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# Antilock-Braking System Using Fuzzy Logic

*K. Subbulakshmi*

Department of ECE,
Bharath University, India

**Abstract:** This paper proposes an innovative way to interface the concept of FUZZY LOGIC and ABS system used (mainly in transportation and motors) and tests on an experimental car with antilock-braking system (ABS) and vehicle speed estimation using fuzzy logic. Vehicle dynamics and braking systems are complex and behave strongly non-linear which causes difficulties in developing a classical controller for ABS. Fuzzy logic, however facilitates such system designs and improves tuning abilities. The underlying control philosophy takes into consideration wheel acceleration as well as wheel slip in order to recognize blocking tendencies. The knowledge of the actual vehicle velocity is necessary to calculate wheel slips. This is done by means of a fuzzy estimator, which weighs the inputs of a longitudinal acceleration sensor and four wheel speed sensors. If lockup tendency is detected, magnetic valves are switched to reduce brake pressure. Performance evaluation is based both on computer simulations and an experimental car. To guarantee real-time ability (one control cycle takes seven milliseconds) and to relieve the electronic control unit (ECU), all fuzzy calculations are made by the fuzzy coprocessor SAE 81C99A. Measurements in the experimental car prove the functionality of this automotive fuzzy hardware system.

**Key words:** Fuzzy Logic · ABS system · Electronic Control Unit

## INTRODUCTION

Fuzzy Control, a relatively new, intelligent, knowledge based control technique performs exceptionally well in nonlinear, complex and even in not mathematically describable systems. Thus the use of fuzzy logic for an antilock-braking system (ABS) seems to be promising.

**Antilock-Braking Systems:** An anti-lock braking system or ABS is a safety system which prevents the wheels on a motor vehicle from locking up (or ceasing to rotate) while braking.The aim of an ABS is to minimize brake distance while steer ability is retained even under hard braking [1].

**Fuzzy Logic:** Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In contrast with "crisp logic", where binary sets have binary logic, fuzzy logic variables may have a truth value that ranges between 0 and 1 and is not constrained to the two truth values of classic logic. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions [2].

**Linguistic Variables:** While variables in mathematics usually take numerical values, in fuzzy logic applications, the non-numeric linguistic variables are often used to facilitate the expression of rules and facts [3].

**Need for Fuzzy Logic in ABS:** Without fuzzy ABS the braking pressure reaches a very high level and the wheels block within short. These results in an unstable behavior, the vehicle cannot be steered anymore and the stopping distance increases [4].

With fuzzy ABS controller activated, steer ability is not only retained during the whole braking maneuver, but the slowing down length was considerably shortened as well [5].

**Analysis of Antilock-Braking Systems:** The aim of an ABS is to minimize brake distance while steerability is retained even under hard braking. To understand the underlying physical effect which leads to wheel-blocking during braking, consider Figure 1a: Coefficient of friction is shown as a function of wheel slip, relating to the terms given in Figure 1b.

**Corresponding Author:** K. Subbulakshmi, Department of ECE, Bharath University, India.

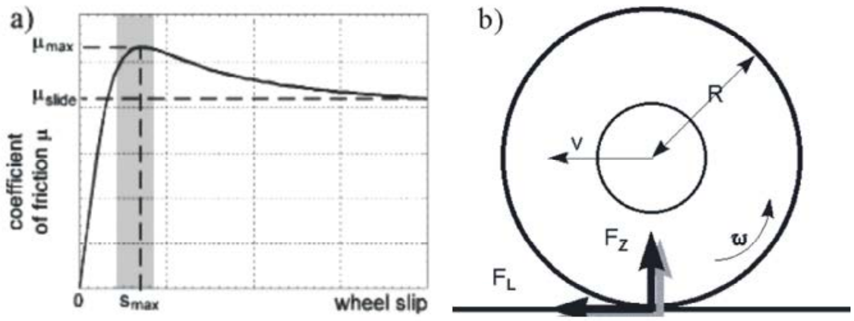



Fig. 1a,b: a) Friction characteristics, b) Wheel model

**FZ:** Wheel load
**R:** Wheel radius
**w:** Angular wheel frequency
**v:** Velocity of wheel center
**FL:** Longitudinal force

At the beginning of an uncontrolled full braking, the operating point starts at s = 0, then rises steeply and reaches a peak at $s = s_{max}$. After that, the wheel locks within a few milliseconds because of the declining friction coefficient characteristic which acts as a positive feedback. At this moment the wheel force remains constant at the low level of sliding friction. Steering is not possible any more.

Therefore a fast and accurate control system is required to keep wheel slips within the shaded area shown in Figure 1a.

**Sensors and Actuators:** This is one of the key components for the FUZZY LOGIC implementation of the ABS. The (experimental) car is fitted with sensors and actuators shown in Figure 2. Each wheel is connected to a metallic gearwheel, which induces a current within an attached sensor. The frequency of the rectangular shaped current is proportional to the angular frequency $w_{i,j}$ and can be evaluated by a microcontroller. In addition to common ABS fitted cars, a capacitive acceleration sensor for measuring the longitudinal acceleration $a_x$ is implemented [6].

Furthermore Figure 2 depicts the hydraulic unit including main brake cylinder, hydraulic lines and wheel brake cylinders. By means of two magnetic two-way valves each wheel, braking pressure $p_{i,j}$ is modulated [7].

**Three Discrete Conditions Are Possible:**

- Decrease pressure
- Hold pressure firm
- Increase pressure (up to main brake pressure level only).

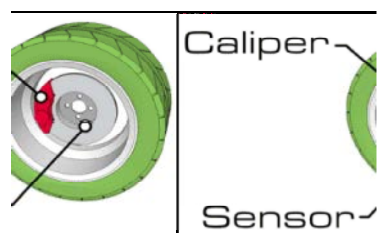
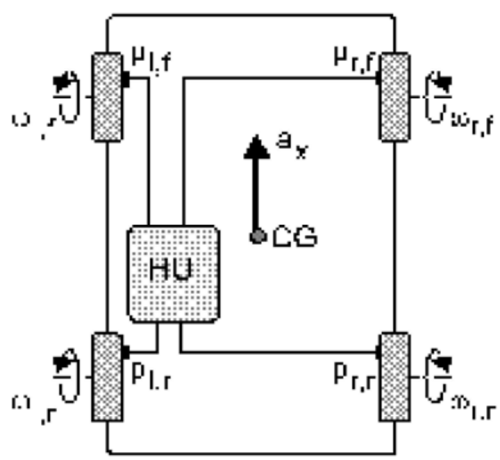



Fig. 2:

Each valve is hydraulically connected to the main brake cylinder, to the wheel brake cylinders and to the recirculation.




CG: Center of gravitiy
$a_x$: Longitudinal acceleration
$w_{i,j}$: Angular wheel frequency
HU: Hydraulic Unit
$p_{i,j}$: Wheel brake pressure
I: l=left, r=right
j: f=front, r=rear

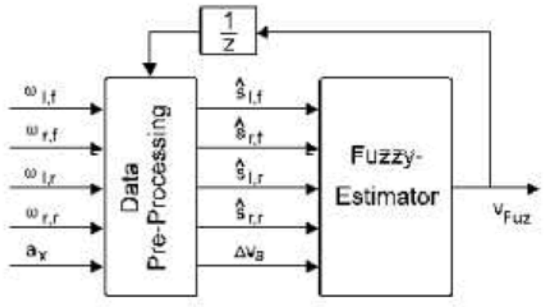



Fig. 3: Estimation of car velocity

**Estimation of Vehicular Speed Using Fussy Logic:** As described Earlier, the knowledge of the actual vehicle speed over ground is vital in order to calculate wheel slips correctly. Daiß and Kiencke presented an estimation system based on Kalman-Filter which performs well, but is not suitable because of very high performance requirements. In this approach the speed estimation uses multisensor data fusion that means several sensors measure vehicle speed independently and the estimator decides which sensor is most reliable. Figure 3 represents the schematic structure of the fuzzy estimator. The signals of the four wheel speed sensors w $_{i,j}$ are used as well as the signal of the acceleration sensor $a_x$.

In a data pre-processing block the measured signals are filtered by a low pass and the inputs for the fuzzy estimator are calculated: four wheels slip $S_{i,}\exists_i$ and an acceleration value D $v_a$. The applied formulas are:

$$S_i\exists_j(k) = \frac{v_{FUZ}(k-1) - \omega_{i,j}(k-1).R}{v_{FUZ}(k-1)}.100\%$$

$$\Delta v_a(k) = \frac{\left(a_x(k) - a_{offset}(k)\right)T}{V_{FUZ}(K-1)}.100\%$$

Where by $a_{Offset}$ is a correction value consisting of an offset and a road slope part. It is derived by comparing the measured acceleration with the derivative of the vehicle speed v $_{Fuz}$, which is calculated with the fuzzy logic system. After this subtraction, the signal is lowpass filtered to obtain the constant component $a_{Offset}$. v $_{Fuz}$(k-1) is the estimated velocity of the previous cycle. A time-delay of T is expressed by the term 1/z.

The fuzzy estimator itself is divided into two parts. The first (Logic 1) determines which wheel sensor is most reliable and the second (Logic 2) decides about the reliability of the integral of the acceleration sensor, shown in Figure 4. This cascade structure is chosen to reduce the number of rules.

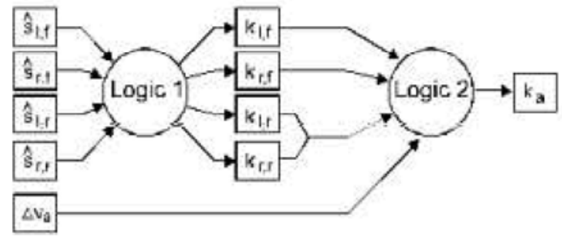



Fig. 4: Structure of the fuzzy estimator

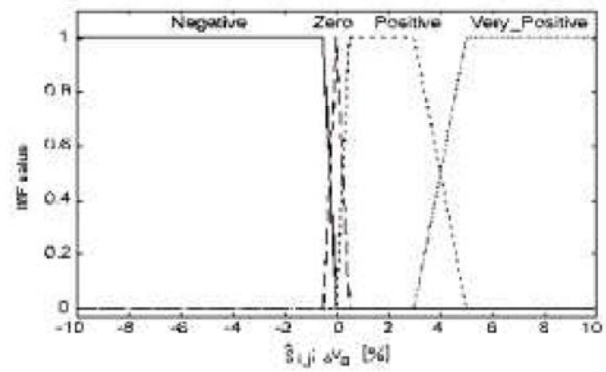



Fig. 5: Input membership functions

**Comparison of ABS with and Without Fuzzy Logic:** To classify the present driving condition vehicle acceleration is taken into consideration. This should be explained for three situations:

- D $v_a$ Positive: Braking situation, all wheels are weighted low because of wheel slips appearing.
- D $v_a$ Zero: If wheel speeds tend to constant driving the acceleration signal is low weighted in order to adjust the sensor.
- D $v_a$ Negative: The experimental car was rear wheel driven therefore rear wheels are less weighted than front wheels

Here, three linguistic values are sufficient. The output of the estimation is derived as a weighted sum of the wheel measurement plus the integrated and corrected acceleration:

$$V_{FUZ}(k) - \frac{\sum_{i=1}^{4} k_i\,\omega_i(k)\,R + k_a\left[v_{FUZ}(k-1) - Ta_{x,Corrected}(k)\right]}{\sum_{i=1}^{4} k_i + k_a}$$

**The Fuzzy-ABS Algorithm:** The input variables are transformed into fuzzy variables slip and dvwheel/dt by the fuzzification process. Both variables use seven linguistic values, the slip variable is described by the terms;

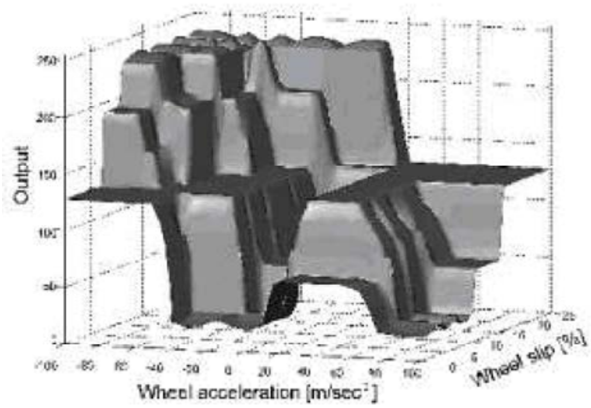



Fig. 7: Fuzzy characteristic surface

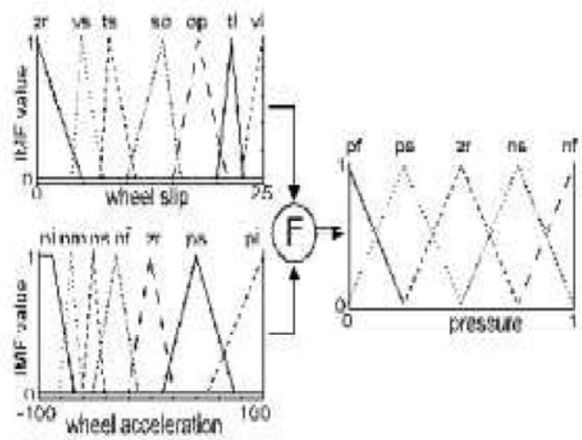



Fig. 8: Structure of fuzzy ABS controller

- slip = {zero, very small, too small, smaller than optimum, optimum, too large, very large},

and the acceleration dvwheel/dt by

- dvwheel/dt = {negative large, negative medium, negative small, negative few, zero, positive small, positive large}.

As a result of two fuzzy variables, each of them having seven labels, 49 different conditions are possible. The rule base is complete that means, all 49 rules are formulated and all 49 conditions are allowed. These rules create a nonlinear characteristic surface as shown in Figure 7.

The optimal breaking pressure results from the defuzzification of the linguistic variable pressure. Finally a three-step controller determines the position of the magnetic valves, whether the pressure should be increased, hold firm or decreased.

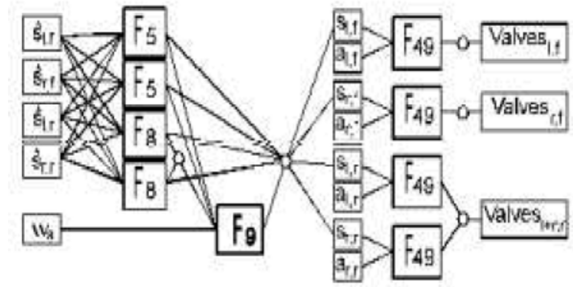



Fig. 9: Fuzzy calculations

Figure 9 summarizes the total amount of fuzzy calculations. Numbers within a rectangle indicate the quantity of fuzzy rules.

**Simulation of a Full Braking:** After implementation of the whole system in SIMULINK, a full braking on high-m -road was carried out, with and without the fuzzy ABS.

Without fuzzy ABS the braking pressure reaches a very high level and the wheels block within short. These results in an unstable behavior, the vehicle cannot be steered anymore and the stopping distance increases.

With fuzzy ABS controller activated, steer ability is not only retained during the whole braking maneuver, but the slowing down length was considerably shortened as well.

The following graphs show the steady decline of the vehicle speed, the fluctuating decline of the wheel speed of the left front wheel as an example and the fluctuating level of the wheel slip. The applied braking pressure is depicted in the last diagram. The other wheels behave approximately similar.

**Implementation of the Fuzzy ABS Controller:** The fuzzy ABS controller uses the microprocessor SAB 80C166 together with the fuzzy coprocessor SAE 81C99A [3]. Due to the implementation of Fuzzy algorithms into the hardware of the coprocessor, the calculation speed of the host processor increased significantly. While the control cycle time was set to a standard value of 7 m sec, the computation time was only 0.5 m sec! This offers facilities for implementation of extended vehicle dynamics control.

The flexibility of the coprocessor is considerable, up to 64 rule bases are possible, each of them having up to 256 inputs and rules. Furthermore an interface to most commonly used microprocessors is available. Arbitrary shapes of membership functions, different defuzzification modes including “Center of Gravity", an enormous rule engine with up to 10 million rule calculations per second makes this device a very interesting product in the field of real time fuzzy control.

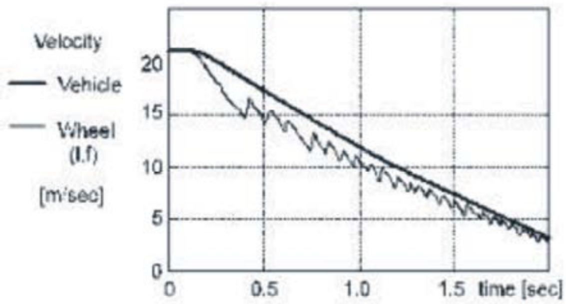



Fig. 10a: Simulations of a braking

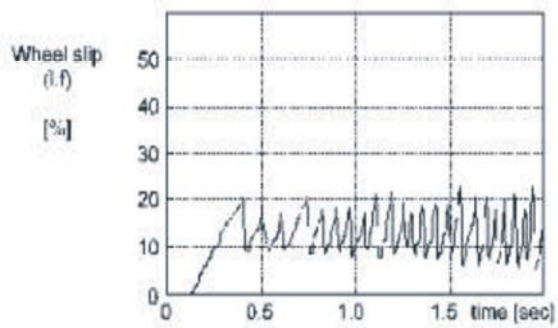



Fig. 10b: Simulations of a full braking

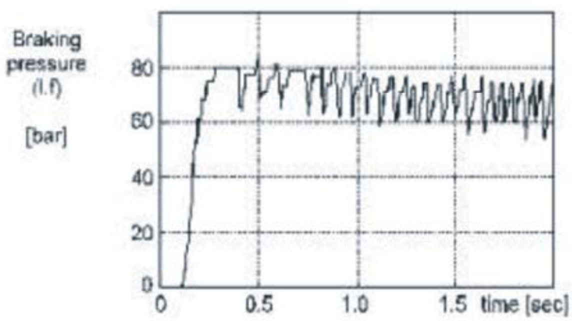



Fig. 10c: Simulations of full braking

## CONCLUSION

The basis of the controlling algorithm consists of a nonlinear characteristic surface, which was created by fuzzy logic. The convincing advantage of fuzzy logic is the ability to modify and tune certain parts of this characteristic surface easily and carefully. Just the linguistic rules or variables need to be varied. This simplifies the development and shortens the development time considerable. Implementation of the fuzzy ABS leads to excellent results of braking behavior of the test vehicle. The deceleration level and steer ability is comparable to commercially available systems. Thus the ABS with FUZZY logic will help the driver to steer while braking heavily and could prove to be lifesaving.

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