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# Anti-lock Braking System Control Based on Fuzzy Logic

## Fuzzy logika alapú blokkolásgátló fékrendszer vezérlése

Nurlybek Shamshiden*, Sinan Koçak**
*Institute of Mechatronics and Vehicle Engineering, Óbuda University, Budapest, Hungary
**Doctoral School on Safety and Security Sciences, Óbuda University, Budapest, Hungary
shamshidenn@gmail.com, sinan.kocak@bgk.uni-obuda.hu

***Abstract*—Safety driving systems of the vehicles such as Anti-lock Braking System (ABS) assists drivers to control automotive to safe from road accidents. It is possible to reduce these accidents with proper calculations. The traditional ABS method used is reliable, but it can be developed using different techniques. In this article, fuzzy logic-controlled ABS is implemented to improve braking performance and directional stability by comparing five different defuzzification techniques. In the Fuzzy Logic Toolbox of the MATLAB package program, remarkable results have been obtained by using Centroid (COG), Bisector, Mean of Maxima (MoM), Largest of Maxima (LoM), and Smallest of Maxima (SoM) defuzzification methods.**

***Keywords***: Fuzzy logic, Anti-lock braking system, defuzzification

### 1 INTRODUCTION

Nowadays, the anti-lock brake system (ABS) has become standard in many new model vehicles. This intelligent automobile braking system provides the tires to maintain traction on the road surface while braking. Thus, it importantly prevents the car from skidding and locking the wheels.

In the late 1920s, the automobile and aeronautical engineer Gabriel Voisin first implemented ABS for an airplane with limited technology. Once the ABS brakes placed on the aircraft, the break performance increased by 30%. Moreover, the airplane tires were not burned or burst as a result of braking[1].

In the 1960s, a full-mechanical ABS built in the high-performance cars Jensen FF, the Ferguson P99, and an experimental all-wheel-drive Ford Zodiac. However, the system proved expensive and ineffective [1].

In 1978, Robert Bosch company was the first world company to launch the ABS with electronic control, and it slowly became standard equipment in all vehicle segments [2]. Moreover, ABS was listed as a first the first active safety system. In 1986, based on the ABS platform, it was followed by the Traction Control System (TCS), and in 1995, Robert Bosch developed the Electronic Stability Program (ESP) [3].

Today, electrical-controlled brake systems are well developed safe brake systems that minimize the braking distance and provide more excellent vehicle controllability. In a vehicle equipped with ABS, the control unit continually evaluates the speed of all wheels [4]. The ABS brake system has sensors that detect each wheel's rotational speed that provides a safe drive by automatically activating when the brake pedal is pressed suddenly, and hard. The Sensors on each wheel detect the brake pressure and transfer this information to the electrical control unit which senses when any wheel is about to lock [5]. This braking system regulates the brake pressures of all four wheels independently of each other.

The ABS execution requires some data collection operations and many uncertain parameters, such as weather, environmental conditions, road type, and friction coefficient [6]. The engineers perform different system applications and tests in the laboratories to increase safety and make a comfortable driving. Among optimal controllers, various control methods have been successfully applied for better brake performance. This article aims to address approximate reasoning rather than precise with the fuzzy logic approach for controlling ABS. Based on experimental calculations and rules, it will be more transparent to get data from sensors and work on pumps and valves. A detailed fuzzy logic controller provides more advantages among other used methods in ABS [7].

In this paper, the authors described ABS's principle, the reason for using fuzzy logic, and compared the traditional five different types of defuzzification methods. The defuzzification methods of Centroid (CoG), Mean of Maxima (MoM), Largest of Maxima (LoM), and Smallest of Maxima (SoM) are shown graphically and discussed in detail, respectively.

### 2 ANTI-LOCK BRAKING SYSTEM PRINCIPLE

A typical ABS consists of a central microprocessor, four-wheel speed sensors (one for each wheel), and two or four hydraulic or pneumatic valves in the brake control circuit. The Control unit always analyses the wheel's rotational speeds; if the wheel rotates slower than the vehicle, it sends a signal to release valve pressure.

A classified ABS is according to the number of sensors and brake types used or channel numbers. There are different types of anti-lock braking system:

- one channel, one sensor,
- two channel, four sensors,

- three channel, tree sensors,
- three channel four sensors,
- four channel, four sensors.

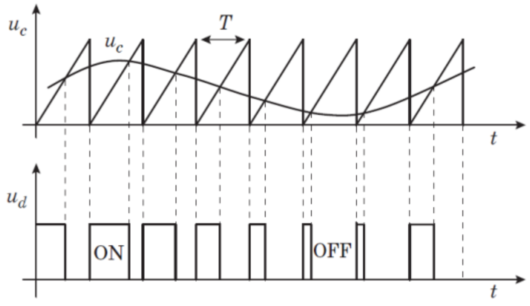
The number of valves and channels used are the same. Accordingly, one channel means one valve for all wheels, four channels - four valves for each-wheel. however, ABS sensors and valves may be in different numbers. The four-channel system is the most advantageous. In this case, each wheel has its sensor, and the computer controls each separately.

The Speed sensors measure the speed of each wheel and work on the principle of electromagnetic induction. The gear rotor at the wheel hub rotates with the wheel. The rotor teeth, passing through the sensors magnetic field, generate an electrical signal, and the frequency of the signal changes directly proportional to the wheel speed.

The ECU is an electronic control unit that receives, filters, and amplifies sensor signals to calculate the wheels rotational speed and acceleration. The electronic control unit receives signals from the sensors in the circuit and controls the brake pressure according to information unit [8].

The brake controller generates a pulse width modulated (PWM) control inputs to each brake's solenoid valve due to the estimated wheel slip ratio function. Compared to conventional on-off control inputs in the brake system, PWM control inputs significantly reduce vibration [9]. The PWM scheme uses high-frequency periodic signals with period T to be the carrier wave and determines the duty ratio defined as the on-off period ratio [10]. In Figure 1, a sawtooth signal PWM) is used to control the valves.

The hydraulic braking system and microprocessor create some time delay; therefore, to calculate the error, it is not correct to use the slip coefficient value obtained at the systems output. It is necessary to predict the future value of the slip coefficient in real-time, and it is used to control the error [10].




1. figure: Using PWM

## 3 FUZZY LOGIC APPROACH

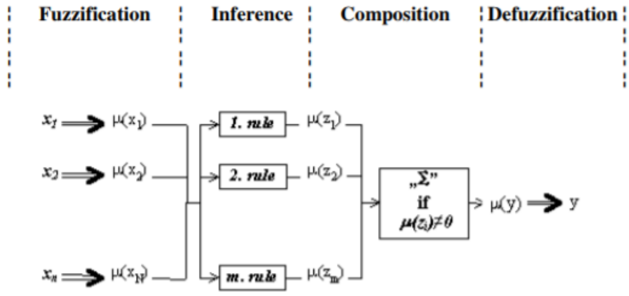
In 1965, Lotfi Askar Zadeh, a professor of electrical engineering at the University of California, was the first person who presented a new theory of Fuzzy Sets and Systems [11]. Based on another Zadeh's paper on fuzzy algorithms for complex systems and decision processes published in 1973, Ebrahim Mamdani has proposed fuzzy inference methodology. This method was first methodology built using fuzzy set theory. The paper was published in 1975 in international journal [12].

Since its launching in the 1970s, journal of fuzzy sets theory has advanced in various ways and many disciplines. At present, many applications using the fuzzy set theory in artificial intelligence, computer science, control engineering, robotics, decision theory, expert systems, logic, management science, operations research, pattern recognition, and medicine, etc [13].

The fuzzy Logic theory is the best approach for precise control, and thousands of methods are used to achieve maximum efficiency. In general, fuzzy logic can be characterized as multi-valued logic with distinguished characteristics that aim to model the phenomenon of uncertainty and some parts of the natural language meaning via a graded approach [14] [15].

The fuzzy sets is a generalization of the classical set theory that provides invaluable flexibility for reasoning by introducing the concept of a degree in verifying a condition, thus ensuring that a situation is in a state other than true or false, making it possible to consider inaccuracies and uncertainties.

Figure 2. shows a fuzzy decision-making process, gradually fuzzification, inference, composition, and defuzzification.



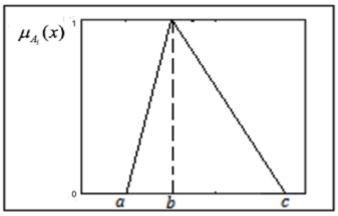

2. figure: Traditional fuzzy process flow-chart [16]

### 3.1 Fuzzification

Fuzzification is the process of making a crisp quantity fuzzy [17]. The input variables value is determined corresponding to the membership function range (0-1) for crisp value [18]. In this article, triangle membership functions used which defined by three different parameters specified as a, b, c,

$$\mu_{A_i}(x) = \begin{cases} 0 \quad if \quad x \le a_i \\ \dfrac{x-a_i}{a_i-b_i} \quad if \quad a_i \le x \le b_i \\ \dfrac{c_i-x}{c_i-b_i} \quad if \quad b_i \le x \le c_i \end{cases} \cdot \tag{1}$$

The membership function shape of the triangle is shown in figure 2.




3. figure: Fuzzification of triangle-shaped membership function

### 3.2 Inference

The experts use knowledge to perform deductive reasoning. When membership functions and commands have ruled, it is desirable to deduce or infer a conclusion [8].

The most common way to represent human knowledge is to form it into natural language expressions of the type IF premise (antecedent), THEN conclusion (consequent).

This expression based on the IF-THEN rule is often called deductive form. Typically, if the premises (antecedent) are known, this refers to an inference that can infer or derive another fact called a conclusion (consequent).

For example, let the parameters of inputs be $x_1$, $x_2$, …, $x_n$, the output is $y$, and the structure of the rules are [19],

$$\text{IF } x_1 \text{ is } A_{1,i_1} \text{ and} \dots \text{and } x_n \text{ is } A_{n,i_n},$$

$$\text{THEN y is } Y_{i_1,\dots,i_n}. \tag{2}$$

where $A_{k,ik}$ is the premise $i_k$ belonging to the input $k$, $Y_{i1,\dots,in}$ is the fuzzy rule consequence, $i_j=1..n_j$, $n_j$ is the number of the premise sets belonging to the input j.

### 3.3 Composition

The composition sub-process is the firing strength calculation—three different operators into account, respectively, which are suitable for the case study.

First, t-norm AND (3) operator should use for the data combination based on the rule antecedent.

$$w_i = \min\left(\mu_{A_{i,j}}(x)\right) \tag{3}$$

Second, the implication process, the consequent set of data combinations should be projected for each rule. The minimum (4) operator used for implication.

$$y_{B_i} = \min\left(w_i, \mu_{B_i}(x)\right) \tag{4}$$

where $w_i$ is the firing strength of rule $i$ and $\mu_{Y_i}$ is the consequent set belonging to rule $i$.

The last is the aggregation process that combines obtained values from each rule results. The maximum (5) operator applied for the final step for composition.

$$y = \max\left(y_{B_i}\right) \tag{5}$$

where $y_{B_i}$ is the sub-conclusion for rule i.

### 3.4 Defuzzification

In fuzzy inference systems, the defuzzification sub-process transitions from the output linguistic variables membership function to its exact (numeric) value.

The purpose of defuzzification is to accumulate the results of all output linguistic variables and get the quantitative value of each of the output variables, which may be used by the control actuators external relation to the fuzzy inference system. There are many defuzzification methods applied to get fuzzy results from the operating system. However, this paper considers five different defuzzification method for better ABS performances.

*A. Centroid/Center of Gravity (CoG) Method*

Centroid widely used fastest defuzzification method is also called to as the Center of gravity (COG) method. It is a basic general defuzzification method that computes the center of gravity of the area under the membership function [20].

This method calculated by the following formula:

$$y = \frac{\int_{\min}^{\max} x\mu(x)dx}{\int_{\min}^{\max} \mu(x)dx} \tag{6}$$

where the variable y is the result of defuzzification; x is the variable corresponding to the output linguistic variable and taking values from x = min to x = max; min and max - left and right point of the interval of the carrier of a fuzzy set; μ(x) is the membership function of a fuzzy set.

*B. Bisector of Area (BoA) Method*

This method is similar to the centroid method. However, the method of bisector calculates the position under the composited curve where the areas on both sides are equal [21].

The equation defines the calculation for the BoA defuzzification method following as,

$$\int_{\alpha}^{y_{BoA}} \mu_A(y)dy = \int_{y_{BoA}}^{\beta} \mu_A(y)dy \tag{7}$$

where $\alpha = \min\{y \mid y \in \mu_A\}$ , $\beta = \max\{y \mid y \in \mu_A\}$ .The vertical line $y = BOA$ partitions the region between $y=\alpha, y=\beta, z=0$, and $z=\mu_A(y)$ into two regions with the same area.

*C. Mean of Maxima (MoM) Method*

This method calculates the average of those output values that have the degrees of highest membership.

The equation defines the calculation for the MoM defuzzification method following as,

$$y_{MoM} = \frac{\int_G y dy}{\int_G dy} \tag{8}$$

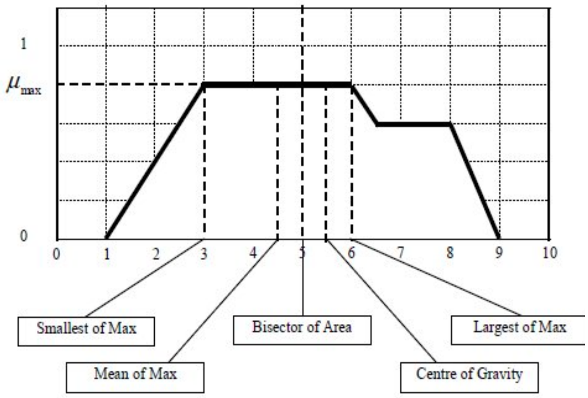
where G is the set of all elements of the interval [y, y] with the maximum degree accessories to fuzzy set y.

*D. Largest of Maxima Method*

This method determines the first maximum value of the domain that has the degrees of the highest membership.

*E. Smallest of Maxima Method*

This method determines the last maximum value of the domain that has the degrees of the highest membership.




4. figure: Result of defuzzification methods [22]

## 4 Anti-Lock Braking System Using Fuzzy Logic

*A. Structure of Fuzzy ABS model*

The proposed ABS fuzzy model has two inputs and one output, classified by speed, distance and brake. Their membership functions are explained in Table 1-2.

For speed value taken 0-80 km/h. Distance represented by 0-8 m. The output scale is 0-100 %, where 0 is the easiest braking, and 100 is the hardest braking.

1. table: Input membership functions

| | | |
|---|---|---|
| Speed [km/h] | Slowest | $\mu_{Slowst}= f$: (0,0,20) |
| | Slow | $\mu_{Slow}= f$: (0,20,40) |
| | Normal | $\mu_{Norm}= f$: (20,40,60) |
| | Rapid | $\mu_{Rapid}= f$: (40,60,80) |
| | Rapidest | $\mu_{Rapdst}= f$: (60,80,80) |
| Distance [m] | Closest | $\mu_{Closest}= f$: (0,0,2) |
| | Close | $\mu_{Close}= f$: (0,2,4) |
| | Normal | $\mu_{Norm}= f$: (2,4,6) |
| | Far | $\mu_{Far}= f$: (4,6,8) |
| | Farthest | $\mu_{Farthest}= f$: (6,8,8) |

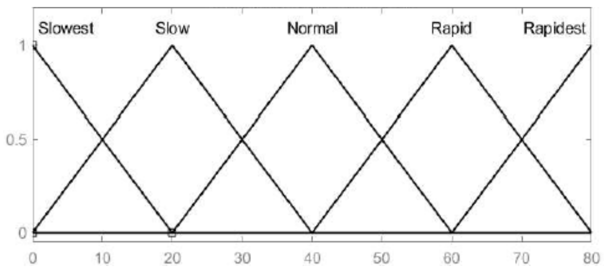
2. table: Output membership functions

| | | |
|---|---|---|
| Braking [%] | Easiest | $\mu_{Easiest}= f$: (0,0,25) |
| | Easy | $\mu_{Easy}= f$: (0,25,50) |
| | Normal | $\mu_{Norm}= f$: (25,50,75) |
| | Hard | $\mu_{Hrd}= f$: (50,75,100) |
| | Hardest | $\mu_{Hst}=f$: (75,100,100) |

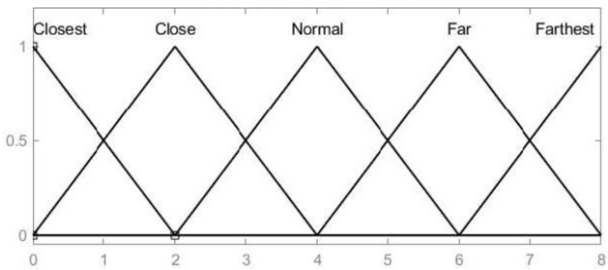
The braking membership table shows the matrix case corresponding to the 25 rules. The table is designed by accepting IF-THEN conditions to perform fuzzy logic operations and braking conditions in inference. In this design process, output conditions are defined by including each input membership functions. Triangular curves used for membership variables are given in figures 5-7.

3. table: Rule base matrix

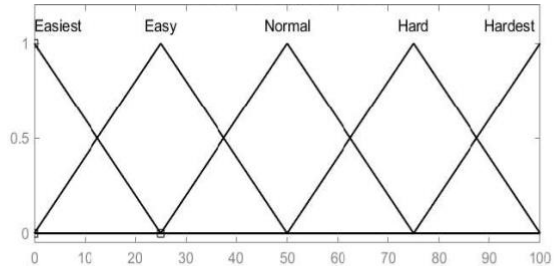
| | | **Distance** | | | | |
|---|---|---|---|---|---|---|
| | | Closest | Close | Normal | Far | Farthest |
| **Speed** | Slowest | Normal | Easy | Easiest | Easiest | Easiest |
| | Slow | Hard | Normal | Easy | Easiest | Easiest |
| | Normal | Hard | Hard | Normal | Easy | Easiest |
| | Rapid | Hardest | Hardest | Hard | Normal | Easy |
| | Rapidest | Hardest | Hardest | Hardest | Hard | Normal |




5. figure: Input variable “Speed [km/h]”




6. figure: Input variable “Distance [m]”



7. figure: Output variable "Braking [%]"

## *B. Comparison of Defuzzification Methods*

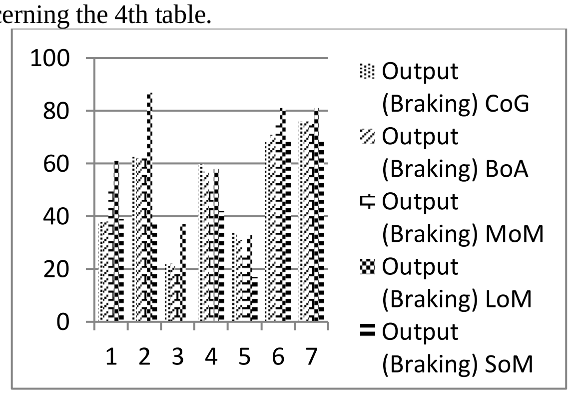
The defuzzification method's selection concludes to a large extent the 'quality' of control and the controller's computational performance. For a specific application, an appropriate defuzzification method can be selected based on control and computational performance.

Table 4 shows the consequences of a braking calculation example with different input values to compare five different methods.

4. table: Comparation of traditional defuzzification methods

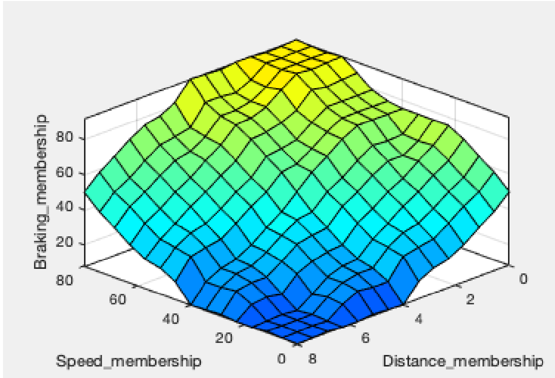
| Input | | | Output [%] | | | | |
|---|---|---|---|---|---|---|---|
| p | Speed [km/h] | distance [m] | CoG | BoA | MoM | LoM | SoM |
| 1 | 10.5 | 2.3 | 37.6 | 38 | 50 | 61 | 39 |
| 2 | 30 | 1.8 | 62.5 | 62 | 62.5 | 87 | 38 |
| 3 | 3 | 6 | 21.8 | 22 | 18.5 | 37 | 0 |
| 4 | 42.5 | 3.3 | 59.8 | 57 | 50 | 58 | 42 |
| 5 | 55.9 | 7.3 | 33.8 | 31 | 25 | 33 | 17 |
| 6 | 63 | 4.5 | 68.1 | 71 | 75 | 81 | 69 |
| 7 | 80 | 5.5 | 75.9 | 76 | 75 | 81 | 69 |

Figure 8 shows the comparison scale of the minimum and maximum variability of the defuzzification methods, which depends on the speed and distance ratio by concerning the 4th table.

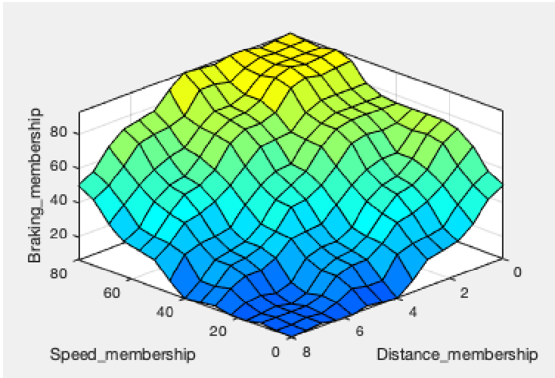



8. figure: Effect of the different defuzzification methods

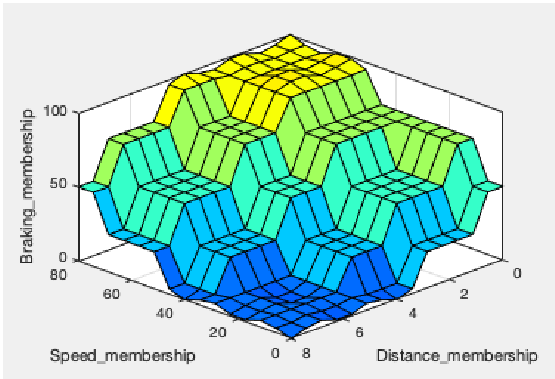
Figure 9-13 shows defuzzified surfaces of the braking p (situation number) of 4th performance, for Centroid 59.8, Bisector 57, MoM 50, LoM 58, SoM 42 by speed 42.5 km/h, and distance 3.3 m.



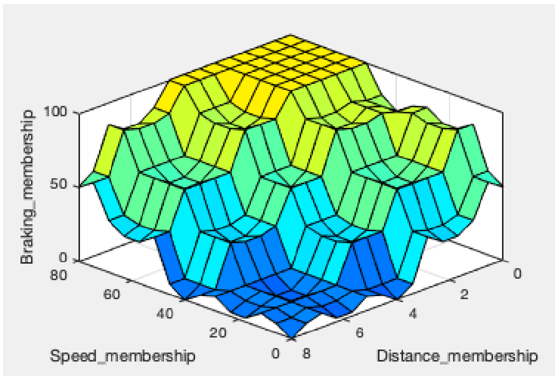
9. figure: Braking in case of Centroid method



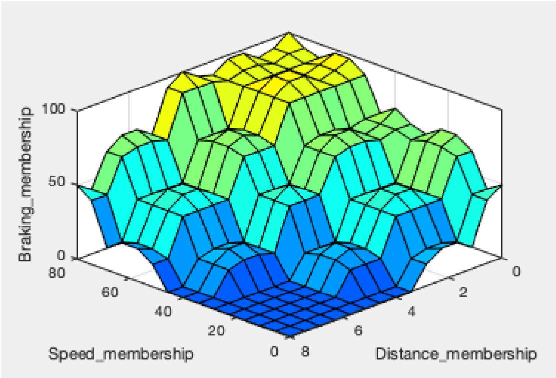
10. figure: Braking in case of Bisector method"



11. figure: Braking in case of MoM method



12. figure: Braking in case of LoM method




13. figure: Braking in case of SoM method

Based on the results, authors can make the following conclusion:

− Centroid and Bisector methods have similar performance in brake values.

− It appears that the MOM, LOM, and SOM methods are not very suitable for the application of fuzzy control.

− LOM method gives maximum results.

− SOM method gives minimum results.

As shown in the graph, analysis of the performances of the systems is not difficult to determine. The authors lean at the surface result on the top and bottom graphical model while finding minimum and maximum performance.

## 5 Conclusion

The systems creation could be complicated while modeling the system, such as mathematical, dynamic, and simulation models. In theory, any design can be seen as a straightforward type. However, in practice investigating or implementing a model could require more studies and efforts.

In this study, the authors investigated ABS performance based on fuzzy logic using centroid, bisector, MoM, LoM, and SoM defuzzification methods. The research was completed and tested with the Fuzzy Logic Toolbox on MATLAB software. The five defuzzification methods comparison results are calculated and presented in a waveform. As a result, the authors have proven that the ABS has better performance in many cases at the centroid and bisector defuzzification methods. In future studies, the authors aim to conduct additional research to improve the results of this article.

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