FUZZY LOGIC CONTROLLED ABS SYSTEM FOR IMPROVED BRAKING PERFORMANCE AND DIRECTIONAL STABILITY

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ABSTRACT

A fuzzy logic controlled Anti-Lock Braking System (ABS) is developed to improve the braking performance and directional stability during braking, and steering and braking maneuvers on nonuniform friction surfaces. The system consists of two controllers working in parallel. The first controller works on the longitudinal slip, and the second controller is responsible for the yaw motion control of the vehicle. The fuzzy logic controller is implemented on a four-wheel nonlinear vehicle model with nonlinear tire behavior. Simulations involving vehicles with the fuzzy logic controlled ABS and non-ABS vehicles are carried out to assess the controller performance.

1. INTRODUCTION

The ability to provide for the reduction of its speed quickly and in a stable manner is one of the vital functions of a motor vehicle. Generally, every vehicle has the means to slow down, and during normal driving operations the driver is able to manipulate the brakes to retain the safety of the vehicle. Critical conditions arise, however, when the driver is exposed to unexpected situations. A large proportion of situations threatening the safety of the moving vehicle occur while the driver tries to decelerate or stop the vehicle in an emergency situation. An emergency situation may arise during one or any combination of the following operations:

- braking on slippery surfaces,
- braking during cornering, and
- braking on a surface with different friction coefficients as seen by the right and left tires of the vehicle.

The motor vehicle is a dynamical system that can respond very quickly under certain conditions. A driver with average driving and response capabilities may be unable to react in time. This brings in the need for a reliable safety enhancing system into the view of automobile designers. Anti-Lock Braking (ABS) systems fill this need by enhancing stability and increasing braking capability of an automobile. The main objectives of the ABS are to make the vehicle stable in the conditions of braking on a straight line, braking during cornering, and braking on surfaces with different friction coefficients. Only after these objectives are achieved, attention will be paid to the rather secondary objective of reducing the braking distance.

Automobile anti-lock braking systems have appeared as the standard equipment in the last few decades. [Schürr and Dittner, 1984] developed the FAG Anti-Skid Braking system (ASBS), which was a four-sensor four-channel unit and could also be applied to drum brakes. [Newton and Riddy, 1984] studied the adoption of simpler ABS configurations to front wheel passenger cars and developed a two channel Lucas Girling Stop Control System. [Shinomiya et al, 1988] performed a study on the production of an electronic ABS system. [Oppenheimer, 1988] investigated the parameters influencing the stopping distance of passenger cars with and without slip control. [Göhring et al, 1989] illustrated in their study, the particularities of different control systems with different sensor and channel numbers. They reached the conclusion that only complex systems could achieve the demanded safety features from ABS, and cost reduction should be sought by decreasing the cost of components used to build an ABS. [Watanabe and Kobayashi, 1992], conducted a study about an accurate rule based Kalman filtering technique for estimating the absolute speed of a vehicle which was critical in determining the correct control action. [Bohman and Law, 1993] performed a study describing the simulation and evaluation of a Slip Control Braking System using a comprehensive vehicle model. [Nakazawa et al, 1995] worked on the feasibility of improving braking performance of commercial vehicles by using an electronic braking system. Their braking system enabled the braking force at each wheel to be independently controlled. [Naito et al, 1996] performed a study to develop a four-channel ABS. [Koibuchi et al, 1996] studied the improvement of vehicle dynamics in limit cornering. Their simulations and tests have verified that vehicle stability and course trace performance in limit cornering had been improved by active brake control of each wheel.

[Mauer et al, 1994] studied the means to adapt the braking pressure to changing road conditions by analyzing the relation between brake torque and slip ratio in real time. A fuzzy logic controller and a decision logic network identified the current road condition, based on current and past readings of the slip ratio and brake pressure. Recently, [Will and Zak, 2000] proposed a fuzzy logic antilock brake system for straight line braking only and compared the performance of the fuzzy logic controller with that of a manual brake system.

Most of the studies carried so far are concentrated on only the slip control aspect of the braking phenomena considering straight line braking with uniform friction surfaces. But during cornering and especially on μ-split surfaces the danger is not due to slipping of the wheels; directional control may also be lost. The controller should be able to stabilize the vehicle under these conditions, as the aim of the ABS is to make the vehicle safe during braking action. Thus a fuzzy logic controller, which consists of two controllers working in parallel, is proposed here to satisfy these requirements. The first controller works on the longitudinal slip, and the second controller is responsible for the yaw motion control of the vehicle. It is implemented on a four-wheel nonlinear vehicle model with nonlinear tire behavior. Simulations with and without the fuzzy logic controlled ABS are carried out to assess the controller performance and the results illustrate the benefits of the proposed controller.

2. MATHEMATICAL MODEL

The mathematical model for the vehicle used in this study consists of three parts; the tire model, the vehicle body model, and the fuzzy logic controller. These will be discussed briefly in the following.

Nonlinear Tire Model

In a vehicle dynamical model, tire forces result in the most significant changes in the states of the vehicle. Major errors in the simulation of the motion of a vehicle are mostly related to the errors associated with the tire model. Thus, the tire model must be accurate and reliable, covering a wide range of operating conditions. On the other hand, a realistic tire model may not be as easy to implement in the vehicle model and will require more time to run on a computer, resulting in a slower simulation. If real-time simulation is desired, this factor may turn out to be critical.

Considering these points, the tire model presented by [Allen et al, 1987] is selected for use here. Allen model is a nonlinear model taking many parameters of a tire into consideration for the calculation of lateral and longitudinal forces. The model responds realistically over the full manoeuvring range. The equations to produce the nonlinear tire forces can be generalized in the following form,

$$F_x = f(s, \alpha, F_z, \mu, ...) \quad (1)$$

$$F_y = g(s, \alpha, F_z, \mu, ...) \quad (2)$$

where F_x and F_y are the tire forces in the x and y directions, s is longitudinal slip, α is lateral slip, F_z is normal tire load, and μ is friction coefficient.

Nonlinear Vehicle Model

For automobiles, vehicle models vary from quarter car models, involving only one wheel and one-fourth of the vehicle mass, to two-wheeled bicycle model, and four-wheeled multi-body models. In this study, the behavior of the vehicle when braked during cornering will be of interest and the longitudinal, lateral, and yaw motions are all significant. Thus, a four-wheeled vehicle model is selected, Figure 1. It can simulate the behaviour of the vehicle in the longitudinal, lateral, and yawing directions resulting from the tire forces developed by the four individual tires. The lateral and longitudinal weight transfers are made closer to reality by the addition of roll and pitch motions of the vehicle caused by the lateral acceleration during cornering and acceleration.

The motion of the vehicle body is described by six states; three of which are the longitudinal velocity, lateral velocity, and yaw velocity. The remaining three states are the position variables determining the location of the vehicle on the plane of the road. Further, each wheel has a rotational degree of freedom. A detailed formulation of the vehicle model is presented by [Yazıcıoğlu, 1999]

The states of the system are changed by the external traction and cornering forces, which depend on the states of the vehicle. The independent external inputs are the steering angle of the front wheels and/or the individual wheel braking moments. The changes in longitudinal and lateral slip values trigger lateral and/or longitudinal tire forces to develop. Differing tire forces manipulate the states and changing state values in turn change the tire forces. The block diagram of this closed loop dynamical system is shown in Figure 2.

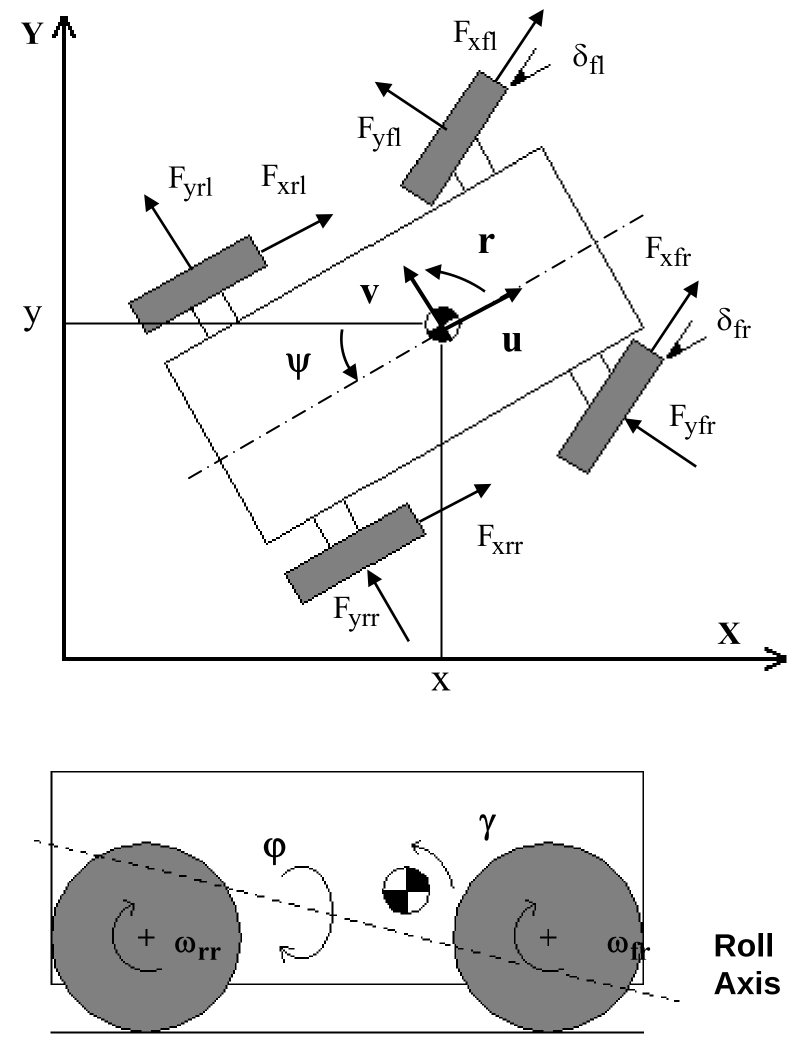

Figure 1. Four wheel vehicle model with seven degrees of freedom

The equations of motion of the vehicle may be written in the general form,

$$\dot{\underline{x}} = \underline{f}(\underline{x}, \underline{u}) \tag{3}$$

where the state and the control input vectors are given as

$$\underline{x} = [u \quad v \quad r \quad \omega_{fl} \quad \omega_{fr} \quad \omega_{rl} \quad \omega_{rr} \quad x \quad y \quad \psi]^T \tag{4}$$

$$\underline{u} = [\delta_{fl} \quad \delta_{fr} \quad M_{bfl} \quad M_{bfr} \quad M_{brl} \quad M_{brr}]^T \tag{5}$$

where u, v, and r denote the longitudinal, lateral, and yaw velocities; ω_{ij} denote the rotational speeds of wheels; x, y, and ψ are the location and direction of the vehicle body on the road surface; δ_{ij} are the steering angles of the front wheels; and M_{bij} are the individual wheel braking moments.

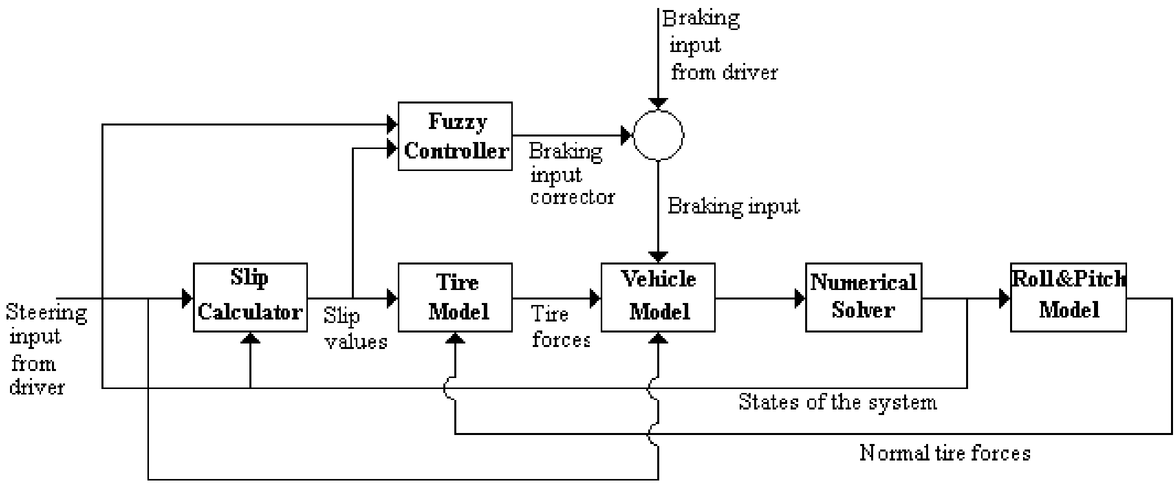

Figure 2. Block diagram of the closed loop system

The derivatives of the states can be calculated from the ten nonlinear equations, making the use of a marching numerical method possible to solve for the values of the states for the next time step. Since the nonlinearities of the functions are smooth, with the use of small time steps accurate and fast calculations can be achieved.**Fuzzy Logic Controller**

The primary objective of a slip controller is to keep the longitudinal slip values of the tires within a desired range. The maximum value of braking force is usually obtained at longitudinal slip values ranging from 0.025 to 0.125 for friction coefficient values between 0.2-1.0. However, for an anti-lock braking system control of longitudinal slip is not the only problem. The cornering force, which is the main factor for cornering ability for the vehicle, depends on the longitudinal slip ratio besides the lateral slip angle. A small amount of increase in longitudinal slip results in a very steep decrease in lateral force generating ability. Thus the cost of a small improvement in braking distance may be a large reduction in the directional control of a vehicle. Usually the ability of changing direction provides a better advantage in emergency situations, than ability to stop in a shorter distance. Obviously, proper use of both is the best and this is possible through the use of an ABS, which does not merely control the longitudinal slip for stopping distance but also cares for increasing the cornering ability.

To realize all these improvements to the vehicle dynamical system, a fuzzy logic controller that consists of two controllers working in parallel is proposed, Figure 3. The first controller works on the longitudinal slip input and according to the estimated coefficient of friction. It gives out a correction value to the braking moment input that the driver applies by the brake pedal. The second controller is responsible for the yaw motion control of the vehicle. The yawing position of a vehicle may change under the effect of different friction coefficients available for the left and right wheel pairs. The driver may not be able to control this motion due to the large force difference between the two sides of the vehicle. Operating on the sideslip angle, β, the second controller gives out another correcting moment on top of the correcting moment by the first controller. The combination of the two single input-single output sub controllers, results in a double input-single output overall controller. The output of the controller is converted to the rate of change of the braking moment. The current brake force is modified with this value at each time step of the controller. The dynamical behaviour of the braking system is neglected. It is assumed that the output command of the controller is physically realizable.

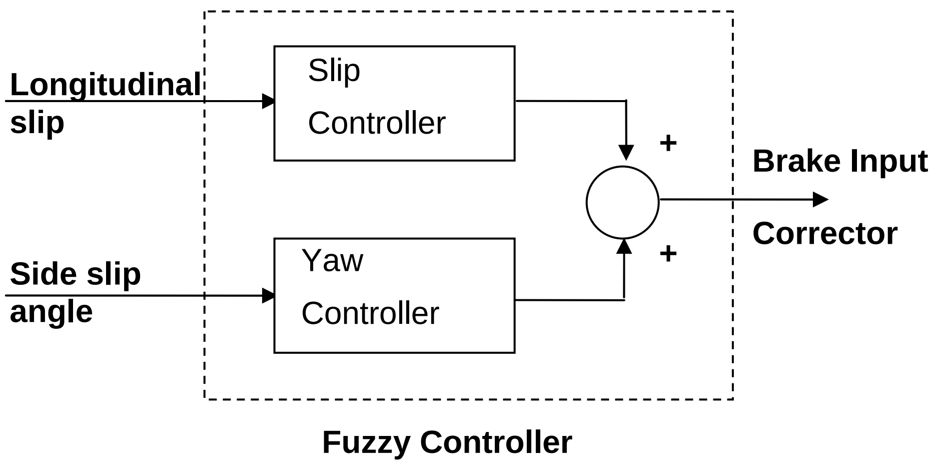

Figure 3. Fuzzy controller

The input and output variables of the slip and yaw controllers have five membership functions (triangular and trapezoidal) each, as shown in Figures 4 and 5, respectively. Throughout the implementation phase, the fuzzy toolbox of Matlab is used. The Mamdani fuzzy inference method is implemented in the fuzzy toolbox of Matlab. The defuzzification is performed by the “centroid method”.

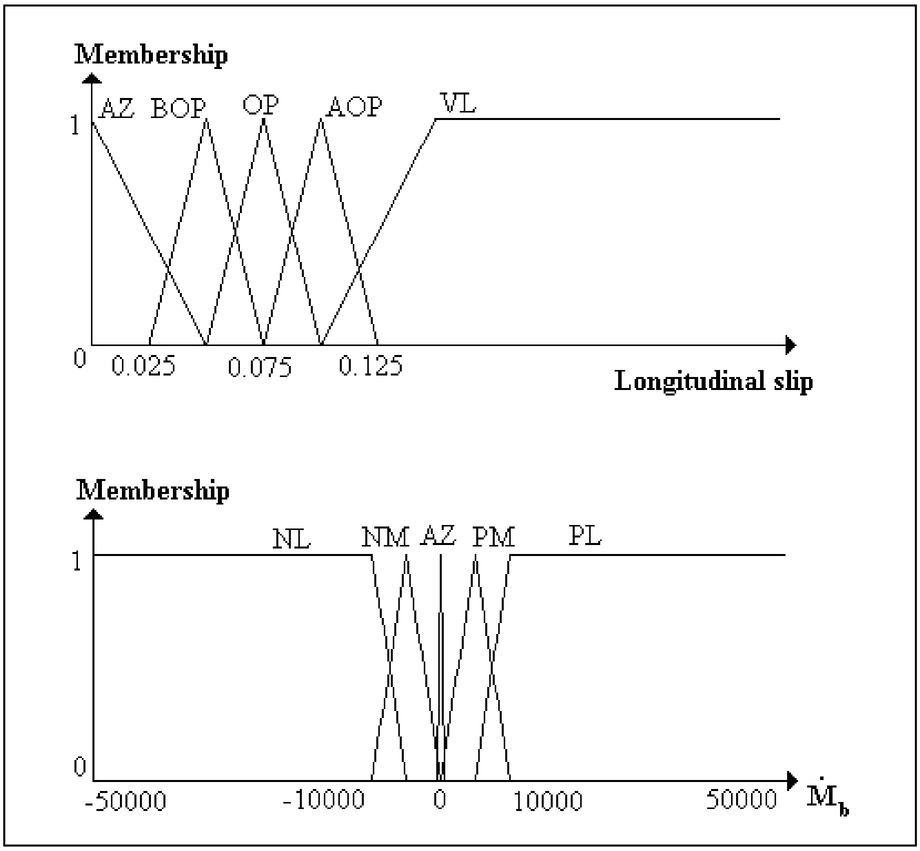

Figure 4. Membership functions for the slip controller

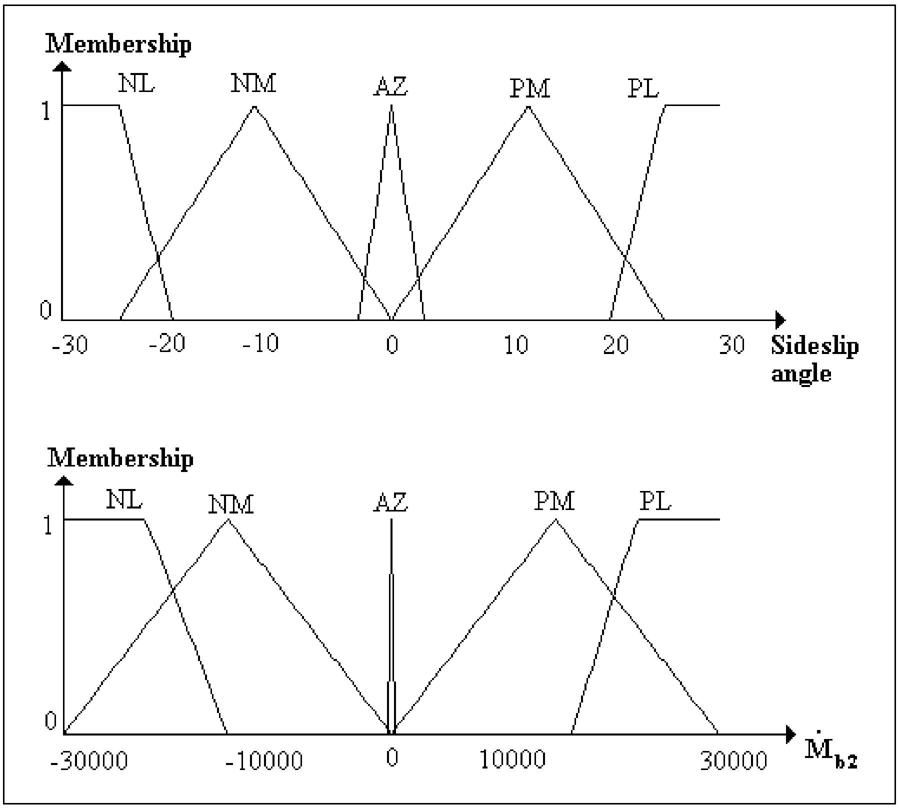

Figure 5 Membership functions for the yaw controller

Friction coefficient range, from 0 to 1.2, is divided into three zones namely, dry, wet, and ice for the friction coefficient ranges of 0 to 0.3, 0.3 to 0.7, and 0.7 to 1.2, respectively. For each zone, a different set of membership functions drive the slip controller. The sideslip angle controller uses the same membership function ranges for μ-split conditions. The road condition is made up of different coefficients of nominal friction values at the left and right sides of the vehicle. This difference results in different braking forces on each side of the vehicle, putting a yaw moment on the vehicle.

The rules operating the slip controller are as follows:

1. If longitudinal slip (S) is very large (VL), then rate of change of braking moment ($\dot{M}_b$) is negative large (NL).
2. If longitudinal slip (S) is approximately zero (AZ), then rate of change of braking moment ($\dot{M}_b$) is positive large (PL).
3. If longitudinal slip (S) is optimum (OP), then rate of change of braking moment ($\dot{M}_b$) is approximately zero (AZ).
4. If longitudinal slip (S) is below optimum (BOP), then rate of change of braking moment ($\dot{M}_b$) is positive medium (PM).
5. If longitudinal slip (S) is above optimum (AOP), then rate of change of braking moment ($\dot{M}_b$) is negative medium (NM).

The rules operating the yaw controller are as follows:

1. If sideslip angle (β) is negative large (NL), then rate of change of braking moment for yaw control ($\dot{M}_{b2}$) is negative large (NL).
2. If sideslip angle (β) is negative medium (NM), then rate of change of braking moment for yaw control ($\dot{M}_{b2}$) is negative medium (NM).
3. If sideslip angle (β) is approximately zero (AZ), then rate of change of braking moment for yaw control ($\dot{M}_{b2}$) is approximately zero (AZ).
4. If sideslip angle (β) is positive medium (PM), then rate of change of braking moment for yaw control ($\dot{M}_{b2}$) is positive medium (PM).

5. If sideslip angle (β) is positive large (PL), then rate of change of braking moment for yaw control ($\dot{M}_{b2}$) is positive large (PL).

The controller first checks if the brake is applied. If it is not, zero output is produced. Then for each wheel the lock condition is checked. Lock condition takes place if longitudinal slip value exceeds a predetermined value. If a wheel locks first, the correcting moment for the slip controller is evaluated by using the longitudinal slip ratio at that wheel. After that, vehicle sideslip angle is checked for its sign and value. If absolute value of sideslip angle is above a predetermined value, the correcting moment from the yaw controller is calculated by using the sideslip angle. If that wheel is not locked, then both of the correcting moments are zero. Then, the corrections are imposed on the driver's braking input.

$$M_{b_{n+1}} = M_{b_n} + \dot{M}_{b1_n}\Delta t + \dot{M}_{b2_n}\Delta t \tag{6}$$

Estimation of Unmeasured States

Ordinarily, the only measured state is the velocity of the vehicle. For vehicles with slip control systems, this information may be used together with the peripheral acceleration of wheels to have an idea of the amount of longitudinal slip. This procedure is known, however, to give poor results. A better implementation is to install accelerometers on the vehicle, to measure the longitudinal, lateral, and yawing accelerations. The noise in the measured data may cause problems, but by appropriate filtering techniques accurate results may be obtained with current technology, [Watanabe and Kobayashi, 1992], and [Best et al, 2000]. If the measured longitudinal, lateral, and yawing accelerations at time step n are P, Q, and R, the accelerations can be calculated from

$$\dot{u}_n = P_n + v_n r_n \tag{7}$$

$$\dot{v}_n = Q_n - u_n r_n \tag{8}$$

$$\dot{r}_n = R_n \tag{9}$$

Then the values of the longitudinal, lateral, and yaw velocities at time step n+1 may be calculated numerically.

$$u_{n+1} = u_n + \int \dot{u}_n dt \tag{10}$$

$$v_{n+1} = v_n + \int \dot{v}_n dt \tag{11}$$

$$r_{n+1} = r_n + \int \dot{r}_n dt \tag{12}$$

Since the rotational velocities of the wheels are directly measured, the rest of the variables can be calculated by the controller circuit in real time. The approximate friction coefficient may also be found by simply normalizing the longitudinal acceleration by the gravitational acceleration

$$\mu_{nom} = \frac{P}{g} \tag{13}$$

3. SIMULATION RESULTS

To assess the performance of the fuzzy logic controller, three different braking modes are considered:

- Braking without steering,
- Both steering and braking, and
- Braking on a μ-split surface.

Simulations are carried out, first for an automobile with conventional (non-ABS) brakes, and then for the same vehicle equipped with the fuzzy logic controlled ABS.

Three kinds of road surfaces, i.e., dry, wet, and ice with nominal coefficient of friction values 0.85, 0.5, and 0.15, respectively, are considered. For the dry and wet surface conditions, the initial velocity is taken as 100 km/h. For icy road surface, the initial speed is reduced to 50 km/h. A total braking torque of 3000 Nm is applied as a step input, which can quite closely mimic the conditions during an emergency situation. The initial braking torque distribution is taken as 70 % for the front and 30 % for the rear wheels. The reference values for the longitudinal slip ratios are pre-specified as 0.075. When steering is involved, the steering angle of the front wheels is taken to be 2°.

The results obtained from the tests on the vehicle without the ABS and with the fuzzy ABS taken into consideration are summarized in Table 1.

For wet and icy road conditions the results will not be better than the dry condition, so the simulations were not carried out. The results on the dry road will be more optimistic than those on other road surfaces.

This simulation is important because it shows the results of the ability of the vehicle to gain lateral deflection during maximum deceleration. Slowing down to a safer speed than the initial speed is also important because other unwanted situations may occur after the first obstacle is cleared. Both of the steering and braking actions must take place for safer results.

Table 1. Simulation results

	W/O ABS		**FUZZY ABS**	
SMB	Vehicle stopped with all wheels locked immediately		Vehicle stopped with oscillating manipulated input until 1 s.	
	x (m)	49.84	**x (m)**	45.32
B&S	Vehicle stopped with all wheels locked. Could not be steered. Went straight on.		Vehicle stopped while it was possible to steer with a small sideslip angle.	
	x (m)	49.84	**x (m)**	47.73
	y (m)	0.06	**y (m)**	3.42
	ψ (°)	0.73	**ψ (°)**	13.98
	$\|\beta\|$ (°)	~0	**$\|\beta\|$ (°)**	< 1
μSP	Vehicle spun out before 1 s has passed when u=17.37 m/s (62.5 kph)		Vehicle stopped without spinning out with a small deflection. Can be recovered.	
	x (m)	21.46	**x (m)**	51.09
	y (m)	0.02	**y (m)**	1.26
	ψ (°)	30.17	**ψ (°)**	4.54
	$\|\beta\|$ (°)	-30	**$\|\beta\|$ (°)**	< 1

4. CONCLUSIONS

In most of the accidents, an obstacle appears in front of the vehicle and the driver has to take action after recognizing the danger. This action depends on many parameters such as the distance between the vehicle and the obstacle, the state of the other lanes - being occupied or not -, the condition of the road surface, etc. The vehicle without an ABS is safe only when there is sufficient clearance before the obstacle, the road is straight, and the coefficient of friction is the same for the left and right side of the vehicle. If any of these conditions do not apply, the passengers inside the vehicle may encounter dangerous situations.

The tuning of ABS leads to a compromise between the stopping distance and lateral displacement ability. An anti-lock controller designed for minimizing braking distances may perform poorly in steering.

During straight motion braking, there is a 10 % difference in the braking distances favoring the vehicle with the fuzzy logic controlled ABS. Further, the lateral stability of the vehicle with fuzzy ABS is better, because all the wheels of the vehicle without ABS are locked.

For the case of braking and steering at the same time (B&S), the results indicate a definite improvement with the use of the fuzzy ABS. The vehicle with the fuzzy ABS safely and stably stops in a shorter distance than the vehicle without ABS and also is able to displace from its initial line of travel at an amount, which is equal to more than a lane's width. Due to the present sideslip controller its sideslip angle, β, is kept very small.

When the vehicle has to slow down on a road with different friction coefficients on the right and left sides, the vehicle without ABS is in a dangerous situation. This vehicle immediately loses its stability giving no chances to the driver to counter steer to retain the stability of the vehicle. This may sometimes be a more dangerous condition than actually hitting the obstacle. When it comes to the vehicle with the sideslip controlling fuzzy ABS, as soon as the driver steps on the brakes, the controller takes control of the situation and helps the vehicle stop with a smooth deceleration and a controllable and small deflection from its initial course.

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