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Optimization of Bang-of-Bang TS-Fuzzy Based via DARLA Technique for ABS System

Nahid Ebrahimi Meymand *, Aliakbar Gharaveisi

Electrical Engineering Department, Shahid Bahonar University of Kerman, Kerman ,Iran

n.ebrahimi@yahoo.com, a_gharaveisi@yahoo.com

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Abstract

Anti-lock Braking System (ABS) which is a nonlinear and time variant system may not be easily controlled by classic control methods. This is due to the fact that classic linear controllers are just capable of controlling a specific plant in small region of state space. To overcome this problem, a more powerful control technique must be employed for complex nonlinear plants. Fuzzy controllers are potential candidates for the control of such systems, while they have an intrinsic ability to control a complex set of dynamics like ABS in an appropriate wider region in the state space.This paper introduces a new zero order Takagi-Sugeno fuzzy controller. The input membership functions of the proposed controller have been optimized such that the ABS performance enhances over different braking situations. Simulation shows the effectiveness of the proposed controller under various road conditions. The optimization is done by using DARLA, a powerful heuristic technique.

Keywords: *Anti-lock Braking System (ABS), Discrete Action Reinforcement Learning Automata (DARLA), Fuzzy Controller*

1. Introduction

Anti-lock Braking System recognized as an important contribution to road safety, which is designed to keep a vehicle steerable and stable during heavy braking moments by preventing wheel lock. It is well known that wheels will slip and lock up during severe braking or when braking on a slippery road surface. This usually causes along stopping distance and sometimes the vehicle will lose steering stability [1]. The aims of ABS are to reduce stopping distance and increase steering by maximizing friction force between tire and road. It is well known that friction coefficient is a nonlinear function of slip. This Relationship can be shown as Fiqure 1[2].

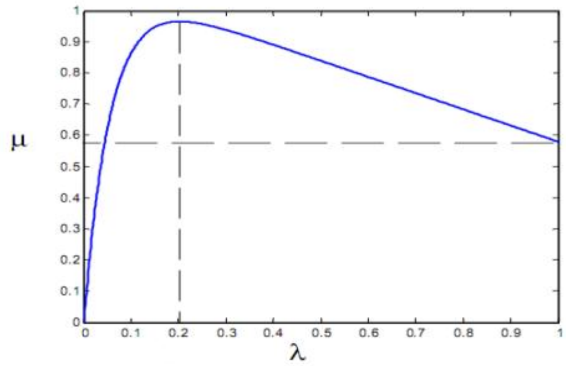

Figure 1. Dependence of friction coefficient on slip ratio

Most of the ABSs expected to keep the vehicle slip in a desired range, where the corresponding friction force reaches its maximum value [3]. From zanten in [4], optimal performance can be achieved if the slip is kept between 8% and 30%[5], however in most ABS control strategies, optimal slip is considered a constant value equal to 0.2[6,7].
Different control methods have been developed up to now, to keep wheel slip in desired interval. For example sliding mode control [8, 9], adaptive control [10,11], neural control [12] and fuzzy control [13-15] are applied to ABS. Among these controllers, fuzzy controllers have an intrinsic ability to control a complex set of dynamics like ABS in an appropriate wider region in the state space.
In this paper a novel designing method of fuzzy controller has been proposed and an optimal Takagi-Sugeno fuzzy controller is designed. The proposed method is optimized by Discrete Action Reinforcement Learning Automata (DARLA) and determines best variation limits for each of T-S fuzzy logic coefficients.
This paper is organized as follows: The system dynamics of a quarter vehicle is presented in section 2. Details on the proposed controller design are given in section 3. Section 4 shows the simulation results. Finally, Section 5 gives a short conclusion.

2. System dynamics

By considering Newton's law applied to the wheels and body of a vehicle, the movement equation can be written as following: [13]

$$Jw = rF_x - T_b \tag{1}$$

$$m\dot{x} = -F_x \tag{2}$$

$$F_x = m(l) F_z \tag{3}$$

$$F_z = mg \tag{4}$$

Where the following notations are used:

m	Mass of vehicle
v	Vehicle speed
w	Angular speed of wheel
F_z	Vertical force
F_x	Friction force of tire
T_b	Braking moment
r	Wheel radius
J	Wheel inertia
$m(l)$	Friction coefficient

The wheel slip for a braking operation can be found from the following equation:

$$\lambda = \frac{v - rw}{v} \tag{5}$$

From this equation, it can be explained that if the wheel velocity is zero, the wheel slip will equal to 1 (λ=1), which is called wheel lock up. However, in normal driving condition $v = rw$ therefore λ=0 [1, 17].

3. Proposed Controller Designing

3.1 Fuzzy logic controller

The wheel slip for a braking operation can be found from the following Applied Controller in this paper is a Takagi-Sugeno Fuzzy Logic controller (TSFL controller). This TSFL controller has two input variable (error and error derivation) and just one output. 25 fuzzy rules are considered for this controller as follows:

$$IF\ (e\ \ is\ MF_i)\ \ And\ \ \left(\frac{de}{dt}\ is\ MF_j\right)\quad Then\ U_l = C_l \quad \begin{array}{l} i,j = 1,2,\dots,5 \\ l = 1,2,3 \end{array} \tag{6}$$

Output controller will be determined as following:

$$U_c = \frac{\sum_{l=1}^{3} w_l U_l}{\sum_{l=1}^{3} w_l} \tag{7}$$

Where e is error signal, MF_i and MF_j are the input membership functions, w_l is firing strength of each rule.

The output membership function takes constant values of +1,-1 and 0. Where +1 means that braking oil pressure is increasing, while -1 means that braking oil pressure is decreasing and 0 means that braking oil pressure is constant.

The final control signal is a bang of bang signal obtained by comparing output of fuzzy controller with threshold values as shown in Figure 2.

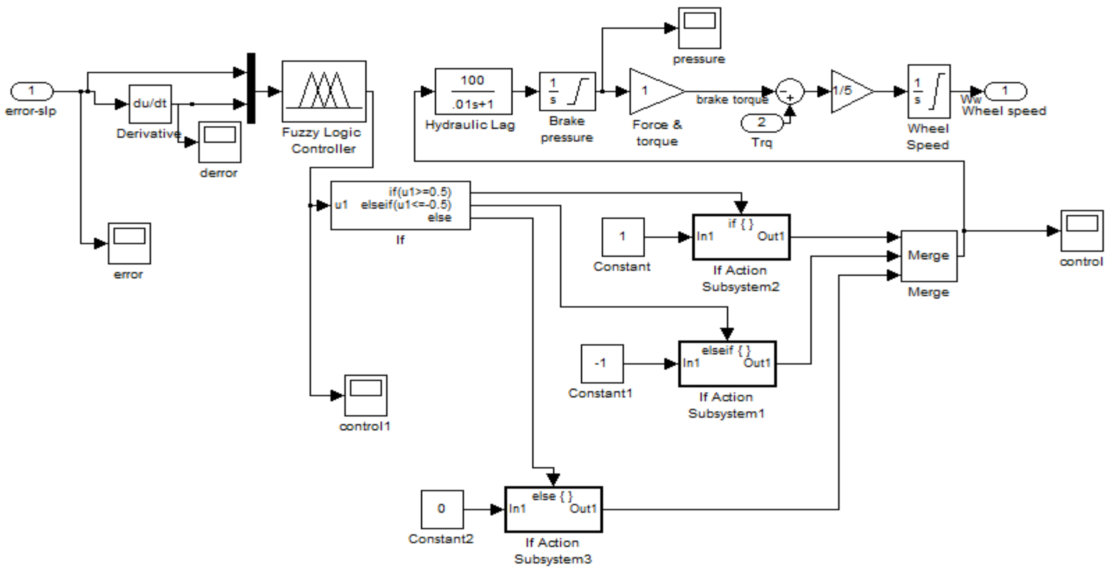

Figure 2. Obtaining final control signal

3.2 Optimizing Proposed Controller

To optimize fuzzy controller stated in the previous section, we use the reinforcement learning method for optimizing input membership functions. Each membership function in the fuzzy controller, except first and last one, specified with three parameters: first point, midpoint and final point.
First and final membership functions have a cutting part, so they are specified by two parameters only. On the other hand each of the above membership functions could be specified by distance between midpoints of two neighbor membership functions and the distance between first and final points from the midpoint.
In this fuzzy controller, both inputs are characterized with 5 fuzzy sets as Figure 3.

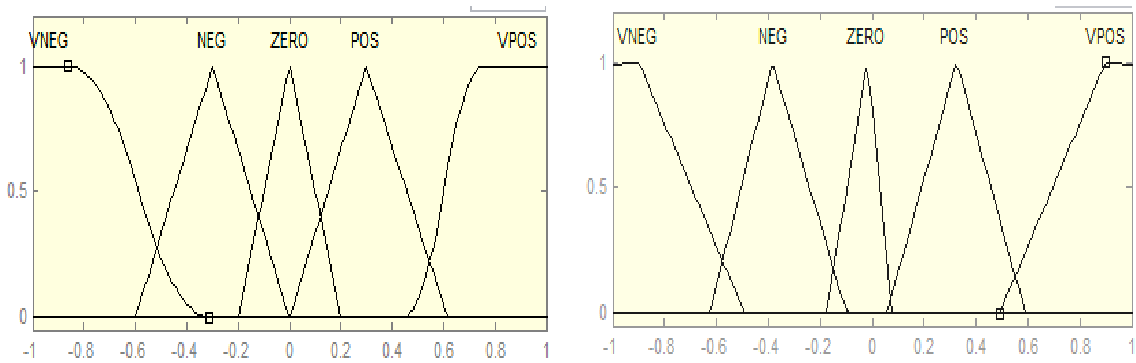

Figure 3. membership functions of input variables

Therefore these sets specified with 26 parameters.

3.3 Discrete Action Reinforcement Learning Automata (DARLA)

As In Darla, the variation limits of controller coefficient are divided into usually same length limits and Discrete Probability Distribution Function (DPDF) for each of those limits is assigned .These DPDFs initially set as a uniform one. Probability of selection of each limit is performed by DPDF and after each selection of decision variables .The shape of DPDFs is changed proportional to fitness of that selection. Figure 4 shows diagram of DARLA method [18].

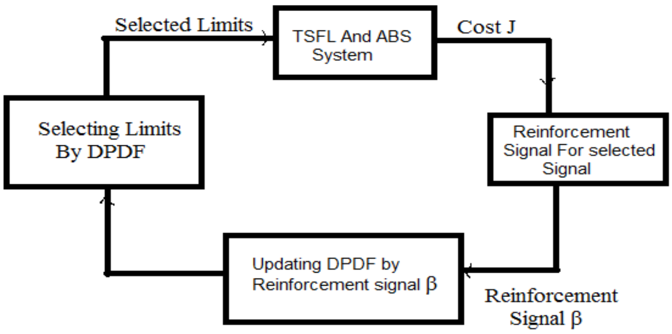

Figure 4. Diagram of DARLA method

As stated, there are 26 fuzzy controller coefficients and it is supposed each variable varies between 0 and 0.8. This limit was divided into 10 equal limits. Number of division does not have severely effected on design performance, yet it must be selected large enough [18] as Equation 8.

$$f_i^{(0)}(n) = \begin{cases} \dfrac{1}{10} & n = 1, 2, \ldots, 10 \\ 0 & otherwise \end{cases} \tag{8}$$

Where $f_i^{(k)}(n)$ is the probbility of selecting pth limit in *each* is the probability of selecting limit in each controller coefficient at kth iteration. After selecting limits by cumulative probability of DPDF. Center of each limit is taken to construct TSFL [18] and cost J is calculated as (9).

$$J^k = G_1 \int_0^T e\,dt + G_2 \int_0^T \left(p - p_{opt}\right) dt \tag{9}$$

Where J^k is cost at kth iteration. T is simulation time and must be large enough. e is error signal, p is oil braking pressure and p_{opt} is optimal oil braking pressure. G_1, G_2 are cost element weights and considered as:

$$G_1 = 15.8 \quad , \; G_2 = 0.7 \times 10^{-6} \tag{10}$$

After calculating cost, reinforcement signal β will be calculated as Equation 11 [18, 19, 20].

$$\beta^{(k)} = \min\left\{1, \max\left\{0, \frac{J_{mean} - J^{(k)}}{J_{mean} - J_{min}}\right\}\right\} \tag{11}$$

Where J^k is kth reinforcement signal, and J_{mean} and J_{min} are average and minimum of previous costs, respectively. Defining reinforcement signal as (11) gives average of costs, has non-increasing behavior and guarantees convergence of method [18].
After obtaining reinforcement signal DPDFs are updated by (12).

$$f_i^{(k+1)}(n) = a_i^{(k)}\left(f_i^{(k)}(n) + \beta^{(k)} Q_i^{(k)}\right) \qquad i = 1, 2, \dots, n \tag{12}$$

Where $Q_i^{(k)}$ is an exponential function centered in selected limit and defined as:

$$Q_i^{(k)} = r_q 2^{-\left(n - \tilde{n}_i\right)^2} \tag{13}$$

Where $\tilde{n}_i$ is selected limit and r_q is a positive constant. $a_i^{(k)}$. In (13) is a normalization factor calculated as:

$$a_i^{(k)} = \frac{1}{\sum_{n=1}^{10} f_i^{(k)}(n) + \beta^{(k)} Q_i^{(k)}} \tag{14}$$

After sufficient iterations, the selection probability of optimal limit for each DPDF is maximized. Limits with highest probability of selection at the end of iterations for each of controller coefficient are the optimum limit for that coefficient. Limits with highest probability of selection at the end of iterations for each of controller coefficient are the optimum limit for that coefficient [18].
Figure 5 and 6 show cost variation versus algorithm iterations as expected it has non-increasing behavior for dry and icy roads.

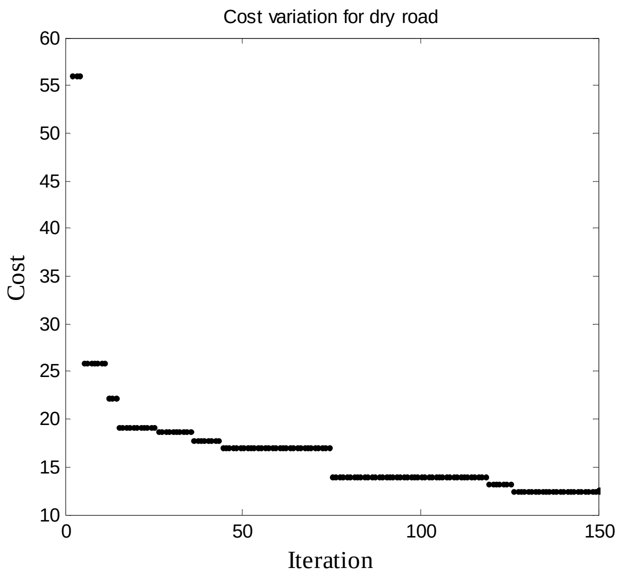

Figure 5.Cost variation for dry road

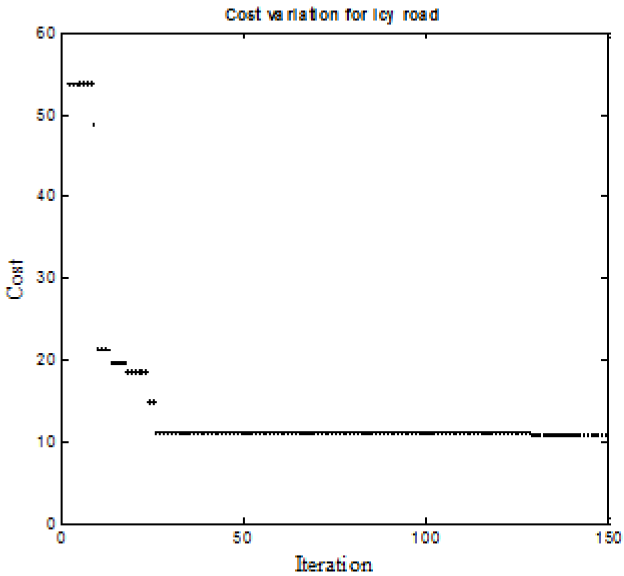

Figure 6. Cost variation for icy road

The limits with highest probability of selection at the end of iterations for each of controller coefficient are the optimum limit for that coefficient.

4. Simulation results

In order to simulate proposed controller, we use the environment of Matlab/ Simulink software. In our simulations, two different road surfaces are considered: A dry road and an icy road and we desire to regulate slip to 0.2.

The parameters of the ABS used in this study are m= 50, J=5, r=1.25 ft, $g = 32.18\ ft/s^2$.

Beside the proposed controller, we used bang- bang controller as comparative based.

Figure 7 and figure 8 illustrates slip plots of the ABS based on the optimized fuzzy controller, compared to the ABS with bang-bang controller for dry and icy roads respectively.

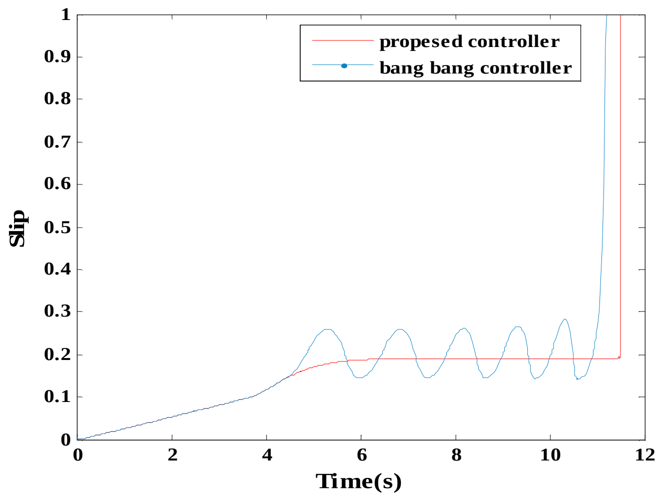

Figure 7. wheel slip for dry road

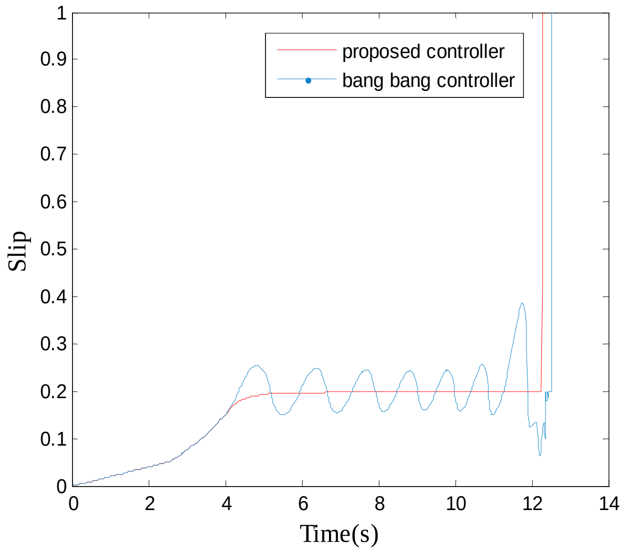

Figure 8. wheel slip for icy road

It can be seen that ABS based on bang-bang controller tracks the desired slip but it has many oscillations, while it is obvious that performance of the system with optimized fuzzy controller is better on both dry and icy roads. Due to the fact that the wheel and vehicle velocity are nearly zero at low speeds, the magnitude of slip tends to infinity as the vehicle speed approaches zero.

Figure 9 and figure 10 show the comparison between proposed controller and bang- bang controller in term of stopping controller for dry and icy road.

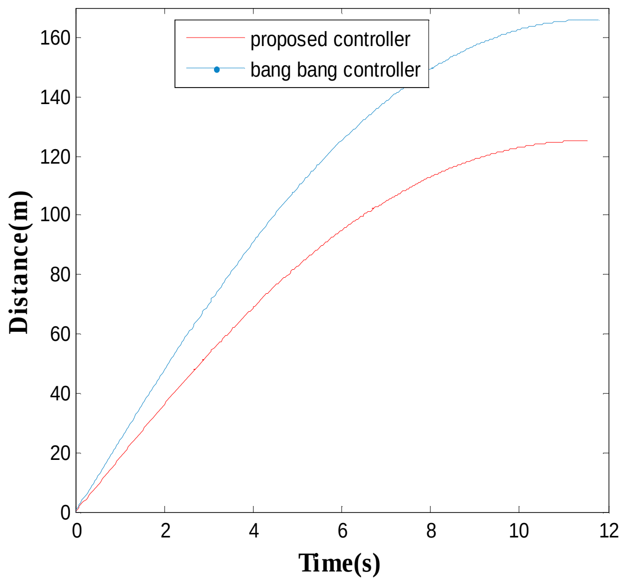

Figure 9. Stopping distance for dry road

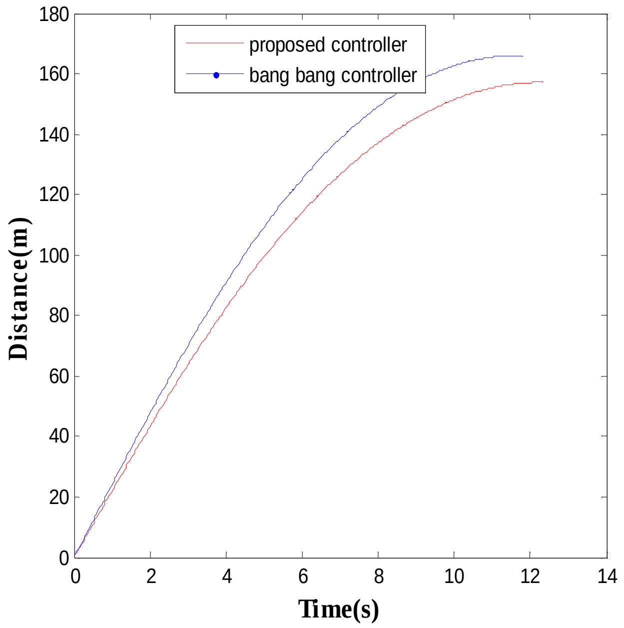

Figure 10. Stopping distance for icy road

It can be seen that the proposed controller has the capability to reduce more stopping distance.
Figure 11 and Figure 12 shows the final control signals for dry and icy road surfaces.

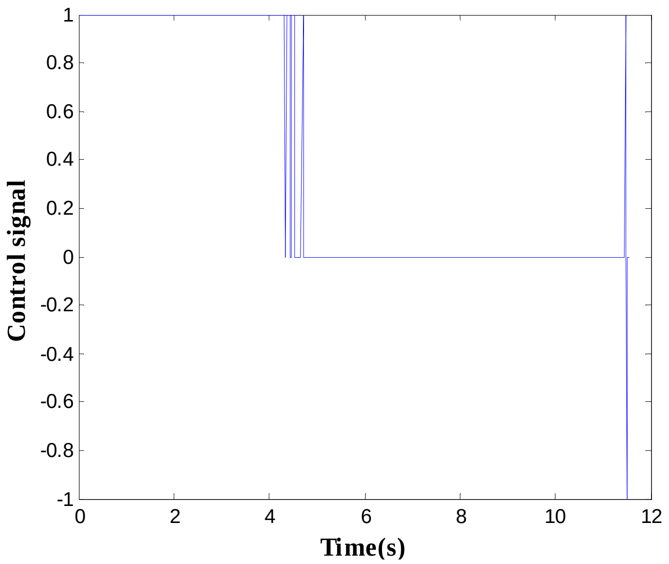

Figure 11. Control signal for dry road

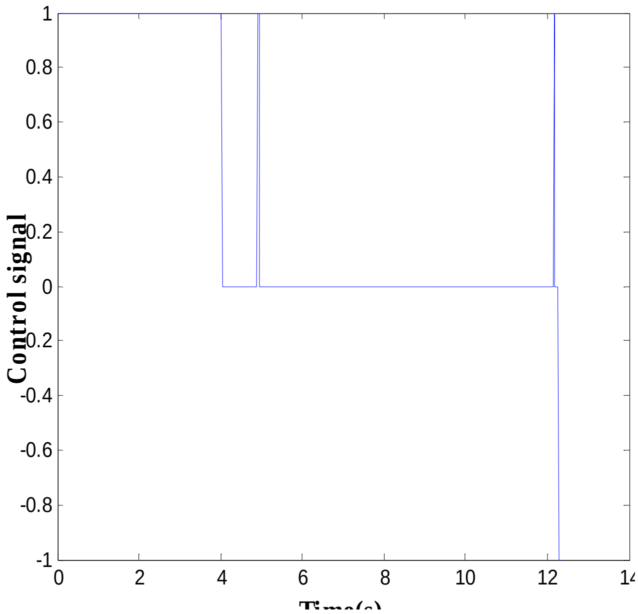

Figure 12. Control signal for icy road

. It can be seen that control signal in this design is a discrete signal which can be used in practical systems.

At the final, in Figure 13 and Figure 14 the vehicle velocity and the wheel speed are shown.

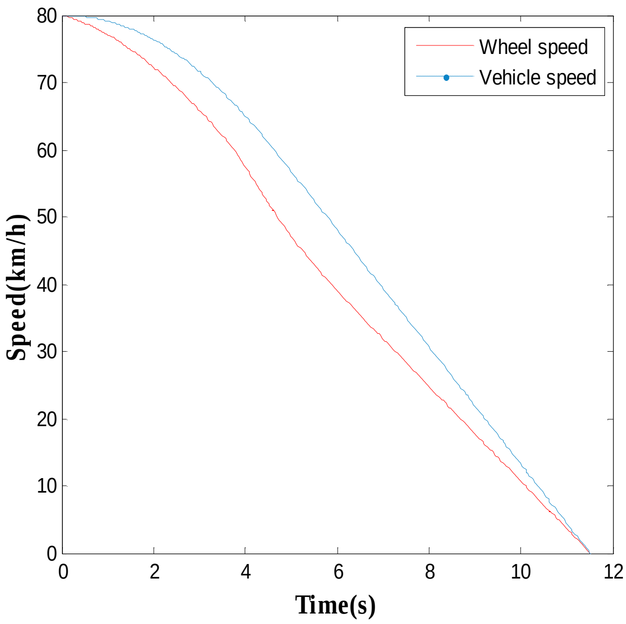

Figure 13. Wheel and vehicle speed for dry road

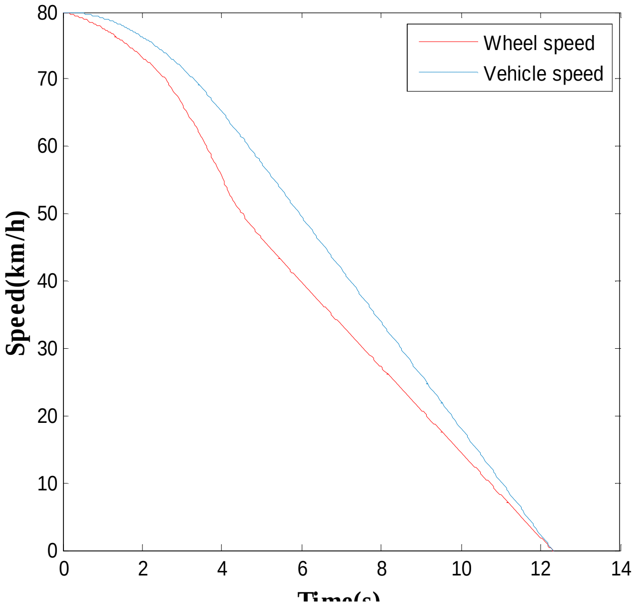

Figure 14. Wheel and vehicle speed for icy road

5. Conclusion

. In this paper, a novel method for optimizing fuzzy slip controller called DARLA was introduced .This method is based on reinforcement learning automata and does not require system dynamics and any further information.This paper successfully demonstrates that this method can achieve favorable tracking regardless of various road conditions.

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