World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Yaw stability regulation of electric vehicles based on model predictive control

Abdussalam Ali Ahmed [1, *], Neeloufir Abdulsalam Alhaaj [2] and Mustafa Emheisen [3]

[1] *Mechanical and Industrial Engineering Department, Bani Waleed University, Bani Waleed, Libya.*
[2] *Control System Engineering, College of Electronic Technology, Bani Walid, Libya.*
[3] *Electrical Engineering Department, Bani Waleed University, Bani Walid, Libya.*

World Journal of Advanced Research and Reviews, 2023, 19(01), 1490–1498

Publication history: Received on 20 June 2023; revised on 26 July 2023; accepted on 28 July 2023

Article DOI: https://doi.org/10.30574/wjarr.2023.19.1.1531

Abstract

The yaw stability control system contributes significantly to the vehicle's lateral dynamics in order to enhance the vehicle's handling and stability. Controlling the lateral stability of a vehicle requires maintaining the proper yaw rate and side slip angle. For this purpose, a Model Predictive Control-based electric vehicle is built along with a stability control system. With a 2DOF vehicle model and a single track, the desired yaw rate is obtained. The controller is created using the Model Predictive Control (MPC) method. This controller modifies the steering angles of the front wheels and generates the necessary control moment for stabilizing the vehicle's yaw path. The stability control system and the developed controller are evaluated using a nonlinear single-track vehicle model, and the simulation results demonstrate improved vehicle performance and a good yaw rate compared to the vehicle's state without the controller.

Keywords: Vehicle Stability; Yaw Rate; Model Predictive Control

1. Introduction

Controlling the lateral dynamic motion of a road-vehicle is crucial for vehicle dynamic control, as it determines the vehicle's stability. A yaw stability control system is one of the primary systems published in the literature for lateral dynamics control. In order to construct an efficient control system, it is necessary to identify a suitable yaw stability control system component [1].

The lateral stability of the vehicle is a crucial performance that determines the vehicle's high-speed safety. The lateral dynamic performance is affected by numerous variables, such as the vehicle's structure, characteristics, starting operation, road conditions, tire steering angle, etc. Consequently, the design of the vehicle's lateral stability controller involved a complicated nonlinear problem. Recent research on the lateral stability of a vehicle included two factors: First, the research of vehicle lateral stability employs modern control theory and methods, such as model predictive control [2], sliding mode control [3], and so on, to use the yaw rate or slip angle as the controller's control parameters. The estimation of vital vehicle metrics and condition utilizing cutting-edge technology is another factor [4].

Some scholars propose control methods for vehicle stability and control, for example, Fuzzy PID control [5], Neural Network-Based Controller [6], traditional PID control method [7], Sliding Mode Control (SMC) [8], H/sub infinity / analysis and synthesis [9], Design of linear quadratic regulator (LQR) control [10], fractional-order PID control [11], and a hybrid LQR-PID control [12]. In addition to many other control methods available in research published in scientific journals and conferences.

* Corresponding author: Abdussalam Ali Ahmed
Mechanical and Industrial Engineering Department, Bani Waleed University, Bani Walid/Libya.

This study will develop a Simulink model of a vehicle stability system utilizing a model predictive controller and two vehicle models. The vehicle model utilized for this purpose will have seven degrees of freedom.

The study is structured as follows: in part II, the 7-DOF vehicle model represents the mathematical model of the actual vehicle. In the third section, the 2-DOF vehicle model is used for controller design and depicts the reference or desired model. In part IV, the control strategy demonstrates the complete Simulink model of the vehicle control system, whilst in section V, findings and simulation investigations of the yaw stability are shown to prove the superior tracking performance attained by utilizing a model predictive controller. In Section VI, conclusions are drawn.

2. Simulation models

This part of the paper shows two important models used in creating the control system of the vehicle, the first model is expressive of a 7 DOF model represents an actual vehicle, while the second model is 2 DOF model and is called the reference or bicycle model which to design of the controller and is also used to calculate the ideal reference yaw rate value.

2.1. Vehicle model

As depicted in Figure 1, the 7 DOF whole vehicle model includes the lateral, longitudinal, and yaw movements of the vehicle as well as the four-wheel movements. The vehicle's pitch, roll, and vertical movement were disregarded. Consequently, the longitudinal, lateral, and yaw movements of the vehicle, as well as the tire movement, were described as [13]:

The following describes the dynamic equations for the lateral, longitudinal, and yaw motions of the vehicle body.

- For yaw motion:

$$I\,\dot{Y}_r = L_1(F_x^{fR} + F_x^{fL})sin\delta + L_1(F_y^{fR} + F_y^{fL})cos\delta - L_2(F_y^{rL} + F_y^{rR}) + \frac{D}{2}(F_x^{fR} - F_x^{fL})cos\delta + \frac{D}{2}(F_x^{rR} - F_x^{rL}) + \frac{D}{2}(F_y^{fL} - F_y^{fR})sin\delta \quad (1)$$

- For lateral motion:

$$\dot{v_y} + v_x Y_r = \frac{1}{m}[(F_y^{fL} + F_y^{fR})cos\delta + (F_y^{fR} + F_y^{fL})sin\delta + (F_x^{fR} + F_x^{fL})sin\delta + F_y^{rR} + F_y^{rL}] \quad (2)$$

- For longitudinal motion:

$$\dot{v_y} + v_x Y_r = \frac{1}{m}[(F_y^{fL} + F_y^{fR})cos\delta + (F_y^{fR} + F_y^{fL})sin\delta + (F_x^{fR} + F_x^{fL})sin\delta + F_y^{rR} + F_y^{rL}] \quad (3)$$

F_y^{fL}, F_y^{fR}, F_y^{rL}, F_y^{rR}, F_x^{fR}, F_x^{fL}, F_x^{rR}, F_x^{rL} are the components of forces for the front left tire, front right tire, rear left tire, and the rear right tire along x axis y and axis coordinates; D is the displacement between left and right tires; a ,b are the displacement of the COG of the vehicle to both of front and rear axle; v_x , v_y are the car longitudinal and the car lateral velocity, Y_r is the vehicle yaw rate, δ is the front wheel steering angle, m is the vehicle total mass, I is the vehicle moment inertia about its yaw. F_x and F_y represent the tire forces, which will be determined using the Dugoff tire model.

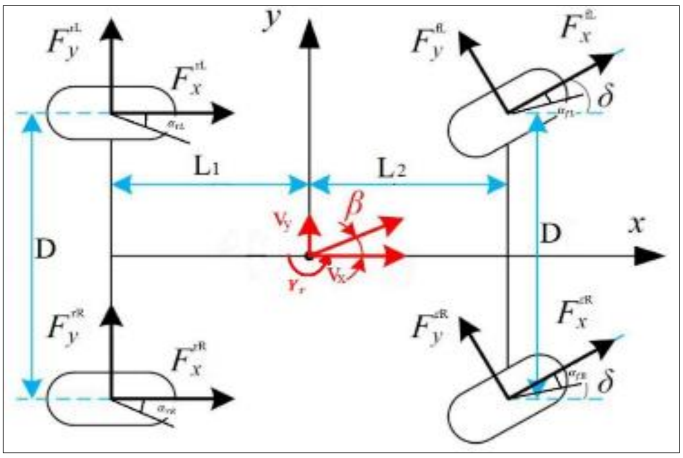

Figure 1 The Vehicle model.

2.2. 2 DOF vehicle model (Biyscle model)

In vehicle dynamic studies, the conventional 2 DOF vehicle model, often known as the bicycle model and seen in Figure 2, is widely used for yaw stability control analysis and controller design. This model is linearized from the nonlinear vehicle model on the basis of the following assumptions, which include:

(1) Tire force (F_x and F_y)operates in the linear region, (2) The vehicle moves on flat or plane road (planar motion), (3) Left and right wheels at the front and rear axles are lumped into a single wheel at the center line of the vehicle, (4) Constant vehicle speed i.e. the longitudinal acceleration equal to zero (a_x=0), (5) Sideslip angle are assumed to be small (0), (6) No braking is applied at the two wheels, (8) Both front wheels have the same steering angle, and (9) desired vehicle sideslip is assumed to be zero in steady-state conditions.

The following equations represent the differential equations of lateral and yaw motions of the reference model:

$$mv(\dot{\beta}_d - Y_{rd}) = (F_y^f + F_y^r) - Y_{rd} \quad (4)$$
$$I_z Y_{rd} = a.F_y^f - b.F_y^r \quad (5)$$
$$F_y^f = C_{af}.\alpha_f \quad (6)$$
$$F_y^r = C_{ar}.\alpha_r \quad (7)$$
$$\alpha_f = \delta - \beta_d - \frac{L_1.Y_{rd}}{v} \quad (8)$$
$$\alpha_r = -\beta_d + \frac{L_2.Y_{rd}}{v} \quad (9)$$

Where:

Y_{rd}, β_d are the desired vehicle yaw rate and desired vehicle sideslip angle.

C_{af} , C_{ar} are the longitudinal and the lateral stiffness of front wheel and rear wheel.

L_1 , L_2 are the displacement of the COG of the vehicle to both of front and rear axle.

α_f , α_r are the slip angle of front and rear tire.

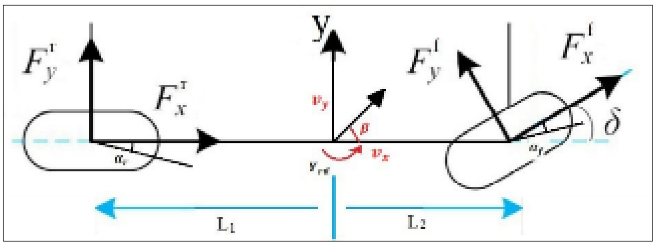

Figure 2 2 DOF vehicle model (Bicycle model**)**

In this model, the front and rear lateral tire forces F_y^f and F_y^rdisplay linear characteristics and are characterized as a linear function of the front and rear cornering stiffness, C_1 and C_2.

$$F_y^f = C_1.\alpha_f \quad (10)$$

$$F_y^r = C_2.\alpha_r \quad (11)$$

Where α_f and α_r are the sideslip angle at each wheel.

2.3. Dynamic response of vehicle model

MATLAB Simulink is used to analyze and simulate the previously mentioned vehicle model. It is presumed that the car is moving at an average speed of 70 km/h. In the simulations, the motorcar receives step and sinusoidal steering signals. The driver steering input for the step maneuver is shown in Figure 3. The step steering angle's amplitude is assumed to be 2 degrees (0.035 rad).

In the other case, the vehicle receives the sinusoidal steering input. The driver's steering input for the manoeuvre is shown in Figure 4. The peak value of the steering angle is assumed to be 2 degrees (0.035 rad).

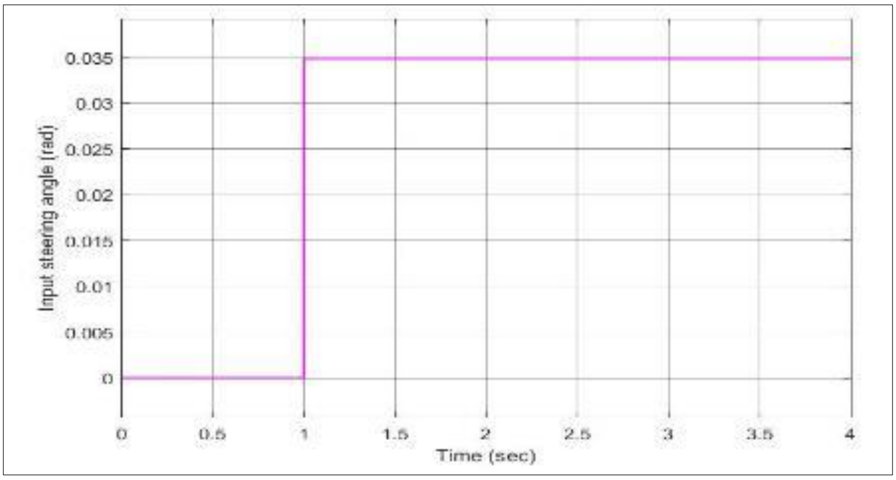

Figure 3 The steering input of vehicle maneuver

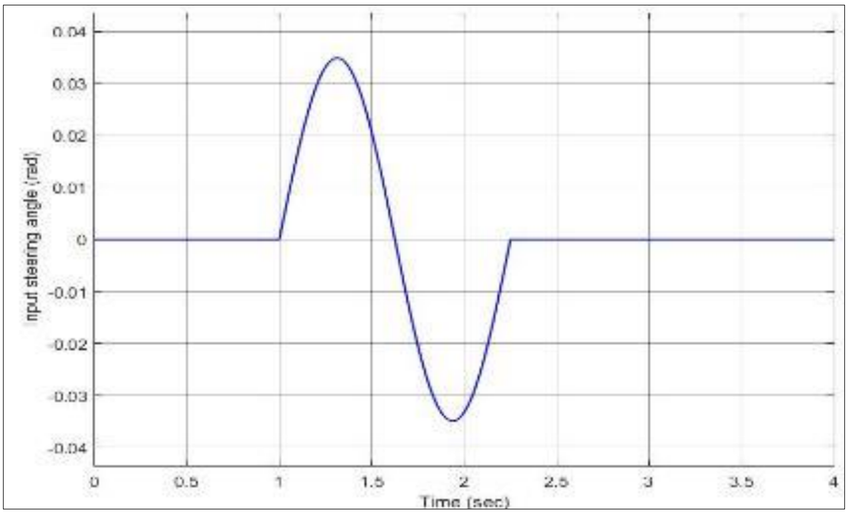

Figure 4 The steering input of vehicle with a lane change maneuver.

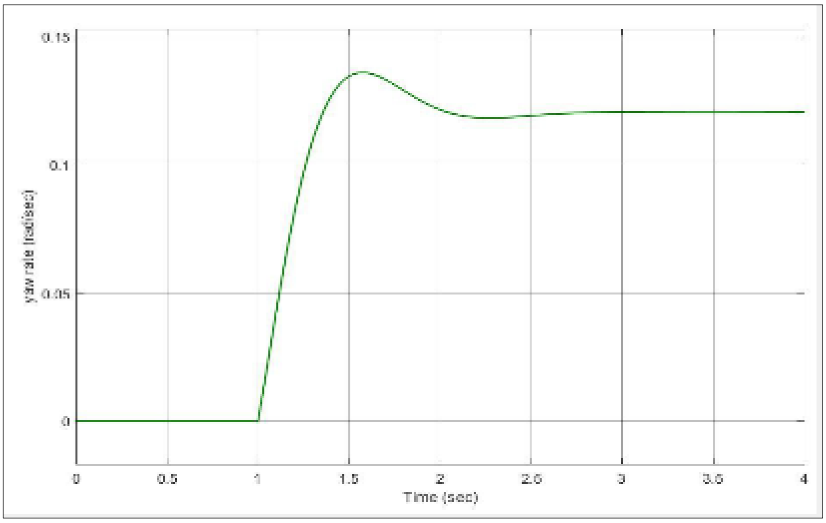

Figure 5 The vehicle yaw rate at a step signal of steering angle

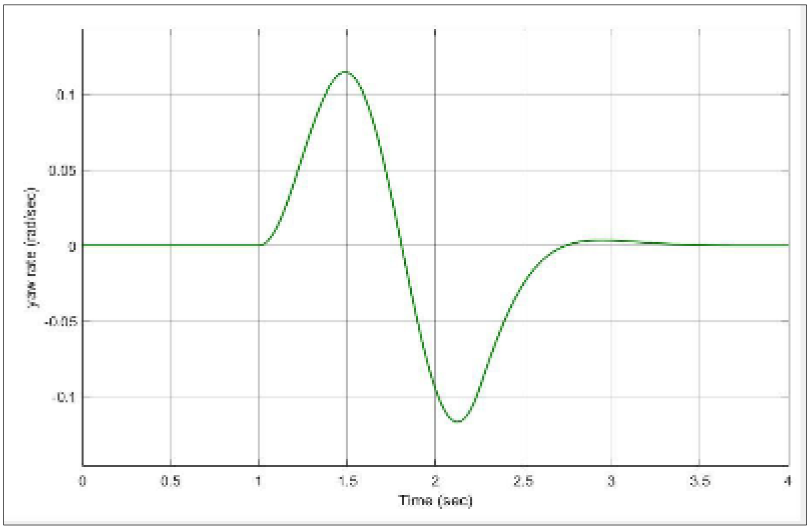

Figure 6 The vehicle yaw rate on a lane change maneuver

In this paper, step and change of lane manoeuvres, as well as driving angle, will be used to measure and compare the vehicle's performance. This simulation produced the car's yaw rate performance for the passive scenario, which can be seen in Figures 5 and figure 6.

3. Model Predictive Control

An effective method for managing both linear and non-linear dynamic behavior of systems is the Model Predictive Controller (MPC), an advanced control system engineering technique. A Model Predictive Controller's (MPC) capability to handle multivariable dynamics and operational limitations effectively is its key advantage.

Figures 7 depicts the model predictive control block diagram and the fundamental notion of model predictive control with receding horizon control. It fits the following description of a strategy method: utilizing historical and current data to make predictions about the process output at a limited control horizon. Then, a control signal sequence is calculated by the optimizer taking into consideration the cost function and the constraints. The final step is performing the first control actions each time.

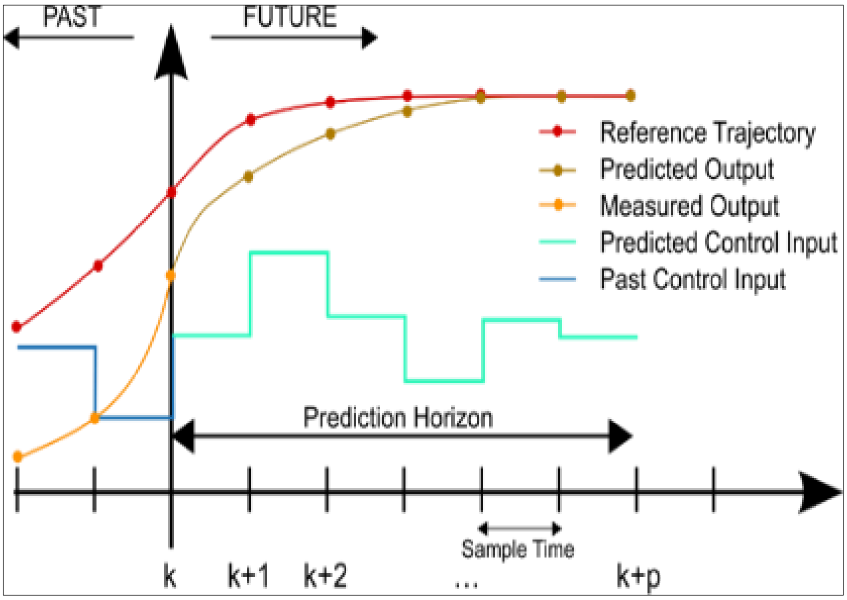

Figure 7 Basic principle of model predictive controller

4. Control techniques and strategies

n this paper, model predictive controller (MPC) is designed to enhance and improve the yaw stability of four-wheel drive vehicle. A control system is designed which includes three components: the Bicycle model reference vehicle model (reference vehicle model), planar model of the vehicle (A nonlinear model which represents actual vehicle), and the controller (MPC Controller). The structure of the control system of vehicle model with controller is illustrated in Figure 8.

A method for determining the ideal values of vehicle yaw rate and sideslip angle can be done using reference model and based on the steering angle (δ) which can be derived through the driver action.

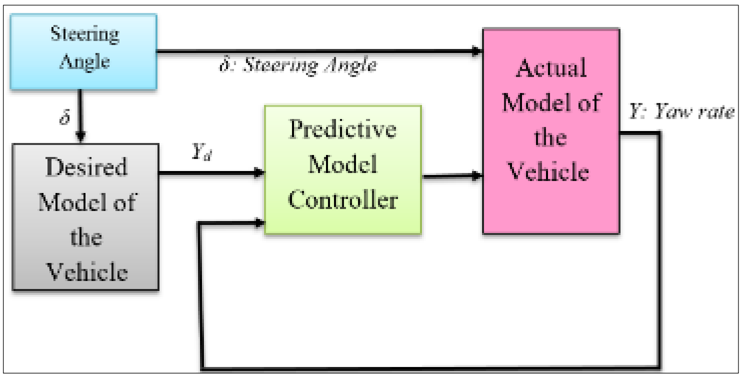

Figure 8 Vehicle control system Simulink structure

5. Matlab simulations and discussion

As mentioned previously, in this paper the MPC controller was used, however we decided to compare the simulation results that resulted from the use of the MPC controller with the results of other simulations in which the traditional PID controller was used, where it was found that there was a slight difference in the results of the yaw rate and the sideslip angle when using the two controllers.

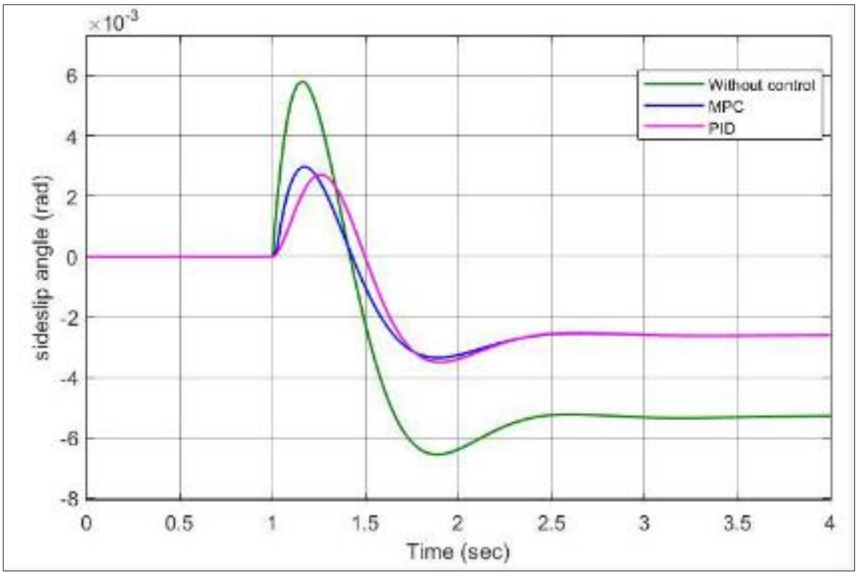

Figure 9 The vehicle sideslip angle at a step signal of steering angle

In order to evaluate the suggested controller system, two independent simulation experiments are carried out. a step steering angle was used for the initial simulation. The steering angle's amplitude is set to 2 degrees (0.035 rad), and the vehicle's speed is assumed to be 70 km/h.

The side slip angles are shown in Figure 9. The side slip angles of both controllers may be greatly reduced by steering the car's axles.

This simulation revealed differences in vehicle yaw rate for the passive and active scenarios, which can be observed in Figure 10. These results demonstrate that the controlled vehicle yaw rate response closely matches the planned yaw rate. Model predictive control is obviously more successful than PID in terms of effectiveness.

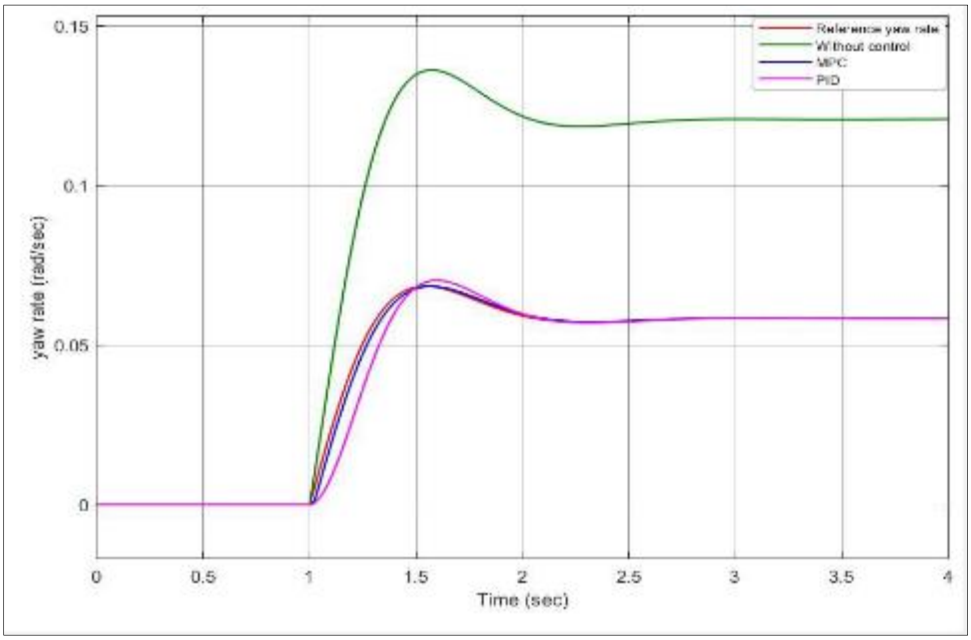

Figure 10 The vehicle yaw rate behavior at a step signal of steering angle

The second simulation involves changing lanes maneuver. The steering input is set to a sinusoidal input with a 2 degrees (0.035 rad) amplitude.

Figure 11 and figure 12 demonstrate that the vehicle's yaw rate is nearly identical to the reference yaw rate. Furthermore, it is obvious that the side slip angle has gone down. Overall, the simulation findings show that all controllers, with the MPC controller preferred, are enhancing the lateral vehicle's performance.

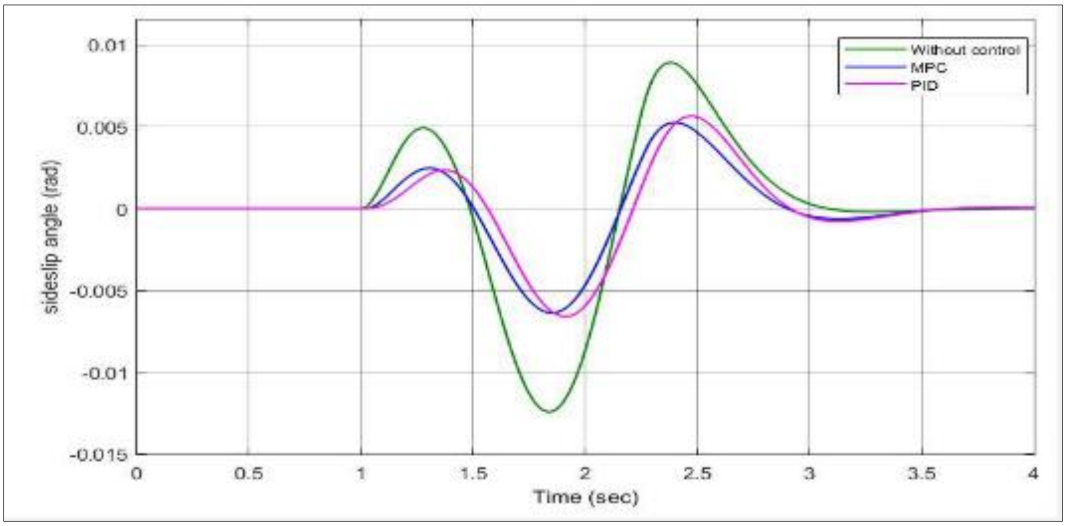

Figure 11 The vehicle sideslip angle on a lane change maneuver

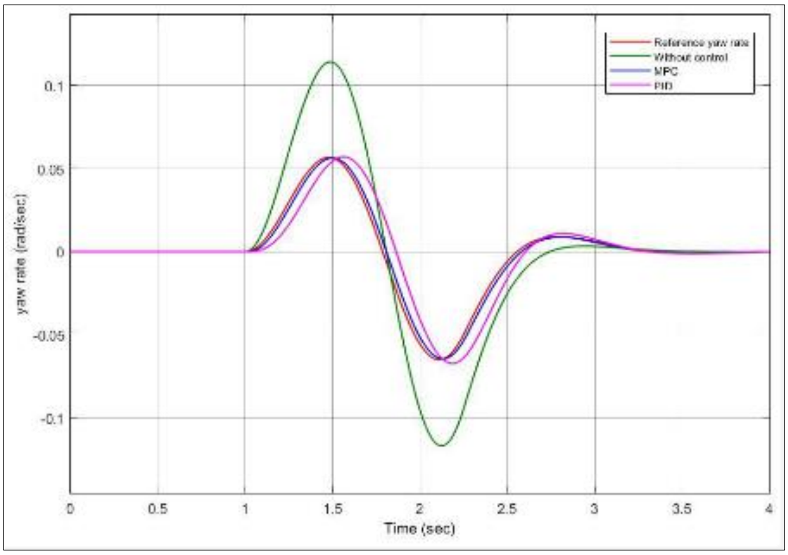

Figure 12 The vehicle yaw rate behavior on a lane change maneuver.

6. Conclusion

Aiming at improving the stability of vehicles and handling, the MATLAB Simulink model of the vehicle is implemented with MPC and PID controller to improve and ensure the vehicle yaw stability in this paper. To make sure this controller works well it has been tested at two scenarios of the input steering angle which are a step signal and a lane change maneuver. The results and plots show significant differences between the vehicle yaw rate and the vehicle body sideslip angle behaviors in the case when there is no control and the vehicle performance in the case with the model predictive controller. It is found that the yaw rate of the vehicle improved significantly, therefore, a vehicle control system constructed with MPC can achieve and enhance the required stability and performance of the vehicle. Also, it's noted that the Model predictive control is obviously more successful than the PID controller in terms of effectiveness.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no competing interests.

References

[1] M. K. Aripin, Y. Md Sam, Kumeresan A. Danapalasingam, K. Peng, N. Hamzah, M. F. Ismail, "A Review of Active Yaw Control System for Vehicle Handling and Stability Enhancement", International Journal of Vehicular Technology, vol. 2014, 2014.

[2] K. Huh, C. Seo, J. Kim, D. Hong, "Active Steering Control Based on the Estimated Tire Forces," Proc. of ACC, San Diego, USA, June 1999, pp. 729–733.

[3] T. Hiraoka, O. Nishihara, H. Kumamoto. "Modelfollowingsliding mode control for active four-wheel steering vehicle," JSAE, vol.25, no.4, 2004, pp. 305–313.

[4] D. M. Bevly, J. Ryu, J. C. Gerdes, "Integrating INS sensors with GPS measurements for continuous estimation of vehicle sideslip, roll, and tire cornering stiffness," IEEE Transactions on the intelligent transportation system, vol.4, no.7, 2006, pp. 483–493.

[5] A. A. Ahmed, A. Sami, A. Alsharif, A. S. D. Alarga, J. Santhosh and A. Albagul, "Evaluation of Electric Vehicle Stability Using Fractional PID and Fuzzy PID Based Controllers," 2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA), Sabratha, Libya, 2022, pp. 116-120, doi: 10.1109/MI-STA54861.2022.9837532.

[6] A. A. Ahmed, A. Alsharif, T. Triwiyanto, M. Khaleel, C. W. Tan and R. Ayop, "Using of Neural Network-Based Controller to Obtain the Effect of Hub Motors Weight on Electric Vehicle Ride Comfort," 2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA), Sabratha, Libya, 2022, pp. 189-192, doi: 10.1109/MI-STA54861.2022.9837608.

[7] Zhang Jinzhu and Zhang Hongtian, "Vehicle stability control based on adaptive PID control with single neuron network," 2010 2nd International Asia Conference on Informatics in Control, Automation and Robotics (CAR 2010), Wuhan, China, 2010, pp. 434-437, doi: 10.1109/CAR.2010.5456803.

[8] H. BENARIBA and A. BOUMEDIENE, "Lateral Sliding Mode Control of an Electric Vehicle," 2018 6th International Conference on Control Engineering & Information Technology (CEIT), Istanbul, Turkey, 2018, pp. 1-5, doi: 10.1109/CEIT.2018.8751932.

[9] S. Mammar, "Lateral vehicle control using gain scheduled H/sub /spl infin// controllers," Proceedings of Conference on Intelligent Transportation Systems, Boston, MA, USA, 1997, pp. 248-253, doi: 10.1109/ITSC.1997.660483.

[10] A. Lu, Z. Lu, R. Li and G. Tian, "Adaptive LQR Path Tracking Control for 4WS Electric Vehicles Based on Genetic Algorithm," 2022 6th CAA International Conference on Vehicular Control and Intelligence (CVCI), Nanjing, China, 2022, pp. 1-6, doi: 10.1109/CVCI56766.2022.9964887.

[11] X. Dong, H. Pei and M. Gan, "Autonomous Vehicle Lateral Control Based on Fractional-order PID," 2021 IEEE 5th Information Technology,Networking,Electronic and Automation Control Conference (ITNEC), Xi'an, China, 2021, pp. 830-835, doi: 10.1109/ITNEC52019.2021.9586818.

[12] I. Yogurtçu, S. Solmaz and S. Ç. Baslamish, "Lateral Stability Control Based on Active Motor Torque Control for Electric and Hybrid Vehicles," 2015 IEEE European Modelling Symposium (EMS), Madrid, Spain, 2015, pp. 213-218, doi: 10.1109/EMS.2015.41.

[13] You Seung-Han, Hahn Jin-Oh, Lee Hyeong-cheol, New adaptive approaches to real-time estimation of vehicle sideslip angle, Control Engineering Practice. volooume. 17, December. 2009, pp. 1367–1379.

[14] Ahmed AA, Abunada ARH. Vehicle Yaw Rate Control Based on Fuzzy PID Control Technology. J Adv Res Mech Engi Tech 2018; 5(3&4): 17-23.

[15] L. Zhai, C. Wang, Y. Hou and C. Liu, "MPC-Based Integrated Control of Trajectory Tracking and Handling Stability for Intelligent Driving Vehicle Driven by Four Hub Motor," in IEEE Transactions on Vehicular Technology, vol. 71, no. 3, pp. 2668-2680, March 2022, doi: 10.1109/TVT.2022.3140240.

[16] W. Zhang, Z. Wang, L. Drugge and M. Nybacka, "Evaluating Model Predictive Path Following and Yaw Stability Controllers for Over-Actuated Autonomous Electric Vehicles," in IEEE Transactions on Vehicular Technology, vol. 69, no. 11, pp. 12807-12821, Nov. 2020, doi: 10.1109/TVT.2020.3030863.

[17] Abubaker Abasalam A. Emheisen, Abdussalam Ali Ahmed, Nasr Ismael Alhusein, Abdurahim Alfadel Sakeb, Abdulhamid.S. Abdulhamid,“ Car Wheel slip Modelling, Simulation, And Control Using Quarter Car Model”, International Journal of Engineering Trends and Technology (IJETT), Vol. 28, No. 06, October2015.

[18] S. Wang, X. Zhao, Q. Yu, S. Zhang, P. Shi and M. Yu, "Research on Strategy of the Stability Control System of Dual-Motor Drive Electric Vehicle," 2019 IEEE International Symposium on Circuits and Systems (ISCAS), Sapporo, Japan, 2019, pp. 1-5, doi: 10.1109/ISCAS.2019.8702238.

[19] S. Wang, X. Zhao, Q. Yu, S. Zhang, P. Shi and M. Yu, "Research on Strategy of the Stability Control System of Dual-Motor Drive Electric Vehicle," 2019 IEEE International Symposium on Circuits and Systems (ISCAS), Sapporo, Japan, 2019, pp. 1-5, doi: 10.1109/ISCAS.2019.8702238.

[20] Almabrok Rahel Almaktar Shakaf, Adel Ramadan Hussien Mohamed, Abdussalam Ali Ahmed, “Effect of Aerodynamic Drag Force Parameters on Electric Vehicle Motion Performance”, World Wide Journal of Multidisciplinary Research and Development, Volume 4, Issue 1 (2018) pp. 197-201

[21] S. Zheng et al., "Model predictive control based vehicle stability control via active front steering," 2017 Chinese Automation Congress (CAC), Jinan, China, 2017, pp. 4660-4665, doi: 10.1109/CAC.2017.8243602.

[22] Z. Li, P. Wang, H. Liu, Y. Hu and H. Chen, "Coordinated longitudinal and lateral vehicle stability control based on the combined-slip tire model in the MPC framework," 2021 5th CAA International Conference on Vehicular Control and Intelligence (CVCI), Tianjin, China, 2021, pp. 1-2, doi: 10.1109/CVCI54083.2021.9661187.

[23] Abebe, B. A., Santhosh, J., Ahmed, A. A., Murugan, P. and Ashok, N. (2020). Non-Linear Mathematical Modelling for Quarter Car Suspension Model. International Journal on Emerging Technologies, 11(5):536–544.

[24] Z. A. Leman, M. Hatta Mohammad Ariff, H. Zamzuri, M. A. Abdul Rahman and S. Amri Mazlan, "Model Predictive Controller for Path Tracking and Obstacle Avoidance Manoeuvre on Autonomous Vehicle," 2019 12th Asian Control Conference (ASCC), Kitakyushu, Japan, 2019, pp. 1271-1276.

[25] Y. Guan, H. Zhou, Z. He and Z. Liu, "Vehicle Safety and Comfort Control base on Semi-Active Suspension," 2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI), Hangzhou, China, 2020, pp. 259-263, doi: 10.1109/CVCI51460.2020.9338527.