Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Study of Vehicle ESP System and Analysis of Dynamics in the Vehicle by Simulation using vedyna

Master's Final Degree Project

Vinoth Chandrasekaran
Project author

Mantas Felneris
Supervisor

Kaunas, 2018

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Vehicle Engineering (621E20001)

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Declaration of Academic Integrity

I confirm that the final project of mine, Vinoth Chandrasekaran, on the topic "Study of vehicle ESP system and analysis of dynamics in the vehicle by simulation using veDYNA" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this project.

I fully and completely understand that any discovery of any manifestations/case/facts of dishonesty inevitably results in me incurring a penalty according to the procedure(s) effective at Kaunas University of Technology.

(name and surname filled in by hand) (signature)

KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Study programme: VEHICLE ENGINEERING (621E20001)

TASK ASSIGNMENT FOR FINAL DEGREE PROJECT OF MASTER STUDIES

Given to the student:

1. Title of the Project

Study of vehicle ESP system and analysis of dynamics in the vehicle by simulation using vedyna / ESP sistemos transporto priemonės tyrimas ir transporto priemonės dinamikos analizė imituojant vedyna.

2. Aim and Tasks of the Project

To study the ESP system and analyze various conditions leading to skidding, understeer, oversteer, and rollover by using veDYNA.

3. Initial Data:

The dimensions of the Lamborghini Aventador LP 700 – 4 fed in veDYNA software is mentioned below.

VEHICLE DIMENSIONS	DIMENSIONS
Wheelbase	2.7 (m)
Wheel track rear	1.7 (m)
Wheel track front	1.72 (m)

Vehicle length	4.78 (m)
Vehicle width	2.02 (m)
Vehicle height	1.136 (m)
Vehicle mass	1731 (kg)

4. Main Requirements and Conditions

- The principle of ESP system and conditions leading to skidding, understeer, oversteer, and rollover.
- Simulation in veDYNA vehicle dynamics software by using various regulations of testing methods such as steerstep, steady-state circle drive, braking on mu-split, double lane change and slalom test.

5. Structure of the Text Part

- Studying about the working method of Electronic Stability Programme.
- Analysing various methods leading to skidding, understeer, oversteer, and rollover.
- Choosing a specific vehicle model Lamborghini Aventador LP 700 – 4 to analyze the dynamics of the vehicle.
- Using different regulations and testing methods to analyze conditions such as skidding, understeer, oversteer, and rollover by using vehicle simulation software veDYNA.
- Discussion about the simulation results leading to skidding, understeer, oversteer, and rollover.
- Conclusion about the research work done.

6. Structure of the Graphical Part

- The dimensions of the specific car model Lamborghini Aventador LP 700 – 4 was fed to the veDYNA simulation software.
- Experimentation of different tests like steerstep, steady-state circle drive, braking on mu-split, double lane change and slalom test.
- From the generated graphs of the plot–gui in veDYNA simulation software, it was found that high lateral acceleration and yaw rate lead to skidding, understeer, oversteer, and rollover of the vehicle.

7. Consultants of the Project

Student:	Vinoth Chandrasekaran	______________________
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Supervisor:	Mantas Felneris	______________________
	(Name, Surname)	*(Signature, date)*
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	(Name, Surname)	*(Signature, date)*

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List of abbreviations

ABS: Antilock Braking System

AIS: Automotive Industry Standards

ARAI: Automotive Research Association of India

COG: Center of Gravity

DSC: Dynamic Stability Control

DOF: Degree of Freedom

ESP: Electronic Stability Programme

ESC: Electronic Stability Control

ECE: Economic Commission for Europe

ECU: Engine Control Unit

LTV: Light Transport Vehicle

NHTSA: National Highway Traffic Safety Adminstration

RSC: Roll Stability Control

SUV: Sport Utility Vehicle

TCS: Traction Control System

UNECE: United Nations Economic Commission for Europe

VSC: Vehicle Stability Control

YSC: Yaw Stability Control

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Study field and area (study field group): Transport Engineering (E12), Engineering Science.
Keywords: *ESP, ECE, AIS, veDYNA, Matlab, Understeer, Oversteer, Skidding, Rollover, Yaw stability, Roll stability, Braking, Robert Bosch, Vehicle, Dynamics.*
Kaunas, 2018. 92 pages.

Summary

Electronic Stability programme is an active safety system which was introduced by Robert Bosch to improve the stability of the vehicle and prevent the vehicle from an emergency situation such as skidding, understeer, oversteer and rollover accident. With the increase in production of vehicle in developing countries like India, China and introduction of more sports variants by countries like Germany, Italy has lead to increase in number of accidents, so it is of utmost importance that active safety system like ESP must be implemented in all vehicle to protect the passengers from fatalities and reduce the road accidents.

To study about the ESP system and analyze the various properties that influence skidding, understeer, oversteer, and rollover specific car model Lamborghini Aventador lp 700 – 4 was chosen and tested by using various regulations in modelling simulation software veDYNA. The testing regulations such as steer step, double lane change, slalom test, circle drive and mu-split was used with varied parameters to know about the limits of the vehicle in various conditions. The graphs generated in the plot - gui of veDYNA software was used to analyze the yaw rate, yaw angle, roll angle, sideslip angle, steering wheel angle and lateral acceleration of the vehicle.

The aim of the research is to study about the effectiveness of ESP system using theoretical methods and apply various methods leading to skidding, understeer, oversteer, and rollover using vehicle simulation software veDYNA which is linked with Matlab/Simulink interface.

Chandrasekaran, Vinoth. ESP sistemos transporto priemonės tyrimas ir transporto priemonės dinamikos analizė imituojant vedyna. Magistro baigiamasis projektas / vadovas / Mantas Felneris; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.
Studijų kryptis ir sritis (studijų krypčių grupė): Transporto inžinerija (E12), Inžinerijos mokslai.
Reikšminiai žodžiai: *ESP, ECE, AIS, veDYNA, Matlab, nepakankamas pasukamumas, per didelis pasukamumas, slydimas, virtimas, stabilumas sukimuisi, stabilumas virtimui, Robert Bosch stabdymas, transporto priemonių dinamika.*
Kaunas, 2018. 92 p.

Santrauka

Robertas Boschas sukūrė aktyvią saugos sistemą - elektroninę stabilumo programą, siekiant pagerinti transporto priemonės stabilumą bei užkirsti kelią avarinėms situacijoms tokioms kaip slydimui, nepakankamam ar per dideliam pasukamumui, kai prarandamas priekinių ar galinių ratų sukibimas su keliu ir galiausiai apvirtimui. Dėl padidėjusių transporto priemonių gamybos apimčių besivystančiose šalyse tokiose kaip Indija, Kinija ir padidėjusio susidomėjimo sportinių transporto priemonių kategorijoje tokiose šalyse kaip Vokietija, Italija dėl ko padidėjo ir nelaimingų atsitikimų atvejų. Todėl yra labai svarbu diegti aktyvias saugos sistemas kaip ESP, taip siekiant išvengti žūtčių keliuose bei sumažinti nelaimingų atsitikimų kiekį keliuose.

Siekiant išsiaiškinti ESP sistemos veikimą ir pagrindines savybes, kurios įtakoja slydimą, nepakankamą ar per didelį pasukamumą bei virtimą buvo pasirinktas Lamborghini Aventador lp 700 - 4 sportinis automobilis, kuris buvo analizuojamas programoje veDYNA sumodeliuojant įvairias situacijas. Modeliuojamos tokios situacijos kaip žingsninis sukimas, dvigubas juostos keitimas, slalomo testas, važiavimas ratu, važiavimo pradžia įkalnėje pritaikant skirtingus parametrus, siekiant išsiaiškinti transporto priemonės ribas prie skirtingų situacijų. Programos veDYNA sugeneruoti grafikai buvo panaudoti siekiant išanalizuoti transporto priemonės nuokrypio dydį ir kampą, virtimo kampą, šoninio slydimo kampą, vairo pasukimo kampą ir skersinį pagreitį.

Pagrindinis tyrimo tikslas – išsiaiškinti ESP sistemos efektyvumą pritaikant teorinius metodus skirtingose situacijose įskaitant transporto priemonės slydimą, nepakankamą ir per didelį pasukamumą, bei virtimą. Įvairios situacijos sumodeliuotos taikant programą veDYNA, kurios veikimas pagrįstas Matlab/Simulink programos principais.

Introduction

Electronic stability programme

Electronic stability programme (ESP) is an active safety system which has been evolved from antilock braking system (ABS) and traction control system (TCS). Electronic stability programme is also called as electronic stability control (ESC), vehicle stability control (VSC) or dynamic stability control (DSC). It was mainly introduced into automobile industry by Robert Bosch to control the vehicle from three important conditions such as skidding, self-steering behavior (oversteer and understeer), and rollover.

The main function of ESC is to increase the performance of the vehicle by allowing the driver to drive the car in the intended path during an emergency situation or extreme maneuvers to avoid rollover (e.g. fast cornering or lane changing with emergency braking). It also increases the vehicle stability by decreasing the loss of traction (skidding).

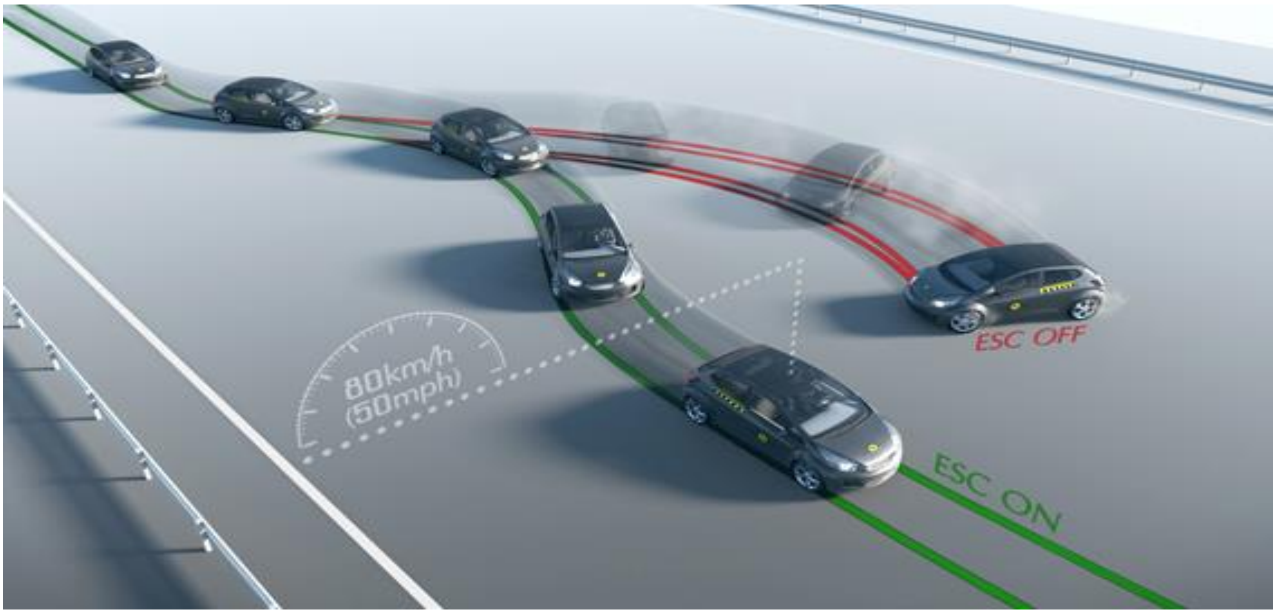

Figure 1. Vehicle ESP On and Off [35]

With the continuous rise in demand for the vehicle by the people for traveling and transportation of goods, which has lead to the rise in a number of the vehicle produced every year by the automotive industry. Further research and advancement in the field of automotive engineering have to lead to advancement in the active and passive safety vehicle system. More system like ESP should be invented to increase the stability of the vehicle and to decrease the number of fatality rate.

The thesis work is done to investigate the behavior of vehicle during skidding, self-steering behavior (understeer, oversteer) and rollover by using the theoretical principle of ESP in simulation software veDYNA/Matlab. For the better understanding of the vehicle behavior, particular car model (Lamborghini Aventador LP 700 - 4) has been chosen and all the parameters for this car are fed to the veDYNA vehicle simulation software. According to the ECE, AIS regulations test such as double lane change, slalom test, steady-state circle drive, steer step and mu-split was experimented and comparison from the simulated graph are made to study about the ESP system.

veDYNA

veDYNA is a vehicle simulation software by a German company TESIS and it is used for testing the vehicle dynamics of passenger car, sports car, formula car, SUV, and truck. The veDYNA simulation software is linked with Matlab/Simulink interface which shows the result as a graph in plot – gui of veDYNA and programmed result in Matlab interface.

veDYNA is used for applications such as the desktop investigation of vehicle dynamics, concept studies of vehicle parameters, driving performance test, virtual test, standard test or customized test and evaluation of vehicle requirements and performance targets. It is being used by the automotive industry such as AUDI, BMW, FORD, GENERAL MOTORS, MAGNA and VOLKSWAGEN for vehicle testing.

1. Literature review

The research study was done by B.J.S. Van Putten on “Design of an electronic stability program for vehicle simulation software” [1] using veDYNA vehicle simulation software to compare vehicle system with and without ESP which shows the differences such as sideslip angle, steering wheel angle and vehicle trajectory of the vehicle. The author had also compared the values of the redesigned cycle with Duisburg cycle to show the effectiveness of the ESP system.

The research carried out by E.K. Liebemann, K.Meder, J. Schuh, G.Nenninger - Robert Bosch GmbH Germany on ‘‘Safety and performance enhancement: the Bosch electronic stability control (ESP)” [2] says that ESP is an active safety system which has been very effective and had reduced the number of fatalities in accidents and avoiding rollovers. It has also been concluded that ESP increases the stability of vehicles by controlling the yaw rate and lateral acceleration.

The study was done by authors Shengqin Li, Le He on ‘‘Co-simulation study of vehicle ESP system based on Adams and Matlab” [3] describes the working principle of electronic stability System in the theoretical method as well as by using the simulation software when the ESP system is disabled and enabled. It has been concluded that the ESP braking system can increase the vehicle stability and vehicle simulation software like veDYNA, Adams and carsim decreases the cost of testing.

The study carried out by Tejas Shrikant Kinjawadekar on “Model-based design of electronic stability control system for passenger cars using carsim and Matlab-Simulink” [4], The Ohio State University 2009 describes the importance of vehicle simulation software in the testing of ESP system using various testing methods to obtain accurate results rather using experimental methods in outdoor conditions which requires lot of time and money. It was also found out that the roll stability control and yaw stability control stabilized the self-steering behavior and rollover rate in the presence of ESP system by comparing the graphs generated from the vehicle simulation software.

The research was done by Sohel Anwar on “Yaw stability control of an automotive vehicle via generalized predictive algorithm” [5] 2005 American Control Conference June 8-10, 2005. Portland, OR, USA has been studied that the testing of yaw stability control mode in extreme conditions like snow in slalom method by using vehicle simulation software is better when compared to outdoor testing conditions. It is difficult to test vehicle‘s Yaw stability control in Scandinavian countries where the temperature is very low with extreme weather conditions like snow, ice which makes really difficult for the automotive car makers to test the vehicle.

The study was done by Insurance Institute for Highway Safety on ‘‘Electronic stability programme - reducing multiple-vehicle crashes as well as single-vehicle” [6] clearly shows that single vehicle accidents are more when compared to multiple vehicle crashes. It is been confirmed by this study that ESP can reduce single vehicle as well as multiple-vehicle crashes. The highway institute also studied the effectiveness and importance of ESP system in saving lives of road users. Researchers made a comparison of vehicle crashes for passenger cars, SUV with ESP system optional and mandatory from 2001 - 2004 and found out that fatality rate of single vehicle accidents reduced a lot when the car is equipped with ESP system.

According to the Federal Motor Vehicle Safety Standards ‘‘Electronic stability control systems; controls and displays of national highway traffic safety administration” [7] - Department of transportation it is mandatory for all the passenger cars, multipurpose passenger vehicles, trucks, and buses to be equipped with Electronic stability programme. NHTSA states that installation of ESP system reduced the single- vehicle accidents by 34 percent and single vehicle accidents of sports utility vehicle by 59 percent. ESP has the capacity to avoid rollovers by 71 percent of passengers cars and 84 percent of the SUV rollovers. From this NHTSA study, it is clearly evident that ESP plays a huge role in preventing rollovers and accidents.

The study done by Maria Krafft, Anders Lie (Swedish Road Administration), Claes Tingvall (Swedish Road Administration, Monash University Accident Research Centre), Anders Kullgren (Folksam Research Sweden) on ‘‘The effectiveness of ESC (electronic stability control) in reducing real-life crashes and injuries” [8] shows the different types of studies involving the reduction in rate of single-vehicle crashes when the vehicle is equipped with ESP system. The study also states about the involvement of ESP system in low friction surfaces when the road surface is covered by snow or ice. From this study, it is very clear that the ESP should be mandatory in all vehicles.

The research done by Yiannis E. Papelis, Ginger S. Watson, Timothy L. Brown On ‘‘An empirical study of the effectiveness of electronic stability control system in reducing loss of vehicle control” [9] where the ESP systems were tested in different vehicles by male and female drivers and it was found that vehicle equipped with ESP system was able to control the vehicle at high speed. The overall investigation leads to the conclusion that 34 percent of drivers gained more control of the vehicle if the vehicle is equipped with ESP. The comparison was done between SUV and passenger car in different conditions without ESP system, which further lead to rollover in SUV due to the high center of gravity and skidding in passenger cars due to light weight and loss of traction in tyres.

The regulations stated by automotive industry standards on ‘‘Electronic stability control systems” [10] has many rules and test procedures to be followed for the vehicles fitted with ESP system in India. In order to find the lateral acceleration, side slip angle, yaw rate, understeer and oversteer of the vehicle certain requirements such as general requirements, performance requirements, test conditions and test procedures are performed. By this regulation, it is concluded that ESP system can pass the test only if it meets the regulations given by the AIS 133.

The literature review shows that the electronic stability programme should be made mandatory in all vehicle as it improves the stability of the vehicle and avoids accidents in extreme conditions like skidding, understeer, oversteer, and rollover. It is also clear that availability of more vehicle simulation software in the automotive industry like veDYNA can reduce the time, money and human error in the vehicle testing.

2. Theoretical framework

2.1. History and background of ESP

The main function of ESP is to increase the performance of the vehicle by allowing the driver to drive the car in the intended path during an emergency situation or extreme maneuvers to avoid rollovers (e.g. fast cornering or lane changing with emergency braking). It also increases the vehicle stability by decreasing the loss of traction (skidding). Electronic stability programme is also called as electronic stability control or dynamic stability control. The Electronic stability control was first introduced by Robert Bosch and it was used in production by Mercedes-Benz (S) Class sedan in 1995. When the journalist applied sudden brakes in order to avoid hitting the moose on the highway, which lead to rollover of Mercedes-Benz A class in October 1997.

Father of the ESP, Anton Van Zanten, also patented an anti-skid concept for driving. The native Dutchman, who had earned a Ph.D. in the natural sciences, joined Bosch in 1983. His remit was to further develop the ABS to improve braking behavior in corners. Development work started on April 1984. ESP was invented by Anton van Zanten [11], who is a native Dutchman and he earned a Ph.D. in the natural sciences and later on joined Bosch in 1983. He was keen on developing the ABS system for a vehicle and after continuous testing, calculations lead to the development of electronic stability programme.

Figure 2. Testing ESP prototypes in a 1983 Mercedes-Benz 230 TE on Bosch ground [11]

2.2. Skidding, oversteer, understeer, and rollover

2.2.1. Cause of rollover

A rollover happens more frequently while cornering and during the extreme maneuver. They can happen due to several factors such as vehicle type, road conditions, environmental factors and behavior of the driver. The causes of rollover can be classified into different types

Figure 3. Rollover accident due to extreme maneuver [36]

Vehicle type

Rollover mainly depends on the type of vehicle being driven by the driver, as the center of gravity of the vehicle plays a major role in causing the vehicle to rollover.

Speed

Most of the rollover happens at high speed which causes the driver to make countersteering to the desired direction. Rollovers due to speed are reported more on highways and roads where the speed limit is very high.

Alcohol

An investigation done by highway department said that alcohol can make the driver lose control of the vehicle and lead to rollover. Influence of alcohol had lead to more number of rollover accidents.

Location

Rural roads account for high rollover incidents than any other type of roads. As the roads in the rural area are without a proper guardrail, median and road sign boards.

Routine driving

Daily commuting by people over long distance may lead to speeding, distraction, impaired driving which may further lead to a rollover accident.

Single-vehicle crashes

This type of vehicle crash accounts for more than 85% of a rollover not involving any other types of vehicle crashes, so it means that driver behavior is the main reason for rollover incidents.

Types of rollover

Rollover occurs in two different ways and can be classified as tripped and untripped.

Untripped

Untripped rollover occurs very less when compared to tripped rollover and they mostly occur in heavy vehicles like bus, truck. It happens during an extreme maneuver at high speeds to avoid a collision which leads to untripped rollover.

Tripped

Tripped rollover accounts for 95% and there are many reasons for this type of rollover where the vehicles get tripped due to the guardrail, objects on the road which makes the vehicle to skid or turn around causing tripped rollover.

Types of tripped rollovers

Guardrail

When the vehicle travels at high speed it loses control as the driver intends to take a right turn, where the left side of the car touches the guardrail at high force causing the vehicle to rollover.

Steep slope

A rollover happens due to the steep slope and it happens mostly in off-road vehicles when the driver evaluates the slope and tries to turn left or right causing the vehicle to rollover from top of the slope. It also happens when the driver climbs the slope and loses traction in the tyre which further causes the vehicle to topples over.

Soft Soil

This type of rollover occurs when the driver intends to take a sharp turn on the road curves and the vehicle takes a sharp turn where one side of the wheel touches the soil, pavement, snow etc losing the adhesion coefficient decreases making the vehicle to slip sideways and rolling of the wheels occurs which causes a rollover.

2.2.2. Cause of skidding

Skidding mostly occurs when the vehicle travels at high speeds on snow, stone or uneven road surface when a tyre loses the contact with road surface. They can also occur due to very hard braking or accelerate very fast suddenly in the corner, forcing the vehicle to skid or allowing the driver to lose control of the vehicle. It happens in the vehicle due to loss of traction in the front or rear of the tyre and they can further lead to rollover if a system like ESP is not present in the vehicle.

2.2.3. Cause of oversteer and understeer

Self-steering behavior is one of the characteristics of vehicle dynamics and it can decrease the stability of the system. Oversteer happens when the vehicle turns more than the intended path made by the driver and understeer happens when the vehicle turns less than intended path made by the driver.

2.3. Major components of ESP system

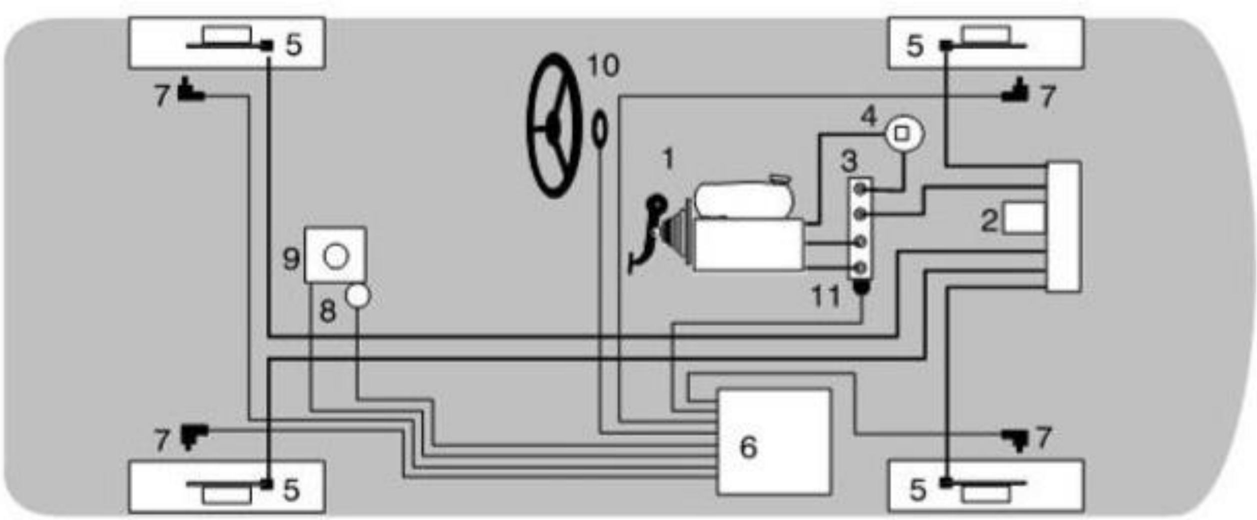

Figure 4. Major components of ESP system [12]

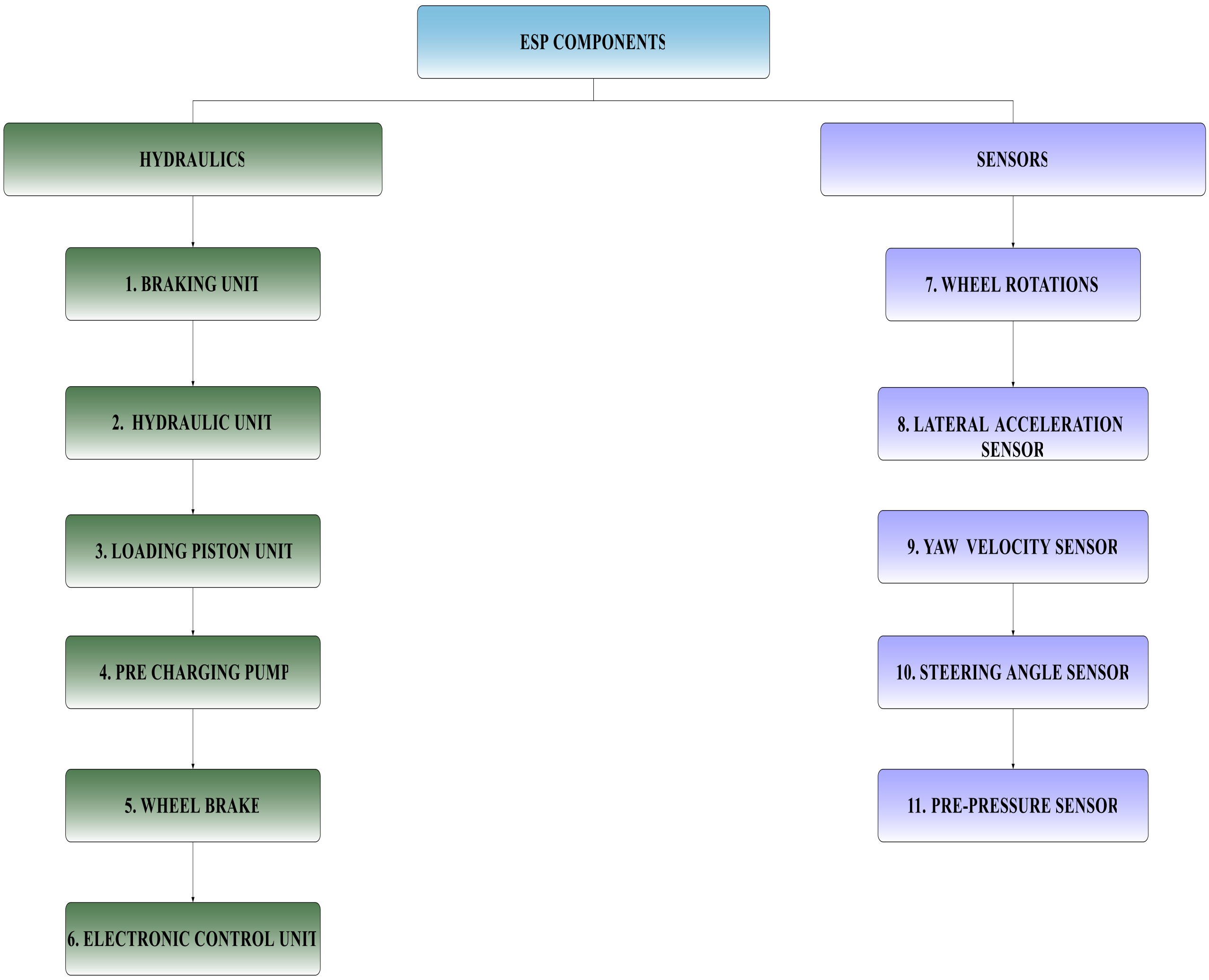

Figure 5. Flowchart of ESP components

2.4. Working of ESP

The ESP system works on the principle of differential braking to control the yaw rate and roll of the vehicle. Electronic stability programme controls the vehicle in different situations such as skidding, oversteer, understeer, and rollover.

2.4.1. Differential braking

Differential braking is done to control the brake individually on the front or at the rear of the vehicle, which in turn is used to control the understeer, oversteer and rollover condition. This method can be well understood by single track model or bicycle model. If there is any unusual behavior in the car stability, it is detected automatically by the ECU unit of the ESP system. Later on, bakes are applied on the particular wheel and sometimes torque is also reduced in the engine to control the vehicle as soon as possible.

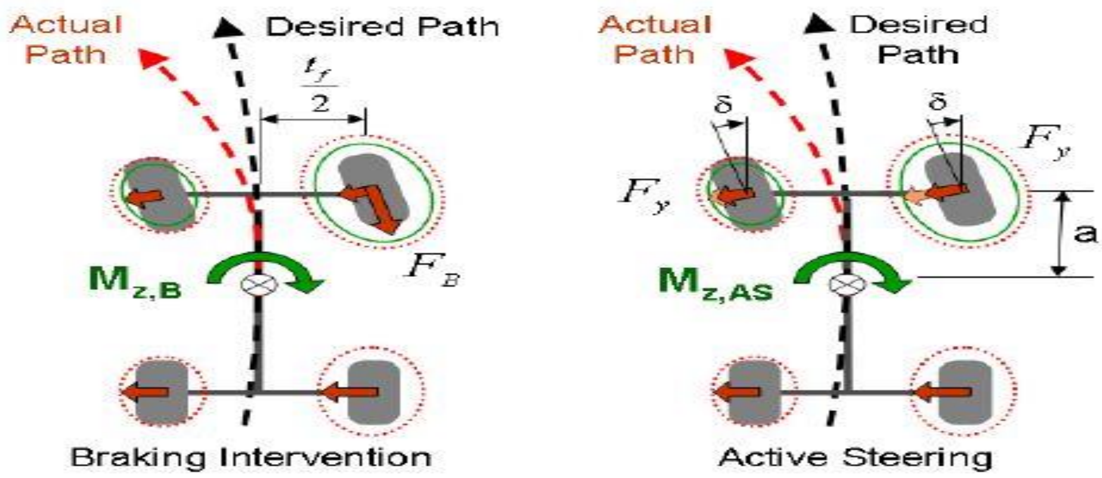

Figure 6. Corrective yaw moment through braking intervention (left) and active steering system through steering angle intervention (right) [33]

2.4.2. Yaw stability control

ESP uses the principle of differential braking to control the slip angle and yaw rate, yaw stability control is part of the electronic stability programme. Yaw stability control acts immediately when there is a loss of friction between tyre at high speed and prevents the vehicle from leaving the pathway. Yaw disturbance[27] is caused by the decrease in the tyre pressure and also by the uneven road surface which is covered by snow. YSC continuously calculates the angle of the steering wheel and longitudinal speed to control the yaw rate.

Yaw rate is linearly related by steering wheel angle and yaw rate gain[13][29]: yaw rate = (steering wheel angle) × (yaw rate gain) and for a vehicle with neutral steer with negligible slip angle: Yaw rate = (lateral acceleration)/(vehicle speed). From the above relations, ideal yaw rate of the vehicle can be found.

The vehicle slip rate is the difference between actual and ideal yaw rates[13][29] : (Vehicle slip rate) = (actual yaw rate) – (ideal yaw rate). The vehicle is said to oversteering if the vehicle slip rate is positive and the vehicle is said to be understeering if the vehicle slip rate is negative.

There is two type of self-steering behavior which is being controlled by YSC. When the oversteer situation occurs, the vehicle tends to move away from the intended path and the understeer situation happens when the vehicle tends to turn less than the intended path. But, oversteer is very dangerous when compared to understeer which may lead to severe consequences. The vehicle slip rate is continuously calculated by yaw stability sensor which applies the brake on the selective wheel and reduces the torque to correct the yaw moment which in turn improves the vehicle stability.

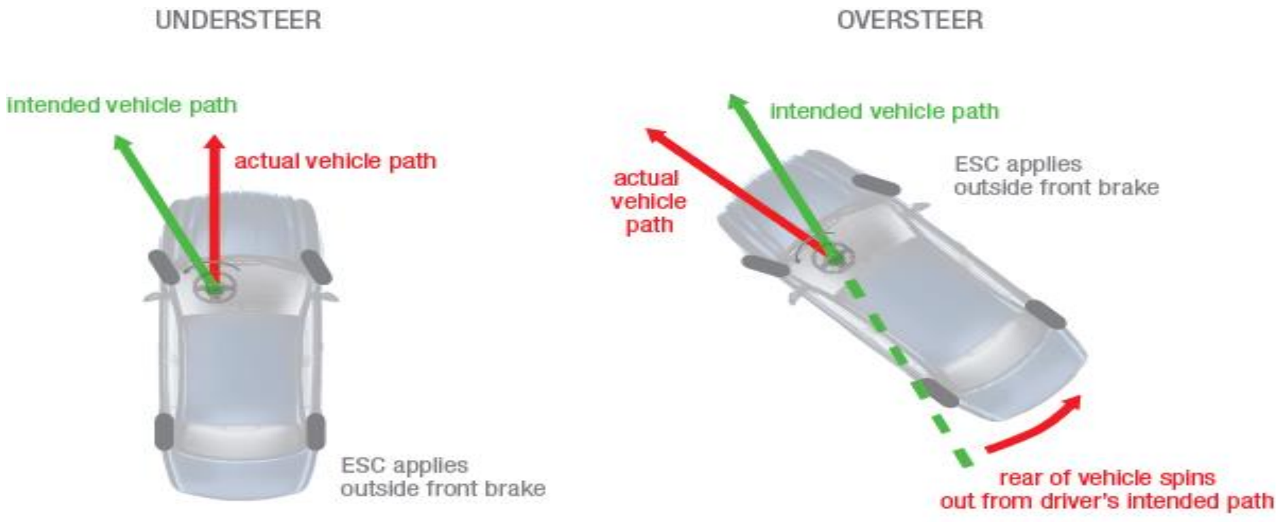

Figure 7. Insurance Institute for highway safety and highway loss data institute [6]

2.4.3. Roll stability control

Roll stability control detects the rollover situation and automatically applies brake by using the principle of differential braking. RSC reduces the vehicle speed by reducing the engine torque and it regularly checks the lateral acceleration with its threshold frequency when the rollover situation occurs. They usually brake on the front wheels to prevent rollovers and also decreases the speed of the vehicle and in RSC mechanism lateral acceleration is taken as threshold frequency as the rollover is caused by the side force acting on the vehicle [4] [14] [15] [16] [26].

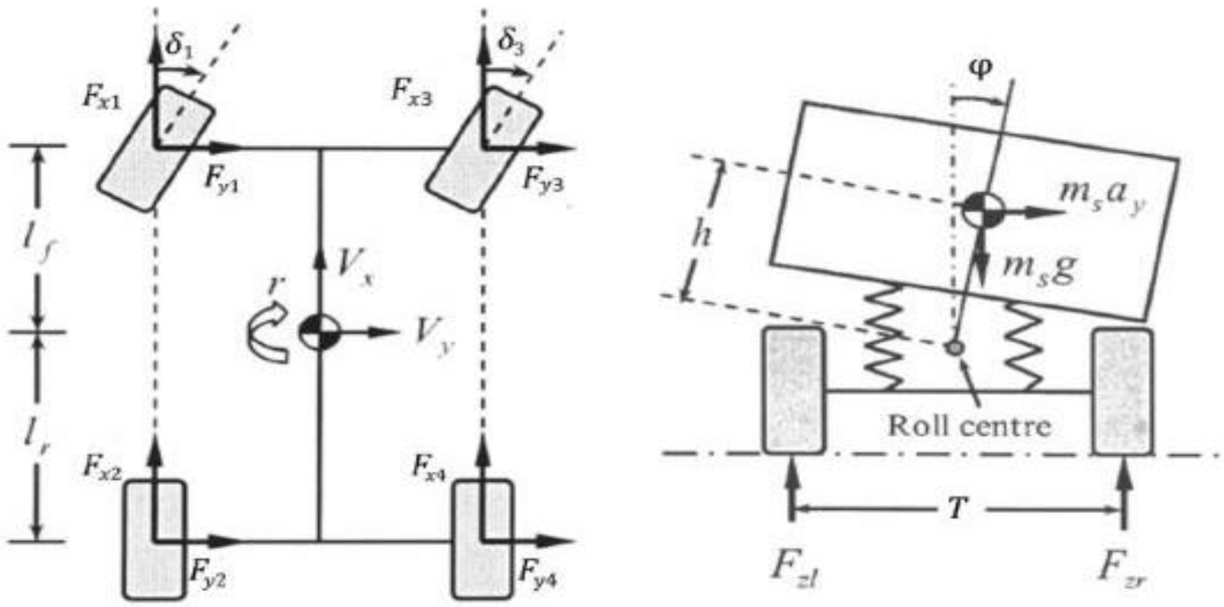

Figure 8. Roll stability control mechanism [30]

2.4.4. Single track model

Single track model is a linear model with 2 DOF freedom, which is also called as "bicycle model" [28]. They are used to calculate the forces and moments acting on the vehicle and the forces are classified into longitudinal acceleration, lateral acceleration, and yaw rate. Longitudinal acceleration is the specification of speed and velocity of motion and lateral acceleration is the force that tends to push the vehicle sideways, and yaw rate is the angular velocity or rotation of change of the heading angle when the vehicle is in a horizontal position.

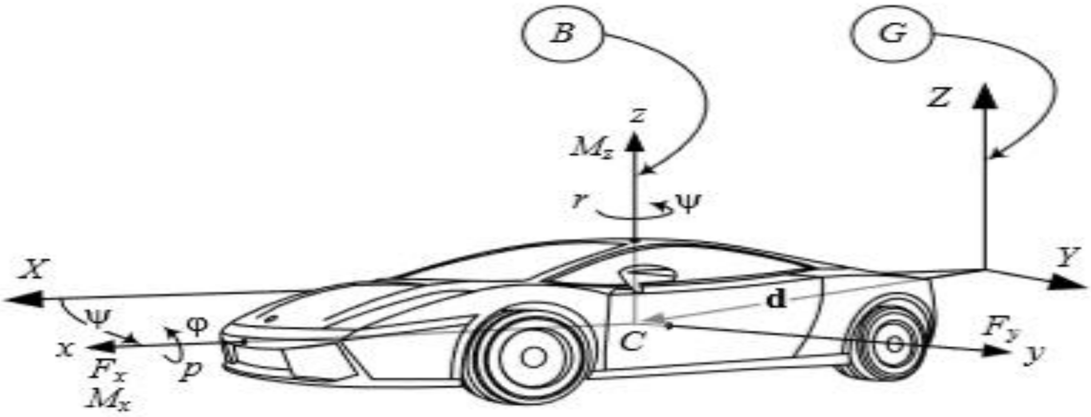

Figure 9. A vehicle with yaw on and roll rotation [31]

In the neutral steer car when there is lateral acceleration the vehicle follows the route on an angled path because the front and rear slip angles are same [8]. Whereas, in the understeer and oversteer car the front and rear slip angles are different so there is a curvature in the path of the vehicle. In case of the understeer car, there is more cornering stiffness in the rear and in case of oversteer car there is more cornering stiffness in the front.

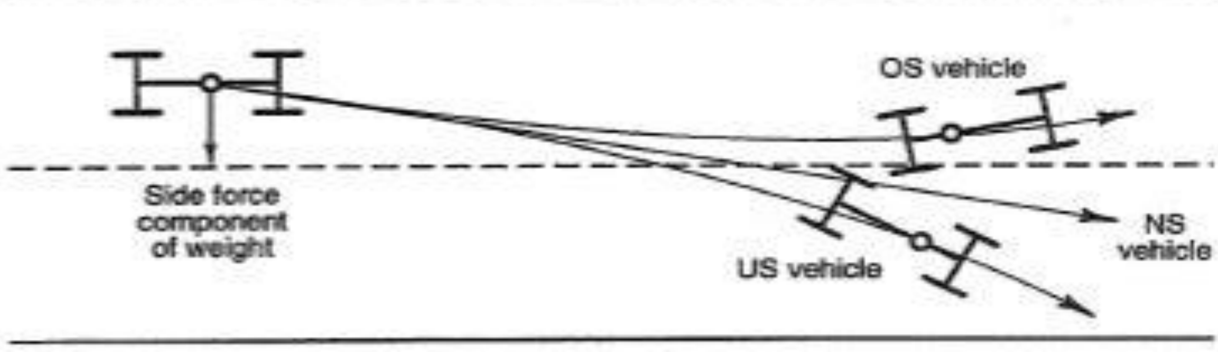

Figure 10. Oversteer, neutral and understeer [8]

By sine theorem,

$\frac{R_f}{sin(90^0 - \alpha_r)} = \frac{l}{sin\left(\delta_f - (\alpha_f - \alpha_r)\right)}$

$R_f \approx R,$

l = wheelbase

δ_f = steering angle

α_f = slip angle at the front

α_r = slip angle at the rear

R = distance between the center of gravity and center of the curve

$sin(90^0 - \alpha_r) \approx 1,$

$sin\left(\delta_f - (\alpha_f - \alpha_r)\right) \approx \delta_f - (\alpha_f - \alpha_r)$

$\delta_f = \frac{l}{R} + (\alpha_f - \alpha_\gamma)$

$R = \frac{l}{\delta_f - (\alpha_f - \alpha_r)}$

conditions

$\alpha_f - \alpha_r > 0$: understeer

$\alpha_f - \alpha_r = 0$: neutral

$\alpha_f - \alpha_r < 0$: oversteer

Self steering gradient

$EG = \frac{d\delta_f}{da_y}$, EG depends on design parameters of the vehicle

$EG = 0$: neutral

$EG > 0$: understeer

$EG < 0$: oversteer

$$EG = \frac{m \cdot (C_r \cdot S_r - C_f \cdot S_f)}{l \cdot C_f \cdot C_r}$$

m = mass of the vehicle

S_f = distance from the centre of gravity to the front axle

S_r = distance from the centre of gravity to the rear axle

$C_{f,r}$ = Cornering stiffness

$C_{f,r} = \frac{dF_{y\,f,r}}{d\,\alpha_{f,r}}$, Fy = side force, α = slip angle

If the force in the rear $C_r \cdot S_r$ is more than the front $C_f \cdot S_f$, then the car will have understeer behaviour, which causes the vehicle to turn less than intended the path. If the force in the front $C_f \cdot S_f$ is more than the rear $C_r \cdot S_r$, then the car will have oversteer behaviour which causes the vehicle to turn more than intended path [12].

2.5. Accident statistics and importance of ESP

There are a lot of accidents which occurs due to several reasons and the main type of accident is the single-vehicle accident, where the vehicle collides with animal, objects on the road, rollover accidents or goes of the road. According to national highway traffic safety administration [17], overall crash reduction got reduced by 14% in cars and 28% in LTV when the vehicle was fitted with ESP system.

Table 1. Accident statistics with ESP [17]

	Crash reduction by ESP (%)	
Accident types	Cars	LTV‘s
Run off-road crashes	36	70
Single vehicle crashes	36	63
Rollover crashes	70	88
Multi-vehicle crashes	19	34
Overall crash reduction	14	28

In the survey taken by Insurance Institute for highway safety [18] on ESP effectiveness during 10 years in the USA, ESP reduced the fatal vehicle crash by 33 percent, 20 percent for multiple-vehicle crashes, 49 percent for single vehicle crashes. The effectiveness of ESP was found higher for SUV than for cars. It is confirmed by this statistics that fatal crashes are reduced when the system is equipped with ESP.

ESP is very important active safety system and with the increase in installation rate of ESP all around the world which has to lead to a decrease in a number of single vehicle accidents. From the installation rate graph of Bosch braking system, it is clearly evident that ESP prevents single-vehicle crashes and the installation rate of ESP is increased.

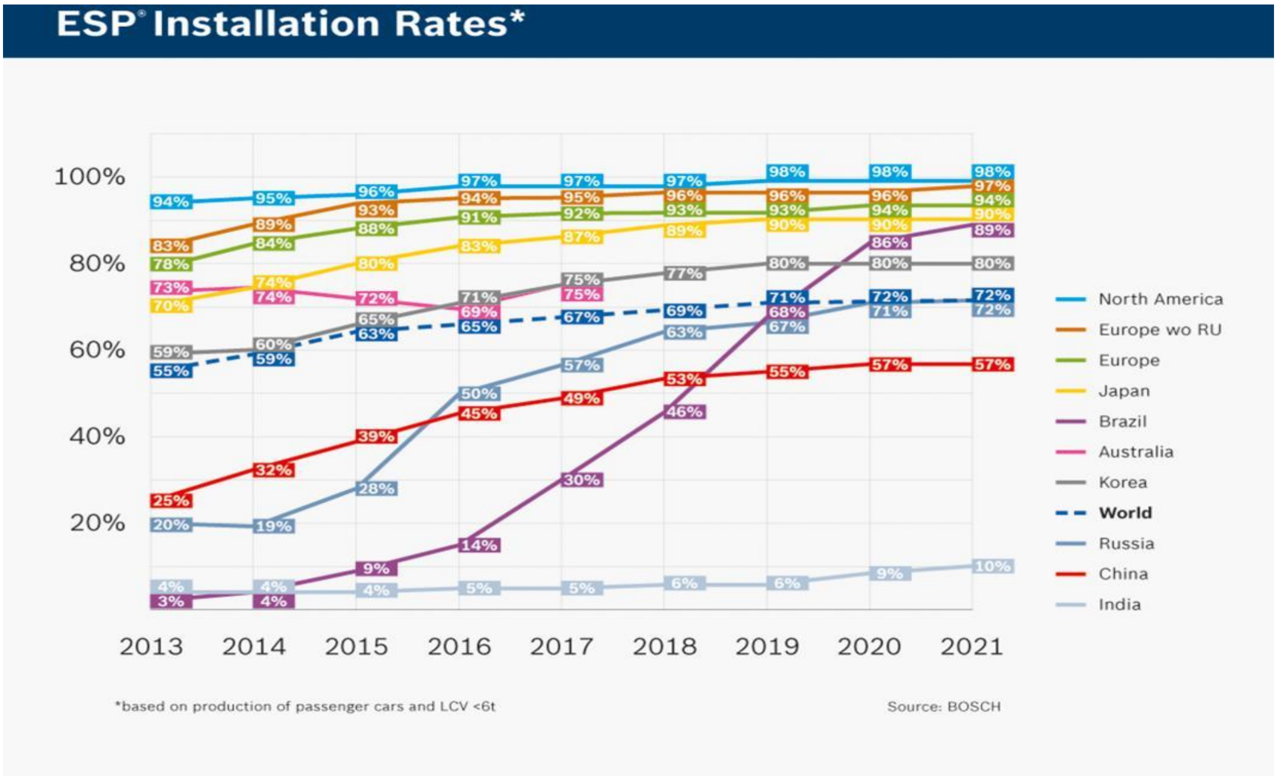

Figure 11. Installation rate of ESP worldwide [35]

2.6. Importance of vehicle modelling and simulation

ESP system requires a lot of time in tuning the model according to different parameters taken from the track testing, off-road testing, and it also needs a lot of time [4]. Testing the vehicle involves a lot of risk for the driver as the vehicle is tested beyond its limit and human error may occur. For testing the limits of the vehicle in different conditions requires a team of engineers to change the parts every time before the vehicle is tested.

When comparing the above condition, it is way better to use modelling and simulation method to test the vehicle. Vehicle modelling takes very less time to change the parameters and results of various testing methods are displayed fast. It may not be as accurate as real-life testing of the vehicle but its almost same as outdoor testing methods [32].

2.7. Regulations and testing methods of ESP

2.7.1. ESP regulations

There are many types of regulations passed by different countries for the balanced technical specifications and improvement of Electronic stability programme which is planned to be fixed its cars and light vans [19] [20] [21].

In 2007, the United Nations Economic Commission for Europe (UNECE) passed a regulation that it is compulsory for heavy vehicles and trucks to be fitted with Electronic stability Programme from 2010 [22].

According to Automotive Industry Standards, AIS-133 for Electronic Stability Control Systems by Automotive Research Association of India (ARAI), the vehicles of the certain category which is fitted with Electronic stability programme should perform several procedures and test conditions to test the effectiveness of ESP [10].

2.7.2. Testing methods

There are various testing methods to analyze the conditions leading to skidding, understeer, oversteer, rollover and they can be classified into

Go steer step

Go steer step [23] method is used to evaluate the vehicle handling characteristics, where the vehicle is a accelerate by a given input speed and then the steering wheel is turned suddenly according to the given parameters. The result from this method is used to find the lateral acceleration, which is the main reason for a rollover situation.

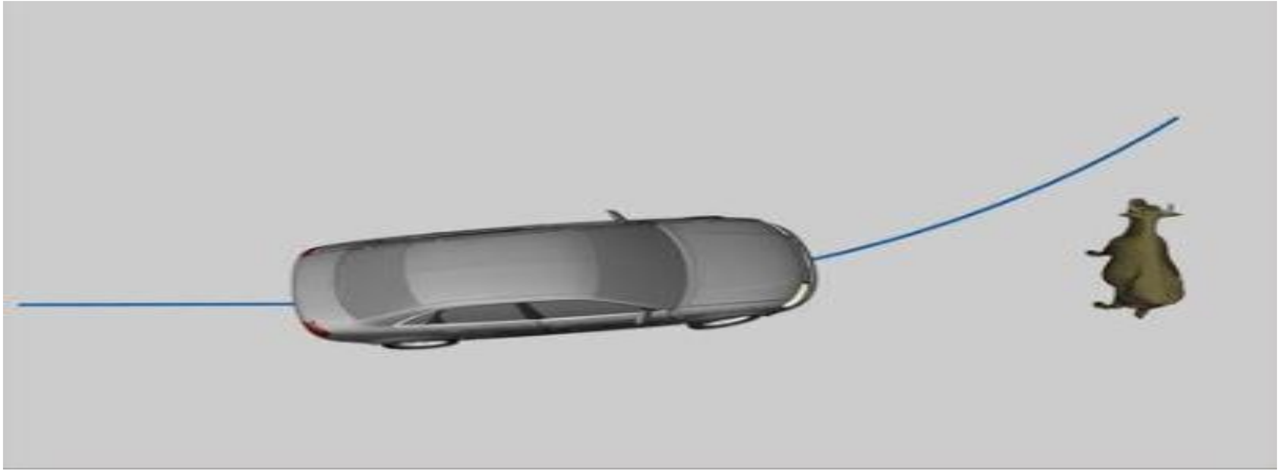

Figure 12. veDYNA GmbH [23]

Go steady-state circular drive

Go steady state [23] is a type of test in which the vehicle is constantly accelerated on a circular path of radius(r) until the lateral acceleration(a_y) is achieved. This test is done to understand the oversteer and understeer of the car which is called as the self-steering behavior.

Yaw velocity amplification describes the yaw angle above the average steering angle of the front axle and the steering wheel angle is the function of lateral speed which is determined from steering characteristics.

The velocity of the vehicle over the steering neutral line shows the oversteering behavior and velocity below the steering neutral line shows the understeering behavior. The speed characteristics show the maximum speed of an understeering vehicle and it also indicates the speed at which steering is very active.

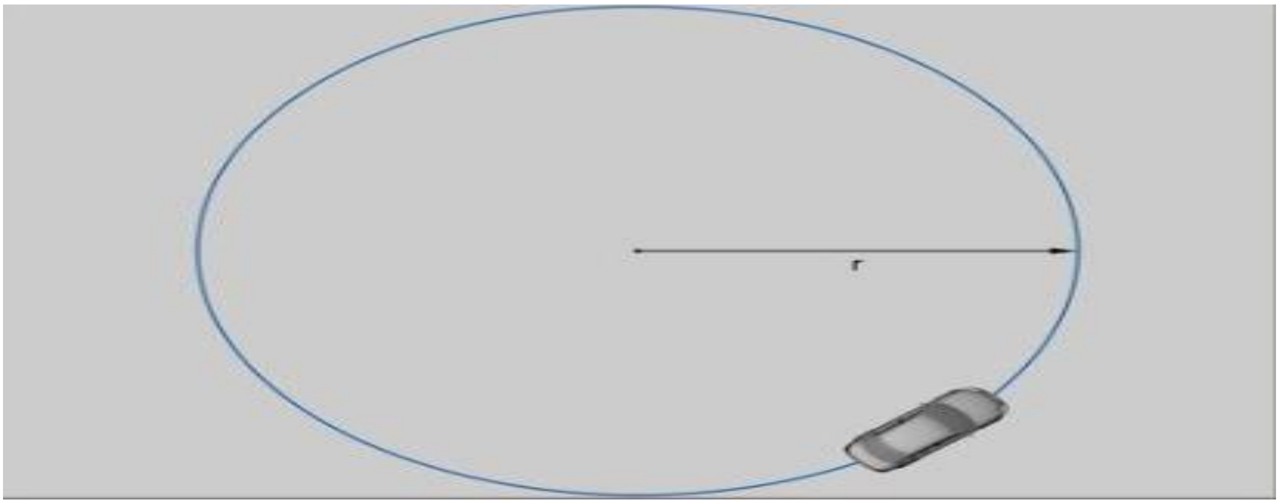

Figure 13. veDYNA GmbH [23]

Mu-split

Mu-split is the test done to find the braking effect on the road with different coefficients on the left and right side of the road. The vehicle accelerates to the given speed and suddenly decelerated by full pressing of brake pedal until the vehicle comes to halt. It is one of the best methods for a testing vehicle with and without ABS, ESP system.

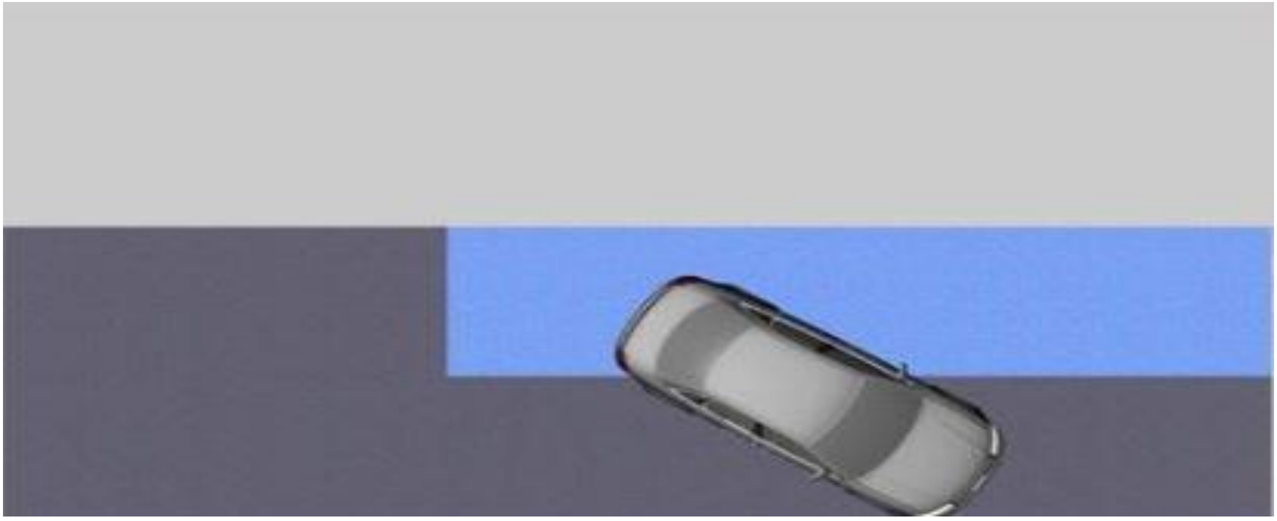

Figure 14. veDYNA GmbH [23]

Slalom test

Slalom test [25] procedure involves driving a vehicle through the road with series of cones placed at a certain distance continuously. The vehicle is accelerated continuously and the vehicle follows the sinusoidal path and the results obtained from this shows the vehicle trajectory, vehicle speed, yaw angle, yaw rate. This procedure can be used for comparison of different types of vehicles such as a car, SUV, truck etc to find the rate of rollover.

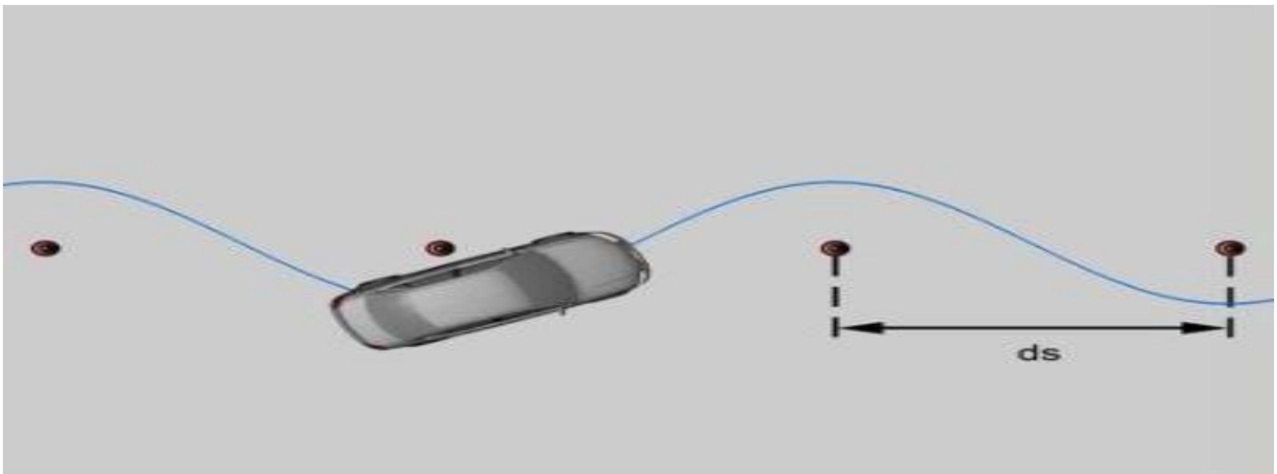

Figure 15. veDYNA GmbH [23]

Double lane change

Double lane change is also called as “moose test” and this test consists of several cones on the side lane with the entry as well as exit point [24]. The width of the entry lane depends upon the size of the vehicle and width of the exit lane is normally 3m wide. The throttle is released after 2m from starting of the lane and the vehicle velocity is measured in overrun mode at top gear in the exit lane. In this process, if the cones are not overturned by the vehicle, then the test is passed. In the vehicle simulation software veDYNA [23], the same procedure is followed as mentioned above and once the test is completed, results are plotted in the veDYNA graphical user interface. From the simulated graph, the properties such as vehicle trajectory, steering wheel angle, lateral acceleration, roll angle are displayed.

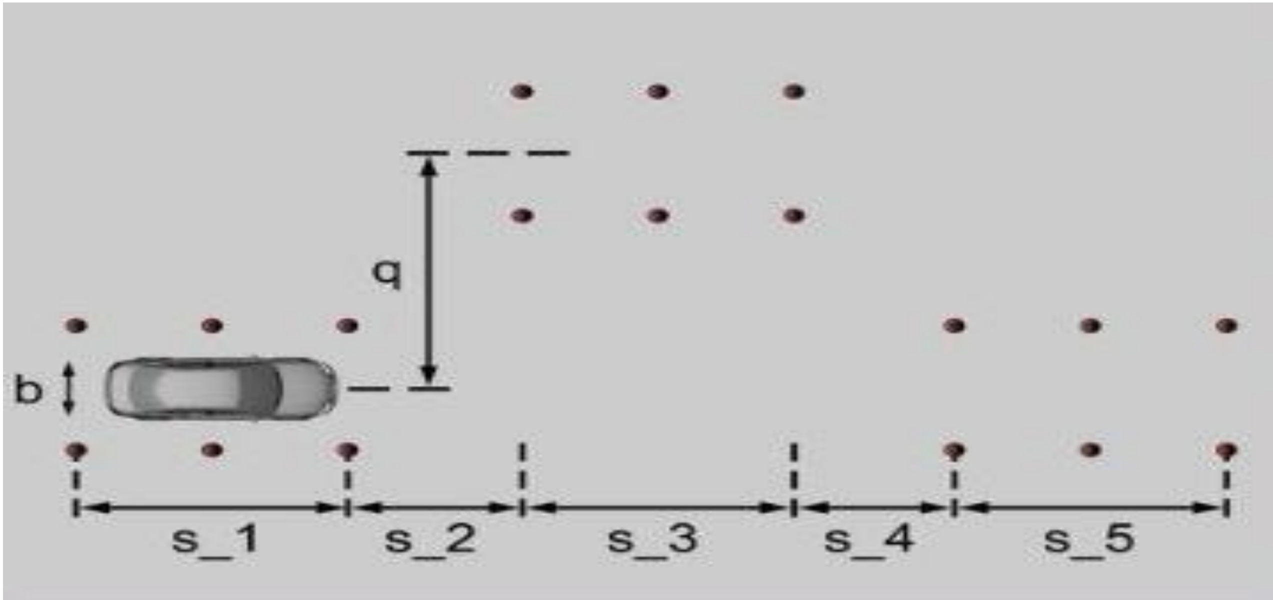

Figure 16. veDYNA GmbH [23]

3. Research methodology

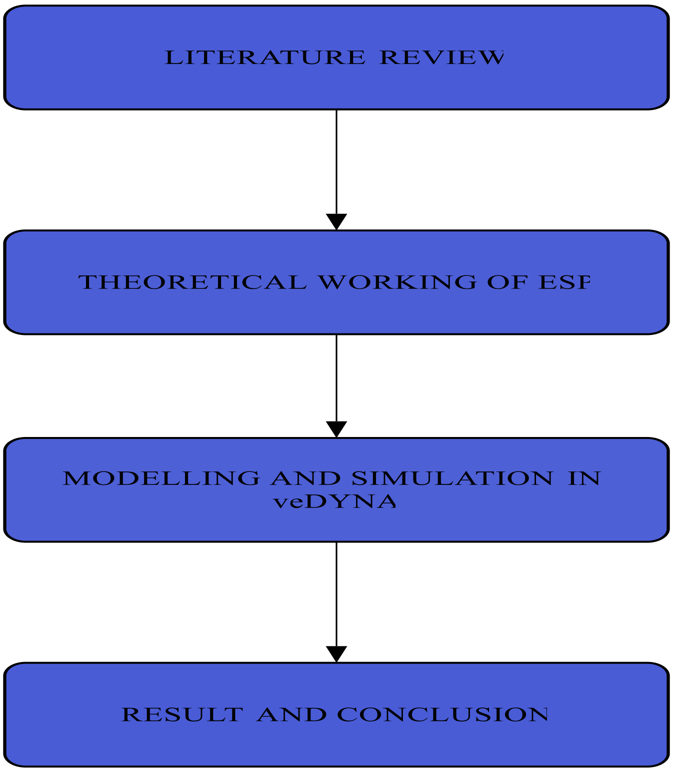

Figure 17. Flowchart of research methodology

3.1. Modelling in vedyna

The modelling and simulation in vehicle simulation software veDYNA involve a lot of procedure to get the desired output characteristics of the vehicle. For the better understanding and research purpose, the specific model of car was chosen and tested under various conditions to understand the situations leading to oversteer, understeer, and skidding. Modelling in veDYNA consist of three parts such as vehicle configuration, simulation control, and user procedure.

3.1.1. Vehicle configuration

The specific model Lamborghini Aventador LP 700 – 4 was chosen for testing under different conditions and parameters such as general vehicle data, front axle, rear axle and drive train were fed into the veDYNA software. These parameters were further used for further simulation procedure. There are four different types of sections in vehicle configuration of veDYNA.

Generic vehicle data - VEHICLE DIMENSIONS, MASS AND LOAD, AERODYNAMICS, BRAKE SYSTEM

Front axle - TYRE, BRAKE, STEERING, AXLE MASS AND INERTIA, INITIAL WHEEL ORIENTATION, AXLE MASS AND INERTIA, INITIAL WHEEL ORIENTATION, AXLE KINEMATICS, AXLE COMPLIANCE, SPRING, DAMPER, STABILIZER

Rear axle - TYRE, BRAKE, AXLE MASS AND INERTIA, INITIAL WHEEL ORIENTATION, AXLE MASS AND INERTIA, INITIAL WHEEL ORIENTATION, AXLE KINEMATICS, AXLE COMPLIANCE, SPRING, DAMPER, STABILIZER

Drivetrain - ENGINE, DRIVELINE, MANUAL TRANSMISSION

3.1.2. General vehicle data

The general vehicle data consist of vehicle dimensions, mass, and load, aerodynamics and brake system. In this step vehicle dimensions such as vehicle height, wheel track front, vehicle width, wheel track rear, wheelbase, vehicle length of the vehicle were calculated and fed into the vehicle dimension section and then in the mass and load section, the mass of the vehicle is given which further displays the vehicle centre of gravity (COG). In the brake system of the vehicle, brake pressure was evenly distributed as 50% in the front and 50% in the rear and for the aerodynamic properties, the assumption was made by the software on its own without the side wind force acting on the vehicle.

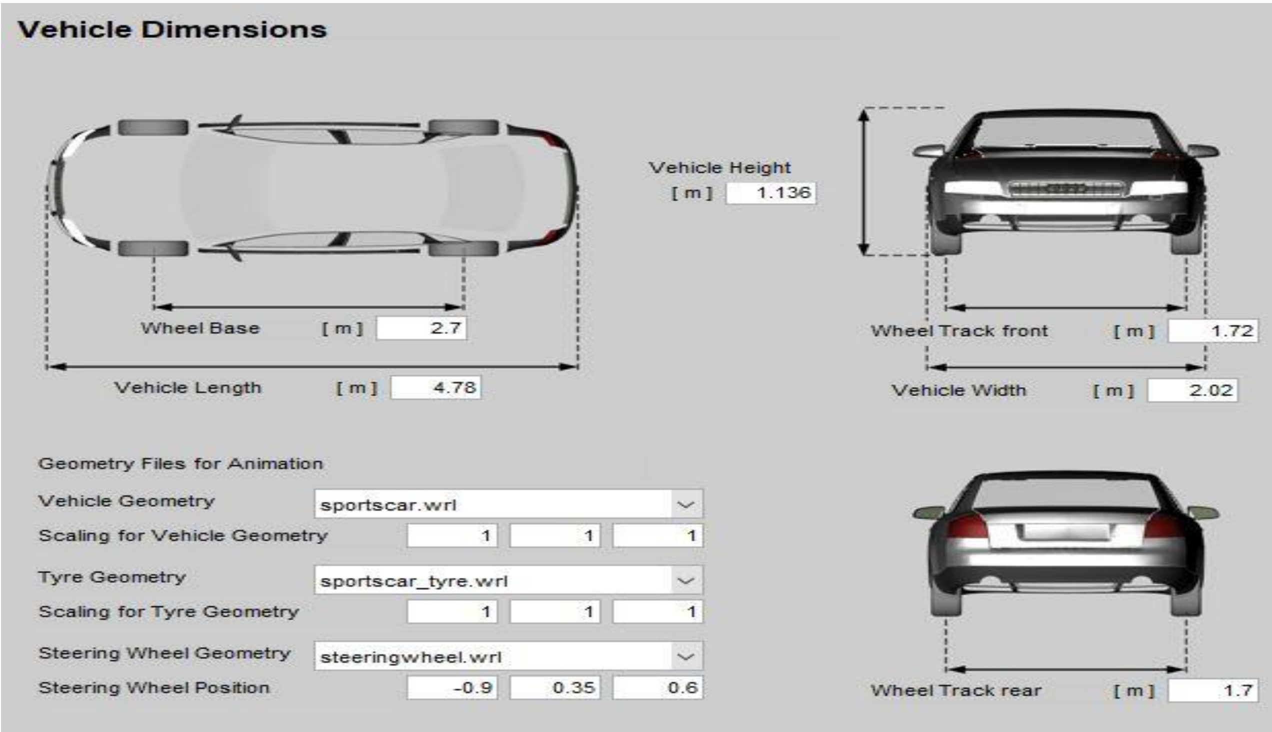

Figure 18. Specification of vehicle dimension

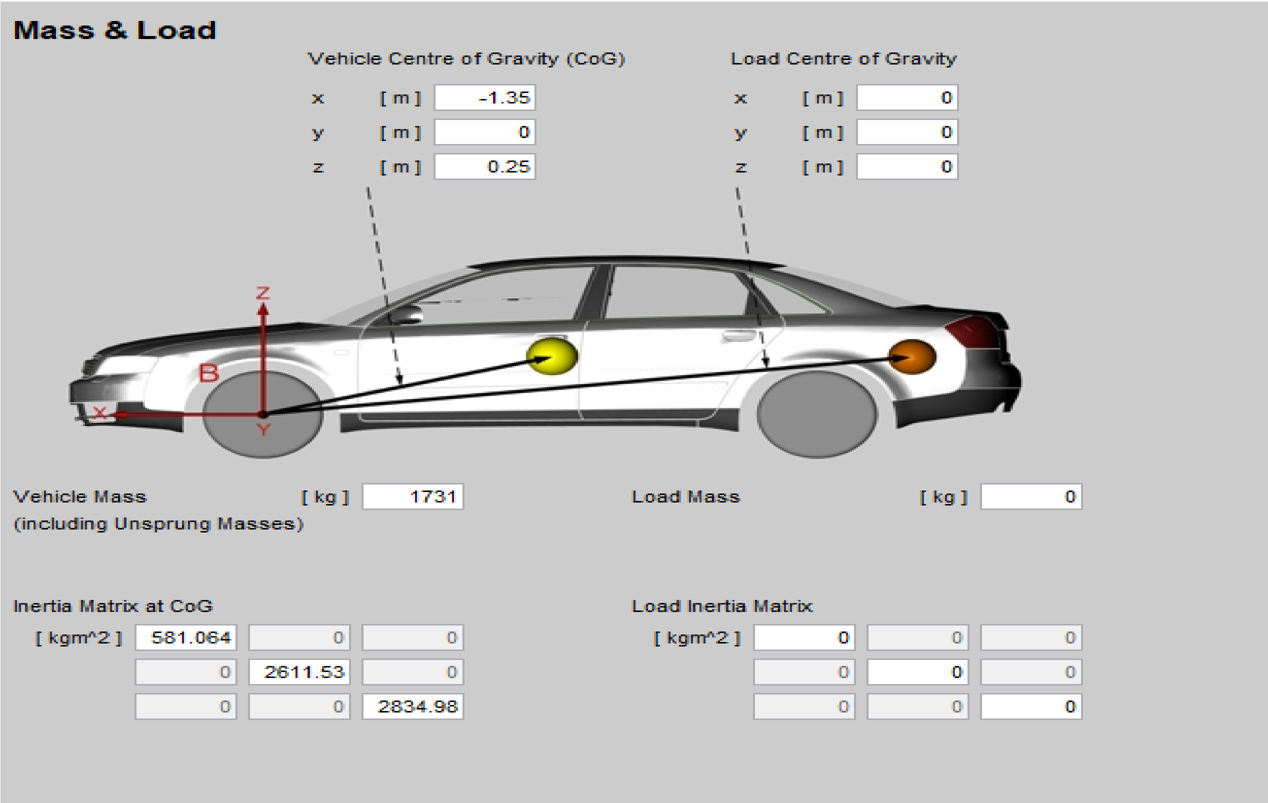

Figure 19. Vehicle mass and load

Front axle

The front axle system in the veDYNA consists of several components such as a tyre, brake, steering, axle mass and inertia, initial wheel orientation, axle kinematics, axle compliance, spring, damper and anti-roll bar.

The front tyre is chosen according to European norm ECE R 30, front brake friction coefficient as 0.35, steering as parallel steering and for axle mass and inertia, initial wheel orientation, axle kinematics, axle compliance, spring, damper, stabilizer values were assumed and given automatically by the veDYNA software.

Rear axle

The rear axle system in the veDYNA consists of several components such as tyre, brake, axle mass and inertia, initial wheel orientation, axle mass and inertia, initial wheel orientation, axle, kinematics, axle compliance, spring, damper, stabilizer.

The front tyre is chosen according to European norm ECE R 30, rear brake friction coefficient as 0.35, and for axle mass and inertia, initial wheel orientation, axle kinematics, axle compliance, spring, damper and stabilizer values were assumed and given automatically by the veDYNA software.

Drivetrain

The drivetrain consists of an important system like the engine, driveline, manual transmission or automatic transmission. All the values are assumed by the veDYNA software automatically and value changes accordingly when the parameter in the simulation control is changed.

3.1.3. Determination of parameters

It consists of divisions such as maneuver, driver, road, trace and user procedure where all the procedure for basic modelling instruction is given.

Maneuver – Longitudinal dynamics, lateral dynamics, and constraints

Driver – Driver type, driver parameters, and driver speed

Road – Road type, XY – layout, Z – profile

Trace – Trace file, trace interval

User procedure – User procedure

3.1.4. Model simulation

1. Go steerstep

In the go steer, step procedure maneuver type was changed to steer step, driver as a basic driver, road type two lane with straight and flat, trace file as steer step and user procedure to steady-state circular drive. For this method, two test was done by using by changing the force in front axle of the vehicle to test the rollover situation.

Table 2. Maneuver phases go steerstep

Phase	**Longitudinal Dynamics**	**Lateral Dynamics**	**Constraints**
Maneuver definition	SteerStep.m	SteerStep.m	SteerStep.m
Find Static Position	Cruise Control (0)	Absolute Steering Input (0)	Neutral gear
Acceleration	Cruise Control (target)	Fixed Steering Wheel	Gears 1-5
Stabilisation	Cruise Control (vtarget)		
Steering wheel step		Absolute steering input (δh)	
Stabilisation		Fixed Steering Wheel	

Table 3. Maneuver parameters of go steerstep

Specifier	Description
Change of steering wheel angle [deg]	100
Steering rate [deg/s]	300
Vehicle speed [km/h]	60

2. Go steady-state circle drive

In the circular drive, method maneuver was changed to circle drive, driver as basic, road type as two-lane with a circle and flat, trace as circle drive and user procedure as a steady-state circular drive. For this type of testing two tests were done, where the force in the axles was changed in the front and rear axle. During the first test, lateral force in the front axle was increased and in the second test lateral force in the rear was increased to test the self-steering behavior.

Table 4. Maneuver phases go steady-state circle drive

Phase	Longitudinal Dynamics	Lateral Dynamics	Constraints
Maneuver definition	Circle Drive.m	Circle Drive.m	Start1s.m
Find Static Position	Cruise Control (0)	Abs. Steering Input (0)	Neutral gear
Acceleration on a circular drive with a constant radius	Nominal lateral acceleration control	Control steady-state circular run	Gears 1-5

Table 5. Maneuver parameters of go steady state circular drive

Specifier	Description
The radius of the driving circle [m]	100
Maximum lateral acceleration [m/s^2]	9
Time to reach maximum acceleration [s]	200

3. Go-braking-on-musplit: braking on mu-split

In this method maneuver was changed to mu-split, driver as basic, road as straight and flat, trace as a brake on mu-split and user procedure as go braking on mu-split. For this method test was done for two different coefficients of friction.

Table 6. Maneuver phases go braking on mu-Split

Phase	Longitudinal dynamics	Lateral dynamics	Constraints
Maneuver definition	Brake-on-Musplit.m	Brake-on-Musplit.m	Brake-on-Musplit.m
Find static position	Acceleration Pedal Input (0)	Abs. Steering Input (0)	Neutral gear
Acceleration	Cruise Control	Controlled Straight Line Driving	Gear 1 – 7
Drive slalom course	Cruise control	Fixed steering wheel	
Straightline driving	Acceleration pedal input		Full brake

Table 7. Maneuver parameters of go braking on mu-split

Specifier	Description
Lower friction coefficient	0.1 for 1st test, 1 for the 2nd test
Vehicle velocity [km/h]	80

4. Go slalom: slalom test

In this method maneuver was changed to slalom, driver as basic, road type two-lane as straight and flat, trace as slalom and user procedure as go slalom. For this method, three test were done for three different vehicle types such as a car, SUV, and truck at the same speed 80 kmph.

Table 8. Maneuver phases go slalom

PHASE	LONGITUDINAL DYNAMICS	LATERAL DYNAMICS	CONSTRAINTS
Maneuver definition	Slalom.m	Slalom.m	Slalom.m
Find static position	Basic driver	Fixed steering wheel	Neutral gear
Acceleration		Basic driver	Gear 1- 5
Drive slalom course		Basic driver	
Straightline driving		Basic driver	

Table 9. Maneuver parameters of go slalom

Specifier	Description
Distance between cones (ds) [m]	30
Number of cones	7
Vehicle velocity [km/h]	80
Maximum lateral displacement [m]	2

5. Go double lane change: double lane change

In this method, maneuver definition was changed to circle drive for longitudinal, lateral and constraints. The two tests were done at different speed at 80 kmph and 160 kmph, using the same vehicle configuration. By double lane change method, the rollover rate was tested.

Table 10. Maneuver phases of go double lane change

Phase	Longitudinal Dynamics	Lateral Dynamics	Constraints
Maneuver definition	Circle Drive.m	Circle Drive.m	Start1s.m
Find Static Position	Cruise Control (0)	Abs. Steering Input (0)	Neutral gear
Acceleration on a circular drive with a constant radius	Nominal lateral acceleration control	Control steady-state circular run	Gears 1-5

Table 11. Maneuver parameters of go double lane change at 80 km/h

Specifier	Description
Length of 1st lane (s _1) [m]	15
The distance between 1st and 2nd lane (s_2) [m]	30
Length of 2nd lane (s_3) [m]	25
The distance between 2nd and 3rd lane (s_4) [m]	25
Length of 3rd lane (s_5) [m]	30
Overall vehicle width (b) [m]	2
Vehicle speed (km/h)	80

Table 12. Maneuver parameters of go double lane change 160 km/h

Specifier	**Description**
Length of 1st lane (s _1) [m]	15
The distance between 1st and 2nd lane (s_2) [m]	30
Length of 2nd lane (s_3) [m]	25
The distance between 2nd and 3rd lane (s_4) [m]	25
Length of 3rd lane (s_5) [m]	30
Overall vehicle width (b) [m]	2
Vehicle speed (km/h)	160

4. Simulation results

4.1.1. Steerstep test

The roll angle becomes high when there is an increase in yaw rate of the vehicle. When the lateral force in the front tyre was changed from 3180 N to 5000 N, the tyre loads at the inner left wheel became zero due to the high lateral force acting on the tyre and the wheel lifts. So, increasing the lateral force increases the lift of the wheel, which further leads to rollover at later on stage. The roll angle is abruptly increased when the lateral acceleration force is more on the tyres.

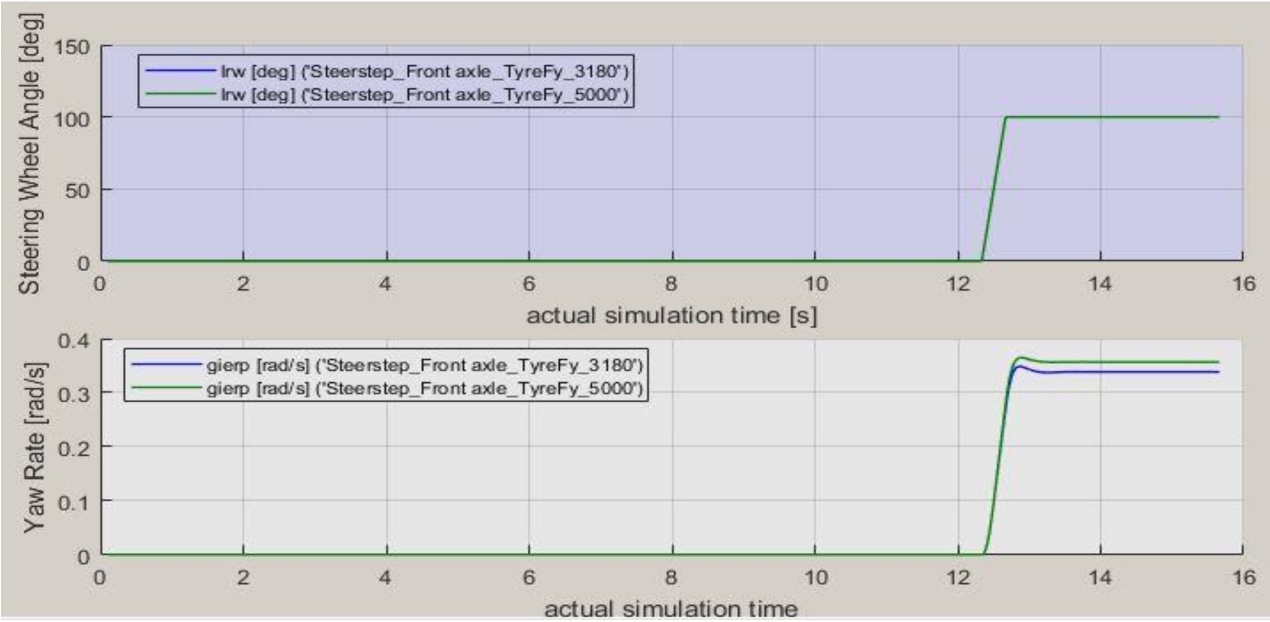

Figure 20. Steerstep yaw rate response due to steering wheel input graph

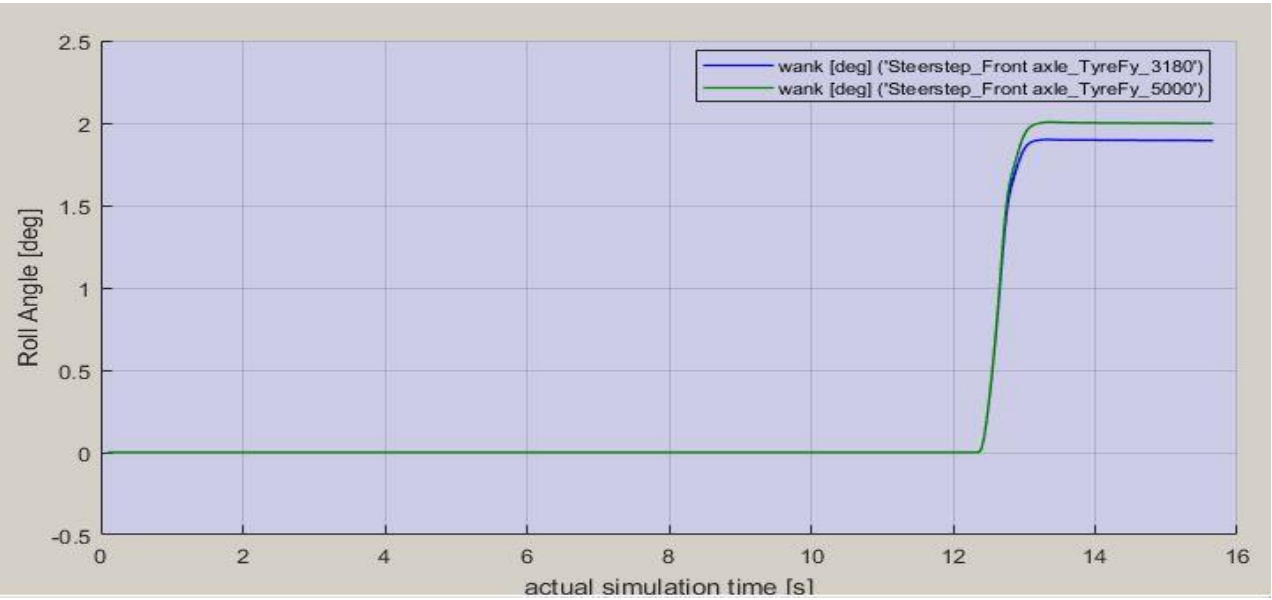

Figure 21. Steerstep roll angle graph

4.1.2. Steady-state circle drive test

The generated graphs show the understeer and oversteer behavior when the force is changed on the front axle and rear axle.

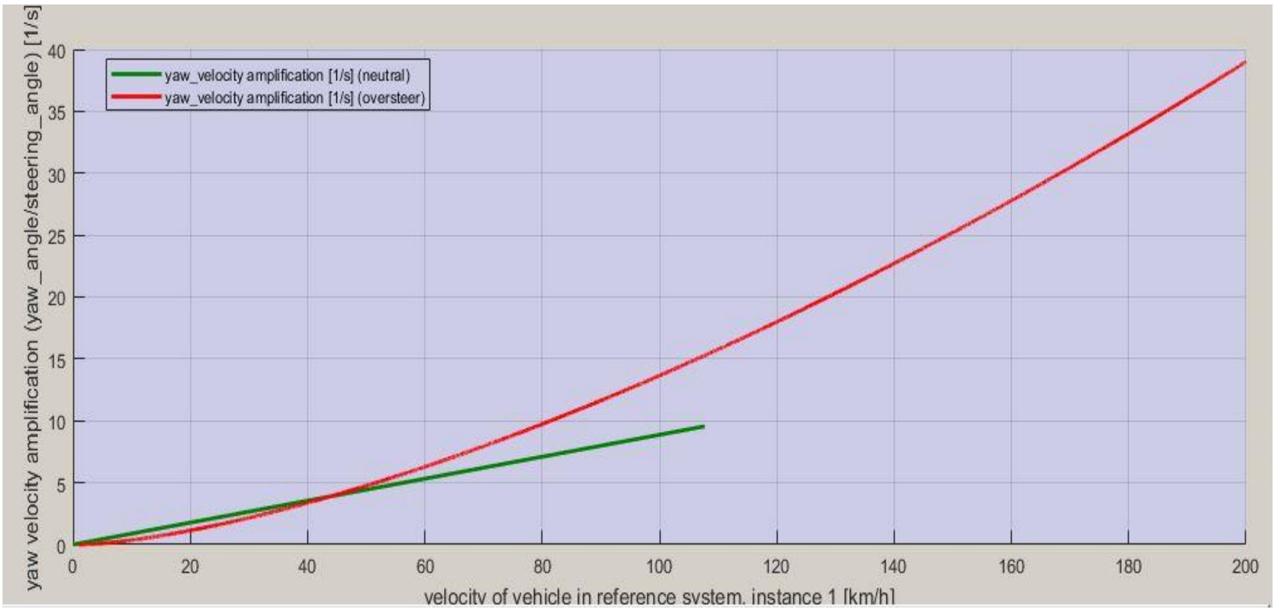

Figure 22. Steady-state circle drive yaw velocity amplification oversteer graph

Front axle more force (oversteer)

In the graph 1, yaw velocity amplification which is yaw angle over the average steering angle has changed abruptly due to the force on the front axle. From the graph 1, we can see that velocity amplification is above the neutral steering line. As the velocity amplification is more than the neutral steering line, it clearly shows the oversteer characteristics of the vehicle.

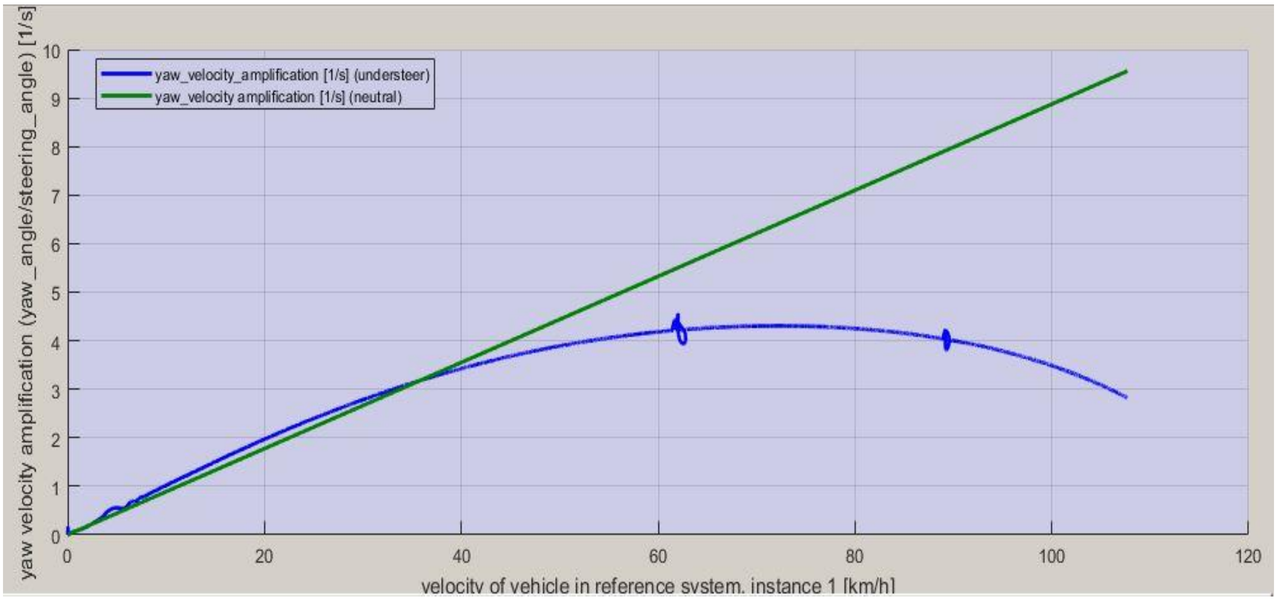

Figure 23. Steady-state circle drive yaw velocity amplification understeer graph

Rear axle more force (understeer)

In the graph 2, the yaw velocity amplification is below the neutral steering line due to the presence of more force on the rear axle than on the front axle. The velocity amplification is well below the neutral steering line which shows the understeer behavior of the vehicle.

4.1.3. Braking on mu-split test

The generated graphs show the braking effect on the left and right side of the road with a different coefficient of friction.

From the generated graph 1, it can be seen that the yaw angle of the vehicle is more when the friction coefficient is higher on one side than on the other side. It can be seen from the graph 2, that the yaw rate is very high when the skidding occurs, as the coefficient of friction is very less on the left side which leads to high yaw rate.

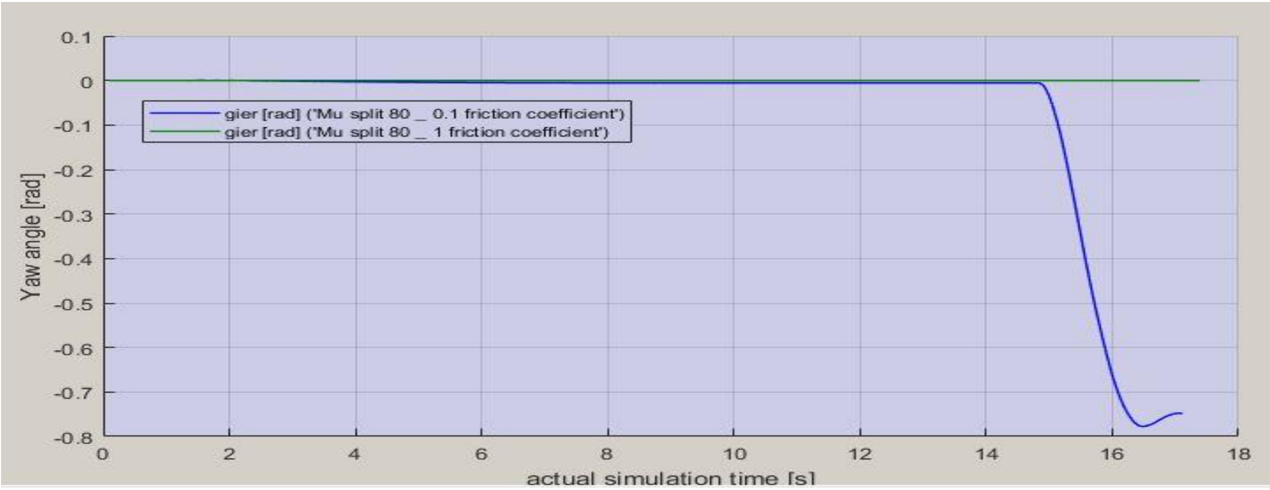

Figure 24. Mu-split yaw angle graph

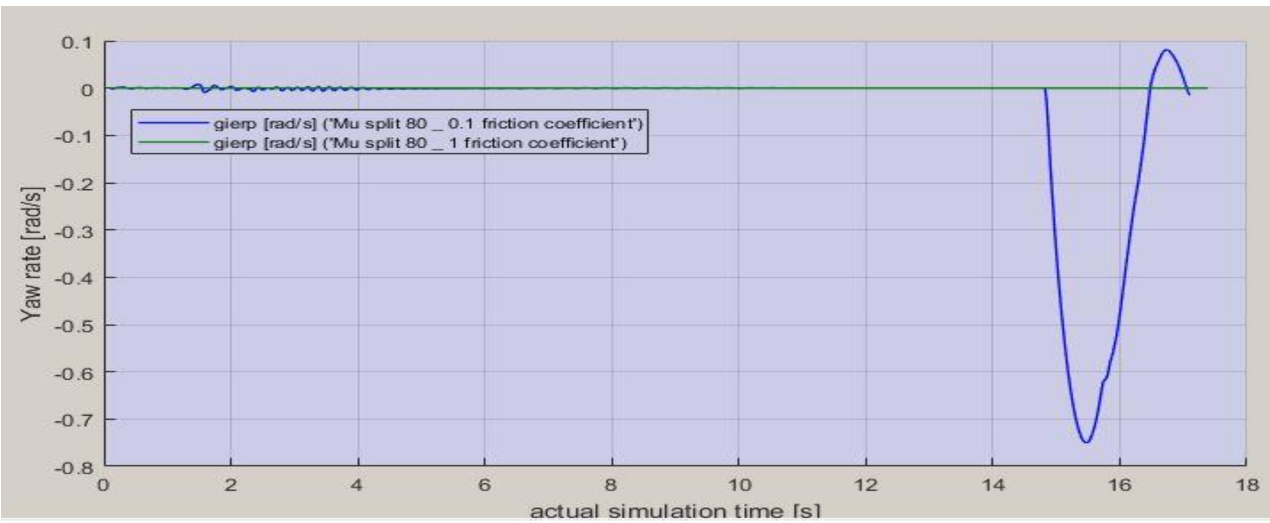

Figure 25. Mu-split yaw rate graph

4.1.4. Double lane change test

The generated graphs show the test results for two different speeds in a double lane change at 80 kmph and 160 kmph.

From the graphs, it is evident that the lateral acceleration of the vehicle at 160 kmph is very high when compared to lateral acceleration at 80 kmph. High lateral acceleration force will lead to rollover accidents.

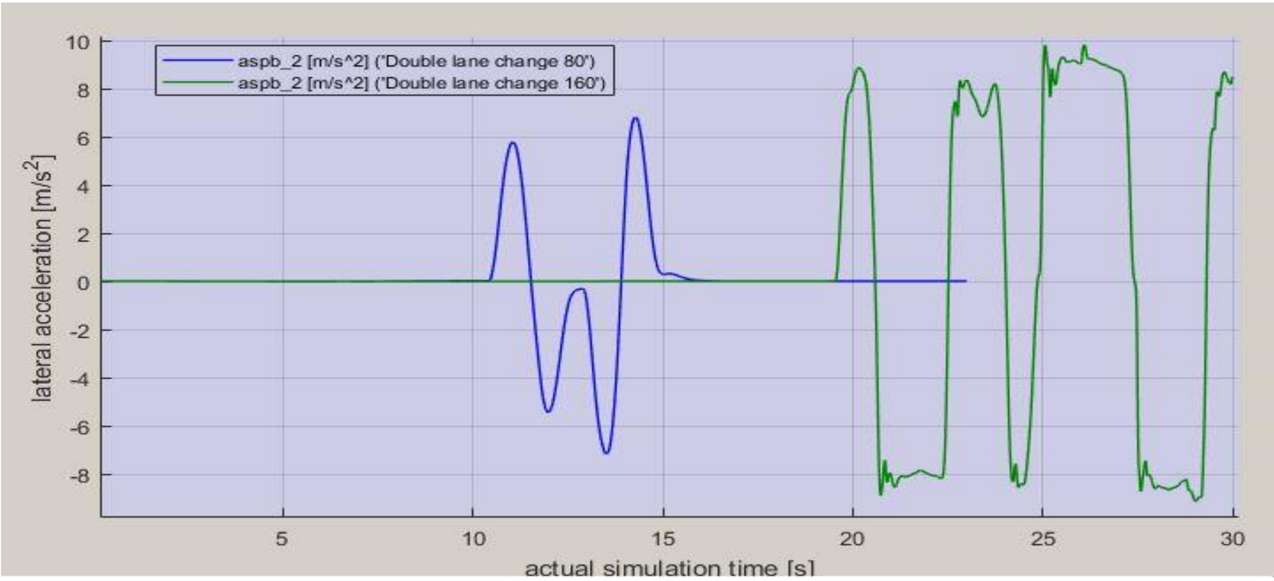

Figure 26. Double lane change lateral acceleration graph

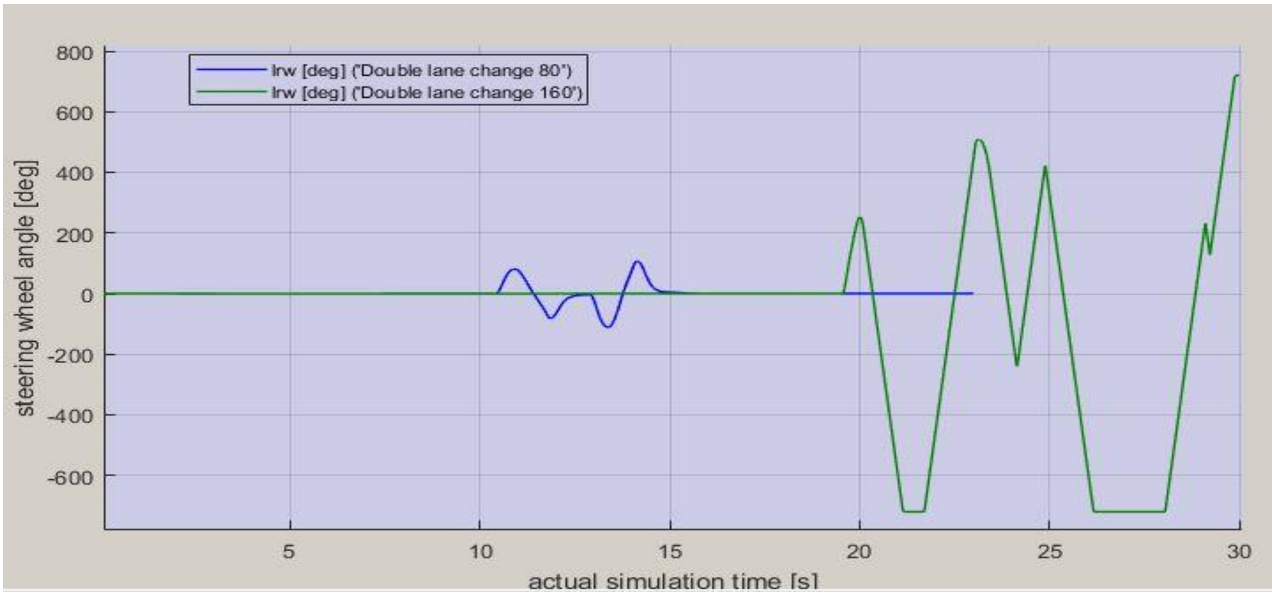

Figure 27. Double lance change steering wheel angle graph

4.1.5. Slalom test

From the generated graphs of three different vehicles at 80 kmph, it can be seen that yaw angle of the truck is very high when compared to car and SUV. The high roll angle is due to high center of gravity, track width and mass of the vehicle.

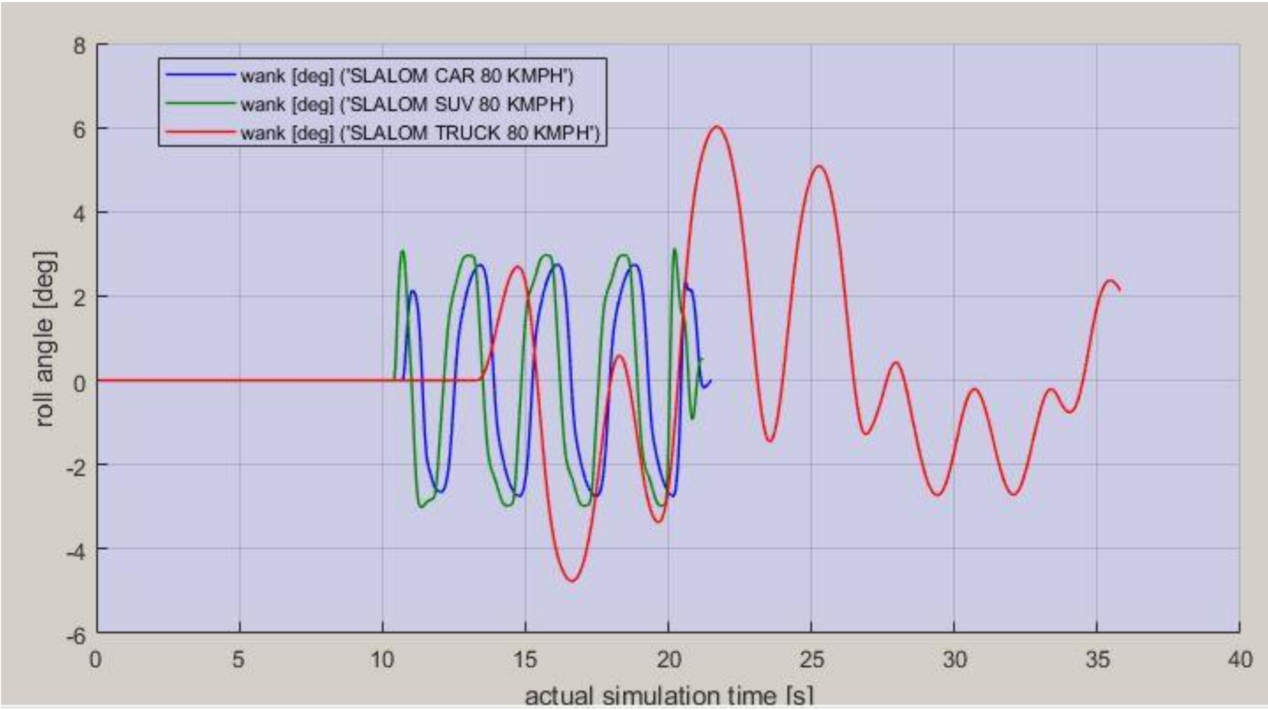

Figure 28. Slalom roll angle graph

Conclusion

The ESP working principle was studied to analyze the conditions leading to skidding, understeer, oversteer, and rollover in the vehicle. The paradigm vehicle model was simulated by using various testing regulations and by comparing the results of the veDYNA, it is clearly evident that high lateral acceleration and yaw rate leads to skidding, understeer, oversteer, and rollover in the vehicle.

1. For the steady state drive, when the force was changed in the front axle oversteer clearly happens at 40 kmph and understeer happens at 26 kmph. It is well noted that high axle force leads to understeer and oversteer of the vehicle.

2. In the steerstep test when the force of 3180 N and 5000 N was applied in the front axle, the yaw rate in the front axle was found be 0.34 for 3180 N and 0.36 for 5000 N.

3. Braking on the mu-split at 80 kmph for two different coefficients 0.1 and 1, it was found that yaw rate went as low as - 0.74 for 0.1 coefficient and it was constant for the coefficient of 1.

4. For the double lane change, the steering wheel angle at 80 kmph was maximum of 100 degrees and at 160 kmph it was found to be 700 degrees. It shows steering angle is more at higher speeds of the vehicle.

5. In the slalom test for three different vehicles at 80 kmph, the roll angle for car and SUV was 2 degree and 3 degrees, whereas for the truck it was maximum of 6 degree which clearly shows that heavy vehicles have high rollover rate when compared to light passenger vehicles.

6. The vehicle simulation software veDYNA used for testing can decrease the cost and reduce the human error in vehicle testing and

7. The various conditions leading to skidding, undesteer, oversteer and rollover shows that it can be reduced only by implementing the active safety system like ESP.

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Appendices

Appendix 1

Table 13. The specifications of the Lamborghini Aventador LP 700 – 4

1. VEHICLE DIMENSIONS	
VEHICLE LENGTH	4.78 m
WHEEL BASE	2.7 m
VEHICLE WIDTH	2.02 m
WHEEL TRACK FRONT	1.72 m
VEHICLE HEIGHT	1.136 m
WHEEL TRACK REAR	1.7 m
2. MASS AND LOAD	
VEHICLE CENTRE OF GRAVITY (COG)	
X	-1.35 m
Y	0 m
Z	0.25 m
VEHICLE MASS	1731 kg
INERTIA MATRIX AT CENTRE OF GRAVITY	
X	581.064 [kgm^2]
Y	2611.53 [kgm^2]
Z	2834.98 [kgm^2]
3. FRONT AXLE (TYRE DESCRIPTION ACCORDING TO EUROPEAN NORM ECE R 30)	
TYRE WIDTH	205 mm
RATIO OF TYRE HEIGHT TO TYRE WIDTH [×100]	60
TYPE OF TYRE	R
TYRE RIM DIAMETER	13 inch
LOAD INDEX	88
TYRE SPEED SYMBOL	V = 240 km/h

4. REAR AXLE (TYRE DESCRIPTION ACCORDING TO EUROPEAN NORM ECE R 30)	
TYRE WIDTH	225
RATIO OF TYRE HEIGHT TO TYRE WIDTH [×100]	50
TYPE OF TYRE	R
TYRE RIM DIAMETER	16
LOAD INDEX	88
TYRE SPEED SYMBOL	H = 210 km/h
5. DRIVETRAIN – GENERAL	
TRANSMISSION TYPE	MANUAL
DRIVETRAIN – ENGINE TORQUE CHARACTERISTICS	
MAXIMUM ENGINE SPEED	7500 rpm
ENGINE SPEED AT MAXIMUM ENGINE POWER	7000 rpm
ENGINE SPEED AT MAXIMUM ENGINE TORQUE	6000 rpm
ENGINE IDLE SPEED	833 rpm
ENGINE TORQUE AT 1.2 * IDLE SPEED	232.9 Nm
MAXIMUM ENGINE TORQUE	292.1 Nm
ENGINE TORQUE MAXIMUM POWER	263.2 Nm
FRICTION TORQUE AT 1.2 * IDLE SPEED	- 27.8 Nm
FRICTION TORQUE AT MAXIMUM ENGINE SPEED	- 45.8 Nm
INERTIA OF FLYWHEEL	0.211 [kgm^2]
TORQUE DELAY	0.05 s
SCALING FACTOR	1

Vehicle configuration

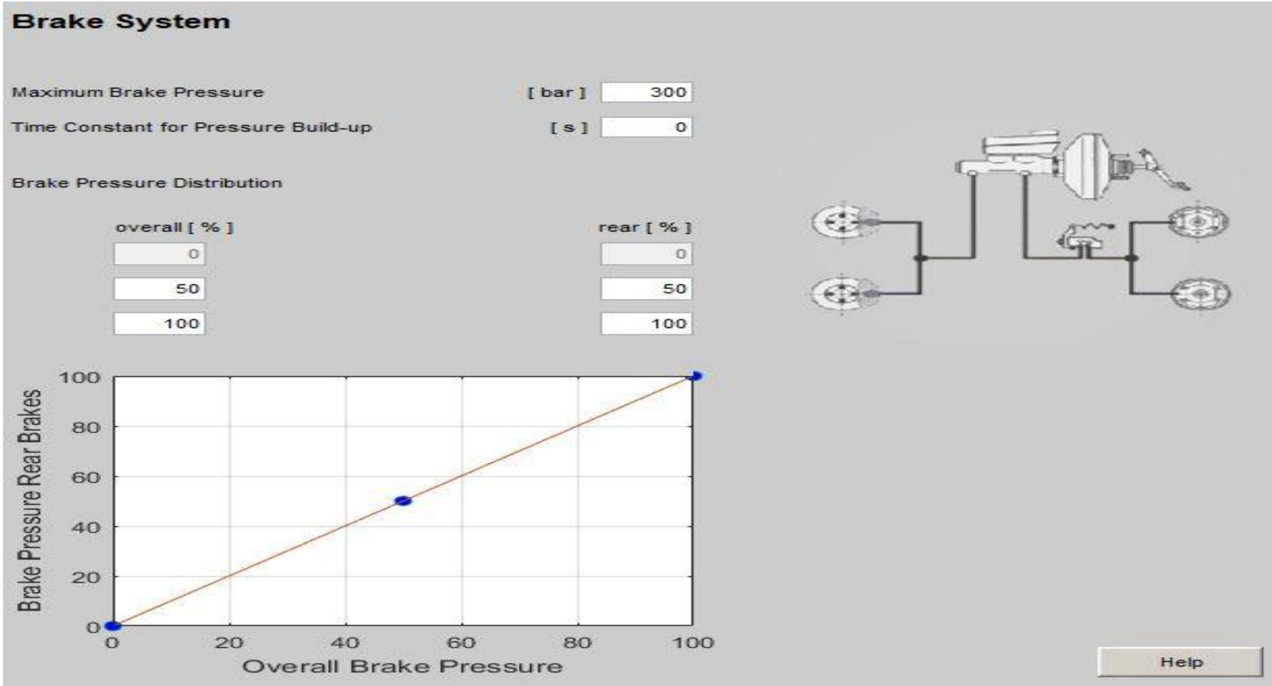

Figure 29. Vehicle brake system

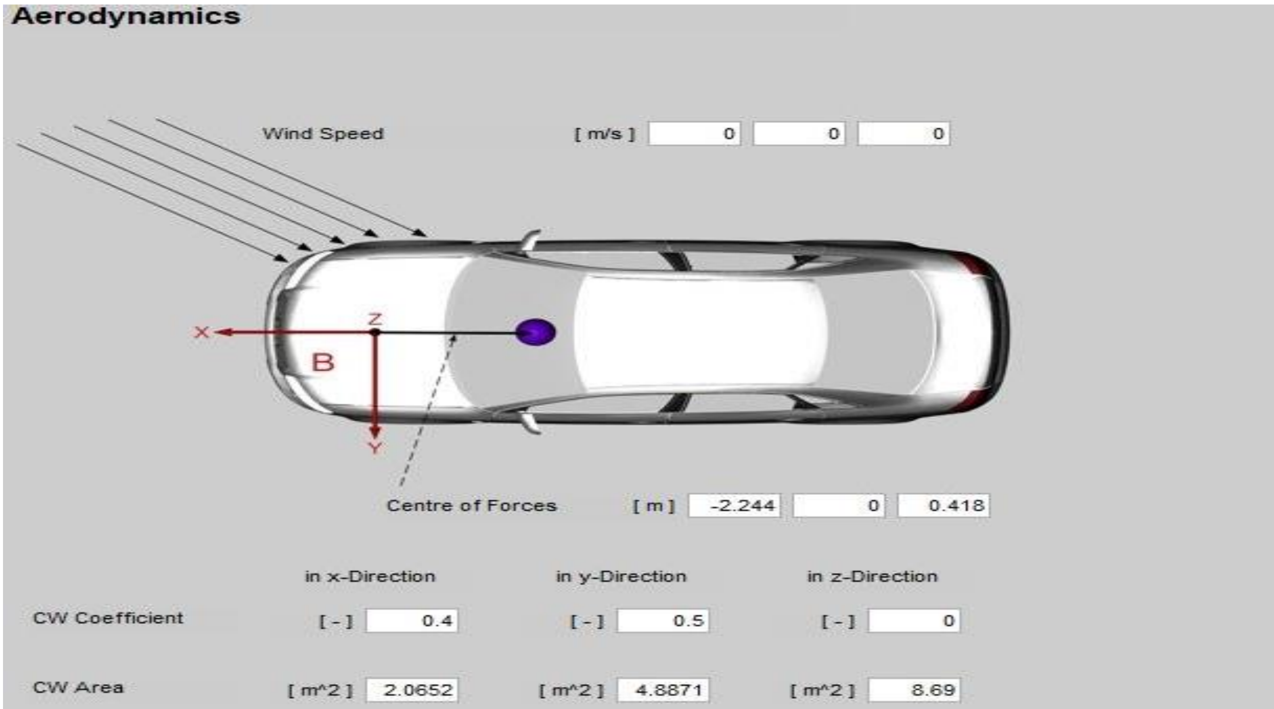

Figure 30. Vehicle aerodynamics

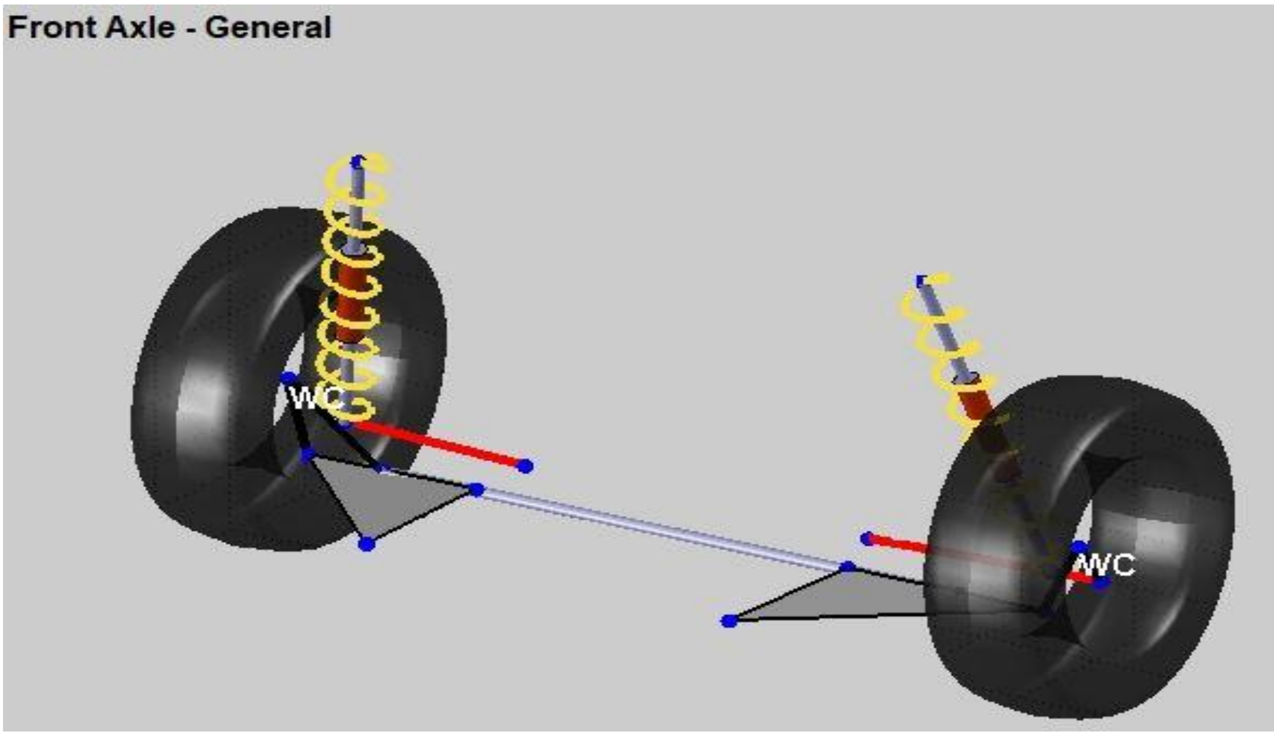

Figure 31. Front axle - general

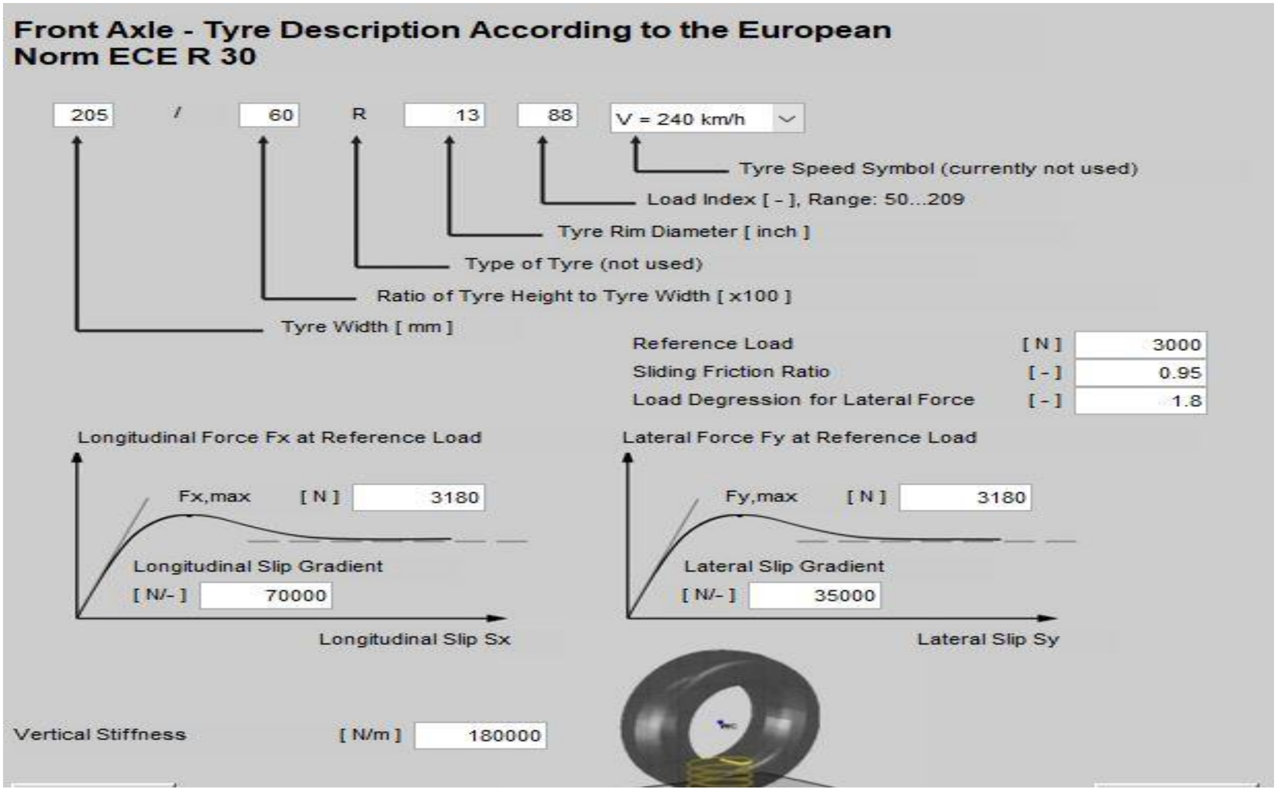

Figure 32. Front axle - tyre description

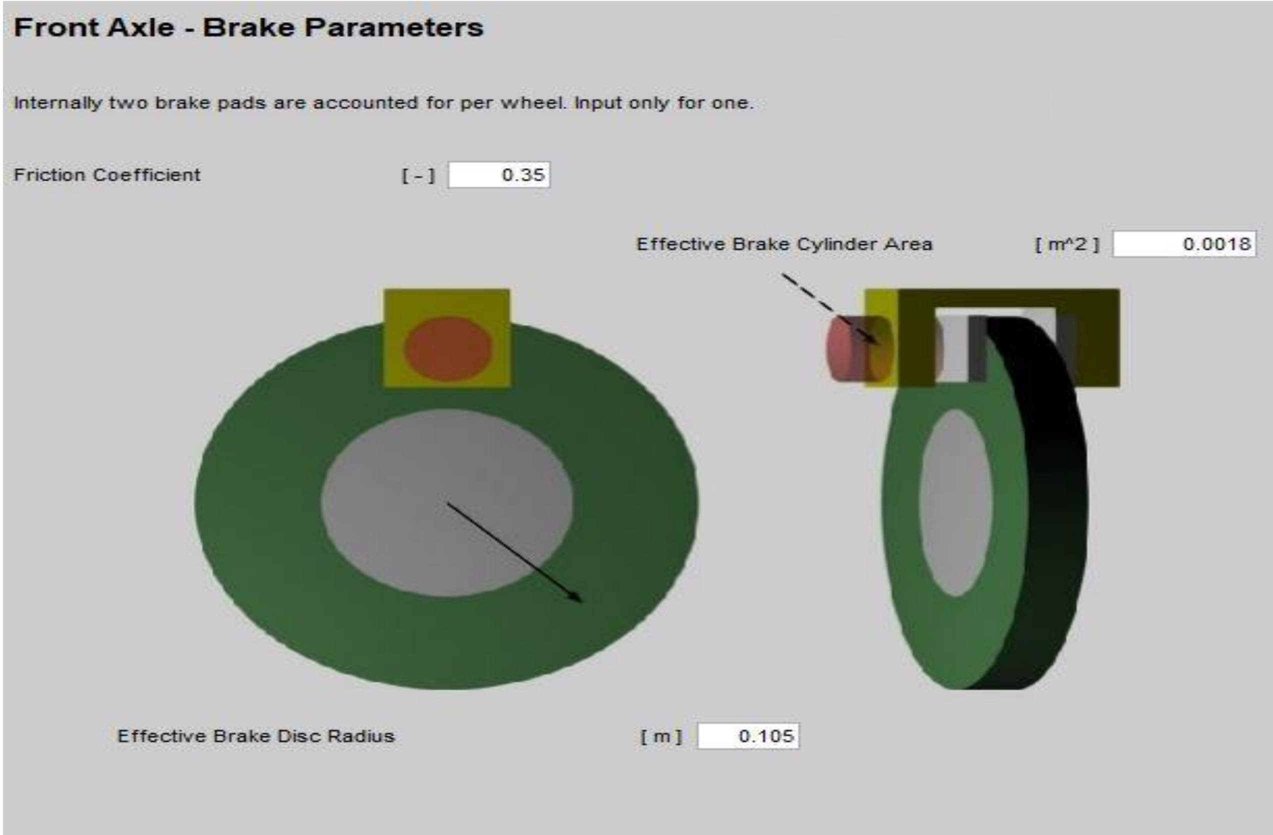

Figure 33. Front axle - brake parameters

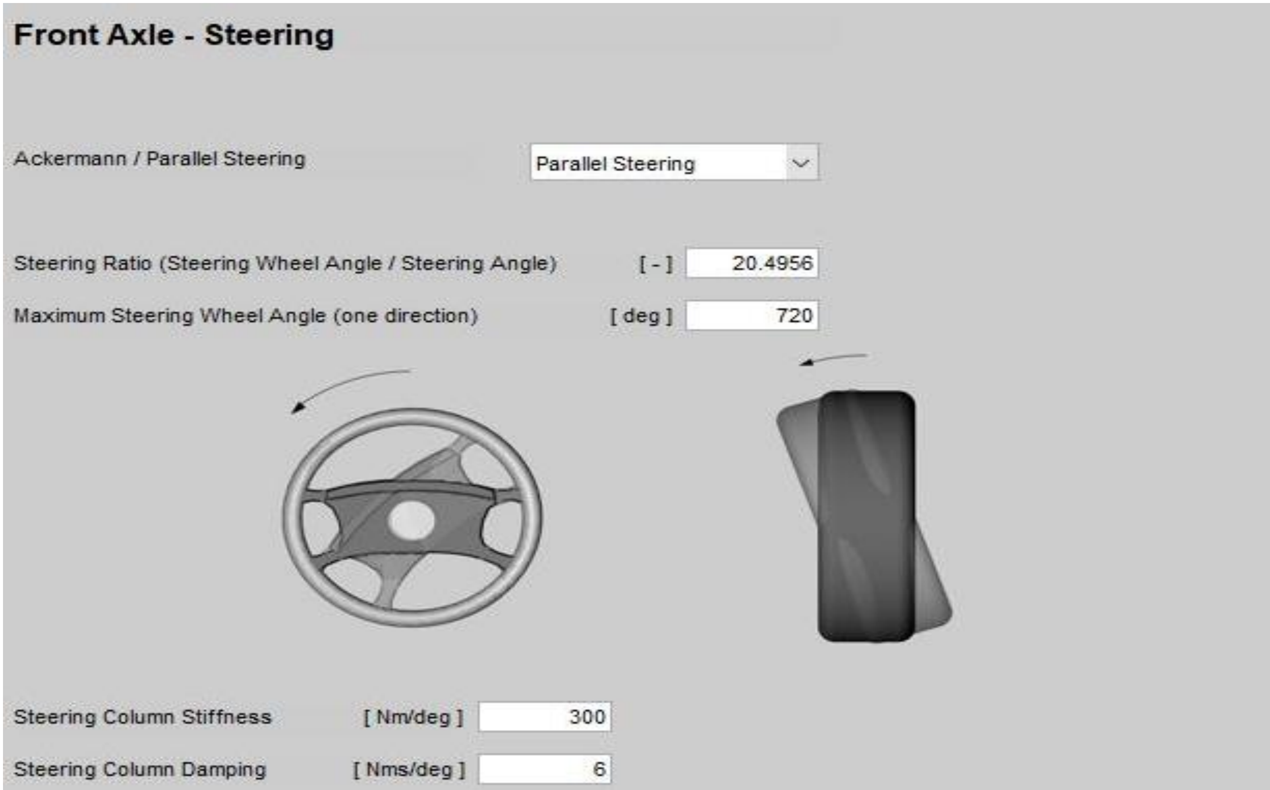

Figure 34. Front axle - steering

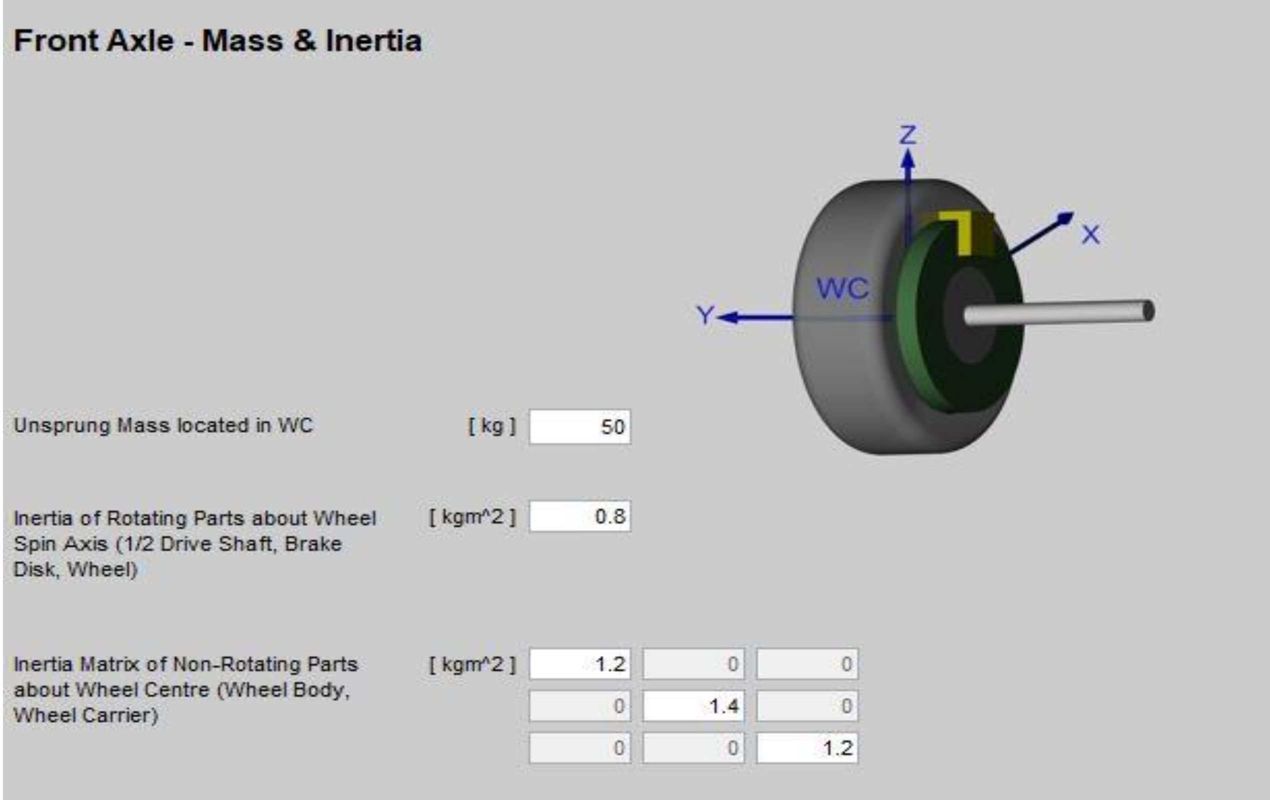

Figure 35. Front axle - mass and inertia

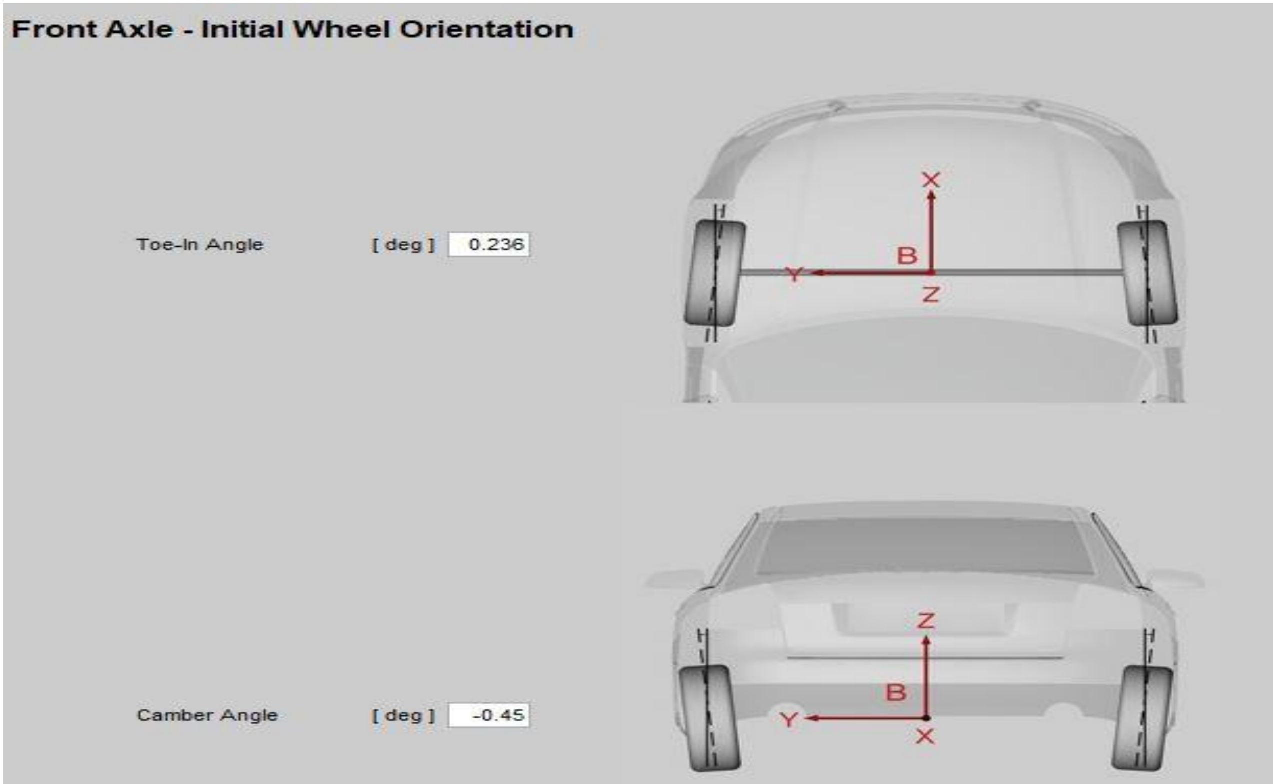

Figure 36. Front axle - initial wheel orientation

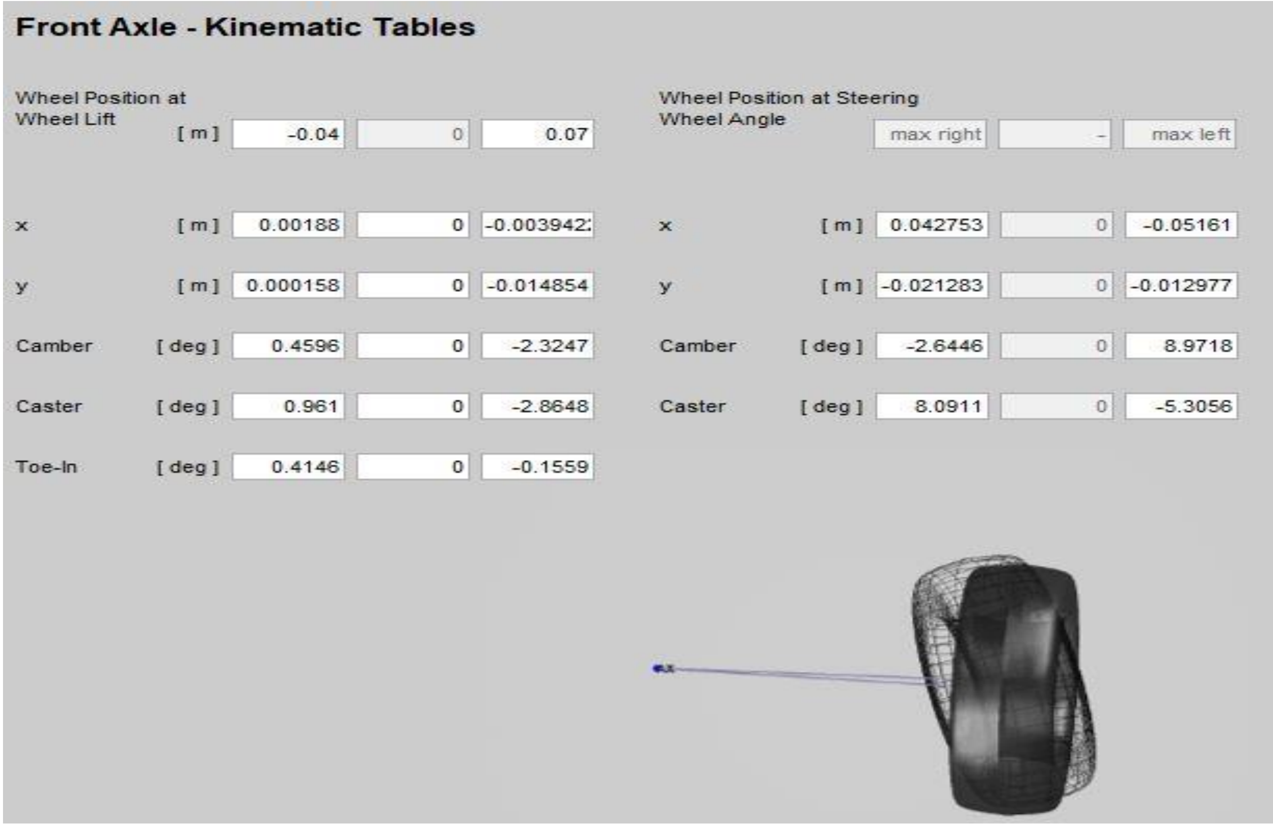

Figure 37. Front axle - kinematic tables

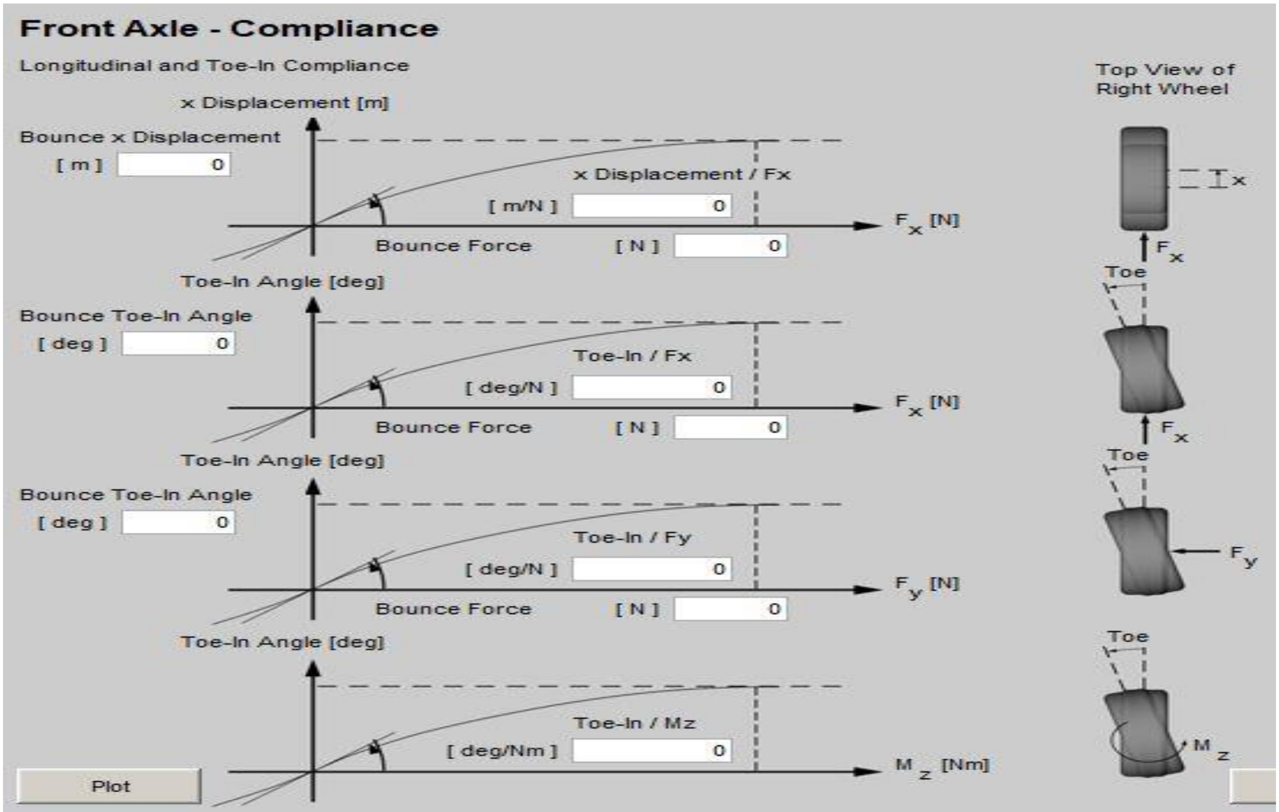

Figure 38. Front axle - compliance

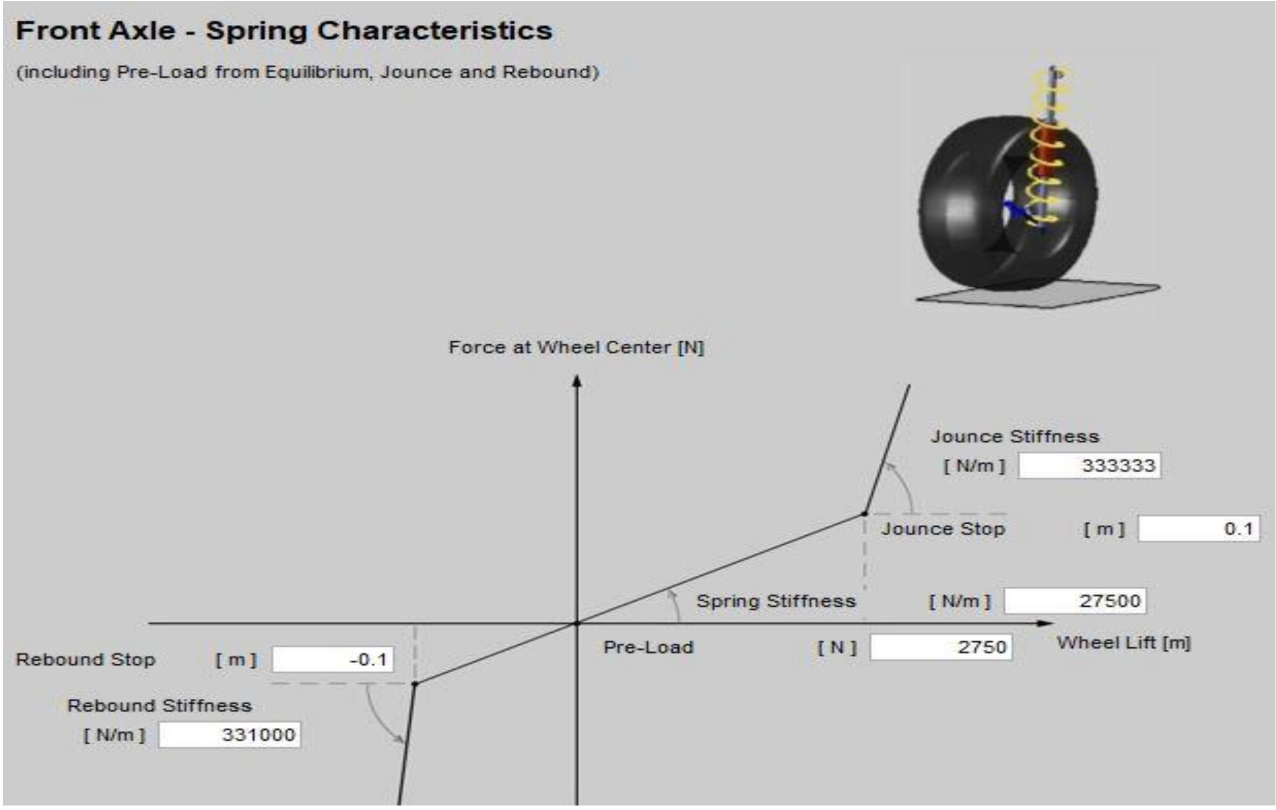

Figure 39. Front axle - spring characteristics

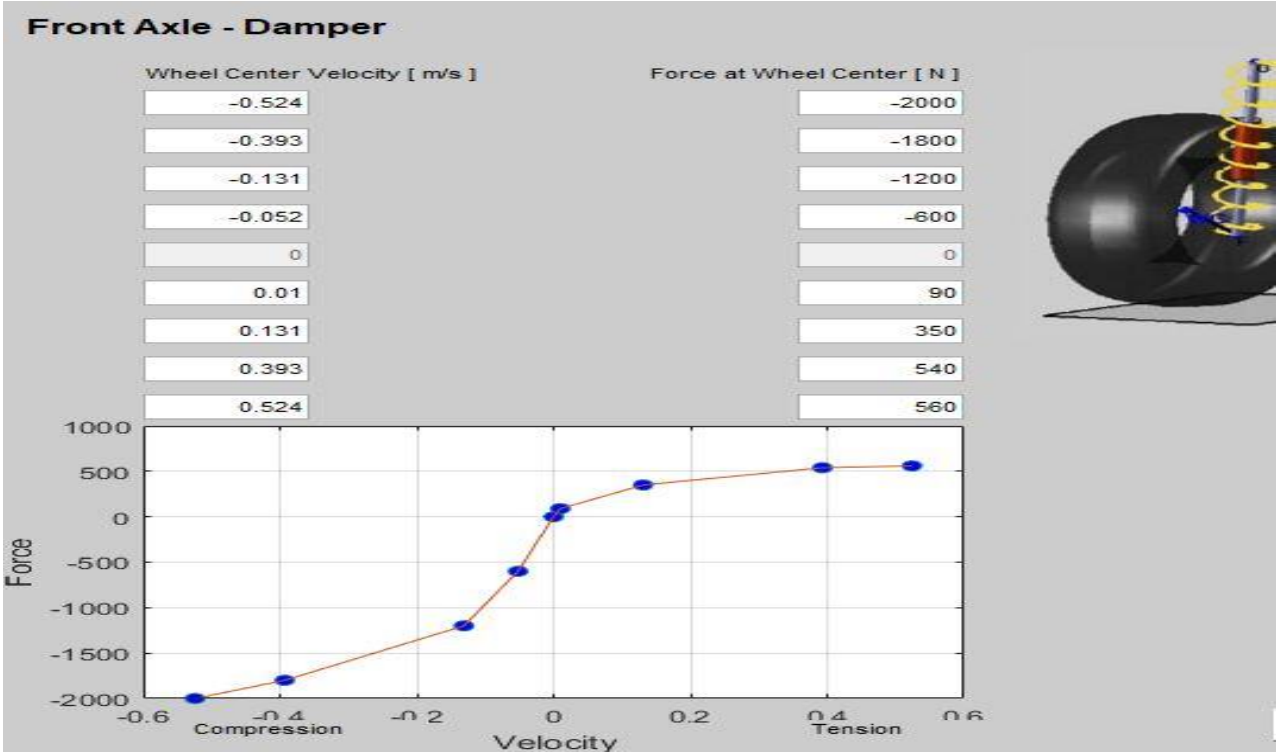

Figure 40. Front axle - damper

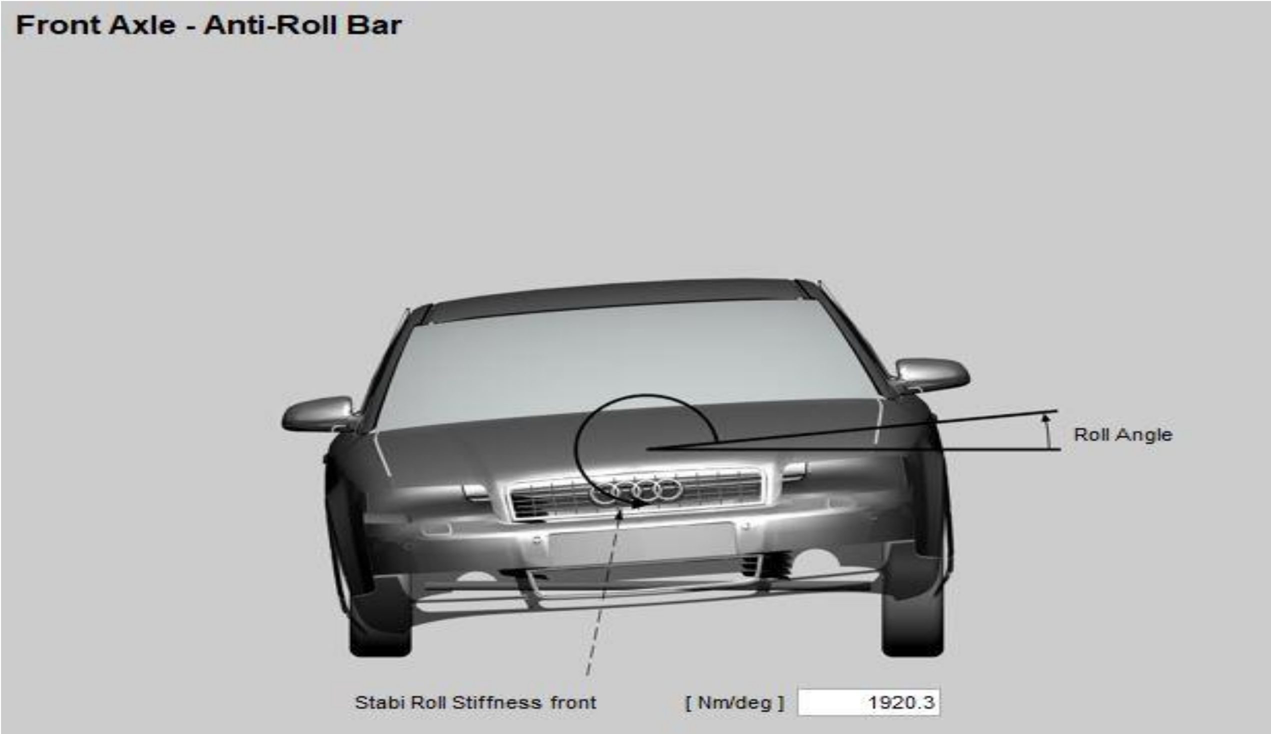

Figure 41. Front axle - anti-roll bar

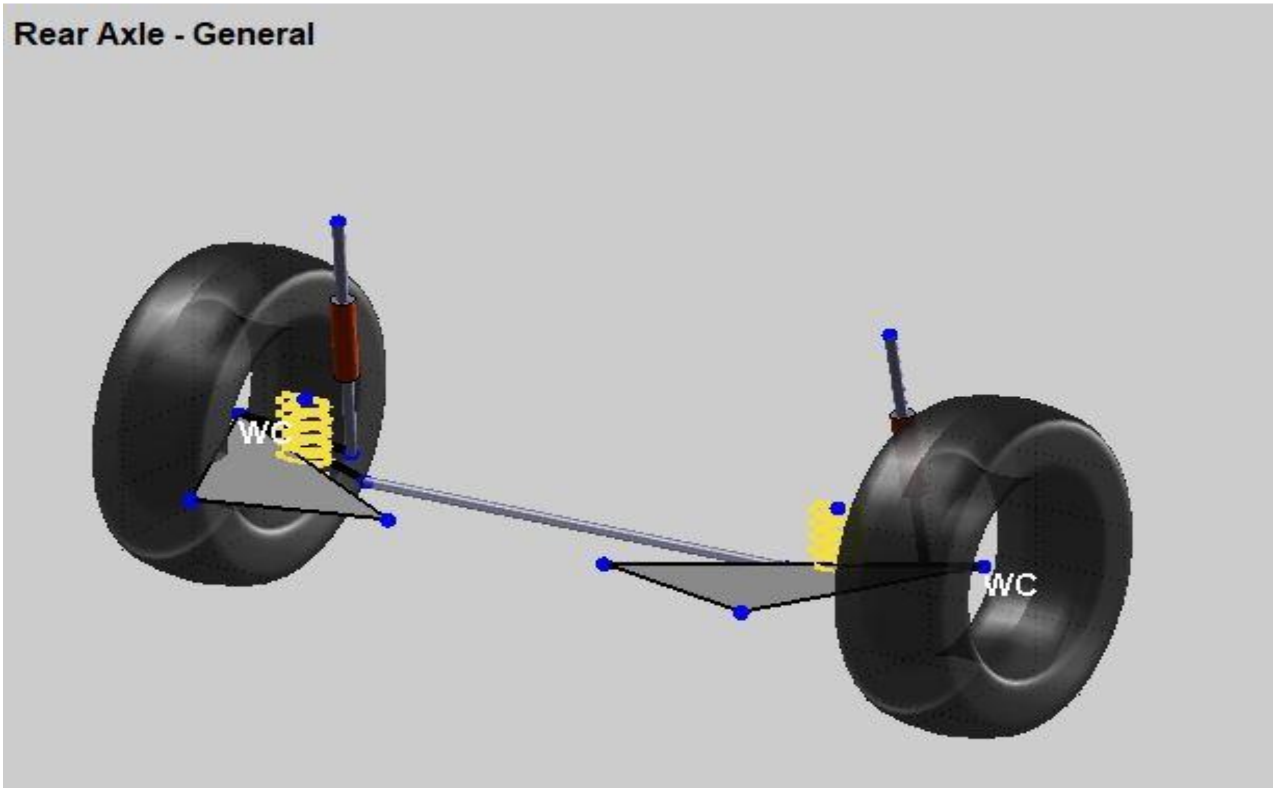

Figure 42. Rear axle - general

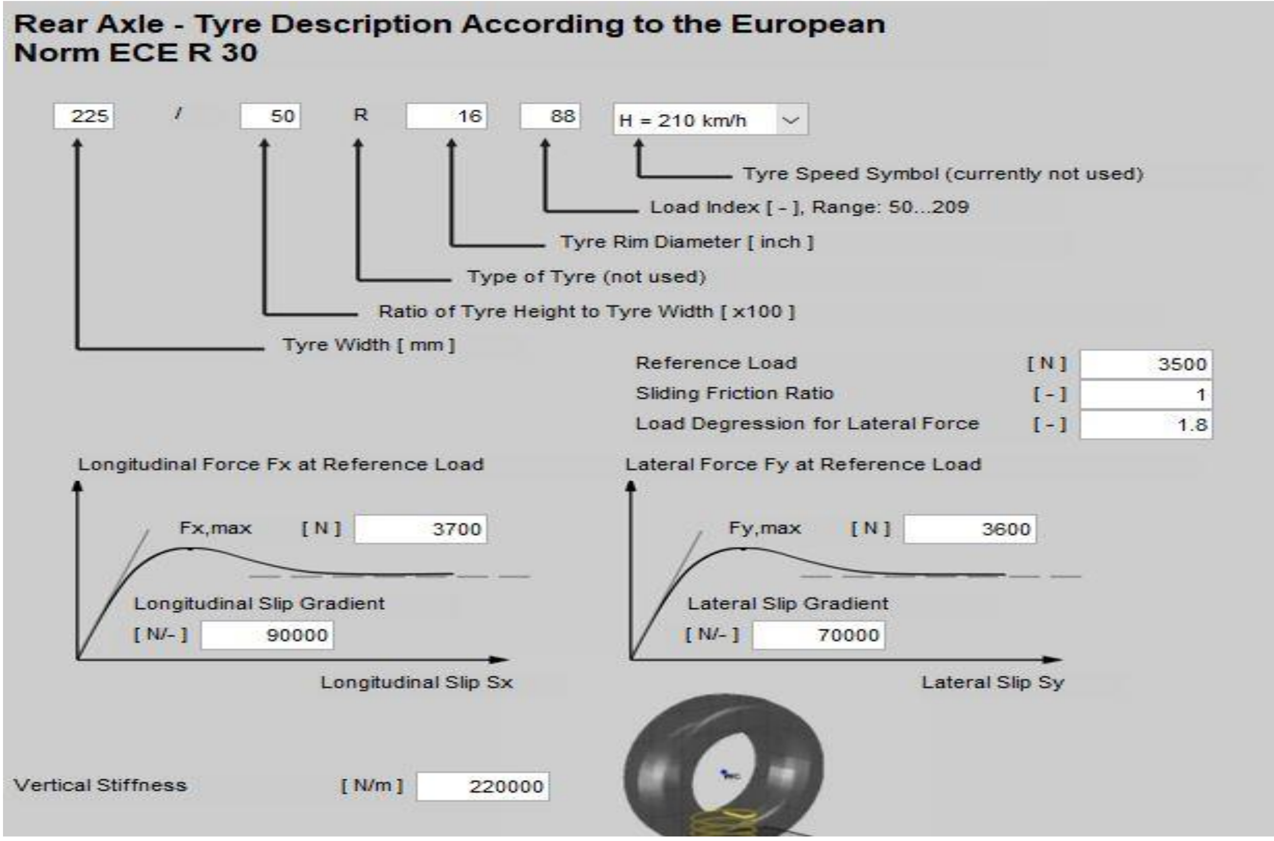

Figure 43. Rear axle - tyre description

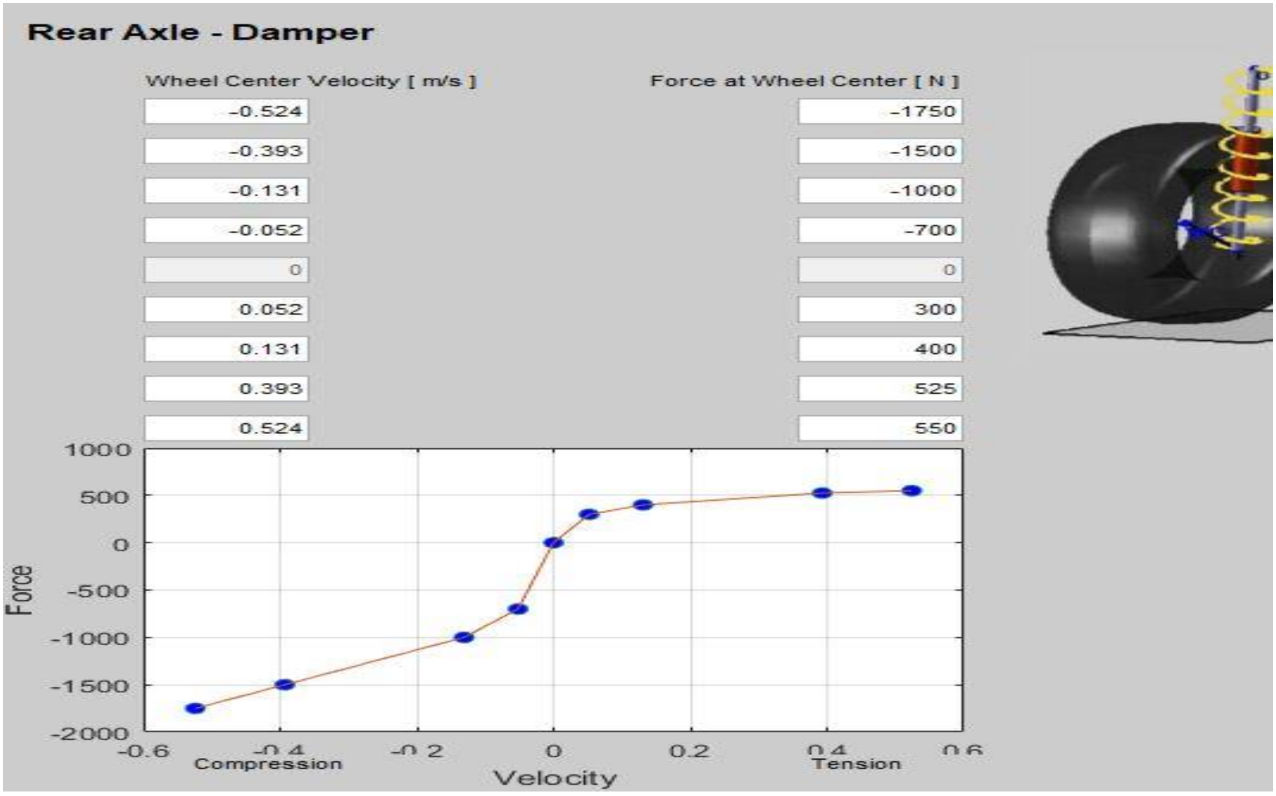

Figure 44. Rear axle - damper

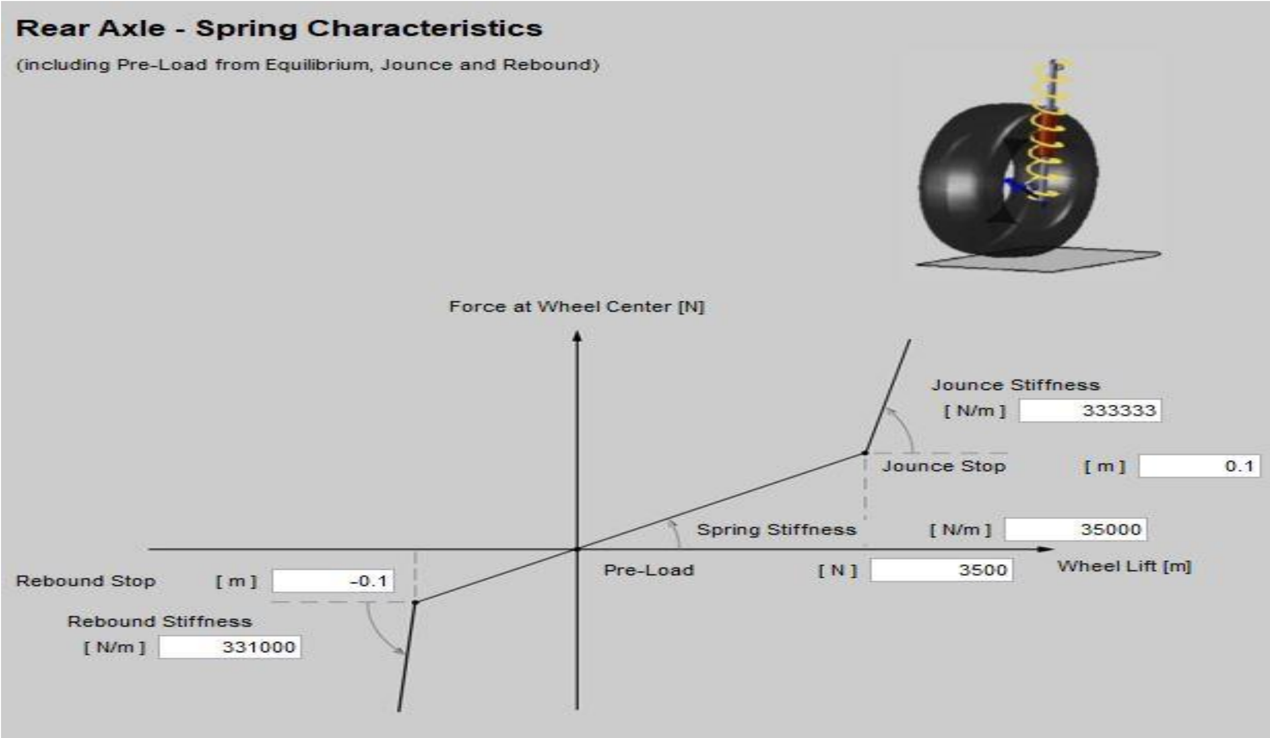

Figure 45. Rear axle - spring characteristics

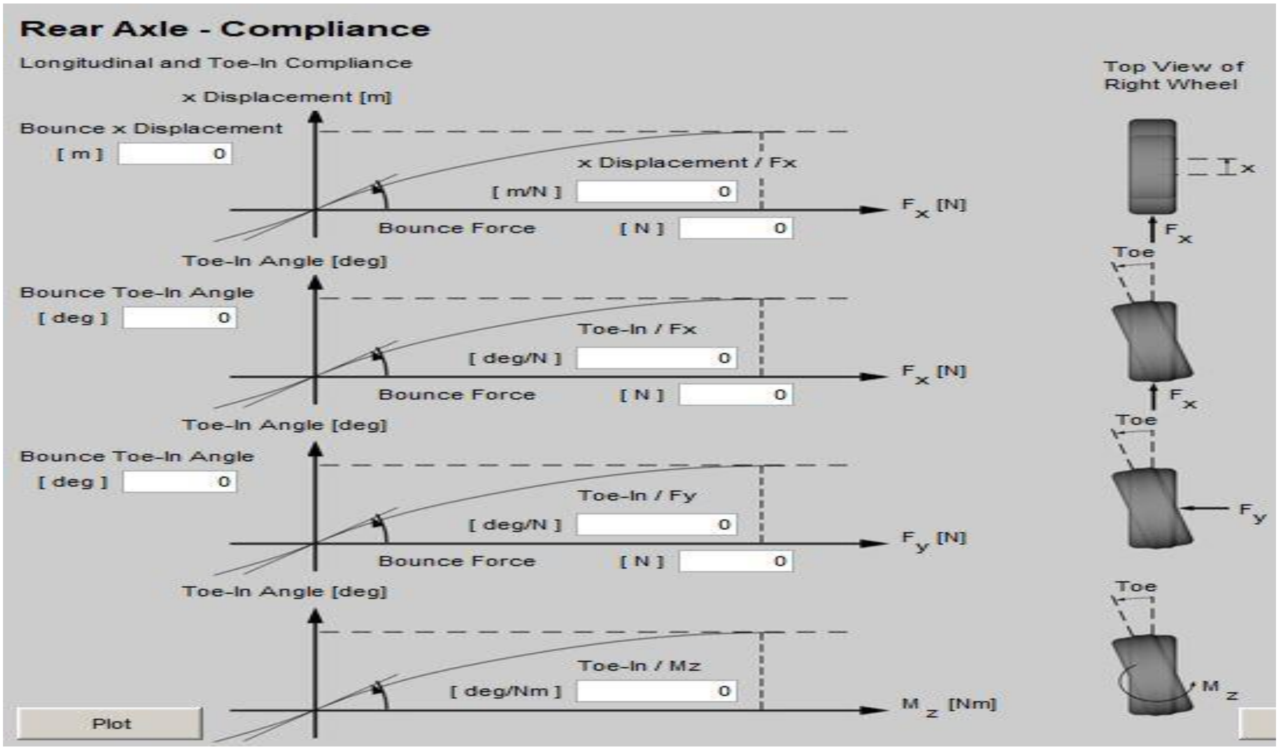

Figure 46. Rear axle - compliance

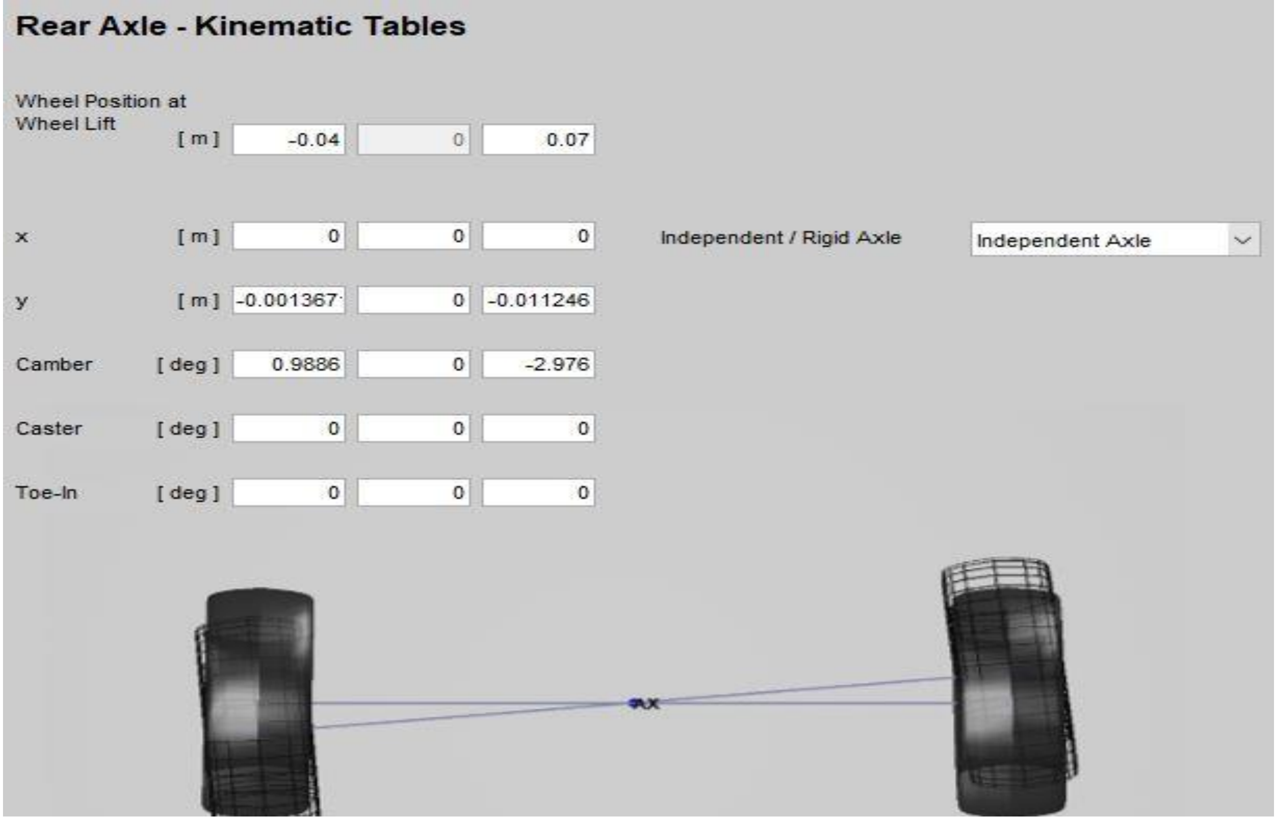

Figure 47. Rear axle - kinematic tables

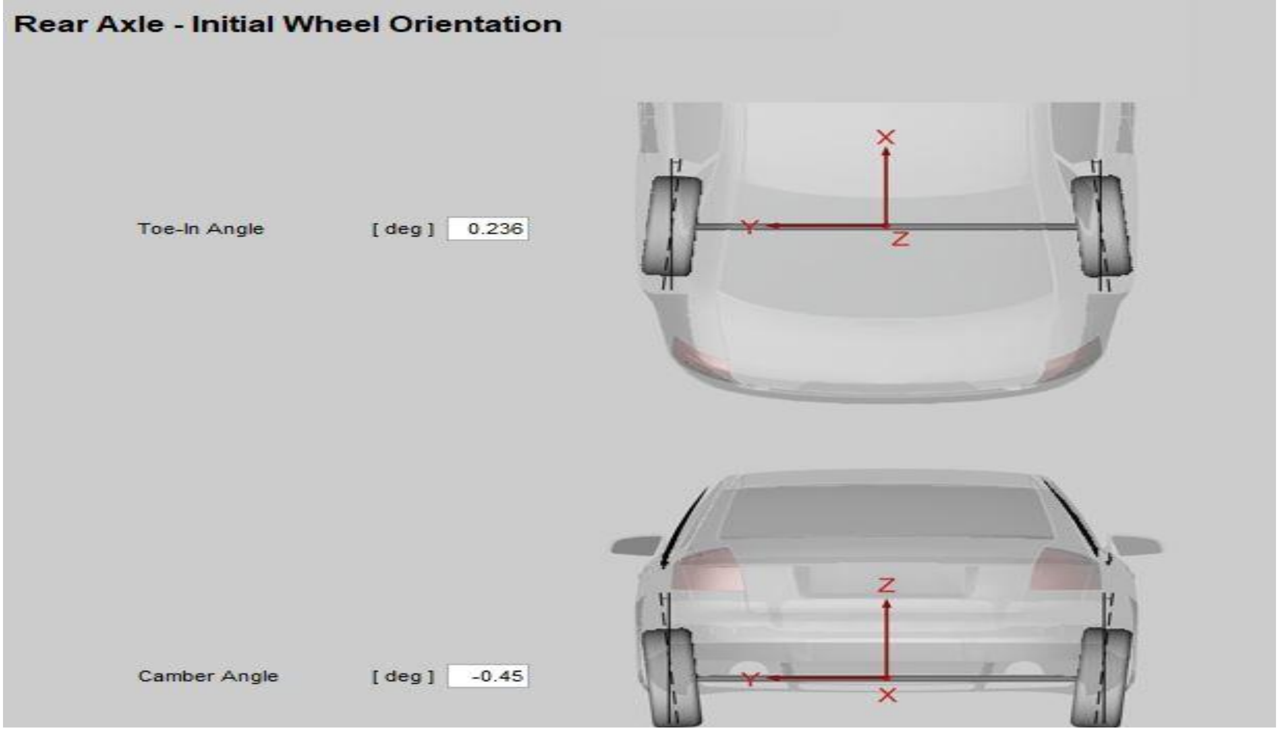

Figure 48. Rear axle - initial wheel orientation

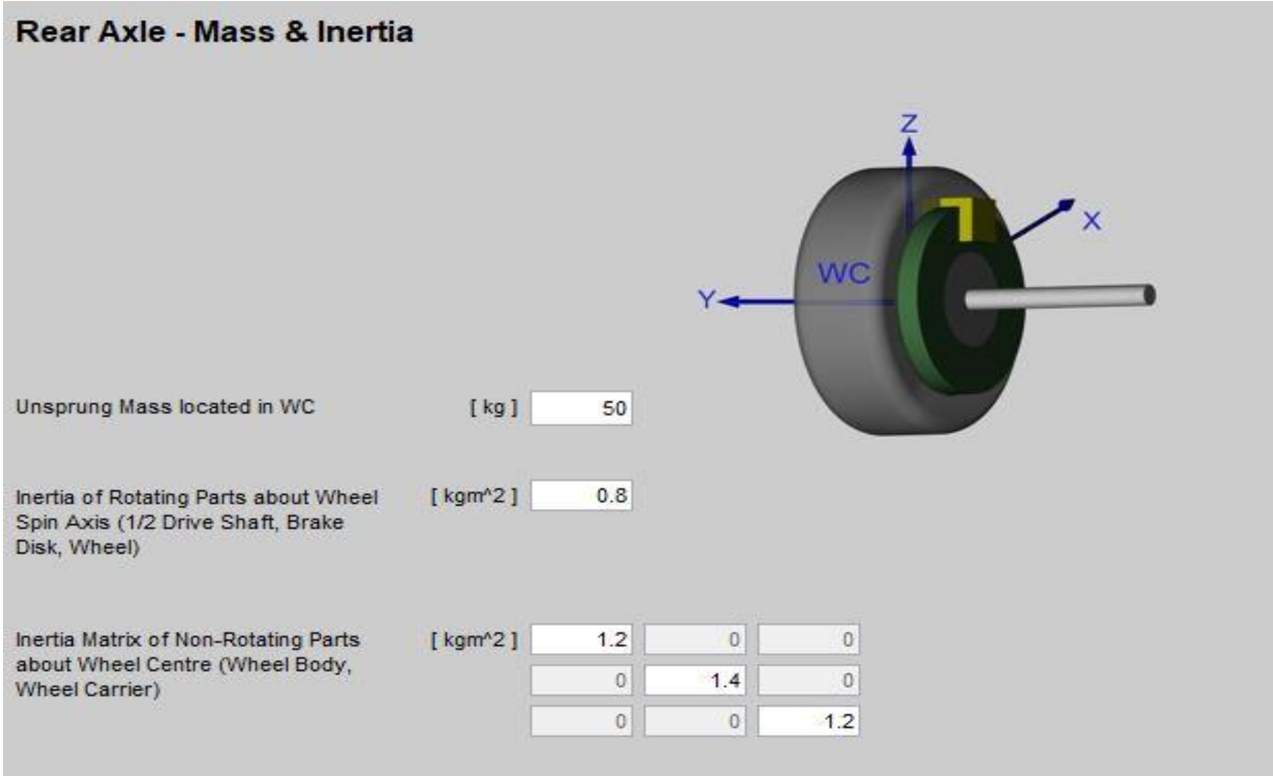

Figure 49. Rear axle - mass and inertia

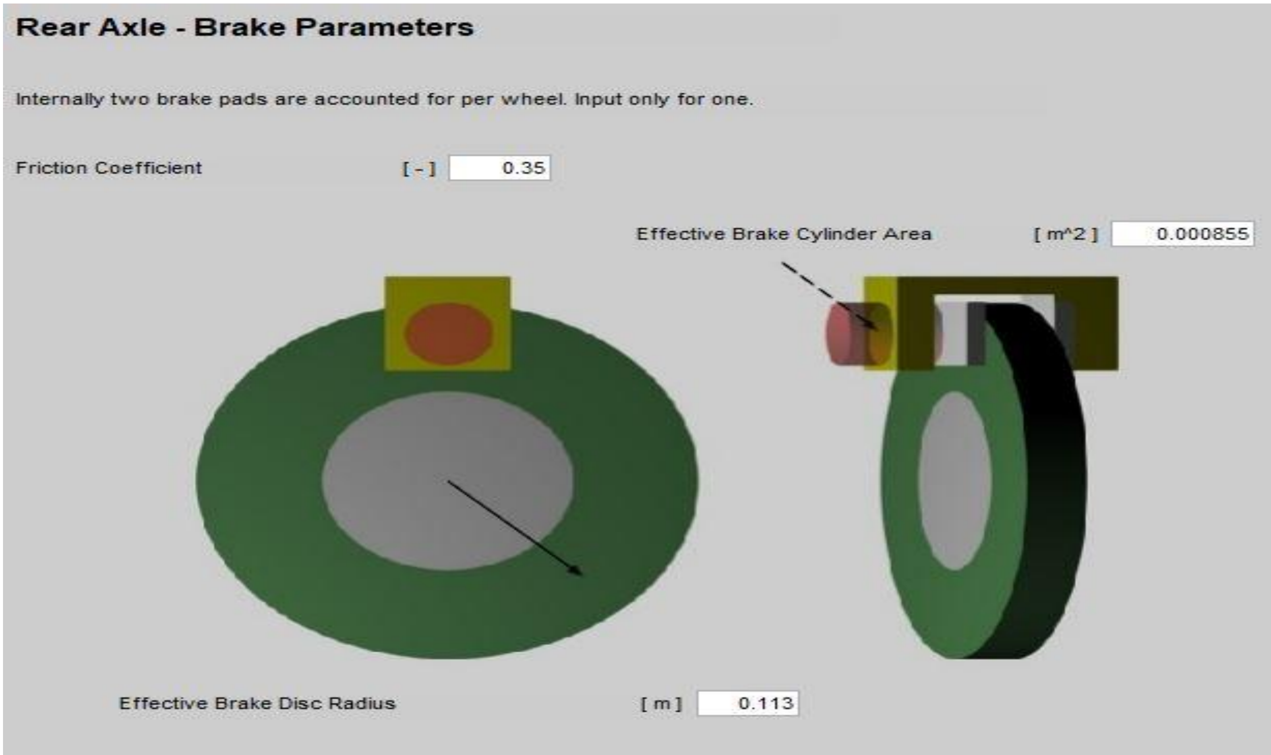

Figure 50. Rear axle - brake parameters

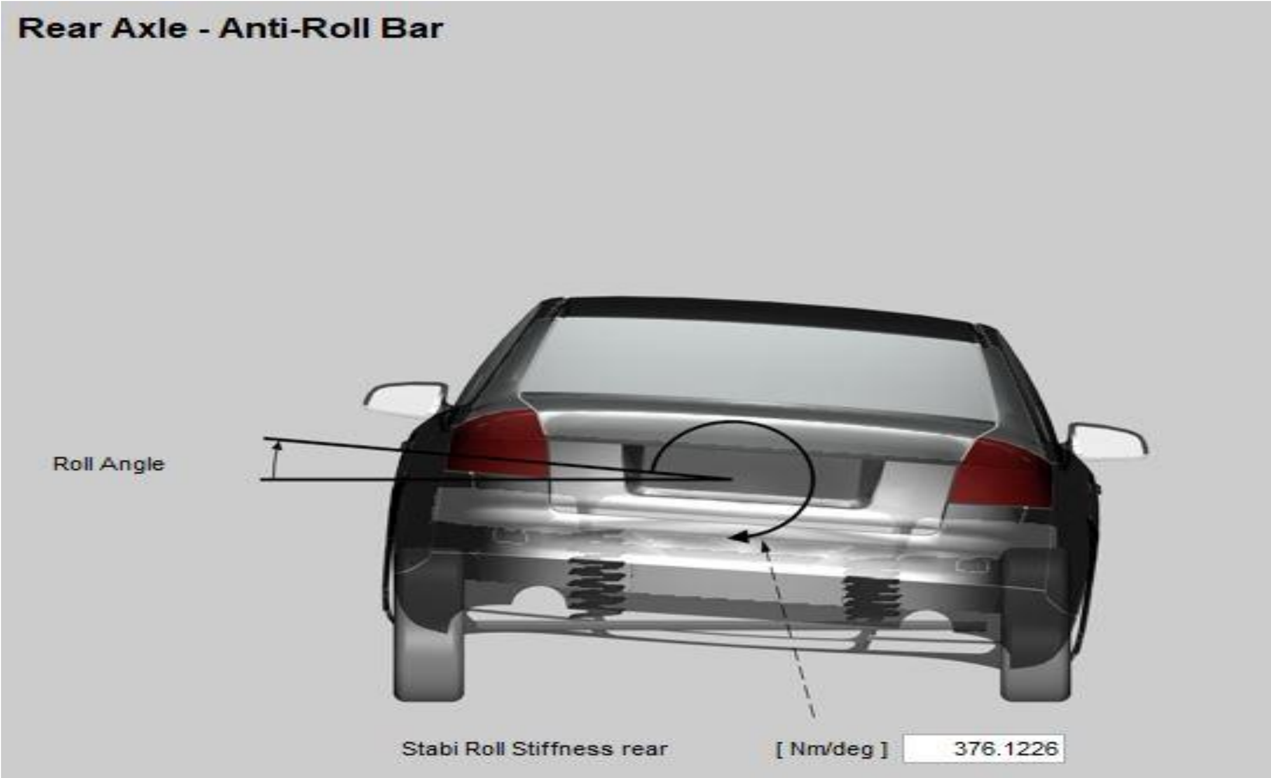

Figure 51. Rear axle - anti-roll bar

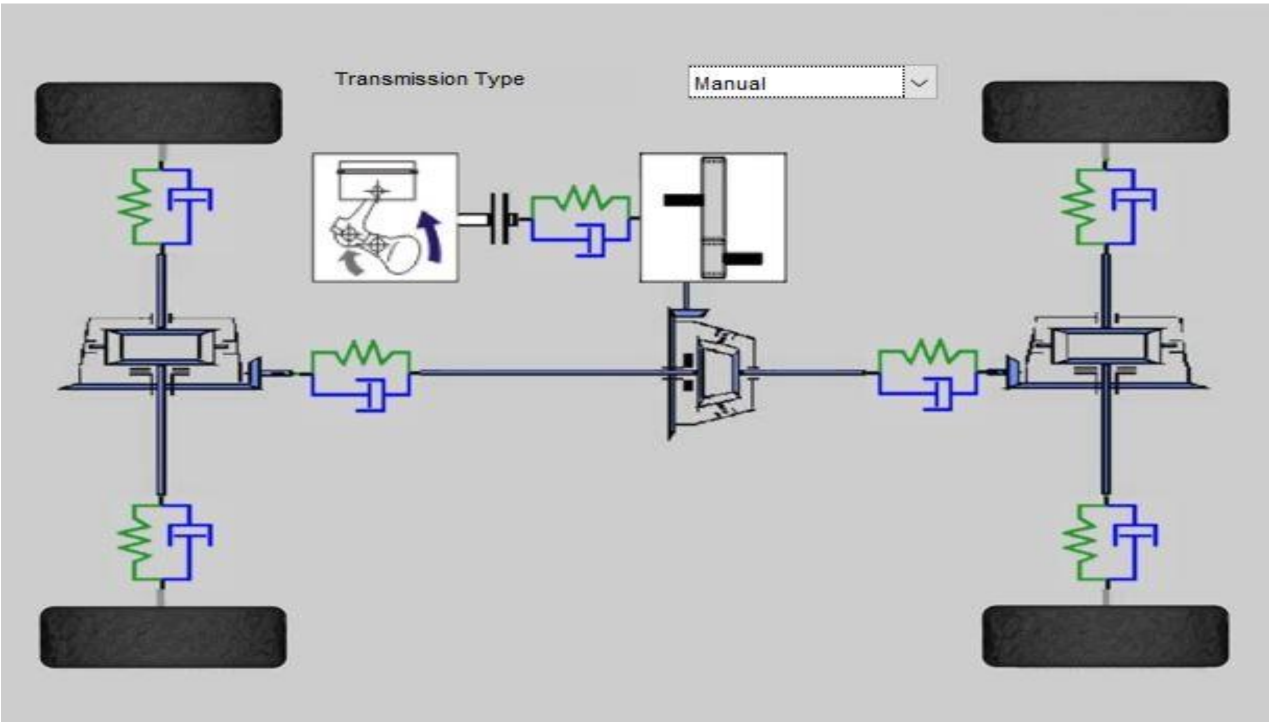

Figure 52. Drivetrain - engine - transmission - manual

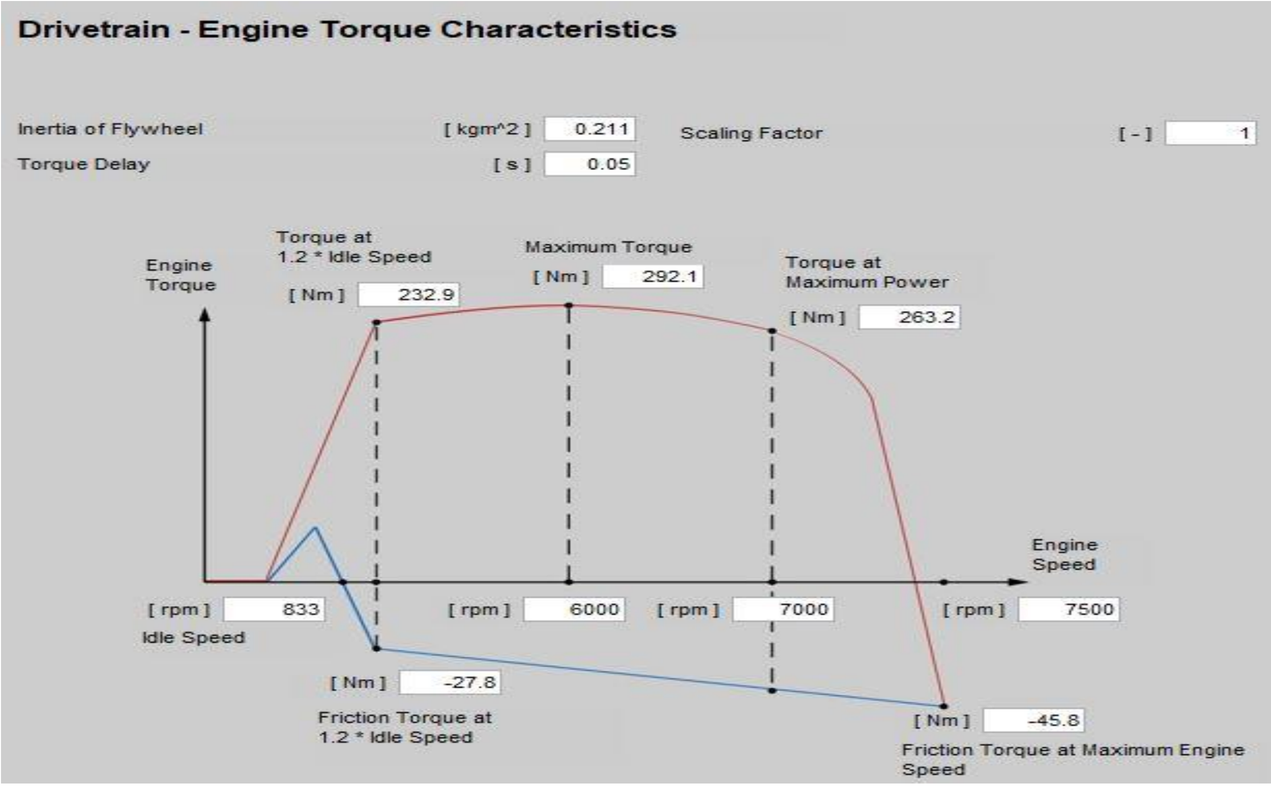

Figure 53. Drivetrain - engine torque characteristics

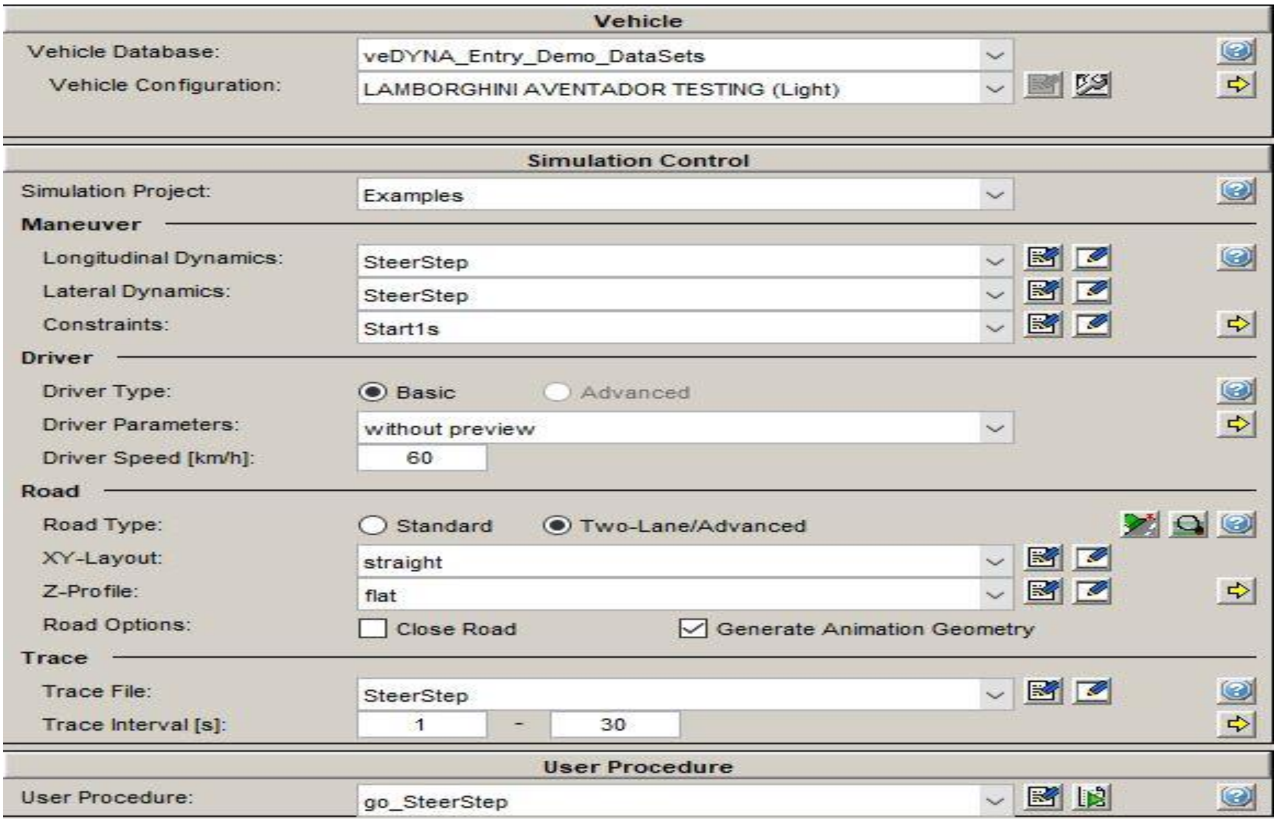

Figure 54. Steerstep - simulation control

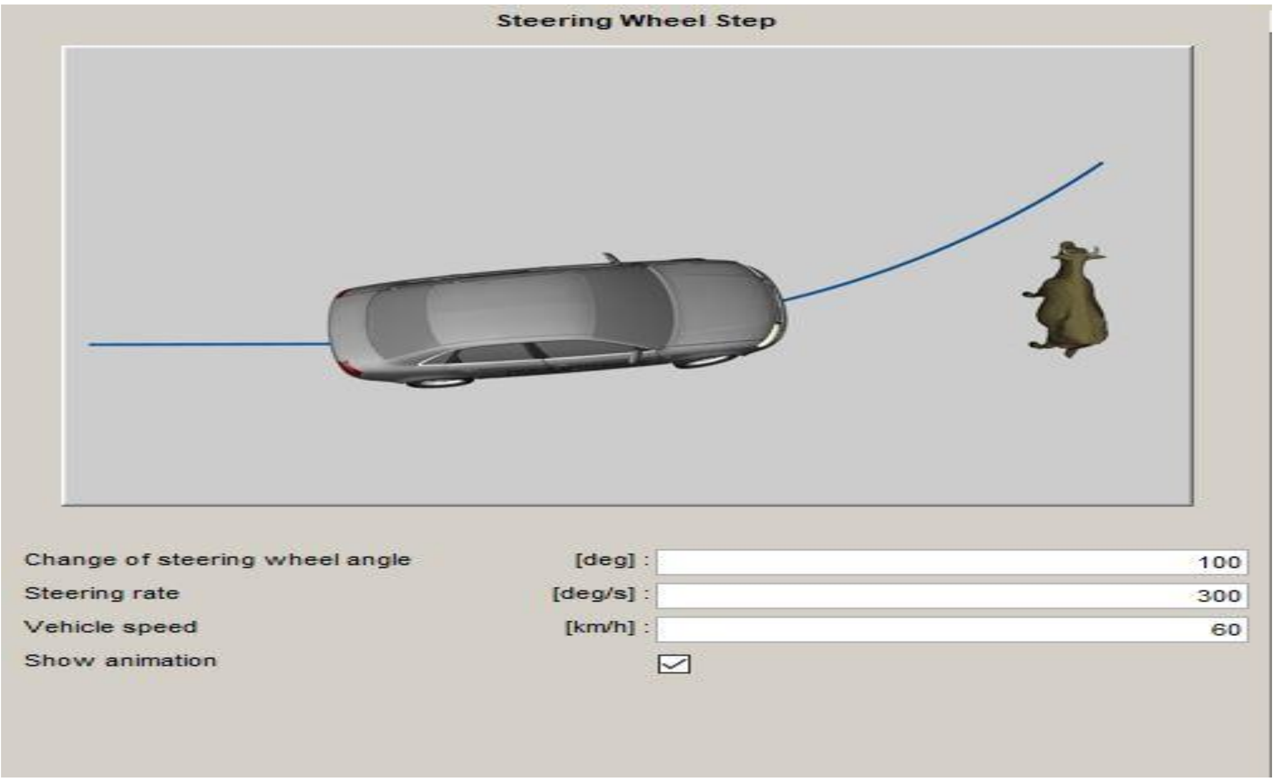

Figure 55. Steerstep - user procedure

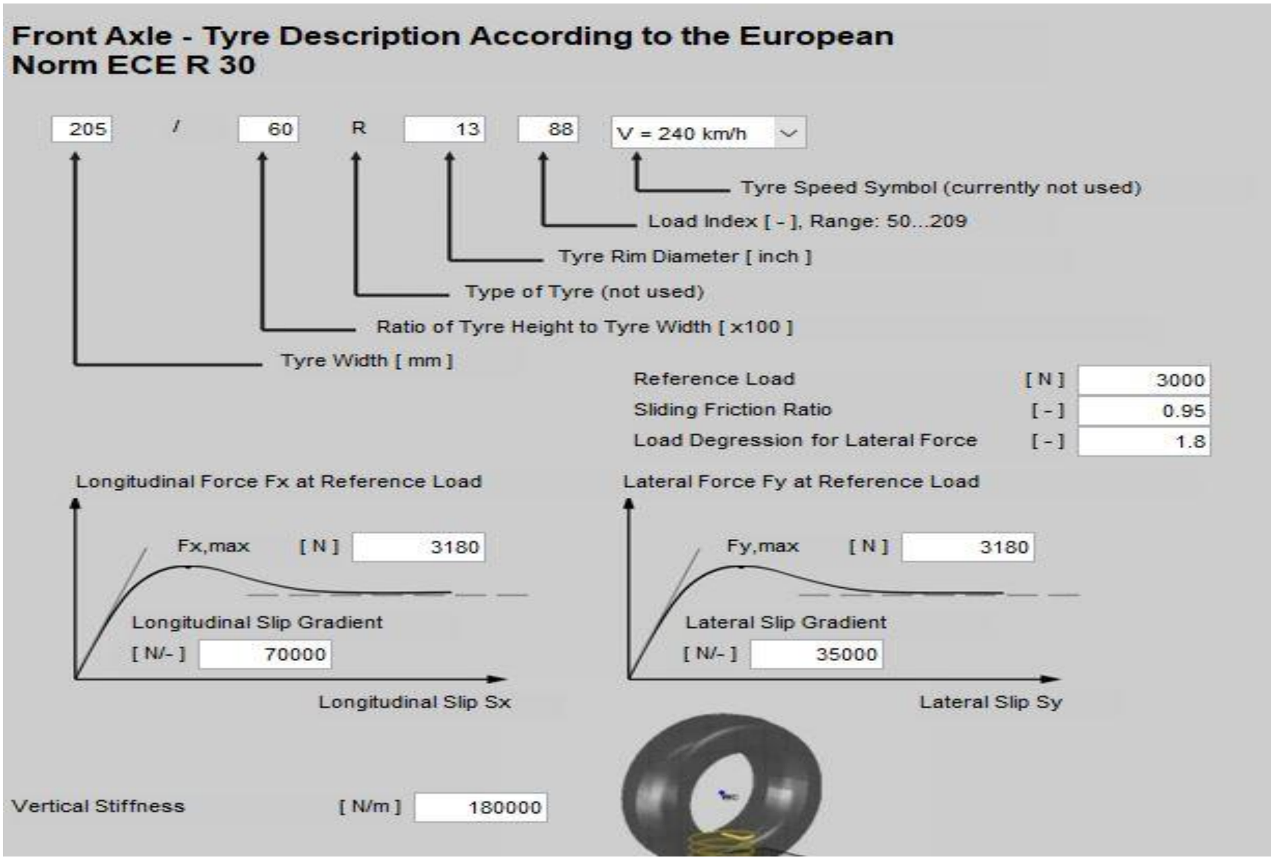

Figure 56. Steerstep - front axle force 3180 N

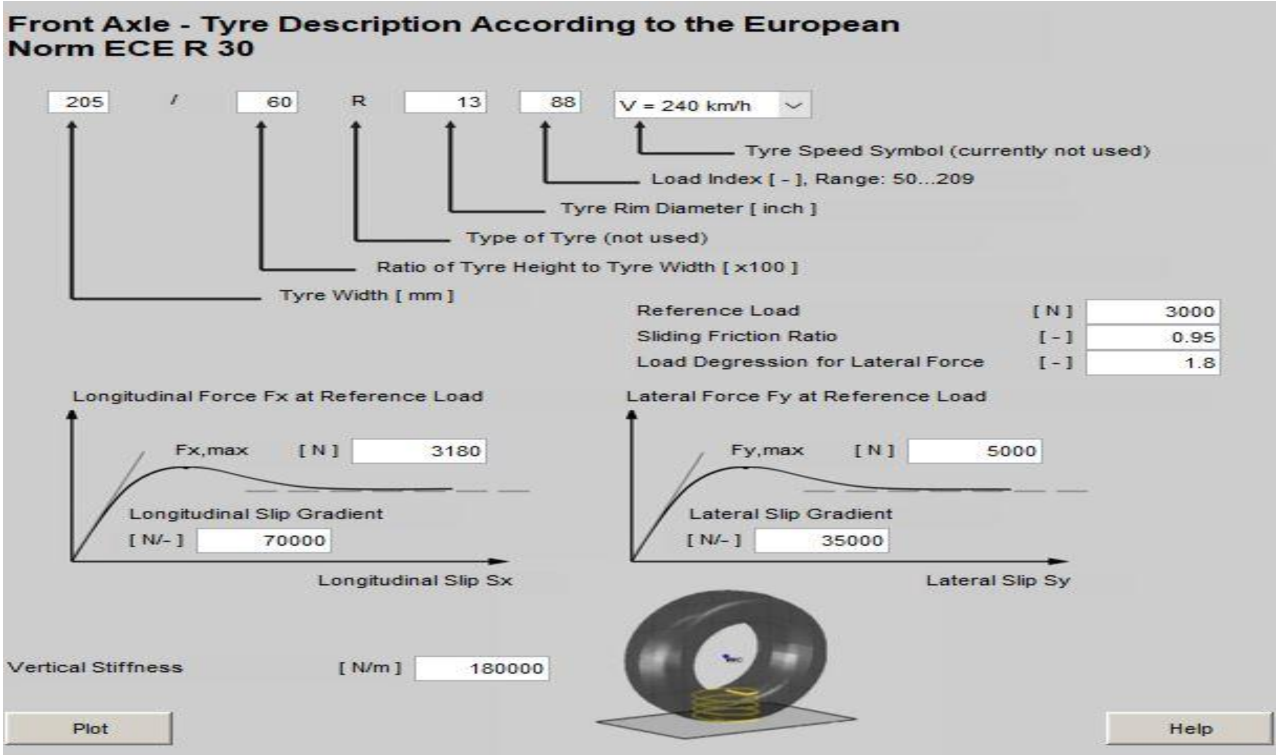

Figure 57. Steerstep - front axle force 5000 N

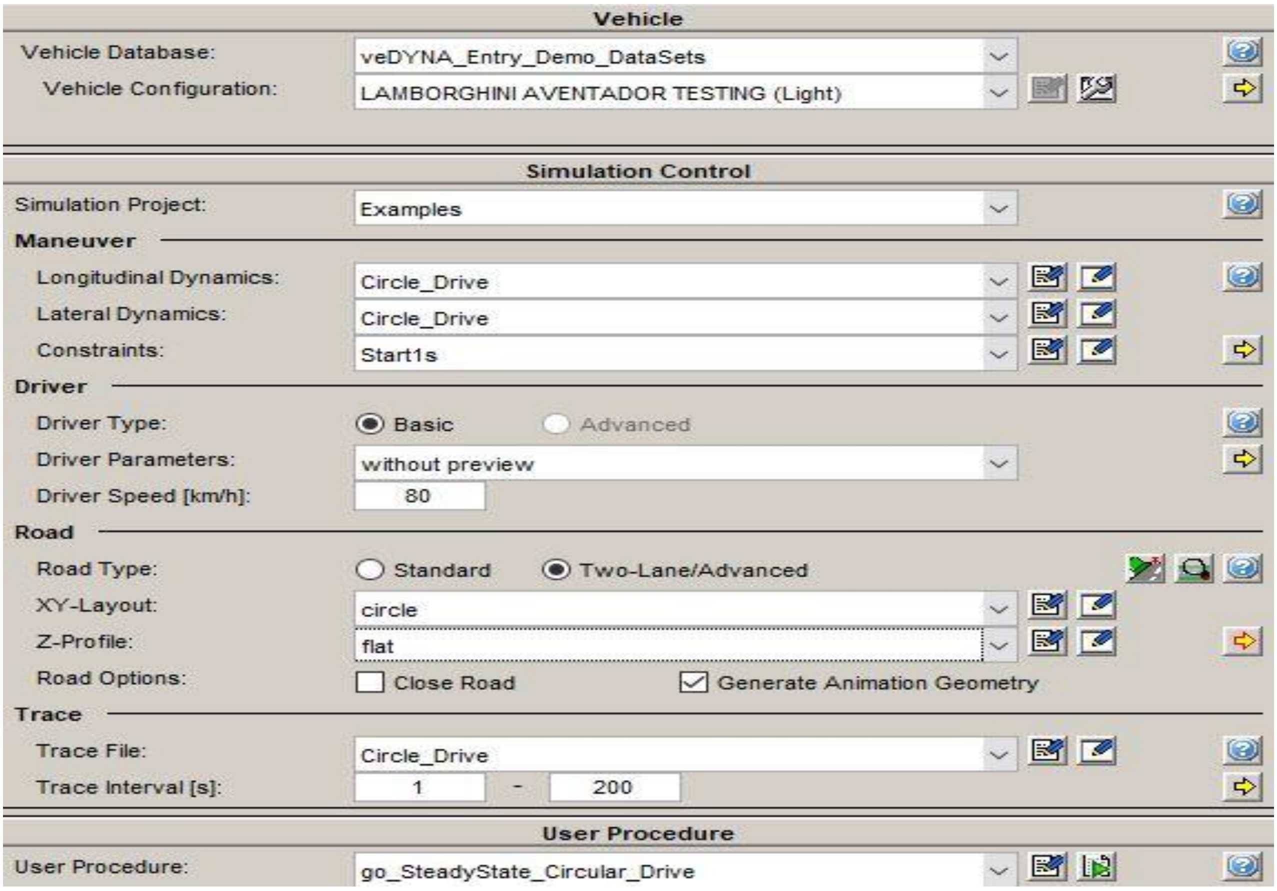

Figure 58. Circle drive - simulation control

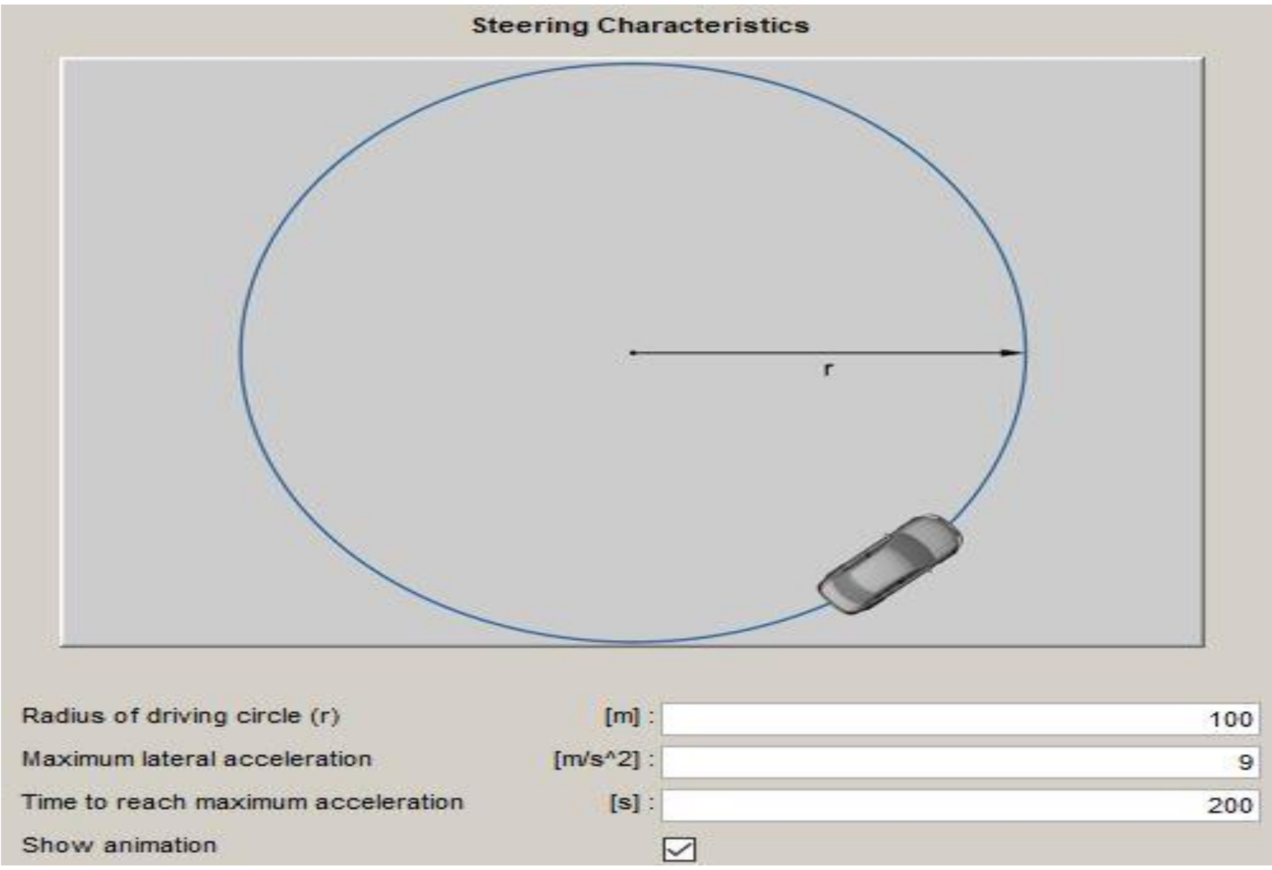

Figure 59. Circle drive - user procedure

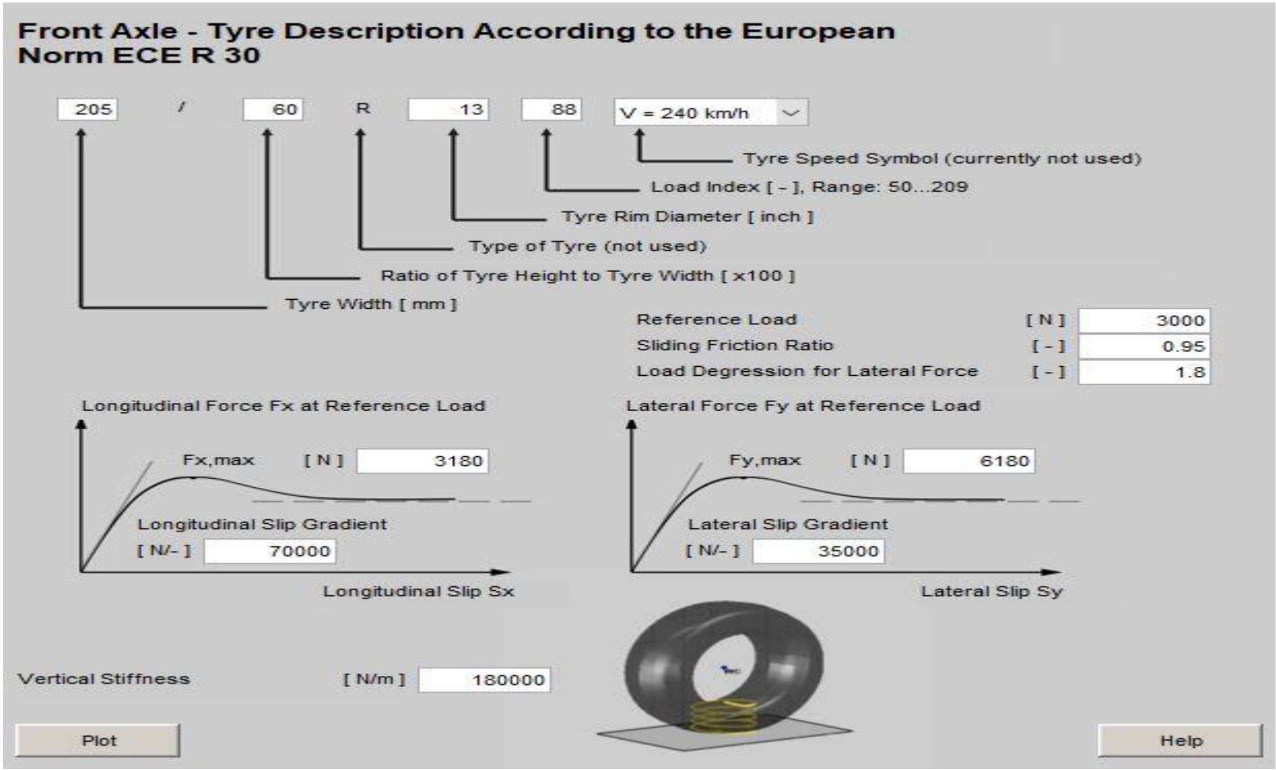

Figure 60. Circle drive - front axle more force (oversteer)

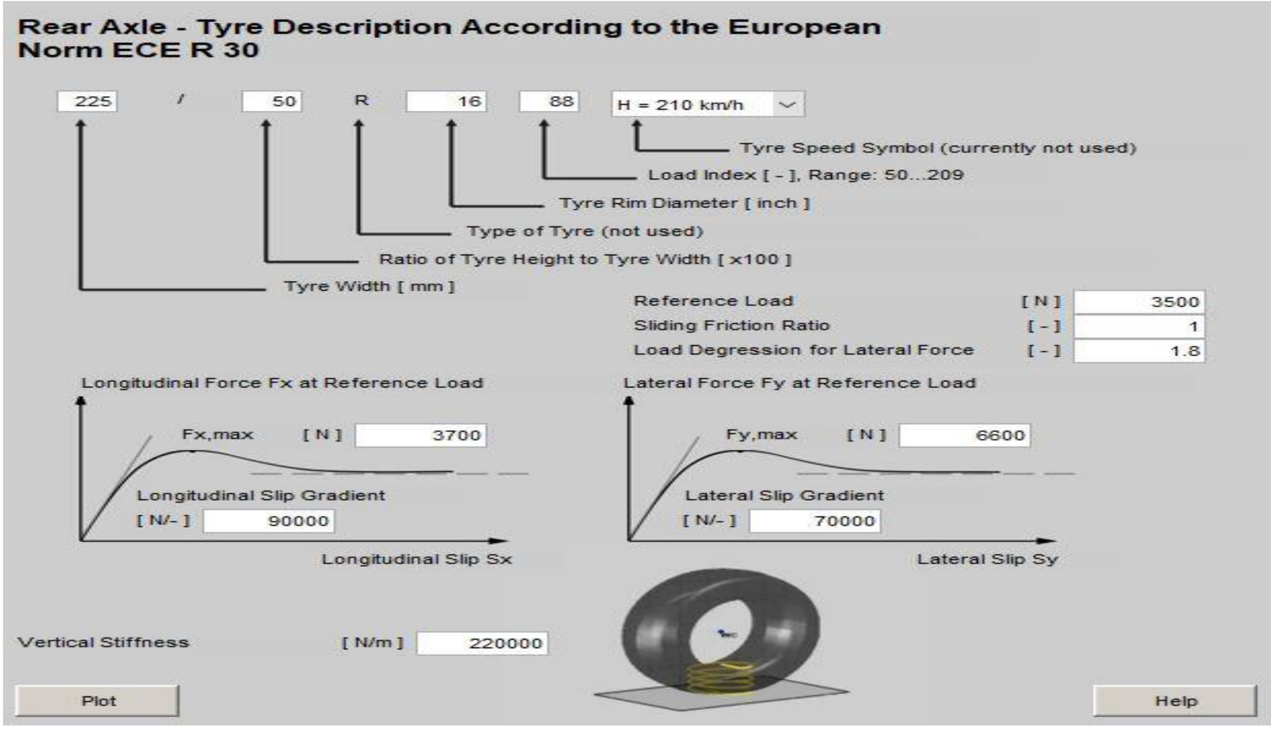

Figure 61. Circle drive - rear axle more force (understeer)

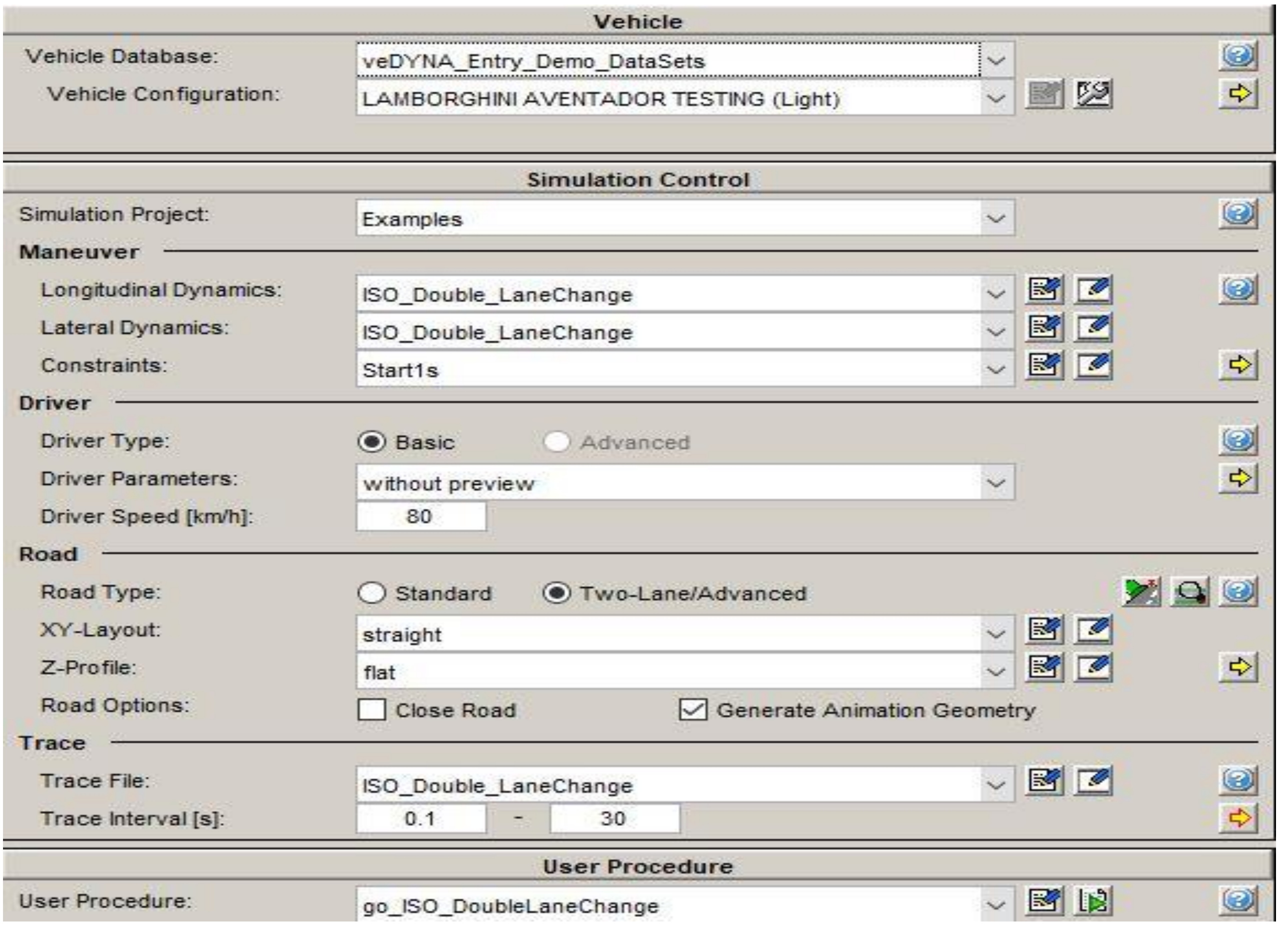

Figure 62. Double lane change - simulation control

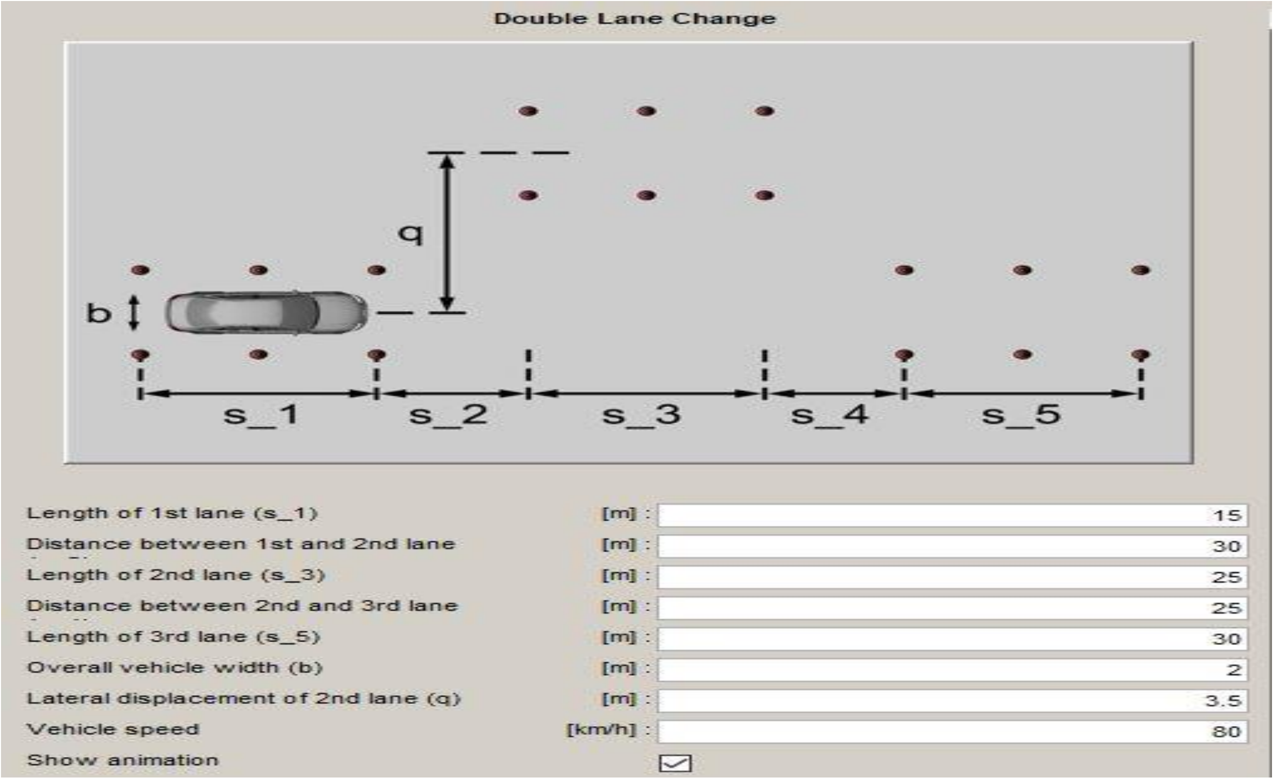

Figure 63. Double lane change 80 km/h - user Procedure

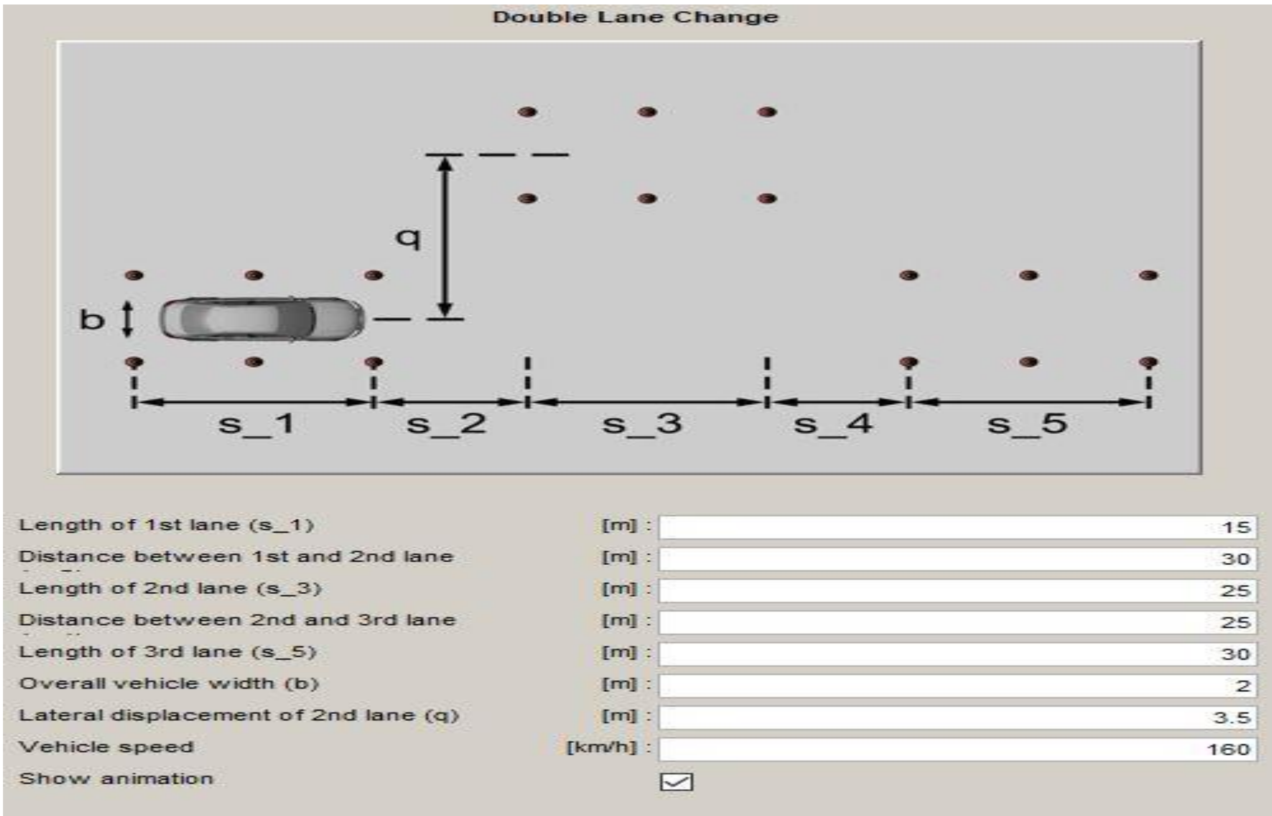

Figure 64. Double lane change 160 km/h - user procedure

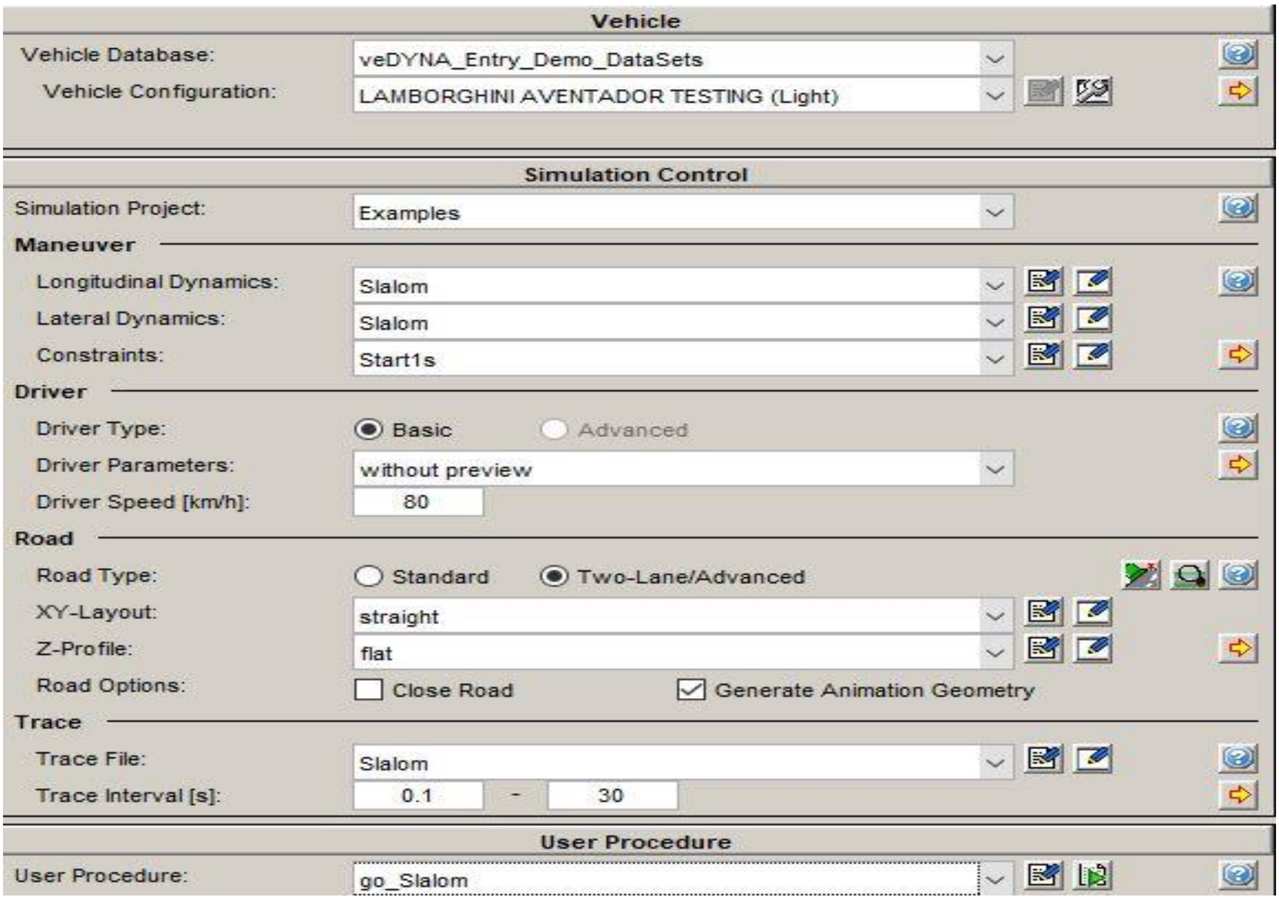

Figure 65. Slalom - simulation control

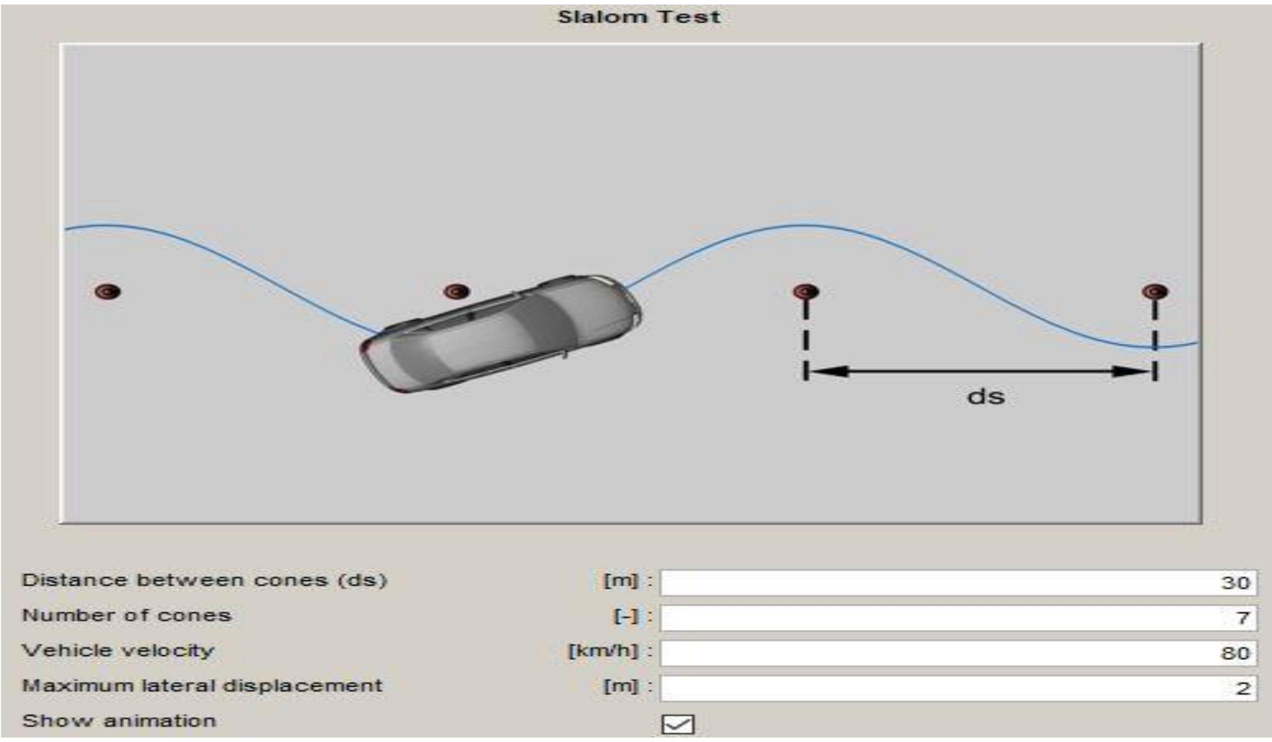

Figure 66. Slalom - user procedure

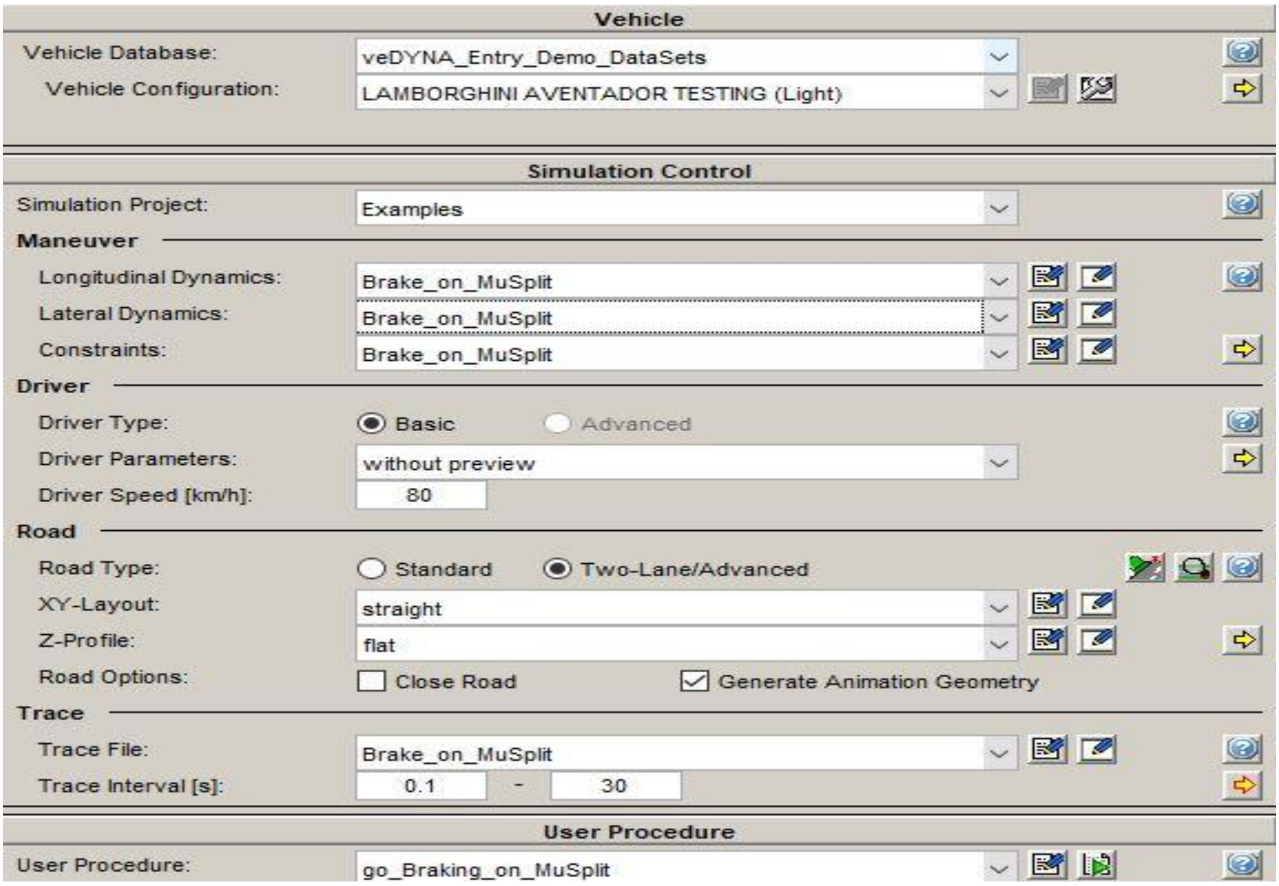

Figure 67. Mu-split - simulation control

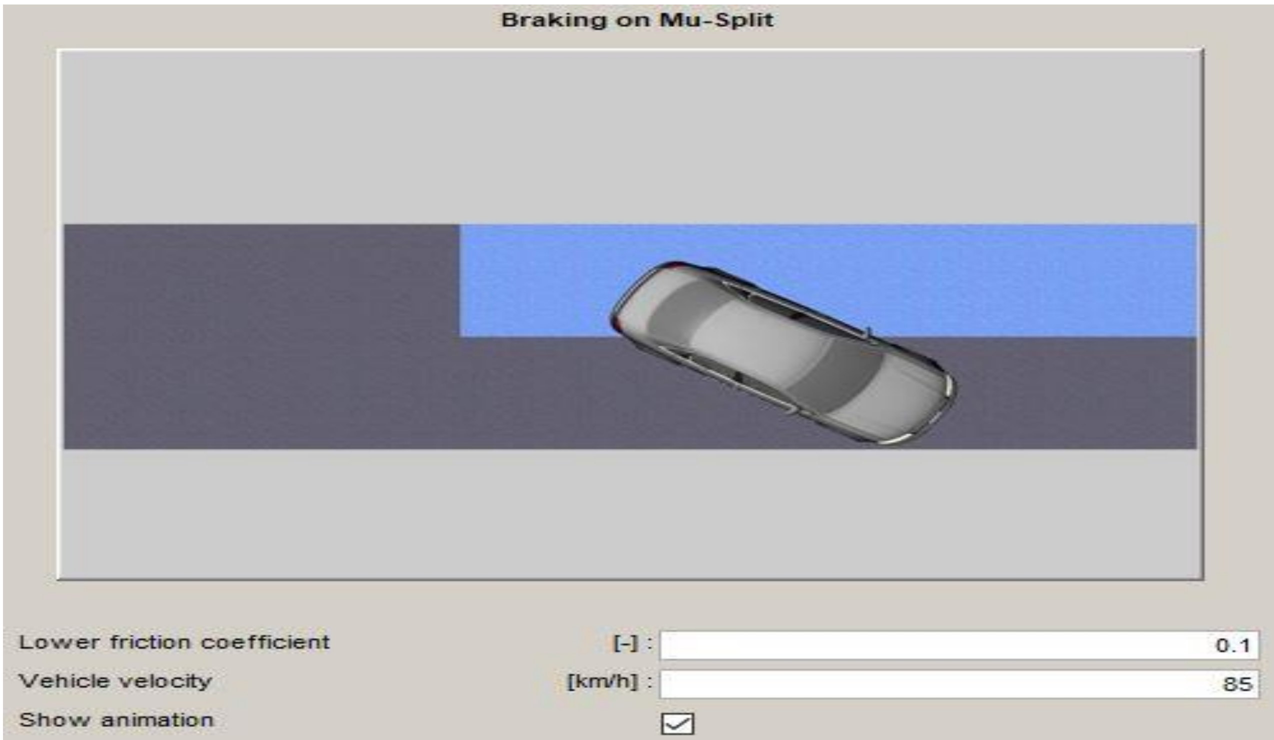

Figure 68. Mu-split - user procedure

Graphs

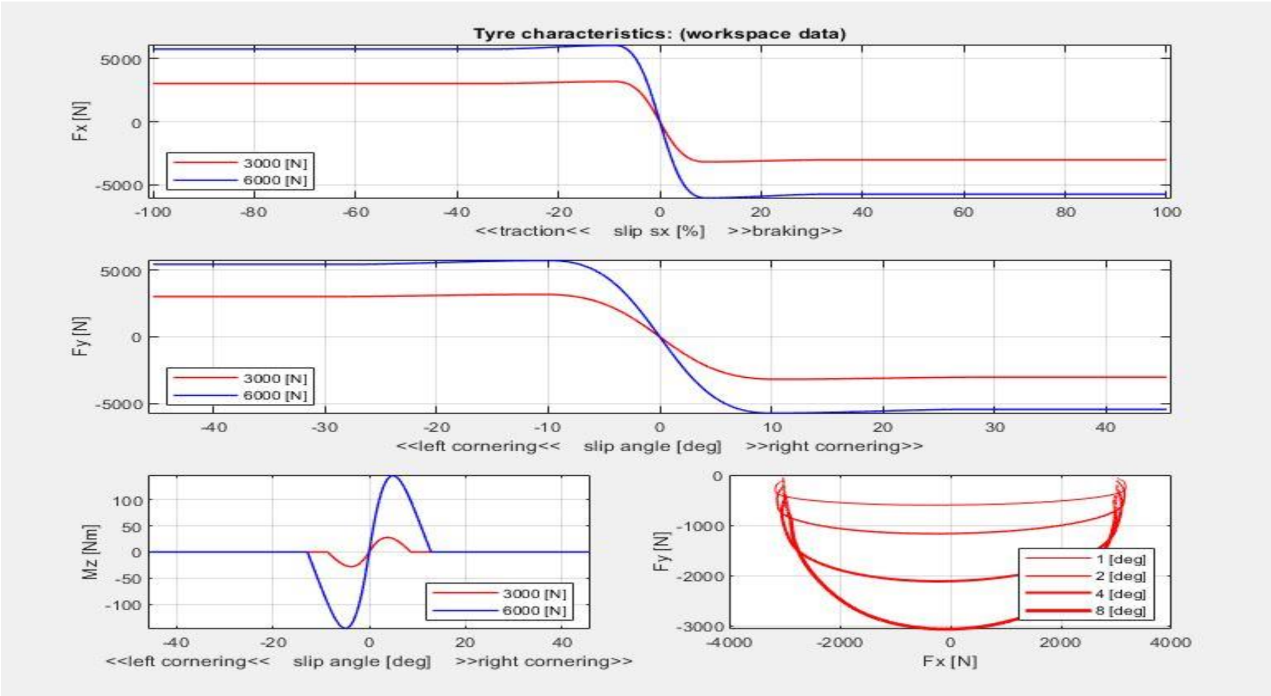

Figure 69. Front tyre characteristics graph

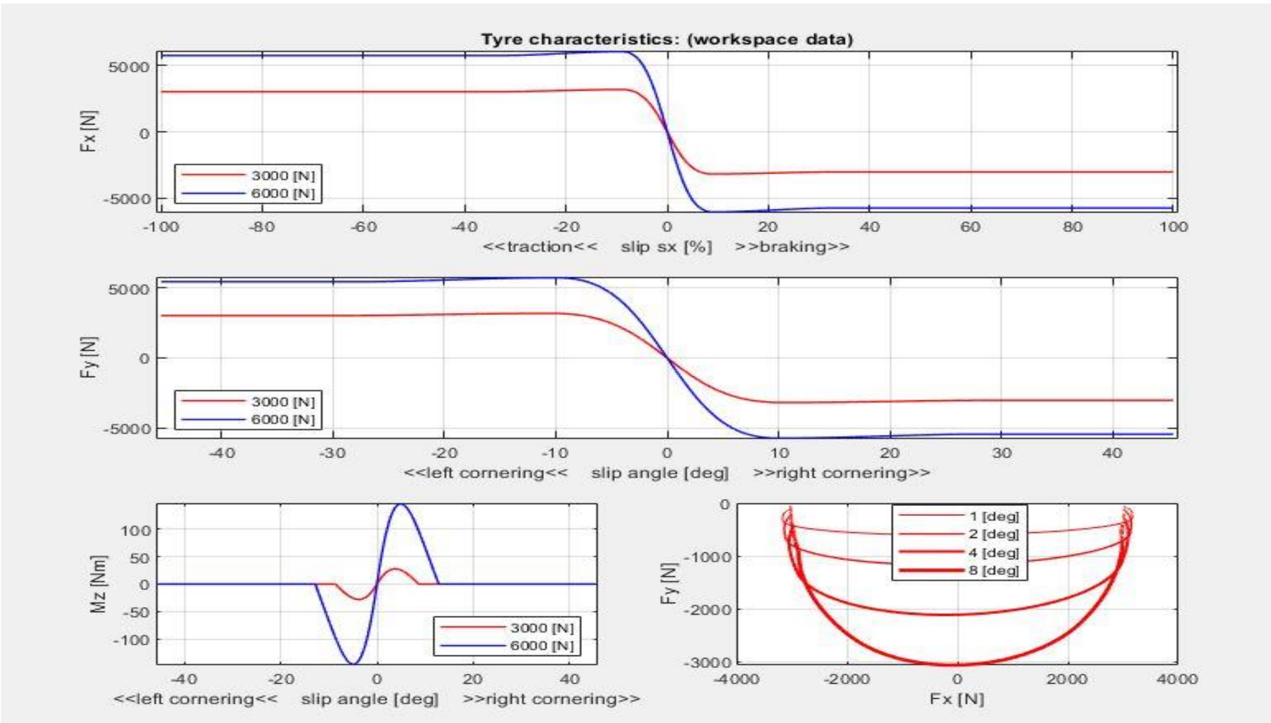

Figure 70. Rear tyre characteristics graph

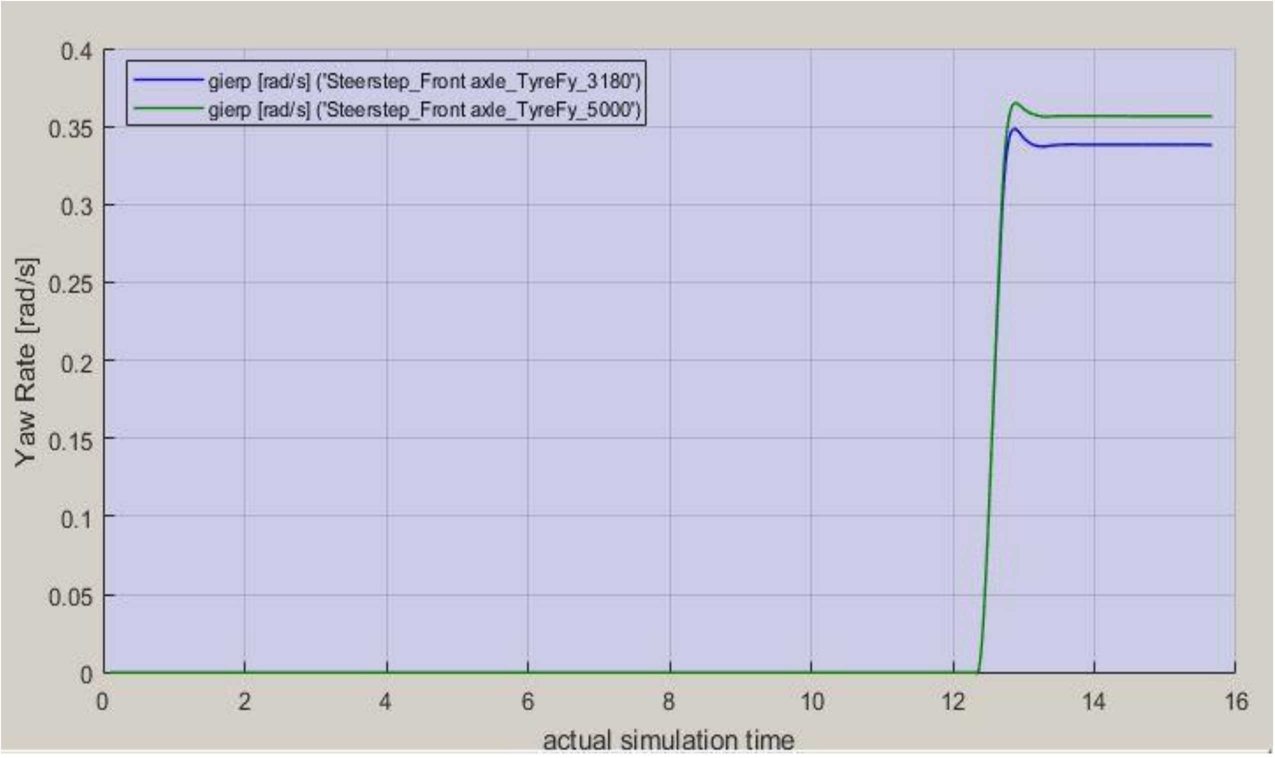

Figure 71. Steerstep yaw rate graph

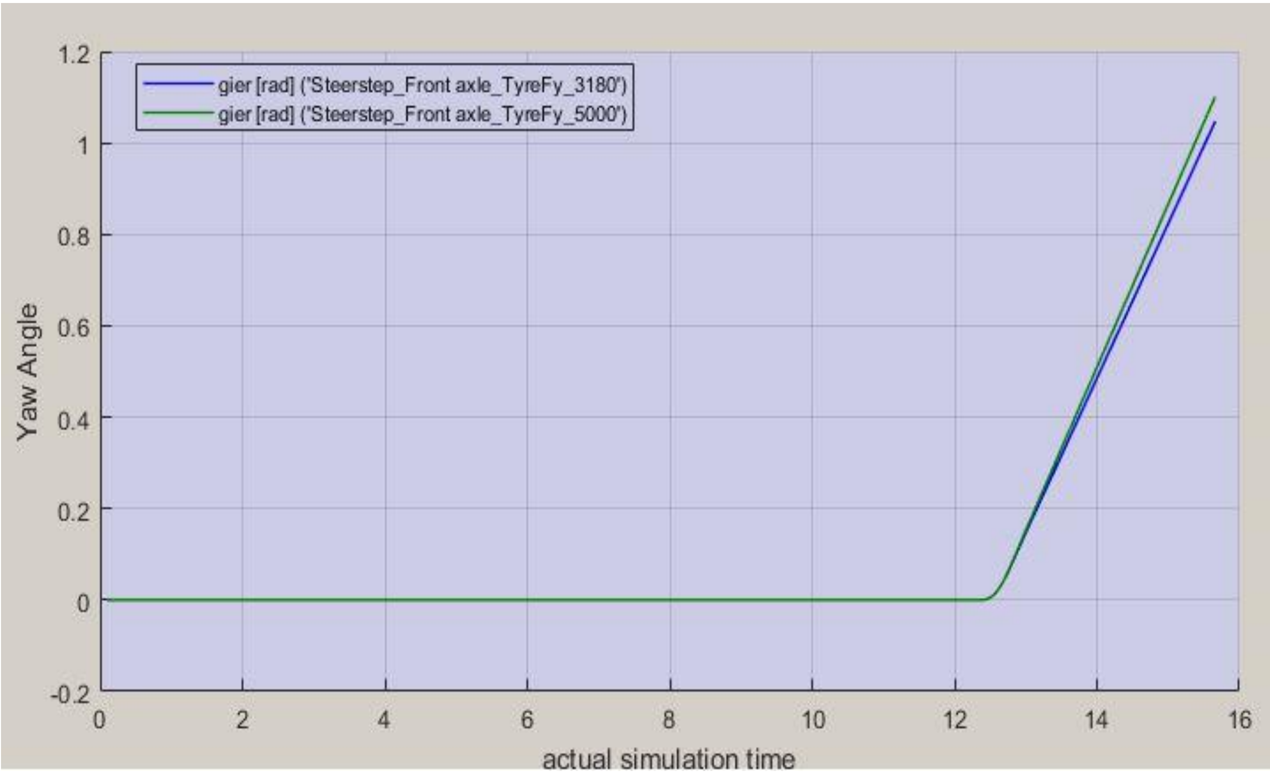

Figure 72. Steerstep yaw angle graph

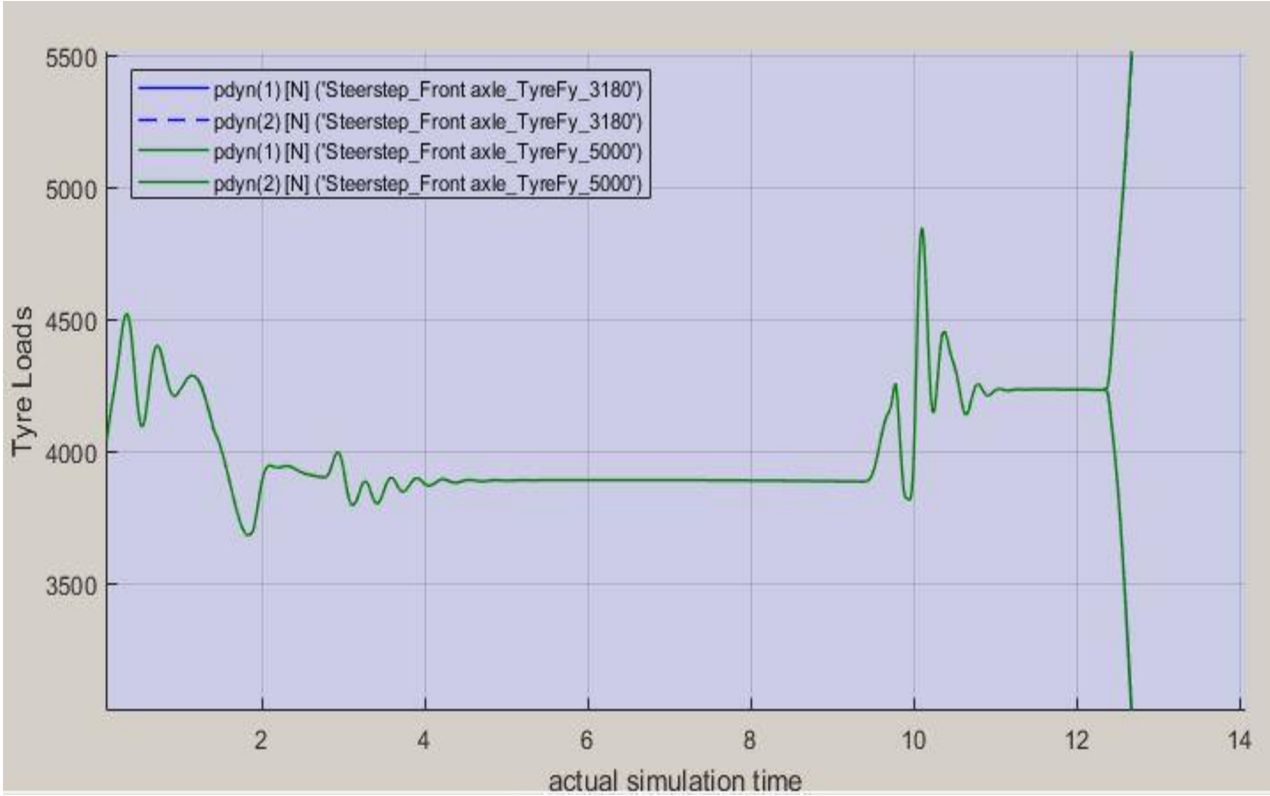

Figure 73. Steerstep tyre loads graph

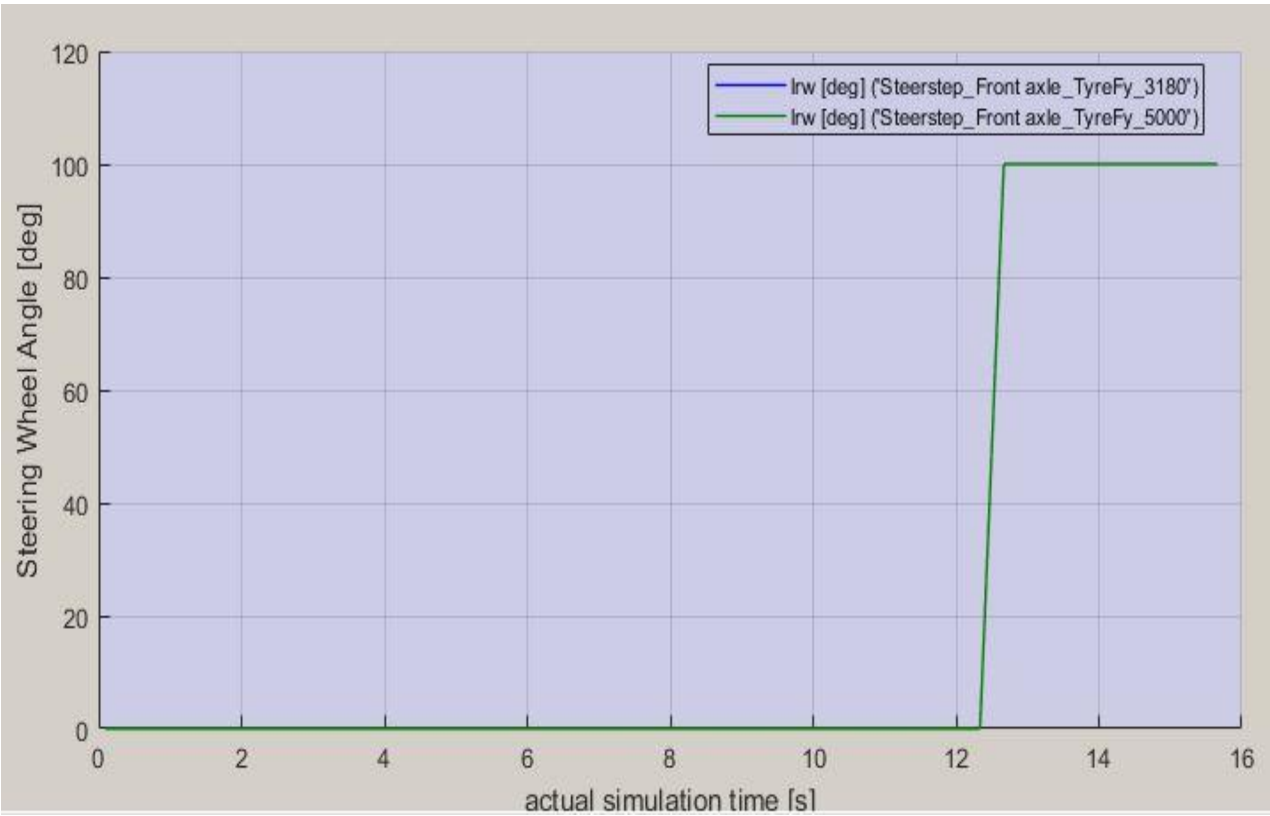

Figure 74. Steerstep steering wheel angle graph

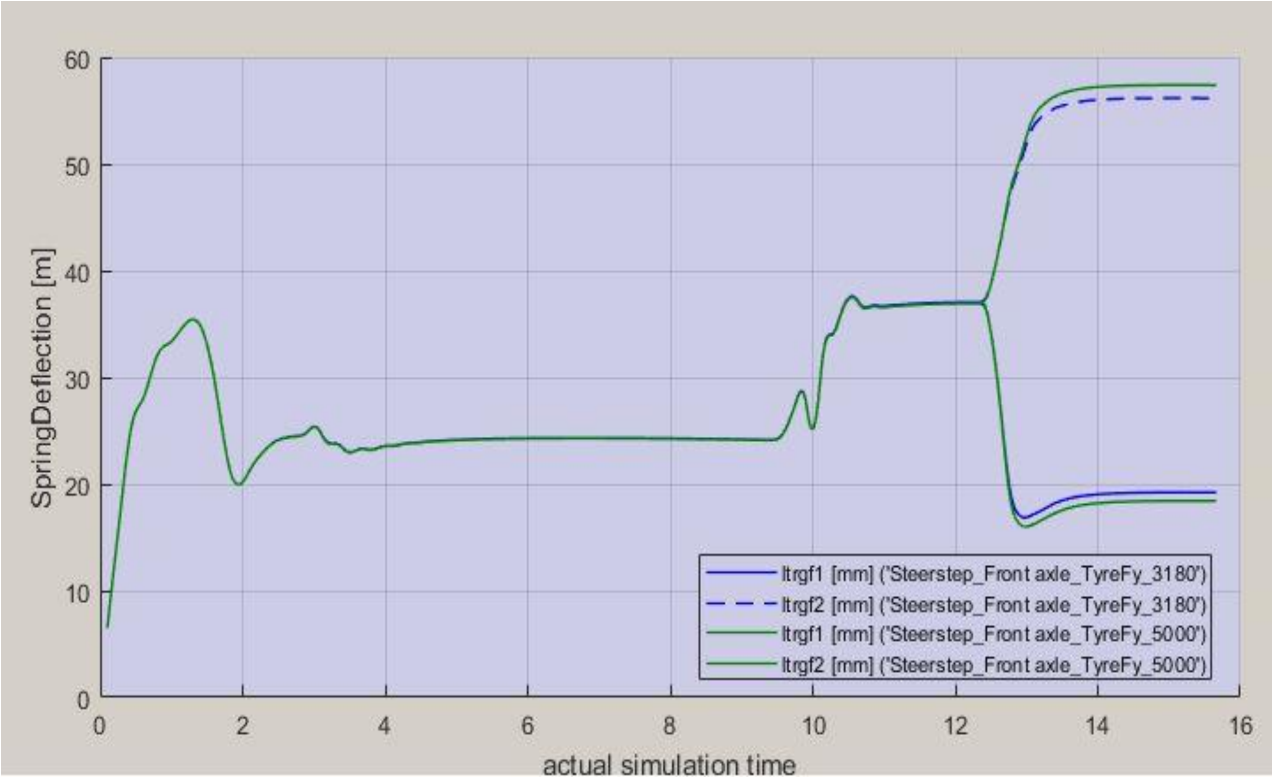

Figure 75. Steerstep spring deflection graph

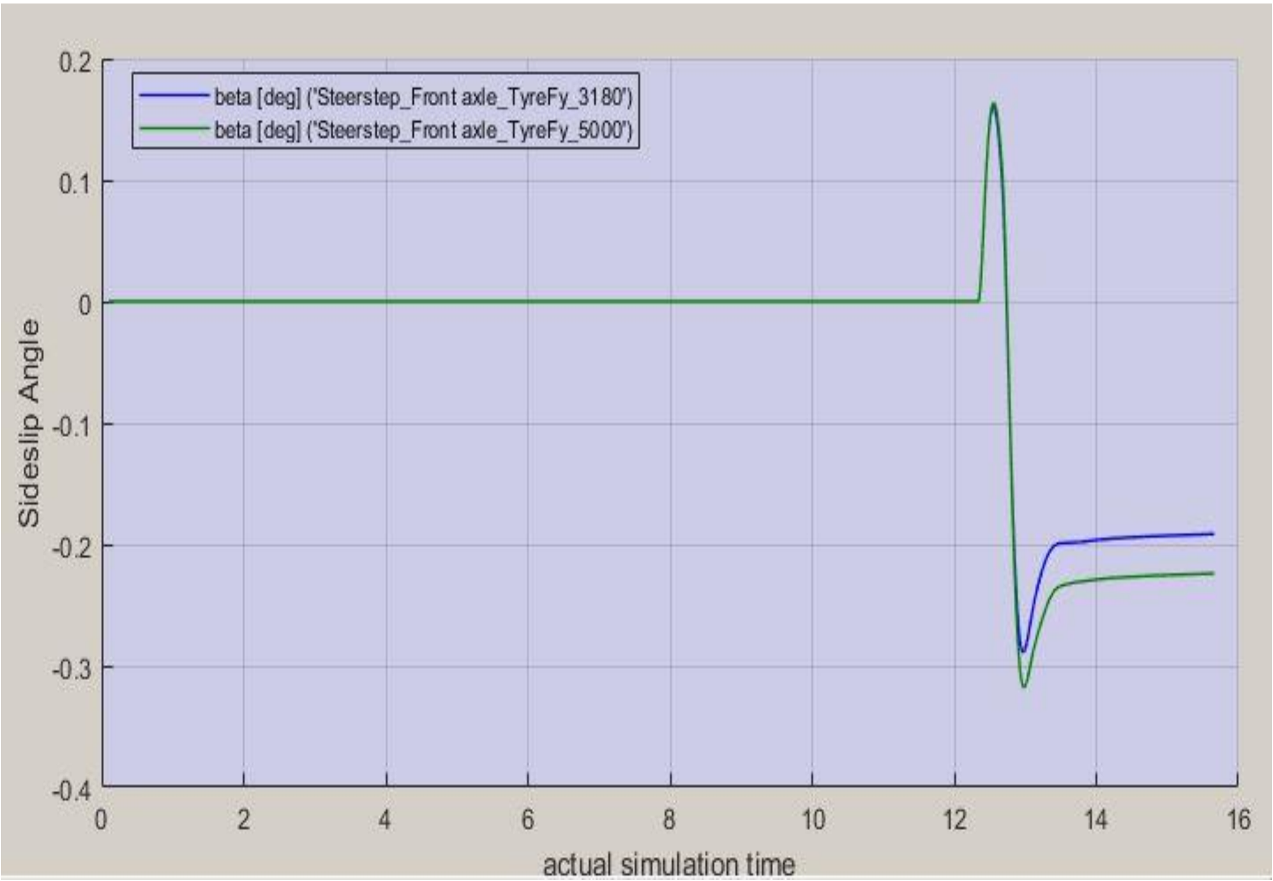

Figure 76. Steerstep sideslip angle graph

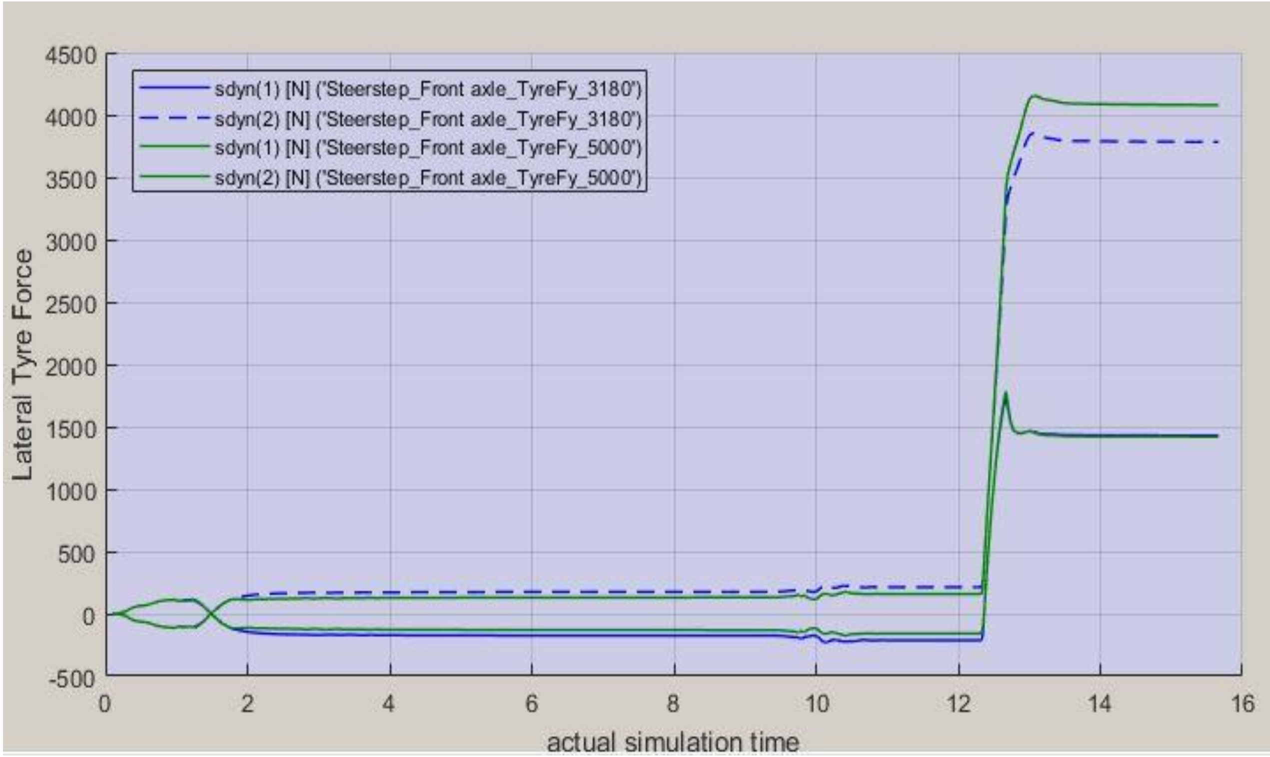

Figure 77. Steerstep lateral tyre force graph

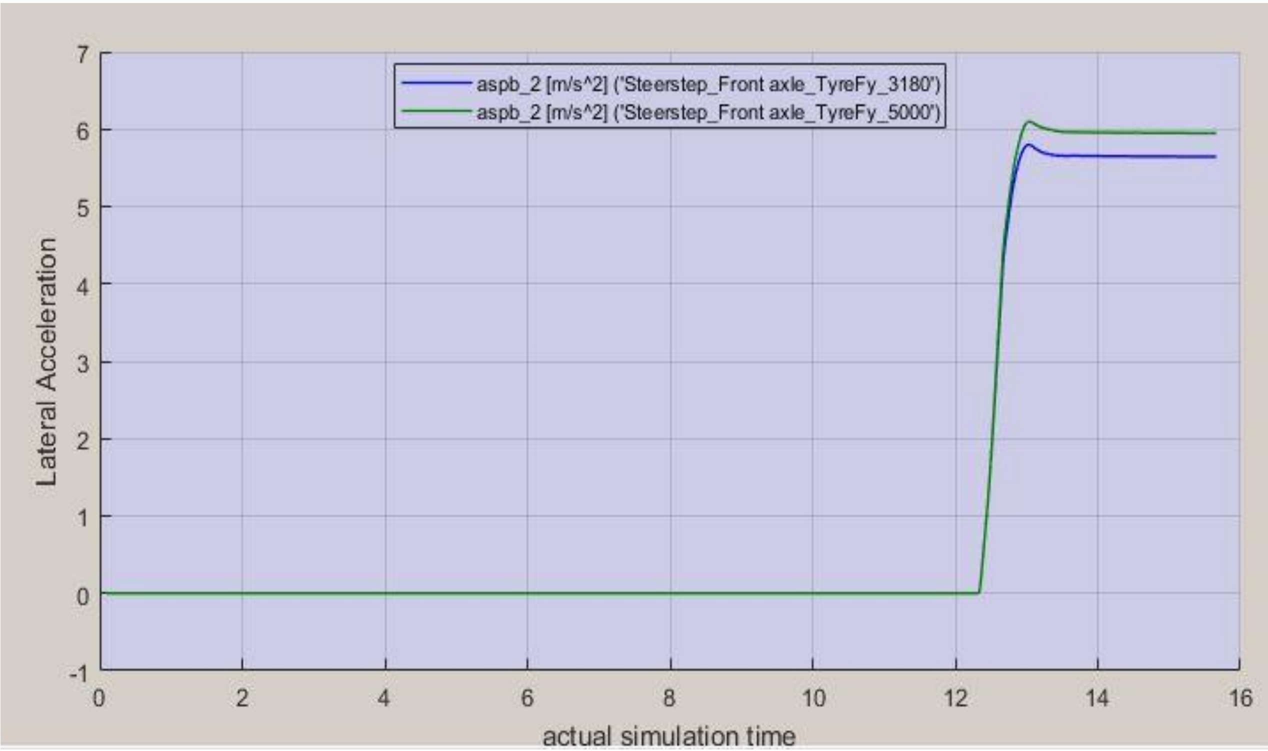

Figure 78. Steerstep lateral acceleration graph

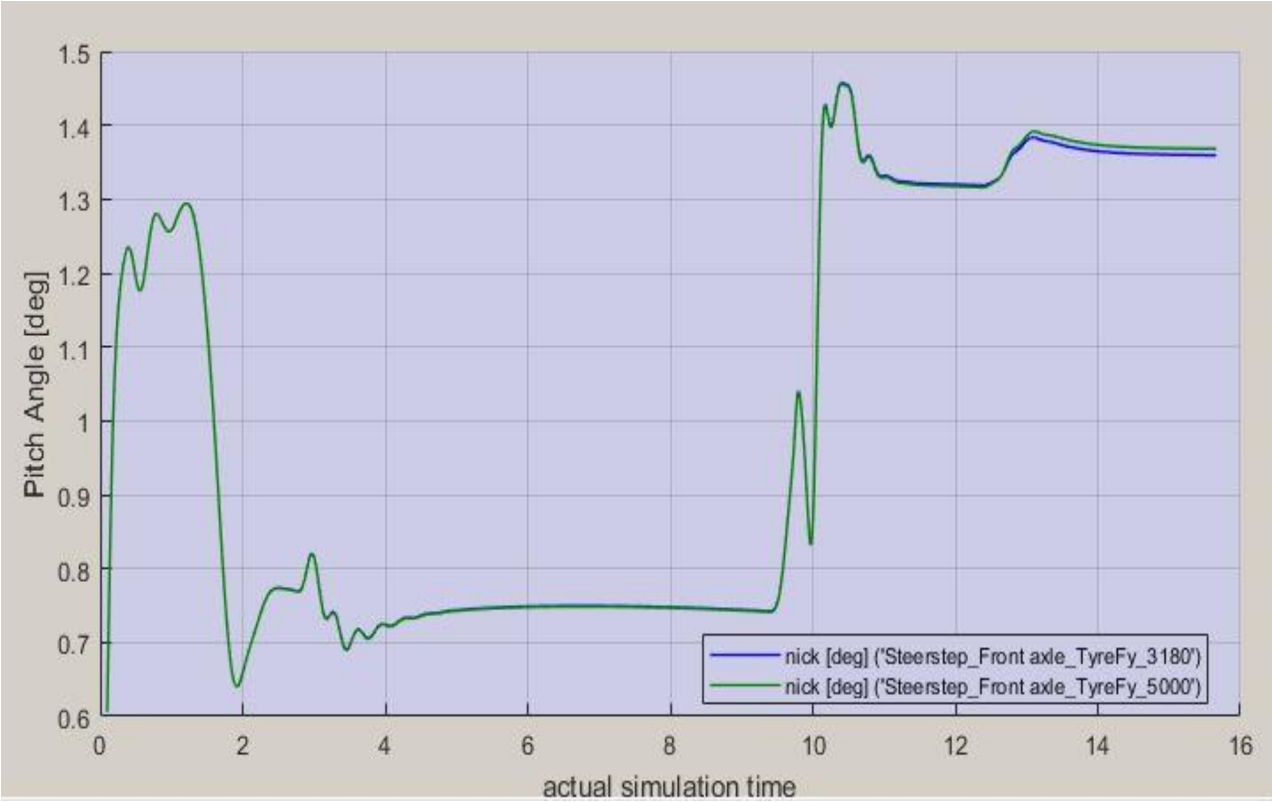

Figure 79. Steerstep pitch angle graph

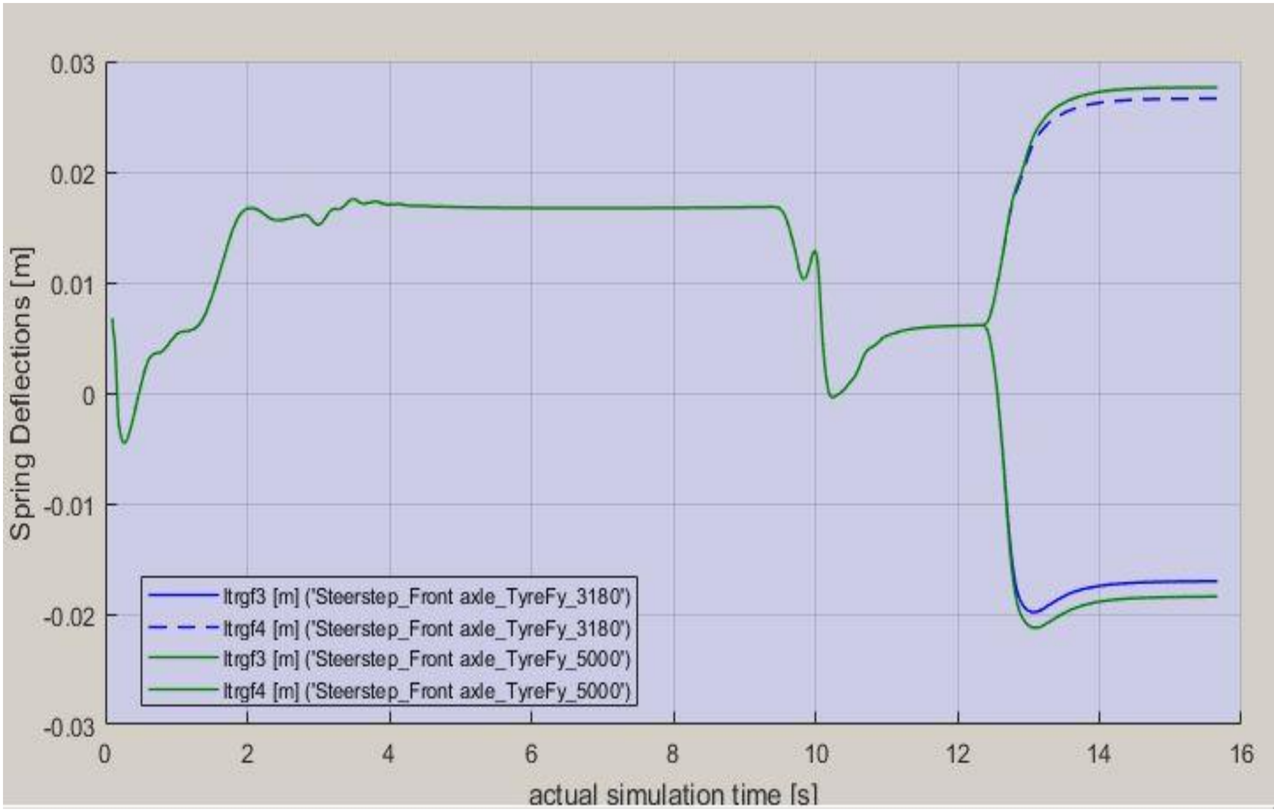

Figure 80. Steerstep spring deflections graph

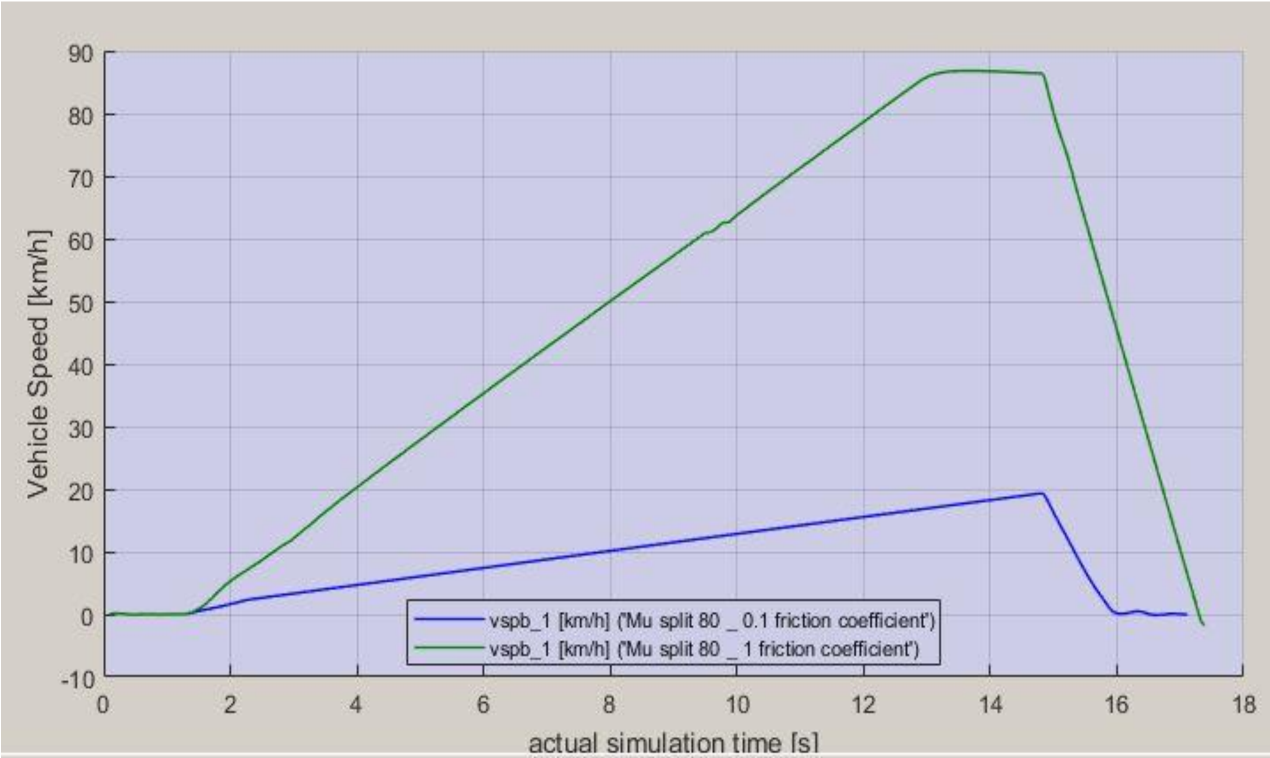

Figure 81. Mu-split vehicle speed graph

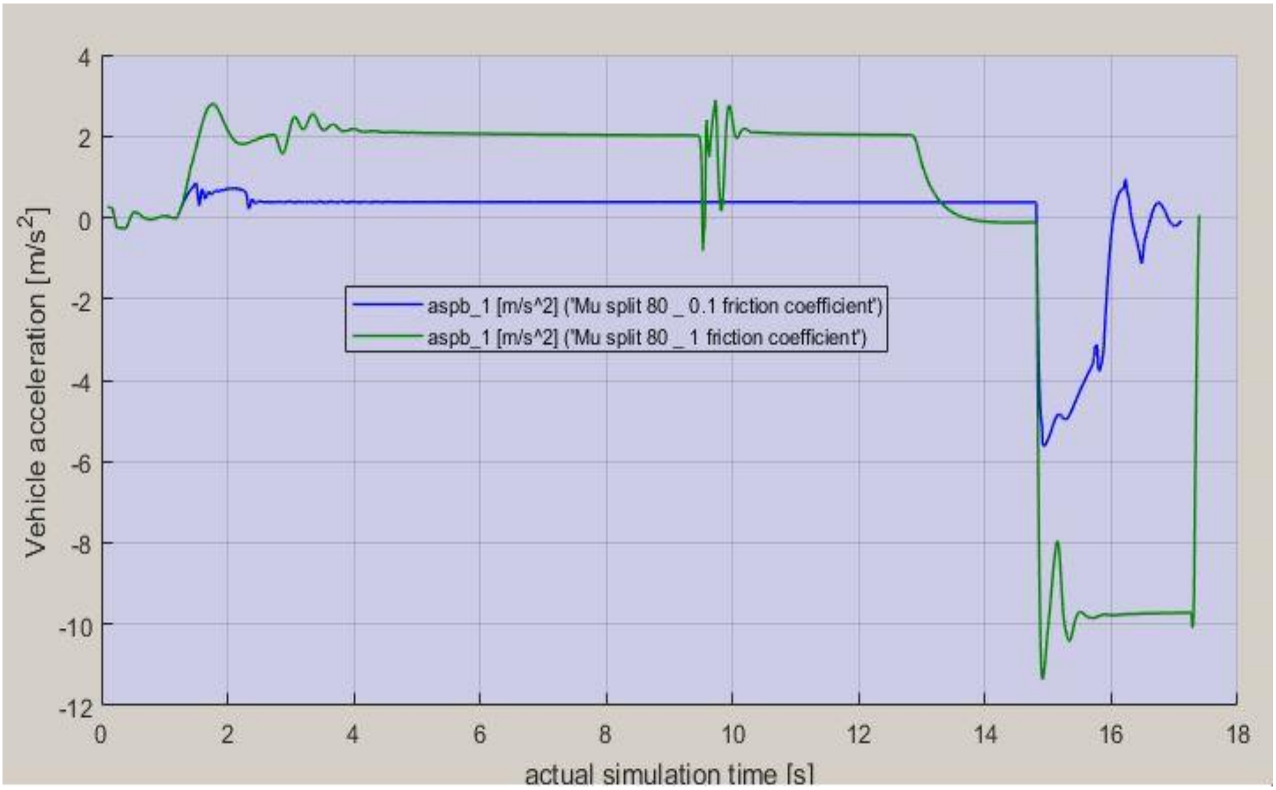

Figure 82. Mu-split vehicle acceleration graph

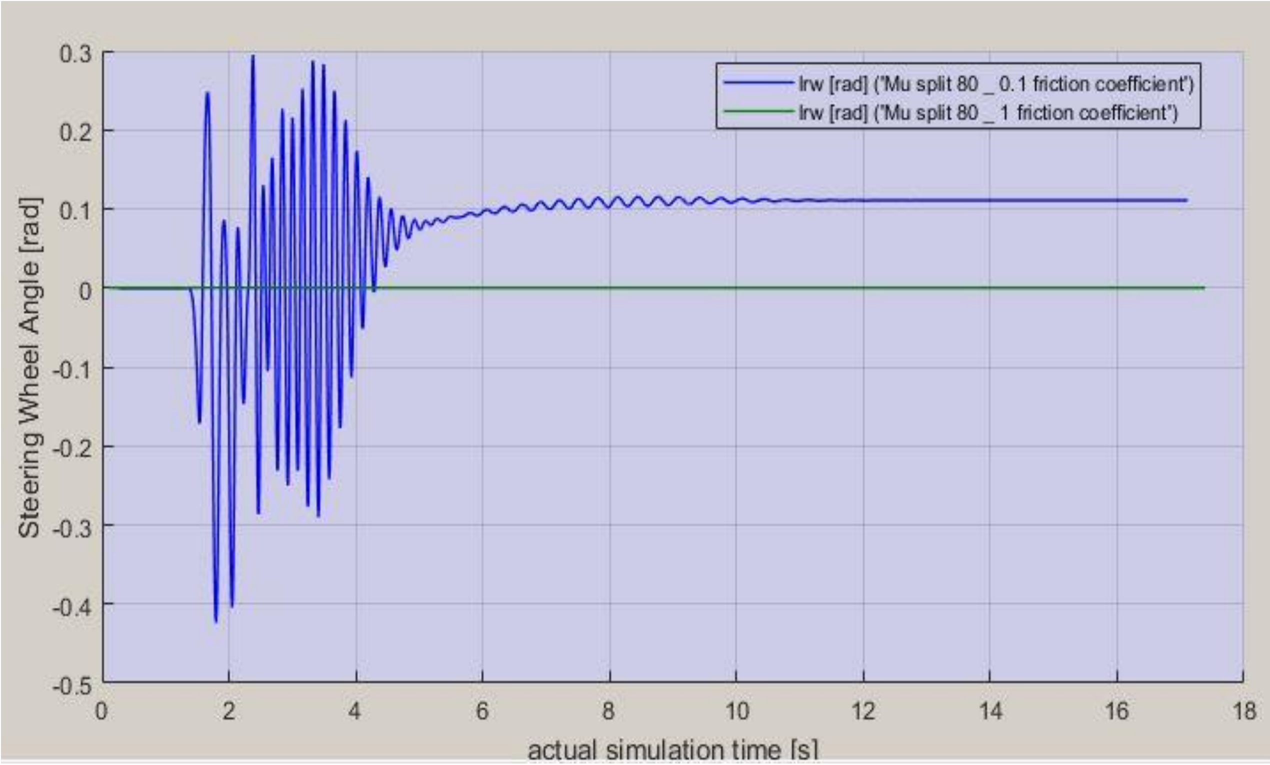

Figure 83. Mu-split steering wheel angle graph

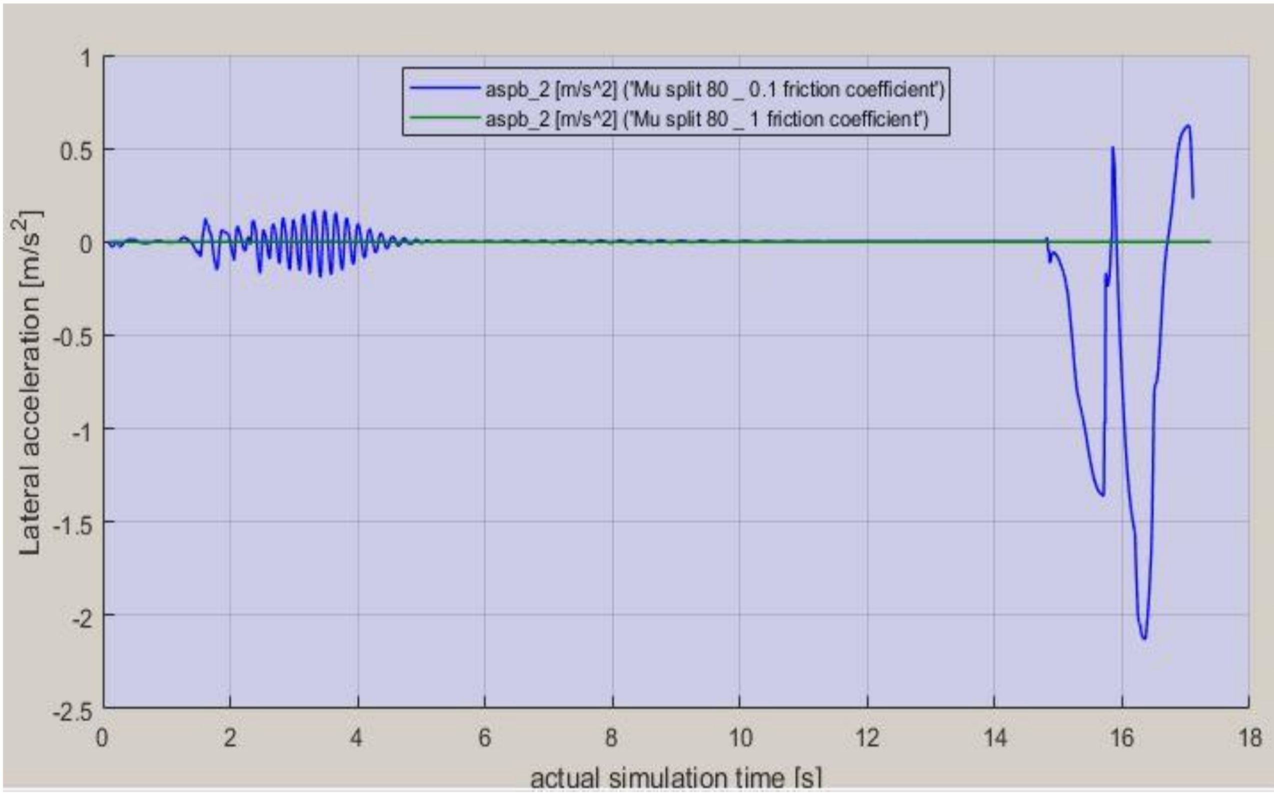

Figure 84. Mu-split lateral acceleration graph

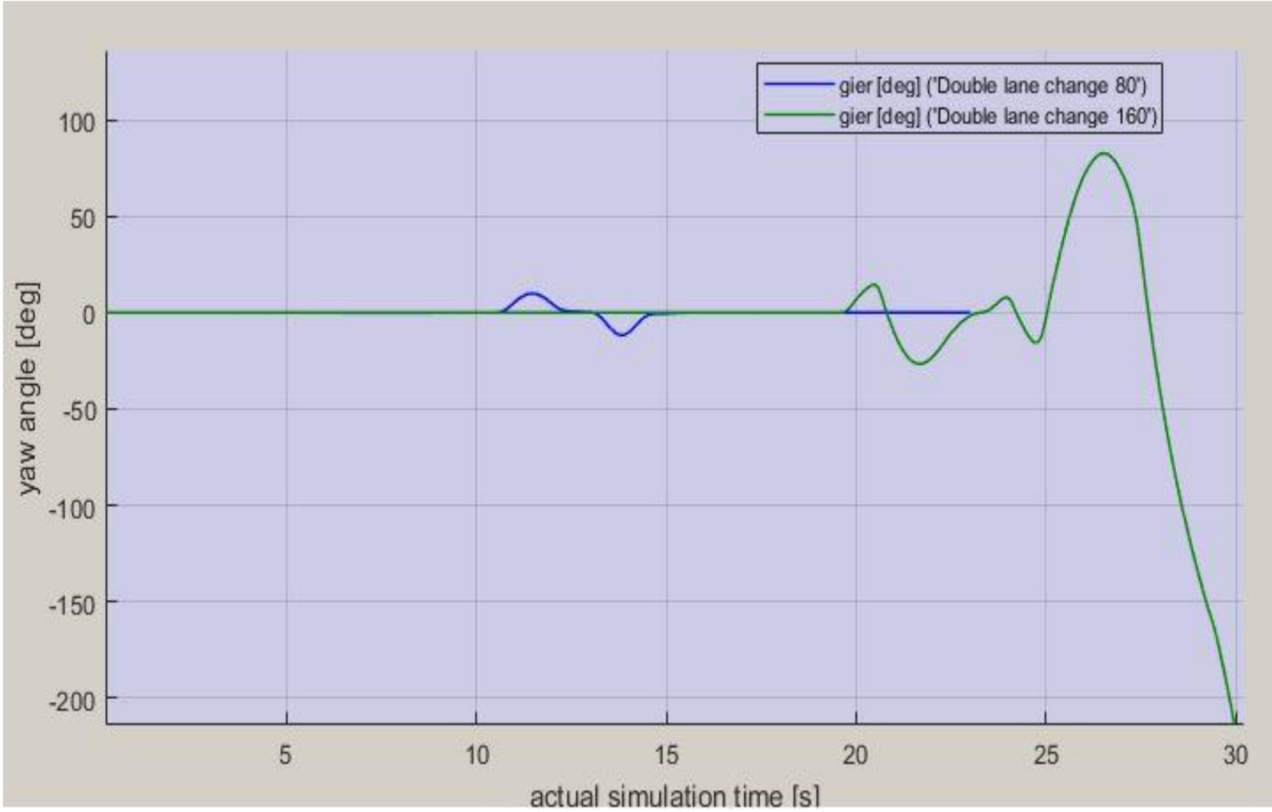

Figure 85. Double lane change yaw angle graph

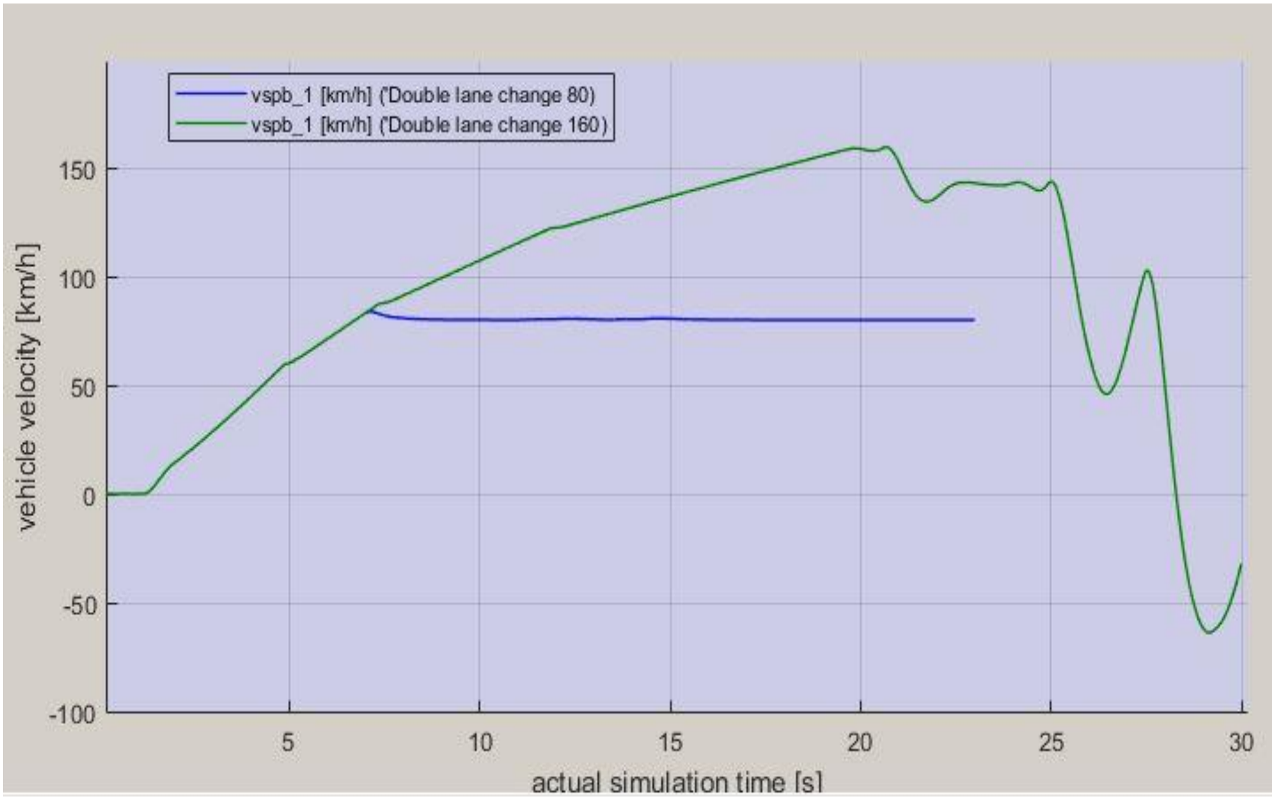

Figure 86. Double lane change vehicle velocity graph

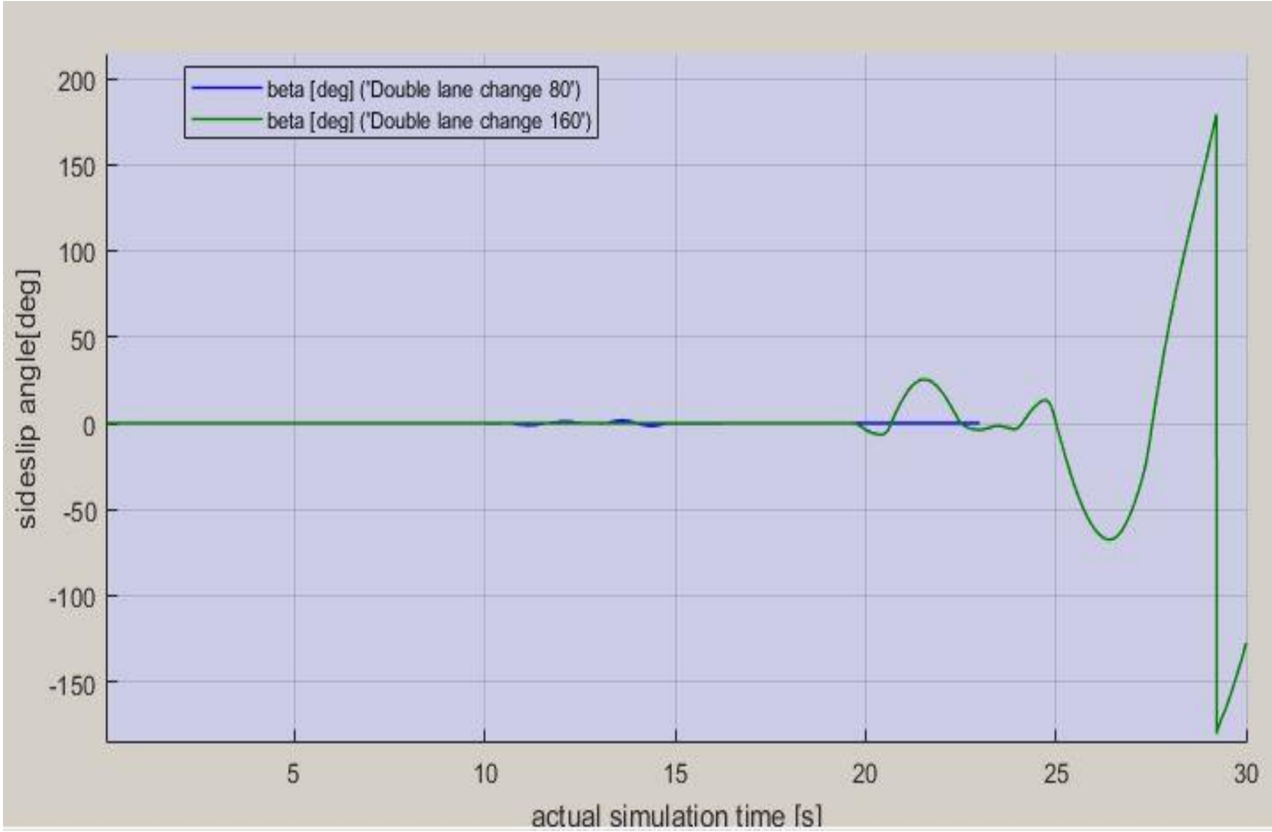

Figure 87. Double lane change sideslip angle graph

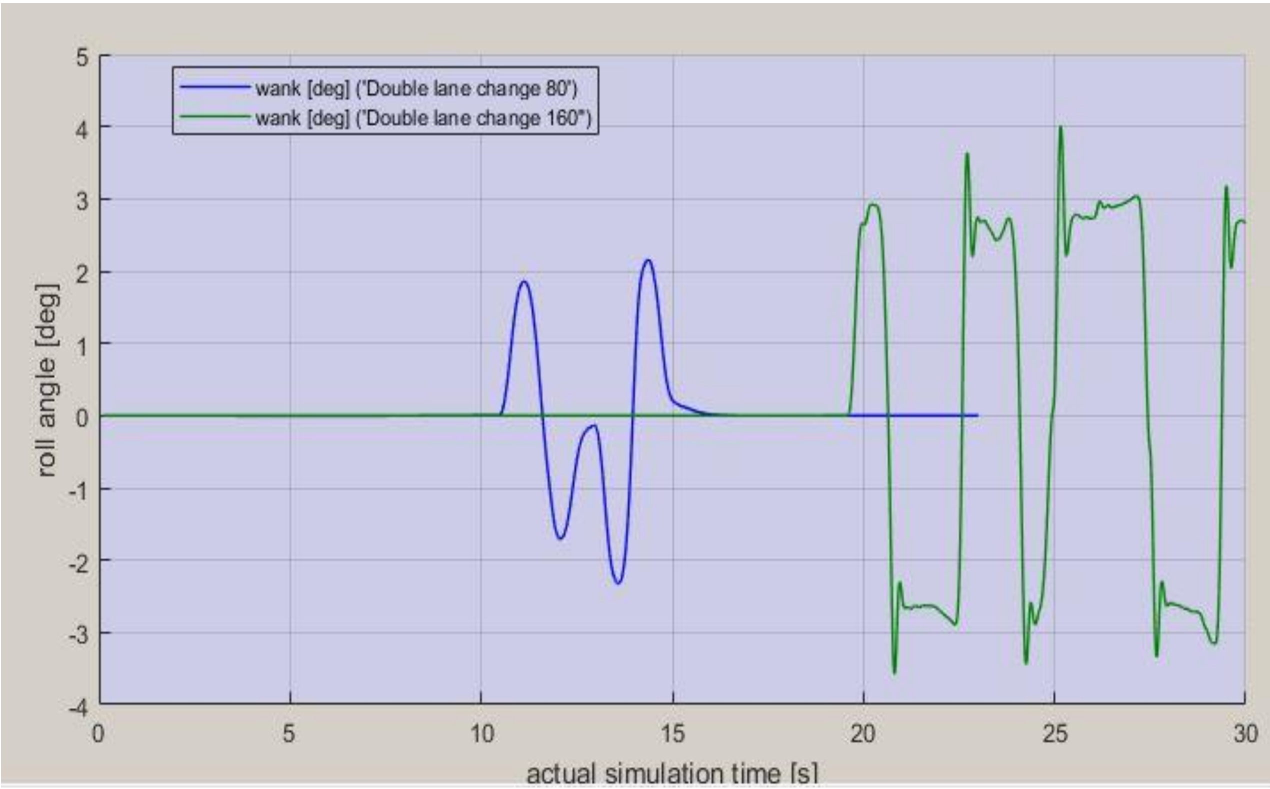

Figure 88. Double lane change roll angle graph

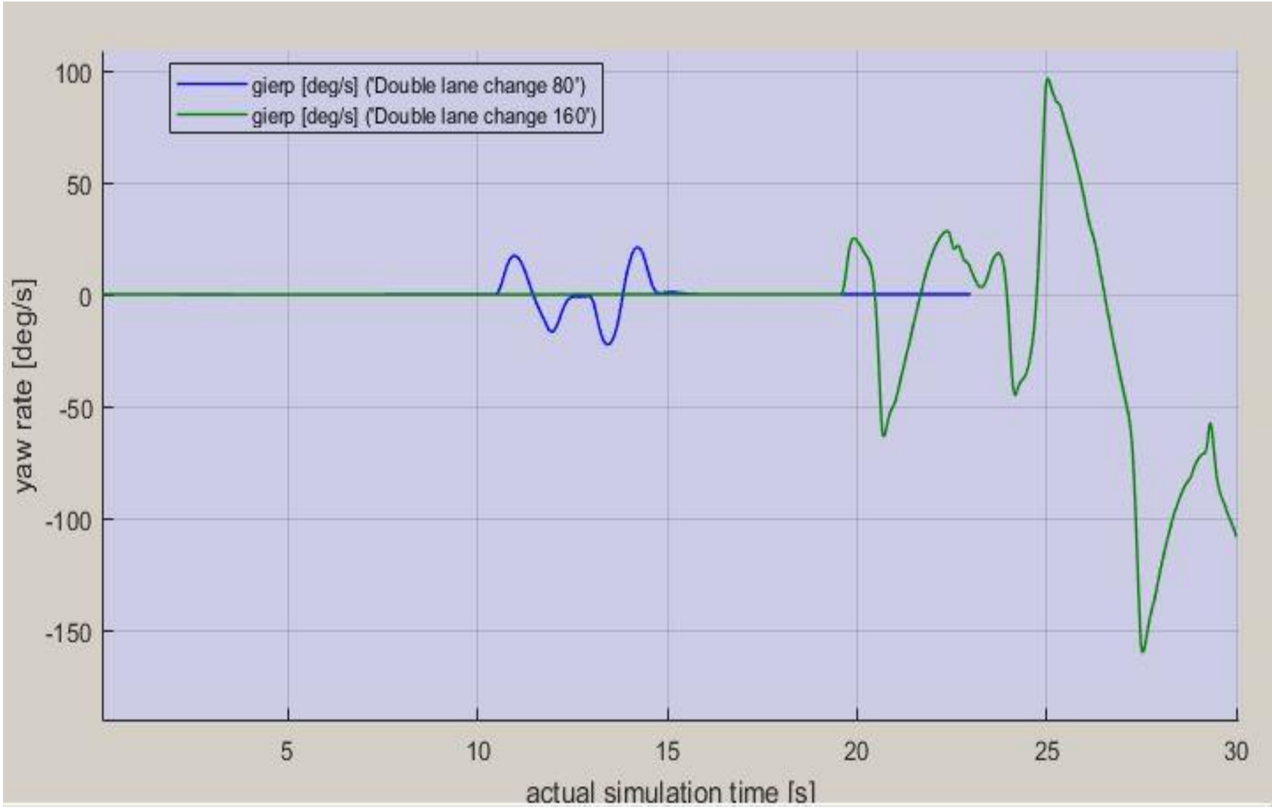

Figure 89. Double lane change yaw rate graph

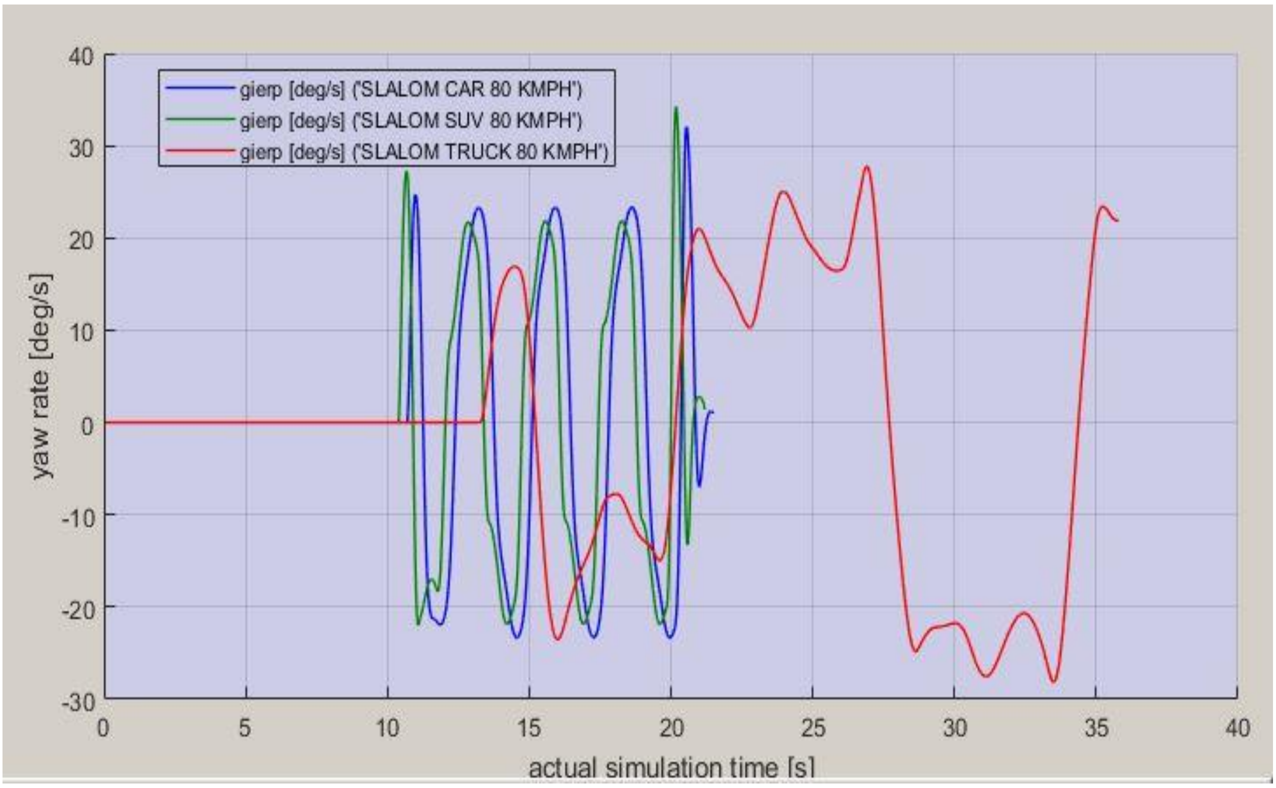

Figure 90. Slalom yaw rate graph

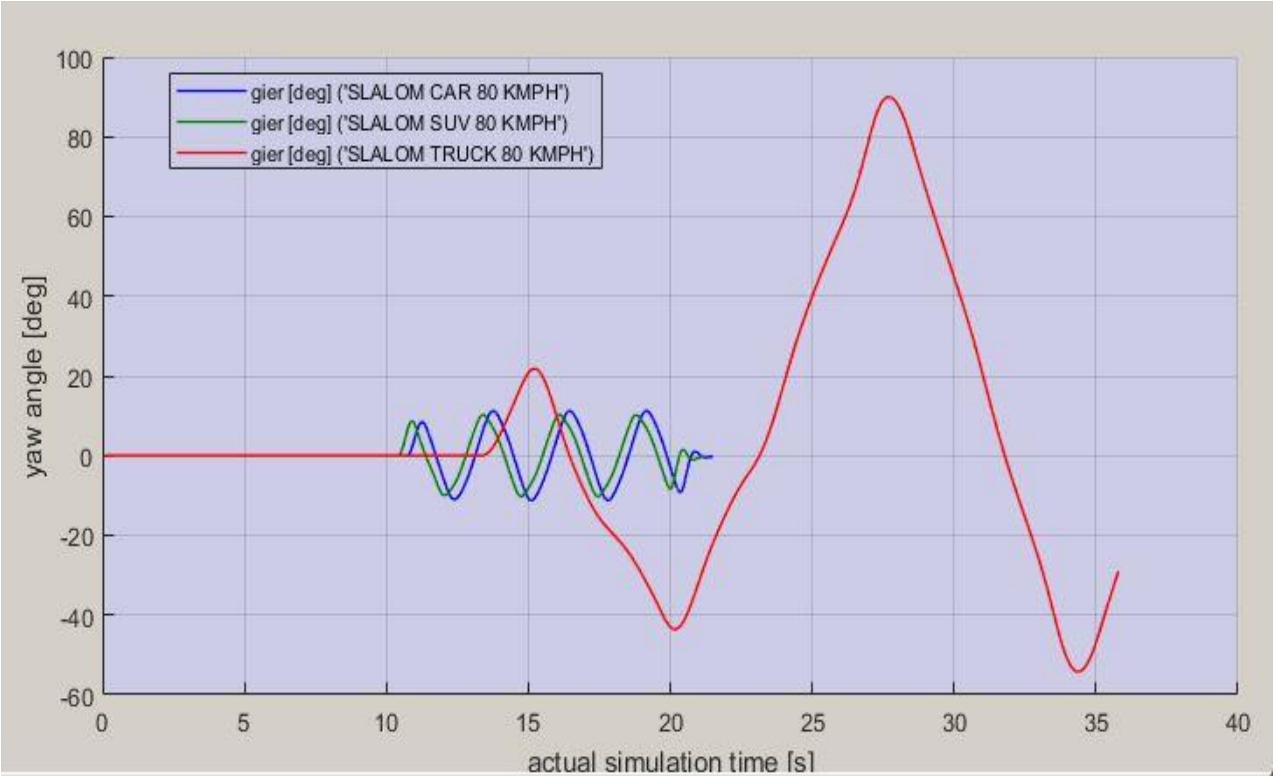

Figure 91. Slalom yaw angle graph

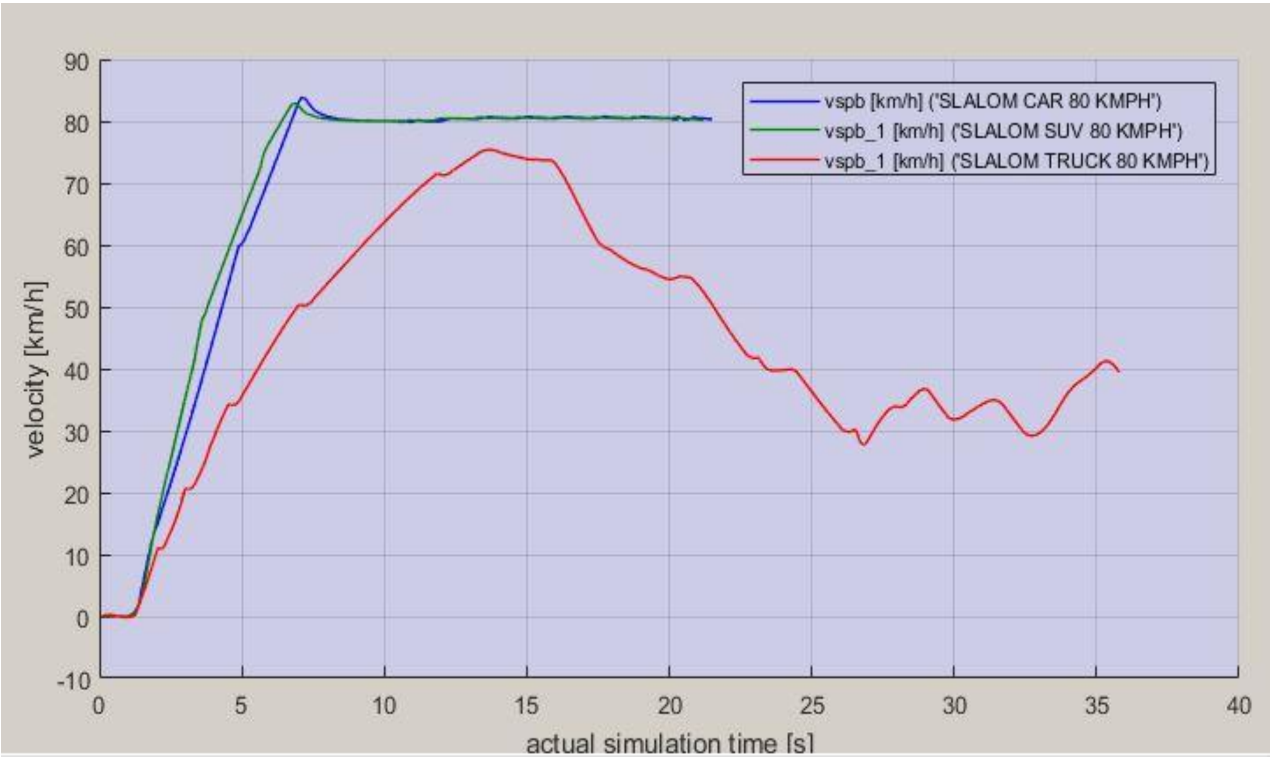

Figure 92. Slalom velocity graph

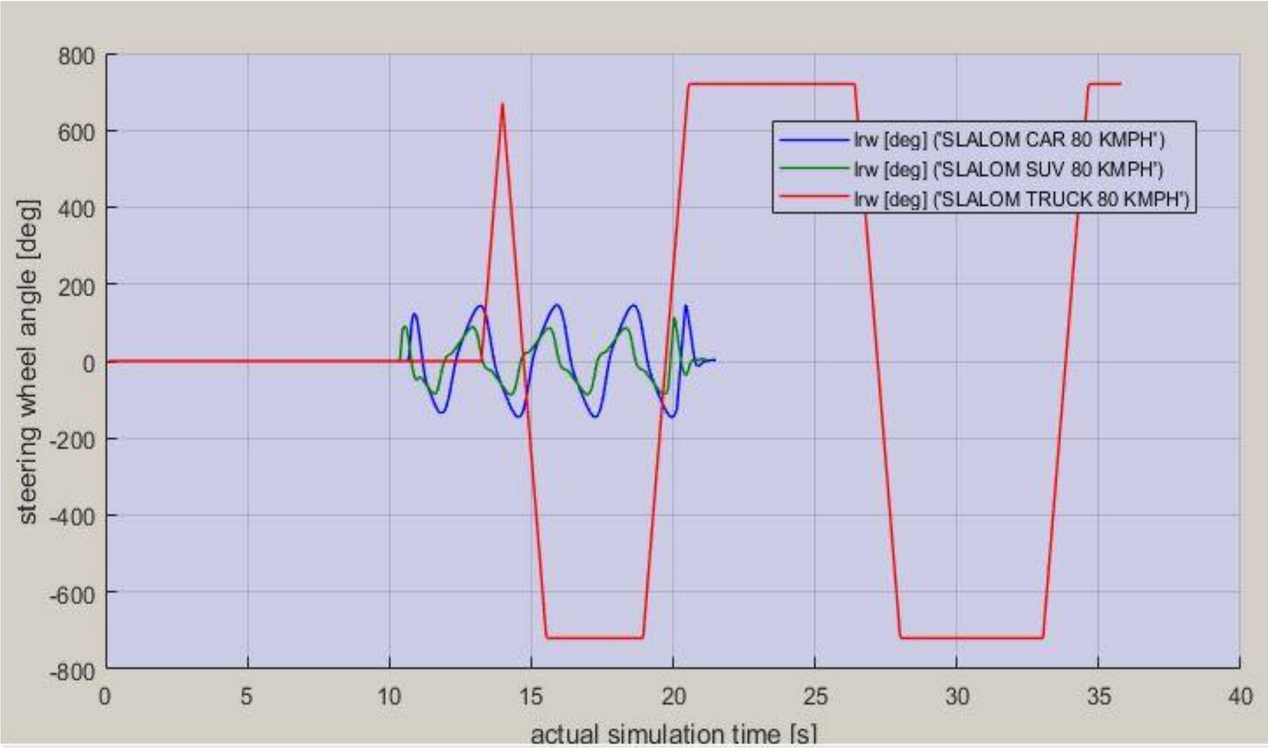

Figure 93. Slalom steering wheel angle graph

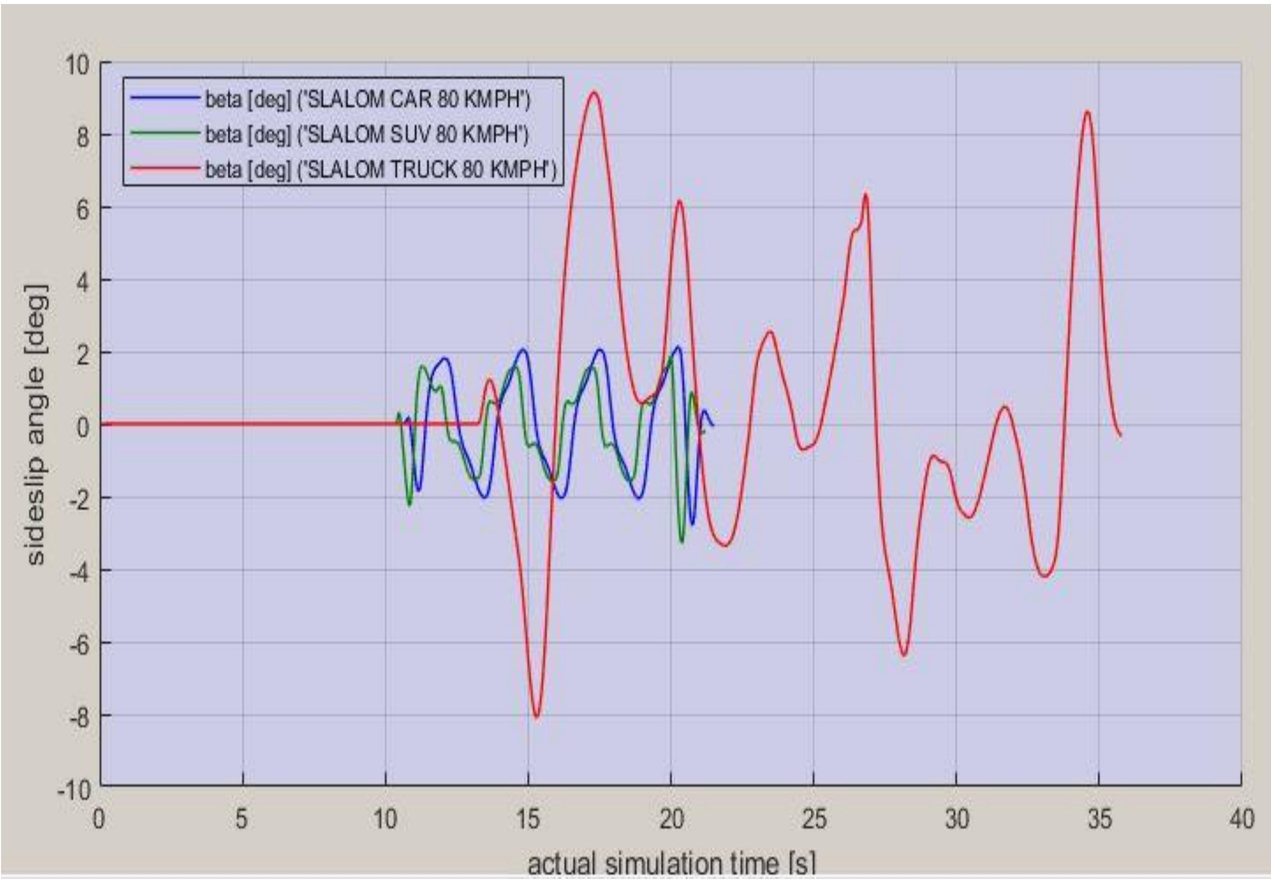

Figure 94. Slalom sideslip angle graph

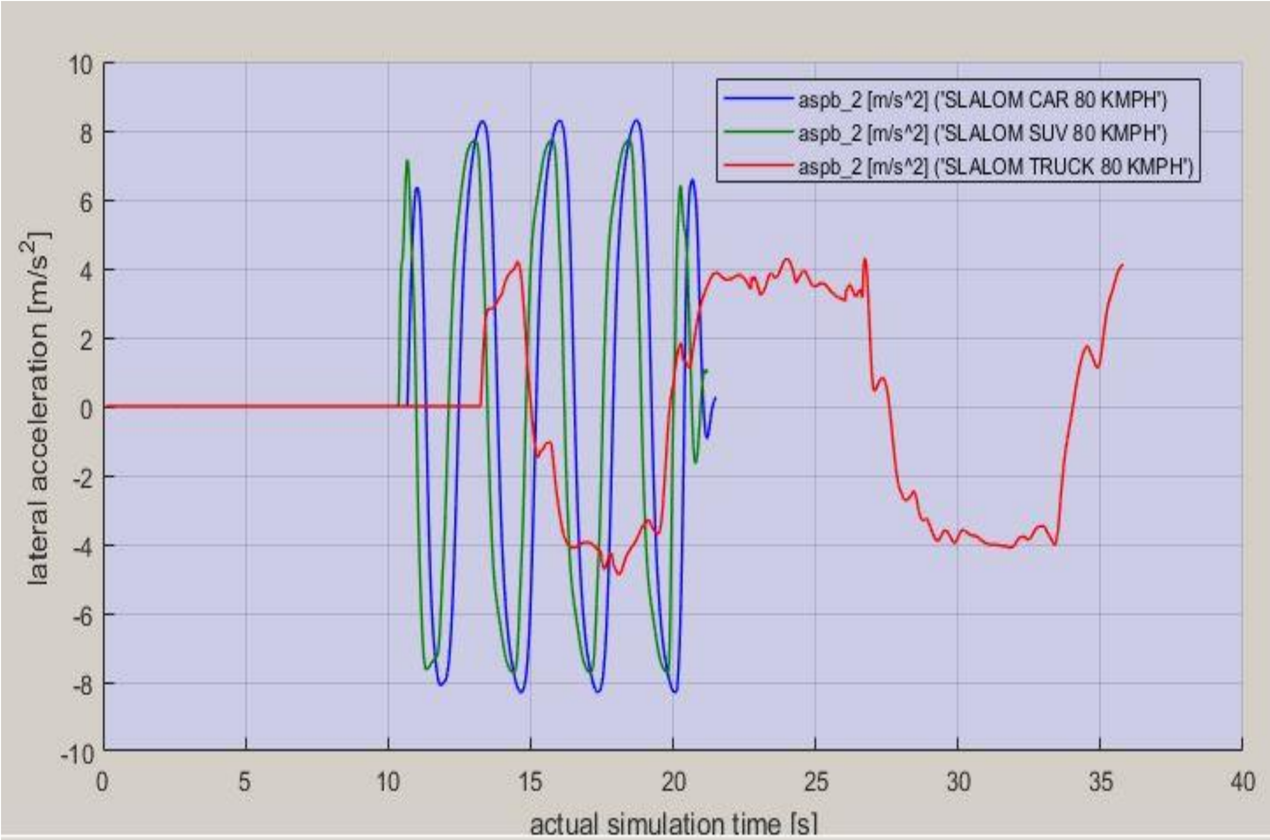

Figure 95. Slalom lateral acceleration graph

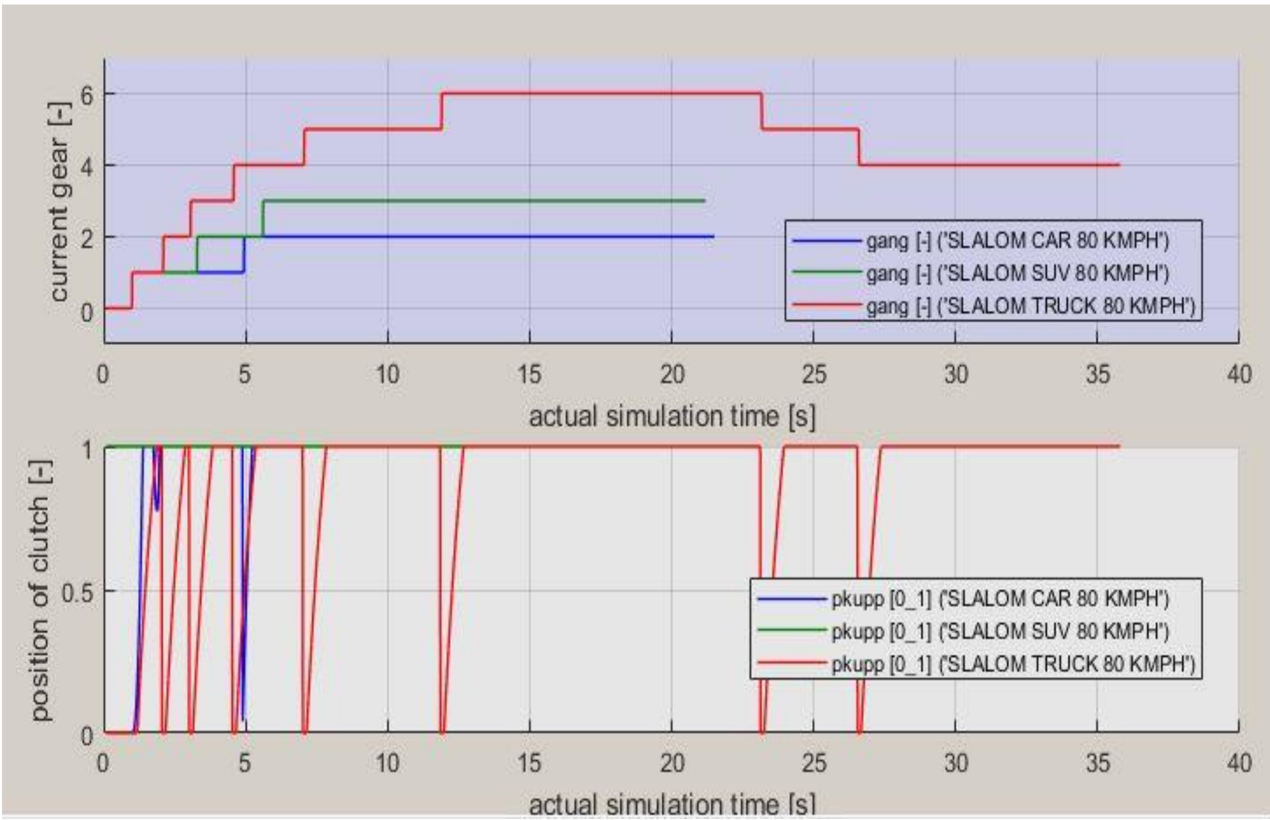

Figure 96. Slalom current gear and position of the clutch graph

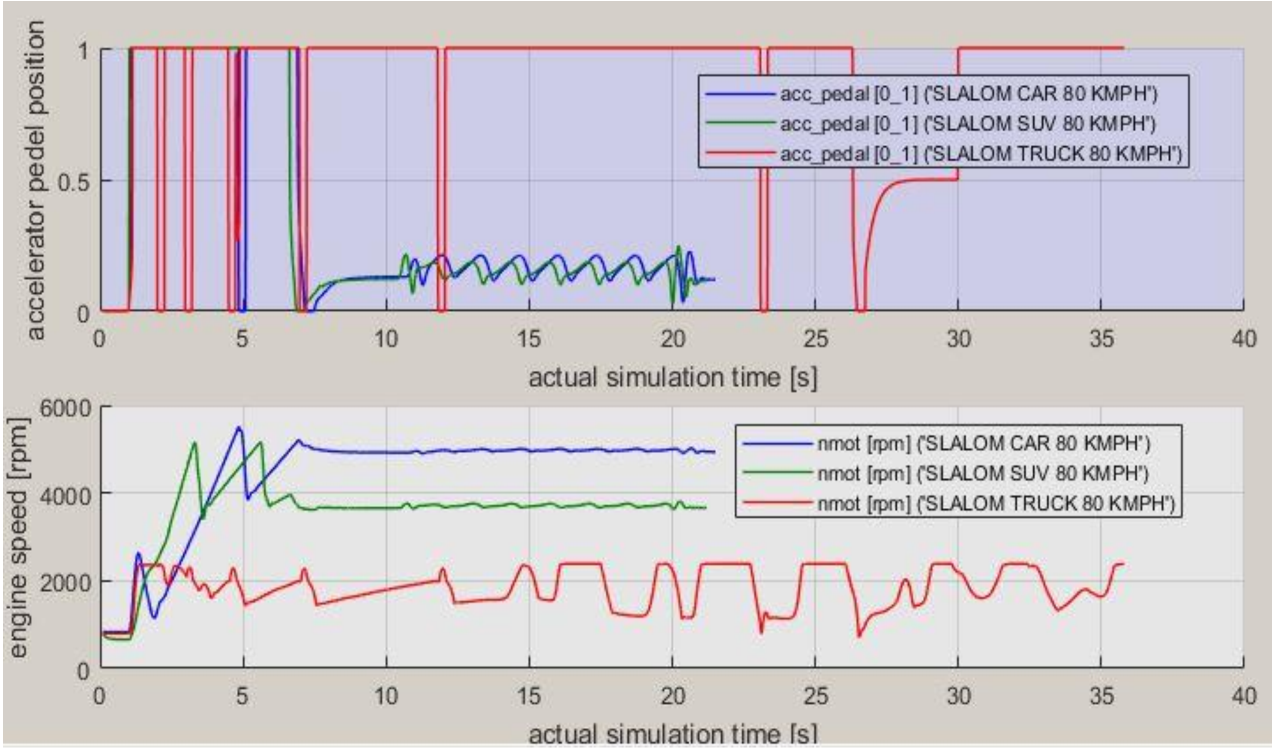

Figure 97. Slalom engine speed and acceleration pedal position graph

Matlab

1. Vedyna chassis initial output car

=================================I==========I==========I==========I=====
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I Mass I x I y I z I Txx I Tyy I Tzz I Txy I Txz I
Tyz I
I [kg] I [m] I [m] I [m] I [kgm^2] I [kgm^2] I [kgm^2] I [kgm^2]
I [kgm^2] I [kgm^2] I
=================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
Vehicle Body I 1531.000 I -1.350 I 0.000 I 0.283 I 415.938 I 2227.295 I 2319.490 I 0.000
I 0.000 I 0.000 I
Unsprung Front Left I 50.000 I -0.000 I 0.860 I 0.000 I 1.200 I 1.400 I 1.200 I
0.000 I 0.000 I 0.000 I
Unsprung Front Right I 50.000 I -0.000 I -0.860 I 0.000 I 1.200 I 1.400 I 1.200 I -
0.000 I 0.000 I -0.000I
Unsprung Rear Left I 50.000 I -2.700 I 0.850 I 0.000 I 1.200 I 1.400 I 1.200 I 0.000
I 0.000 I 0.000 I
Unsprung Rear Right I 50.000 I -2.700 I -0.850 I 0.000 I 1.200 I 1.400 I 1.200 I -
0.000 I 0.000 I -0.000 I
=================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
Total I 1731.000 I -1.350 I 0.000 I 0.250 I 581.064 I 2611.527 I 2834.982 I 0.000 I -
0.000 I 0.000 I
=================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
Wheel base front to rear axle : 2.700 m
Wheel track front : 1.720 m
Wheel track(s) rear : 1.700 m 1.700 m

Tyre radius front : 0.288 m
Tyre radius rear : 0.315 m

Precalculated loads

front : 8.491 kN 50.00 %%

rear : 8.491 kN 50.00 %%

sum : 16.981 kN 100.00 %%

2. Vedyna chassis initial output SUV

```
===================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
                               I   Mass   I    x     I     y    I     z    I    Txx    I    Tyy   I    Tzz    I    Txy   I    Txz    I
Tyz   I
                               I   [kg]   I   [m]    I    [m]   I    [m]   I  [kgm^2] I  [kgm^2] I  [kgm^2] I  [kgm^2]
I  [kgm^2] I  [kgm^2] I
===================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
 Vehicle Body                    I 2308.449 I   -1.478 I    0.000 I    0.388 I 1023.914 I 4722.707 I 4817.107
I   -0.000 I    0.304 I   -0.000 I
 Unsprung Front Left             I   63.930 I    0.000 I    0.825 I    0.000 I    0.880 I    1.420 I    0.868 I
0.000 I    0.000 I    0.000 I
 Unsprung Front Right            I   63.930 I    0.000 I   -0.825 I    0.000 I    0.880 I    1.420 I    0.868 I
-0.000 I    0.000 I   -0.000 I
 Unsprung Rear Left              I   62.846 I   -2.989 I    0.832 I    0.000 I    0.880 I    1.420 I    0.868 I
0.000 I    0.000 I    0.000 I
 Unsprung Rear Right             I   62.846 I   -2.989 I   -0.832 I    0.000 I    0.880 I    1.420 I    0.868 I
-0.000 I    0.000 I   -0.000 I
===================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
 Total                           I 2562.000 I   -1.479 I    0.000 I    0.350 I 1236.107 I 5329.188 I 5561.109 I   -
0.000 I    0.000 I   -0.000 I
===================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I
```

Wheel base front to rear axle : 2.989 m

Wheel track front : 1.651 m

Wheel track(s) rear : 1.665 m 1.665 m

Tyre radius front : 0.402 m

Tyre radius rear : 0.402 m

Precalculated loads

front : 12.700 kN 50.53 %%

rear : 12.433 kN 49.47 %%

sum : 25.133 kN 100.00 %%

3. Vedyna chassis initial output truck

==================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I

I Mass I x I y I z I Txx I Tyy I Tzz I Txy I Txz I
Tyz I

I [kg] I [m] I [m] I [m] I [kgm^2] I [kgm^2] I [kgm^2] I [kgm^2]
I [kgm^2] I [kgm^2] I

==================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I

Vehicle Body I 8070.000 I -1.505 I 0.000 I 1.001 I299677.186 I103251.739
I102960.353 I 0.000 I 302.816 I -0.000 I

Unsprung Front Left I 190.000 I 0.000 I 1.100 I 0.000 I 30.000 I 15.000 I 32.000 I
0.000 I 0.000 I 0.000 I

Unsprung Front Right I 190.000 I 0.000 I -1.100 I 0.000 I 30.000 I 15.000 I 32.000
I -0.000 I 0.000 I -0.000 I

Unsprung Rear Left I 190.000 I -3.880 I 1.100 I 0.000 I 30.000 I 15.000 I 32.000 I
0.000 I 0.000 I 0.000 I

Unsprung Rear Right I 190.000 I -3.880 I -1.100 I 0.000 I 30.000 I 15.000 I 32.000
I -0.000 I 0.000 I -0.000 I

==================================I==========I==========I==========I=====
=====I==========I==========I==========I==========I==========I==========I

Total I 8830.000 I -1.542 I 0.000 I 0.915 I301413.000 I107000.000 I107000.000
I 0.000 I 0.000 I -0.000 I

==================================I==========I==========I==========I=====
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Wheel base front to rear axle : 3.880 m

Wheel track front : 2.200 m

Wheel track(s) rear : 2.200 m 2.200 m

Tyre radius front : 0.517 m

Tyre radius rear : 0.524 m

Precalculated loads

front	:	52.196 kN	60.26 %%
rear	:	34.426 kN	39.74 %%
sum	:	86.622 kN	100.00 %%

4. Go steerstep

Evaluation of response at speed = 60.0 km/h

0.9 steady yaw rate at T = 0.38 sec

First max. of yaw rate at T = 0.55 sec

Ratio max. yaw rate / steady yaw rate = 1.024

TB value = 0.123 s*deg

5. Go steadystate circle drive

Front axle

Sideslip angle crosses zero at v = 59 [km/h]

Yaw velocity amplification gradient of neutral steering model = 0.318298 [1/s]

Characteristic speed = 108 [km/h]

Lateral acceleration gradient of neutral steering model = 0.004362 [rad*s^2/m]

Rear axle

Sideslip angle crosses zero at v = 59 [km/h]

Yaw velocity amplification gradient of neutral steering model = 0.319435 [1/s]

Characteristic speed = 72 [km/h]

Lateral acceleration gradient of neutral steering model = 0.004400 [rad*s^2/m]

6. Go slalom

Slalom test 80 kmph - drive through time is 8.105714s

Slalom test SUV 80 kmph - drive through time is 8.103946s

Slalom test truck 80 kmph - drive through time is -16.840000s