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Kinematics and Compliance Correlation Between a Multibody Model and an Experimental Vehicle to a Center of Excellence in Vehicle Dynamics Simulation

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ABSTRACT : *The automotive industry has increased the use of simulation as a fundamental resource of a vehicle design. In the chassis engineering, more specifically in the suspension and steering systems development, it has not been different. However, aiming a reliable virtual model behavior in relation to a physical vehicle, it is necessary and fundamental to complete several steps in the model construction. One of them is the kinematics and compliance (KnC) correlation, which results in the virtual model suspension and steering systems behaving appropriately to the physical vehicle corresponding systems. With the experimental data collected and processed in MATLAB, the multibody model is developed with the aid of ADAMS/Car software. From multiple simulations in this software, the suspension and steering system parameters are adjusted until the multibody virtual model properly matches to the physical test vehicle behavior.*

KEYWORDS *Vehicle dynamics. Kinematics and compliance correlation. Virtual multibody models. Center of excellence in vehicle dynamics. Automotive engineering.*

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I. INTRODUCTION

According to Jazar [8], the vehicle dynamics importance proves itself once it is in the engineering student's syllabus for over one hundred years. For this author, this study came up with the definition of methodologies on the behavior of the various systems connected to vehicles, and currently, this subject tends to seek the modeling and optimization of systems through multibody analysis. For Marques et al. [10], multibody can be defined as a set of bodies interconnected by joints and under action of forces, interacting with each other and the rest of the system.

Bitencourt [2] said that virtual simulation born as resource to sportive vehicles, currently being used for simpler segments, like the urban cars. In their studies, Czechowicz e Mavros [4] also use simulation to develop analysis by fundamental vehicle dynamics parameters. However, to do so, the authors perform a kinematics and compliance (KnC) correlation of a multibody model aiming that it represents a physical vehicle for the proposed analysis can be carried out. As in the work presented above, Özcan [12] uses a multibody model developed in ADAMS/Car to optimize the steering system in commercial vehicles such as small trucks.

In the present context, the centers of excellence in vehicle dynamics have gained ground in major automakers around the world, such as SIM Center, a project with partnership between the industry, the academy by Pontifícia Universidade Católica de Minas Gerais (PUC Minas) and the Banco Nacional de Desenvolvimento Econômico e Social (BNDES). In general, the centers in excellence in vehicle dynamic allows tests of virtual models of vehicles, which means it isn't necessary tests vehicle building to analyze the project settings, for example, in initial project steps. However, for the use of the presented equipment in the project development, it is necessary to develop correlated and consistent virtual models with physical vehicles. The KnC parameters correlation is the first step to achieve this goal.

II. VEHICLE DYNAMICS

In suspension designs, a key parameter is the weight distribution in the axis. Since the mass is concentrated in the vehicle's center of gravity and is supported by the tire contact with the ground, there is a weight distribution on the front axle and rear axle, according to Gillespie [7]. The relationship of this distribution is due to the relative distances from the center of gravity (CG) to the front and rear axles of the vehicle, as shown in Figure 1.

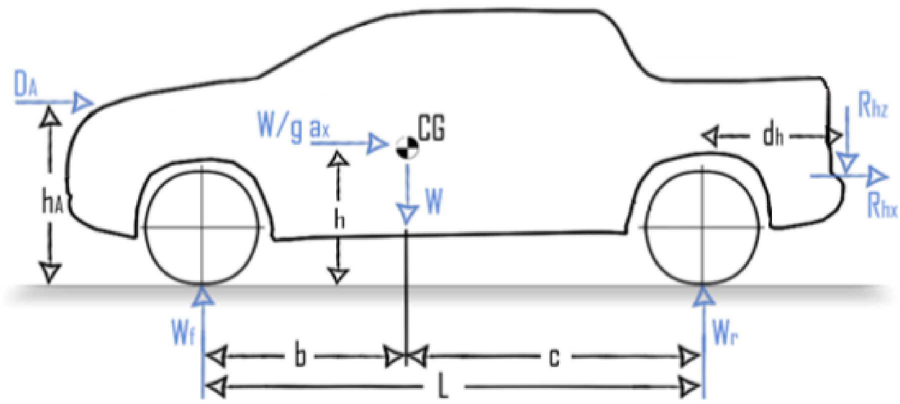

Fig.1. Weight distribution

Also, according to Figure 1, the longitudinal acceleration component (ax), directly related to the gravity acceleration (g), is applied to the vehicle's CG. The center of gravity is h height from ground. It is also noted that the sum of b and c distances is called L and is defined as the wheelbase, in other words, the longitudinal distance between the vehicle front and rear axle. The values of the respective weights distribution by axes can also be obtained by equations 1 and 2.

$$\mathbf{Wf} = \frac{\mathbf{W*C}}{\mathbf{L}} \quad (1)$$

$$\mathbf{Wr} = \frac{\mathbf{W*b}}{\mathbf{L}} \quad (2)$$

Where Wf is the vehicle's weight on front axle, W [kg] is the total vehicle's weight, c[mm] is the parallel distance from the ground between center of gravity and rear axle, L[mm] is the distance between axis, Wr is the vehicle's weight on rear axle and b [mm] is the parallel distance from the ground between center of gravity and front axle.

The drag force (DA) can influence the vehicle dynamics depending on the system boundary conditions to perform the analysis. Considered applied at a given ground height (hA), the drag force may be disregarded in cases where the vehicle is at zero speed and acceleration. Likewise, components due to the presence of a trailer in the vehicle (R_{hz} and R_{hx}) may be disregarded when the analysis is made on a vehicle parked on a flat road without slope. According to Struble [16], the non-sprung mass is equivalent to the entire weight of the suspension, wheels and tires. Also, according to this author, the sprung mass is the rest of the vehicle's weight. Abe [1] concludes by commenting that, even though the sprung mass suffers from the rolling-accelerating effect around the longitudinal axis of the vehicle, the non-sprung mass can remain rigid and independent of the former. Relative to vehicle coordinate axes, the Society of Automotive Engineers (SAE) defines the axes shown in Figure 02.

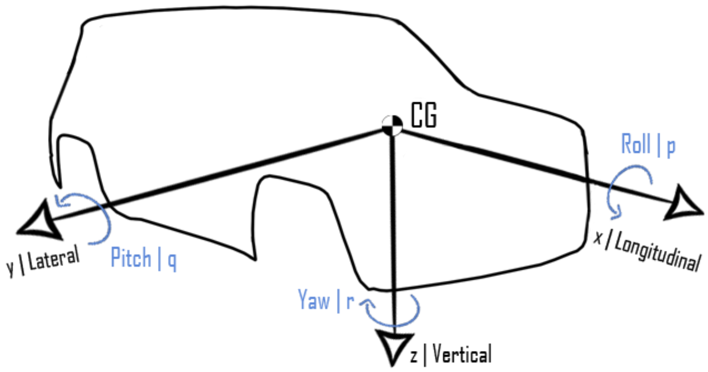

Fig.2. SAE coordinate system

In the figure above, it is possible to notice that the coordinate system is taken in relation to the vehicle's CG, that is, it is defined that the coordinate system is taken fixed in the vehicle (body fixed). It is also possible to observe that the longitudinal axis (X axis) is taken as positive towards the rear of the vehicle, while the vertical direction is from top to bottom and is defined as the positive Z axis. Lastly, the left to right side axis is defined as the positive Y axis. Around the X, Y, and Z axis are observed the effects of roll, yaw, and pitch. As Milliken and Milliken (2002) [11] point out, rotation around X is defined as roll. Still for the author in question, the yaw is observed by the rotation around the Z axis and the pitch around the Y axis.

III. MULTIBODY MODEL REPRESETATION

Intuitively, a multibody system is a system composed of several components. About these components, each one presents its characteristics and they interact with each other, according to the system operation, during the simulation. According to Roberson and Schwertassek [13], multibody system has been used by Aerospace Engineering since the 60s. However, being a widely used feature in several areas of engineering in these days, Kortüm [9] says that multibody systems are directly linked to the computing evolution. For Schiehlen [14], these systems can be defined as algorithms ready for implementation in computers, so that the simulation and the animation generated from it are the main parts of the results. As presented by Eberhard and Schiehlen [5], the dynamics of multibody systems is based on analytical mechanics, being applied to the most diverse types of vehicles and other machines and equipment.

As Blundell and Harty [3] explain, multibody analysis allows the system construction with numerous flexible bodies and elastic connections between them. Shabana [15] presents that multibody systems analyze not only body translation but also rotation. Thus, the equations are usually nonlinear and must be solved by numerical methods, not just the analytical ones.

IV. MULTIBODY MODEL ADJUSTMENT IN ADAMS/CAR

With the aid of ADAMS, multiple analyzes can be performed to analyze the dynamic behavior of a vehicle. Due to this, several advantages can be observed from the moment that multibody programs, for example, are used. These include the reduction of design cost, since a model can describe the behavior of the system and, as a result, allows the optimization of the system and avoids extra costs with building prototypes. Focusing on the vehicular research, ADAMS has a customization called ADAMS/Car. The software with this customization is intended especially for the development of automotive designs. In a new ADAMS/Car project, subsystems are created and, when these items are ready, assemblies such as front and rear suspension can be adjusted.

With what was presented, the multibody model can be adjusted according the physical vehicle data by changing parameters in each subsystem. Besides that, the suspension geometry is also adjusted according to the defined points in the structural design. Table 1 presents some of the main changes to be made in the multibody model.

Table 1: List of subsystems

SUBSYSTEM	ADJUSTMENTS TO BE MADE
STEERING	Steering ratio and assistance curves (only for electric power steering vehicles)
TIRES	Tire radius, flexibility, weight and rim's diameter in the tire data file
SUSPENSION	Bushing flexibility curves, static toe and camber, spring load and flexibility, damper load and flexibility

With the adjusted model, a KnC analysis was performed in ADAMS/Car. This analysis is a set of tests that, among several performed simulations, it is possible to obtain the same parameters from the experimental tests with the physical vehicle such as the parallel, opposite, longitudinal, lateral and steering tests.

V. SUSPENSION PARAMETER MEASUREMENT MACHINE

Using a physical vehicle, the desired experimental parameters were obtained using a suspension parameter measurement machine (SPMM), as shown in Figure 3. According to Gil [6], the SPMM is a machine capable of measuring and provide the kinematic characteristics of a vehicle's suspension.

Fig.3. Suspension parameter measurement machine

Similar to other KnC banks of the same size, the equipment used for obtaining the kinematics and compliance parameters in the present work can be basically divided in three main groups: General platform, platform for the wheels and the electric actuators, besides the diverse sensors that compose the instrumentation of the equipment. Featuring six degrees of freedom, the SPMM 5000e's central platform, equipment used to obtain experimental data, is responsible for performing the roll, pitch and yaw movements.
The tests performed on the experimental physical vehicle are the same as those performed on the virtual multibody model and are presented in Table 2.

Table 2: Correlation tests

SUBSYSTEM	ADJUSTMENTS TO BE MADE
STEERING	Steer the steering wheel angle
PARALLEL	Parallel loads are applied in the two tires of the front or rear axis, causing translation in Z-axis.
OPPOSED	Opposite loads are applied in the two tires of the front or rear axis, causing translation in Z-axis.
LATERAL	Lateral loads are applied on the tires
LONGITUDINAL	Longitudinal loads are applied on the tires
ALIGNING	Auto aligning torque applied on the tires

VI. CORRELATION

Once the experimental tests were completely performed, the SPMM Post Processing, AB Dynamics software for data post-processing and report generator, was used. It selects all data relative to the application of forces and displacements of the equipment in the vehicle, as well the displacements and excitations. From this imputed data, the software performs a sequence of calculations that allows the achievement of the kinematics and compliance parameters. As result, the program in question also generates multiple files with several points of the curves measured and calculated parameters. To make it possible, MATLAB runs in the background with a sequence of routines still written by AB Dynamics. It stands out that the original code was modified in order to make exports of more steering data possible.

As presented, a file with the experimental data is generated for each of the tests to be analyzed: steering, parallel, opposite, lateral, longitudinal and aligning. With a several data obtained, many of them not being used since SPMM generates more KnC parameters than those that were correlated, a MATLAB routine was developed which extracts only the desired parameters in a narrow range, that is, it only extracts the KnC parameters that will be correlated and correspond to a complete turn of the steering wheel. After the optimization program is executed, a final file is generated with the interest data for the correlation. This file was opened in a spreadsheet that also received data from tests performed with the multibody model. As the model values in the ADAMS/Car were far from the experimental values, various suspension point coordinate adjustment techniques and other model parameters were adjusted, leading to a new KnC analysis. Intuitively, the data was exported and loaded into the correlation worksheet again. The process was repeated until the model parameters corresponded as satisfactorily as possible to the experimental vehicle data. For reasons of industrial confidentiality, the methods used to adjust such parameters will not be addressed in this paper.

VII. CORRELATION RESULTS

As previously shown, the present work sought to perform six distinct tests and simulations to validate the correlation of kinematics and compliance parameters: Steering, parallel, opposed, lateral, longitudinal and aligning. In the present topic, the results obtained with the tests and simulations above will be shown.

With exception of steering test, which makes sense to analyze only in the front suspension system due to steering wheel, the other tests and simulations were performed and analyzed in all four wheels. However, due to the similar behavior and the large number of charts and data obtained for analysis, the parameters to be presented here were filtered and will be displayed alternately according to the tests performed. As will be done in the parallel test, the opposite test analysis was given based on the effects of wheel rate, bump steer, bump camber and bump spin. In addition, complementary analyzes such as wheel contact with ground path and wheel center displacement were also taken into consideration.

According to the displacement on the Z axis, Figure 4 shows the force variation in the same direction and positive sense of the axis in question.

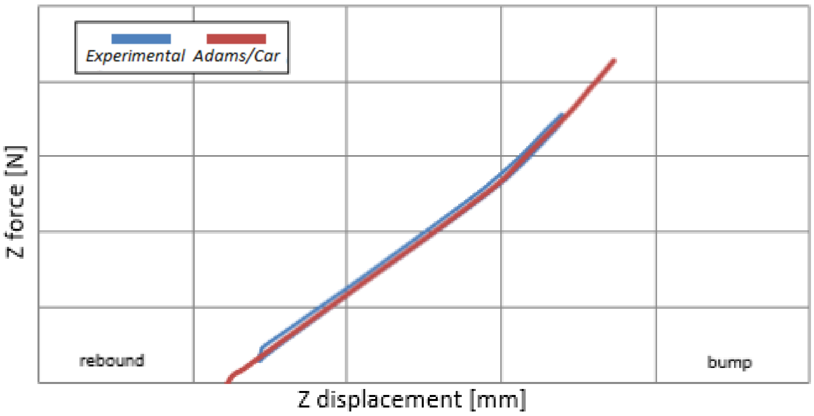

Fig.4. LF Wheel rate in opposed test

Applied to the left wheel of the front axle, Figure 5 also shows when another force under the same conditions presented is applied to the right wheel of the front axle (RF).

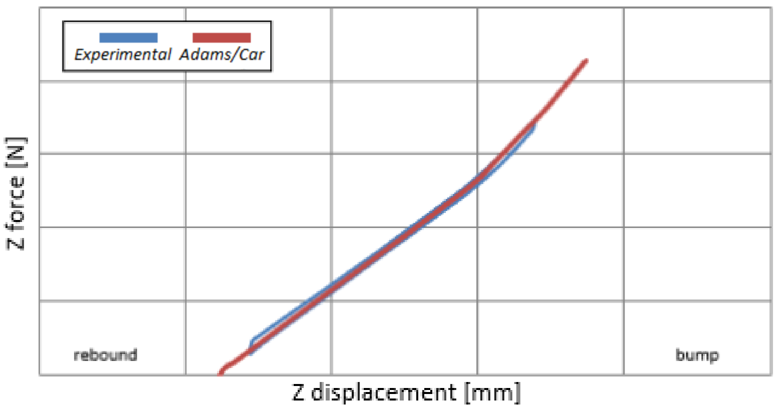

Fig.5. RF Wheel rate in opposed test

In other words, the two graphs above are related to the wheel rate on the left and right front wheels, respectively.

As mentioned earlier, the parallel test simulation outputs were analyzed by the same behaviors as the opposite test. As happened with the bump steer, the bump spin and bump camber parameters (Figure 6) were completely correlated with the actual vehicle. In both front and rear suspension, on both right and left wheels, the camber and spin values obtained through the simulation almost overlap the experimental values.

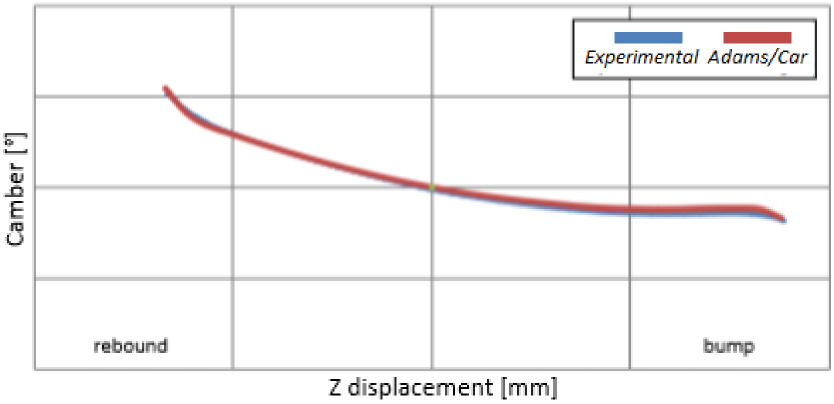

Fig.6. Bump camber in parallel test

Another important parameter in the parallel test was the displacement of the contact point between the tire and the ground. It is important to highlight that in the case of the SPMM, the ground is represented by specific wheel positioning trays, as previously discussed in this work.

Considering the right front wheel, Figure 7 shows the correlation of the contact point variation on the Y axis by the Z displacement. As well as the left rear wheel correlation, the results obtained were satisfactory and can be considered as correlated.

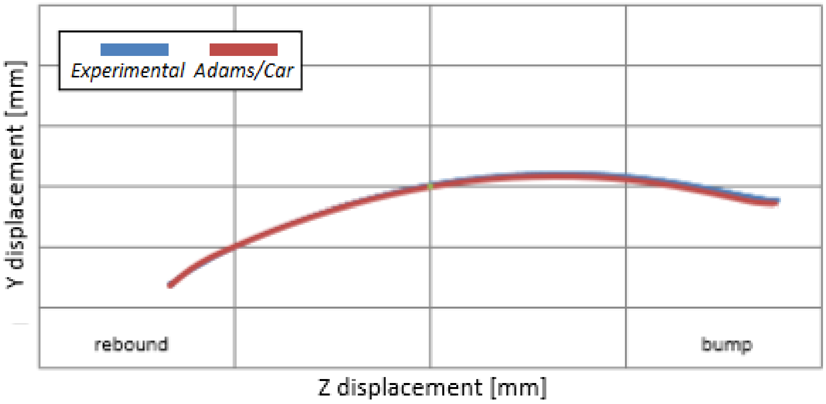

Fig.7. Bump camber in parallel test

Considering the camber, toe and spin compliances, the lateral test also showed good results. At this point, it is important to notice that the loads were applied only on the left side of the vehicle. The purpose of using this methodology is to observe how the opposite sides of the suspension respond.

As can be seen from Figure 8, the toe compliance curve for the left front wheel showed an error of less than 10% at the point of greatest divergence between the experimental curve and the model curve, approaching considerably well over the rest of the analyzed range. Regarding the rear axle, the result was even better, presenting an error smaller than 5%.

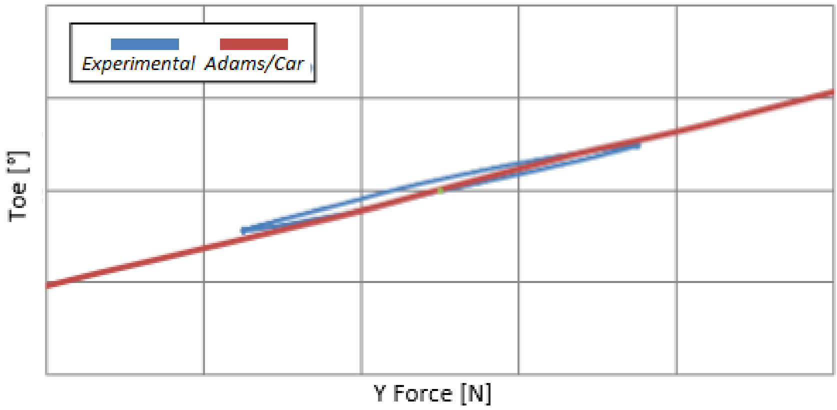

Fig.8. LF toe compliance in lateral test

The expected results for the longitudinal test should be similar to the parallel test and, as noted, were indeed. Thus, it could be concluded that the correlation of the suspension parameters when the vehicle is excited longitudinally was performed and matches the physical vehicle. As an example and seeking to validate these assertions, Figure 9 shows the toe compliance of the left front wheel.

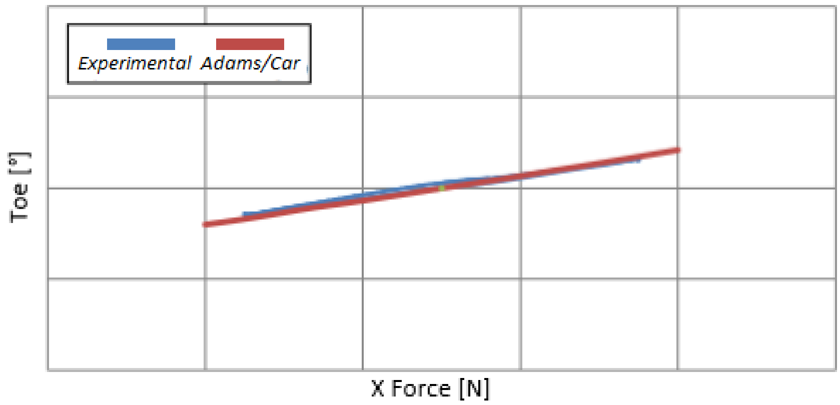

Fig.9. LF toe compliance in lateral test

About the parameters regarding the contact between the wheel and the ground and the displacements of the wheel center, the obtained curves for the aligning test showed good results, being very close to the physical vehicle data. Exemplifying these results, Figure 10 shows the compliance of the wheel-ground contact with the Y axis.

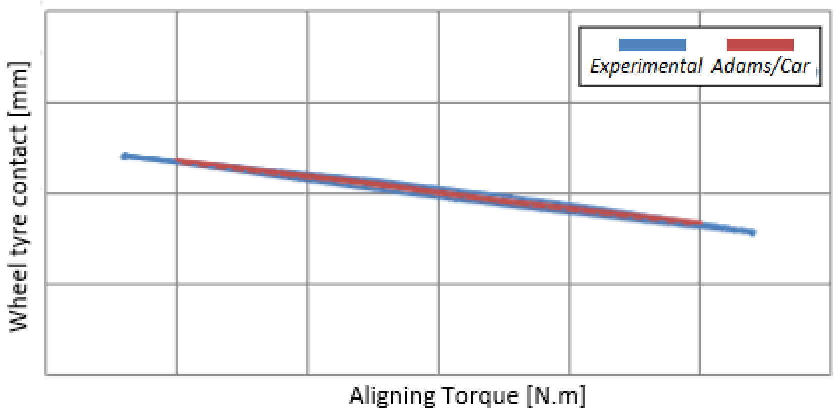

Fig.10. LF ground-tire compliance in aligning test

Unlike the tests that have been presented so far, the steering test does not consist of front and rear suspension systems analysis. Induced by name, the steering test consists of parameters concerning the steering system and, consequently, the front suspension system for front wheel steering vehicles.
Let the relationship between right and left wheel steering be known as Ackermann. Figure 11 shows this parameter and proves that the virtual model is correlated to the physical vehicle data in the presented parameter.

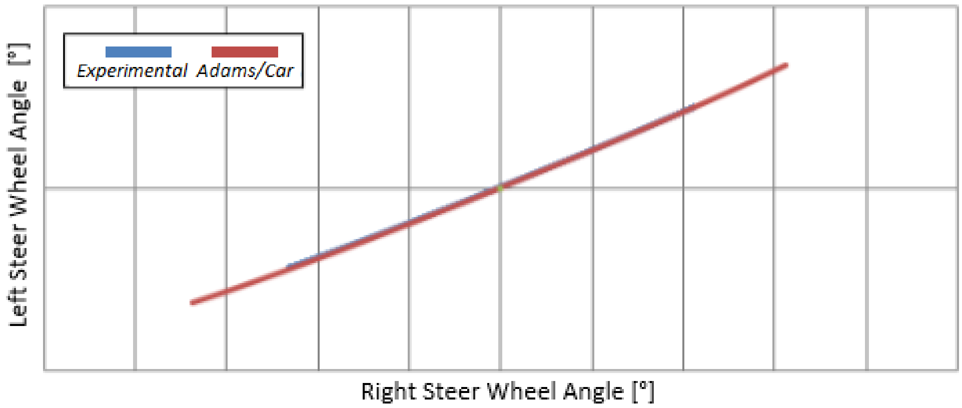

Fig.11. Ackermann in steering test

Following the analysis of the data obtained, another parameter of extreme importance and that good correlation results was found is TAU, also known as steering wheel angle by wheel steer angle. Among several factors that affect the behavior of this parameter, can be cited relative angles to the steering column and the assistance curve in electric steering vehicles, for example. According to Figure 12, it is concluded that the TAU values of the multibody model came very close to the physical vehicle data.

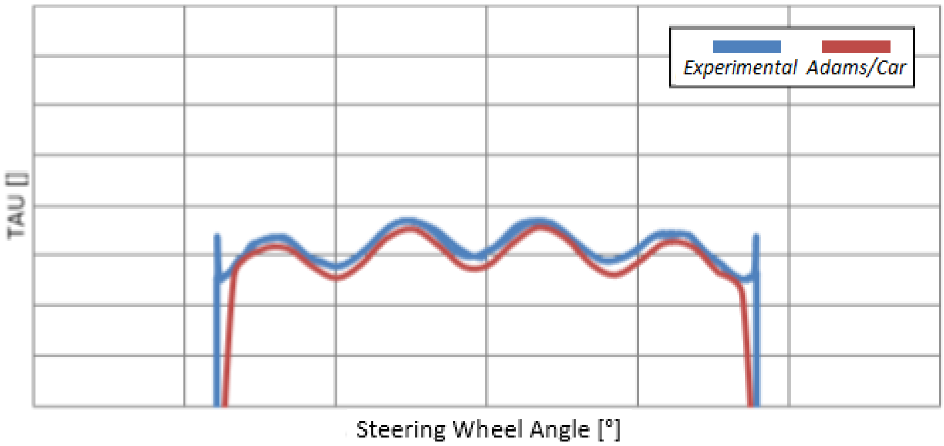

Fig.12. TAU

Therefore, as presented in the charts above, the multibody virtual model is considered correlated to the physical vehicle regarding kinematic and compliance parameters. From this statement, the next steps for converting the model to a vehicle dynamics simulator can be performed.

VIII. CONCLUSIONS

Engineering aims to a future where computational systems will be even more fundamental. Regarding this knowledge area, systems simulation is already one of the most fundamentals and indispensable resources for engineers. When robotics is incremented to these assets by the electro-electronic development, mechanical engineering can reach even higher and better results.

In the presented context, automotive engineering area which approach the development of chassis systems and its peripheric subsystems has been investing on vehicle dynamics excellence centers as can be exemplified by SIM Center. Only used for high performance cars in the past years, in these days that type of technology began to be used to develop urban cars, making possible the simulation of the entire dynamic of a physical vehicle.

Nevertheless, aiming simulations which can provide reliable results, a few steps have to be made before. Contemplating these steps, one of the firsts of them is to do a kinematics and compliance correlation. Because of that, the present work developed a kinematics and compliance correlation between a virtual model and a physical vehicle, starting with the obtention of the experimental data from a suspension parameter measurement machine. From this point and using ADAMS/Car software, a multibody model was correlated with the experimental data obtained from the physical vehicle.

At the end of the correlation, the results showed that the multibody model was correlated to the experimental vehicle. This conclusion could be made once the maximum error between virtual simulation and experimental data was about fifteen percent. Also, it is emphasized that this error could be reduced with some more virtual loops with the aid of ADAMS/Car. Once the multibody model has its kinematics and compliance parameters correlated, a handling correlation can be done to use the virtual model in a vehicle dynamics simulator.

The future of engineering cannot be separated of the development of the computational science and the electro-electronic resources. Surrounding that, the present work made a correlation between an experimental vehicle and a multibody virtual model to be implemented on a simulation center of vehicle dynamics, interconnecting mechanics, simulation and robotics. This kind of approaching have been increasing in the past years and shall be a fundamental part of major Engineering applications.

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