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DEVELOPMENT OF A TIRE MODELING WITH ADAMS/SIMULINK TO STUDY THE VEHICLE CONTROL

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Abstract. *A tire model plays an important role in the study of the dynamic behavior of a vehicle when designing a control system such as stability control. In this study, the Magic Formula tire model was implemented using Matlab/Simulink® and MSC Adams®, for this a co-simulation was developed. Tire modeling is the first step requested where vehicle handling stability requires to be investigated. The tire model was implemented based on a set of mathematical equations of the magic formula. Simulink® blocks that represent tire responses are simplified into subsystems that generated longitudinal force, lateral force and aligning moment. The results of every tire are computed and observed. The implemented model was compared with the existing model of magic formula in the MSC Adams® software. The output variables generated from the implemented model are compared with MSC Adams® default output variables. The results are analyzed and discussed. Since the model is corrected and validated, it will be used in designing a control for vehicles.*

Keywords: *tire, vehicle dynamic, magic formula, co-simulation, model.*

1. INTRODUCTION

Simulation of multibody systems is an important tool for the vehicle design, especially in the early stages of the process to evaluate its dynamic behavior while reducing development costs. According to Vieira et. al. (2012), vehicle handling is the key consideration in modern vehicle design. Handling is directly associated with safety and comfort.

The main forces and moments that affect the vehicle movement, beyond the aerodynamic and gravitational forces, are applied through the contact between the tire and the ground. An understanding of the basic features of the interaction between the tire and the ground is essential to the study of vehicle performance and its basic characteristics like the handling and maneuverability. Thus, the tire model is a central element for the development of a representative model of vehicle dynamics. Tire studies are commonly divided into two aspects: longitudinal and lateral behavior. Information regarding the lateral behavior of a tire helps determine the vehicle handling and lateral stability properties according with Burhaumudin et. al. (2012).

There are several simulation tools of multibody systems. In this work, in order to design a co-simulation environment for a vehicle, we used the MSC Adams® software to develop a model of a vehicle system interacting with the road. The model of the tire is also designed using Matlab/Simulink® software to in the future implement the controls. Thus, this tire model and vehicle handling model will be used for vehicle dynamic analysis and control. The forces and moments that are generated by the tire will affect the vehicle body stability and a control algorithm can be required to control vehicle state to enhance vehicle handling stability.

The goal of this paper is to develop a vehicle model for improving dynamic study in the stable area. The use of formula magic tire model is investigated by adjusting the model from Simulink® with the model from MSC Adams®.

2. VEHICLE MODEL

According to Kasprzak (2006) there are innumerable tire models in use around the world, which vary in complexity, scope and purpose. They can be based on detailed tire structural models, finite element calculations or semi-empirical equations. Purposes range from tire ride modeling, envelopment of road surface irregularities, tread shape analysis, rolling resistance calculations, tire dynamics, tire force and moment. All tire models in use have their own strengths, weaknesses and applications to which they are well suited.

In this work, the contact between the tire and the road is modeled by the PAC89 tire model of MSC Adams® based on magic-formula. This model calculates the forces Fx and Fy and moment My in the point of contact between the tire and the ground as a function of: normal load, longitudinal and lateral slip and angle of inclination of the road.

2.1 Tire Model

Figure 1 presents the correlation between the tire forces and velocity in contact. For the equations of motion and the model some hypotheses must be considered: 1) the system is treated as a rigid and symmetrical body to the long of the longitudinal axle, possessing three degrees of freedom, 2) the resultant lateral force exerted by the ground is perpendicular to the plan of the wheel and acts directly on the projection of the wheel's center, 3) the slip angle (α_i) is small and assumes a linear relation between the slip angle and the friction force.

These hypotheses became possible that the differential equation of motion is linear and no much information will be lost with this simplification. Thus the motion of the system can be considered as rigid body in plan x-y.

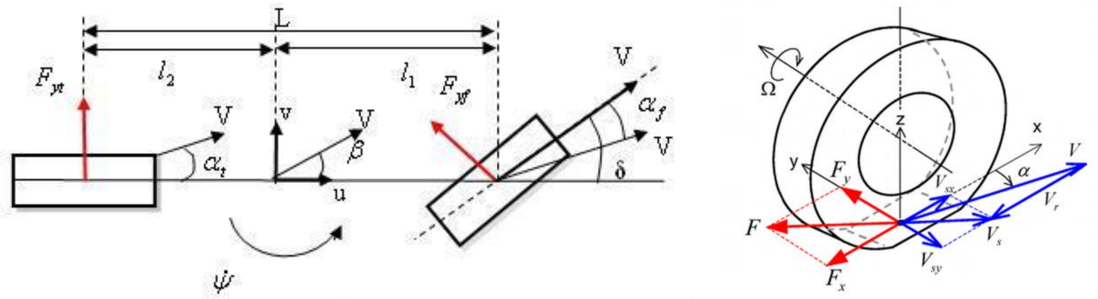


Figure 1- Tire references (Xu, 2011)

Where:

F_{yt} and F_{yf} = lateral force on the rear axle and the front axle (N)

β = sideslip angle of the vehicle (rad)

δ = steering angle (rad)

α_t and α_f = slip angle of the tire on the rear and front axle (rad)

$\dot{\psi}$ = yaw velocity (m/s^2)

V= vehicle speed (m/s^2)

v_x and v_y = components of the velocity along x and y (m/s^2)

v_t and v_f = velocity on the rear and front (m/s^2)

L= wheelbase (m)

l_1 = distance between center of mass and front axle (m)

l_2 = Distance between center of mass and rear axle (m)

Ω= wheel velocity (rad/s)

The Magic Formula Model is a semi-empirical model and needs a set of parameters to describe the tire properties. This model is capable of describing steady-state tire force and moment characteristics at pure and at combined slip conditions.

Published by Pacejka (1993) the general formula that calculates the longitudinal force, the lateral force and the aligning torque, is:

$$y(x) = D\sin(C\arctan(Bx - E(Bx - \arctan(Bx)))) \tag{1}$$

With:

$$\begin{aligned} Y(x) &= y(x) + S_V \\ x &= X + S_H \end{aligned} \tag{2}$$

Y(x) represents the forces, the moment or pneumatic trail and X denotes the slip angle or the longitudinal slip. Thus to use the magical formula, it is necessary to get some parameters for the modeling and simulation, as shown:

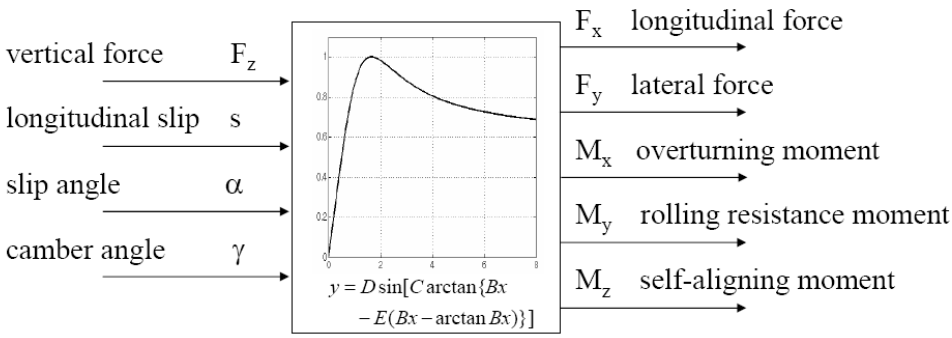


Figure 2. Representation of the parameters of exit and entrance of magic formula

According to Genta (1997) the slip angle and the longitudinal slip are calculated with the slip velocities at the contact point. Then can be calculated:

$$\tan\alpha = \frac{V_{sy}}{|V_x|} \tag{3}$$

$$s = -\frac{V_{sx}}{V_x} \tag{4}$$

The tire rotational velocity and lateral slip are time dependent because of the variable interaction forces in between the tire and the road. (MSC Adams®, 2006).

Figure 3 present a set curves $F_y(F_x)$ at constant slip angle (α). The experimental curve can be expressed as an ellipse approximated.

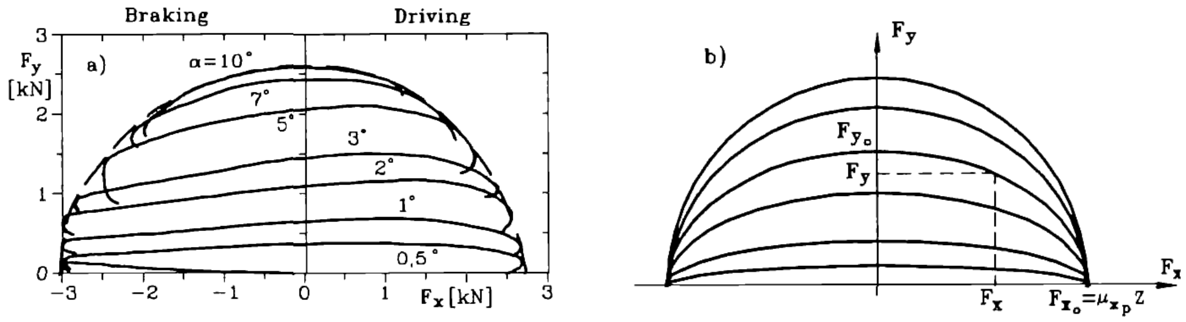


Figure 3. Experimental Graph and Ellipse approximated (Genta, 1997)

The ellipse approximated can be obtained as:

$$\left(\frac{Fx}{Fx\max}\right)^2 + \left(\frac{Fy}{Fy\max}\right)^2 = 1 \tag{5}$$

Where F_{ymax} and F_{xmax} are respectively the force F_y exerted, at the given sideslip angle, when no force F_x is exerted and the maximum longitudinal force exerted at zero sideslip angle.

Longitudinal force has influence not only in lateral force, but also in the self-aligning moment. Therefore an interaction between the longitudinal force and the self-moment should be considered. According to MSC Software Corporation (2006), an incremental aligning torque due to longitudinal force should be applied in the total self-aligning moment M_z:

$$M_z = M_{z(pacejka)} + F_x \times deflection \tag{6}$$

$$deflection = \frac{F_y}{lateral\ stiffness} \tag{7}$$

3. ADAMS SIMULATION

The tire rotational velocity and lateral slip are time dependent because of the variable interaction forces in between the tire and the road. (MSC Software Corporation, 2006) Thus, the Magic Formula was implemented in MSC Adams® using the Pac 89 tires function as shown in Figure 4.

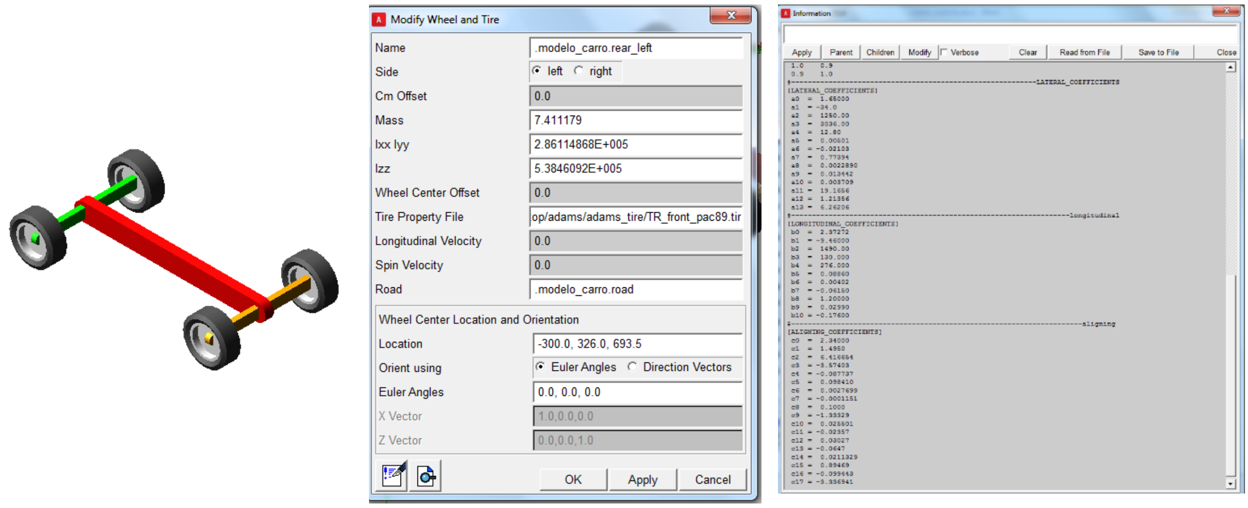


Figure 4. MSC Adams® Simulation

The model was based on a small commercial car with the parameter presented in table 1. The same concept and parameters were development, but all the equation was implemented in Simulink® and the visualization was made in the MSC Adams®. It was developed a co-simulation between MSC Adams® and Simulink®.

Table 1. Simulated vehicle parameters

Components	Units	Value
Total vehicle mass	kg	980
Wheelbase	m	2.443
Gravity center height	m	0.53
Rear axle to gravity center	m	1.460
Tire radius	mm	340.6
Tire width	mm	255

4. CO-SIMULATION

According to Zhu et. al. (2010), the co-simulation technique based on MSC Adams® and Matlab/Simulink® cooperation can be a useful tool for development. This technique can be applied for a design of a mechatronic system like vehicles, mobile robots, manipulators, wheelchair and other mechatronic system with a complex mechanical structure and a dynamic behavior with a control system.

In mechatronic design, normally the engineers create separated models and then make a connection between them according to Brenzina et. al. (2011). For future studies, the authors have the same idea; first create a correct vehicle model and then the control system. Thus, the co-simulation allows this combination. In this paper, the co-simulation used is present in figure 5.

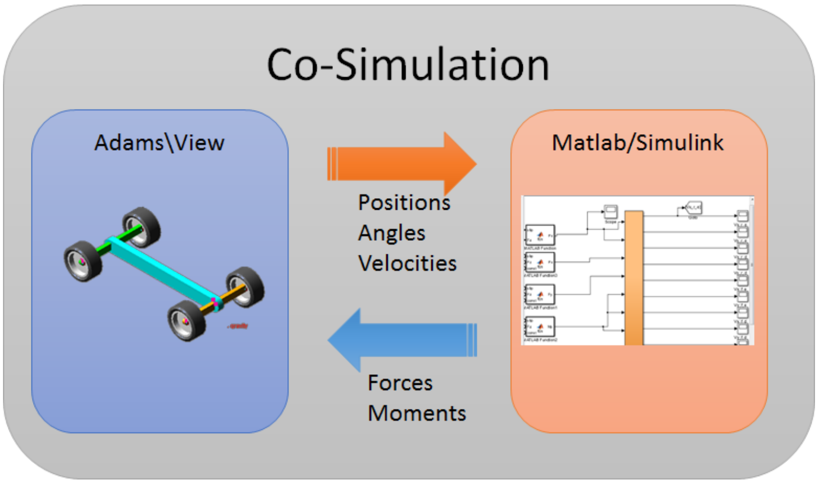


Figure 5 – Co-Simulation proposed (Brezina et al., 2011)

The co-simulation developed in this paper is to import the vehicle platform (inertia and dimension as shown in table 1) into Matlab® through the interface of module Adams/Control® and combine the force and moment of the tire contact to make sure that we can simulate the correct tire models using the model proposed. Also with this co-simulation facilitates the view of vehicle behavior.

Figure 6 shows the forces and moments applied on the wheel to simulate the pacejka tire model. The tire was built using a cylindrical solid body, a planar joint was also included to represent the ground (road). The force and moment were applied in the wheel center to avoid any moment in the vehicle. In the MSC Adams® are measured the longitudinal and lateral velocity and the rotation speed of each wheel.

The input and the output parameter of the MSC Adams® model is huge. Therefore, all the input and output should be multiply for four. The MSC Adams® block in the Matlab/Simulink® has in total around of 12 inputs (lateral and longitudinal force and moment) and 14 outputs (lateral and longitudinal velocity, wheel rotation and vehicle position). The figure 6 presents the input applied in one wheel of the vehicle.

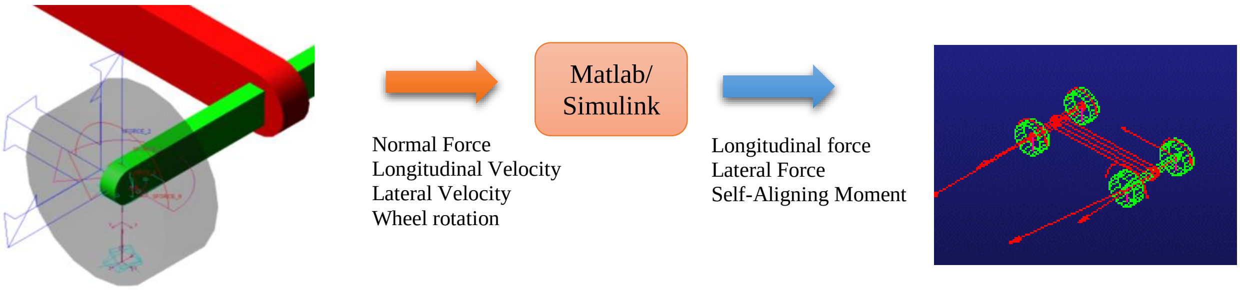
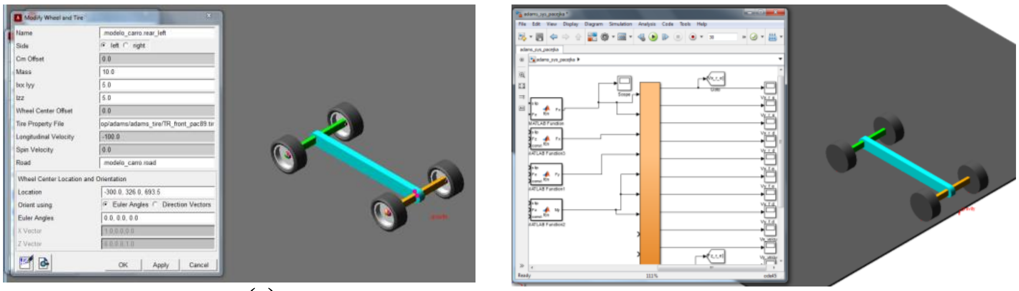


Figure 6 – Simulation parameters for Pacejka simulation in Matlab/Simulink®

5. SIMULATION AND COMPARISON

Two different models were developed in this paper. First, it was using the tire model already implemented in MSC Adams® software and the second was a co-simulation where the tire model was implemented in Matlab/Simulink® (Figure 7). The parameters used are the same in the both models, thus the same vehicle parameters of table 1 and the pacejka coefficients.

The proposed model was validated via simulation, as in work Han et. al (2000). Therefore, the proposed model (second model) was compared with an existent tire model in the MSC Adams® software (first model).



(a) (b)

Figure 7. Simulation model of: (a) PAC 89 MSC Adams® and (b) Simulink/Adams®

The goal of the simulation was to follow a reference position with the same input condition. Therefore, the same torque was applied in the rear wheels in the both models. Figure 8 presents the same torque value in the rear wheel, thus the vehicle will go straight ahead. It can be observed in the simulation and the behavior was the same in PAC 89 MSC Adams® and co-simulation in Simulink®. Therefore, the Simulink® line was overlying the Adams® line in the beginning.

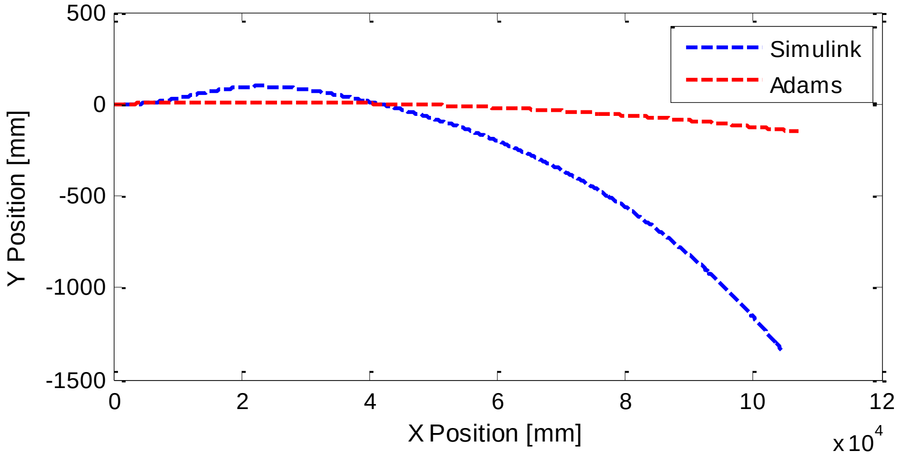


Figure 8- Planar position of the vehicle in the both models

Different torque was applied in the rear wheels, thus the vehicle performs a curve. As the model is simply and the idea of this paper is only modeling the tire, it was not yet made a steering system on the front wheels. Therefore, the vehicle will make smooth and slowly with according to the lateral slip. The simulation results are presented in figure 9.

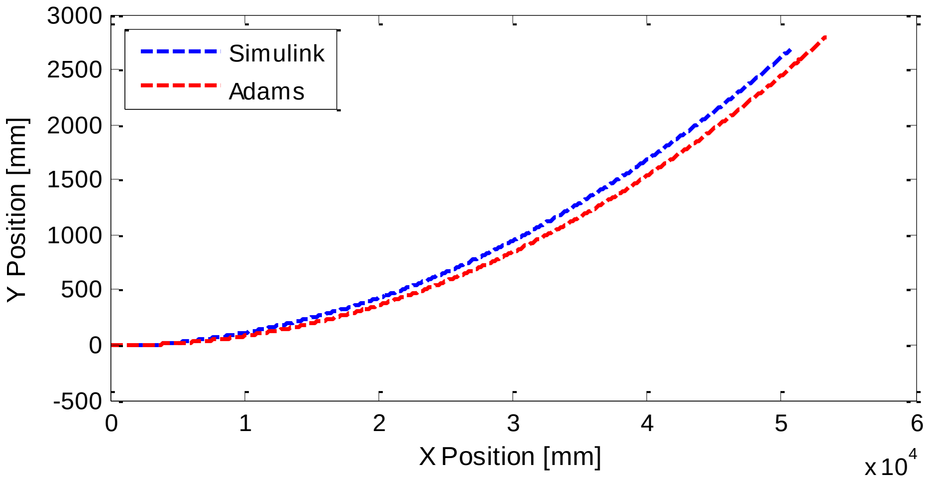


Figure 9 – Planar position of the vehicle for the both models

To evaluate the difference between the simulation results, it was used the linear correlation (r) between the MSC Adams® and Simulink® position.

$$r^2 = \frac{\left(\Sigma(x_i - \bar{x})(y_i - \bar{y})\right)^2}{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2} \tag{8}$$

The correlation coefficient (r^2) is the intensity measure of the linear relationship between the two variables. A value of the square correlation coefficient closer to 1 indicates a strong relationship between the two variables. From figure 8, the correlation coefficient for X position variables was 1, thus a strong relationship. However, the coefficient for Y position was 0.9993 and for the figure 9 is 0.9991. Therefore, this also can be notice for the planar position of the vehicle; there was a small difference in the vehicle position between the two models. Also for the relation between X and Y the correlation coefficient was 1 for the figure 8 and 9.

This happened probably because of some approximation or the data transfer in the co-simulation, but was just a little and the correlation still has a strong relationship.

Figure 10 presents the longitudinal force applied in each wheel for Adams® and Simulink® simulations, it can be noticed that the forces were similar, the difference was in the right rear wheel because of the torque applied in the wheel. The Adams® only measure the force on the contact between the tire and ground, however, in the Simulink® it is the force input for the Adams®. Therefore, the longitudinal force for the right rear wheels is the sum of the force applied and the pacejka longitudinal force. Some force overlying other as present in Figure 10.

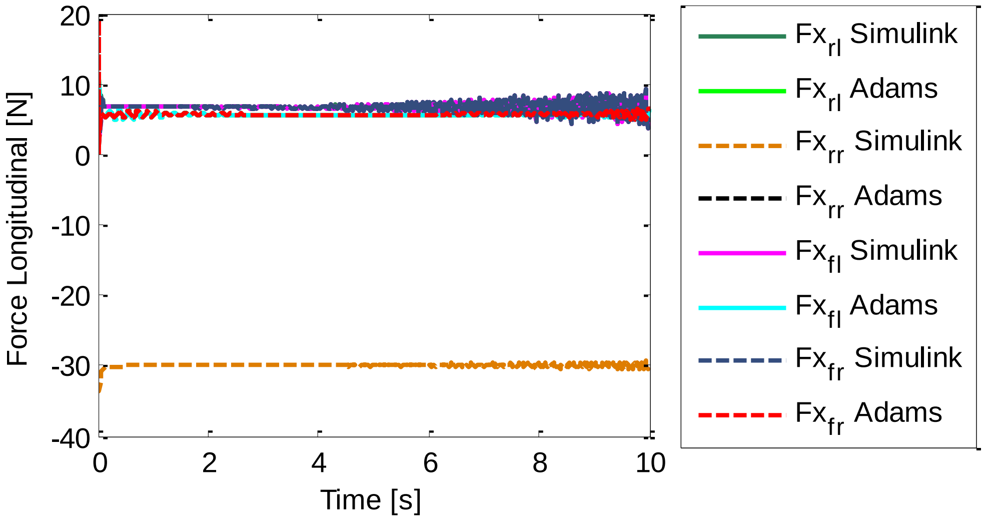


Figure 10 – Longitudinal force in each wheel for both models

Figure 11 presents the lateral force in all wheels. The behavior was the same in the longitudinal force, however, showed a variation between the force in Adams® and Simulink®. In Simulink® it can be observed a higher oscillation in the lateral force, although in Adams® was more constant. Probably this happened because the difference in the models and the integrators. For each step in Simulink, the forces and moments should be calculated and send to Adams®. Thus, maybe because of that the correlation coefficient was different when analyzed only the lateral displacement.

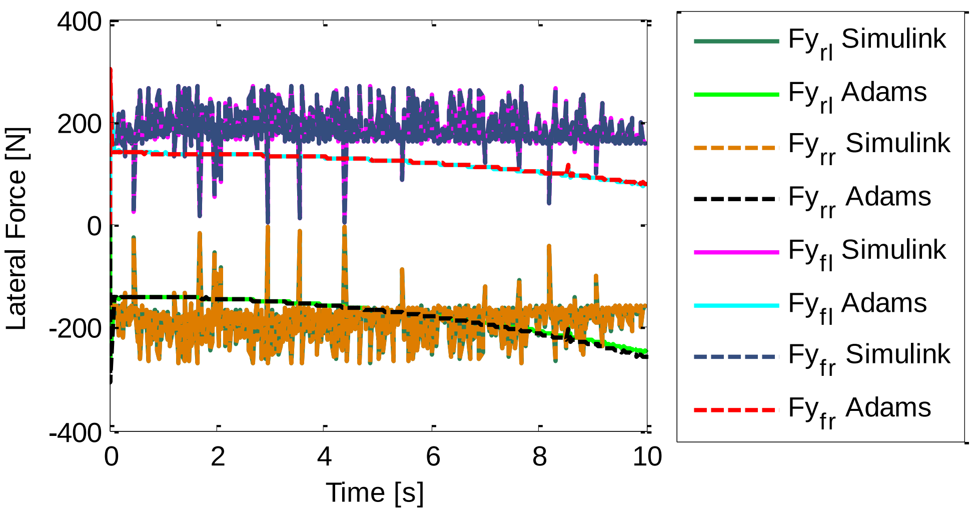


Figure 11 – Lateral force in all wheels for both simulations

6. CONCLUSION

Vehicle model was developed in order to initiate a future project in vehicle stability control. The implemented model was validated using PAC 89 from MSC Adams® software. The relationship between the tire and the ground proposes response expressions in terms of displacement, velocity and force that could help in discussing the dynamic behavior of the vehicle.

Taking this study as a starting point, it is necessary to study controllers that are more complex and implement these controls in this development vehicle model. In future work, it aims to study lateral dynamics with wheels controls, therefore maneuvers will be implemented as lane change and pulse steering. Therefore was important to understand how the PAC 89 MSC Adams® behavior and the pacejka tire model, because of it is one of the tire models most currently used.

From the result, it can be noticed that the co-simulation between Simulink® and MSC Adams® was similar behavior in the MSC Adams® exist model. However, the simulation time was superior in the co-simulation and a lot of input and output was necessary for only tire model, as well, for the development of control theory probably will be used the MSC Adams® tire model. Now the model is already known and with this article was possible to visualize the implementation of the model pacejka.

Another important point in this paper, it is how the contact should be done to represent correctly the pacejka model and the vehicle model. Therefore, all parameters in the pacejka formula should be raised or calculated according to the specific vehicle position and condition. In the co-simulation, the MSC Adams® was practically used as a visualization software.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Brezina, T.; Hadas, Z.; Vetiska, J., 2011, "Using of Co-simulation ADAMS-SIMULINK for development of mechatronic systems," MECHATRONIKA, 2011 14th International Symposium , pp.59 - 64.

Burhaumudin, M. S., Samin, P. M., Jamaluddin, H., Rahman, R. A. and Sulaiman, S, 2012, “Integration of Magic Formula Tire Model with Vehicle Handling Model”, International Journal of Research in Engineering and Technology (IJRET), vol. 1, no. 3.

Han, D., Sohn, J., Kim, K., Lee, J., Yoo, W., Lee, B., Choi, J. ,2000, “Development and comparative study on tire models in the AutoDyn7 program”. KSME international journal, 14(7), 730-736.

Vieira, R. S., Nicolazzi, L. C. and Roquerio, N., 2012, “Four-Wheel Vehicle Kinematic and Geometric Constraints for Definition of Tire Slip Angle”, International Journal of Automotive Technology, vol. 13, no. 4, pp. 553-562.

Kasprzak, Edward M., et al, 2006, “ Tire Asymmetries and Pressure Variations in the Radt/Milliken Nondimensional Tire Model”, Society of Automotive Engineers.

Pacejka, H.B. and Bakker, E, 1993, “The Magic Formula Tyre Model”, Vehicle System Dynamics, v. 21, pp.1-18.

Genta, Giancarlo, 1997, “Motor Vehicle Dynamics”, vol. 43, 1st ed.. World Scientific, .532 p.

MSC.Software Corporation, 2006, ADAMS/Tire Manual.

Xu, Nan, Dang Lu, and Shenhai Ran, 2011, "A predicted tire model for combined tire cornering and braking shear forces based on the slip direction." Electronic and Mechanical Engineering and Information Technology (EMEIT), 2011 International Conference on. Vol. 4.

Zhu Da-lin; Qin Jin-yi; Zhang Yi; Zhang Hu; Xia Min-min, 2010, "Research on Co-simulation Using ADAMS and MATLAB for Active Vibration Isolation System," Intelligent Computation Technology and Automation (ICICTA), 2010 International Conference on , vol.2, pp.1126 -1129.

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