RESEARCH NOTE

DESIGNING A GENETIC-FUZZY ANTI-LOCK BRAKE SYSTEM CONTROLLER

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(Received: March 12, 2003– Accepted in Revised Form: Aug. 5, 2005)

Abstract ***Anti-lock braking systems (ABS) have been developed to reduce tendency for wheel lock and improve vehicle control during sudden braking especially on slippery road surfaces. The objective of such control is to increase wheel tractive force in the desired direction while maintaining adequate vehicle stability and steerability and also reducing the vehicle stopping distance. In this paper, a genetic-fuzzy ABS controller is designed. The objective function is defined to maintain wheel slip to a desired level so that maximum wheel tractive force and maximum vehicle deceleration are obtained. All parameters of membership functions and rules of the fuzzy system that is Takagi-Sugeno-Kang (TSK) type are obtained using a genetic algorithm. Simulation results show very good performance of the controller for different road conditions.***

Keywords ***Anti-lock braking system (ABS), genetic-fuzzy controller, vehicle model.***

چکیده یکی از زمینه های تحقیق فعال در صنعت خودرو، ترمز بموقع و بدون انحراف خودرو در تمامی سرعت ها و شرایط مختلف جاده ها می باشد. لذا نصب یک سیستم ایمنی نظیر سیستم ترمز ضد قفل (ABS) امروزه به عنوان یک سیستم ضروری در خودروها مطرح است. تجهیز خودروها به این سیستم باعث حفظ فرمانپذیری و پایداری خودرو بویژه در جاده های لغزنده می گردد. در این مقاله یک کنترل کننده فازی- ژنتیکی برای سیستم ترمز ضد قفل طراحی می گردد. کنترل کننده فازی از نوع TSK می باشد که تمام پارامترهای توابع عضویت و قوانین آن توسط روش ژنتیک با بهینه نمودن تابع هدفی که لغزش چرخ را در گستره مطلوبی قرار دهد و شتاب توقف خودرو را ماکزیمم نماید حاصل شده است. نتایج شبیه سازی نشان دهنده عملکرد بسیار خوب این کنترل کننده در شرایط مختلف جاده می باشد.

1. INTRODUCTION

When braking force is applied to a rolling wheel, it begins to slip; that is, the wheel circumferential velocity (V_w) will be less than the vehicle velocity (V_v). Slip (λ) is defined as the difference between vehicle velocity and wheel circumferential velocity, normalized to vehicle velocity:

$$\lambda = \frac{V_v - V_w}{V_v} \quad (1)$$

If sufficient braking force is applied, wheel slip and wheel acceleration will increase and the wheel will lock up. A locked wheel has no lateral stability. The relation between slip, vehicle velocity, and the coefficient of friction (μ) is complicated and changes with different road conditions, different vehicle speeds, and tire types. Figure 1 shows typical lateral and longitudinal coefficients of friction as a function of wheel slip [1].

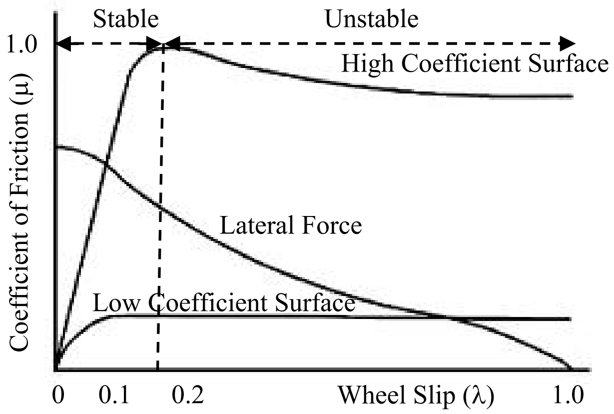

Figure1. Coefficient of friction versus wheel slip

The lateral coefficient of friction is greatest at zero slip and decreases as wheel slip increases. Lateral friction provides lateral stability, the ability to steer and control the direction of the vehicle. The longitudinal coefficient of friction is zero at zero slip and for most road conditions, as wheel slip increases, it increases to a point (peak value) where μ start to decrease as slip increases. If braking force is not quickly reduced at this point, the reduction in road force leads to a rapid increase in slip and eventual lockup. Anti-lock brake systems sense this point and reduce braking force so that lockup is avoided and provide adequate vehicle stability and steerability, passengers' safety, and also reduce the vehicle stopping distance. It would appear that maintaining wheel slip at the value of λ that gives the peak value of μ would be ideal. Unfortunately, the position of the peak varies for different road conditions, different vehicle speeds, and tire types. Most control strategies define their performance goal as maintaining slip near a value of 0.2 throughout the braking trajectory. This represents a compromise between lateral stability, which is best at zero slip and maximum deceleration, which usually peaks for some value of slip between 0.1 and 0.3. The goal of ABS control is to maintain wheel slip to a known and desired level. The ABS must handle external disturbances such as variations in the adhesive force between the road and tire due to changes in road conditions, loading, steering, and variations in the frictional force due to irregularities in the road surface.

Application of ABS has been a great improvement in the automotive industry. Types of the first ABS, due to high cost has been used in airplane to reduce the braking distance. A review of ABS research and development are presented in [2]. Up to now, various control techniques have been developed [3-6] which maintain the wheel slip to a desired level. Some of approaches which are proposed to design the ABS controller consist of sliding mode, fuzzy, fuzzy-neural, fuzzy-sliding mode, fuzzy-neural sliding mode, and hybrid controllers. Some of these methods have not shown proper performance for different road conditions.

In this paper, a genetic-fuzzy ABS controller according to Figure 2 is designed such that the input variables to the controller are obtained by wheel speed and vehicle acceleration sensors. All parameters of membership functions and rules of the fuzzy system that is Takagi-Sugeno-Kang (TSK) type are obtained using the genetic algorithm. The objective function is defined to maintain wheel slip to a desired level so that maximum wheel tractive force and maximum vehicle deceleration are obtained. Performance of the proposed controller is tested on a vehicle model with effect of dynamic load transfer from the rear axel to the front axle, with the hydraulic brake system, for different road conditions, and different reservoir and pump pressures. Simulation results, that are verified through several numerical simulations using Matlab/Simulink, show very good performance of the controller for different road conditions and wheel slip is kept to the desired level.

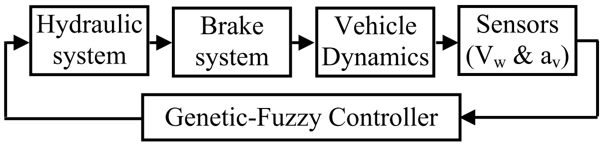

Figure 2. Block diagram of the proposed ABS

2. VEHICLE DYNAMICS

The vehicle dynamic model is dealing with the movements of vehicles on a road surface. The movements of interest are acceleration, braking, ride, and turning. Dynamic behavior is determined by the forces imposed on the vehicle from the tires, gravity, and aerodynamics. A simplified longitudinal vehicle model consists of vehicle/tire/road dynamics and hydraulic brake system dynamics by neglecting lateral vehicle dynamics is described in this section [7-10].

2.1 Vehicle / Tire / Road Dynamics Figure 3 shows the simplified model of vehicle/tire/road dynamics which contains one wheel rotational dynamics, linear vehicle dynamics, and the interactions between them [7]. Suspension and steering system dynamics are not considered. A list of variables and parameters used in this paper is given in Table 1.

According to Figure 3, the rotational dynamics of the i-th wheel (i = 1,...,4) and the linear vehicle dynamics are given by the following differential equations:

$$J_w\dot{\omega}_{wi} = T_{ei} - T_{bi}sign(\omega_{wi}) + R_wF_{ti} - T_{wi} - B_w\omega_{wi} \quad (2)$$

$$M_v\dot{V} = -\sum_{i=1}^{4} F_{ti} - F_v \quad (3)$$

Engine torque at the i-th wheel is assumed to be zero during braking and the moment of inertia of rotating parts referred at the wheel is considered to be constant. Torque due to wheel friction (T_w) and force due to vehicle friction (F_v) are described as follows:

$$T_{wi} = R_w B_r N_{vi} \quad (4)$$

$$F_v = F_a + B_r N_v \quad (5)$$

Tire traction force is a function of normal force at tire/road contact and road/tire adhesion coefficient.

$$F_t = \mu N_v \quad (6)$$

Normal forces are functions of vehicle dynamics, such as acceleration, speed, grade, vehicle mass, loading, and etc. These forces determine the tractive effort obtainable at each wheel. During braking, load is transferred from rear axle to the front axle, thus, normal forces at front and rear wheels respectively increase and decrease. Normal forces carried on each axle under braking acceleration are considered on the flat surface [10]. The longitudinal coefficient of friction (μ) is a function of wheel slip (λ) and changes with different road conditions, different vehicle speeds, and tire types. Figure 4 shows typical adhesion coefficient versus wheel slip for different road conditions [7].

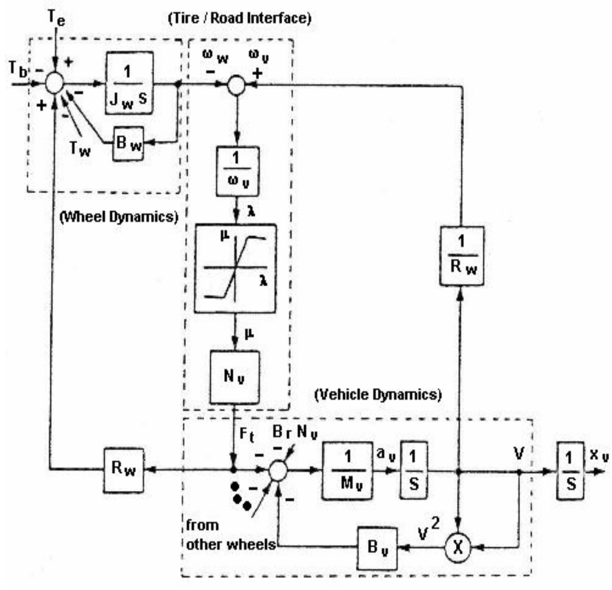

Figure 3. Vehicle/tire/road dynamics

Table 1. ABS Variables and Parameters

T_b	brake torque at the wheel (N.m)
T_e	engine torque at the wheel (N.m)
T_w	torque due to wheel friction (N.m)
P_b	output hydraulic pressure (kpa)
P_{low}	reservoir pressure (kpa)
P_p	pump pressure (kpa)
F_a	aerodynamic drag force (N)
F_t	tire tractive force (N)
F_v	force due to vehicle friction (N)
ω_v	angular speed of free-spinning wheel (rad/s)
ω_w	wheel angular speed (rad/s)
V	vehicle linear speed (m/s)
λ	wheel slip
N_v	normal force at tire/road contact (N)
a_v	vehicle linear acceleration (m/s^2)
M_v	vehicle mass (kg)
J_w	moment of inertia of wheel ($kg.m^2$)
R_w	wheel radius of a free-rolling tire (m)
μ	road/tire adhesion coefficient
ρ	density of the fluid
B_v	aerodynamic drag coefficient
B_r	tire rolling resistance coefficient
A_1,A_2	orifice area of hydraulic valves

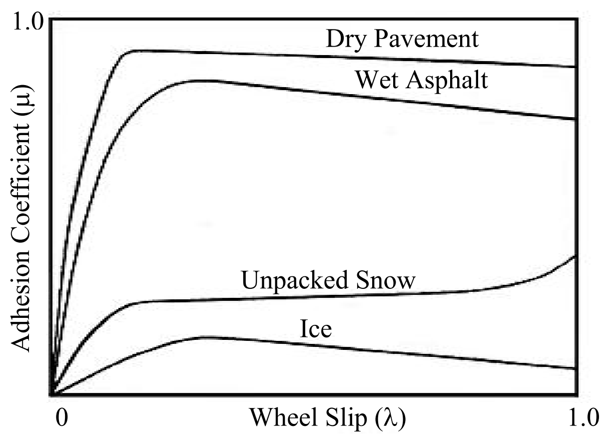

Figure 4. Typical adhesion coefficient versus wheel slip

2.2 Brake Hydraulic System Dynamics The hydraulic system has the standard structure shown in Figure 5 [9].

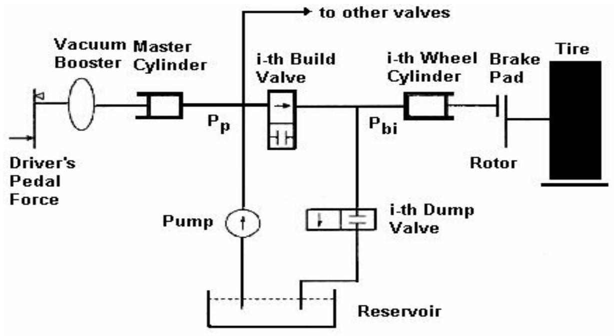

Figure 5. Hydraulic system

Hydraulic system dynamics for the i-th wheel cylinder can be modeled as follows:

$$C_f \dot{P}_{bi} = A_1 C_{d1i} \sqrt{\frac{2}{\rho}(P_p - P_{bi})} - A_2 C_{d2i} \sqrt{\frac{2}{\rho}(P_{bi} - P_{low})} \quad (7)$$

The coefficients C_{d1i} and C_{d2i} are the control inputs, which can take the values 0 or 1 depending on the corresponding valve being open or closed. C_f is the coefficient of the flow and the time derivative function of hydraulic pressure. Brake torque depends on different factors, such as, brake friction coefficient, fluid pressure, vehicle speed, temperature, and etc. It can be approximated by a first order differential equation of the brake pressure [8]. In this brake model, time delays are considered 3ms for transferring hydraulic pressure from valves to the wheel cylinder and 12ms for the wheel cylinder.

3. DESIGNING GENETIC-FUZZY CONTROLLER

In this paper the TSK fuzzy system is proposed for designing the controller. The TSk fuzzy system is constructed by the following rules [11]:

$$R^l: \ if \quad x_1 isB_1^l,..., \ x_n isB_n^l \ then$$
$$y^l = C_0^l + C_1^l x_1 + ... + C_n^l x_n \quad (8)$$

Where B_i^l are fuzzy sets, $l = 1,2,..., M$ and C_i^l are constants. Given an input $x = (x_1,...,x_n)^T \in U \subset R^n$ the output $f(x) \in V \subset R$ of the TSK fuzzy system is computed as the weighted average of the y^l's in (8), that is:

$$f(x) = \frac{\sum_{l=1}^{M} y^l \prod_{i=1}^{n} \mu_{B_i^l}(x_i)}{\sum_{l=1}^{M} \prod_{i=1}^{n} \mu_{B_i^l}(x_i)} \quad (9)$$

Where $\mu_{B_i^l}(x_i)$ is value of membership function of the i-th input for antecedent of the l-th rule. Fuzzy rules is written so that wheel slip for any road is maintained at the value of slip which gives the peak value of the longitudinal coefficient of friction and maximize vehicle deceleration. So, to achieve that goal, a fuzzy controller is designed with three inputs consisting of slip (λ), difference of slip $(d\lambda)$, and difference of acceleration (da_v) with seven fuzzy rules. The output of the controller sets brake pressure according to equation (7). The membership functions for input variables of the controller are considered by Gaussian curves and their parameters consist of variance and center of gravity, and also parameters of consequences of rules, for a chromosome, are obtained using a parallel genetic algorithm by optimizing the following objective function [12]:

$$F_{obj}(\lambda(t)) = -\sum_{t=0}^{t_{sim}} \left[\lambda(t) - \lambda_{opt}(t)\right]^2 \quad (10)$$

Where $\lambda_{opt}(t)$ is optimal wheel slip under different road conditions, t_{sim} is the simulation time. Each chromosome contains 58 elements. The first 30 elements of each chromosome represent parameters of membership functions for input variables of the controller, while; the remaining 28 elements represent parameters of consequences of the fuzzy rules. The population size is considered 100. The genetic algorithm is run in parallel with two separate populations of 50 chromosomes with the probability of crossover (p_c) and mutation (p_m) under supervisor, based upon the roulette wheel selection mechanism. In order to avoid losing the best solutions in the succeeding iterations, the best chromosome is used from the old population into the new population. After the end of each stage of running, 50 percent of chromosomes of each population is selected and displaced by the roulette wheel selection mechanism. After several generations the algorithm converges to the best chromosome, which represents the optimal solution of the problem.

4. SIMULATION RESULTS

Parameters of consequences of fuzzy rules and parameters of membership functions for input variables of the controller are obtained using a parallel genetic algorithm by optimizing the objective function (10). Performance of the proposed controller is tested on the vehicle model with effect of dynamic load transfer from the rear axel to the front axle, with the hydraulic brake system, for different road conditions, and different reservoir and pump pressures. This performance compared with the case when maximal brake torque are applied causing a wheel lockup and with the case when wheel slip is kept to a desired level causing the maximum wheel tractive force, the maximum vehicle deceleration, the minimum stopping distance, and adequate vehicle stability and steerability. Simulation results, that are verified through several numerical simulations using Matlab/Simulink, show that the controller has very good performance. It is assumed that the vehicle is moving at 30 m/s, equivalent of 108 km/h or 67.11 mph. The road surface changes from the dry asphalt to an icy asphalt after 30 m and then changes from the icy asphalt to the dry asphalt after 30 m. Figure 6 shows typical road coefficient of adhesion versus wheel slip curves for two different road sufaces. Figure 7 shows plots of road conditions, vehicle and wheel speeds, wheel slip, brake torque, and vehicle position without the controller. in this case the wheels are locked (slip is equal to one). A locked wheel has no lateral stability so, the vehicle is not steerable. Figure 8 shows plots of road conditions, vehicle and wheel speeds, wheel slip, brake torque, and vehicle position with the proposed controller for 100 kpa in reservoir pressure. As can be seen in figuers 8, the brake torque forces so that the wheel slip track the maximum adhesion coefficient on both dry asphalt and ice very closely and the stopping distance of the proposed controller is about 20 m less than the stopping distance without the controller. It is also shown that in the case of genetic-fuzzy controller the slip is kept at a small value by maximum tracking of adhesion factor and the vehicle has good steerability. Figure 9 shows plots of vehicle speed, wheel slip, brake torque, and normal forces at front and rear wheel with the proposed controller for 100 kpa in reservoir pressure. As seen in figuers 9, During braking, load is transferred from rear axle to the front axle, thus, normal forces at front and rear wheels respectively increase and decrease. Figure 10 shows membership functions for input variables of the controller. Figure 11 shows plots of vehicle speed, wheel slip, brake torque with controller for 100 kpa in reservoir pressure. It is assumed that the vehicle is moving at 30 m/s and the road surface changes from the dry asphalt to an icy asphalt after 14 m and then changes from the icy asphalt to the dry asphalt after 12 m. Figure 12 and Figure 13 show plots of vehicle speed, wheel slip, and brake torque with the proposed controller for low and high reservoir pressure. Figure 14 and Figure 15 show plots of vehicle speed, wheel slip, and brake torque with fuzzy-logic controller [4]. In this controller initial forward speed is 30 m/s and ice is between 14 and 26 m of the dry asphalt road. By comparing the genetic-fuzzy controller with the fuzzy-logic and PI controller under identical operating conditions, it can be seen that in the case of the genetic-fuzzy controller, wheel slip track the maximum adhesion coefficient on both dry asphalt and ice very closely at slow and fast vehicle speeds. The stopping distance of the proposed controller is about 7 m less than the stopping distance with the PI controller. Also, the vibration due to torque and slip valuation is much higher in the case of fuzzy-logic and PI controller. In the case of proposed controller compared to fuzzy-logic and PI controller, slip is kept very small value at slow vehicle speed, so, the vehicle has adequate lateral stability and good steerability.

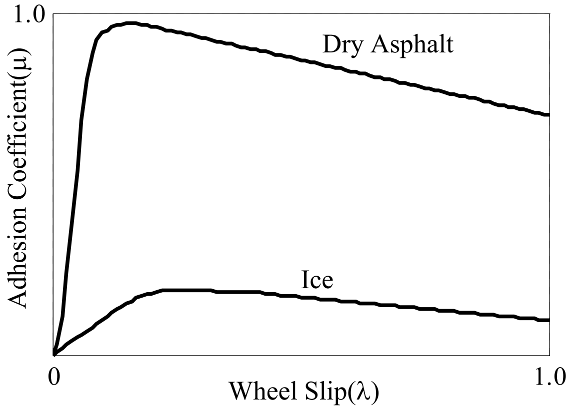

Figure 6. Typical road coefficient of adhesion versus wheel slip curves for two different road sufaces

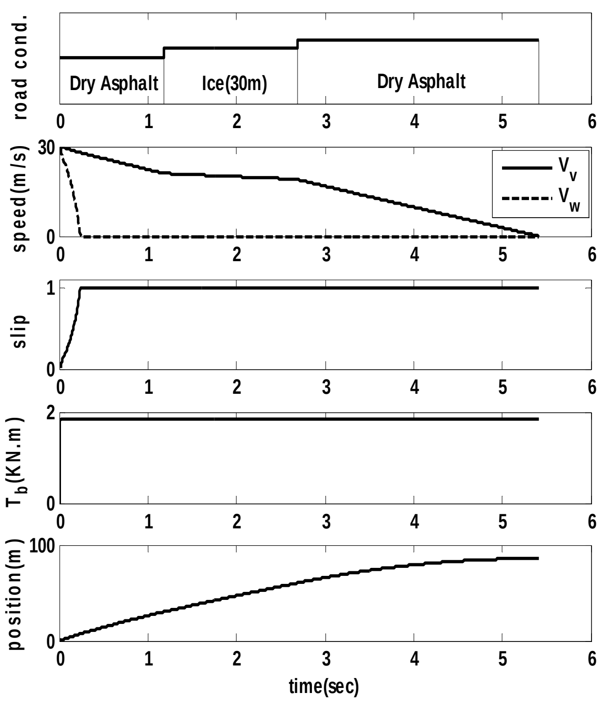

Figure 7. Plots of road conditions, vehicle and wheel speeds, wheel slip, brake torque, and vehicle position without the controller

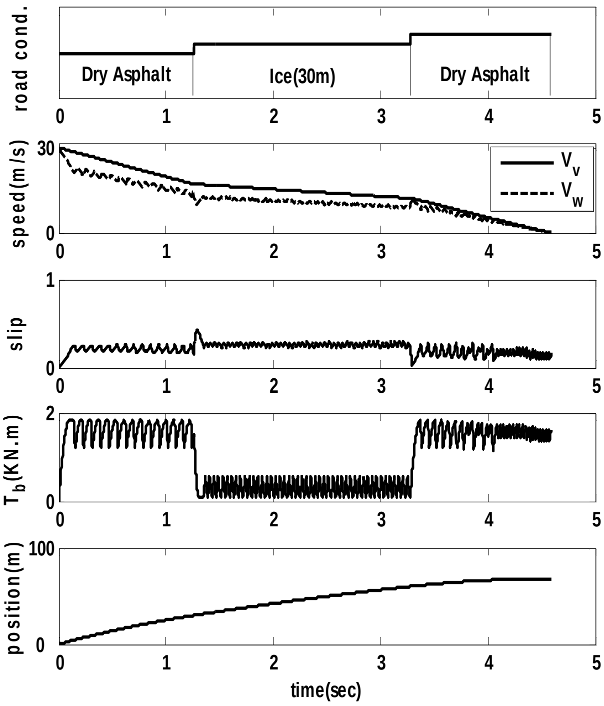

Figure 8. Plots of road conditions, vehicle and wheel speeds, wheel slip, brake torque, and vehicle position with the proposed controller

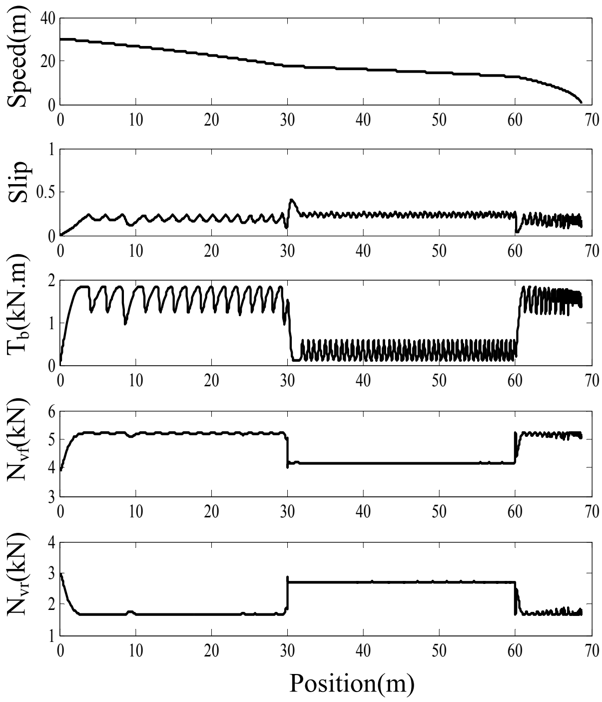

Figure 9. Plots of vehicle speeds, wheel slip, brake torque, and normal forces at front and rear wheel with the proposed controller

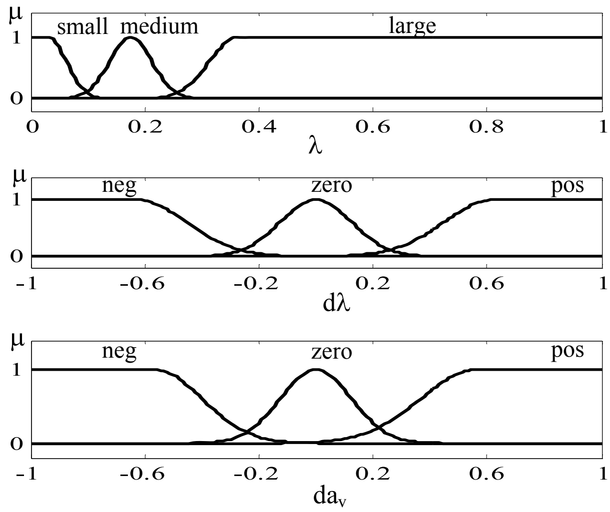

Figure 10. Membership functions of controller inputs

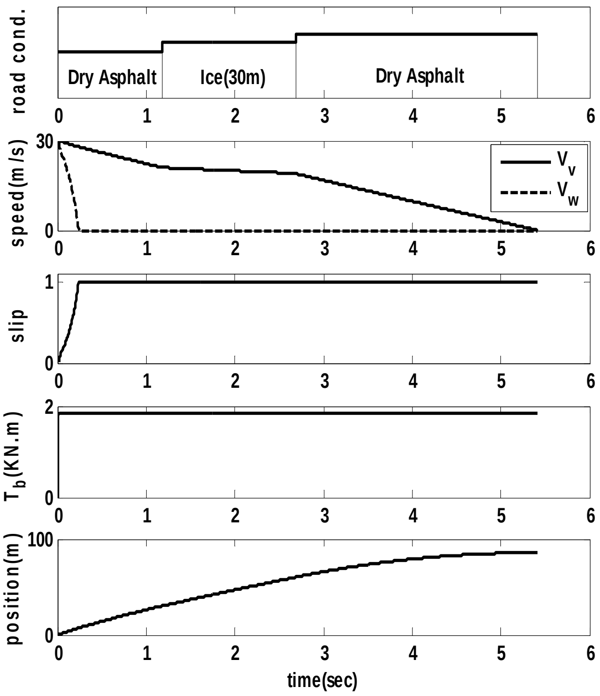

Figure 11. Plots of vehicle speeds, wheel slip, and brake torque for 100 kpa in reservoir pressure and ice between 14 and 26 m with the proposed controller

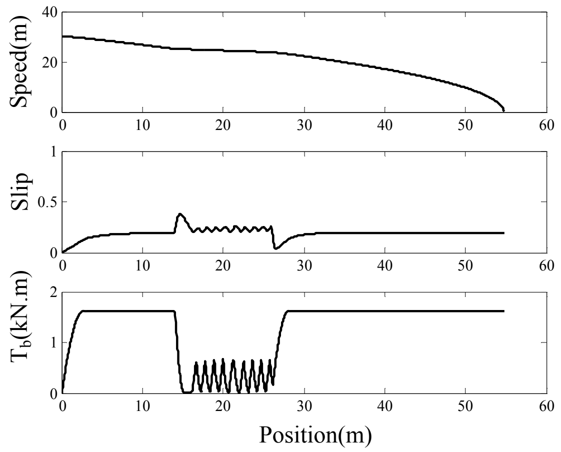

Figure 12. plots of vehicle speeds, wheel slip, and brake torque for low reservoir pressure (10 kpa) and ice between 14 and 26 m with the proposed controller

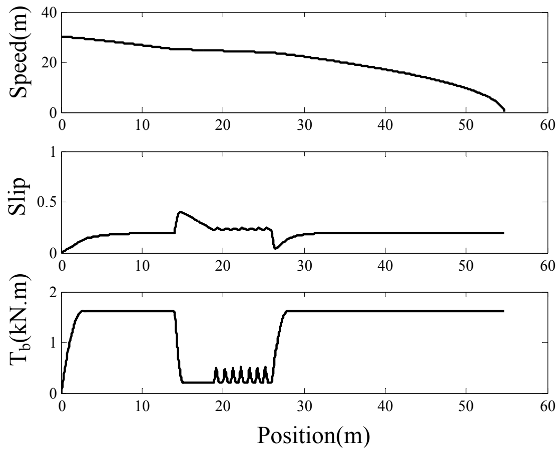

Figure 13. plots of vehicle speeds, wheel slip, and brake torque for high reservoir pressure(200 kpa) and ice between 14 and 26 m with the proposed controller

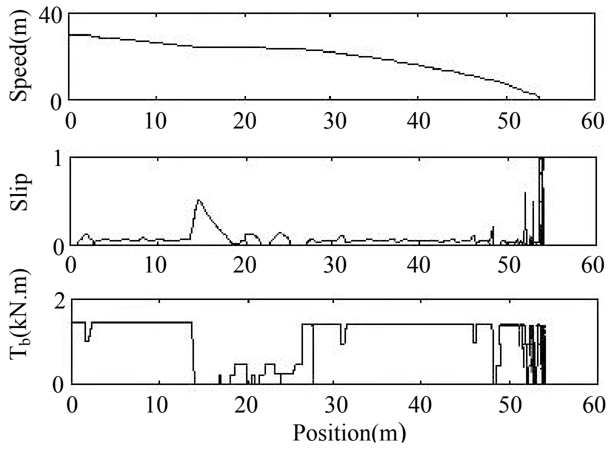

Figure 14. plots of vehicle speeds, wheel slip, and brake torque for ice between 14 and 26 m with the fuzzy-logic controller

at a small value by maximum tracking of adhesion factor, the braking distance has been reduced by more than 20%. It is also shown that in the case of the genetic-fuzzy controller the oscillations is much less than of the fuzzy-logic and PI controller. In the proposed controller compared to fuzzy-logic and PI controller, slip is kept very small value at slow vehicle speed, so, the vehicle has good steerability.

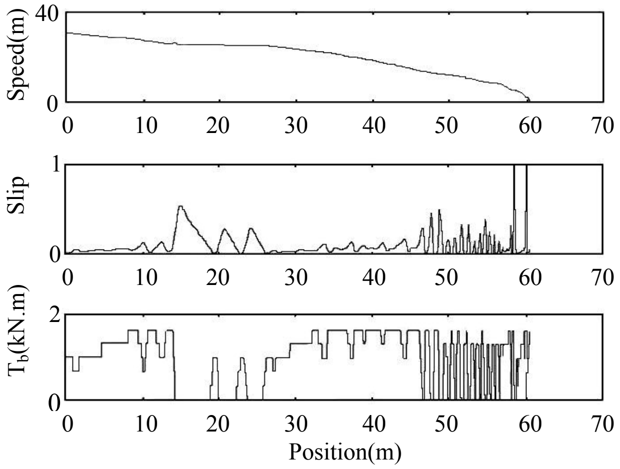

Figure 15. plots of vehicle speeds, wheel slip, and brake torque for ice between 14 and 26 m with the PI controller

5. CONCLUSION

In this paper a genetic-fuzzy ABS controller is designed. The input variables to the controller are obtained by wheel speed and vehicle acceleration sensors. All parameters of membership functions and rules of the fuzzy system that is TSK type are obtained using the genetic algorithm. The objective function is defined to maintain wheel slip to a desired level so that maximum wheel tractive force and maximum vehicle deceleration are obtained. Performance of the proposed controller is tested on a vehicle model with effect of dynamic load transfer from the rear axel to the front axle, with the hydraulic brake system, for different road conditions, and different reservoir and pump pressures. Simulation results, that are verified through several numerical simulations using Matlab/Simulink, show very good performance of the controller for different road conditions and wheel slip is kept to the desired level. It is shown that in the case without the controller the wheels are locked and the vehicle is not steerable, but in the case of genetic-fuzzy controller the slip is kept

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