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A STUDY ON THE INFLUENCE OF GEOMETRIC SUSPENSION PARAMETERS ON A FSAE VEHICLE STEERING FORCE REDUCTION

André Tognolli
Centro Universitário da Fei - Avenida Humberto Alencar Castelo Branco, 3972-Assunção, São Bernardo do Campo-SP, 09850-901.
andre.tognolli@gm.com

Agenor de Toledo Fleury
Centro Universitário da Fei - Avenida Humberto Alencar Castelo Branco, 3972-Assunção, São Bernardo do Campo-SP, 09850-901.
agfleury@fei.edu.br

Roberto Bortolussi
Centro Universitário da Fei - Avenida Humberto Alencar Castelo Branco, 3972-Assunção, São Bernardo do Campo-SP, 09850-901.
roberto@fei.edu.br

Abstract. *This paper explores the method of modeling and validation of computational tools able to accurately replicate the dynamic behavior of a Formula SAE vehicle. Based on limitations in conducting physical tests, it is possible to mathematically predict the forces and momentum generated on the steering column of the vehicle, minimizing effort and improving driver comfort even before the component is physically manufactured. The results in permanent state due technical instrumentations were used in the physical vehicles and compared with other proposals (skid Pad test). As the software simulating the same path, it was possible to adopt values of speed and wheel steering, allowing to compare the dynamics of the vehicle, through the signals from other sensors installed in the data acquisition system, validating the behavior of the models presented in permanent state. Other aspects were studied to understand vehicle behavior concerning lateral stability and steering behavior. In order to improve the steering system, the axle sleeve was changed, resulting in driver's less effort on handling. This proposal was compared to virtual models noting the efficiency of multibody models and was observed the decrease in an effort to turn the steering wheel.*

Keywords: *Vehicle dynamics, Steering kinematic, Mechanical trail, Multi-body simulation.*

1. INTRODUCTION

The motivation for this work is the search for alternative solutions to the steering system of the vehicle, without use of hydraulic or electrical assistance. This motivation comes against concepts that are left behind in the development of a car project because the geometric and kinematic parameters that are connected to the vehicle can be modified; thereby promoting a final arrangement that meets the requirements of comfort, safety and performance.

The proposal is show a geometric and kinematic arrangement of a steering system that meets the reduction in effort in steering column, predicting the sensitivity of the model and its efficiency and allowing accurate conclusions on the correctness of vehicle dynamics (MILLIKEN e MILLIKEN, 1995). The main goal is to build and validate multibody models able to reproduce vehicle behavior on a test track. Thus, one can analyze the various phenomena caused when the computational model is subjected to input compatible with test, to provide an accurate tool in the control.

2. PROCESS METHODOLOGY

The work was conducted at the University Center of FEI, using the model Formula SAE RS7, as base of the study. The vehicle shown in Figure 1 participated in world competitions in the years 2012 and 2013, classified among the top ten prototypes in the competition held in Michigan, USA.

Figure 1. Formula SAE RS7

The work was done following the methodology described in Figure 2.

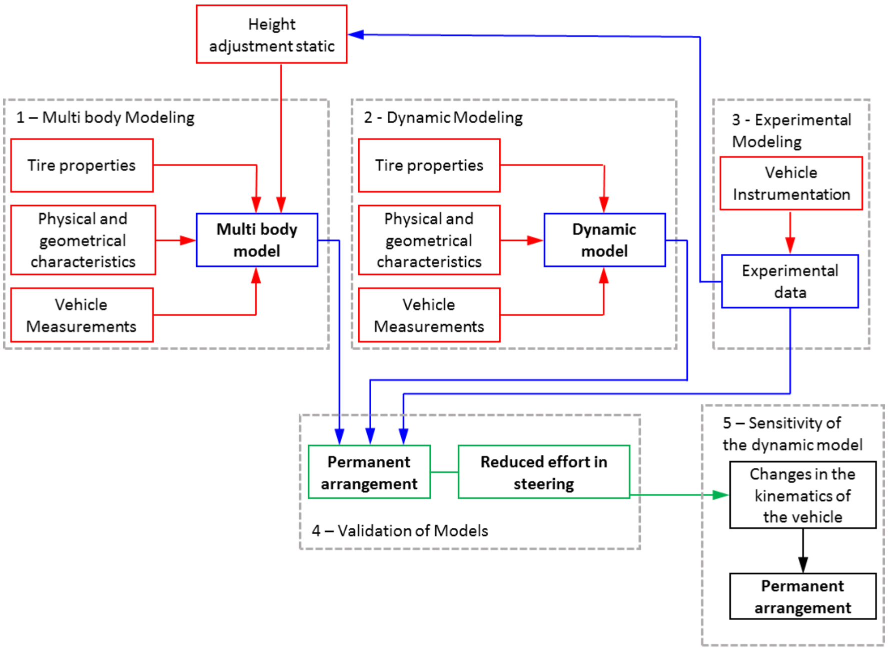

Figure 2. Flow chart of the study methodology

In the first stage, with support of NX7.5 software, it is possible to have the physical characteristics of each component, as mass and inertia, and these components are classified as sub-systems which serve as input in multibody modeling using the ADAMS/Car software (MSC Adams/Car 2012).

Which through connecting joints is characterized by their ability of calculate vinculares strength of each subsystem. According to Figure 3, it is possible to have an idea of the building the model.

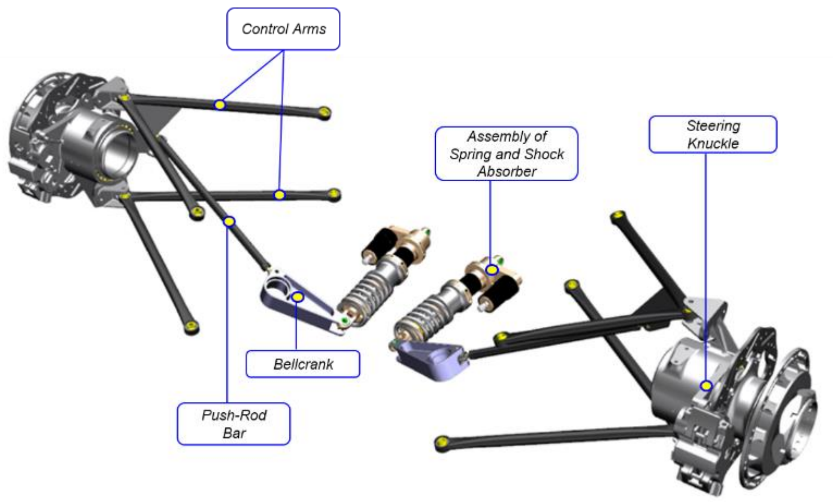

Figure 3. Rear Suspension - Joints

The geometric characteristics of the vehicle were used as input data, as well as tire properties that were generated through experimental data obtained of Flat Trac, by *Calspan TIRF* (KASPRZAK e GENTZ, 2006).

For elaboration of the multibody models also were required experimental data such as: location of center of gravity disposed in Figure 4, as well as the behavior of elements of force, such as rear springs stiffness (a) and characteristic curve of shock absorber (b), which can be seen in Figures 5.

Figure 4. Experimental localization (center of gravity)

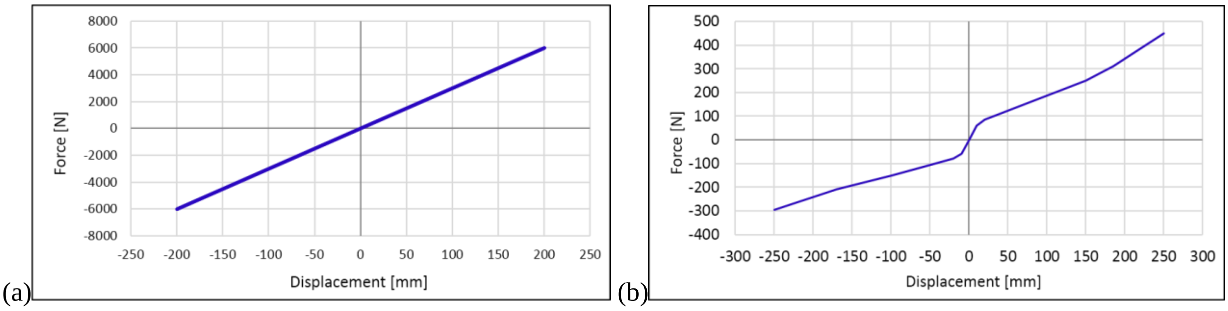

Figure 5. Elements of force

A dynamic model using the software *CarSim* was suggested in the analysis in order to obtain comparative responses to multibody model, also serving to analyze the sensitivity of the model in the methodology. When a kinematic variation is suggested aiming to reduce the steering torque, all the constructive geometric data of the vehicle Formula SAE RS7 were used as input, as well as the damping curves. The curve of potency and torque of engine (c) and gear ratio transmission (d), were similar to the request Adams, and can be seen in Figures 6.

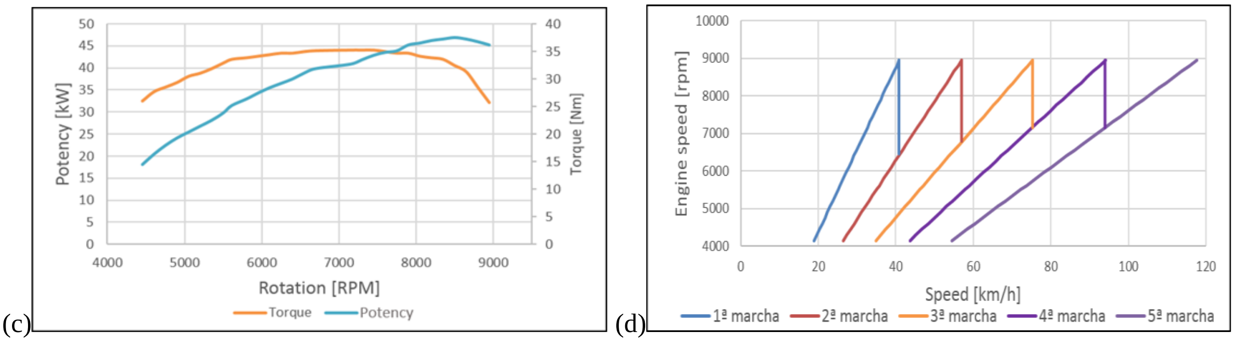

Figure 6. The data of engine and transmission

With the help of *Optimum Kinematics* software, the kinematic curves about the work of suspension could be used as input data in the dynamic modeling using the *Carsim*.

In Table 1 are showed the definitions for the geometrical parameters in the construction of virtual models, as well as the brake parameters and the gear ratio for running order.

Table 1. Parameters used in simulations.

Mass of Front Axle	104,5 Kgf	Piston area of the rear caliper	470 mm²
Mass of Rear Axle	123,5 Kgf	Piston area of the kingpin	195mm²
Total Mass	228 Kgf	Front brake balance	50%
Experiment tilt angle	73,5°	Coefficient of friction of the brake pad	0.4
Distance from CG to rolling axis	103,8 mm	Effective radius of the front disc	93
Distance from front rolling axis to ground	218 mm	Effective radius of the rear disc	81
Distance from rear rolling axis to ground	215 mm	Pedal ratio	5.1
Distance from CG to ground	320,2 mm	Transmission ratio (primary)	2,80
Distance of wheelbase	1570 mm	1° Gear	2,42
Distance from CG to rear axle	719,5 mm	2° Gear	1,73
Distance from CG to front axle	850,4 mm	3° Gear	1,31
Front gauge	1165 mm	4° Gear	2,42
Rear gauge	1187 mm	5° Gear	1,05
Piston area of the front caliper	1260 mm²	Final ratio	0,84

The experimental model was done based on the instrumentation of the vehicle and with data acquisition using the *Motec EDL3* system, as can be seen in Figure 7, adopting criteria for assembly according with (SEGERS, 2008).

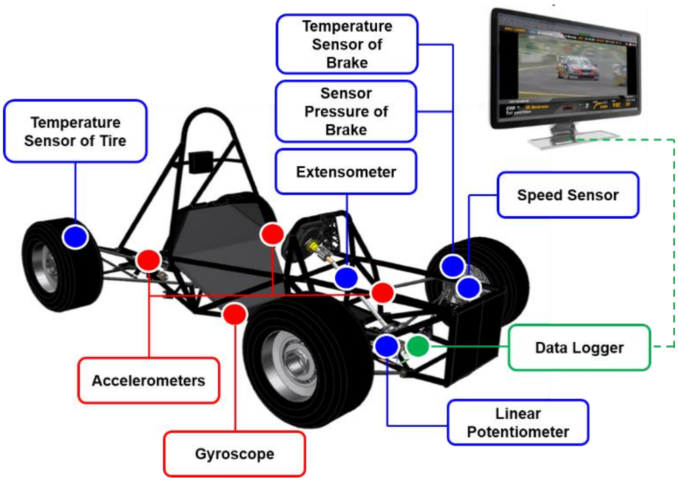

Figure 7. Arrangement Instrumentation

The vehicle was subjected to some static tests and on the track, covering a circular path in permanent arrangement.

In order to validate the proposal of reduction in perceived exertion in the steering vehicle, a new steering knuckle was installed in the vehicle. The results of the experimental test were compared with virtual simulations, where can be validated their behavior in permanent arrangement.

Once the models were validated, is possible to compare and quantify the reduction in steering torque, and map the phenomena caused in the vehicle behavior by the influence of the new steering knuckle during maneuvers.

Finally are established significant geometric changes in the vehicle kinematics as caster angle, lateral displacement of the ball joint or ratio of the gear rack, in order to get the same gain of reduction, established in the proposed work, with the steering knuckle, mapping the phenomena caused in vehicle behavior, enabling control before any component or adjustment are made.

3. RESULTS AND CONCLUSIONS

The layout of the track is arranged according to the metrics imposed in the Formula SAE competition (SAE 2014 FSAE Rules).

One can clearly see in the Figure 8, extracted from the dynamic model from *Carsim.*

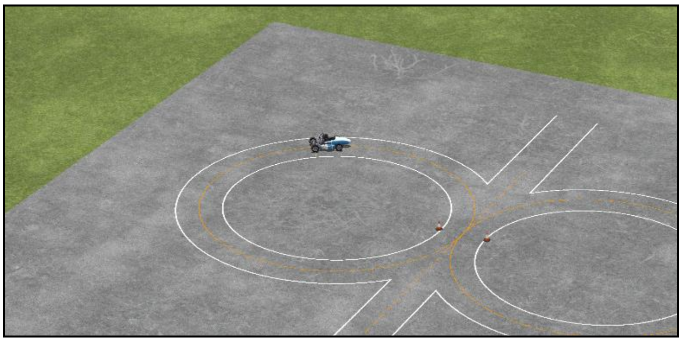

Figure 8. Model track *Skid Pad* in *Carsim*

Once the virtual models have been consolidated against the experimental model in permanent arrangement, is possible perform numerous variations in the input parameters of the models of *Adams* and *CarSim*, evaluating the responses of more conclusive way, finding best setting in vehicle project before even if any set is constructed.

The goal of this work is to modify the dimensional properties in the geometry of the steering and suspension system, through the displacement of the wheel hub center with reference to line of kingpin. This modification is known as "Caster offset", and was made possible by the longitudinal displacement of the wheel hub on the steering knuckle.

The Figure 9 allows a detailed analysis of modification, comparing the steering knuckle of the first scenario that performed the initial tests, with the proposal of a new steering knuckle containing the longitudinal displacement of the wheel hub, because the pivot point between the steering knuckle and the lower suspension arm staying in the left of the center line of the used in the original vehicle. With the shift of 20 mm in the center of the wheel hub, we note that the point of articulation between the new steering knuckle and the suspension arm is located behind the center of the turned. It is noteworthy that the control arms are unchanged keeping its geometrical points identical to the original models, thus ensuring the same caster angle for the two steering knuckle settings.

The proposal of displace 20 mm the wheel hub for front of the vehicle, resulted in increased between axis, which went from 1550 mm to 1570 mm. Another parameter that has been impacted by performing the "caster off set" was the mechanical trace, because when the line of the kingpin crosses the ground, a dimension of 25 mm is generated for the experiment at the initial stage of the simulation, with the new steering knuckle, the mechanical axis trace now has 5 mm.

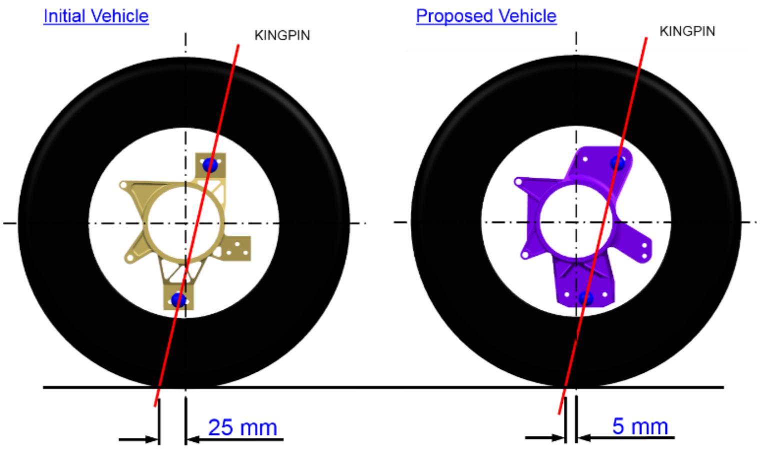

Figure 9. Longitudinal displacement of the wheel hub center

Two new steering knuckles were produced, one left and another right, keeping the mechanical properties of the current part. Small variations in mass and inertia associated with the new design of the piece were despised.

In Figure 10, the physical parts are shown in the left frame, where the steering knuckle is like the tests started, and the right frame is possible to check the new steering knuckle that was also subjected to the experimental test, with the aim of prove the effectiveness in reducing the effort to turn the steering wheel.

Figure 10. Physical characteristics the knuckle simulation.

For conclusive answers, simulations were made using virtual models in permanent arrangement using the maneuver "Skid Pad", and compared to experimental model. However, the longitudinal velocity imposed in these simulations was only 30 km/h, as shown in Figure 11.

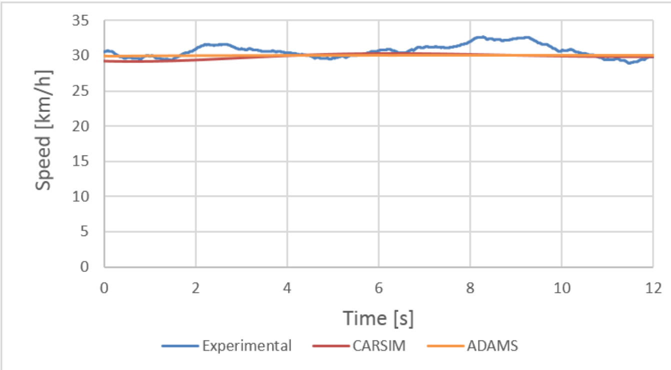

Figure 11. Kingpin proposed (vehicle speed: 30km/h)

In Figure 12, there is the variation of the steering angle in function of time, where the results should to remain similar to those shown in the analysis of the original steering knuckle.

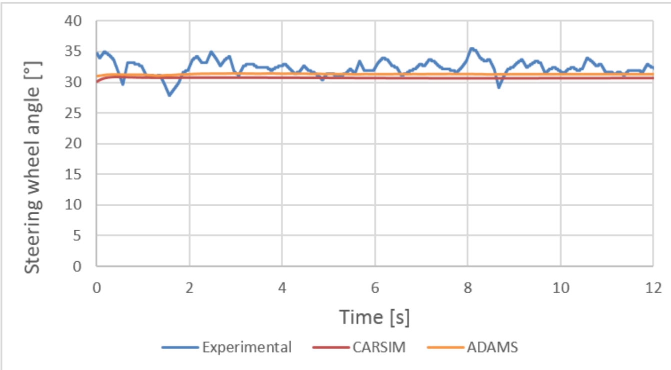

Figure 12. Steering wheel angle with kingpin proposed

The yaw rate to the virtual models showed good correlation. Even with a small variation between the experimental signal and the simulated result, the vehicle with the new steering knuckle suffered no change of behavior according to Figure 13.

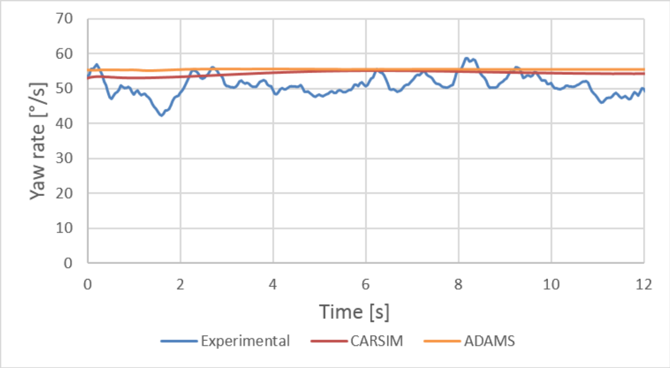

Figure 13. Steering wheel angle with kingpin proposed

The maneuver with the steering knuckle which promoted the lowest mechanical trace was tested with speed of 30 km/h, using the same circuit that the steering knuckle with highest velocity mechanical which had previously been analyzed, so the dynamic behavior of car remained constant since the results of lateral acceleration, yaw rate and steering wheel angle, just as well the displacement through the turning radius, remained close. No disturbance was perceived, so it is possible confirm, based on the results, that the proposal of a new the steering knuckle do not change the vehicle behavior on a permanent arrangement.

Figure 14 is an overlap with experimental data between the steering knuckles that executed maneuvers of constant radius.

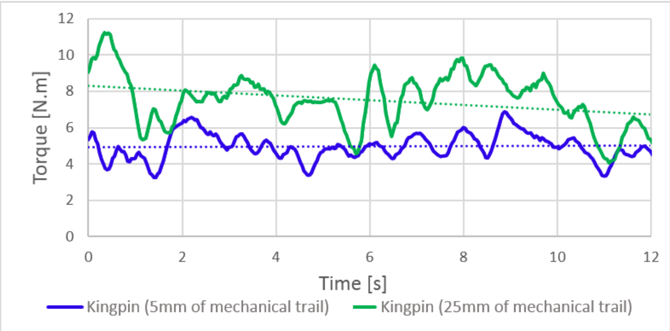

Figure 14. Comparative effort in steering column (experimental model)

The steering knuckle with greater mechanical trace, showed higher torque ranges in order 11N.m, and the lower impact signal is represented by the part which had geometrical modifications for the formation of lower mechanical trace. Even in the presence of noise in the data acquisition performed by the strain gauge installed on the steering column, the comparative remained with linear response and it is possible seen in the previous figure that had a gain reduction in the effort about 34%, showing the efficacy of this proposal. The Figure 15 represents a linearized signal, the result of multibody simulation performed by Adams, so this comparison shows 37% reduction.

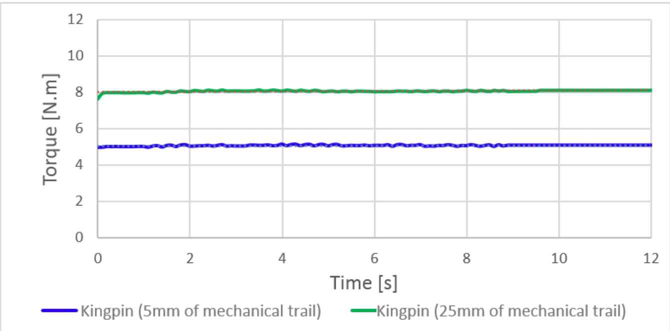

Figure 15. Comparative effort in steering column (multibody *Adams* model)

The model of the vehicle in *Carsim*, was equivalent to the previous two models, because the answer in the proposal of reduction in the steering column effort reached values of 35%, as shown in Figure 16.

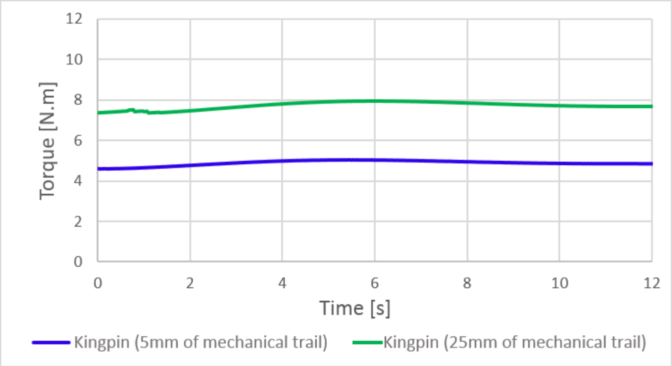

Figure 16. Comparative effort in steering column (*Carsim* model)

3.1 Sensibility of *Carsim* model

Once the effort signal on the steering column have been analyzed in detail, it is of great importance to study other ways and solutions that promote the same reduction in torque direction and analyze the impacts against the dynamic behavior of the vehicle, together with the constructive limitations.

Using the model *Carsim*, some proposals have been made in order to quantify and establish a good relationship of compromise between performance and comfort. These simulations were made in permanent arrangement, in the Skid Pad maneuver with turning radius of 8.3 meters and a constant speed of 30 km/h.

The first proposal showed at work through the longitudinal displacement of the wheel hub center, generated direct impact on the construction of a new steering knuckle, providing a new dimension of mechanical trace, equal to 5 mm, and consequently a reduction in auto torque alignment and effort toward, as discussed in the previous section.

A second proposal would be linked to steering box by changing the ratio of pinion-rack.

To compare the effectiveness of this proposal have been set up two scenarios for simulation in *Carsim* model.

In the first scenario, was done the proposal of the working set, maintaining the longitudinal displacement of the kingpin and resulting in a mechanical trace equal to 5 mm, steering wheel angle depending on the gear rack ratio "C", equal to 140mm / ° caster angle equal 8°, and angle of lateral inclination of kingpin equal to 4°.

The second scenario was configured to fit the same level of effort than the first scenario, but using the old steering knuckle which generated a mechanical trace of 25 mm and the relationship of the direction, was changed to 80 mm /°, caster angle was equal to 8°, and the front tilt angle of the kingpin was 4°.

The Figure 17 indicates that the response of effort was practically the same for both simulations.

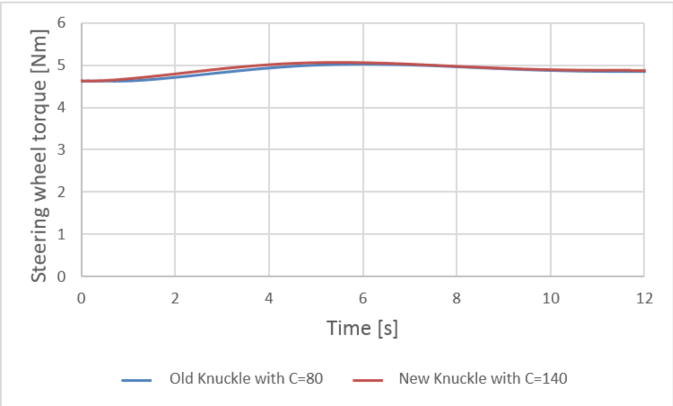

Figure 17. Comparative effort in steering column (*Carsim* model)

However, significant changes were noted in the steering angle, between the settings because while the pilot of the first stage requires 30° tilt the steering wheel, the second needs 55° to perform the same operation, as illustrated in Figure 18.

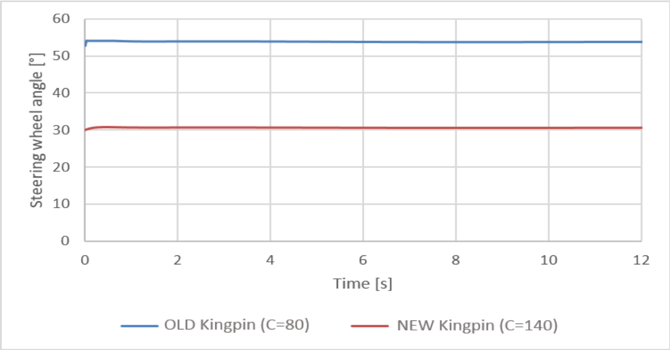

Figure 18. Range of the steering wheel angle - sensitivity of the model

Other impacts related to this proposal are linked to a new steering box model contemplating a new relationship, not to mention the risks associated with the pilot as raise the tendency of even take a hand off the wheel when performing maneuvers in curves.

A third proposal can be discussed only in case the parameter to be changed it be only the caster angle.

For this simulation, the first scene will be set in *Carsim* with the same characteristics of the first stage of the previous proposal, though the second scenario will have steering ratio "C" equal to 140 mm/°, keeping the mechanical trail with 25 mm, and the angle front tilt of kingpin equal to 4°, changing only the caster angle to 4.5°. As a result of this simulation, it is possible to see the equality results of the torque in the steering, according Figure 19.

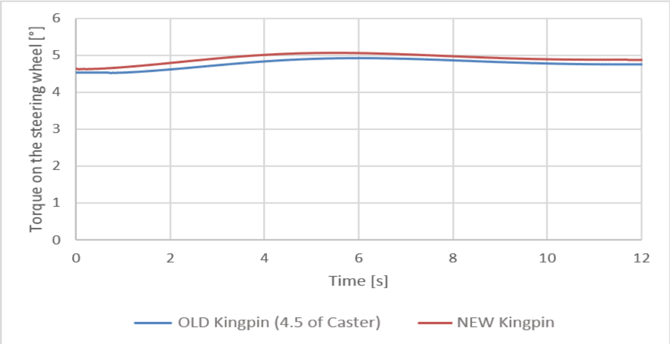

Figure 19. Similarity between the efforts - sensitivity of the model

This proposal is very favorable when compared with change proposed components previously, because it allows a more simple arrangement between the steering knuckle and spherical joints of control arms through serrated brackets. However, some phenomena can happen in response to behavior that the vehicle will take in the maneuvers. A new curve of camber gain in function of steer angle was extracted according to Figure 20, in order to observe the responsiveness that the vehicle will bring, when required extreme lateral acceleration conditions.

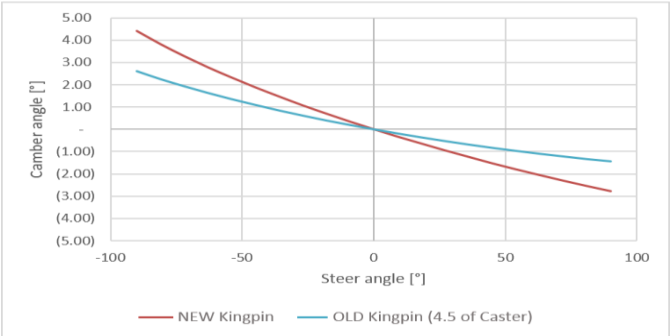

Figure 20. Camber angle x steer angle (*Optimum Kinematics*)

For this purpose, it is necessary to investigate whether there was an increase in the tire drift angle or an increase in drift from the chassis angle. And even with small change, the tendency to slip can be accelerated, and the vehicle can lose stability early.

4. CONCLUSIONS AND DISCUSSIONS

According to the responses used for validation of the models, it is extremely to emphasize that the data for steering wheel and longitudinal velocity taken on the road have not served as input in simulations, so, parameters for steer and speed were given as constant inputs in the mathematical models. The best gain with this strategy is the exclusion of noise in the experiment, coming from the pavement imperfections, vibrations of powertrain and transmission, as well as pilot actions.

On the other hand, it is also important to emphasize that some simplifications have been made in the models that do not include aerodynamic forces, since in low speeds they represent small variations, or flexibility models or even the application of the tire model recommended for a system of curves in flat floor, thus representing the dynamic behavior associated only to the linear region of wheel sets. However, it is correct to affirm that the multibody model of Adams and *Carsim* model showed good correlation when compared to the linearized responses of lateral acceleration and yaw rate, despite the unexpected oscillating signals when subjected to maneuvers like the Skid pad. The models represent the physical vehicle within an error rate below 10%, which meets the expectations one had at the beginning.

After consolidation of the models, a change in the kinematic behavior was proposed, through the longitudinal displacement of the wheel hub on the front steering knuckle, thus enabling a geometric reduction in the mechanical wake. In consequence, a lower torque is perceived on the steering column, reducing driver’s efforts to drive the car. This was confirmed via a strain-gage assembly that gathered signs in manoeuvers carried out with each steering knuckle. A significant drop in the effort employed by the pilot to perform the maneuver on a permanent arrangement became clear.

Considering that the mechanical trail is not the only parameter to be taken into account to predict an improvement in the vehicle, other geometric factors were also changed, using the *Carsim* model for virtually antecipate the vehicle's behavior.

The purpose of measuring the sensitivity of the model to meet the possibility of taking a better decision, provides significant reduction in cost and run time, assuring to the Formula FEI team, better understanding of the dynamic behavior of the vehicle, according to the proposals that the team constantly promotes in search for the most correct setting of the vehicle.

5. ACKNOWLEDGEMENTS

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