Effects of Camber Angle on a Sports Car Steering Response

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***Abstract*—This report studies the driving experience of different camber angles on a sports car in different driving scenarios. The camber angle is varied between -10 to 10 degrees and the tests are performed in three different driving scenarios: a) a constant turn, b) a step steer response, c) a sinusoidal steer response.**
To evaluate the driving experience, the following performance indicators are analyzed: A) yaw velocity, B) yaw velocity response gain, C) yaw velocity overshoot ratio D) lateral acceleration response time, and E) lateral acceleration overshoot. The study concludes that a more negative camber angle results in a sportier driver experience but also yields a more oversteered behaviour.

***Index Terms*—Vehicle dynamics; Tire model; Camber effect; Simulation**

I. Introduction

This report contains the study of the static camber angle γ change on the steady state cornering and the transient state sinusoidal wave response of the car with yaw response gain and lateral acceleration gain .

γ is one of the angles made by the wheels of a vehicle; specifically, it is the angle between the vertical axis of the wheels and the vertical axis of the plane and can be viewed from the front and the rear end of the car. Fig. 1 depicts γ of the car [1]. The car is said to have $+\gamma$ when the tires are tilted outwards away from the chassis at the top of the tire and $-\gamma$ when the tire are tilted towards the chassis at the top of the tire.

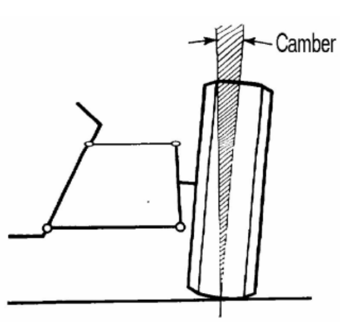

Figure 1. Camber angle of the wheel [1]

The cornering stiffness (C_α) of the tire varies with γ, which helps enhance the C_α due to the straightening out of the arc of contact patch of the tire. This phenomenon is called *camber thrust*. If the tire is leaning with the positive camber it will act away from the radius of curvature of the turn, if the tire is leaning with the negative camber then the force will act towards the center of curvature of the turn. In short, a negative γ always helps increase the cornering force from the tire.

A. Tire model

This section describes the change in the lateral force F_y with changing slip angle α for different γ. The graph shows a decrease in the normalized F_y with increasing positive γ (Camber angle). IPG carmaker uses the Pacejka Tire Model fitted with the Magic Formula for the simulations [2].

B. General trends of suspension arms on camber gain

The double wishbone suspension generally found in the sports cars have endless combination of the lengths of the arm which can produce different characteristics of camber gain. Longer A arms give less camber gain compared to short ones while increasing the turning diameter of the car. The best combination is the the presence of unequal A arms in which the upper A arm is tilted towards the ground in the neutral position which provides good negative camber gain in bump/rebound but provides low positive camber gain in roll. [3] Also ultimately the roll gradient of the car will determine how much the car rolls and how much roll camber gain it achieves after rolling in the corner. The roll gradient is given by equation 1.

$$\frac{\phi}{A_\gamma} = K_\phi = \frac{-WH}{K_{\phi F} + K_{\phi R}} \tag{1}$$

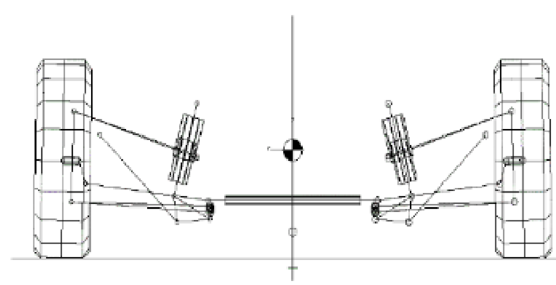

Figure 2. Unequal length non-parallel design of double wishbone suspension [4]

C. Steering geometry on the camber gain

While steering geometry on the camber gain is of no significance to the rear wheel, it is of great importance to the front wheel which has a steering geometry with caster angle built into it. The presence of the caster angle increases the trend for the inner tire to have positive gain and the outer tire to have negative gain while the car is steered for the turn [3].

II. Tire Model

For the model, we are using the default tire available in IPG carmaker, RT_245_35R20, for both the front and rear of the car. Fig. 3 and 4 show the nature of F_y and self aligning moment M_z of the tire with changing γ. It is clear that the negative γ has an increase in the F_y and the yaw performance of the vehicle but it is naive to just conclude that the negative camber angle will increase the handling performance of the vehicle since the suspension geometry is a very complicated mechanism and we have to capture the effect of all the forces acting on the vehicle while cornering to better draw a conclusion of its performance.

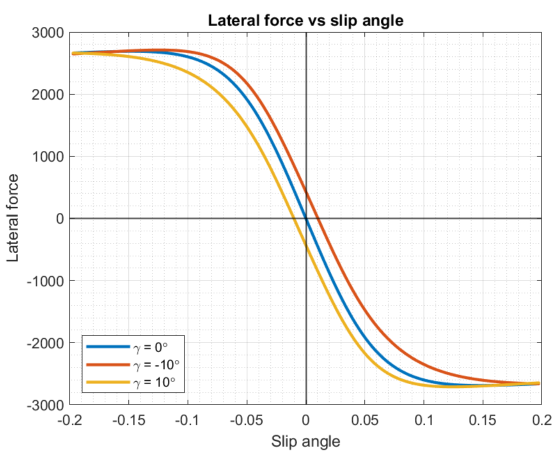

Figure 3. Lateral force vs slip angle

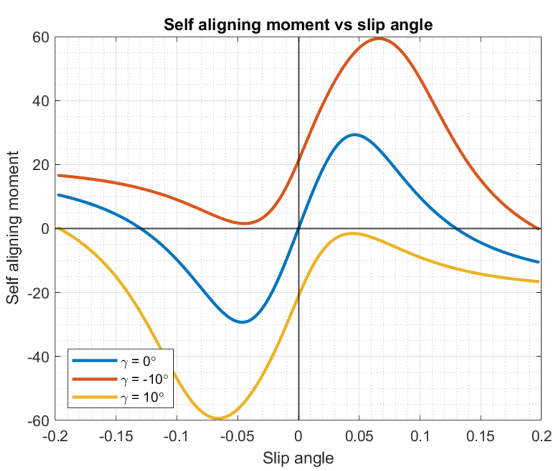

Figure 4. Self-aligning moment vs slip angle

III. Key Performance Indicators

Although the steering and handling performance of the vehicle is subjective and can be measured with the driver response sheet, this method is quite vague and does not always help in estimating the correct performance of the vehicle in the design perspective. Also, some changes in the suspension geometry is not perceivable by the general driver unless he/she is a racing expert. Hence it is necessary to develop some key performance indicators to assess the performance of the vehicle.

The following performance indicators are crucial in determining the lateral performance of the car with the different static γ sets on the same kinematic suspension geometry.

A. Yaw rate

Yaw rate r (or yaw velocity) is a common parameter in determining how a car will behave at cornering. It depicts how fast the car turns about its vertical axis and how quickly the car reacts to the steering input. A typical graph for the yaw behavior of the vehicle for a quick step response is shown in Fig. 5.

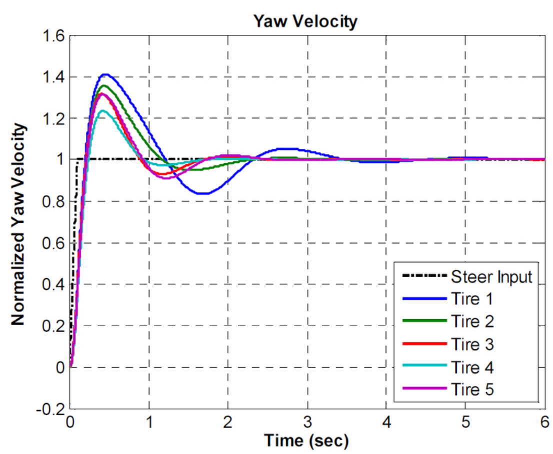

Figure 5. Yaw velocity response (normalized) [5]

This graph is characterized by a few transient effect parameters which will help us analyze the behaviour of the vehicle under extreme driving maneuver condition.

1) Yaw velocity response time: Yaw velocity response time is the elapsed time between when the steering input reaches 50% of its steady state value and the r reaches 90% of its steady state value. This helps to analyze how quickly the car reacts to the inputs of the steering wheel in presence of a step input.

2) Yaw velocity overshoot ratio: Yaw velocity overshoot is the ratio between its peak value and steady state value for a step steer input. This will help us to determine how controllable the car is and how quickly it turns into the steady state behaviour after the given input is applied.

B. Lateral Acceleration

1) Lateral acceleration response time: Lateral acceleration response time is the time elapsed between when the steering input reaches 50% of its steady state value and a_y reaches 90% of its steady state value. This parameter is similar to the yaw velocity response time which is used to estimate the performance of the car but is used to determine the lateral acceleration response time.

2) Lateral acceleration overshoot: Lateral acceleration overshoot is the ratio of the peak lateral acceleration to the steady state a_y of the car. It helps us to determine how stable the car is in terms of a_y after a step response is applied. A few other parameters to analyze the step response of the car can be for the fixed type of maneuver.

- Lateral Acceleration a_y vs time
- Yaw rate r vs time
- Side slip angle β vs time

These will be discussed more in IV.

IV. Simulation Results

A. Car Model and Parameters

To perform the standard tests and check the effect of γ on various parameters as defined previously, we need to first standardize the car to be tested. The effect of these parameters can be greatly perceived on a sports car rather than a normal family car. Hence, Porsche 911 GT3 RS is chosen as the test car to perform various maneuvers.

The car in IPG Carmaker comes with different sets of tires in the front and in the rear. In order to increase the influence of the tire on camber angle and thus, the handling performance, we change the tires to a standard tire set as mentioned in II as this is one of the standard tire specification for a sports car.

The various parameters of the car are as shown in Table I.

Table I
Vehicle parameters

Weight	1595 kg
Vehicle Width	1880 mm
Vehicle Length	4507 mm
Wheelbase	2450 mm
Track Width F	1541 mm
Track Width R	1590 mm
Maximum Steering Angle	600 °
Turning Circle	10.6 m
Driving Axle	RWD
Vehicle Body	Rigid

The suspension of the car is set up with Linear 2 Degree-Of-Freedom (DOF) for the front and the rear and can be tuned to obtain different suspension kinematics. Static γ is varied with 3 different angles. $\pm 5°$, neutral and $\pm 10°$ while all other parameters are kept constant. These angles were chosen since they represent a certain maximum camber angle that is normally used (5°) and an extreme case (10°) which is rarely used with a bigger disadvantage. [3]

B. Steady State Cornering

The steady state cornering test is performed using the ISO 4138 test criteria [6], for which the testing parameters are defined as follows:

The open loop track is created in IPG with a straight portion to gain speed with a constant circle afterwards to test the steady state cornering behavior with changes in the vehicle speed. Steering angle δ is varied in order to maintain stability.

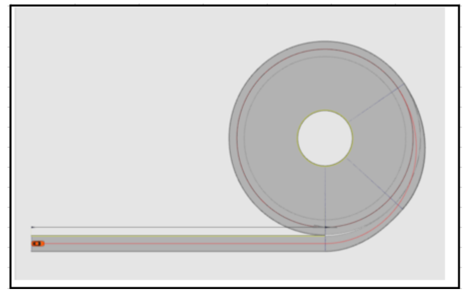

Figure 6. Constant radius track 30m

- Track Radius = 30 m
- Circle entry speed = 50 km/h
- Speed increase from 50 km/h to 60 km/h in steps of 1 km/h for 1s such that the car follows a steady state behaviour

The following results are obtained after conducting the test in IPG Carmaker:

1) Under steer gradient: δ vs a_y (Fig. 7) helps determine the understeer gradient K_{us} of the car. The car clearly shows a gain in a_y with the decrease in the static γ of the wheel. Both the cases ($+\gamma$ and $-\gamma$) show an under steering behaviour but a positive static $\gamma = 10°$ in the front axle shows more under steering behaviour due to less F_y available in the front axle. The variation in δ between 6 m/s^2 and 7 m/s^2 is due to the car reaching a constant speed of 60 km/h and zero acceleration beyond this speed. The same effect is also seen in the Yaw rate vs steering angle (Fig. 8). r is increasing with the decrease in the γ of the wheel.

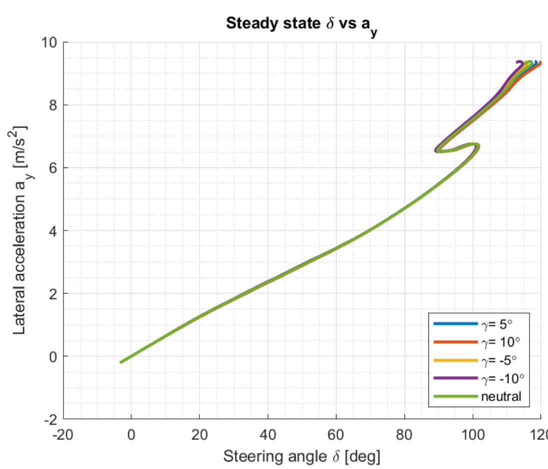

Figure 7. Lateral acceleration vs the steering wheel angle

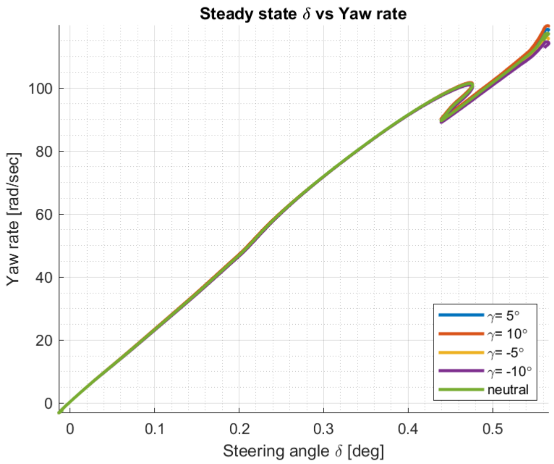

Figure 8. Yaw rate vs steering angle for different camber

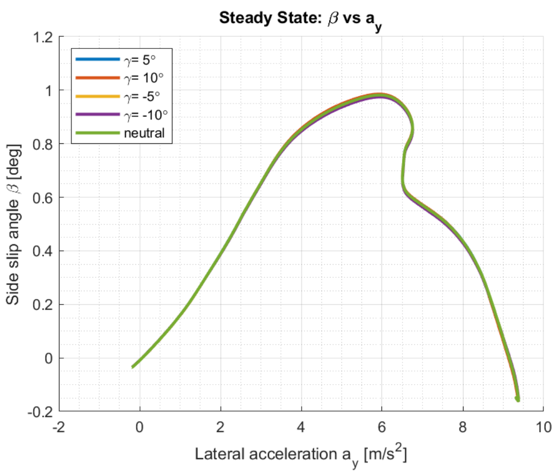

Figure 9. Side slip angle vs lateral acceleration

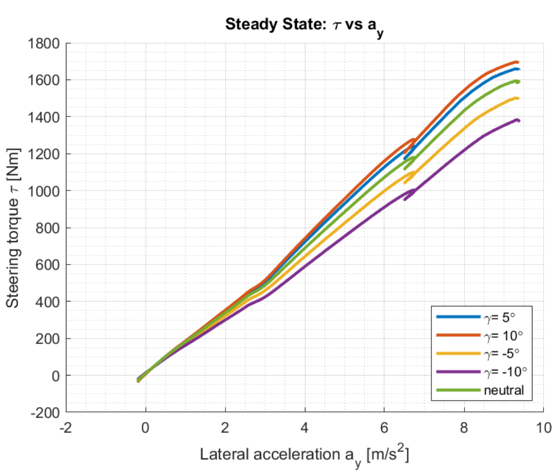

Figure 10. Steering wheel torque vs lateral acceleration

2) Vehicle Stability: β vs a_y (Fig. 9) helps determine the lateral stability of the car. β shows an aggressive change with the increase in the a_y for the car with front axle $\gamma = -10°$ as compared to the car with $\gamma = +10°$. The car has become more sporty in nature and has an increase in the tendency to over steer while cornering.

3) Steering effort: The steering wheel torque τ vs a_y defines the steering effort (Fig. 10). $\gamma = -10°$ shows an increase in τ which weighs up the steering feel of the car and gives it more sporty feel. This increase is sometimes desired if you are driving at high speed or driving in a slippery condition where the heavy steering feel will reduce your chance to commit any unwanted maneuver. This is also due to the fact that the M_z increases on the tire as the tire attains a negative γ.

C. Frequency sweep test

The frequency sweep test is performed similar to ISO 7401 [7]. The vehicle first accelerates from 0 to 80 km/h and then the vehicle is held at a steady state for 10 seconds. The steering input is given to the car as a sinusoidal sweep with amplitude of 50 degrees from 0.2 Hz to 5 Hz and the vehicle is stopped. For both sine and step test the track is defined as a patch of 2km x 2km to test the performance of the car without giving any errors.

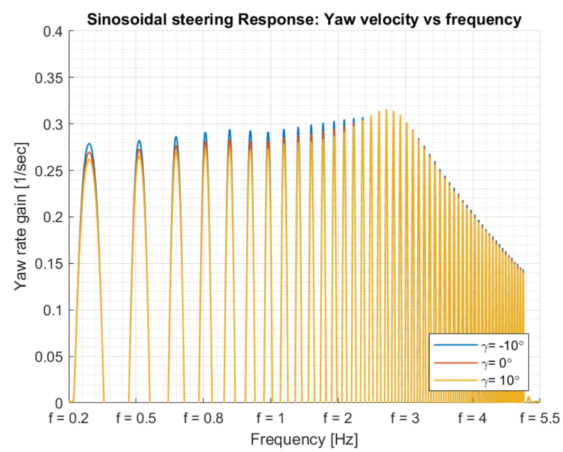

Figure 11. Yaw rate gain vs frequency

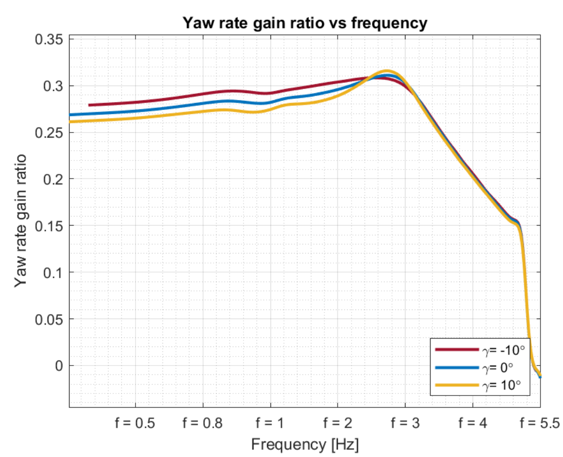

Figure 12. Yaw rate gain with the fitted maxi-ma

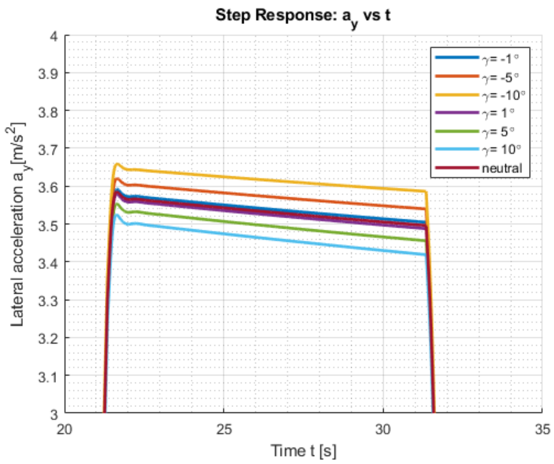

Figure 13. Lateral acceleration for different camber angle

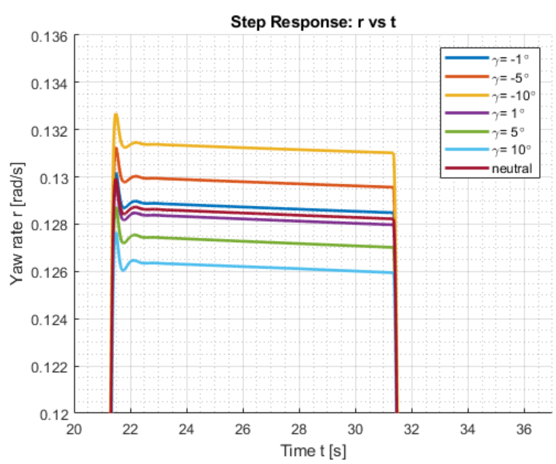

Figure 14. Yaw rate for different camber angle

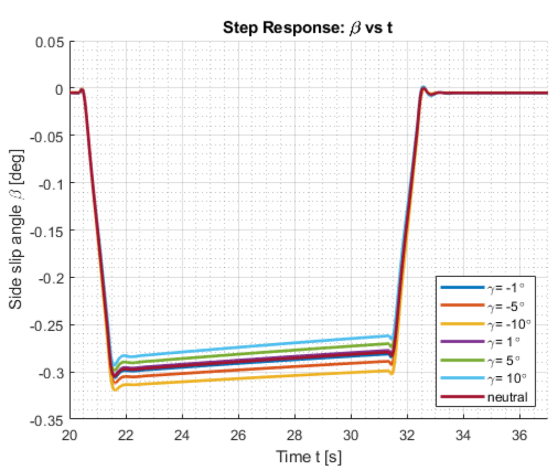

Figure 15. Side slip angle for different camber angle

When the parameters that govern the vehicle motion characteristic are changed, the shape of the yaw rate gain changes. In [8], it is shown that the ratio of the peak gain to the low frequency gain is $\left|G_{(peak)}\right| / \left|G_{(0.2)}\right|$. The relation between this ratio and the vehicle controllability, as shown in Fig. 11, is judged by comparing the data between cars. As seen in Fig. 12, the car with more negative γ responds quickly to less steering input and the ratio of the peak to the low frequency value is low hence the car is more agile to inputs and responds to be more predictive when the frequency of the steering input is increased.

D. Step Response test

The step response test is done similar to ISO 7401 [7]. This test consists of a car which accelerates to 80 km/h and remains in this state for 10 seconds to attain a steady state of acceleration. An input of 20 degrees steering angle δ is given in a step format and the car drives in this state for 10 seconds. After completing the maneuver the car is brought to a rest. With the decrease in the static camber of the wheel the following observations are made:

E. Increase in the maximum lateral acceleration and gain

It can be seen in Fig. 13 that, higher γ yields a higher a_y due to the presence of camber thrust between the road and the tire. The lateral acceleration gain is also increased due to the presence of a higher F_y on the front axle of the vehicle.

F. Increase in the yaw rate and yaw rate gain

Fig. 14 shows an increase in r of the car. This shows that the presence of a negative γ increases r due to the presence of higher forces on the front axle of the vehicle. It also increases the yaw response gain of the vehicle.

G. Increase in the side slip angle

Fig. 15 shows an increase in the magnitude of the side slip angle β of the car which shows that the vehicle has become more agile and responsive. The decrease in the overshoot ratio with a decrease in the static γ also shows that the handling characteristic of the vehicle has improved.

V. Conclusions

Proper adjustment of γ depends in part on the suspension geometry of the car and in part on how it is driven. For example in most cars, you want to have a good contact patch from each wheel, most of the time, with an average load of people in the car. Front wheels usually are specified for a small amount of positive γ (top of wheels further apart than the bottom), which will end up being vertical wheels with a normal load in the car. Again, this depends on suspension design, but that seems to be the general rule. For this case, a standard fixed γ for all driving conditions would suffice. But then there are those that like to race. If you expect to make high g-cornering forces, when the car leans over, you might need to optimize γ for cornering. In high speed turns, you would want the outside wheels to be near zero camber as much as possible for the best tire contact patch. The outside wheels provide the greatest traction in such conditions of the suspension geometry. Because of the lateral load transfer, the outside wheel has the highest load. Therefore, a negative γ is most likely required which is measured when the car is stationary and unloaded in order to achieve this effect in hard cornering. However, as seen in the steady state cornering test in Fig. 7, for the same δ, a higher a_y is produced for negative γ. Thus, it would be preferable to have a low negative γ at low turning speeds and increase γ further at higher speeds. Also as can be seen in the image 10 the higher lateral force can be achieved with less amount of steering effort and hence the driver feels at ease to take the car at higher cornering G's. This validates the need for an active camber control as explained and proven in [9].But, having a high γ for all driving conditions leads to poor straight line acceleration and less stability during straight line braking. This effect can be counteracted by using more negative camber at the front wheel compared to the rear wheel which will increase the dynamic ability of the car at the corner entry and will optimize the car for the longitudinal acceleration and straight line braking. But for normal driving, less tire wear and better traction is expected with manufacturer settings; on the contrary, better performance comes with greater tire wear under different alignment setting.

Also, greater γ increases unnecessary loads on the suspension arm and wheel rim. The tire and rim are susceptible to more damage if it hits a bump with an aggressive camber angle due to the distribution of the impact on a small area and increase the chances of puncture or tire blowout. Further studies can be done on analyzing how an active camber can optimize the surface usage of the tire in each turn.

An example of the simulation in IPG for constant steady steer test can be found in the link in [10].

ACKNOWLEDGEMENT

We thank Dr. Shyrokau for the supervision and providing the software of IPG Carmaker.

REFERENCES

[1] Karl-Heinz Weis. *Tool Machines with Brains -Touchless Wheel Alignment with Neural Networks*. 12 2014.

[2] H.B. Pacejka. Tire and vehicle dynamics. *Tire and Vehicle Dynamics*, 01 2012.

[3] William F. Milliken and Douglas L. Milliken. *Race car vehicle dynamics. Warrendale, Pa: Society of Automotive Engineers*. Aero Publishers, 05 1995.

[4] Adriano Schommer, Paulo Soliman, Lucas Farias, and Mario Martins. Analysis of a formula sae vehicle suspension: Chassis tuning. 09 2015.

[5] Srikanth Sivaramakrishnan and Saied Taheri. Using objective vehicle-handling metrics for tire performance evaluation and selection. *SAE International Journal of Passenger Cars - Mechanical Systems*, 6:732–740, 04 2013.

[6] *ISO 4138:2012(en), Passenger cars — Steady-state circular driving behaviour — Open-loop test methods*. 2012. https://www.iso.org/obp/ui/#iso:std:iso:4138:ed-4:v1:en.

[7] *ISO 7401:2011(en), Road vehicles — Lateral transient response test methods — Open-loop test methods*. 2011. https://www.iso.org/standard/54144.html.

[8] Leonard Segel Howard Dugoff, P. S. Fancher. An analysis of tire traction properties and their influence on vehicle dynamic performance. *SAE Transactions*, 79:1219–1243, 1970.

[9] Daan Roethof, Tarik Sezer, Mustafa Arat, and Barys Shyrokau. Influence of active camber control on steering feel. *SAE International Journal of Passenger Cars - Mechanical Systems*, 9:124–134, 04 2016.

[10] *IPG Carmaker Simulation - Data and Media files*. https://github.com/wuyenlin/VD_Project.

APPENDIX

$\gamma-$ Camber angle
$C_\alpha-$ Cornering stiffness
$\alpha-$ Slip angle
F_y- Lateral force
$r-$ Yaw rate (yaw velocity)
$\phi-$ Body roll angle
a_y- Lateral acceleration
$\beta-$ Side slip angle
M_x- Self-aligning moment
$W-$ Static weight
H$-$Distance from roll center to CoG in vertical direction
$K_{\phi F}-$ Front roll stiffness
$K_{\phi R}-$ Rear roll stiffness