

1802. Development of fuzzy anti-roll bar controller for improving vehicle stability

Javad Marzbanrad¹, Golamhossein Soleimani², Mehdi Mahmoodi-k³, Amir H. Rabiee⁴

¹School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran

²Department of Industrial Management, Allameh Tabatba'i University, Tehran, Iran

³Young Researches and Elite Club, Tabriz Branch, Islamic Azad University, Tabriz, Iran

⁴Department of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran, 1684613114

³Corresponding author

E-mail: ¹marzban@iust.ac.ir, ²g.soleimani@atu.ac.ir, ³m_mec_tab@yahoo.com,

⁴ah_rabiei@mecheng.iust.ac.ir

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Abstract. The main objective of this paper is to develop active control mechanism based on fuzzy logic controller (FLC) for improving vehicle path following, roll and handling performances simultaneously. At the first stage, 3DOF vehicle model which includes yaw rate, lateral velocity (lateral dynamic) and roll angle (roll dynamic) are developed. The controller produces optimal moment to increase stability and roll margin of vehicle by receiving the steering angle as an input and vehicle variables as a feedback signal. The effectiveness of proposed controller and vehicle model are evaluated during fishhook and single lane-change maneuvers. Simulation results demonstrate that FLC by reducing roll angle, lateral velocity and acceleration, vehicle roll resistance and handling properties are improved. Finally the sensitivity and robustness analysis of developed controller for varying longitudinal speeds are investigated.

Keywords: vehicle dynamic, rollover, handling, stability, active safety controller.

1. Introduction

There are two perspectives for handling ratings. One perspective is how safe the vehicle is to drive. The other is how well the vehicle gives an enthusiast driver a pleasurable sense of control. Suspension system and its components (stiffness and damping rates) have significant role in vehicle motion and handling properties. Coil springs which usually are used in passenger vehicle suspension system are less stiff with better ride comfort compared to leaf springs. Therefore, the roll stiffness of the vehicle with coil springs is usually less than in vehicles with leaf springs. In order to improve the roll characteristic of coil springs an antiroll bar mechanism must be used (Fig. 1).

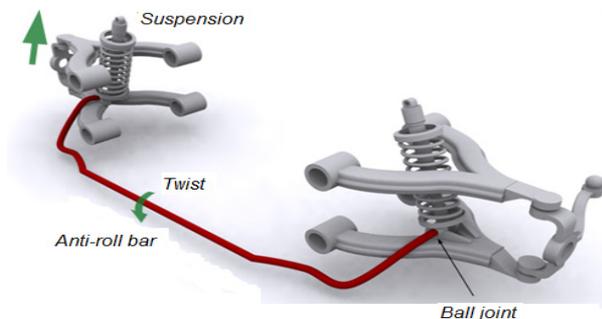


Fig. 1. Anti-roll bar system in passenger car suspension [1]

Various mechanisms such as optimal geometry passive [2], semi active [3], active [4] suspensions and anti-roll bar [5] systems have been studied to compromise the trade-offs between ride and handling. Due to active suspension systems cost, energy usage and packaging difficulties, they are used on a limited basis for Luxury and special vehicles. Whilst, anti-roll bar recently has

become practical solution to improve vehicle handling, roll-stability and ride comfort. Also, active control systems such as DYC, AFS, and VDC are developed in previous researches to improve vehicle stability and roll resistance [6-10]. Papelis et al. [7] utilized Electronic stability control (ESC) to assist driver in maintain vehicle control and prevention of vehicle loss of control. Their results showed that using ESC 25 % reduces loss of control in severe maneuvers.

Previous researches studied the mechanism and systems for prevention of rollover while ensuring not to satisfy handling and ride properties. In [8] a novel FLC is proposed to improve vehicle safety by regulating dampers in semi active suspension system. The controller stabilize the sprung mass which improves vehicle handling and reduces possibility of overturning. Singh and Darus [9] presented an active roll control system using an active suspension based on fuzzy logic control for enhancement of vehicle roll dynamics. Mashadi et al. [10] developed a DYC system based on LQR, for vehicle path following with considering the driver performance. They used 2 DOF vehicle model for developing of LQR controller. Their results showed that LQR controller could be properly applied for vehicle path following and improving handling characteristic. They tried to maintain the lateral acceleration and velocity under 0.8 m/s^2 and 40 m/s respectively.

In previous studies various control strategies are utilized to control vehicle path control, improving ride, handling and rolling resistance systems [11-17]. Wu et al. [11] developed a robust chassis controller to improve vehicle handling performance and lane keep ability by utilizing H_∞ controller. Wang et al. [14] used fuzzy inference engines to design steering controller and determine the given driving speed for autonomous vehicle. Mashadi et al. [10, 12] proposed an optimal LQR and PID controllers for vehicle path following based on intelligent optimization method. They utilized genetic algorithm procedure to adapt a set of optimized controller parameters suitable for various driving styles, road conditions and the initial errors of vehicle position and orientation.

A unified chassis control proposed in [18] to prevent vehicle rollover, and to improve vehicle maneuverability and its lateral stability by integrating electronic stability control (ESC) and active front steering (AFS). The rollover prevention was achieved through speed control, and the vehicle stability is improved via yaw rate control. Cao et al. [19] proposed the integrated controller of the yaw and rollover stability controls using nonlinear prediction model. The linearization tire model was built up as the rollover predictive model and its accuracy obtained by real vehicle tests. These researches were focused on improving handling, ride or rollover resistance separately by active control systems. Whilst in this paper a tradeoff between handling properties and rollover resistance compromised through anti roll bar moment system which is controlled based on FLC. The proposed control structures are typically based on combination of the steer angle, roll angle, longitudinal speed, yaw and roll moments, lateral acceleration and velocity, which controls the yaw rate and the roll motion simultaneously.

2. Vehicle model

In order to investigate the roll over resistance and handling behavior of vehicle simultaneously, integrated lateral and roll dynamics should be considered. So, in this paper two vehicle model is utilized. At the first, a 3 DOF roll model for controller designing is developed which its degrees includes: lateral velocity, yaw and roll. In addition to realize the simulating of the vehicle model, a comprehensive vehicle model (an 8 DOF model) in [10] is utilized to simulation.

2.1. An 8 DOF model

In this article, to simulate the control of a vehicle during roll tests, as demonstrated in Fig. 2, a non-linear 8-DOF is used. The DOFs associated with this model are the longitudinal velocity u , the lateral velocity v , the yaw rate r , the roll Φ , and four wheel rotational speeds, ω_{fl} , ω_{fr} , ω_{rl} and ω_{rr} :

$$m(\dot{u} - rv) = \sum F_x, \tag{1}$$

$$m(\dot{v} + ru) + m_s h_s \ddot{\Phi} = \sum_{i=1}^4 F_y, \tag{2}$$

$$\sum F_x = F_{xfl} + F_{xfr} + F_{xrl} + F_{xrr}, \tag{3}$$

$$\sum F_z = F_{yfl} + F_{yrl} + F_{yrl} + F_{yrr}, \tag{4}$$

$$I_{zz} \dot{r} - I_{xz} \dot{\Phi} = \sum M_z, \tag{5}$$

$$I_{xx} \dot{\Phi} - I_{xz} \dot{r} = \sum M_x, \tag{6}$$

$$\sum M_z = a(F_{yfl} + F_{yfr}) - b(F_{yrl} + F_{yrr}) + \frac{T}{2} [(F_{xfl} + F_{xrl}) - (F_{xfr} + F_{xrr})] + \sum_{i=1}^4 M_{zi}, \tag{7}$$

$$\sum M_x = -m_s h(\dot{v} + ru) + (m_s g h - k_\Phi) \Phi - C_\Phi \dot{\Phi}. \tag{8}$$

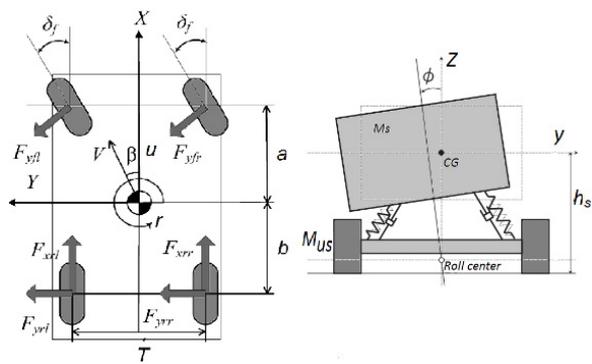


Fig. 2. Vehicle 8 DOF including roll, yaw and longitudinal model

2.2. Vehicle roll model

In order to evaluate the roll behavior of vehicle during sever maneuvers, the main parameters which effects on vehicle roll stability should be considered such as: variation of center of gravity, vehicle track, tire and suspension properties. In this paper as shown in Fig. 3, a 3 DOF vehicle model which combines 2 DOD bicycle model (r and v) with 1 DOF roll model (Φ) is developed.

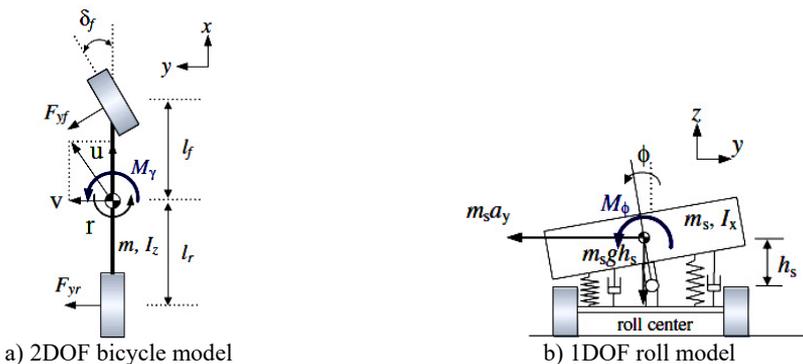


Fig. 3. Vehicle 3 DOF model (yaw and roll)

By imposing Newton's second law of motion along the y -axis and the torque balance around the z -axis and x -axis, the equation of motion for lateral, yaw and roll dynamic can be expressed respectively as:

$$ma_y - m_s h_s \ddot{\Phi} = (F_{yf} \cos \delta + F_{yr}), \quad (9)$$

$$I_z \dot{r} = (aF_{yf} \cos \delta - bF_{yr}) + M_r, \quad (10)$$

$$I_x \ddot{\Phi} - m_s h_s a_y = m_s h_s g \sin \Phi - k_\phi \Phi - C_\phi \dot{\Phi} + M_\phi, \quad (11)$$

where a_y , r and Φ lateral acceleration, yaw rate and roll angle respectively. M_ϕ and m_s are sprung and roll mass respectively, and h_s is the distance between central of gravity to roll center of sprung mass. Also, F_{yf} and F_{yr} are lateral forces of front and rear tires respectively. K_ϕ and C_ϕ are Roll stiffness and Roll damping coefficients of suspension system which are calculated through damping (C_s), springs (K_s) and anti-roll bar (K_{ARB}) stiffness of rear and front axles:

$$K_\phi = K_s \left. \frac{T^2}{2} \right|_f + K_{ARB} |_f + K_s \left. \frac{T^2}{2} \right|_r + K_{ARB} |_r, \quad (12)$$

$$C_\phi = C_s \left. \frac{T^2}{2} \right|_f + C_s \left. \frac{T^2}{2} \right|_r. \quad (13)$$

2.3. Load transfer

If the vehicle body rolls, the left and right wheels at both front and rear axles will increase in load at one side and decrease at the other side. This is called the load transfer due to roll. Defining the load transfer for the axle load ΔF ; the roll moment around the roll center at the wheels in the plane perpendicular to the vehicle longitudinal direction has to be in equilibrium, as shown in Fig. 3, the following equations are derived:

$$\Delta F = \frac{a_y m_s g}{T} \left[\frac{K_{\phi f} h}{K_{\phi f} + K_{\phi r} - m_s g h_s} + \frac{b}{l} h_s \right]. \quad (14)$$

These equations give the load transfer between the left and right wheels due to a constant lateral acceleration. The equations show that a higher vehicle center of gravity distance from the roll axis, h_s , results in a larger load transfer at the front and rear wheels. Furthermore, a load transfer at the front and rear wheels is basically proportional to the front and rear roll stiffness ratios to the total roll stiffness, respectively.

The original rollover resistance ratings were determined solely from the vehicle's static stability factor. The SSF of a vehicle is a calculation of rollover resistance, based on its most important geometric properties. As shown in Fig. 3, vehicle's SSF is calculated taking the moments about the center of contact for the outside tires yields:

$$M_s a_y h - M_s \Phi h_s + F_z T - \frac{M_s g T}{2} = 0, \quad (15)$$

$$\frac{a_y}{g} = \frac{T/2 + \Phi h_s}{h_s}, \quad (16)$$

$$SSF = \frac{T/2}{h_s}. \quad (17)$$

The lower the SSF number, the more likely the vehicle is to roll over in a tripped single-vehicle crash. A higher SSF value equates to a more stable, less top-heavy vehicle.

3. Controller design

In this study, two types of controller are developed, one based on FLC for nonlinear vehicle model and the other is based on linear quadratic regulation for linear vehicle roll model. In both cases front steering angle and momentum deduced by controller for prevention of increasing roll angle are defined as system inputs. State variables include lateral velocity, yaw rate, roll angle and roll rate as:

$$x = [v \quad r \quad \Phi \quad \dot{\Phi}]^T. \tag{18}$$

By considering 3 DoF vehicle model in previous section, state space for designing controller described as:

$$A = \begin{bmatrix} -\frac{2(C_f + C_r)}{mu} & \frac{2(bC_r - aC_f)}{mu} - u & 0 & 0 \\ \frac{2(bC_r - aC_f)}{I_z u} & \frac{2(a^2 C_f + b^2 C_r)}{I_z u} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{2m_s h_{roll}(C_f + C_r)}{I_x mu} & \frac{2m_s h_{roll}(bC_r - aC_f)}{I_x mu} & \frac{m_s g h_{roll} - K_{roll}}{I_x} & -\frac{C_{roll}}{I_x} \end{bmatrix}, \tag{19}$$

$$B = \begin{bmatrix} \frac{2C_f}{m} & \frac{2aC_f}{I_z} & 0 & \frac{2m_s h_{roll} C_f}{m I_x} \end{bmatrix}^T.$$

Since the main objective of this study is to reduce roll angle or increase rollover threshold (stability), so controller should regulates the lateral load transfer (LLT) in its optimal condition. LLT criteria as a function of lateral acceleration, roll and roll rate is obtained as:

$$LLT = \frac{F_L - F_R}{F_L + F_R} = \frac{2}{mgT} (m_s h_s a_y + K_\phi \phi + C_\phi \dot{\phi}). \tag{20}$$

When one of the tires losses its contact with road and applied force on tire eliminates, rollover occurs. In this condition, LLT becomes 1 and rollover happens. In other words, when the forces at the both sides are equal, LLT becomes zero and vehicle is in most stable condition.

3.1. Fuzzy controller development

Owing to its simple practical nature, Fuzzy type controllers shown in Fig. 4 are developed for roll resistance of the vehicle model. This type of controllers has the advantages of using expert's attitude and experimental results. The anti-roll moment control law for the desired state space vector $X_d = [y_d \quad v_d \quad \Phi_d \quad r_d]^T$ is achieved by this control system.

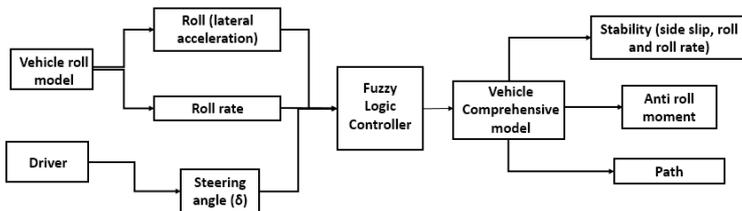


Fig. 4. The FLC structure

In this paper, control strategy is developed by FLC, applying Mamdani implication (Fig. 5). The main objective of this controller is to maintain vehicle stability and prevention of vehicle

rollover during maneuvers.

Three steps are taken to create a fuzzy controlled system [20]:

- Fuzzification: Using membership functions to graphically describe a situation (Fuzzification is the process of changing a real scalar value into a fuzzy value).
- Rule evaluation: Application of fuzzy rules (The rules are composed of a set of if-then rules, from which an inference mechanism is formed).
- Defuzzification: Obtaining the crisp or actual results (The centroid defuzzification technique is utilized in this paper to defuzzify set to get a numerical output as the control signal).

In this paper FLC applying Mamadani implication and based on state variables and control parameters, three condition are considered for fuzzification which demonstrate the status of control strategy parameters; low, normal, and high. The rules are composed of a set of if-then rules, from which an inference mechanism is formed. In other words rules describe the relation between state variable and control parameters.

As shown in Fig. 4 a FLC is developed to design a control strategy, which has two state variables as inputs (roll rate and lateral acceleration) and one control parameter as an output (Anti-roll moment). The antiroll-bar controller is modeled in the FLC and their membership functions of the inputs and outputs are shown in the figure 5.

The designed FLC has 2 inputs, 3 MFs for each input and 9 fuzzy rules for each input. Requested anti roll moment is normalized so that the number 0.5 allocated to optimum moment. Therefore, the center of MFs are located in 0.5. Also, as shown in Fig. 5, rules are set to respect the rules overlap. The surface of them are shown in the figure 6. Rules based on vehicle roll model are regulated whenever, lateral acceleration and roll-rate of vehicle is increased, controller commands anti-roll bar system to produce more moment to improve vehicle handling properties and prevention of rollover.

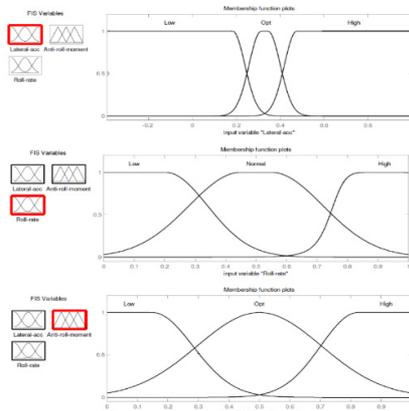


Fig. 5. Membership functions of the two modes in the FLC

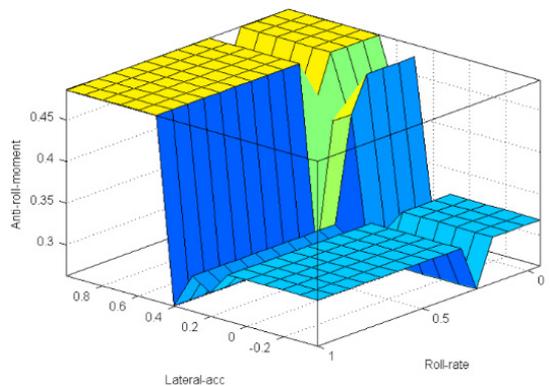


Fig. 6. The two modes rules surface

4. Simulation results

To evaluate the vehicle roll and handling dynamic behavior and the effectiveness of anti-roll bar over Fishhook maneuver, numerical evaluation are conducted using MATLAB/SIMULINK environment. This simulation code is validated and used extensively of [10]. Steering angle as an input signal to vehicle closed loop model in fishhook maneuver is illustrated in Fig. 7.

Vehicle path following (path, lateral deviation), roll (load transfer, roll rate, roll and lateral acceleration), handling performance (side slip, lateral velocity and acceleration) and control effort (roll moment) at constant speed over Fishhook maneuver are presented in three cases (Figs. 8-15 respectively); FLC (120 km/hr), without control at 90 km/hr and 120 km/hr.

Vehicle path following and deviation of desired path, demonstrate that controller can properly

control the vehicle dynamic variables to track driver intended path with minimize deviation. Also, as shown in Figs. 8 and 9, increasing longitudinal velocity during fishhook maneuver results in more deviation of vehicle from track.

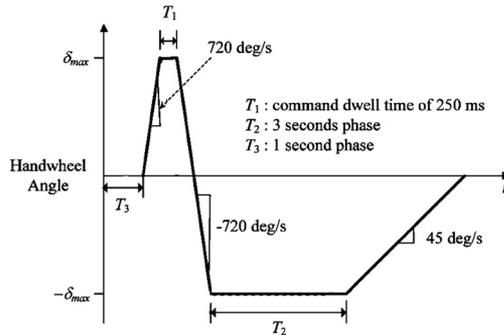


Fig. 7. Steering angle in fishhook maneuver

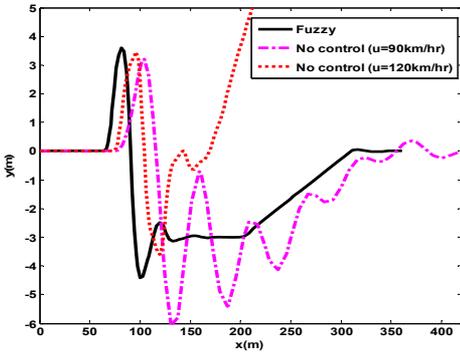


Fig. 8. Fishhook maneuver path

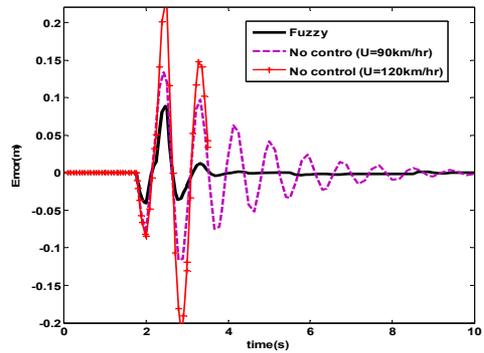


Fig. 9. Lateral deviation in fishhook maneuver

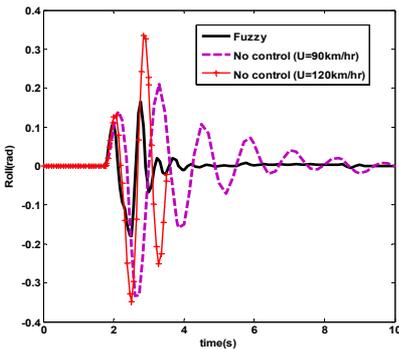


Fig. 10. Roll angle in fishhook

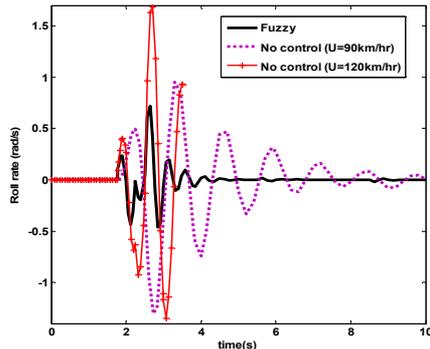


Fig. 11. Roll rate in fishhook

Simulation results of vehicle roll variables includes roll angle, roll rate, load transfer and controller moment over fishhook maneuver are depicted in Figs. 10-13 respectively. FLC has the minimum amount and oscillations of control effort and roll responses. Also, it is obvious that in without control cases, vehicle tends to rollover and with increasing the vehicle longitudinal speed from 90 km/hr to 120 km/hr turning over occurs at $t = 3.8$ second.

Furthermore, from the handling properties includes lateral acceleration of Fig. 14 and side slip angle of Fig. 15 it can be concluded that the both controllers achieves the optimal handling conditions. In controlled cases, lateral acceleration and side slip angles remain under 0.6 g and 4 degree during maneuver, which ensures vehicle stability and handling properties.

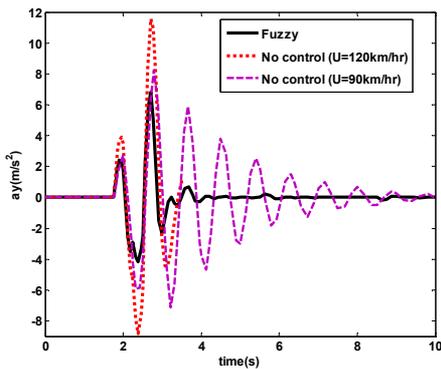


Fig. 14. Lateral acceleration in fishhook

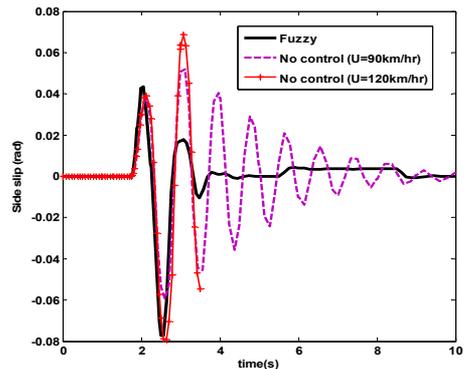


Fig. 15. Side slip angle in fishhook

5. Conclusion

In this study, the effectiveness of anti-roll bar mechanism was investigated for improving vehicle, stability, roll resistance, path following and handling properties. For this purpose FLC theory based on vehicle 3 DOF roll dynamic are developed to produce optimal momentum. Controller are trained to follow desired side slip, roll angle, and yaw rates during various fishhook maneuvers. An 8 DOF vehicle model in MATLAB/Simulink environment is utilized to simulate the controller performance and vehicle behavior. Simulation results clarified that, control strategy hold the lateral acceleration and side slip angles less than limited critical overturning and instability for various speeds and maneuvers. Moreover, the FLC roll and handling controller showed better results, with smaller control effort, roll and side slip angles in severe maneuvers. Finally, in regard to that in quick emergency maneuvers, vehicle has a greater likelihood to roll over, the sensitivity analysis of FLC to longitudinal speed is conducted. It showed that proposed controller could be more effective in high speed, which prevents the vehicle overturning in quick maneuvers.

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Javad Marzbanrad is an Associate Professor at IUST. His research interests are automotive, control and vibration and solid mechanics. Now, he is the faculty of School of Automotive Engineering in IUST.



Golamhosein Soleymani is a Ph.D. student in industrial management engineering at the Tabatabaee University. He is interested in automotive, vibration and nonlinear systems.



Mehdi Mahmoodi-k received the M.S. degree in IUST, Tehran, in 2011. Now he is a Ph.D. student in School of Mechanical Engineering, IUST. His current research interests include hybrid vehicles, vehicle dynamic, control and optimization.



Amir H. Rabiee received the B.S. and M.S. degrees in mechanical engineering from IUST, Iran in 2009 and 2011. He is currently a Ph.D. student in IUST and his research interests focus on fluid-structure interaction control and active suspension systems.