mode controller to control wheel slip based on the vehicle's forward motion. The suggested controller predicts future wheel slip values and takes the appropriate action to keep the wheel slip at the desired level. The performance of the control algorithm when applied to a quarter automobile is evaluated using simulations and experimental studies with unexpected changes in road conditions. The proposed controller has been found to have a faster convergence rate and a better noise response than earlier approaches. When traditional control systems fail to meet acceptable performance requirements, grey system theory, which has some prediction abilities, is proposed as a feasible alternative strategy. A switched controller has defects in real systems that restrict switching to a finite frequency. Chattering is caused by oscillations in the vicinity of the switching surface. Chattering is undesirable because it requires a lot of control action and may also stimulate high-frequency dynamics that were overlooked during modelling. For the controller to function effectively, chattering must be minimised (eliminated). The sliding mode optimizer searches the internet for the best wheel slip that relates to the vehicle's greatest deceleration. The PID controller and the sliding mode optimizer work together to adjust the vehicle's brake torque and maintain optimal wheel slip. Simulations are used to demonstrate the performance of proposed control methods in reference [18].

To maintain the ideal slip value, Jingang Guo et al. [56] presented a sliding mode controller (SMC) based on the exponential ranging law for the ABS. The sliding mode design approach has two parts: developing a sliding surface that meets design standards, and constructing the switching feedback gains required to move the plant's state trajectory to the sliding surface. The generalized theory of Lyapunov Stability is used to design these structures. The most significant disadvantage of SMC is the talking issue, which can be mitigated through parameter tuning. Using a Mamdani fuzzy logic controller with two inputs and one output, parameter optimization is done to the reaching law. The sliding mode function S and the derivative of the sliding mode function S' are the two inputs, and the output is the exponential approach law parameter.

A basic yet efficient model known as the 3-DOF longitudinal prototype is utilised to test the brake control algorithm. The model is completed with the Burckhardt tyre model and an experimental motor model from the Database of Advanced Vehicle Simulator (ADVISOR) of a 32kW permanent magnet synchronous motor. The author proposes a regenerative braking algorithm that enhances the fraction of motor braking torque in overall braking torque. Both the motor and the friction brake system will function together if the available motor braking torque is less than the needed braking torque. The maximum braking torque of the motor will be utilised.

The friction brake system will give the difference between the needed stopping torque and the actual motor torque. Only the motor brake will do the work if the available motor braking torque is greater than the needed braking torque, and the motor controller will manage the input signal to ensure the required braking torque. The monitoring of the slip ratio becomes increasingly rapid and accurate as the amount of motor braking torque increases, as does the braking distance and conversion energy. The efficiency of ABS with a Bang-bang controller and the proposed SMC controller, both with and without optimal parameter, is monitored using MATLAB/Simulink, as well as the distribution of braking force using different actuators.

### 3.5 Control Method based on Gain Scheduling for Adaptive Control

Ting and Lin [57] proposed a method for incorporating the wheel slip limitation as a priori into control design in order to avoid skidding. Using a control framework for wheel torque and steering, the original problem is turned into a state regulation with input constraints. A low-and-high gain strategy is used to produce the restricted controller and optimise the usage of the wheel slip under lorry showed that the identification takes less than 40 seconds in both burdened and unladen scenarios.

### 3.6 ADAMS Modelling

Using the ADAMS (Automatic Dynamic Analysis of Mechanical System) computer programme, [60] the ABS performance on a single-wheel model was modelled and simulated. The tests investigated the relationship between braking force and wheel spin. As the brake torque is applied to the wheel, slip builds until the wheel is locked and slippage occurs. The simulation results demonstrated how a simple ABS algorithm might be transformed into a vehicle braking model to prevent wheel locking while braking forcefully.

### 3.7 Genetic Algorithm

The Genetic Algorithm is a worldwide search technique based on natural genetic operations and Darwin's "survival of the fittest" principle, but with a randomly organised data interchange. Because of its advantages over traditional optimization techniques, GA-related research is gaining popularity. GA converts the parameters

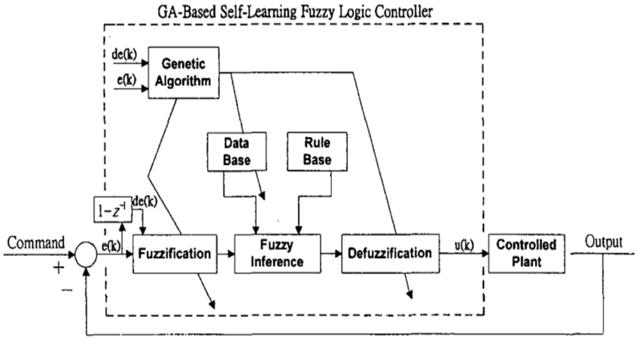


Fig.11. Genetic Algorithm based Fuzzy Logic System [49]

constraint for the converted problem. Simulations demonstrate that the proposed control approach is capable of reducing wheel slide and has good synchronization between wheel torque and wheel steering when tracking on a snow road.

To improve the control performance and resilience of ABS in diverse vehicle types and environmental situations, a robust adaptive control algorithm has been devised [58]. Lyapunov methods are used to prove the ABS asymptotic stability. The control goal is to maximize tire friction under the assumption that the optimal slip value is known. According to the reference, the slip error is bound to converge to zero asymptotically without any prior knowledge of the tyre force and system characteristics. The control system's robustness in the face of changes in system parameters is ensured.

### 3.8 Control based on load

A simple algorithm for managing the braking forces of a truck that consists of an electro-pneumatic brake system (EBS) has been devised [59]. The algorithm calculates the vehicle's mass and adjusts the brake forces proportional to its mass. Wheel speed and brake pressure signals, as well as engine data such as rotational speed and torque, are used to identify the vehicle. Vehicle tests on a 15-tonne involved in an optimization problem into finite-bit binary strings called chromosomes. Following that, a chromosomal population forms, with each chromosome that represents a possible solution to the optimization problem. The performance index of each chromosome is then calculated. Then three basic operations namely reproduction, crossover, and mutation, are carried out, which are analogous to genetic evolution. The reproduction job selects a new chromosomal generation at random. Crossover occurs when two chromosomes are exchanged. More chromosomes are created during the crossover operation. [49] Fu-Wei Chen et al. focuses on using the Genetic algorithm in a fuzzy logic-based controller. Figure 12 shows the block diagram of a Fuzzy Control System and Figure 11 shows the Block Diagram of Genetic Algorithm based Fuzzy Control System

### 3.9 Fuzzy logic in ABS

Uncertain or inexact concepts can be represented using fuzzy logic or fuzzy sets. It results from the classification of elements into classes with no clearly defined boundaries [61] [62]. Fuzzy set theory [63], on which fuzzy controllers are based, provides for the quantitative expression of imprecise and qualitative information. Because they deal with inexactness in a rigorous manner, fuzzy logic controllers are useful in handling the uncertainties and non-linearities associated with sophisticated control systems like traction control and ABS [64].

The ABS controller tries to limit wheel slip to a minimum, but there are a lot of variables to take into account. Brake torque is non-linearly proportional to brake lining temperature, and braking fluid viscosity varies with temperature, affecting the rate at which brake pressure can be increased or decreased. An ABS or ASR must take into consideration changes in road surfaces, vehicle weights, and steering. Wheel speed sensors may fail due to wear patterns in brake components. Brake lining adhesion, braking hysteresis, tyre inflation pressure, tyre wear patterns, and other external variables must all be considered.

Antilock braking systems were originally designed for aviation and were prohibitively expensive for road vehicles. Tseng, H.C. et al. [65] describes a design for aeroplane ABS that uses neural networks modified using this method to get a satisfying system response via an adaptive law.

Kumar et al. [74] investigated how an electric vehicle's ABS and collision avoidance systems may be controlled together (CAS). Fuzzy logic approaches are used to create integrated control of two subsystems. The control algorithm is designed and tested in a laboratory environment using a free scale microcontroller and a prototype electric automobile. A network capacity protocol called CAN is utilised to connect all sensors, ABS, and CAS. The findings show that integrating ABS with CAS control keeps the vehicle at a safe distance from objects while not compromising the performance of either system. For the ABS system, a different researcher [75] [76] [77] devised an adaptive PID-type fuzzy controller. A platform is constructed to execute a series of experiments in order to control the ABS. The platform is fitted with and tested with a

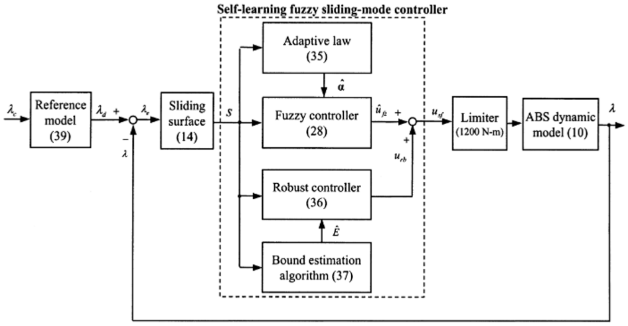


Fig.12. Self-Learning fuzzy sliding-mode controller [94]

and fuzzy logic. The aircraft ABS design was examined using the competing principles of neural network identification and fuzzy logic adaptive inference. The non-linearities that look-up tables are known for were simulated with neural identifiers and then integrated into the ABS design. The proposed rule-based fuzzy logic controller handled highly nonlinear aeroplane dynamics well, as well as shifting operating conditions and uncertainties. This system has been proven to be reliable in a variety of runway ground conditions.

To solve the ABS problem for unknown environmental conditions, FC has been proposed [14] [66] [67] [68] [69]. The analysis is complicated by the huge set of fuzzy rules. Based on the sliding mode control (SMC) methodology, some academics have introduced fuzzy control design methodologies. The fuzzy sliding-mode control (FSMC) design methods are the name for these approaches [70] [45]. The FSMC has the advantage of requiring fewer fuzzy rules than the FC because just one variable is defined as the fuzzy input variable. Furthermore, the FSMC system is more resistant to variation in parameter [45]. Although FC and FSMC are both excellent methods, the fuzzy rules must be fine-tuned beforehand using time-consuming trial-and-error procedures. Adaptive fuzzy control(AFC) which are based on the Lyapunov synthesis approach has been widely investigated to address this challenge [45] [71] [72] [73]. The fuzzy rules can be automatically commercialized ABS module controlled by a controller. A personal computer simulates and copies the car and tyre models for real-time control. The tests modify the road surface conditions, vehicle weight, and control procedures to determine braking properties.

Lin and Hsu [78] presented a design method for ABS called self-learning fuzzy sliding-mode control (SLFSMC). In the proposed SLFSMC system, the main tracking controller is a fuzzy controller that is used to imitate an ideal controller, and a robust controller is developed to compensate for the disparity between the ideal and fuzzy controllers. The SLFSMC has the advantages of being able to automatically alter fuzzy rules, like the AFC, and minimize fuzzy rules, like the FSMC. In order to calculate the approximation error, bound, an error estimation procedure is also devised. The Lyapunov sense is used to tune all of the parameters of SLFSMC, assuring the system's stability. Finally, a comparison is presented between an SMC, an FSMC, and the recommended SLFSMC in two simulation settings.

The performance of the ABS system is studied using a quarter car model with nonlinear elastic suspension. The fuzzy logic evaluation process is parallelized; thus, the controller output signal is generated quickly, taking less time and fewer steps than adaptive identification controllers. The brake system's sturdiness is put to the test on bumpy roads and in the presence of excessive measurement noise. The simulation results demonstrate how the system functions on various types of roadways and in rapidly changing traffic circumstances. While traditional control systems and even direct fuzzy or knowledge-based approaches [51] [79] [80] [81] [82] [83] [84] have been effectively deployed, their performance will deteriorate when poor road conditions occur. The control algorithms' ability to learn how to compensate for the wide range of road conditions that exist is limited, which is the primary reason of this poor performance.

The fuzzy model reference learning control (FMRLC) technique was established by Laynet et al. [85] and also by Laynet and Passino [86] for maintaining appropriate performance even under bad driving conditions. This controller employs a learning mechanism that monitors plant outputs and updates the rules in a direct fuzzy controller such that the total system acts like a "reference model" that exemplifies the desired behavior. Simulations of various road conditions (wet asphalt, icy) and "split road conditions" (the scenario where, for example, emergency braking happens and the road shifts from wet to icy or vice versa) are used to demonstrate the performance of the FMRLC-based ABS. For tire slip control in ABS systems, Precup et al. [87] designed a Takagi-Sugeno fuzzy controller and an interpolative fuzzy controller. Local controllers in the frequency domain are constructed using local linearized models of the controlled plant. There are also development approaches for the two fuzzy controllers. In comparison to traditional PI controllers, simulation findings reveal that fuzzy controllers provide better control system performance.

Stan et al. [88] compared and contrasted five fuzzy control approaches for ABS systems. A detailed mathematical model of a controlled plant is created and simplified for control design, with a focus on tyre slip management. A new fuzzy control solution based on a class of Takagi-Sugeno fuzzy controllers is proposed. This fuzzy controller combines PI and PID controllers that were created separately and correspond to a set of simplified models of controlled plants that were linearized at critical operating points. Simulation findings confirm the proposed fuzzy control strategy for regulating the relative slip of a single wheel.

R. Keshmiri et al. [89] created a smart fuzzy ABS controller that can adapt slippage performance for different types of roads. The suggested control system has two primary features: The first is a fuzzy logic controller (FLC) that provides ideal braking torque for both front and rear wheels; the second is an FLC that provides the required amount of slip and torque reference qualities for different types of roads. When compared to other brake systems, simulation findings demonstrate that this one is more reliable and performs better. For dynamical control issues, Karakose and Akin [90] introduced a fuzzy control technique that used fuzzy logic system which was dynamic in nature and a block based neural network. Simulation results for the dc motor position control problem demonstrate the usefulness of the proposed strategy.

Ayman A. Aly [91] created an intelligent fuzzy ABS controller that can modify slide performance for a variety of roads in the same direction. The fuzzy optimizer immediately identifies the optimal wheel slips for the new surface, obliging the actual wheel slips to follow the best reference wheel slips. According to the simulation results, the proposed ABS algorithm is capable of preventing wheel obstruction in a variety of traffic scenarios. The resultant fuzzy control is also advantageous as a free model technique in terms of reducing design complexity as well as the controlled system's antisaturating, antichattering, and robustness properties.

Jong Hyeon Park et.al [92] A fuzzy-logic controller and a sliding-mode observer of vehicle speed are used to create an anti-lock braking system (ABS) for commercial buses. Based on the projected wheel slip ratio, the brake controller delivers pulse width modulated (PWM) control inputs to each brake solenoid valve. When compared to standard on-off control inputs, PWM control inputs at the brakes greatly reduce chattering in the brake system. The wheel speed data is used by the sliding-mode observer to estimate vehicle speed, which is subsequently used to determine the wheel slip ratio. The success of the suggested control approach is supported by a series of computer simulations of bus driving using the 14 degrees of freedom bus model.

Mojtaba Ahmadieh et.al [93] proposed a method in which, to optimise the parameters of type-2 fuzzy logic systems, an enhanced Kalman filter was used. The type-2 fuzzy logic system in this study employs a novel type-2 fuzzy membership function with certain values on both ends of the support and the kernel and uncertain values on other sections of the support. The extended Kalman filter was compared to other experimental approaches in the literature, including particle swarm optimization and gradient descent methods. The proposed type-2 fuzzy neural structure is evaluated on a variety of noisy input–output data sets, and it is shown that the extended Kalman filter outperforms gradient descent-based techniques. Although the suggested method is comparable to particle swarm optimization in terms of performance, it is faster and more efficient. In addition, simulation results show that the proposed unique type-2 fuzzy membership function, when combined with the extended Kalman filter, has noise rejection features. The Kalman filter is also used to train the parameters. A type-2 fuzzy logic system is employed in a feedback error learning technique. It's then used to govern a real-time laboratory setting ABS, with positive outcomes.

Yonggon Lee et.al [94] Proposed a genetic Neural Fuzzy ABS controller with a nonderivative neural optimizer and fuzzy logic is developed constituents (FLCs). To maximize the road adhesion coefficient, the nonderivative optimizer determines the ideal wheel slippage. Wheel slippage is greatest on the front and rear wheels. The FLC receives the optimal wheel slips from the nonderivative optimizer as inputs. The fuzzy components then calculate brake torques that cause the actual wheel slips to follow the optimal wheel slips. Vehicle stopping distance is reduced by brake torques that cause actual wheel slips to track ideal wheel slips. The FLCs are tuned using a genetic algorithm.

Figure 13 shows the proposed Neural Fuzzy ABS system. The proposed model was built in Simulink, and only straight-line braking was considered, ignoring the impacts of brake hydraulic system and brake pad levels on transportation delay.

Chih-Min Lin et.al [95] describe a design strategy for ABS that uses self-learning fuzzy sliding-mode control (SLFSMC). The SLFSMC ABS adjusts the brake torque for optimal braking. The SLFSMC system is made up of a fuzzy controller and a robust controller. The robust controller compensates for the approximation error between the ideal and fuzzy controllers, whereas the fuzzy controller is designed to seem like an ideal controller. The tuning methods of the controller are derived in a Lyapunov sense, ensuring that the system remains stable. Furthermore, the suggested SLFSMC ABS does not require the construction of a vehicle-braking model. Simulations indicate the effectiveness of the proposed SLFSMC ABS in responding to changes for a variety of road conditions.

The application of Fuzzy logic-based control systems has also been implemented in Electric Vehicles for ABS. P. khatun et.al. [96] presents research and development of a fuzzy logic-based controller for controlling wheel slide in electric car ABSs. Fuzzy control has the potential to be an essential technique for developing robust traction control since the behavior of braking systems are extremely nonlinear and time variable. Simulation studies are used to develop an initial rule basis, which is subsequently tested on an experimental test facility that simulates braking system dynamics. In the generating region, the test facility consists of an induction machine load. It is shown that the torque-slip characteristics of an induction motor provide a viable foundation for modelling a range of tire/road—driving situations, obviating the requirement for skid-pan trials when developing algorithms. The results demonstrated that the fuzzy controller can adjust for nonlinear behavior that is complex. The robustness of the fuzzy controller has been demonstrated, with the ability to react to a variety of road conditions. Furthermore, the data suggest that fuzzy-logic-based ABS/traction control could improve longitudinal performance and offer significant potential for optimal management of driven wheels, particularly on ice roads.

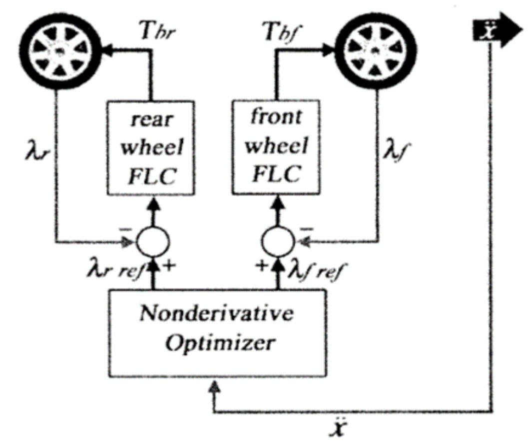


Fig.13. Schematic of proposed Neural Fuzzy ABS Controller [94]

Giovanna Fargion et al. [97] proposed a genetic control based fuzzy system in the ABS for the control of vehicle suspensions which are semi-active. The paper aimed to create a new Antilock Braking System control system of a Soft Computing type, using a new control method based on a fuzzy-type algorithm that has been genetically tuned. The investigation began with a monocorner model and was later expanded to include a complete vehicle model. The authors' model for testing, dubbed the monocorner model by the authors, was developed in MATLAB-Simulink and consists of a single front wheel, two masses (one suspended, one non-suspended), and a set of physical dimensions appropriate for describing the behavior of the elements present in the real system. It has five degrees of freedom: a) upward motion of the suspended mass, b) vertical movement of the non-suspended mass, and c) horizontal translation of the suspended mass. c) suspension mass longitudinal translation d) non-suspended mass longitudinal translation e) wheel rotation Prior to the start of the braking manoeuvre, the car was considered to be driving along a flat, level, and straight road at a constant speed. The Sugeno fuzzy controller in the ABS system received two inputs: circumferential wheel acceleration and longitudinal slippage: brake slip, and the output was the operator's control signal. The monocorner model was also related to the fuzzy controller, which was constructed in Matlab-Simulink.

The Fuzzy controller has learned a correct control plan for how much braking pressure to apply regardless of the current adherence conditions thanks to genetic algorithms training. When the fuzzy-genetic system was compared to the Bosch ABS system, it was discovered that the fuzzy system was less effective at high speeds (low adherence values).

offered a fuzzy fractional-order sliding mode controller concept that was modified. The proposed adaptive fuzzy fractional order sliding mode controller combines a fractional order sliding mode controller and a fuzzy logic controller. A fractional order sliding mode controller's sliding surface is PD, which is based on fractional calculus and is much more durable than typical sliding mode controllers. The fuzzy logic controller receives the fractional order sliding surface and its derivative, which is used to compensate for the effects of changing ABS parameters. The fuzzy logic controller's tuning law is derived using Lyapunov theory, and the system's stability is ensured. The suggested adaptive fuzzy fractional order sliding mode controller gives faster simulation results, less overshoot and more robust than SMC with PI sliding surface and SMC with $PD^{\alpha}$ which is based on fractional calculus.

The terms used are as follows

| | |
|---|---|
| $\lambda_d$ | The Desired Slip |
| $\mu$ | The coefficient of friction of road. |
| $\lambda$ is | The actual wheel slip. |
| $\mu_{eq}$ is | The equivalent controller in sliding mode control. |
| $\mu_{rb}$ is | The hitting controller in sliding mode control. |
| s is | The sliding surface. |
| $\mu_{fz}$ is | The fuzzy controller. |

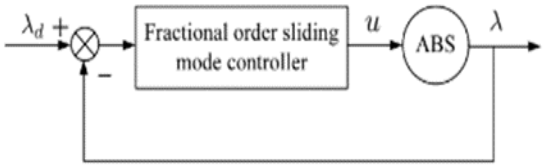


Fig.14. ABS structure with FOSMC Controller [98]

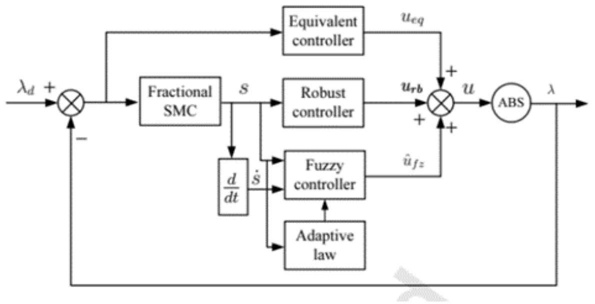
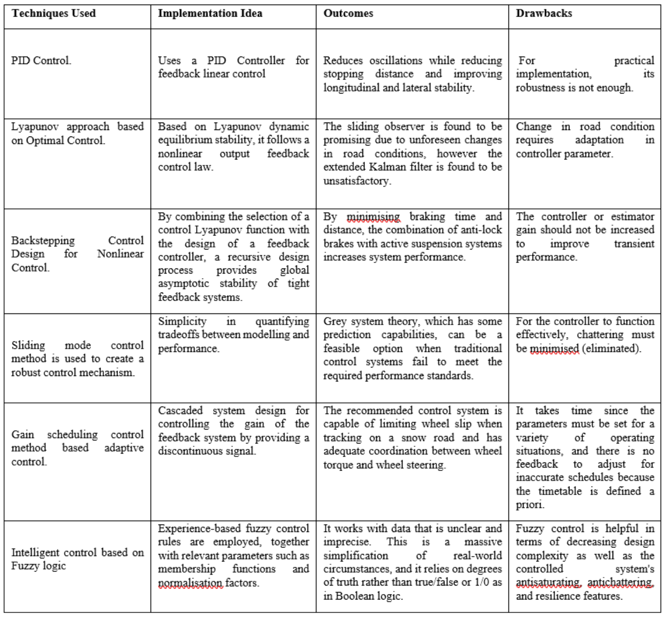


Fig.15. ABS with AFFOSC controller [98]

Figure 14 and Figure 15 show the ABS structure with FOSMC controller and ABS with AFFOSMC controller respectively.

Peter Girovsky et.al [99] presents the results of a research of an anti-lock braking system (ABS) with a fuzzy controller. The fuzzy controller was employed to improve the vehicle's braking effectiveness, especially in critical conditions, such as when stopping on a wet road. The ABS controller was created using the MATLAB/Simulink application. A medium-sized car model was used to simulate the developed controller. During testing, the automobile model was used to simulate three different braking systems. The researchers compared a braking system without an ABS, a system with a limit based conventional ABS, and a braking system with the recommended ABS with a fuzzy controller. These three braking systems were tested on a dry straight road and a mixed adhesion path. The car was put through a manoeuvrability test in which it had to brake while avoiding an object.

Table.1. Comparison of different ABS Control methods



| Techniques Used | Implementation Idea | Outcomes | Drawbacks |
|---|---|---|---|
| PID Control. | Uses a PID Controller for feedback linear control | Reduces oscillations while reducing stopping distance and improving longitudinal and lateral stability. | For practical implementation, its robustness is not enough. |
| Lyapunov approach based on Optimal Control. | Based on Lyapunov dynamic equilibrium stability, it follows a nonlinear output feedback control law. | The sliding observer is found to be promising due to unforeseen changes in road conditions, however the extended Kalman filter is found to be unsatisfactory. | Change in road condition requires adaptation in controller parameter. |
| Backstepping Control Design for Nonlinear Control. | By combining the selection of a control Lyapunov function with the design of a feedback controller, a recursive design process provides global asymptotic stability of tight feedback systems. | By minimising braking time and distance, the combination of anti-lock brakes with active suspension systems increases system performance. | The controller or estimator gain should not be increased to improve transient performance. |
| Sliding mode control method is used to create a robust control mechanism. | Simplicity in quantifying tradeoffs between modelling and performance. | Grey system theory, which has some prediction capabilities, can be a feasible option when traditional control systems fail to meet the required performance standards. | For the controller to function effectively, chattering must be minimised (eliminated). |
| Gain scheduling control method based adaptive control. | Cascaded system design for controlling the gain of the feedback system by providing a discontinuous signal. | The recommended control system is capable of limiting wheel slip when tracking on a snow road and has adequate coordination between wheel torque and wheel steering. | It takes time since the parameters must be set for a variety of operating situations, and there is no feedback to adjust for inaccurate schedules because the timetable is defined a priori. |
| Intelligent control based on Fuzzy logic | Experience-based fuzzy control rules are employed, together with relevant parameters such as membership functions and normalisation factors. | It works with data that is unclear and imprecise. This is a massive simplification of real-world circumstances, and it relies on degrees of truth rather than true/false or 1/0 as in Boolean logic. | Fuzzy control is helpful in terms of decreasing design complexity as well as the controlled system's antisaturating, antichattering, and resilience features. |

A A Umnitsyn and S V Bakhmutov [100] discuss the work of an intelligent anti-lock braking system (ABS), in which electric machines and friction brakes operate as actuators, is discussed in this article. It's tough to combine multiple actuators into a single control object. The employment of a fuzzy logic-based control system is one of the conceivable solutions. The study analyses two tracking algorithms for regulating the anti-lock braking system actuators: sliding control with mixed braking and a fuzzy logic control system; slipping control with one actuator braking - friction brakes.

According to research, using combined braking improves the system's efficacy in a variety of driving scenarios. Linfeng Lv et.al [101] suggest for electric vehicles, an electro-hydraulic compound anti-lock braking system based on interval type-2 fuzzy logic control strategy and its corresponding braking torque allocation strategy was developed to track the ideal slip rate and achieve ideal energy recovery efficiency under a variety of complex road conditions. To determine the ideal total braking torque, the suggested interval type 2 fuzzy logic controller uses four steps: fuzzification, fuzzy inference, type reduction, and defuzzification. In the fuzzy inference process, the slip rate error and change rate of slip rate error are used as inputs, and then the upper and lower membership functions are used to calculate the activation degree interval of different fuzzy rules, improving the anti-interference ability to external and internal uncertainties. A brake torque distribution strategy is created on the basis of safe braking to preserve optimal energy recovery efficiency. The anti-lock brake control mechanism is modelled using the MATLAB/Simulink Software tool under two different driving circumstances. The suggested interval type-2 fuzzy logic anti-lock brake control system achieves optimal regenerative braking energy recovery efficiency under both joint and split road surfaces, as well as improved slip rate control effect and resilience, according to simulation results.

To cope with variations in adherence conditions in roads, an anti-lock braking system based on fuzzy logic has been designed and optimized by Javier Perez Fernandez et.al. [102]. Before being put into operation, traditional control systems must be fine-tuned through simulations and experiments on various surfaces. Large amounts of processing and testing time are necessary in this manner. The major goal of this research is to provide an approach that uses a combination of optimization and simulation to simplify the process of acquiring a controller for antilock brake systems. To achieve this, the suggested fuzzy logic controller was tuned using an evolutionary approach based on the coevolution of two species. The controller adapts to changing adherence conditions by evolving competitively with the environment. Finally, the optimized controller was tested on a real motorcycle to see how it compared to a traditional system. The evolution of two or more species that interact is referred to as coevolution. They can be classified as antagonists/competitive [103] Predator and prey, symbiotic or cooperative [104], [105], mutual exploitation or non - symmetric [106] based on their behavior (host and parasite). Coevolution between competitive species is proposed to overcome engineering difficulties in [107], [108]. Unlike other approaches [36] [109] that apply this coevolutionary process to a set of data, [102] optimizes the control logic by simulating different road conditions. Table 1 summarizes the different ABS control methods used.

## IV. CONCLUSION

To summarize, this article has sought to demonstrate the variety of ABS sensing and transduction approaches now in use. As can be seen from the preceding discussion, the field is quite busy, with research moving forward on multiple fronts. The evolution of modern-day ABS system has been discussed in the paper. From the initial design of ABS, test benches developed for ABS and different algorithms used for enhancing performance of ABS systems have been looked upon. Initially braking systems were not intelligent, with the development of technology and algorithms, many new models were created that focused on the vulnerabilities of braking system and suggested ideas on their improvements.

Because of the intricate interaction between its components and parameters, the braking system based on Anti-lock method control is a highly nonlinear control problem. ABS control system research has addressed a wide range of concerns and challenges. ABS control methods have been established in a variety of ways, and research into better control methods is ongoing. The majority of these approaches necessitate system models, and some of them are incapable of achieving good performance when road conditions change. Soft computing technologies, such as fuzzy control, do not require a precise model. There's a basic rundown of how soft computing is employed in ABS control. The advent of upgraded control algorithms that combine components of fuzzy and neuro-fuzzy logic has resulted in significant performance benefits, and much of the recent work in ABS is focused on software development.

Sliding mode controllers to estimate the wheel speed, Extended Kalman Filter, 2-D non-derivative neural optimizers, self-learning fuzzy mode controller, adaptive PID-fuzzy systems, gain scheduling-based controllers, and intelligent systems have been covered in the paper. The current trend in ABS technology is development of Genetic algorithms, sliding mode along with type 2 fuzzy systems, and optimization of fuzzy controllers for reducing the braking distance even further and use of Coevolutionary optimizations.

## REFERENCES

[1]. H. Heisler, "Vehicle and engine technology," 1999.

[2]. R. Bentley, Automotiv Handbook, Bosch, 1993.

[3]. H. Leiber, "Four Years of Experience With 4-Wheel Antiskid Brake Systems (ABS)," in Society of Automotive Engineers (SAE), 1983.

[4]. L. E. J. G. S. J. L. Harned, "Measurement of Tire Brake Force Characteristics as Related to Wheel Slip (Antilock) Control System Design," in International Automotive Engineering Congress and Exposition, 1969.

[5]. H. B. P. L. L. Egbert Bakker, "A New Tire Model with an Application in Vehicle Dynamics Studies," in Autotechnologies Conference and Exposition, 1989.

[6]. T. M. Yi-Feng Chen, "Sliding mode control with adaptive vss observer," in IEEE International Symposium on Intelligent Control, 1994.

[7]. A. A. Aly, "An Antilock-Braking Systems (ABS) Control: A Technical Review," in Intelligent Control and Automation, 2011.

[8]. J. S. Yong Liu, "Target slip tracking using gain-scheduling for antilock braking systems," in American Control Conference, 1995, 1995.

[9]. Ming-ChangShihMing-ChinWuLian-ChuanLee, "Neuro-Fuzzy Controller Design of Anti-Lock Braking System," in IFAC Proceedings Volumes, 1998.

[10]. K. K. Antony Satyadas, "GA-optimized fuzzy controller for spacecraft attitude control," in IEEE 3rd International Fuzzy Systems Conference, 1993.

[11]. D. M. L Austin, "Recent advances in antilock braking systems and traction control systems.," Journal of Automobile Engineering, pp. 625-638, 2000.

[12]. A. Garcia, "mechathon.com," Mechathon, [Online].

[13]. S. Sivarama krishnan, "Discrete Tire Modelling for Anti-lock Braking System Simulations," Research Gate, 2013.

[14]. G. F. Mauer, "A Fuzzy Logic Controller for an ABS," IEEE Transactions on Fuzzy Systems, vol. 3, no. 4, pp. 381-388, 1995.

[15]. R. A. M. N. C. N. DANKAN GOWDA, "Modelling and Performance Evaluation of Anti-lock braking system," Journal of Engineering Science and Technology, vol. 14, no. 5, pp. 3028-3045, 2019.

[16]. H. K. a. K. B. J. Song, "“A study on an Anti-Lock Braking System Controller and Rear-Wheel Controller to Enhance Vehicle Lateral Stability," Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 221, no. 7, pp. 777-787, 2007.

[17]. F. Jiang, "An Application of Nonlinear PID Control to a Class of Truck ABS Problems," in Proceedings of the 40th IEEE Conference on Decision and Control, Orlando, 2000.

[18]. A. H. Z. Will, "Sliding mode wheel slip controller for an ABS.," International Journal of Vehicle Design., vol. 4, no. 19, pp. 523-539, 1998.

[19]. H. P. W. a. Y. T. G. I. Y. Mustafa, "Advances in engineering software vibration control of an active vehicle suspension systems using optimized model-free fuzzy logic controller based on time delay estimation," Engineering Software, vol. 127, pp. 141-149, 2019.

[20]. X. W. S. S. a. H. L. H. Li, "Vehicle control strategies analysis based on PID and fuzzy logic controls.," Procedia Engineering, vol. 137, pp. 234-243, 2016.

[21]. C. Y. a. J. Y. H. C. Hwang, "Path tracking of an autonomous ground vehicle with different payloads by heirarchial improved fuzzy dynamic sliding mode control," IEEE transactions on fuzzy sets, vol. 26, no. 2, pp. 899-914, 2018.

[22]. S. S. J. Y. Z. Z. M. J. E. N. Wang, "Global Asymptotic model-free-trajectory-independent tracking control of an uncertain marine vehicle," IEEE Transactions on Fuzzy Sets, vol. 26, no. 3, pp. 1613-1625, 2018.

[23]. S.-J. Huang and W.-C. Lin, "Adaptive fuzzy controller with sliding surface for vehicle suspension control.," IEEE transactions on Fuzzy Sets, vol. 11, no. 4, pp. 550-559, 2003.

[24]. J. Zhang et al., "Adaptive sliding mode-based lateral stability control of steer-by-wire vehicles with experimental validations.," IEEE transactions on Vehicle Technology, vol. 69, no. 9, pp. 9589-9600, 2020.

[25]. M. Ye and H. Wang, "A Robust adaptive chattering-free sliding mode control strategy for automotive electronic throttle syste via genetic algorithm.," IEEE Access, vol. 8, pp. 68-80, 2020.

[26]. A. Poursamad, "Mechatronics adaptive feedback linearization control of antilock braking systems using neural networks.," Mechanatronics, vol. 19, no. 5, pp. 767-773, 2009.

[27]. H. Wang et al., "Adaptive neural network sliding mode control for steer-by-wire based vehicle stability control," Journal of Intelligent Fuzzy Systems, vol. 31, no. 2, pp. 885-902, 2016.

[28]. M. Watany, "Performance of a Road Vehicle with Hydraulic Brake Systems Using Slip Control Strategy," American Journal of Vehicle Design, vol. II, no. 1, pp. 7-18, 2014.

[29]. H. B. Pacejka., "Applications of transient tire models," Tire and Vehicle Dynamics, vol. 3, pp. 364-411, 2007.

[30]. M. Burckhardt, Fahrwerktechnik: Radschlupf Regelsysteme., Wurzburg: Vogel-Verlag, 1993.

[31]. A. A. a. S. M. S. M. Tanellia, "Robust Nonlinear Output Feedback Control for Brake by Wire Control Systems," Automatica, vol. 44, no. 4, pp. 1078-1087, 2008.

[32]. R. Freeman, "Robust Slip Control for a Single Wheel," Santa barbara, 1995.

[33]. J. S. Yu, "A Robust Adaptive Wheel-Slip Controller for Antilock Brake System," in Proceedings of 36th IEEE Conference on Decision Contro, San Diego, 1997.

[34]. L. A. R. H. a. C. C. D. J. Yi, "Adaptive Emergency Braking Control using a Dynamical Tire/Road Friction model," in Proceedings of 39th IEEE Conference on Decision Control, Sydney, 2000.

[35]. J. Lüdemann, Heterogeneous and Hybrid Control with Application in Automotive Systems, 2002.

[36]. Y. L. a. J. Sun, "Target Slip Tracking Using Gain-Scheduling for Braking Systems," in Proceedings of the 1995 American Control Conference, Seattle, 1995.

[37]. S. T. a. E. H. Law, “Slip Control Braking of an Automobile during Combined Braking and Steering Manoeuvres, American Society of Magazine Editors, 1991.

[38]. C. Jun, "The Study of ABS Control System with Different Control Methods," in Proceedings of the 4th International Symposium on Advanced Vehicle Control, Nagoya, 1998.

[39]. F. Jiang, A Novel Approach to a Class of Antilock Brake Problems, Cleaveland: Ph.D. Dissertation, Cleveland State University, 2000.

[40]. T. S.-H. M. S. a. K. J. Y. Wang, "A New Approach to Simultaneous Stabilization and Strong Simultaneous Stabilization with D Stability and Its Application to ABS Control Systems Design," in European Control Conference, Porto, 2001.

[41]. S. Solyom, "Synthesis of a Model-Based Tire Slip Controller," Synthesis of a Model-Based Tire Slip Controller, vol. 41, no. 6, pp. 475-499, 2004.

[42]. Ü. Ö. P. D. a. B. A. S. Drakunov, "ABS Cotrol Using Optimum Search via Sliding Modes," in IEEE Transactions on Control Systems Technology, 1995.

[43]. M. S. a. K. Hunt, "Anti-lock Braking Control Using a Sliding Mode Like Approach," in Proceedings of the 2002 American Control Conference, Anchorage, 2002.

[44]. M. C. W. a. M. C. Shih, "Hydraulic Anti-Lock Braking Control Using the Hybrid Sliding-Mode Pulse Width Modulation Pressure Control Method," in Proceedings of the Institution of Mechanical Engineers, 2001.

[45]. C. Ü. a. P. Kachroo, "Sliding Mode Measurement Feedback Control for Antilock Braking Systems," in IEEE Transactions on Control Systems Technology, 1999.

[46]. W. T. a. J. Lin, "Nonlinear Control Design of Anti-lock Braking Systems Combined with Active Suspensions," Technical report of Department of Electrical Engineering, National Chi Nan University., 2005.

[47]. Z.-D. L. a. Z.-Q. Q. R.-G. Wang, "Multiple Model Adaptive Control of Antilock Brake System via Back stepping Approach," in Proceedings of 2005 International Conference on Machine Learning and Cybernetics, Guangzhou, 2005.

[48]. J. K. J. L. a. I. P. T. A. Johansen, "Hybrid Control Strategies in ABS," in Proceedings of the 2001 American Control Conference, Arlington, 2001.

[49]. F.-W. a. L.-L. Chen, "'Nonlinear linearization controller and genetic algorithm-based fuzzy logic controller for ABS systems and their comparison," International Journal of Vehicle Design, vol. 24, no. 4, pp. 334-349, 2000.

[50]. V. V. K. A. a. E. P. Andrei Aksjonov, "Design of Regenerative Anti-lock braking system controller for 4 in wheel motor drive electric vehicle ith road surface estimation.," International Journal of Automotive Technology, vol. 19, no. 4, pp. 717-742, 2018.

[51]. H. S. T. a. M. Tomizuka, "An Adaptive Sliding Mode Vehicle Traction Controller Design," in Proceedings of the 1989 American Control Conference, Pittsburgh, 1989.

[52]. W. C. L. a. D. S. Y. K. Chin, "Sliding-Mode ABS Wheel Slip Control," in Proceedings of 1992 ACC, Chicago, 1992.

[53]. A. S. B. a. J. K. H. J. C. Gerdes, "Brake System Modelling for Vehicle Control," in Proceedings International Mechanical Engineering Congress and Exposition, San Francisco, 1995.

[54]. D. C. a. J. K. Hedrick, "Automotive Powertrain Modelling for Control," Transactions ASME Journal of Dynamic Systems, Measurements and Control, vol. 111, no. 4, pp. 568-576, 1989.

[55]. E. K. a. O. Kaynak, "A Grey System Modelling Approach for Sliding Mode Control of Antilock Braking," IEEE Transactions on Industrial Electronics, vol. 56, no. 8, pp. 3244-3252, 2009.

[56]. X. J. a. G. L. Jingang Guo, "Performance Evaluation of an Anti-Lock Braking System for," Energies, pp. 6459-6476, 2014.

[57]. W. T. a. J. Lin, "Nonlinear Control Design of Anti-lock Braking Systems Combined with Active Suspensions," Technical Report of Department of Electrical Engineering, National Chi Nan University, 2005.

[58]. J. Yu, "Robust adaptive wheel-slip Controller for ABS," in IEEE Conference on Decision and Control, 1997.

[59]. P. Frank, "Load-dependent control of braking forces on commercial vehicles," in Conference on Mechanical Engineering, 1998.

[60]. B. B. M. Ozdalyan, "Anti-lock braking system simulation and modelling in ADAMS," in IEEE Conference Publication, 1998.

[61]. P. a. G. F. Pedrycs, An Intuoduction to Fuzzy Sets, MIT Press, 1998.

[62]. A. Kandel, Fuzzy Mathematical Techniques with Applications, Addison-Wesley, 1986.

[63]. L. A. Zadeh, Fuzzy sets. Information Control, 1965.

[64]. M. a. T. M. Bauer, "Fuzzy logic traction controllers and their effect on longitudinal vehicle platoon systems. Veh. Syst. Dynamics," vol. 25, no. 4, pp. 277-303, 1996.

[65]. H. C. a. C. C. W. Tseng, " Aircraft antilock brake system with neural networks and fuzzy-logic," Journal of Guidance Control and Dynamics, vol. 18, no. 5, pp. 1113-1118, 1995.

[66]. B. Ozdalyan, "Development of A Slip Control Anti-Lock Braking System Model," International Journal of Automotive Technology, vol. 9, no. 1, pp. 71-80, 2008.

[67]. A. B. W. a. S. H. Zak, "Antilock Brake System Modelling and Fuzzy Control," International Journal of Vehicle Design, vol. 24, no. 1, pp. 1-18, 2000.

[68]. K. M. P. a. S. Y. J. R. Layne, "Fuzzy Learning Control for Antiskid Braking Systems," IEEE Transactions on Control Systems Technology, vol. 1, no. 2, pp. 122-129, 1993.

[69]. K. L. a. K. Park, "Optimal Robust Control of a Contactless Brake System Using an Eddy Current," Mechatronics, vol. 9, no. 6, pp. 615-631, 1999.

[70]. W. K. L. a. K. M. Passino, "Intelligent Control for Brake Systems," IEEE Transactions on Control System Technology, vol. 7, no. 2, pp. 188-202, 1999.

[71]. C. Lee, "Fuzzy Logic in Control Systems: Fuzzy Logic Controller Part I, II," IEEE Transactions on Systems Man, and Cybernetics, vol. 20, no. 2, pp. 401-435, 1990.

[72]. S. K. a. J. Lee, "Design of a Fuzzy Controller with Fuzzy Sliding Surface," Fuzzy Sets and Systems, vol. 71, no. 3, pp. 359-369, 1995.

[73]. S. W. K. a. B. K. K. B. J. Choi, "Design of a Single-Input Fuzzy Logic Controller and Its Properties," Fuzzy Sets Systems, vol. 106, no. 3, pp. 299-308, 1999.

[74]. K. L. V. a. K. K. M. S. Kumar, "Fuzzy Logic Based Integrated Control of Anti-Lock Brake System and Collision Avoidance System Using CAN for Electric Vehicles," in IEEE

International Conference on Industrial Technology, Gippsland, 2009.

[75]. L. X. Wang, Adaptive Fuzzy Systems and Control: Design and Stability Analysis, Prentice-Hall, Inc., 1994.

[76]. H. L. a. M. Tomizuka, "Robust Adaptive Control Using a Universal Approximator for SISO Nonlinear Systems," IEEE Transactions on Fuzzy Systems, vol. 8, no. 1, pp. 95-106, 2001.

[77]. C. K. C. a. M. C. Shih, "PID Type Fuzzy Control for Antilock Brake System with Parameter Adaptation," JSME International Journal, Series C, vol. 47, no. 2, pp. 675-685, 2004.

[78]. C.-F. H. C.-M. Lin, "Self-Learning Fuzzy Sliding-Mode Control for Antilock Braking Systems," IEEE Transactions on Control Systems Technology, vol. 11, no. 2, pp. 273-278, 2003.

[79]. H. T. a. M. Tomizuka, Discrete-Time Controller Design for Robust Vehicle Traction, IEEE Control Systems Magazine, 1990.

[80]. R. F. a. R. Fenton, "A Describing-Function Approach to Antiskid Design," IEEE Transactions on Vehicular Technology, vol. 30, no. 3, pp. 134-144, 1981.

[81]. Y. N. a. H. K. S. Yoneda, "Rear Brake LockUp Control System of Mitsubishi Starion," in SAE paper, 1983.

[82]. N. O. H. K. a. M. O. T. Tabo, "Automotive Antiskid System Using Modern Control Theory," IECON, vol. 1, pp. 390-395, 1985.

[83]. H. T. a. Y. Ishikawa, "Anti-Skid Braking Control System Based on Fuzzy Inference". United States of America Patent 4842342, 1989.

[84]. R. G. a. H. Ouwerkerk, "Adaptive Brake Control System," Proceedings of the Institution of Mechanical Engineers, pp. 855-880, 1972.

[85]. K. M. P. a. S. Y. J. R. Laynet, "Fuzzy Learning Control for Anti-Skid Braking Systems," IEEE Transactions on Control Systems Technology, vol. 1, no. 2, pp. 122-129, 1993.

[86]. J. L. a. K. M. Passino, "Fuzzy Model Reference Learning Control for Cargo Ship Steering," IEEE Control Systems Magazine, vol. 13, no. 6, pp. 23-24, 1992.

[87]. S. P. M. B. V. B. R-E. Precup, "Fuzzy Controllers for Tire Slip Control in Anti-lock Braking Systems," in IEEE International Conference on Fuzzy Systems, Budapest, 2004.

[88]. R.-E. P. a. S. A. P. M. Stan, "Analysis of Fuzzy Control Solutions for Anti-Lock Braking Systems," Journal of Control Engineering and Applied Informatics, vol. 9, no. 2, pp. 11-22, 2007.

[89]. R. K. a. A. M. Shahri, "Intelligent ABS Fuzzy Controller for Diverse Road Surfaces," World Academy of Science, Engineering and Technology, vol. 2, no. 2, pp. 62-67, 2007.

[90]. M. K. a. E. Akin, "Dynamical Fuzzy Control with Block Based Neural Network," Department of Computer Engineering, Fırat University, Firat, 2006.

[91]. A. A. Aly, "Intelligent Fuzzy Control for Antilock Brake System with Road-Surfaces Identifier," in IEEE International Conference on Mechatronics and Automation, 2010.

[92]. D. H. K. Y. J. K. Jong Hyeon Park", "Anti-Lock Brake System Control for Buses Based on Fuzzy Logic and a Sliding-Mode Observer," KSME International Journal, vol. 15, no. 10, pp. 1398-1407, 2001.

[93]. M. T. a. O. K. Mojtaba Ahmadieh Khanesar, "Extended Kalman Filter Based Learning Algorithm for Type-2 Fuzzy Logic Systems and Its Experimental Evaluation," IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS., vol. 59, no. 11, 2012.

[94]. Y. L. a. S. H. Zak, "Designing a Genetic Neural Fuzzy Antilock-Brake-System Controller," IEEE Transactions on Evolutionary Computation, vol. 6, no. 2, 2002.

[95]. C.-M. L. a. C.-F. Hsu, "Self-Learning Fuzzy Sliding-Mode Control for Antilock Braking Systems," IEEE Transactions on Control Systems Technology, vol. 11, no. 2, 2003.

[96]. C. M. B. S. a. P. H. M. P. Khatun, "Application of Fuzzy Control Algorithms for Electric," IEEE Transactions on Vehicular Technology, vol. 52, no. 5, pp. 1356-1365, 2003.

[97]. D. T. R. Giovanna Fargionea, "A fuzzy-genetic control system in the ABS for the control of," Elsevier Mechatronics, pp. 89-102, 2016.

[98]. Y. W. M. H. Q. L. Yinggan Tang, "Adaptive fuzzy fractional-order siding mode controller design for antilock braking system," Journal of Dynamic Systems, 2016.

[99]. J. Ž. a. J. K. Peter Girovský, "Optimization of Vehicle Braking Distance Using a Fuzzy Controller," Energies, 2020.

[100]. A. A. U. a. S. V. Bakhmutov, "Intelligent anti-lock braking system of electric vehicle with the possibility of mixed braking using fuzzy logic," Journal of Physics: Conference series, 2021.

[101]. J. W. a. J. L. Linfeng Lv, "Interval Type-2 Fuzzy Logic Anti-Lock Braking Control for Electric Vehicles under Complex Road Conditions," Sustainability, vol. 13, 2021.

[102]. M. A. V. M. V. G. A. C. C. a. J. J. C. A. Javier Pérez Fernández, "Coevolutionary Optimization of a Fuzzy Logic Controller for Antilock Braking Systems Under Changing Road Conditions," IEEE Transactions on Vehicular Technology., vol. 70, no. 2, 2021.

[103]. B. E. F. N. a. A. S. J. A. Cabrera, "A coevolutionary algorithm for tire model parameters identification.," Structure Multidisciplinary optimum., vol. 41, no. 5, pp. 747-763, 2010.

[104]. C. A. Pena-Reyes and M. Sipper, "Fuzzy CoCo: A Cooperative coevolutionary approach to fuzzy modelling.," IEEE Transactions on Fuzzy Systems, vol. 9, no. 5, pp. 727-737, 2001.

[105]. J. W. a. M. H. J. Fan, "“Cooperative coevolution for large-scale optimization based on kernel fuzzy clustering and variable trust region methods," IEEE Transactions on Fuzzy sets, vol. 22, no. 4, pp. 829-839, 2014.

[106]. K.-S. B. a. D.-W. L. K.-B. Sim, "Design of fuzzy controller using schema coevolutionary algorithm," IEEE Transactions on Fuzzy Sets, vol. 12, no. 4, pp. 565-570, 2004.

[107]. J. B. a. V. Z. H. Lipson, "Coevolutionary methods in systems design and analysis.," in 15th Conference International CIRP Design, Shanghai, China, 2005.

[108]. Q. He and L. W. Ã, "An effective co-evolutionary particle swarm optimization for constrained engineering design problems.," Engineering applications in Artificial Intelligence, vol. 20, pp. 89-99, 2007.

[109]. P. D. a. F. M. M. Antonelli, "Genetic training instance selection in multiobjective evolutionary fuzzy systems," IEEE Transactions on Fuzzy Sets, vol. 20, no. 2, pp. 276-290, 2012.