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Vehicle steering pull: from product development to manufacturing

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Abstract: The paper objective is to propose a novel method to evaluate the impact of dimensional variations on vehicle steering pull. Several attributes are important to increase the costumer perception of vehicle quality. Steering pull is one of these factors, which mean consistent pull to one side on a straight road while maintaining a constant speed, also called Vehicle Residual Aligning Torque (VRAT). Camber, caster, toe, and other factors affect VRAT. These factors are geometric characteristics defined on project phases influenced by dimensional variation from manufacturing and assembly process of underbody, suspension and tires. We developed a computer model to predict the dimensional variation of every geometric characteristic based on vehicle parts tolerances and evaluate the main contributors to variation of a common compact automotive vehicle with MacPherson frontal suspension and Twist Beam rear suspension. The computer model allow optimizing wheel alignment characteristics, determining characteristics to add on FMEA and evaluate the dimensional variation impact on the quality results of directional dynamic of the vehicle with this model. The proposed method combines Monte Carlo simulation to validate some the dimensional tolerances, a mutibody software to simulate initial data and a multi-objective optimization software to create a polynomial response surface and simulate the VRAT distribution curve, final directional vehicle trend and factors influence on VRAT. This method improved the time to complete the proposed simulation about 800 times compared to conventional simulation.

Keywords: steering pull, vehicle dynamics, wheel alignment, monte carlo.

1. Introduction

The consistent pull of a vehicle to one side on a straight road is uncomfortable and unsafe to the costumer, responsible for premature tire wear and fuel economy losses. Those are the reasons why the automotive companies evaluate VRAT in the early phases of the project development and such analysis requires tools with good reliability.

Blundell, who treat vehicle dynamics, describe the need and importance of alignment of front and rear wheels of automotive vehicles (BLUNDELL; HARTY, 2004).

Steering pull reduction is as importante as ride comfort and handling performances for driver's safety. Studies of steering pull reduction is required as an essential performance and shall be part of vehicle development process. (PARK et al., 2013)

To ensure the handling and directional stability of the vehicle, automakers shall include tolerances to the nominal values for all components that are part of the suspension (REIMPELL et al., 2001). The angle variations in wheel alignment and the dimensional variations from tires produces forces and moments at the contact between the vehicle and the track. The costumer perceives the effects of those forces and moments when the vehicle is in motion. Vehicle Residual Aligning Torque (VRAT), defined as the average torque required on the wheel to drive straight, is one of those perceived effects by the costumer (OH et al., 2000). VRAT measurements are in Nm, and its values means the directional trend of the vehicle: negative values indicates a trend to the right and positive values indicates a vehicle trend to the left. In 1975, Topping propose one equation to calculate VRAT. The Equation 1 is based on measured data from the test track, and VRAT, also called M_S, has direct relation with Tire Residual Aligning Torque (M_z) and lateral forces acting on tire in the axis Y (F_y). (TOPPING, 1975)

$$M_S = M_z - \left(F_y\right)e \tag{1}$$

Forces and moments are defined as they act on the vehicle and they are usually described by the velocities relative to the vehicle fixed coordinate system, based on the earth fixed coordinate system. Newton's second law is applied to the most analyzes related to vehicle dynamics. The law applies to both translational and rotational systems. Consider the vehicle of Figure 1 where the significant forces acting on a vehicle are displayed. Assuming that the vehicle is not accelerating, the sum of the torques at point A should be zero, according to Equation 2 and we can develop the resolution of forces W_f (Equation 3) and of W_r (Equation 4) (GILLESPIE, 1992).

$$\begin{bmatrix} W_f L + D_A h_a + \left(\frac{W}{g} a_x h\right) + R_{hx} h_h + \cdots \\ + R_{hZ} d_h + Wh\ \sin\Theta - Wc\ \cos\Theta \end{bmatrix} = 0 \quad (2)$$

$$W_f = \begin{bmatrix} Wc\ \cos\Theta - R_{hx} h_h - R_{hZ} d_h - \cdots \\ -\left(\frac{W}{g} a_x h\right) - D_A h_a - Wh\ \sin\Theta \end{bmatrix} / L \quad (3)$$

$$W_r = \begin{bmatrix} Wb\ \cos\Theta - R_{hx} h_h - R_{hZ} d_h - \cdots \\ -\left(\frac{W}{g} a_x h\right) - D_A h_a - Wh\ \sin\Theta \end{bmatrix} / L \quad (4)$$

W_f and of W_r are the forces acting on points A and B of Figure 1, respectively. Those points represent the contact between the tire and the ground and they are important to any computational model to calculate VRAT. We also shall consider the Center of Gravity (CG), the weight of the vehicle (W) the road angle (Θ) forces acting contrary to the movement, as aerodynamics (D_A), the use of trailers (h_h and R_{hZ}), distance between the CG and the axles of the vehicle (b and c), wheelbase (L) and distance between the forces opposing the movement and the ground (h, h_a and h_h).

There are two different methods to quantify the vehicle directional trend. The first method is to estimate VRAT of a vehicle on a straight drive and controlled road with constant velocity.

The second method is to estimate the lateral shift of the vehicle in the same conditions, without any interference of the costumer on the wheel. (LEE et al., 2005).

The main factors to be considerate on the computer model estimation of VRAT are the dimensional variations of the vehicle manufacturing process, the tires characteristics and the constructive standards of the road surface where the vehicle will sold. According to Oh, a well-designed computer model should take into consideration all those factors to estimate VRAT. Those factors are Cross Camber, Cross Caster, Conicity Residual Aligning Torque (CRAT), Plysteer Residual Aligning Torque (PRAT) and Road Crown.

The proposed model simulates a compact vehicle model for five people, Macpherson suspension on the front axis and Twist Beam on the rear.

2. Input factors

2.1. Camber

Nominal values for wheel angles are defined by automotive engineers based on Computer Aided Engineering (CAE) simulations to meet safety, stability and agility requirements (BLUNDELL; HARTY, 2004). Camber is the wheel angle relative to the vertical axis viewed from the front or rear of the vehicle. Positive camber is the wheel tilted away of the vehicle, and the opposite direction is a negative camber (Figure 2). Asymmetric camber angles cause excessive wear on the tire. In general, a tire Camber produces a lateral force toward the tilt. This force is function of tire type, construction, shape, rail, pressure, load, tractive or braking effort and slip angles. The road applies forces on tires. The tire tends to remove the curvature of the

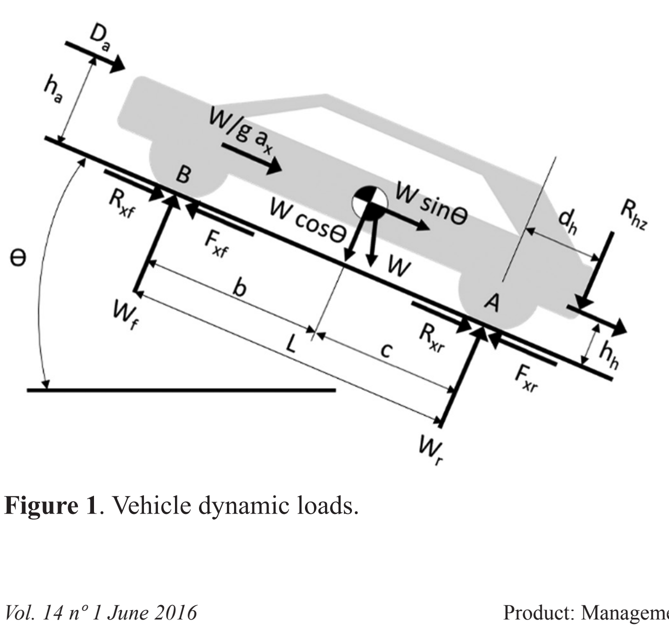

Figure 1. Vehicle dynamic loads.

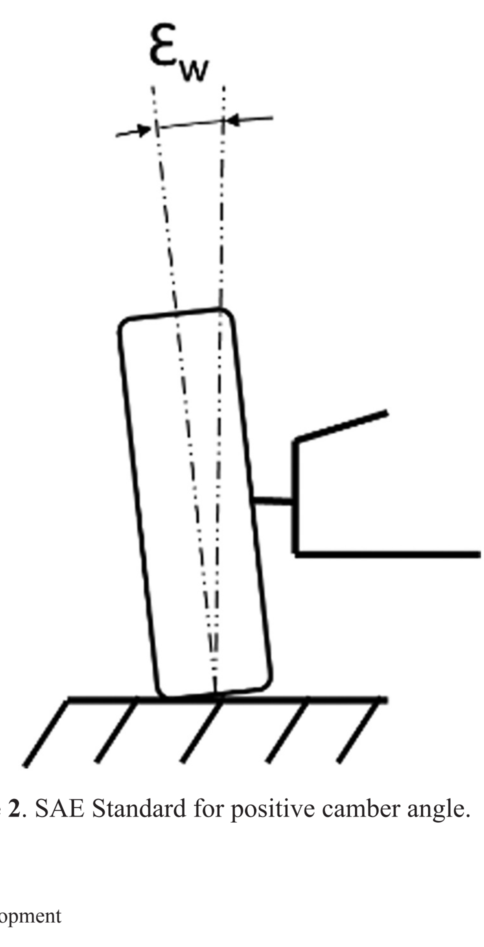

Figure 2. SAE Standard for positive camber angle.

typography on the stationary mode. The resultant force is called camber thrust.

Understanding the phenomenon of camber thrust, its influence gets clear in the analysis of vehicle slip. Therefore, to determine the variations of Camber throughout the manufacturing process becomes an important parameter to evaluate costumer perceived quality. The variations in the manufacturing process generate differences between the nominal design values and what is actually manufactured. These angle differences create asymmetrical results between right and left sides of the vehicle, as shown in Figure 3. This is called Cross Camber. The engineering specification for Cross Camber recommended for passenger vehicles is ±0.5° (REIMPELL et al., 2001).

2.2. Caster

Caster is the angle at which the axis of rotation of the tire is tilted forward or back from the vertical axis viewed from the side of the vehicle. The caster is positive when the pivot axis is inclined backwards and negative when the pivot axis is inclined forward (Figure 4).

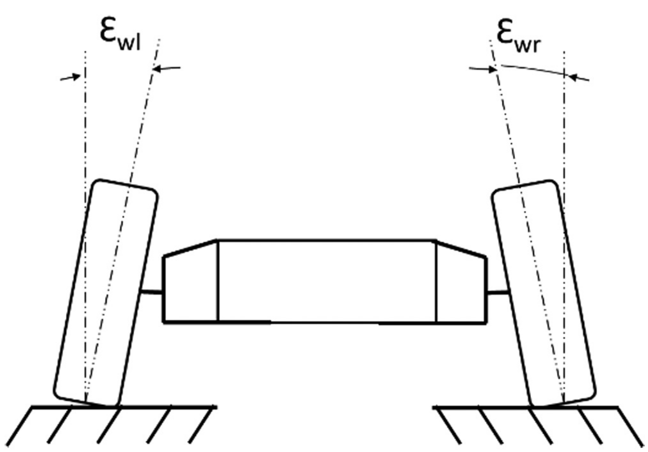

Figure 3. Cross camber.

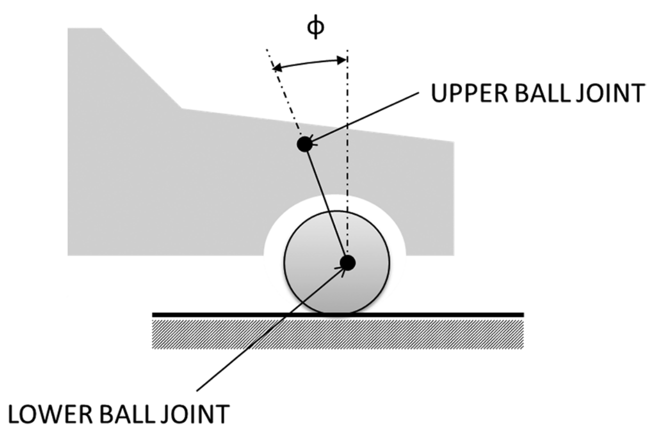

Figure 4. SAE Standard for positive caster angle.

Positive caster tends to straighten the wheel when the vehicle is moving forward, and this is used to improve straight-line stability. The mechanism that causes this tendency is easily illustrated by the drift of the front wheels of a grocery store cart. The rotation axis of a wheel in the grocery store cart is positioned posteriorly where the wheel touches the ground. When the grocery store cart is pushed forward, the pivot of rotation pulls the wheel, and since the wheel is drawn through the ground, it will be aligned behind the steering axis.

Most cars are not particularly sensitive to caster angle variation. But it is important to ensure that the caster is the same on both sides of the vehicle to avoid the vehicle steering pull. A higher caster angle facilitates driving in a straight road, but increases the effort of the driver to turn the steering wheel. Three to five degrees of positive caster is the typical used range.

Variations in the angle of caster occur for the same reasons of variations in camber, as exemplified in Figure 5. The difference between the measurement of Caster the right and left in a vehicle is called Cross Caster, and engineering specification for Cross Camber recommended for passenger vehicles is ±0.5° (REIMPELL et al., 2001).

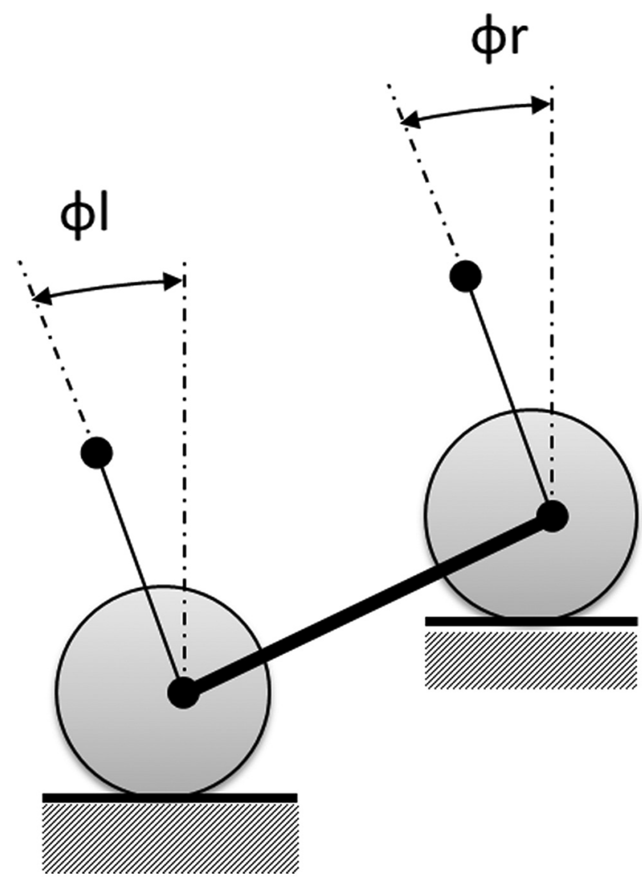

Figure 5. Cross caster.

2.3. Tires

The primary function of the tire is to provide the interface between the vehicle and the road. The tire contact area in a passenger vehicle is smaller than a letter sized sheet of paper. This small contact area of the tire is responsible for vehicle safety during the rainy days, allows quick turns into a parking ramp, to drive over potholes on the road without damage an also it supports the weight of the vehicle (GENT; WALTER, 2005).

In other words, the tire transmits the longitudinal, lateral, and vertical forces between the vehicle and road (Jazar, 2014). Those forces have different intensity and direction for each vehicle produced, even if they are exactly the same model, and these differences come from the manufacturing process. These variations directly affect the VRAT and are caused by the tire conicity, CRAT and PRAT.

2.3.1. Tire conicity

Tire conicity is defined as the lateral force generated in the tires and this force does not change direction relative to the face of the tire due to the change of direction of the tire rotation (Figure 6). One effect of conicity is the tire to roll like a cone, always bending over to the side with smaller circumference. When a load is applied, differences in belt rigidity on each side of the tire can lead to taper shape.

This force caused by the conicity can also change the magnitude and direction during the life of the tire. However the changes should occur after a high mileage under normal wear or aging static if the vehicle is stocked. It is important to consider the inadequate tire pressure and suspension alignment that exceeds the specification limits to diagnose the symptoms of vehicle steering pull.

Measurement of conicity can be used to estimate which setting will be most desirable to minimize the drift condition. VRAT predictions are sensitive to vehicle load. When selecting an alternative configuration based on the magnitudes of conicity, it is important to remember that conicity depends on the tire pressure and it reduces as the pressure increase. Vehicles using high pressure calibration tire may be less sensitive to a given conicity than others at low pressures specified.

2.3.2. CRAT

CRAT is the difference in the tire normal force generated by the momentum created in the longitudinal axis passing through the center of the tire, due the lateral force generated by conicity in tire contact with the road (Figure 7) (REIMPELL et al., 2001). This difference in normal force directly impacts the VRAT, increasing or decreasing the transfer of power to the ground due to this the normal reaction force.

2.3.3. PRAT

Another attribute associated with the tires, and derived from the lateral force generated by the tire due to the variations and asymmetries on the belts and body piles of the tire is the PRAT. It is directly related to the moment generated by the force of plysteer in the roll center of the vehicle. The tests for measuring PRAT are made in both directions of rotation of the tire not to be confused with CRAT.

PRAT and CRAT has the same direction when the tire is rotated clockwise, however when turned counterclockwise PRAT reverses it direction and CRAT continues in the same

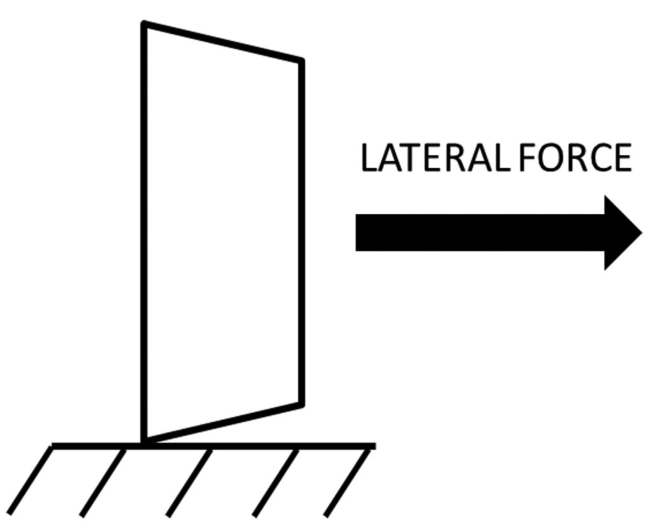

Figure 6. Tire conicity representation.

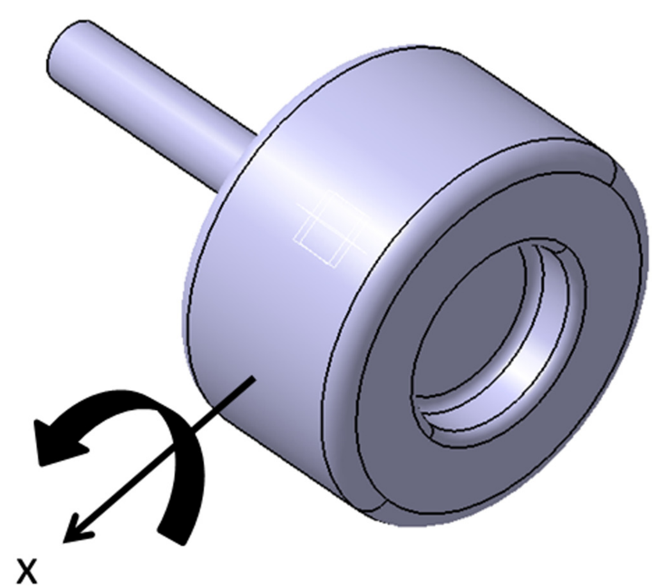

Figure 7. Tire conicity effects on momentum.

direction, and it can be calculated as the difference between measured values found clockwise and counterclockwise. It is for this reason that mathematical models used in the analysis of tire drift effect are different for the left and right sides.

The PRAT influence the effects of the vehicle steering pull changing the normal force of the tire with the road and it is directly associated with the magnitude of plysteer. The value of PRAT is also proportional to the steer angle (PACEJKA, 2005).

2.4. Road crown

Road crown is a significant attribute related to the effect of vehicle steering pull. It is necessary to consider the variations of road crown specifications for each market in which the vehicle will be sold. The current difficulty is to design a suspension set that meets global markets requirements, but it is crucial to ensure product quality. On Brazilian highways minimal road crown recommended for a asphalt pavement is 2\% and may reach 5% for some highways (PEREIRA et al., 2010).

3. Calculating VRAT process capability

3.1. Applying V model

It is important to have a structured process to ensure that the computer model error is acceptable (BLUNDELL; HARTY, 2004). For this reason, each stage of the suggested process is based on V Model. The paper also used part of another engineering based process called design for variation (DFV). Under DFV, probability distributions of system performance characteristics are produced that explicitly account for all sources of uncertainty and variability, including those associated with engineering model uncertainty (REINMAN et al., 2012).

3.2. Aspiration and definition

The objective of this model is to ensure that customers do not have the perception that the vehicle is "pulling" to one side or the vehicle is misaligned. The term pull was used intentionally in order to have a real understanding of costumer expectations: aligned wheel system and robustness to the variations of terrain. The engineering attribute to be controlled is VRAT.

Because VRAT specification is different for each vehicle model and this target is confidential for the automakers, there isn't parameters into the books about vehicle dynamics. The specification for VRAT used in this model is 0 ±0.50 Nm. Note that studies about VRAT shall be applied by automakers in accordance with the market where the vehicle will be sold. VRAT negative values indicate a trend to the right and positive values indicates a vehicle trend to the left..

3.3. Analysis and decomposition

VRAT is calculated as a function of several factors. Basically, you must use the calculation factors influencing the difference in forces acting on the tires of the left and right side. You can divide these factors in vehicle body, tires and external factors. The factors related to the dimensional variation of the body are Cross Camber and Caster Cross. The factors related to the dimensional variation of the tire are Conicity, CRAT and PRAT. There is an external factor that cannot be controlled, but directly influence the result: Road Crown. VRAT will be a function of all these factors.

This modeled vehicle was based on a compact car with MacPherson front suspension and Twist Beam rear suspension.

The specification limits (Table 1) shall be defined during the system decomposition phase. Cross Camber, Cross Caster and Road Crown were previously specified. The specification limits regarding Conicity, CRAT and PRAT were based on measurement data of standard 13 inch tire widely used in compact vehicles.

3.4. Synthesis

The tires must be delivered to the automaker within the limits specified by engineering and validated by the supplier. Cross Camber and Cross Casters are factors resulting from the body welding process and machining or metal forming processes to manufacturing components of the suspension system.

The Cross Camber and Cross Caster angle variation predicted by design can be calculated by using a stochastic model on VisVSA software to determine the dimensional variation (CHIB; GREENBERG, 1995) (LEANEY, 1996). For each geometric point of suspension were added to the dimensional tolerances: normal curve distributions provided by the design of each individual component of the system and assembly tolerances of each subsystem. The results of Monte Carlo simulation with 5000 iterations are angle variations of Camber, Caster and the main contributors for those dimensional variations.

Table 1. Design specification limits.

Factor	Curve	Nominal	Lower Limit	Upper Limit
Cross Camber (degree)	Normal	0	–0.5	0.5
Cross Caster (degree)	Normal	0	–0.5	0.5
Conicity (N)	Uniform	0	–53	53
CRAT (Nm)	Uniform	0	fconicity	fconicity
PRAT (Nm)	Normal	–2	–0.5	0.5
Road Crown (%)	Uniform	2.5	–0.5	0.5

The simulated process variation for Cross Camber is ±0.44° and its Process Capability is 1.14. The process variation for Cross Caster is ±0.44° and Process Capability is 1.02. Process capability results are based on ±0.5° target (REIMPELL et al., 2001). The design dimensional tolerances of the body and suspension can be validated with these results.

3.5. Composition

A mathematical model of a vehicle should be simple, but significant. There is not a unique solution. It is important to state clearly the assumptions behind each simplification, thus making clear under which conditions (GUIGGIANI, 2014). The multibody dynamics model was developed on the MSC.ADAMS Chassis (BLUNDELL; HARTY, 2004). The MacPherson and Twist Beam models contain certain simplifications that do not impact significantly on the result of the model. All simplifications have been used and analyzed on the thesis (WENDLANDT, 1997) and books about simulation of vehicle dynamics (KIM, 2000). The developed model shall reliably predict the behavior of a real vehicle.

This multibody dynamics model was validated by the comparison of measured data acquired in a prototype vehicle and the simulated results (ROY; MARK, 2013) (HAGA, 2006) for bump-steer (Figure 8) defined by toe variation with locked steering wheel during suspension travel, camber variation (Figure 9) with locked steering wheel during suspension travel, vertical motion force (Figure 10) defined d by the necessary force applied to tire patch to move suspension travel and the equivalent spring rate which defines corner assembly motion, also called suspension rate (Figure 11).

3.6. Simulation

A Design of Experiment (DOE) was created at MSC. ADAMS Chassis using D-Optimal algorithm with two hundred iterations. The dynamic simulation model was used to calculate the value of VRAT as proposed in Table 2 on a Dell Precision WorkStation T7400, Intel Xeon E5440 @, 83 GHz (2 CPUs), 16 GB RAM with Windows Vista Enterprise 64-bit got 318 minutes to process 200 iterations, or 95.4 seconds per iteration.

Table 2. DOE factors limits.

Factor	Lower Limit	Upper Limit
Cross Camber (degree)	–1	1
Cross Caster (degree)	–1	1
Conicity (N)	–180	180
CRAT (Nm)	–7	7
PRAT (Nm)	–6	2
Road Crown (%)	1.5	3.5

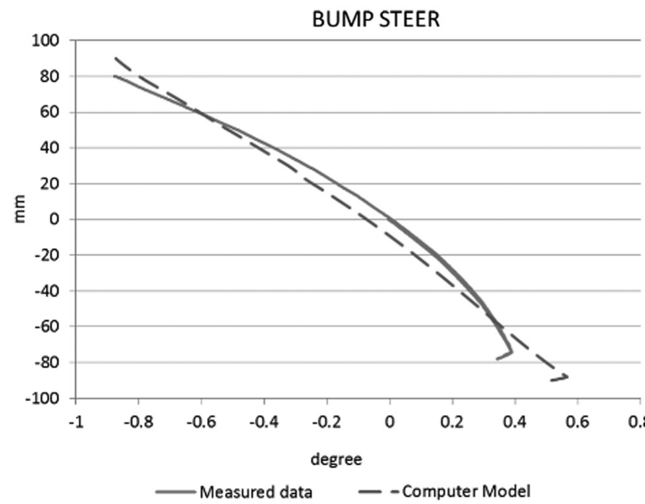

Figure 8. Bumper Steer - computer model validation.

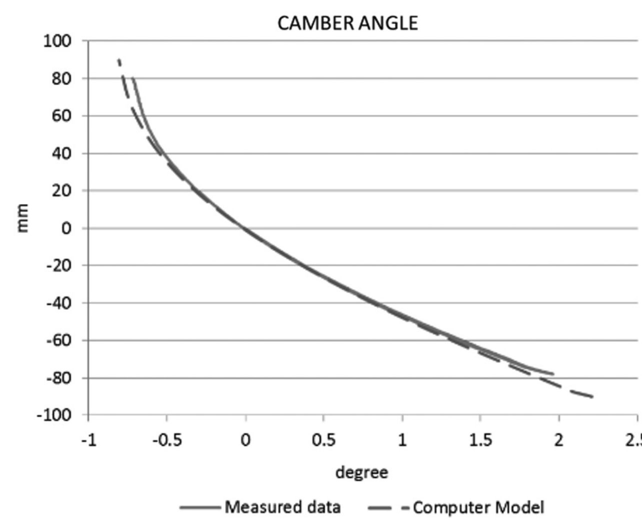

Figure 9. Camber - computer model validation.

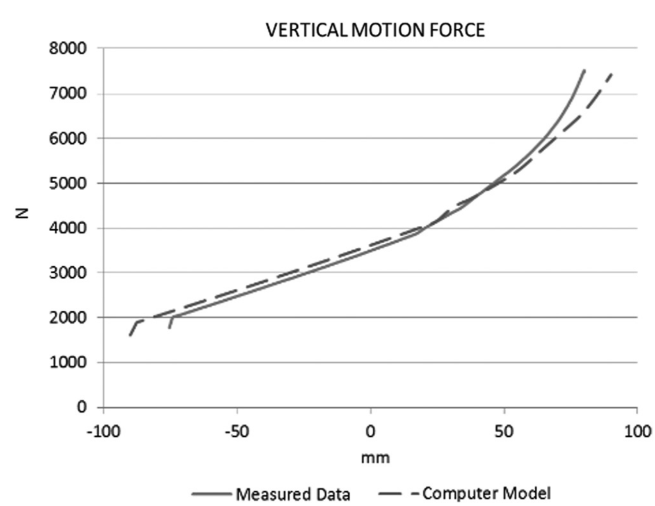

Figure 10. Vertical motion force - computer model validation.

The proposed limits extrapolate the recommended target for each factor. The reason it is the need to evaluate the vehicle behavior when some of the imputs are out of specification and support manufacturing process.

Using multiple regression algorithm to generate a first order polynomial, the coefficients were calculated on modeFRONTIER according the DOE simulated in MSC. ADAMS (BRANKE et al., 2008). VRAT can be estimated now based on the Equation 5. The regression parameter (R^2) for this equation is 99.9%.

$$\begin{aligned} VRAT = &\ 0.77 + 0.12(X\ Camber)\cdots \\ &- 0.26(X\ Caster) - 0.16(Conicity)\cdots \\ &- 0.22(CRAT) - 0.13(PRAT) + 0.1(Road\ Crown) \end{aligned} \tag{5}$$

Equation 5 is valid only for this simulated vehicle. For other vehicle platforms, the model developed in MSC. ADAMS Chassis must be modified and simulated again, where we can determine a new response surface and the different results presented in this paper.

And now it is possible to predict the distribution curve of VRAT with the design specification values as shown in Table 1. Values were applied on a Monte Carlo simulation with 5000 iterations using the Equation 5. The VRAT average value is -0.115 Nm and standard deviation of 0.122 Nm. As the specification limit of VRAT is ±0.50 Nm, the predicted values of Cp and Cpk are 1.37 and 1.05, respectively.

Computer processing time for these 5000 iterations were $8x10^{-4}$ seconds per iteration, using exactly the same computer configuration used to run the DOE at MSC. ADAMS Chassis software. That means a reduction of 95.8% by the usage of the proposed method instead of the common simulation with MSC.ADAMS Chassis.

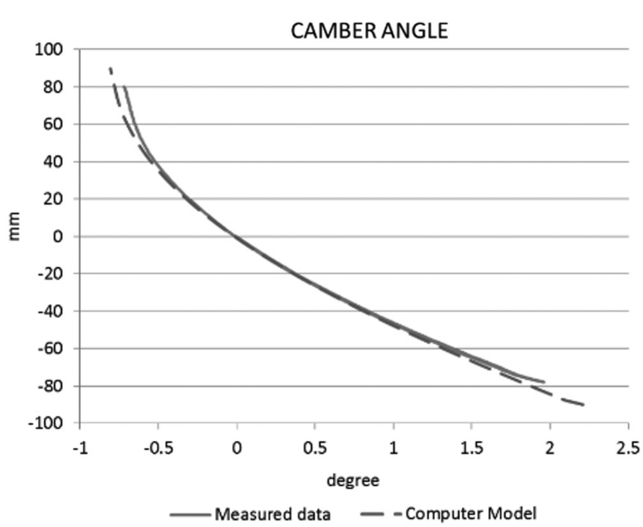

Figure 11. Suspension rate - computer model validation.

3.7. Confirmation

Ten iterations were randomly created and these interations were simulated at MSC.ADAMS Chassis and ModeFrontier to validate the Equation 5. The ModeFrontier model average error is 0.00184 Nm as shown on Table 3. Based on the error found the Equation 5 is approved.

3.8. Review

It is necessary to review and document the entire project development regarding dimensional tolerances and VRAT specifications. This is important to guarantee that the information will be set to determine the necessary controls during the vehicle manufacturing process. It is important to update the Failure Mode and Effects Analysis document (FMEA), generate assembly and detailed drawings. The review phase is important to get the design results into the manufacturing, and it is several times neglected (BLUNDELL; HARTY, 2004). The product and process engineering should have a multidisciplinary team in order to take full advantage of the information generated in this phase to create a robust action plan.

4. Review phase applied on manufacturing issues

We shall develop the diagram parameters to get a better understanding about how model factors interact with the results (Figure 12). The product or process concerned is on the center of the diagram. The inputs are on the left and all desired and undesired outputs are on the right side. Control factors are add to the upper portion and the system noise is in the lower portion of the diagram.

The control factors can be split into body and tire. The tire supplier must deliver the product within the specification, and the automaker is responsible for require to the supplier the statistical control of PRAT, CRAT and Conicity. Furthermore, these factors effects are already included on VRAT equation. That said, the review phase will focus on the relevant body factors under automaker responsibility: Cross Camber and Cross Caster.

Table 3. VRAT Response Surface validation.

Simulation #	MSC.ADAMS (Nm)	ModeFRONTIER (Nm)
1	0.7218	0.724
2	0.8491	0.8514
3	0.1076	0.1093
4	0.0064	0.0089
5	0.6373	0.6389
6	0.2888	0.2908
7	0.1986	0.2005
8	0.2811	0.283
9	0.436	0.4367
10	–0.3883	–0.3868

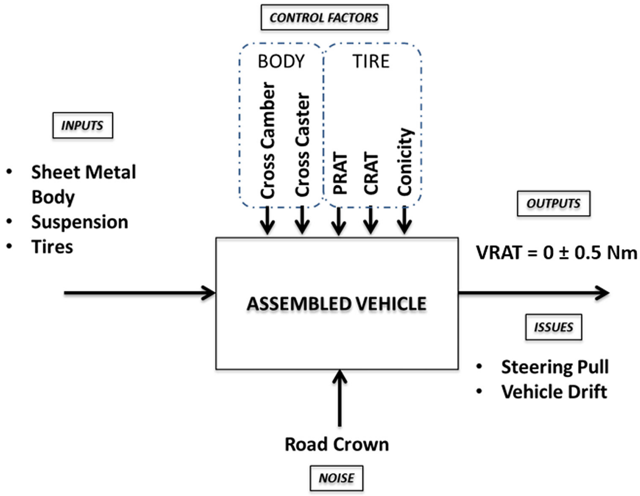

Figure 12. VRAT P-Diagram.

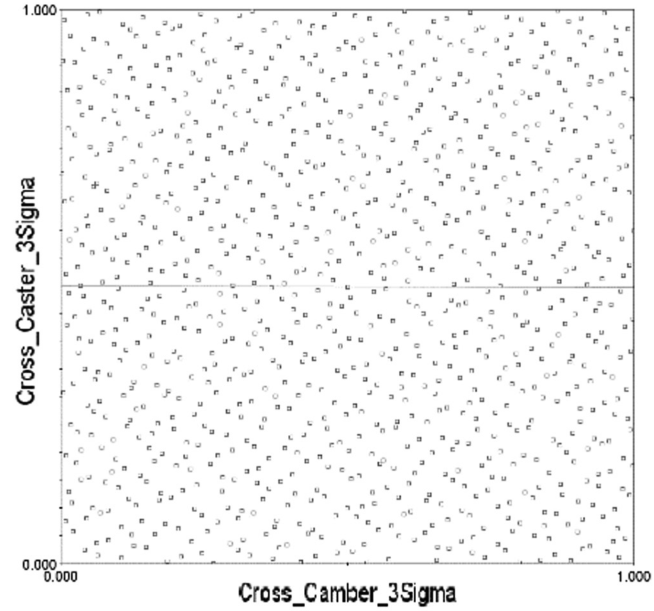

Figure 13. Sobol algorithm applied on cross camber and cross caster standard deviation.

The design of experiments were used to perform this analysis. A thousand random initial values were generated using the Sobol algorithm available on modeFRONTIER. Sobol is a deterministic algorithm that fill in a uniform manner the requested design space (SOBOL, 1975). The factors were adjusted according to the specification Table 1, except for the standard deviation of Cross Camber and Cross Caster. They were adjusted individually to have their limits ranging between 0° and 1° (see Figure 13). This techinic allow an easy and visual evaluation of Cross Camber and Cross Caster standard variation on VRAT standard variation results.

These initial values from Sobol algorithm were used to create a thousand Monte Carlo simulations with 200 iterations each. A total of 200,000 iterations were simulated to generate the graph of Cross Camber, Cross Caster and VRAT standard deviation. The tolerance limits used at Cross Camber and Cross Caster extrapolate the engineering recommendations because is possible to assembly the final product out of specification throughout time. Each vehicle is manufactured with different values of Cross and Cross Camber Caster due the dimensional variation. To analyze all the possible interactions between these factors and VRAT, a response surface was developed based on those iterations (see Figure 14).

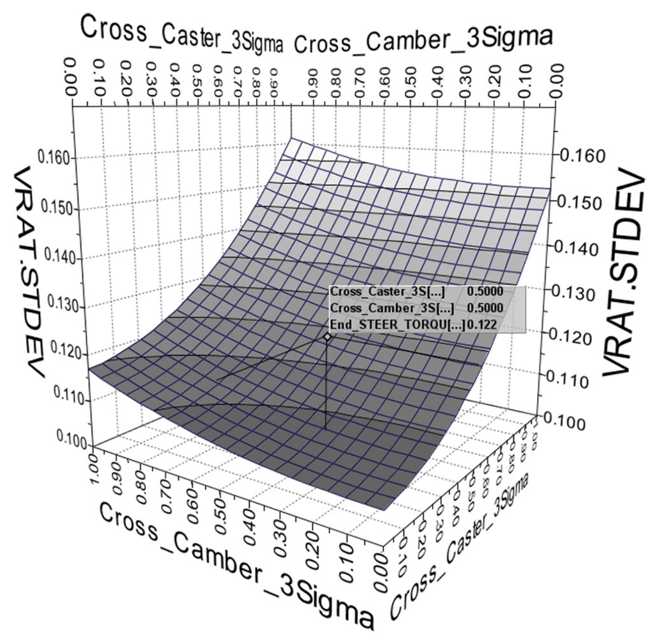

Figure 14. Cross camber and cross caster standard variation effects on VRAT standard variation.

Manufacturing needs to receive the major contributors for VRAT variation from product development team, as components features and fixtures, and use the data to create a Statistical Process Control (SPC) plan. This data is acquired from the stochastic model for Cross Camber and Cross Caster as shown on Figure 15 and 16.

Note that the variation of ±0.37 Nm was the limit defined to start the process evaluation. This limit is lower than the specified target of ±0.5 Nm due the common mean variation that occurs within the process and based on a Cpk of 1.33.

5. Conclusion

The use of V Model has facilitated the integration of all simulation models. Also this process ensures that all factors that influence VRAT variation were evaluated considering

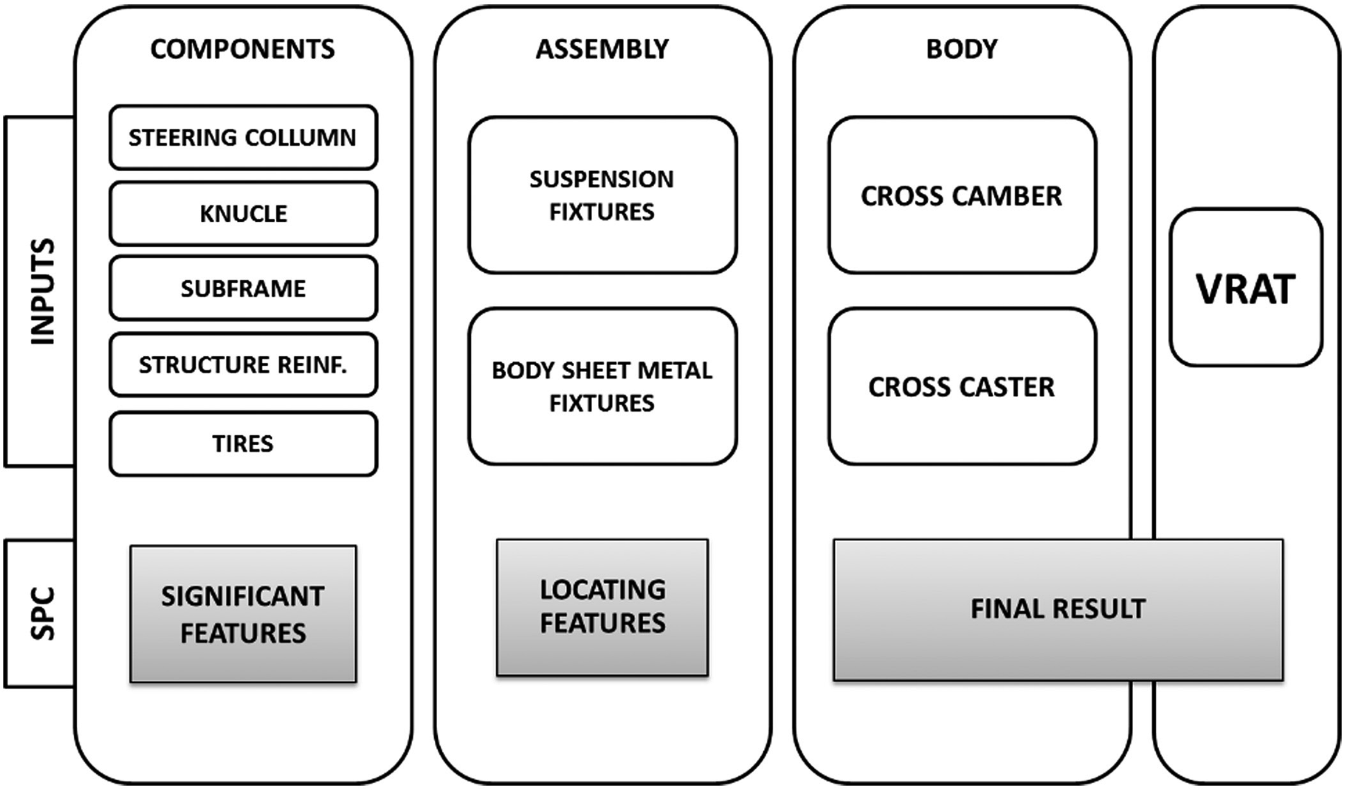

Figure 15. Major contributors for cross camber and cross caster standard variation.

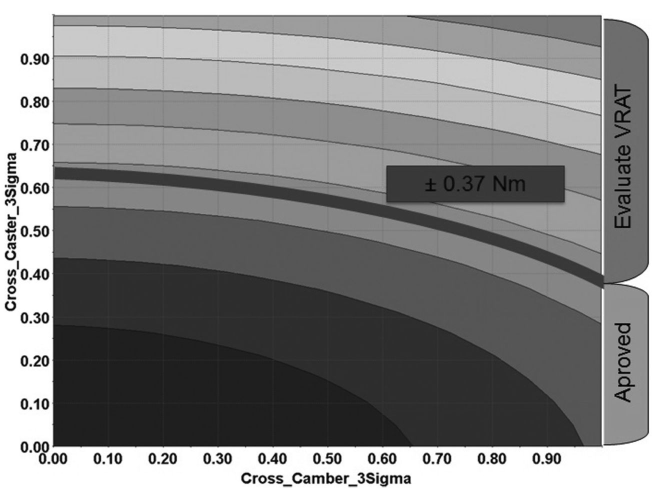

Figure 16. Example of final line checking graph for VRAT.

different scenarios and customer needs. The average error of the response surface compared to the multibody model was 0.00184 Nm and acceptable to the simulated experiment.

All studied factors contribute significantly to calculate VRAT. The division between body and tires allows process suppliers engineering to understand the importance of the dimensional tolerance design to the client and develop control plans to meet the specifications required by product engineering.

This method can reduce the computational cost compared to the common methods that uses only model developed in MSC.ADAMS. The proposed model obtain a reduction of 99.87% on the time to obtain all results. The proposed method got just 13 hours and 22 minutes, compared to a calculated 447 days that would be needed if we used only the MSC.ADAMS Chassis model to simulate results for more than 200,000 iterations.

This proposed method can be used to evaluate other vehicle issues, as clear vision or premature tire wear, and it is a start point for interdisciplinar studies of all those factors that effects vehicle dynamics.

Interdisciplinary computational models should be used to ensure interaction between product development and manufacturing, and complete the development cycle with innovative results for the industry.

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