

Methods in Research about Effect of Caster Angle on Vehicle Steering and Stability

Zhehui Wang^{1, *}

¹ School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan Hubei, 430074, China

* Corresponding Author Email: u201610771@alumni.hust.edu.cn

Abstract. Caster angle is the angle between the king pin and the suspension system viewed from the side of a car. It is an important parameter in vehicle wheels positioning. Generally, positive caster angles improve the steering wheels' returnability but increase the steering drag. The aligning torque increases as caster angle increases from zero to positive value, and goes to negative as caster angle has a negative value. There have been enough researches about the relationship between vehicle behaviour and wheel geometry parameters. Analytic methods are based on transforming a dynamical model to a mathematical model, and describing the vehicles' motion with equations. With it some theories for optimization of caster angle were proposed. Using computer softwares ADAMS/CAR, more accurate models were built to simulate how vehicles act as parameters changes. This method could verify overall design of a vehicle's structure. Experiment with physical models is a classical method, but it still useful today. These researches provide constructive ways in vehicle designing. This paper aims to summarize these existing research methods, show some researches with typical methods, and explain their advantages and shortages and explain their applicability.

Keywords: Caster Angle, Vehicle Dynamics, Direction Stability.

1. INTRODUCTION

1.1. Wheel Positioning Parameters

Wheel geometry is an important aspect which takes an important role in the steerability of a vehicle. Wheel positioning angles include kingpin inclination, toe angle, caster angle and camber angle. Caster angle has a Automobile suspension is the key structure of the chassis, which affects the whole vehicle's ride stability and driving comfort.

During the driving process of the vehicle, the front wheels often vibrate. Under extreme conditions (such as racing cars), the stable wheel angle range is much smaller than that under normal conditions. Although the amplitude of the sway vibration is small, the existence of the sway vibration will still lead to the instability of the vehicle under extreme conditions. When the caster angle of the front wheel kingpin becomes larger and sway vibration occurs at the same time, it will increase the possibility of vehicle instability.

1.2. Effect of Caster Angle on Vehicle Motion

The steering wheels of a road vehicle are required to have the ability to automatically return to the right direction to keep the vehicle moving stable in a straight line.

According to standard ISO8855-2011, caster angle τ is the angle between the Z_V axis and the normal projection of the steering axis on to the X_V - Z_V plane, as Figure 1 shows. The angle is positive when the top of the steering axis is inclined rearward [1].

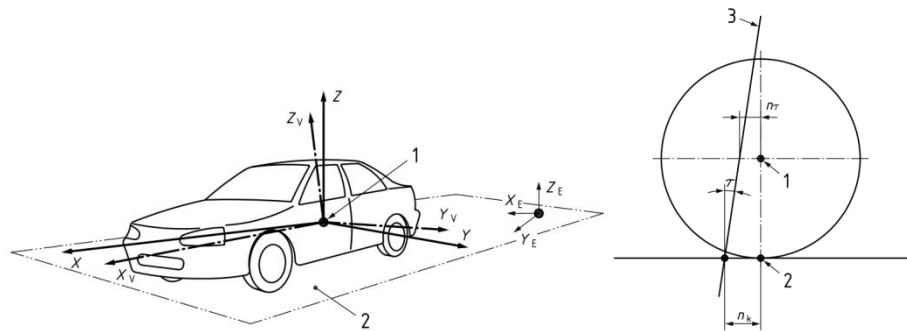


Figure 1. Intermediate axis systems and steering-axis geometry [1]

In this condition, the contact point of road and tire is not on the steering axis. There is always a caster offset n_r at wheel center, and a (caster) offset n_k at ground. When the vehicle makes a turn, for example, the driver turns the front wheels clockwise, the vehicle dynamic requires a centripetal force, which acts on point 2 and point at center of rotation. So, the torque caused by centripetal force tend to make wheels turn anticlockwise, acting as an aligning torque. There have been quite plenty of researches concentrating on this topic, and using various methods to improve the accuracy or simulation effect.

Wang Runqi, Zhou Yongjun, and Yin Peng used a simple model to calculate the torque and steering force effected by front wheel positioning of specific truck type [2].

Ma Jun, Qian Lijun and Gao Jun studied the steering returnability. Their calculating not only considered both of kingpin angle and caster angle, but also involved the interaction of different paraments [3].

Wei Daogao, Li Keqiang, Wang Xiaofeng, et al founded a calculating formula by using the Routh-Hurwitz criterion, based on the equations of 2 free- degrees vehicle dynamic and steering system [4].

Yan Ruilei, Zhao Liang and Wei Yong built a dynamic model of a car to study the effect of front wheel kingpin alignment parameters on vehicle steering stability. They used Simulink complete the calculating [5].

D. de Falcoa, G. Di Massab, and S. Pagano performed their research on the caster dynamic behavior in 2009. They presented a model describing the three-dimensional dynamic behavior of casters [6].

Peter Holdmann, Philip Köhn and Bertram Möller proposed a method for suspension kinematics and compliance-measuring and simulation. They presented a new kinematics and compliance test rig [7], and a typical measuring procedure, in which a certain driving situation was simulated at the test bench.

R. P. Rajvardhan, S. R. Shankapal, and S. M. Vijaykumar used ADAMS/CARS to simulating a SUV's act as front wheels geometry paraments changed [8].

Qian, Lijun and Shi Qin modelled a double wishbone independent suspension in ADAMS/CARS, and measured the positioning parameters according to the jump of the wheels [9].

Argade, Prathamesh S. Patil1 Gaurav N., Akash T. Bhilare3 Anubhav S. Pahade, and Kishor Waghulde studied the effect of caster angle systematically, and got a series of figures, which shows effect of caster angle on parameters of front wheel assembly [10].

G. E. Roe and T. E. Thorp investigated the parameters affecting the caster stability of road wheels experimentally. They designed a kit of equipment to test and measure relative data [11].

Falco, D. D. , G. D. Massa , and S. Pagano designed a test rig to observe how caster angle effect the performance of a tricycle, especially the shimmy in motion [12].

2. ANALYTIC METHODS

Analytic methods are based on dynamic analysis of a vehicle and force analysis of wheel structure mainly including tire, kingpin, and road. Just considering the effect of caster angle and ignore other positioning parameters

Because the steering axis is inclined rearward, contact point is slightly behind the common point where the extension of the kingpin and the road meet. So, there is always a caster offset n_τ at wheel center, and a caster offset n_k at ground. When the vehicle makes a turn, for example, turning the front wheels clockwise, as Figure 3 shows. The car's dynamic requires a lateral force F_0 provide the centripetal force, which acts on *point 2* and points at center of rotation. So, the torque caused by F_0 tends to make wheels turn anticlockwise. So, the torque act as an aligning torque.

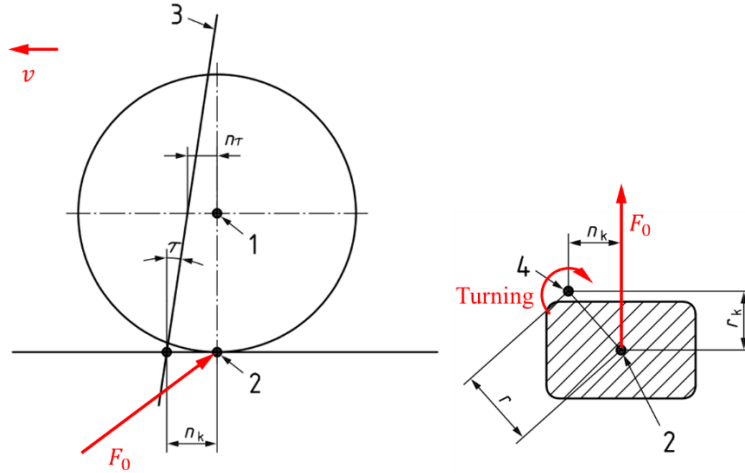


Figure 2. Dynamic analysis in turning

The force F_0 could be calculated as

$$F_0 = \frac{L_b}{L_a + L_b} m a_0 = \frac{F_1}{F_1 + F_2} m \frac{v^2}{R} = \frac{F_1}{g} \frac{v^2}{R} \quad (1)$$

in which, L_a is the distance between front wheels and mass center, L_b is the distance between rear wheels and mass center. R is rotation radius of the steering.

The force F_0 will cause an aligning torque M_0 , which could be calculated by following equation.

$$M_0 = F_0 \cdot e = F_0 \cdot n_k \cdot \cos(\tau) \cdot \cos(\delta) \quad (2)$$

In this equation, τ is the caster angle, δ is the turn angle.

In most analyze of caster angle's effect on vehicle, It is a common approach to ignore the offset n_τ at wheel center. For example, in a study about truck steering, the researchers showed their analyze process.[2] When the vehicle makes a turn, a force is generated at the road-tire interface to provide the centripetal force. For the front wheels, the force on the contact point will cause an aligning torque, which could be calculated as

$$M_0 = F_0 \cdot e = \frac{F_1}{g} \frac{v^2}{R} r \cdot \sin(\gamma) \cos(\delta) \quad (3)$$

In 2012, Ma Jun, Qian Lijun, and Gao Jun proposed a theory for optimization of caster angle. Their analysis was based on a more accurate modeling [3].

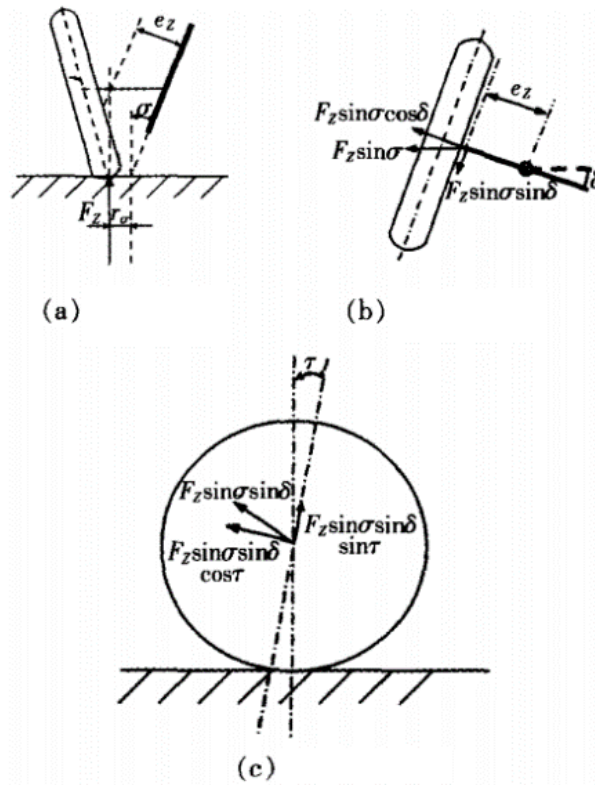


Figure 3. Calculating aligning torque caused by vertical force [3]

The aligning torque is mainly determined by vertical force F_z , lateral force F_y , longitudinal force F_x of the wheel grounding surface, and the length of the moment arm. Caster angle mainly effect the torque M_{SY} caused by the lateral force F_y , and the arm e_y

$$e_y = r \sin(\tau) + e_R \cos(\tau) \quad (4)$$

, in which e_R is pneumatic trail

$$e_R = l/6 \quad (5)$$

l is the length of tire grounding trail

$$l = 0.002\sqrt{(D - \Delta)\Delta} \quad (6)$$

Δ is radial deformation of the steering tire

$$\Delta = 19.1 \frac{CK_{\Delta}(0.5G_1)^{0.85}}{B^{0.7}D^{0.43}p^{0.6}} \quad (7)$$

C is a coefficient determined by type of tire. The value is 1.15 for bias tire, and 1.5 for radial tire. $K_{\Delta} = 0.0015B + 0.42$. B is the width of tire. And p is the pressure of tire.

With methods above, force model of a vehicle had been built exactly. However, they cannot reflect the actual act in motion. Introducing method of system and control theory, the relations between caster angle and vehicles' moving or steering stability could be represented mathematically.

In 2007, to get the match of front wheel caster angle versus steady cornering velocity, exploring for the real ways of improving stability of high-speed cornering, Wei Daogao, et al founded a calculating formula by using the Routh-Hurwitz criterion, based on the equations of 2 free- degrees vehicle dynamic and steering system [4]. A vehicle made in China was used as sample, and according to the formula its caster angle was calculated versus steady cornering velocity. The tests proved that the formula is characterized by a precision in predicting the match of front wheel caster angle versus steady cornering velocity.

In 2014, to study the effect of front wheels' kingpin alignment parameters on the vehicle steering stability, Yan Ruilei, Zhao Liang, and Wei Yong simplified the vehicle as four degrees of freedom

dynamic model, and established the state differential equation [5]. Based on Simulink, the yaw rate transient responses were simulated under force step input, the effect of front wheel kingpin alignment parameters on the vehicle steering stability was analyzed under different vehicle speed. The results show that the change of front wheel caster angle mainly affects vehicle stability at high speeds, both yaw rate over shoot and reaction time tend to reduce with the increase of caster angle, while the change of front wheel inclination mainly affects vehicle stability at low speed, smaller inclination angle and shorter reaction time.

Analysis above just includes the force on tire and simple model of vehicle. To represent the motion accurately, dynamics models is necessary.

In 2010, D. de Falco, G. Di Massab, and S. Pagano presented a model describing the three-dimensional dynamic behavior of caster.[6] Based on the Udwadia-Kalaba formulation, a method was implemented to represent the founder's nonlinear equations of motion. Their model accounts for the flexing and lateral flexibility of the caster frame and phenomena related to the rotation of the wheels. To deviate from the wheel-road interaction parameters, the assumption was made that the wheel does not skid, but other tire models can be easily implemented. The stability of the non-linear system is evaluated by integrating the equations of motion and performing an adaptation process to the natural vibration of the steering.

3. Simulation-based METHODS

With complete software, simulations of car dynamic become much easier and more accurate. ADAMS/CAR is such a design package, which was developed by MDI in partnership with car enterprises, including Audi, BMW, Volvo, etc. As early as 1990s, the tool had been widely used in vehicle dynamics researches.

In 1998, Holdman, Peter et al. introduced a new kinematics and compliance test bench [7]. They explained the design and structure of the test bench and presented a typical measurement process in which a specific driving situation is simulated. They showed how to validate the model of a vehicle for ADAMS with the test bench results. By simulating a specific driving maneuver with ADAMS, the effect of compliance steering on motor vehicle driving behaviour was demonstrated.

In 2010, to study the behaviour of an SUV for different wheel geometry parameters, Rajvardhan, R. P., et al built a multi-body model of Honda-CRV, the vehicle selected for this study, in ADAMS/CAR [8] .They used a lane change motion process to test. A serious figures showed the effect of caster angle on car steering.

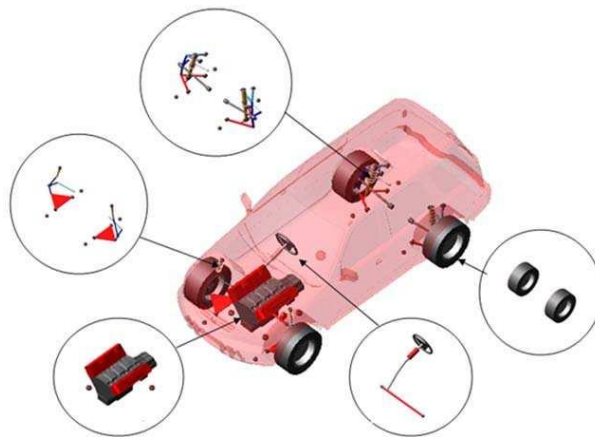


Figure 4. Full vehicle assembly [8]

The variation of pinion torque at different values of caster angles, was shown as Figure 5.

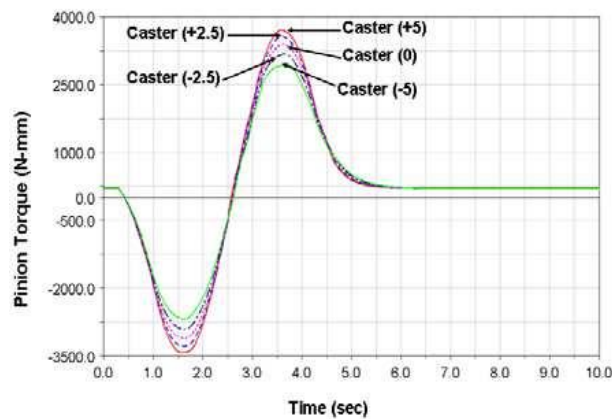


Figure 5. Time variation of pinion torque [8]

Figure 6 shows aligning torque is higher for positive caster. It decreases as the caster angle reduces until zero. When the angle comes to negative, it no longer contribute to the aligning torque, so the total aligning torque continues decreasing.

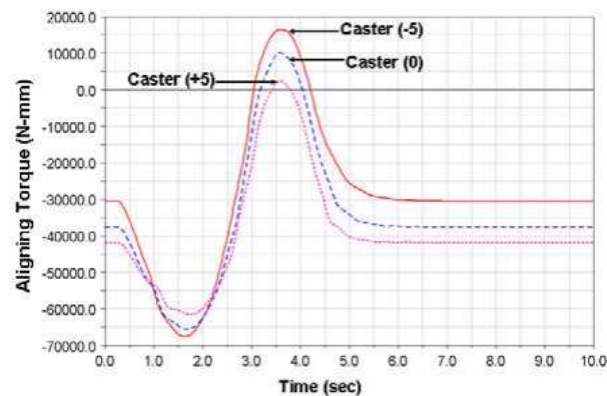


Figure 6. Time variation of aligning torque[8]

Figure 7 shows the variation of steering assistance angle, which is a measure of returnability of the steering wheel back to its initial direction after a turn. Observing the figure in the encircled area, it could be seen that a vehicle with positive caster angle returns back to the initial direction faster than that with lower positive or negative caster angle.

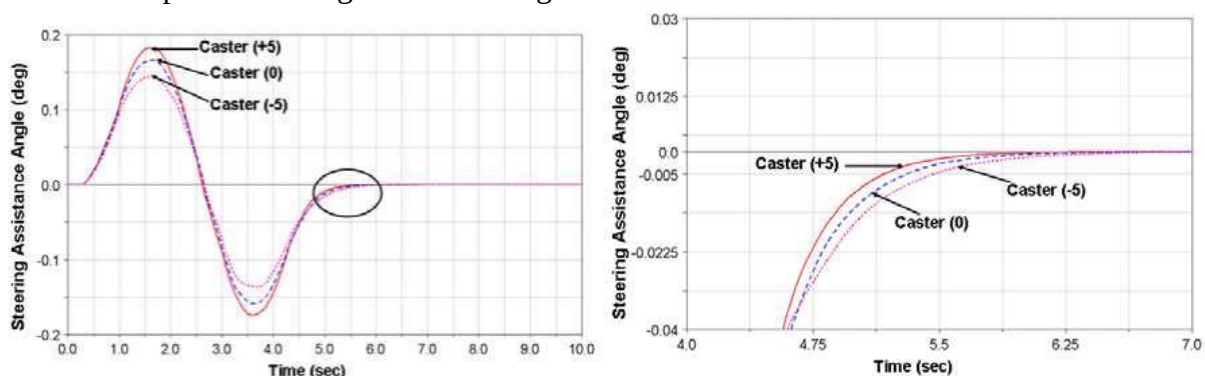


Figure 7. Time variation of steering assistance angle [8]

In fact, caster angle is varying during the motion, due to the jump of steering wheel.

In 2012, Qian, L. , and S. Qin built a suspension and steering subsystems in the software ADAMS/CAR, according to the model they had built in CATIA [9].

They set a situation that the wheel jumping height as jumping on 50 mm, jumping down 50 mm, and got the values of each positioning paramant, including caster angle, as the length varied. From the Figure 8, it is seen that caster angle increased with the length of jump increasing. It will help confirming whether the caster angle's varying range meets the designing requirements or not.

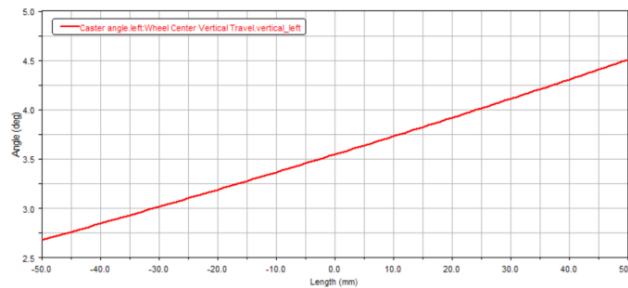


Figure 8. Caster angle according to the jump of the wheels [9]

In 2017, Prathamesh S. Patil et al. systematically analyzed the influence of the caster angle and obtained a series of figures showing the influence of the caster angle on the assembly parameters of the front wheel [10]. A standard model is imported using ADAMS/CAR to study the effect of caster angle. All components of the suspension system such as pivot point, track width, wheelbase and mass have been changed and carried over to the new model as required.

The table of results shows the variation of the wheel parameters as a function of the caster angle change. Even if some parameters have the same value, they show different frequency fluctuations. From their analysis, a conclusion can be drawn about the caster angle range, which is a feasible solution for the prepared car model.

4. Experiment in Laboratory

Before powerful computer being widely used in vehicle designing and simulating, it is a general way to experiment on physical models.

In 1973, G. E. Roe and T. E. Thorpe designed a experiment to investigate the parameters affecting the caster stability.[11] Their experimental test of a model caster wheel on a moving road surface is described.

They investigated the stability of this steerable wheel as a function of various geometric and physical parameters. One of the most important parameter turned out to be the lateral stiffness of the system relative to the steering axis. It was concluded that the overall lateral stiffness of the wheel system is important, of which tire stiffness is a component. The graphical results provide a basis for improving the design of front wheel assemblies for motorcycles and automobiles.

The front wheel assembly's basic geometry of a motorcycle was simulated in the model as Figure 9 shows. The steering axis was rigidly supported. A forward projecting fork and weights were attached to add load. And provision was made for adjustment of rake angle, wheel offset, etc.

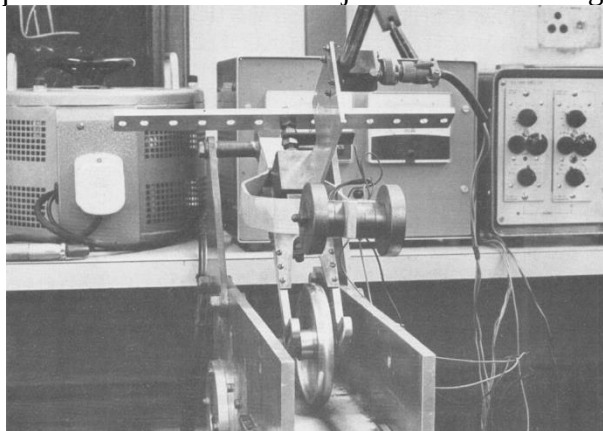


Figure 9. Model wheel and moving road [11]

Nowadays, there are still some researchers who are interested in practical performance of caster angle. They made experiments in laboratories to measure related data.

In 2013, DD Falco, GD Massa, S Pagano, designed a test rig to observe how caster angle effect the performance of a tricycle, [12] especially concentrate on shimmy phenomenon.

Dynamic behavior of vehicles having catered wheels can be affected by wheel shimmy phenomenon, that is a self-sustained vibration of the whole caster around the steering axis. Their paper presents a shimmy investigation conducted on a laboratory caster characterized by low lateral stiffness; numerical models show that this characteristic leads to three different stability conditions depending on the forward velocity: at low speeds the system is unstable and the caster is affected by shimmy oscillations; then there is an intermediate speed range in which the system recovers stability; finally, above a threshold speed value, the system returns to be unstable.

The test rig adopted for the investigation is shown in Figure 10, which consists of a caster, derived from a commercial scooter front assembly, joined to a rigid steel frame. It allows the caster to vertically translate and rotate around its steering axis.

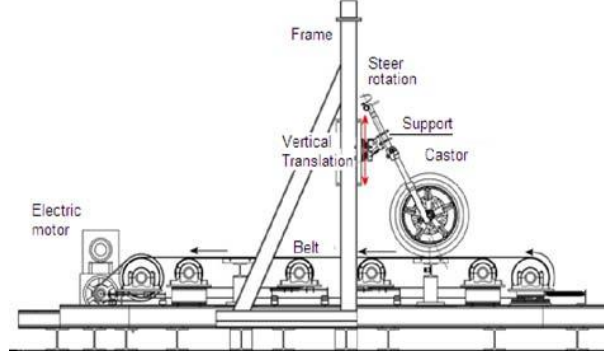


Figure 10. Tricycle test rig scheme [12]

The experimental investigation mainly aims to compare the numerical results with the experimental ones and to define the steering damping required to stabilize the caster according to its main features.

5. Conclusion

All the researches showed that caster angle has a enormous effect on vehicle's steering and stability, and explained how it works.

Analytic methods are useful in vehicle designing. Using appropriate dynamical models, analytic equations could express the act of a motive vehicle accurately. Simulation-based methods are mostly using ADAMS/CAR, by which the researchers could ignore dynamic deducing and calculating but concentrate on the body modeling. Experiment based method is still important, because it could not only finally test a new designed vehicle, but also verify the correctness of a new mathematical model.

REFERENCES

- [1] ISO8855-2011. Road vehicles — Vehicle dynamics and road-holding ability — Vocabulary.
- [2] Wang, R. Q. , Y. J. Zhou , and Y. Peng . "Front wheel positioning of automobiles and the calculating of its aligning torque and steering force." *Journal*
- [3] Ma, J. , L. Qian , and J. Gao . "Study and Analysis on the Kingpin Angle and Caster Angle Based on Steering Returnability." *Automobile Technology* (2012).
- [4] D Wei, et al. "Study on the Match of Front Wheel Caster Angle and Stability of High-speed Cornering." *Transactions of the Chinese Society for Agricultural Machinery* (2007).
- [5] Yan, R. L. , et al. "Effect of Front Wheel Kingpin Alignment Parameters on Vehicle Steering Stability." *Computer Simulation* (2014).
- [6] Falco, D. D. , G. D. Massa , and S. Pagano . "On the castor dynamic behavior." *Journal of the Franklin Institute* 347.1(2010):116-129.
- [7] Holdmann, Peter, et al. "Suspension Kinematics and Compliance-Measuring and Simulation." *International Congress & Exposition*. No. 980897. 1998.

- [8] Rajvardhan, R. P. , S. R. Shankapal , and S. M. Vijaykumar . "EFFECT OF WHEEL GEOMETRY PARAMETERS ON VEHICLE STEERING."
- [9] Qian, L. , and S. Qin . "Optimization of Wheel Positioning Parameters of Automotive Front Suspension Based on ADAMS." Springer Berlin Heidelberg Springer Berlin Heidelberg, 2012:821-827.
- [10] Argade, Prathamesh S. Patil¹ Gaurav N., Akash T. Bhilare³ Anubhav S. Pahade, and Kishor Waghulde. "Studying the Effect of Caster Angle on Wheel Parameters by Dynamic Analysis Using ADAMS CAR Software."
- [11] G., et al. "Experimental Investigation of the Parameters Affecting the Castor Stability of Road Wheels." Journal of Mechanical Engineering Science 15.5(2006).
- [12] Falco, D. D., G. D. Massa , and S. Pagano . "Castor Dynamic Investigation." international review of mechanical engineering (2013).