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Model-based tuning of the steady-state lateral tyre characteristics using test bench measurement data

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Graz, November 2016

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Abstract

Tyres are the most important component of the vehicle, which has a physical connection with the road. Understanding the non-linear behaviour of the tyres at different operating conditions is quintessential to understand the mechanics of tyre with different degrees of freedom. The forces and moments are generated as the tyres are driven. To study these forces numerous tyre modelling approaches are available. However, there exists the necessity of tyre model parametrisation to obtain a clear idea of the influencing tyre parameters while driving and affects the whole vehicle behaviour. To study the experimental data, the tyre models have be fitted and parametrised. The selection of parameters according to the complexity and reproducibility are the primary aspects before modelling the measurement data. The quality of the manual tuning of parameters depends on the starting point and the expertise of the user. Thus it varies the final optimum parameter setting which can neither be traced nor reused. This can be effectively improved by an alternative approach called "Model-Based Tuning" (MBT) technique that uses Design of Experiments (DoE) concept. DoE serves as the standardised process model and helps to find the correlation of the influencing input parameters and the target values using as minimal experiments as possible. MBT generates the systematic knowledge about the function behaviour to solve the target conflicts and aids to find the global optimum setting for the parameterisation of the tyre models. The comparison of MBT with the manual tuning approach is studied in this thesis. The Model-Based Tuning method has been performed with the use of an automotive calibration tool called Cameo, which is developed by AVL GmbH.

Keywords: Tyre modelling, Design of Experiments, Model-Based Tuning, experimental data.

In Co-operation with:

AVL List GmbH, Graz

Contents

List of Figures

List of Tables

Nomenclature

α	side slip angle	[deg]
γ	wheel camber angle	[deg]
κ	longitudinal wheel slip	[deg]
λ	aligning torque	[Nm]
μ	friction coefficient	[-]
μ_0	static friction coefficient	[-]
ω	angular velocity	[rad/s]
B	stiffness factor in Magic Formula	[-]
C	shape factor in Magic Formula	[-]
C_l	longitudinal slip stiffness	[Nm]
C_s	lateral stiffness	[Nm]
D	peak factor in Magic Formula	[-]
dY_0	lateral stiffness of the tyre at lower α in TM Simple Model	[N/degree]
E	curvature factor in Magic Formula	[-]
F_n	normal force	[N]
F_x	longitudinal tyre force	[N]
F_y	lateral tyre force	[N]

F_z	vertical tyre load	[N]
F_{znom}	nominal tyre force	[N]
M_x	overturning moment	[Nm]
M_y	rolling resistance moment	[Nm]
M_z	aligning torque	[Nm]
v	vehicle velocity	[m/s]
v_x	wheel longitudinal velocity	[m/s]
v_y	wheel lateral velocity	[Nm]
X	generic tyre slip quantity	[deg]
Y	generic horizontal tyre force quantity	[N]
Y_∞	saturation value of the lateral force in TM Simple Model	[N]
Y_{max}	maximum value of the lateral force in TM Simple Model	[N]

List of Abbreviations

DoE Design of Experiments

ODoE Optimal Design of Experiments

MBT Model-Based Tuning

OFAT One Factor At a Time

ANOVA Analysis of variance

UUT Unit Under Test

KPI Key Performance Indicator

ADAS Advanced Driver Assistance Systems

MF Magic Formula

1 Introduction

"Automobiles and trucks are machines for using tyres".

- Maurice Olley, 1947

The first practical tyre was made from rubber by John Boyd Dunlop in 1887. However, the importance of tyres been realized only after the mid 1900's where the field of automobile engineering took a great leap in accommodating numerous technical inventions and developments. The tyres are the important element that bound the vehicle to ground and the mechanics involves has a greater significance in the vehicle's big picture. However, even after 130 years of their invention, tyres remain a black box. The behaviour of the tyre is strongly dependent on its design, construction and composition. By experimentation methods, the engineers interpret the influence of in bound and the environmental influences over the tyres and developed numerous physical and empirical models to understand the true behaviour of the tyres[14]. The material used and manufacturing also greatly influences the tyre behaviour making it very difficult to study them. In parallel, tyres also have the non-linearity and ambiguity in nature. Numerous parameters influence the tyre behaviour and these parameters have mutual influence on each other and also influence the vehicle dynamics to a large extent. Extensive studies have been done to understand and identify the physical relationships and separate their influence.

Contextually, the importance of modelling and simulation of tyre behaviour becomes extremely important. The tyre is the automotive part where the vehicle is meeting the road. And this defines the drive characteristics of the vehicle and decides the significant factor of drive comfort. Depending on the vehicle safety and the dynamic loads of the vehicle, the tyre responses with the motive , braking and lateral forces with respect to the physical environment and the set of defined parameters. The criteria for the assessment of the tyre depends on the longitudinal stability, lateral characteristics, friction property of the tyre with the road in all weather conditions, steering properties, driving comfort, durability and economy. Nevertheless, different mathematical models have different influencing parameters. The optimum selection of parameters is very important to ensure the quality of the mathematical model gives the opportunity to understand the tyre behaviour in a short time and more efficiently. So simply, the need for optimisation is inevitable. Finding the conditions within the range of defined values of the input parameters would give the maximum or minimum value of the function (output parameter), so the the response represents the minimal effort and maximised desired result. Model based optimisation technique is very useful to get the interested output with varying input ranges of parameters and then apply the model and evaluate the performances. The aim of this thesis is to investigate the selected tyre models, and to parametrize them using model based tuning and optimise the model parameters. The tyre models are examined in detail and the physical meaning behind the model behaviour is studied. Based on the insight obtained by studying the various tyre models, recommendations for an improved tyre-handling concept is given.

To achieve these objectives, the following steps are followed:

- Literature study to understand the state of the art in tyre modelling.
- Implementation of the tyre models in MATLAB® and perform manual tuning to fit the measurement data.
- Parameterising the tyre models through Model in the Loop (MiL) technique using AVL Cameo™.
- Evaluate the model-based tuning approach in comparison to the manual tuning approach in terms of time, quality and efforts.

The report consists of six chapters. In the second chapter, the literature study focuses on the tyre models and its influence on the vehicle dynamics. Chapter 3 explains the methodologies and tools used to model the tyres and the model based tuning approach used to parametrize the tyre models.. In chapter 4, the details of the model based optimisation cases used and their numerical settings are discussed. In chapter 5, the results of the model based optimisation with original parameters and the optimised parameters are evaluated for the modelling conditions. Chapter 6 provides the conclusions and recommendations for the work.

2 Literature Study

The following chapter is intended to provide a broad overview of the tyres, its functionalities and the methods how they could be modelled.

2.1 Description of Tyres

In vehicle dynamics, the tyre forces and moments are of real importance in understanding the tyre behaviour. This section will explain the basic tyre characteristics and properties, generation of forces and its influences with respect to few mathematical models. The major tyre models and its applications are discussed in many of the recent literatures on tyres and the readers are recommended[11][17][24][22] to read to get a detailed explanations on the tyre modelling and its description.

Today's tyres and wheels have different roles than the wheels used at their very invention. The tyres are now attached to wheels and generate transitional forces. Hence, they are the elements that hold the vertical force of the vehicle and exert the rolling resistance. Later on, first breaking systems were introduced widening the field of requirements of tyres without a major impact on their construction. Later, after the introduction of braking systems, numerous requirements on the tyres increased and also subjected to change the design and construction of them.

The tyres of today have a complex construction as the needs increased and have to withstand the normal load and the nature of the road surface to exhibit forces to act both longitudinally (acceleration and deceleration of the vehicle) and laterally to give the vehicle a stability especially over the turns and operating at different velocities[2]. This has to be realised under a wide range of external conditions with respect to the durability and reliability. The resistance between the tyres and the road should be maintained low, with respect to the physical setup to the vehicle along with the wheels. But practically, However there is no optimised solution to judge the tyre behaviour at different driving conditions thus leading to varying demands for various needs especially under racing conditions.

The schematic representation of a tyre in cross section is shown in the figure below.

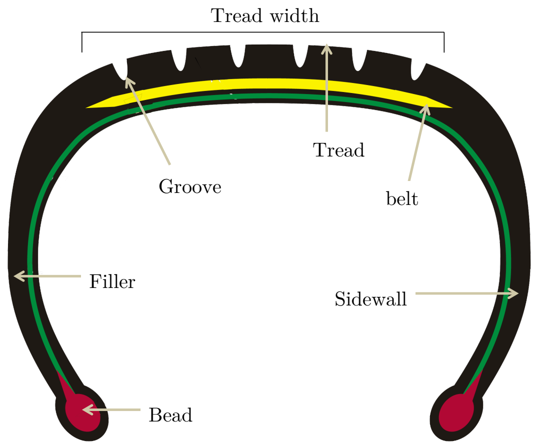


Figure 2.1: Cross-section of a tyre and its elements [2]

The passenger cars are built on the basic idea of the tyre construction is still been in use but with few changes in its structure. Radial tyres are now extensively used in all automobiles with allowable changes in its standard design. As seen from the Figure 2.1, a tyre carcass has several parts such as bead, side wall, belt and plies.

The tyre is almost the composition of more than 20 individual components. The belts are made up of cord or steel. The tread is the exterior part of the tyre that is in contact with the road[2]. The tread is generally reinforced by the cord or steel belt improve the drivability and to reduce the rolling resistance. The contact area, which is formed when the tyre touches the road, is called the contact patch. Grooves are properly designed to circumferentially channel out the water. The lugs are the physical part of the tread that is in contact with road surface and are responsible to dampen the noise levels at different frequencies and to provide traction. Lugs also serve as a marketing tool as it is subjected to the customisation of design. The dynamic forces act on the tyre is literally on the lugs. These forces make the lugs to deform for short time and leave the footprints on the ground. A tread void is the area between the lugs and has a specific influence on the force exertion into the vehicle at deformation. The void ratio is defined as the area of the void to the complete area of the tread which determines for lower values responds with high contact area which leads tot the higher traction values on a perfectly clean dry surface.

Narrow voids are generally referred as sipes, which is responsible to improve the flexibility of the lug for the deformation. This reduces the shear stress in the lug and mitigates the increase in the tyre surface temperature. The bead is the part of the tyre that contacts the rim, which in turn lies on the wheel. The fit of the bead is very important to make sure the tyre does not shift circumferentially when the wheel rotates. The role of the rim is also equally significant as it is a factor in handling characteristics of an automobile. The carcass is the part that absorbs the tension from the tyre's inflation pressure. Therefore, it important to be protected from any damage which in turn saved by the sidewalls.

The lateral force is a main output of the tyre with finite input variations. A tyre produces this force during cornering. This force is mainly studied in detail in this thesis. The centrifugal force occurs while cornering at the centre of gravity. It has several effects depending on the factors such as, the radius of the bend, vehicle's speed, the height of the vehicle's centre of gravity, the track of the vehicle, mass of the vehicle, its frictional properties including the condition of the tyre, weather, and the vertical load distribution in the vehicle.

Another important parameter is the slip angle, which is the angle between the center plane of the wheel and the direction where the velocity is pointed towards (i.e., the angle of the vector sum of the wheel's longitudinal velocity v_x and the sideslip velocity v_y). The rolling resistance has been also discussed which is the resistance to rolling produced by the tyre's contact patch deformation in contact with the road. During cornering, the rolling resistance is increased by a cornering resistance component, which is directly depended on the vehicle speed, tyre pressure, radius of the bend, suspension properties and the lateral slip characteristics. This is also one of the main properties of any tyre, which is directly responsible for the fuel economy of the vehicle. According to the application of the tyre, its properties are been varied.

2.2 Coordinate Systems of a Tyre

It is necessary to explain a coordinate system of axes to describe the tyre characteristics and the moments and forces, which are acting on it with respect to the several parameters. One of the well-known representations of the tyre coordinate system recommended by SAE is shown in the Figure 2.1. The centre of tyre contact with the ground is defined as the origin of the axis system. The X-axis is running forward in a positive direction with the intersection of the ground plane and the wheel plane. The Y-axis runs along the ground plane orthogonally in the right side. The Z-axis is positive downward and its perpendicular to the ground plane. There are three moments and three forces acting on the tyre from the surface. Longitudinal force (Traction) F_x is the force in the X direction of the total resultant force employed on the tyre by the road. Lateral force (cornering) F_y is the force in the Y direction, and Vertical force (Normal load) F_z is the force in the Z direction. On the X-axis, the moment called overturning moment M_x is exerted on the tyre by the ground plane.

Similarly, about the Y-axis, rolling resistance moment M_y is exerted and the moment called aligning torque M_z is exerted about the Z-axis. With this coordinate system, several functional parameters of the tyre can be appropriately defined[24].

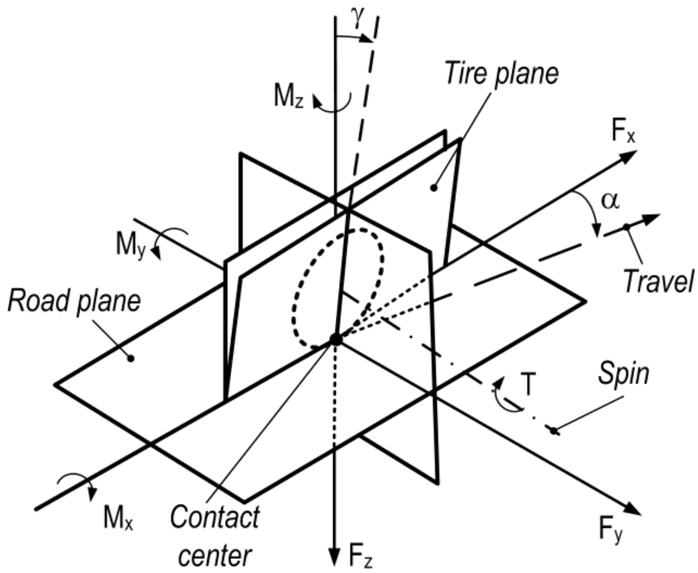


Figure 2.2: Tyre coordinate system[24]

The two significant influencing angles in this axes system namely, the slip angle and the camber angle. Slip angle α and the Camber angle γ (is the angle formed between the XZ plane and the tyre plane). The lateral force at the contact patch is a function of both the camber angle and the slip angle. If the camber effect is nullified, then the lateral force is just the function of slip angle[16]

2.3 Need For Tyre Modelling

In the past two decades, huge improvements have been made in Vehicle dynamics. The vehicles of today are relatively much safe and ergonomically well designed that directly makes the cars comfortable to use. The reason is mainly the incredible progress made on automotive developments like usage of advanced electronic systems, precision engineering and tuning by using modern analysis and simulation methods. This gave an increased quality of the product and conserved development times. Contextually, the importance of modelling and simulation of tyre behaviour becomes extremely important. The tyre is the automotive part where the vehicle is meeting the road.[8]

In the Figure 2.3, we could understand the tyre influences on several aspects of the vehicle behaviour.

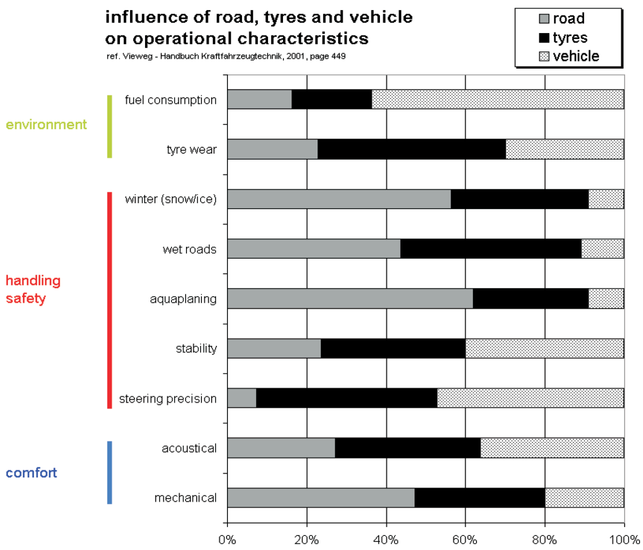


Figure 2.3: Influence of road, tyres and vehicle on operational characteristics[1] [14]

The role of tyres under various operating conditions has specific influences on the whole vehicle. For instance, the Figure2.3 explains how the environmental, vehicle handling and comfort have s specific impact through the road, tyres and the vehicle itself. Importantly, the tyres are the major influencing component that decides the vehicle's total behaviour, stability on different road conditions viz., on snow, wet roads, and also has acoustical and mechanical responses.

2.4 Tyre Models

In this section the important inputs and outputs of a tyre model and features of the different categories of tyre models are explained. Furthermore, three of the tyre models are studied in detail in order to be compared later.

Both physical and semi-empirical models are discussed: TM Simple tyre model, Standard Pacejka model, and Dugoff friction model. Finally, the results obtained through MATLAB®[13] will be plotted on the same chart to compare the differences and similarities between the three models.

A Tyre model calculates tyre forces based on the vehicle condition. Tyre models can be divided into physical and semi-empirical models. The physical models are based on a physical interpretation of the tyre. On the other hand, the semi-empirical models are based on a curve fitting approach. These models depend on non-physical parameters to define the shape of the force-slip. In general, the tyre models often

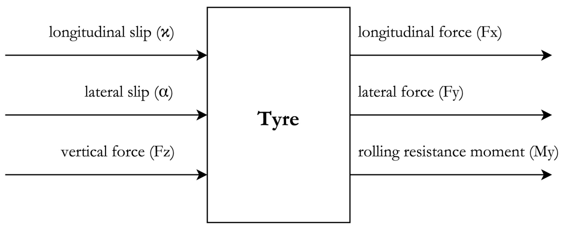


Figure 2.4: Example of few input and output parameters in a tyre model[14]

describe the behaviour of the equilibrium state only.

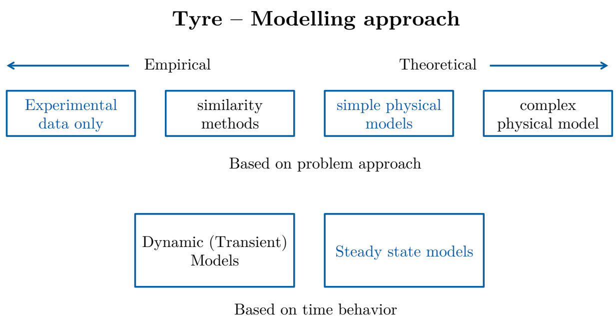


Figure 2.5: Example of few input and output parameters in a tyre model[17]

The figure 2.5 explains how the modelling approach is made with respect tot the experimental and the theoretical means. The blue highlighted modules are taken into account for this thesis.

2.5 The TM Simple Tyre Model

TM Simple tyre model is a very simple tyre model to calculate lateral and longitudinal tyre forces F_y and F_x with respect the given vertical load F_z especially under the steady states conditions. There are few conditions for this model evaluation such as the road is predefined to be even, camber angle is neglected[10].

With C as the bottom point of the wheel, the horizontal force Y can be determined using,

$$Y(X) = K \sin[B(1 - e^{\frac{-|X|}{A}})signX] \tag{2.1}$$

where, X is the relating slip quantity. The coefficients K, B and A are given by,

$$K = Y_{max}; B = \pi - \arcsin \frac{Y_\infty}{Y_{max}}; A = \frac{1}{dY_0} KB (Y_\infty \leq Y_{max}) \tag{2.2}$$

For the given tyre load F_z, Y_{max} is the peak value, Y_∞ is the saturation value or the extreme value, and dY_0 is the initial stiffness value of the curve.

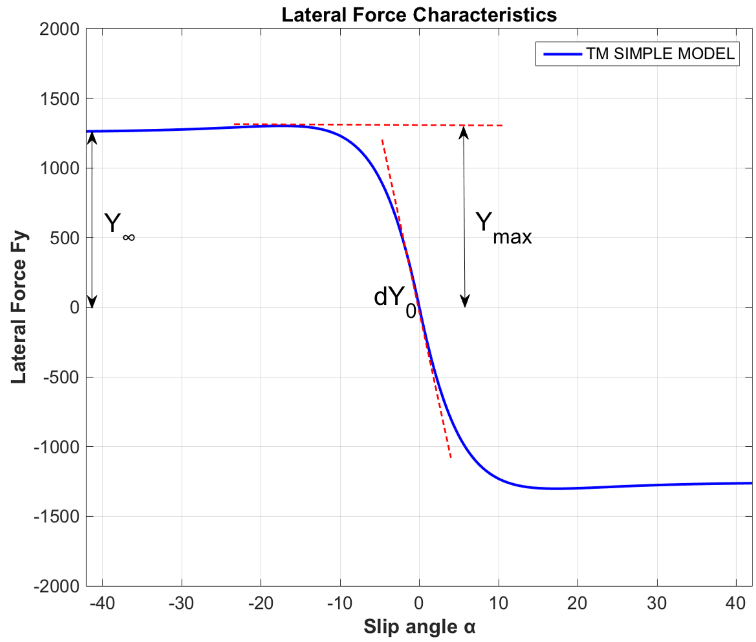


Figure 2.6: Curve produced by TM Simple - Lateral force vs slip angle

The figure 2.6 explains the curve of lateral force vs α by TM Simple model and how the stiffness factor as well as the maximum and saturation side forces influence its behaviour.

In order to consider the influence of the vertical load F_z the polynomials are,

$$Y_{max}(F_z) = a_1.\frac{F_z}{F_{znom}} + a_2.\left[\frac{F_z}{F_{znom}}\right]^2 \tag{2.3}$$

$$dY_0(F_z) = b_1.\frac{F_z}{F_{znom}} + b_2.\left[\frac{F_z}{F_{znom}}\right]^2 \tag{2.4}$$

$$Y_\infty(F_z) = c_1.\frac{F_z}{F_{znom}} + c_2.\left[\frac{F_z}{F_{znom}}\right]^2 \tag{2.5}$$

For the given values Y1 is for F_{znom} (Y_{max1}) and Y2 is for $2 * F_{znom}$ (Y_{max2}), are calculated form the given peak values, the coefficients a1 and a2 can be respectively determined by,

$$a_1 = 2Y_1 - \frac{1}{2}Y_2 \tag{2.6}$$

$$a_2 = \frac{1}{2}Y_2 - Y_1 \tag{2.7}$$

Similarly, the coefficients b1 and b2, are calculated from given initial stiffness values (dY_{01}) for F_{znom} and (dY_{02}) for $2 * F_{znom}$ and c1 and c2 from given saturation values ($Y_{\infty 2}$) for F_{znom} and ($Y_{\infty 2}$) for $2 * F_{znom}$ respectively.
Which, in turn look like,

$$b_1 = 2dY_{01} - \frac{1}{2}dY_{02} \tag{2.8}$$

$$b_2 = \frac{1}{2}dY_{02} - dY_{01} \tag{2.9}$$

$$c_1 = 2Y_{\infty 1} - \frac{1}{2}Y_{\infty 2} \tag{2.10}$$

$$c_2 = 2Y_{\infty 2} - \frac{1}{2}Y_{\infty 1} \tag{2.11}$$

The ratio component in the coefficients i.e., $\frac{F_z}{F_{znom}}$ gives the specific values to parametrise the equation at different F_z and F_{znom} conditions.

The responses of the lateral force at different vertical forces looks like,

The figure 2.7 explains the curve of lateral force vs α by TM Simple model at three different vertical loads F_z viz., 2.5kN, 3.4kN and 5kN and how the stiffness factor as well as the maximum and saturation side forces influence its behaviour.

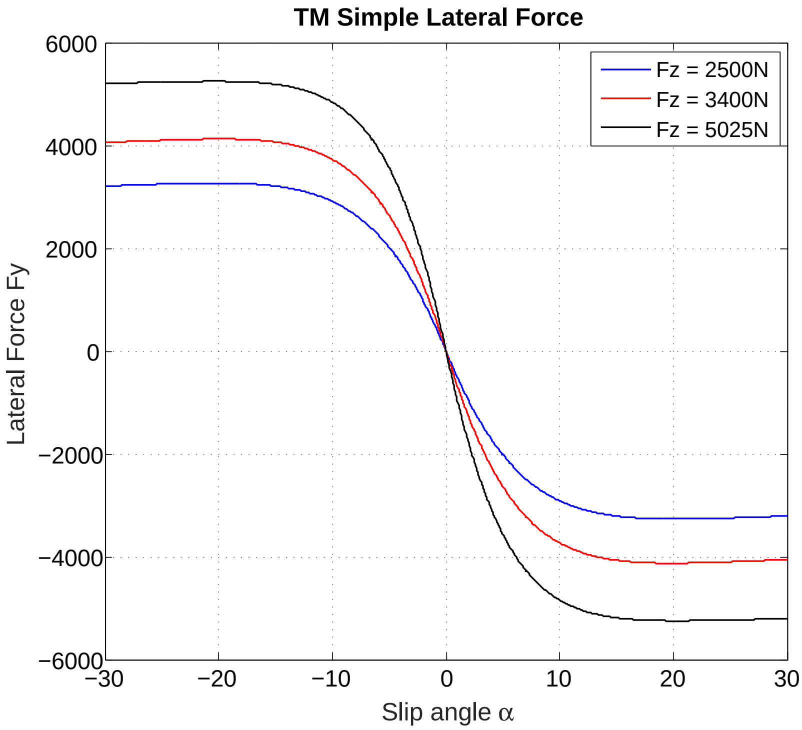


Figure 2.7: TM simple - Lateral force F_y vs slip angle α at vertical forces a). 2.5kN b). 3.4kN c). 5kN

2.6 Magic Formula Tyre Model

One of the famous tyre models known until this day and popular curve fit the steady state tyre force and moment characteristics is called the "Magic Formula" and it was put forth by Pacejka and Bakker in 1992[18]. The simple version of this formula with few influencing parameters is termed as the standard Pacejka Model. The formula uses trigonometric functions to fit the curve to the experimental data[1]. The curve, which is generally the horizontal force equation, has a general form:

For the lateral characteristics of the model as a function of side slip angle α,

$$y = D\sin(C\arctan(Bx - E(Bx - \arctan(Bx)))) \tag{2.12}$$

y - output force of the tyre (F_x, F_y or possibly M_y), x – tyre slip quantity (α or κ), C - stiffness factor, D - shape factor, B - peak factor, E - curvature factor

The tyre-road friction coefficient (μ) is the function of the normalised horizontal force. This can be simply explained as the ratio of the horizontal force to the vertical force[5][23] as shown in the equation 2.13.

$$\mu = \frac{F_H}{F_N} = \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \tag{2.13}$$

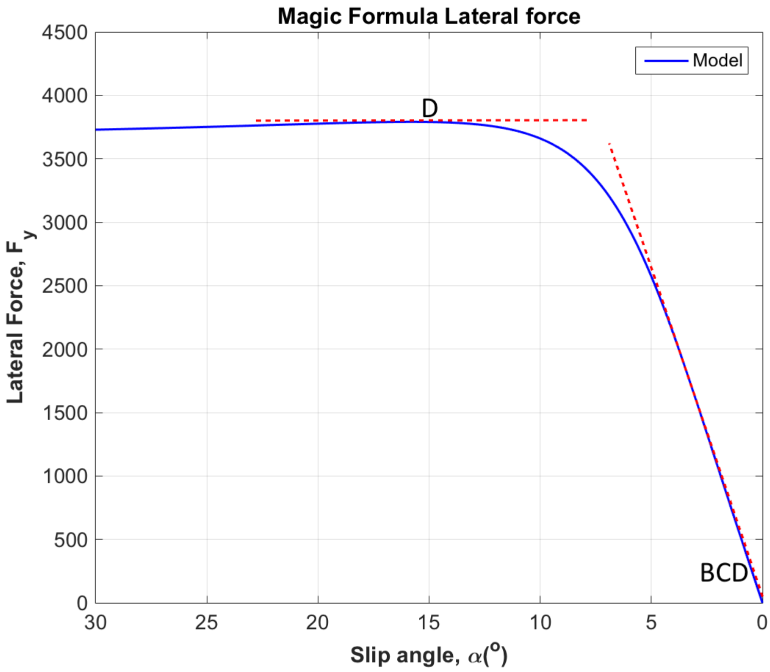


Figure 2.8: Lateral Curve produced by the Magic Formula

The figure 2.9 explains the curve of lateral force vs α by Magic Formula model at three different vertical loads F_z viz., 2.5kN, 3.4kN and 5kN and how the stiffness factor BCD curve as well as the shape and peak factors influence its behaviour.

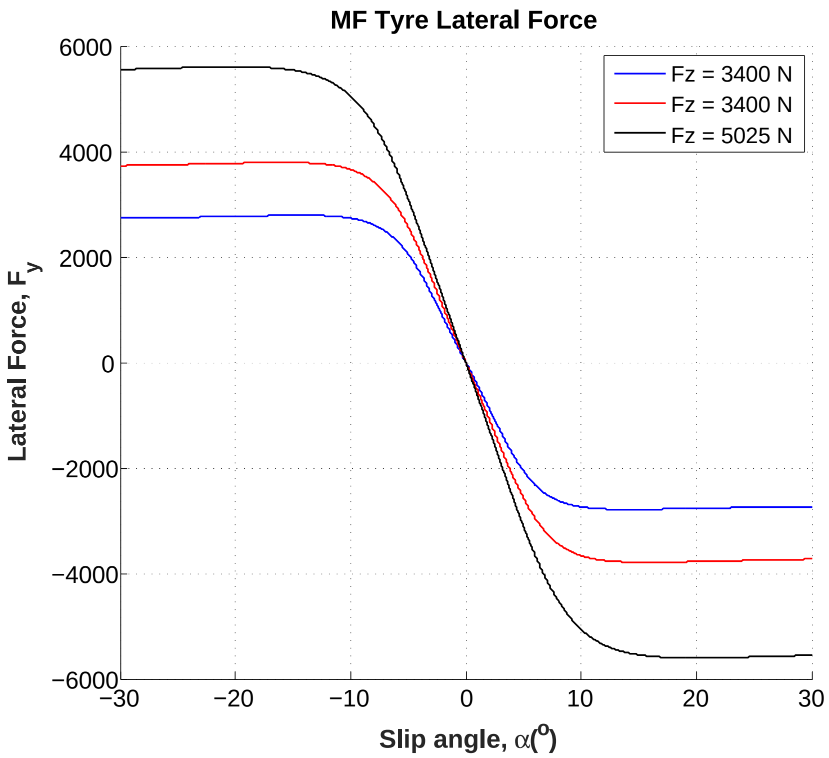


Figure 2.9: MF Tyre - Lateral force F_y vs slip angle α at vertical forces a). 2.5kN b). 3.4kN c). 5kN

2.7 Dugoff Friction Model

The Dugoff model is first documented in 1969[4], and altered for combined slip[8] is the analytical simplified model where the effects of camber and turn slip are neglected. However, the uniform vertical pressure distribution is assumed on the tyre. The individual values for the lateral stiffness and longitudinal stiffness are different in nature. This model deals these two stiffness values separately[20]. The model has a heavy dependency on the friction with respect to the velocity of the tyre[3] [12].

The effects of tyre parameters and the vertical load on the lateral force are very important. During traction or braking, the normal force F_z that indeed supports the vehicle and the longitudinal force at the contact patch that accelerates and decelerates the vehicle depend on the tyre. Theses forces are also influence the lateral force F_y.

According to the classical Law of Friction, as shown in the Figure 2.10 [25], the lateral force F_y, and the braking force (traction force) F_x, acting on the tyre, must always go with the equation,

$$\sqrt{F_y{}^2 + F_x{}^2} = \mu.F_z \tag{2.14}$$

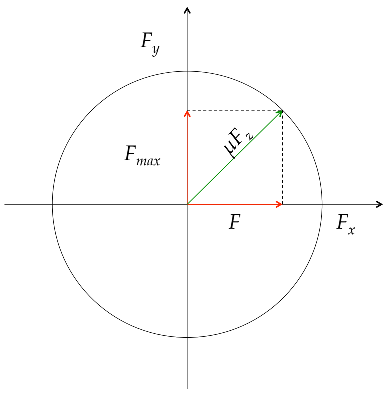


Figure 2.10: Friction Circle[25]

So simply, the resultant of the horizontal forces (both longitudinal and lateral forces) that act on the contact patch between the ground and the tyre, cannot be more than the product of the friction coefficient and the tyre vertical load[15]. So this means, the resultant force vector is restricted to be falling within the circle with radius $\mu.F_z$. This is called the Friction circle[15].

$$F_{ymax} = \sqrt{\mu^2 F_z^2 - F_x^2} \tag{2.15}$$

and if F_x= 0, i.e., if the longitudinal force is zero then, the equation will be,

$$F_{ymax} = \mu.F_z \tag{2.16}$$

In Dugoff's Tyre model, the longitudinal and lateral forces are given by,

$$F_x = \frac{C_l s}{(1-s)}.f(\lambda) \tag{2.17}$$

$$F_y = \frac{C_s.tan\alpha}{(1-s)}.f(\lambda) \tag{2.18}$$

Where λ is given by,

$$\lambda = \frac{\mu.F_z(1-s)}{\sqrt[2]{(C_l.s)^2 + (C_s.tan\alpha)^2}} \tag{2.19}$$

and

$$f(\lambda) = (2 - \lambda)\lambda, if \lambda > 1 \tag{2.20}$$

$$f(\lambda) = 1, if \lambda \leq 1 \tag{2.21}$$

$$\mu = \mu_0(1 - eV_s) \tag{2.22}$$

μ_0 - nominal friction coefficient, e - velocity dependency factor, C_l - longitudinal slip stiffness, C_s - lateral stiffness.

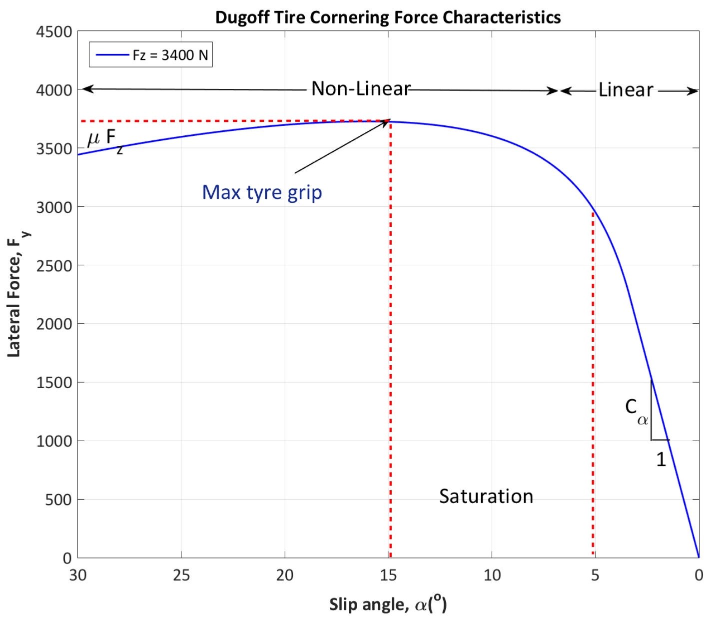


Figure 2.11: Dugoff Tyre -Lateral force characteristics

The figure 2.12 explains the curve of lateral force vs α by Dugoff friction model at three different vertical loads F_z viz., 2.5kN, 3.4kN and 5kN and how the stiffness factors both longitudinal and lateral paramters as well as the friction coefficient influence its behaviour.

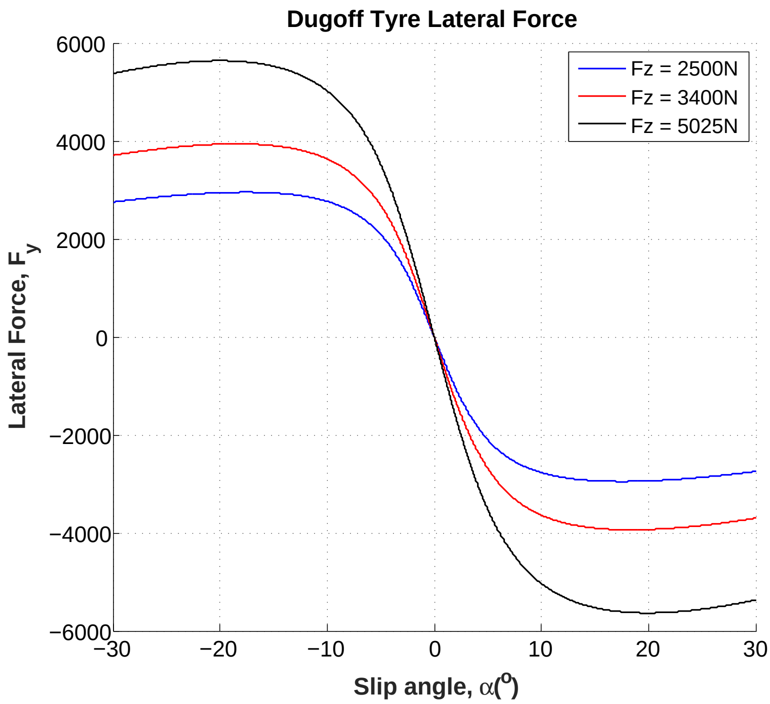


Figure 2.12: Dugoff Tyre -Lateral force F_y vs slip angle α at vertical forces a). 2.5kN b). 3.4kN c). 5kN

3 Methodologies and Tools

This chapter is intended to describe the methods and tools used to reach the result and the analysis.

The linear and non-linear behaviour of the tyres are realised through the tyre models. However, this is the only complement to the experiments and to the theory, which could be integrated together. The computational accuracy of these mathematical models describe dint he previous chapter 2 would need a tool to perform these analysis and identify the behaviour of the model responses. In this work, MATLAB® ® and AVL CAMEO have been used as the modelling tools and perform optimisation using model based tuning approach. This is intended to improve the understanding of the optimal solution for the model parameters discussed and to perform the validation to improve the experimental settings.

The system integration and the subsequent work flow is described in the

The concept of computation through models have realised by combining the data from the experiments and the theory. Nevertheless, it is understood that sometimes the experiment in the automotive engineering are too large, expensive and time consuming. The validation of such experiments has to be scientifically investigated. The computational modelling approach has enhanced the quality of work, reduced the experimental time.

By controlling the input model variables, the target functions and vectors are realised in the simpler way. The experiment of this thesis is focused on the steady state lateral characteristics of the tyre using the test bench measurements with varying inputs and conditions. These experiments have given a set of data and by using the models with the defined mathematical expressions and predict the behaviour of the experiments.

The experimental set-up has been made with specific limitations to understand a specific behaviour of the tyre. So the here lays the requirement to use the simplified versions of mathematical models to ease the governing principles and physical laws.

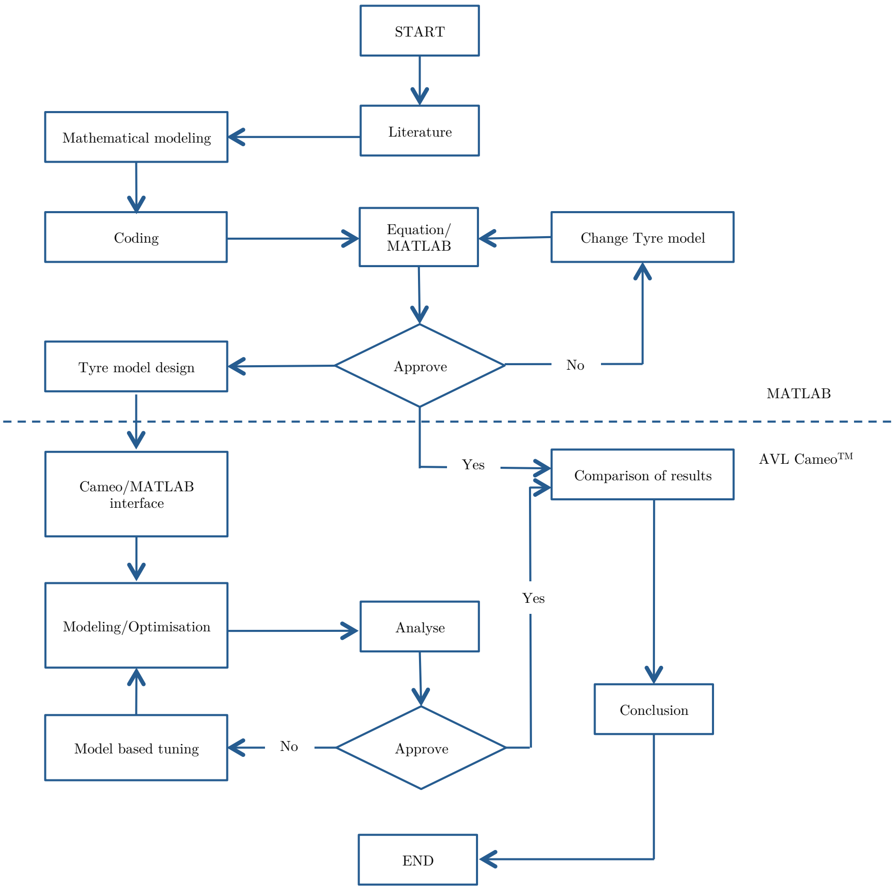


Figure 3.1: Work flow from MATLAB® to AVL CAMEO™

3.1 Test Bench and Tyre Measurements

The test bench measurement at the facility of Graz University of Technology was developed for the examination of the durability and fatigue of the components of the suspensions in a quarter car (i.e., the isolated wheel has been used to study the tyre behaviour with a controlled input variation set-up)[9]. The standardised outer drum diameter of the test bench is 1219mm. With a maximum angular velocity of $25°/s$, it could generate $\pm 15°$ of slip angle α.

The tyre used is of the radial type: 205/55/R16. The speed of the drum could be varied from 0 to 1300 rpm. The normal load (vertical force) were realized using a vertical hydraulic cylinder of maximum of 25kN cylinder force.

The parametrisation of the test bench measurement data using TM Simple[11], has been setup as the first goal. Later, Standard Pacejka MF tyre model and Dugoff tyre model have also been studied to parametrise the friction component and the lateral behaviour of the tyre measurements. The pure lateral force generation has

Figure 3.2: Test bench set up at Institute of Automotive Engineering, TU Graz[9]

been intended to achieve with zero camber influence. The tyre measurements were recorded with 2500N, 3400N, and 5025N as the vertical loads F_z.

For the steady state tyre characteristics, the drum of the test bench has been setup at the velocity of $v_x = 60$ km/h. At the targeted constant velocity as mentioned, the drum at its Z-axis rotates to produce the side slip angle between the tyre and drum. The incremental drum slip angle is between $\pm 12°$ with a step size of 2° and 4° are specified. After the dynamic response of the tyre deformed with respect to the applied vertical load, the lateral force is measured and used for the mathematical modelling. The interested target value and the measured data are saved in the .kal format used to model manually.

Table 3.1: Contents of the test bench data

Experimental measurement values at pure slip conditions		
Pure cornering	Vertical load (N)	2500, 3400, 5025
	Side slip angle	-12 deg to +12 deg
	Camber angle	0 deg
	Longitudinal slip	0%
	Test velocity	60 km/h

3.2 Overview of the Test Bench Measurement Data

The overview of the test bench measurement data in terms of values are given in Table 3.2. For instance, at the vertical load $F_z = 3400$ N, the lateral tyre force measurements are graphically visualised in the Figures 3.3, 3.4 and 3.5.

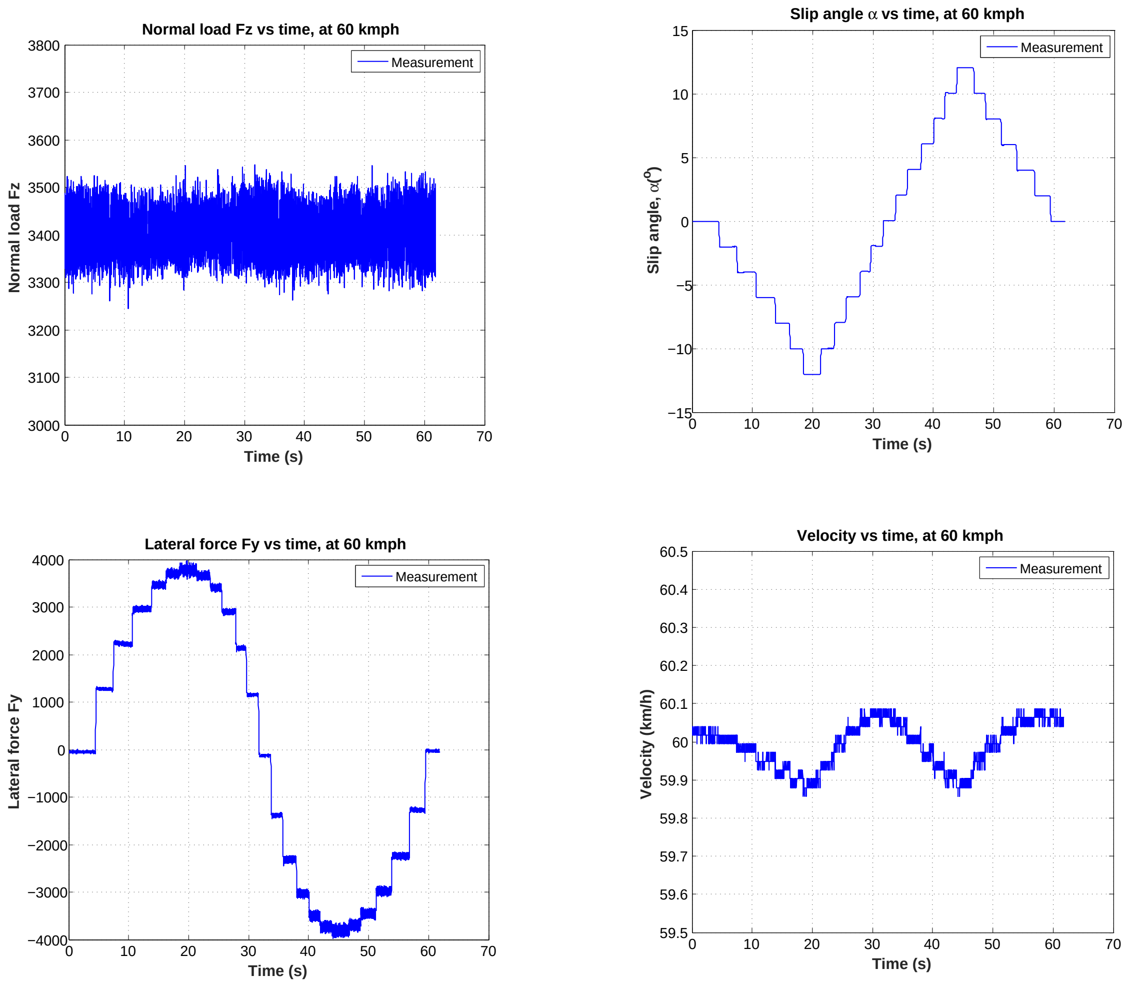


Figure 3.3: An example measurement manoeuvre with constant vertical load F_z= 3400 N, slip angle $\Delta\alpha = 2°$ and the drum velocity $v_x = 60$ km/h

In the figures 3.4 3.5, one could see the interaction of the lateral force with respect to the slip angle. The linear beahaviour of the lateral force is realised at the lower slip angles and at the higher slip angles it is highly non-linear.

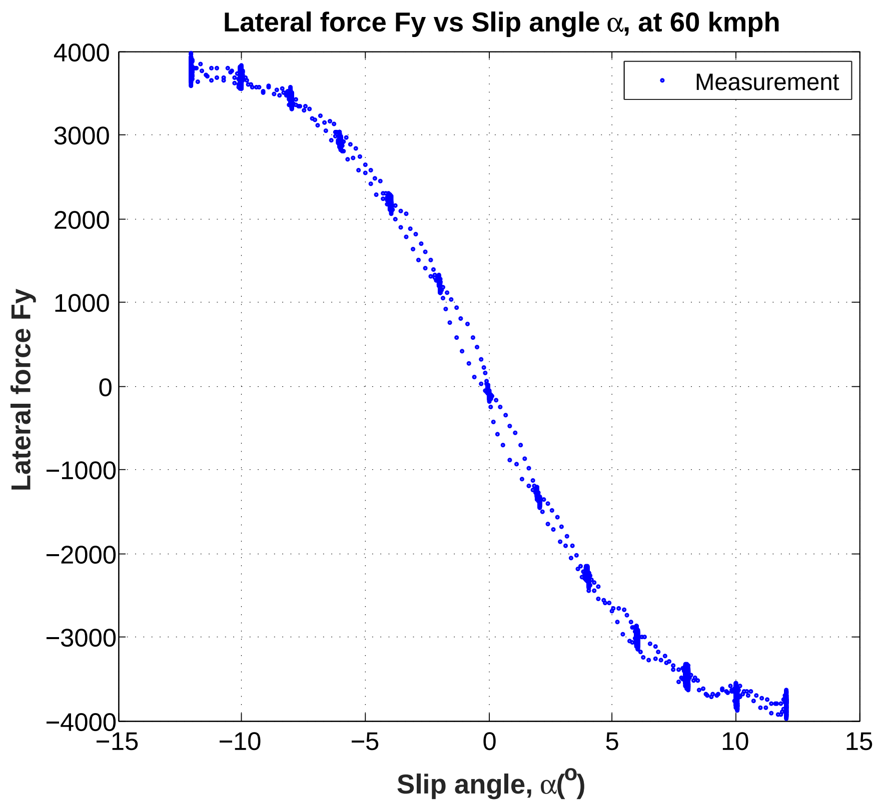


Figure 3.4: Lateral force F_y vs Slip angle α from the measurement data at $F_z = 3400$ N

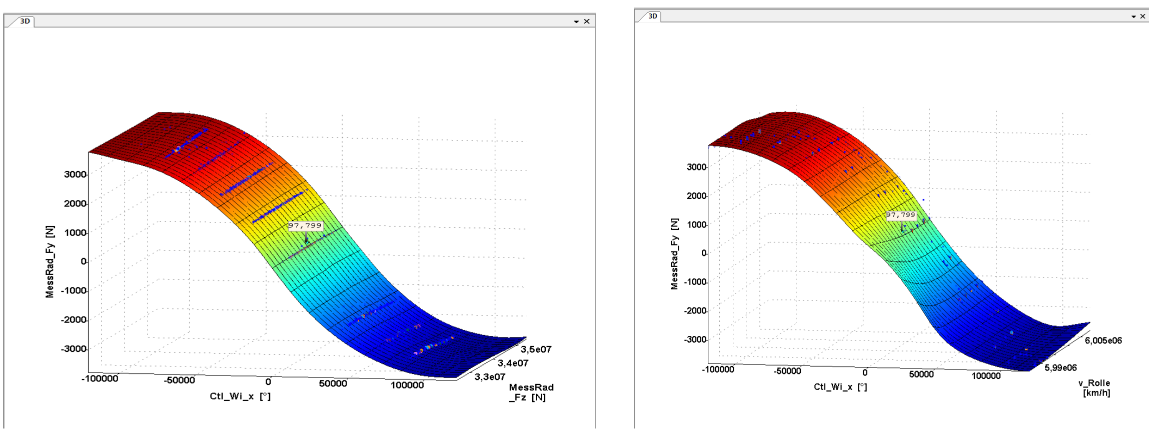


Figure 3.5: Lateral force F_y vs Slip angle α with F_z and $Velocity$ influence modelled in AVL Cameo™

3.3 MATLAB Implementation

In the current scenario, especially to this topic, MATLAB® served as a tool for the technical computations and visualisation within an integrated environment as shown in the Figure ??.

After the derivation of equations for the tyre models in the previous chapter, it has been essential to develop their models in a program that can conduct the simulations and could be used to analyse the results. Initially, MATLAB® is used to develop the mathematical models and the requirements for the exchange of experimental and parameter data. Based on the model requirements, the on-linear tyre equations are developed in .m codes and the set of parameters are saved separately for each tyre model.

3.4 Model Parametrisation

In experimental procedure of the tyre models, the lateral characteristics with respect to the side slip angle α has been the target behaviour evaluation. The parametrisation method and the results are discussed in the following sub sections.

This "one-parameter-at-one-time" method is the iterative approach to a local, "obvious" optimum. This describes depending on the start point of paramterisation, the results are subjected to vary. On the other hand, two calibration experts will generally come to different results, which are difficult to reproduce. It is also hard to solve target conflicts near to the limit.

Pragmatically, no systematic knowledge about the function behavior is generated, which could help to find one global optimal setting, to solve target conflicts and to predict the behaviour of other calibration variants (e.g. passenger car and commercial vehicle variants).

3.4.1 TM Simple Parametrisation

The intended parametrisation data consists of the result of the test bench deformation of the tyre using the experimental setup and modelled using TM simple tyre model developed by W. Hirschberg et al[11]. The following parametrisation has been performed in order to identify the steady state parameters in the model.

- The cornering (lateral) stiffness of the tyre at the lower slip angles $\alpha - dY_0$
- The maximum value of the cornering force Y_{max}
- The saturation value of the cornering force Y_∞

By theory, the parametrisation needs two sets of data, i.e., one at F_{znom} and the second is $2 * F_{znom}$. This model works on the approach of identifying the physical parameters and based on a specific vertical force to the nominal force ratio. The coefficients of the equations are identified and the values are obtained to closer digits of all F_z loads by manual tuning method.

The following tables 3.2 3.3 values of TM Simple parameters for the manual parametrisation will give the reader an understanding about the above explanation.

At any given F_{znom} and for loads F_z = 2500 N, 3400 N, 5025 N,

Table 3.2: Manual tuning - TM Simple Parametrisation values

TM Simple parametrisation values		
Parameters	F_{ymax} at F_{znom}	3295, 4155, 5245
	dY_0 at F_{znom}	535, 715, 1020
	Y_∞ at F_{znom}	3095, 3945, 5155

Table 3.3: Manual tuning - TM Simple coefficients values

TM Simple Coefficients values			
	Fz 2500N – 3400N	Fz 2500N – 5025N	Fz 3400N – 5025N
a1	5470.6	5404.3	5330.5
a2	-1345.6	-1255.4	-1205.5
b1	762.6	764.68	767
b2	-47.6	-50.429	-51.995
c1	4943.1	4923.3	4901.3
c2	-998.09	-971.17	-956.27

In the Figure **??**, the curve behaviour is modelled according to the measurement data and extrapolated to see the digressive bahaviour of the model at higher slip angles.

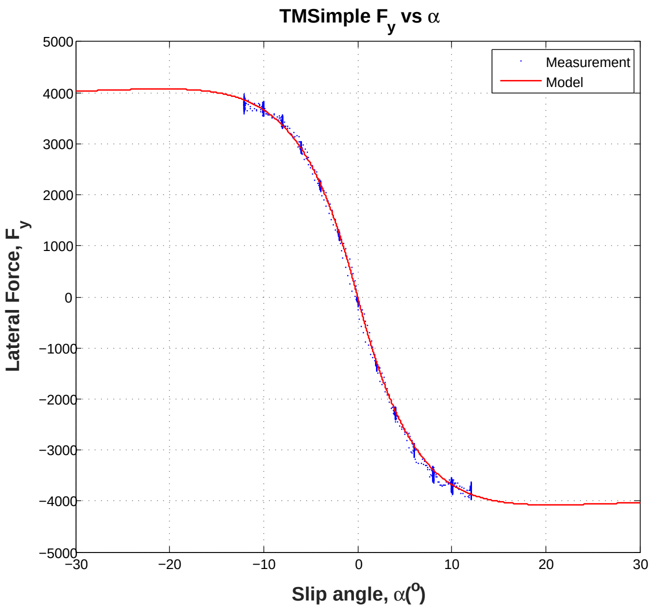


Figure 3.6: F_y vs α after parametrising using TM Simple

3.4.2 Magic Formula Tyre Parametrisation

For the parametrisation of the MF[1] model, the parameters of the model are equated by the formula mentioned in the chapter 2 namely,

C - stiffness factor, D - shape factor, B - peak factor, E - curvature factor, μ - friction coefficient (function of D), c1 - coefficient of B, c2 - coefficient of B.

The following table 3.4 gives the values of Magic Formula parameters for the manual parametrisation will give the reader an understanding about the above explanation.

Table 3.4: Manual tuning – Standard Pacejka Model values

Standard Pacejka model parametrisation values		
Parameters	C	1.2
	E	-2.5
	μ	1.115
	$c1$	365000
	$c2$	6400

In the Figure 3.7, the Magic Formula lateral force curve is fitted according to the measurement data and extrapolated to see the behaviour of the model at lower and

[1]Magic Formula Tyre Model

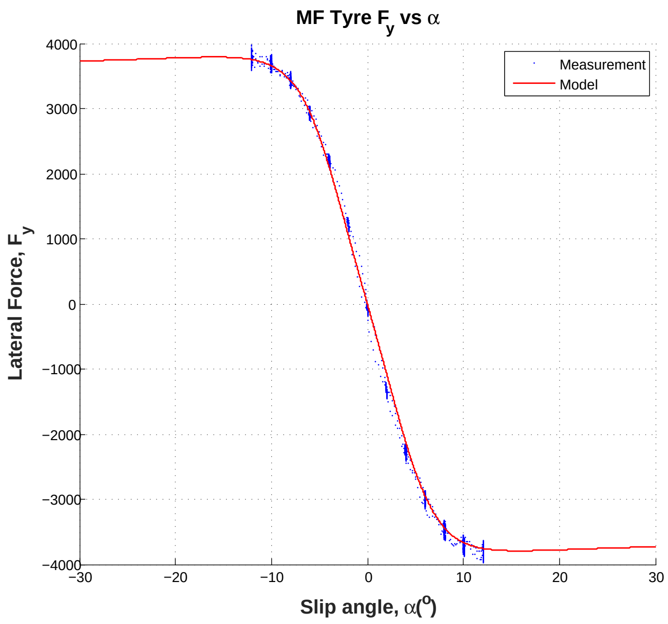


Figure 3.7: F_y vs α after parametrising using Magic Formula

higher slip angles.

3.4.3 Dugoff Tyre Parametrisation

For the parametrisation of the Dugoff tyre model, the parameters of the model are equated by the formula mentioned in the chapter 2 namely,

μ_0 - nominal friction coefficient, C_x - longitudinal slip stiffness, C_y - lateral stiffness.

The following table 3.5 gives the values of Magic Formula parameters for the manual parametrisation will give the reader an understanding about the above explanation.

Table 3.5: Manual tuning – Dugoff Tyre Model values

Dugoff Tyre model parametrisation values		
Parameters	μ_0	1.12
	C_l	46500
	C_s	36500

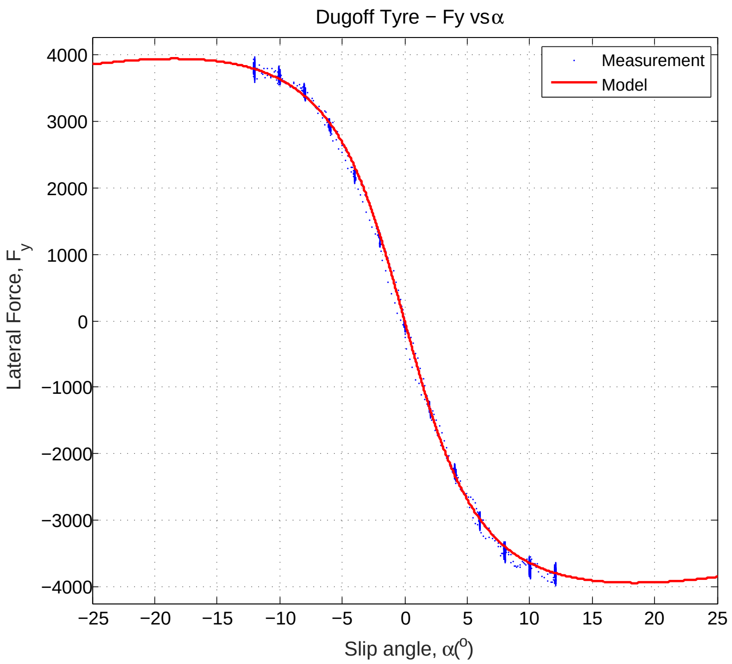


Figure 3.8: Parametrised Dugoff Tyre model

In the Figure 3.8, the Dugoff lateral force curve is fitted according to the measurement data and extrapolated to see the digressive bahaviour of the model at higher slip angles.

3.5 AVL Cameo^{TM}

AVL Cameo^{TM} is the software, used for the purpose of engineering calibration especially for the Gasoline and Diesel Engine applications. However, the software showed potential area of expansion in the Powertrain solutions. Currently, it is acknowledged in the field of Automotive engineering as a powerful tool that gives the customer one window to handle a complete calibration and tuning process, which has the functionality from data collection to mapping. This software environment has the unique feature that combines the complete calibration workflow and fully automated testruns to provide very high efficiency. The control of the operating environment is the advantage for the customer handle the software more simplicity that in turn gives user-specific solutions and adaptations[19][7].

The reason why this software has an edge of its kind is by employing reduced number of prototypes as to reduce the measurement time and conservation valued time of the customer. The testruns are serially evaluated by the modelling and mapping options that in turn give the options of high quality optimisation. This continuous workflow design helps in obtaining the consistency of the calibration process. The objective of using this also includes the measurability, traceability and the reproducibility. The main element in which AVL Cameo^{TM} is used in this project is the methodology called DoE (Design of Experiments). This has been acknowledged widely for developing a possible set of input parameters, which could be useful for studying a mathematical model efficiently. The non-powertrain applications are now being the active expanding opportunities of the software, which includes Tyres, Steering Systems, ADAS, HVEC Systems, Electrical & electronics vehicle controls, and Chassis System & Controls [21].

3.6 DoE - Design of Experiments

DoE is a formal mathematical method for logically planning and steering scientific studies that change empirical variables in a combined manner in order to regulate their effect of a given response. The set of input variables certainly define the operating range with a minimum sample size within which the whole study is been done to gain maximum amounts of possible information. The quality and the nature of the output responses will completely depended on the empirical variables[7].

Thus DoE remains a best-used strategy of experimentation. Numerous statistical methods are available now for the reach of people to understand the ways to perform DoE. The methods include OFAT (One Factor At a Time), Factorial approach, Two-level full factorial (2^k), Optimal design and so on. All design of experiments is based in the similar statistical principles and methodologies of analysis so called ANOVA, which is primarily tested with a statistical significance and regression analysis. These methods allow the user to screen the influencing variables, build a mathematical model, to get predictive equations and also to optimize the response[7].

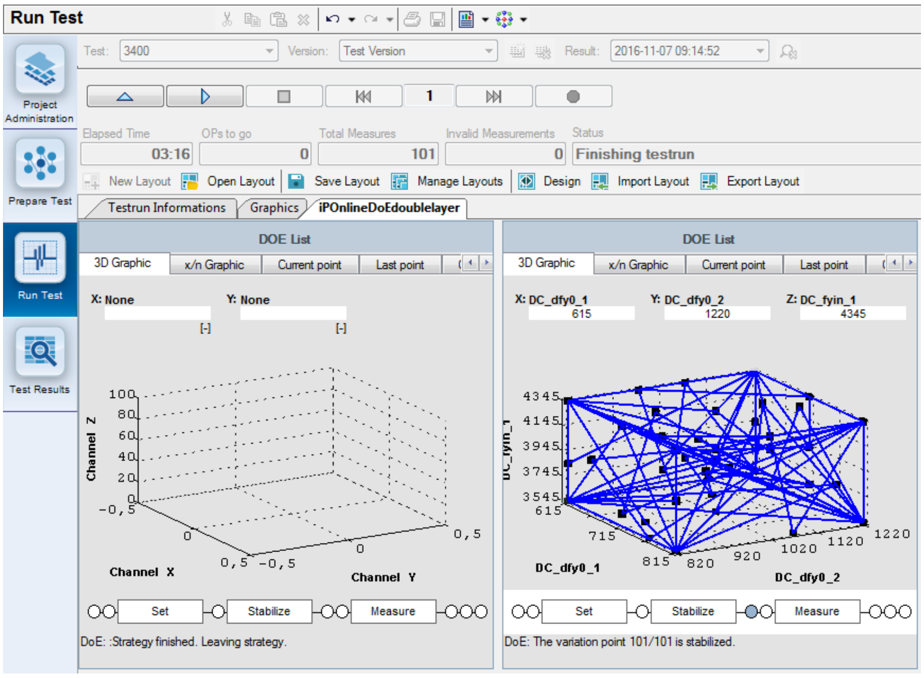


Figure 3.9: Test run after the start of DoE with 100 points

3.6.1 S-optimal design

The optimal representation of the DoE process often referred to ODoE (Optimal DoE) with respect to some statistical criterion. This method allows the parameters to be estimated within the true value and with minimum variance. So this leads to lesser number of experimental testruns to estimate the set of parameters with the same precision, by directly reducing the time and cost of experimentation. This type of DoE could accommodate multivariate environment and optimised when the design space is constrained. This gives the possibility to identify the feasible and non-feasible zones in the response models [7].

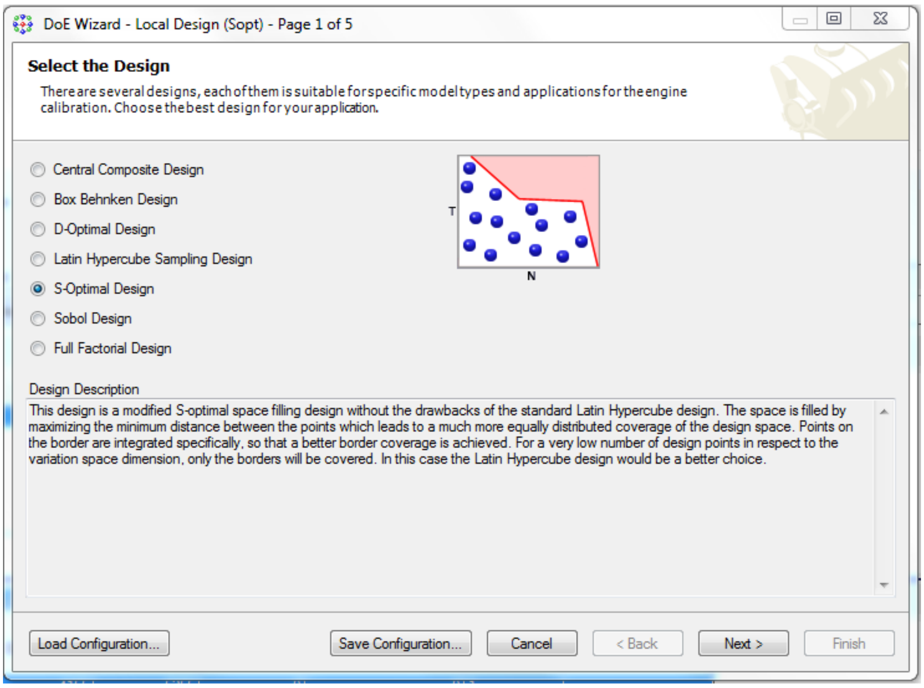


Figure 3.10: S-Optimal design in AVL Cameo™

3.7 Model-Based Tuning

Model based calibration or tuning (MBT) is the statistical model based approach that is helpful in reducing the number of actual test runs and describes the UUT (Unit Under Test) within the design space[19] [21]. With the lower set of measurements, it is capable of generating test data points in order to produce behaviour models. Nevertheless, these models are useful to develop a precise and robust tuning output according to the specific target in optimisation as shown in the Figure 3.11.

Unlike the manual tuning method, MBT acquires an advantage of using minimal variation of parameters through the random collection of data. The quality is better for any user with beginner level expertise to handle, because the start point of the process is the same and end up with a global optimum result. This is also traceable and reproducible. The control of the desired out response is also made sure with the target constraints.

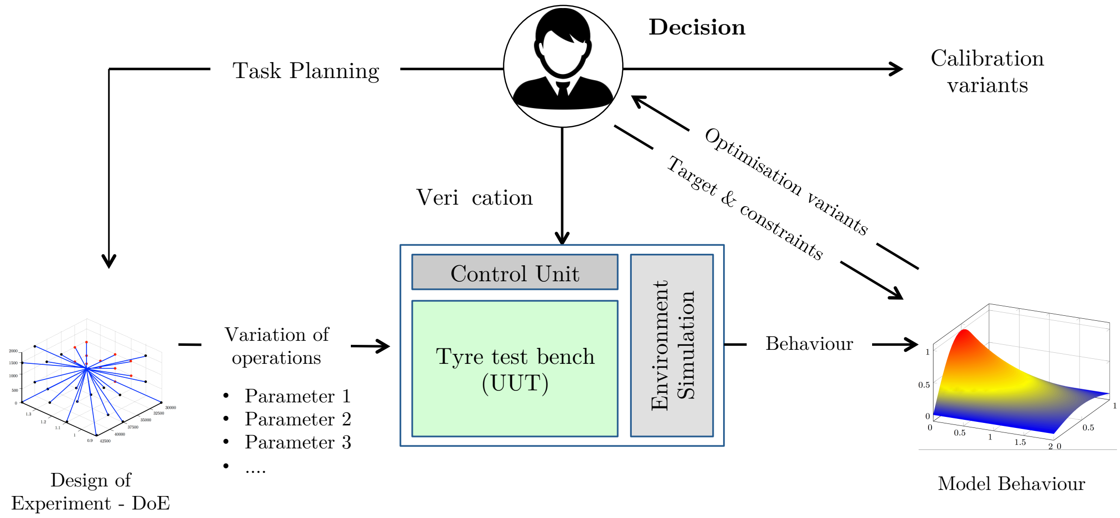


Figure 3.11: Model-Based Tuning in AVL Cameo™ [19]

First the decision has to be made on the interested output responses after influencing the UUT (Tyre test bench) with the specific set of input parameters. This allows planning for the set and nature of the measurement data generation. Here the CAMEO™ is used to plan the test generation. To bring in the access to the developed mathematical model from MATLAB®, the interface should be connected to the software. This is called SiL (Software in Loop) setup. The workflow is now completed after the interface is successfully made to CAMEO with MATLAB® and this could be confirmed with a dialogue message on the screen.

After the DoE test plan and limits setting 3.12, the required parameter setting are defined with ranges (i.e., the maximum limit and the minimum limit of every interested input parameter). After the test run, the necessary measurement results were saved in CAMEO. There is always a possibility to check the raw measurement data in the tabs display in the window in order to check the plausibility and possibility of the generated measurement. It is also recommended to check the data as the user could get a rough idea of how one could compare the measurements to the expected values and also get an idea of the possible errors which could have been occurred while the test has run.

Based on the optimisation requirement, optimisation algorithms could be made use for multi-objective response. The Pareto front trade-offs could be done in this scenario, because the software should understand the interaction of numerous input parameters used and if the results go well with the targets and limiting constraints.

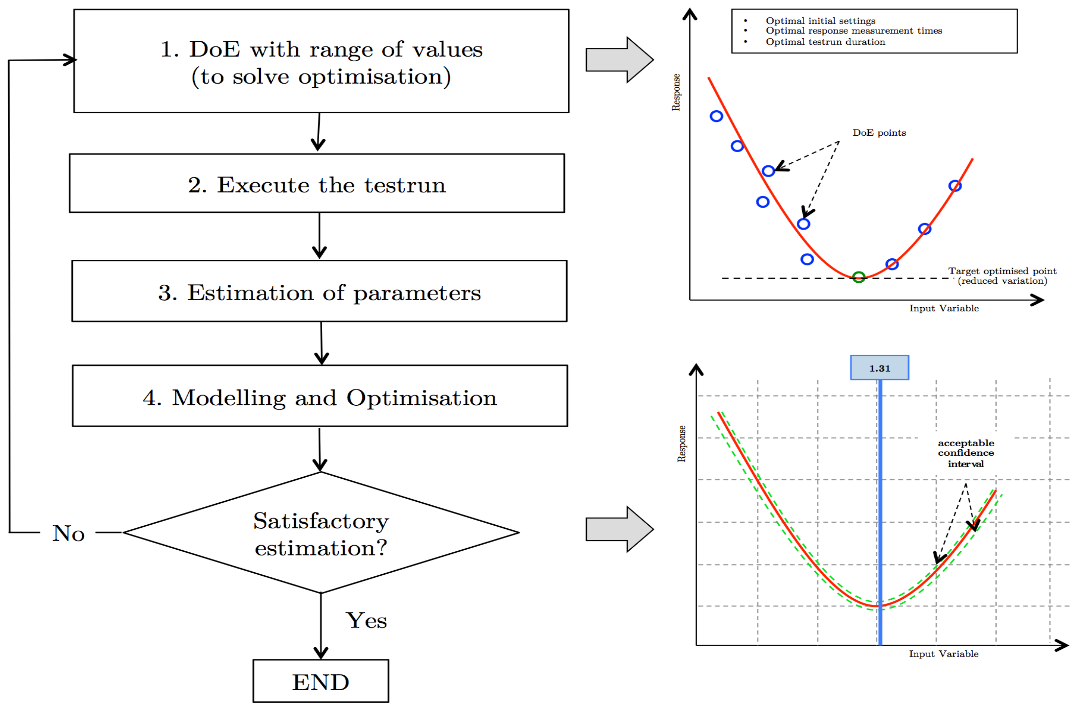


Figure 3.12: Model based DoE procedure in AVL CAMEO^{TM} [6]

The action taken with the results of the trade-off has higher accuracy.

Before considering the result analysis, a final verification on the values is carried out. Tests have been concentrated on and around the optimum points and still lays a possibility of seeing other feasible points within the generated range of the input variables or simply within the operating ranges of the input variables by means of Pareto front. If these verification data points look closely with the modelled results then the models developed are agreed. Then the engineer could use the results of Optimisation and further make a decision to perform the desired tuning setting.

Then consequently, the user can use the model-based approach to minimise the deviation test measurement data from CAMEO after the optimisation with the real tyre model responses. The defined measurement results are carefully examined with lenient constraints. Thus the robustness of setting the tuning process could be evaluated in a wide range of vehicle manoeuvres with lower number of test runs.

4 Test preparation and execution

In this chapter the optimisation procedure used in AVL Cameo^{TM} and the system set up with MATLAB® to model and optimise the responses have been discussed.

The structure of the workflow of the implementing MATLAB® into AVL Cameo™ is figuratively described in the Figure 4.1.

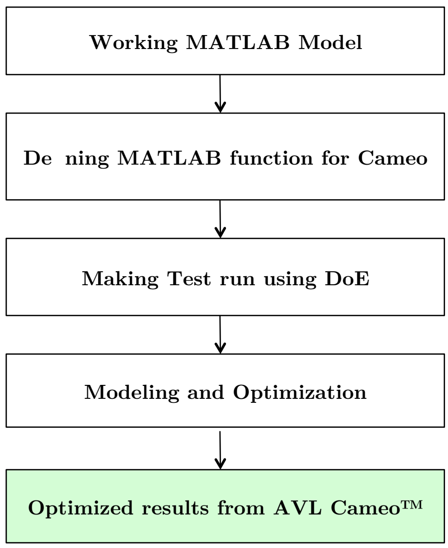


Figure 4.1: Operational Workflow from MATLAB® to AVL CAMEO™

The first step in this workflow is the development of the mathematical models is already discussed in the previous chapters 2 and 3. It is essential to the reader to understand the further steps to get an idea how to implement the MATLAB® into the AVL Cameo™ such as defining the range of the design variables (input parameters), followed by the preparing the test runs using DoE variation list, modelling and optimising using the software's in-build optimisation algorithms and then to analyse the response results. However, it is also essential to compare all the results for different tyre models.

The optimisation procedure (Figure 4.2) is done in two significant subroutines viz.,

1. Test & Measure (Sub-routine 1)
2. Modelling & Optimisation (Sub-routine 2)

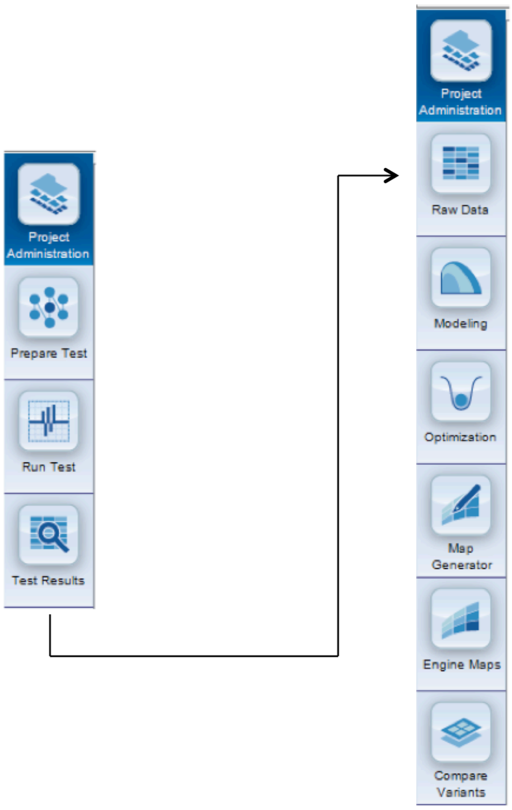


Figure 4.2: Internal work flow in AVL CAMEO^{TM}

4.1 Preparing DoE for Tyre Models

The purpose of optimisation in calibration or tuning is that with the minimum number of functional inputs to obtain the maximum performance of the output with very less time. The modelling and mapping solution of AVL Cameo^{TM} does this job quite well. The set of optimisation procedures in the software allows the engineer to carefully check the degrees in which the test has been conducted with respect to the target functions to understand the responses and its efficiency to match the test data. The goal of optimisation procedure carried out in this project is to minimise the variation between the test data and the model response and to find out the best possible solution. There are many common calculations to achieve this goal, but the effective approach is the normalised-difference method between the steady state points of the measurement data and the model curve.

The first aspect of entering the solution zone is the method selection. The second aspect is the approach of setting up the procedure and third is to post-process the results and validate them. The system has been setup in such a way that the incoming pair-up system MATLAB® is identified by the Cameo™ using a system interface that includes a set of MATLAB® codes to access the mathematical model and to recognise the input channels or the input parameters. All three tyre models that have been discussed in the chapter 2, are with the normal load of 3400 N as the nominal vertical load exerted by a passenger car is around 3000 N. The corresponding measurement data set is taken into account for the modelling and optimisation procedures.

4.1.1 Function Overview

For every tyre model used, MATLAB® codes were developed and a function is created to give an access to CAMEO. The lateral force characteristics are studied in detail with a function of slip angle. Thus, the function tries to ensure that, the tyre follows the reference force profile as closely as possible. The description of the functions and the parameters are discussed below.

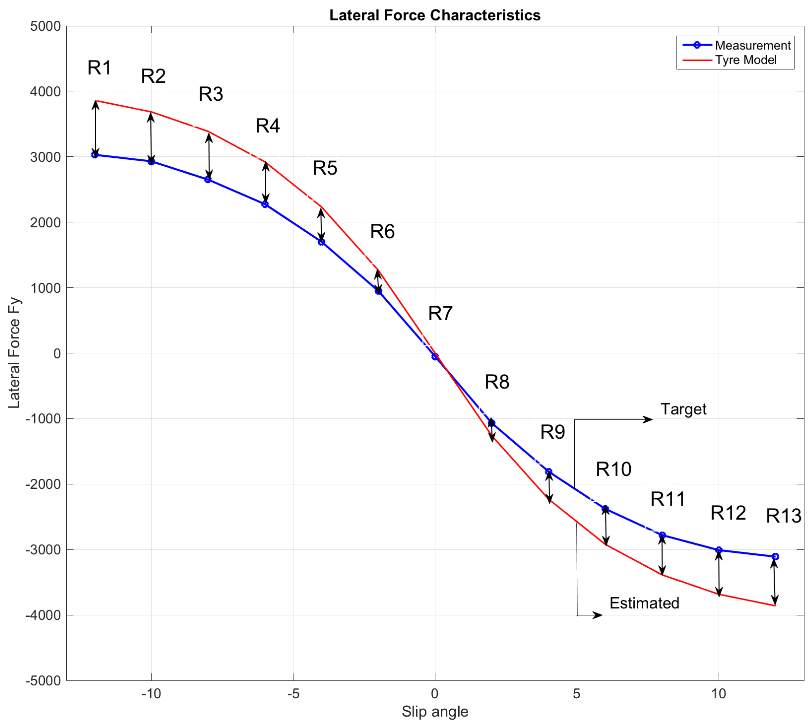


Figure 4.3: Response difference method used for Model-based tuning

As described in the mentioned Figure 4.3, for every model this approach has been used. The interested steady state points in the graph are from responses R1 to R6. The responses R8 to R13 are just the symmetry of the responses R1 to R6. R7 steady state point which posses a average offsetting difference forces of 50 N and have constant difference values in the universal set of DoE and modelling. Thus responds with a poor predicted model behaviour as shown in Cameo Modelling procedure.

Before starting the system interface, defining the channels and methods for Cameo™ to work is essential. Then the connection statues of the MATLAB® system and AVL Cameo™ have to checked. There is an indication of corresponding test name, its version and the result on the top pane of the window. In the channel definition, the input parameters (variation channels) have to be mentioned in a specific format so that the Cameo™ could understand assigned channels are the inputs and finds them in the mathematical models. The methods define the model codes that have been included to pair-up with the software.

4.1.2 Design Variables

In order to calibrate the function for the reference model, few input parameters or the design variables are discussed for every model. According to the Cameo™ nomenclature, the input parameters are called *variation parameters*.

For instance, if three input parameters are to be studied in a range in the tuning task is shown in Table 4.1 and the window in Cameo™ 4.4.

Table 4.1: Range of variation parameters

Typical range of variation parameters (input channels) used in tuning task			
Design Variables	From	To	Start
Variable 1	615	815	715
Variable 2	820	1220	1020
Variable 3	4855	5555	5255

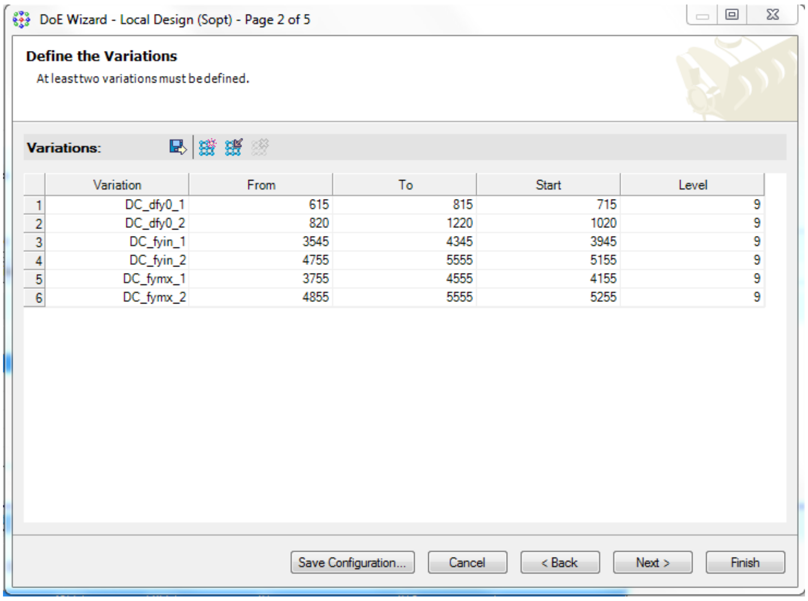


Figure 4.4: Typical design variation table in AVL Cameo^{TM}

4.2 Test & Measure

Primarily, the task has to be started by opening a project and this is also the start of the sub-routine 1. The prepared set of DoE ranges have to be set in the next step of the sub-routine 1 after setting up the test project for the desired tyre model. The label is given to all respective projects with a unique name.

Under the Testrun Strategies tab, the definition of a sub test has to be given. This classifies the preparation of the DoE in two levels as the two level DoE approach is selected. In the first layer of the DoE list, the operating point is defined with the options of the operating point selection, its type, and the respective group. This defined operating point gives access to proceed to the second layer of Testrun Strategies tab where the original testrun could be done.

In the second layer, where all the test operations are to be carried out, the following steps have to be done in order to define the range of the values of the input parameters and the actions (defining the system to be included in the Cameo^{TM} for example: MATLAB®), and the output responses in the measurement tab.

In the variations sub-tab, the Channels are selected. Then the MATLAB® system has to be included and defined when the system should be accessed by the software and also about the time of stabilisation while preparing the DoE. Here, if necessary the reference or the grouping variable is also included and this could be studied in the modelling section and used to solve the intended purpose. In the measurements tab, the list of responses is included.

In the Variation list, the creation of DoE becomes the next step, where the use could select the design type. There are several designs available and each of them is suitable for specific model types and applications for the model calibration.

The lists of design given are:

1. Central composite Design
2. Box Behnken Design
3. D-Optimal Design
4. Latin Hypercube Sampling Design
5. S-Optimal Design
6. Sobol Design
7. Full Factorial Design

Here the S-optimal Design has been used for this project[19], because it has the advantage over one of the successful design approaches - the Latin Hypercube Sampling Design. Maximising the minimum distance between the points given typically fills the design space and this leads to equally distributed coverage of the space. The coverage over the borders and the corners are well done. For lesser number of design points only the borders would be covered. In this case, the Latin Hypercube Sampling Design would perform well. The optimal design description is discussed in the previous chapter.

With minimum of two variations, the input channel ranges are defined and levels at which the point distribution has to be made is also given. If there exists any constraints for the variations for the better investigation over the input parameters are included upon the user's choice. Then the number points in the S-Optimal Design has be given with the interested number of repetition points.

Initiation of the test run is done under *Run Test* worktab where the start and end controls are given to manipulate the DoE test runs. After the test has run, the results are stored in the *Test Results* tab.

Type	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Demand	Demand	Demand	Demand	Demand	Demand	Actual	Actual
1	1	4,2588	0	161107091639,2	2	-1	0	715	1020	3945	5155	4155	5255	2500	
2	1	6,7704	0	161107091641,7	2	-1	0	615	1220	4345	5555	3755	5555	2500	
3	1	8,6112	0	161107091643,5	2	-1	0	715	1020	4045	4755	3755	5555	2500	
4	1	10,405	0	161107091645,3	2	-1	0	615	1220	3545	4755	4555	5555	2500	
5	1	12,355	0	161107091647,3	2	-1	0	615	1020	3945	5555	3755	5205	2500	
6	1	14,227	0	161107091649,1	2	-1	0	815	1020	4345	5155	4155	5555	2500	
7	1	16,021	0	:0161107091651	2	-1	0	615	1070	3745	5155	4155	4855	2500	
8	1	17,846	0	161107091652,8	2	-1	0	665	1070	3545	5055	3755	5205	2500	
9	1	19,703	0	161107091654,6	2	-1	0	740	970	3945	5555	3955	4855	2500	
10	1	21,528	0	161107091656,5	2	-1	0	715	1220	3645	5555	4155	5117,5	2500	
11	1	23,353	0	161107091658,2	2	-1	0	615	1220	3545	5555	4555	5555	2500	
12	1	25,412	0	161107091700,3	2	-1	0	815	1220	4345	4755	3755	5555	2500	
13	1	27,269	0	161107091702,2	2	-1	0	615	820	3545	5555	3755	4855	2500	
14	1	29,078	0	161107091704,9	2	-1	0	815	820	4345	5555	3755	5555	2500	
15	1	30,966	0	161107091705,9	2	-1	0	615	820	4345	4755	3755	4855	2500	
16	1	32,791	0	161107091707,7	2	-1	0	615	820	3845	5355	4155	5205	2500	
17	1	34,663	0	161107091709,6	2	-1	0	615	1220	4345	5555	4555	5555	2500	
18	1	36,52	0	161107091711,4	2	-1	0	615	1220	3545	5555	4555	4855	2500	
19	1	38,36	0	161107091713,3	2	-1	0	615	820	4345	5555	3755	4855	2500	
20	1	40,17	0	161107091715,1	2	-1	0	715	870	3545	5155	4555	5292,5	2500	
21	1	42,011	0	161107091716,9	2	-1	0	815	820	3545	4755	3755	5555	2500	
22	1	43,852	0	161107091718,8	2	-1	0	815	1220	4345	4755	4555	5555	2500	
23	1	45,646	0	161107091720,6	2	-1	0	715	820	3645	5155	4155	4855	2500	
24	1	47,455	0	161107091722,4	2	-1	0	690	920	4345	5155	3755	5292,5	2500	
25	1	49,358	0	161107091724,3	2	-1	0	615	1220	3545	4755	3755	4855	2500	
26	1	51,246	0	161107091726,2	2	-1	0	640	1070	3945	5555	4555	5205	2500	
27	1	53,056	0	:0161107091728	2	-1	0	815	1220	3545	5555	3755	5555	2500	
28	1	54,896	0	161107091729,8	2	-1	0	615	820	3545	4755	4555	5555	2500	

Figure 4.5: Test results window

4.3 Modelling & Optimisation

In Modelling & optimisation procedure, the first step starts with the list of selected data group that shall be shown. The command **All Groups** shows all data groups of the current evaluation of the model (Sub-routine 2) in the figure shown below.

Raw Data

No.		DC_dfy0_1 [-] Variation	DC_dfy0_2 [-] Variation	DC_fyin_1 [-] Variation	DC_fyin_2 [-] Variation	DC_fymx_1 [-] Variation	DC_fymx_2 [-] Variation	DC_Fz1 [-] Variation	DC_Fz2 [-] Variation	TA_R_1 [-] Response	TA_R_10 [-] Response	TA_R_11 [-] Response	TA_R_12 [-] Response	TA_R_1: [-] Respons
1	1	715	1020	3945	5155	4155	5255	3400	5025	-307,92	123,11	137,33	249,54	
2	1	615	1220	4345	5555	3755	5555	3300	4925	149,1	-295,65	-328,21	-225,62	
3	1	615	820	3645	5155	3955	4855	3500	4925	-63,149	-187,13	-170,48	-31,57	
4	1	615	920	4345	5355	3755	5030	3300	4975	170,76	-315,76	-353,56	-251,58	
5	1	615	820	4345	4755	4555	5555	3300	4925	-341,3	-150,02	-75,623	145,31	
6	1	615	1220	4345	4755	4555	5555	3500	5125	-341,3	-150,02	-75,623	145,31	
7	1	790	1220	4145	5355	3755	4942,5	3500	5125	45,004	129,41	20,412	6,0578	
8	1	815	1220	3545	5255	4255	4942,5	3325	4925	-454,72	454,31	446,59	491,75	
9	1	690	1070	3745	4755	3755	4942,5	3325	5025	67,993	-82,413	-138,78	-84,455	
10	1	665	820	4245	4955	4355	5555	3300	5100	-351,14	-12,815	37,332	212,8	
11	1	815	1220	4345	4755	4555	5555	3500	5125	-656,93	412,31	446,22	575	
12	1	615	820	4345	5555	4555	4855	3300	5125	-438,58	-89,981	7,3527	241,61	
13	1	615	820	3545	4755	3755	5555	3500	4925	109,88	-254,33	-276,76	-174,54	
14	1	615	1220	3545	5555	4555	5555	3300	5125	-523,45	-32,446	86,15	330,7	
15	1	815	1220	4345	5555	3755	5555	3500	4925	45,118	162,51	39,08	12,577	
16	1	615	820	4345	4755	3755	5555	3300	4925	415,73	-493,41	-583,76	-504,25	
17	1	815	820	4345	5555	3755	5555	3500	4925	45,118	162,51	39,08	12,577	
18	1	815	820	4345	4755	4555	5555	3500	5125	-656,93	412,31	446,22	575	
19	1	815	820	4045	5355	3755	5117,5	3450	5025	50,151	193,45	68,858	29,739	
20	1	665	820	3745	4755	4455	5030	3475	4975	-485,15	60,805	142,13	338,84	
21	1	765	1170	3645	4855	3955	5555	3325	5125	-153,38	190,23	141,39	175,29	
22	1	815	1220	3545	5555	3755	4855	3500	4925	92,997	263,03	130,85	52,883	
23	1	815	820	4345	4755	3755	5555	3300	5125	208,71	-92,022	-239,47	-230,87	
24	1	815	1220	4345	5555	3955	4942,5	3325	5125	-153,9	256,85	178,27	187,55	
25	1	615	1220	3545	5555	3755	5555	3300	5125	79,383	-214,01	-227,47	-128,06	
26	1	815	1220	3545	4755	4555	4855	3500	5125	-738,71	532,31	587,43	703,5	
27	1	615	820	4345	5555	3755	4855	3500	5125	149,1	-295,65	-328,21	-225,62	
28	1	615	820	3545	4755	4555	5555	3300	4925	-480,2	-62,534	45,04	284,54	
29	1	815	1220	3545	4755	4555	5555	3300	4925	-738,71	532,31	587,43	703,5	
30	1	815	1220	4345	4755	4555	5555	3500	4925	-656,93	412,31	446,22	575	
31	1	815	1220	3545	5555	3755	5555	3500	4925	92,997	263,03	130,85	52,883	
32	1	615	1220	4345	5555	3755	4855	3300	5125	149,1	-295,65	-328,21	-225,62	
33	1	790	1170	4245	5555	4455	5555	3425	5125	-621,54	409,57	451,47	570,17	
34	1	715	1020	3545	5455	4055	4855	3450	4975	-246,83	146,28	149,54	233,31	
35	1	615	820	3545	5555	4555	5555	3300	4925	-523,45	-32,446	86,15	330,7	
36	1	715	1220	3545	4955	4155	4942,5	3425	5025	-326,61	152,45	172,16	281,02	

Figure 4.6: Raw data evaluation in the sub-routine 2

The alphanumeric display of the DoE data have been displayed to show the values and the parameters used along with the responses and the units.

The formula editor tab is available to work off-line as well as to prepare test workflow to calculate the channel data. In the prepare test workflow, the assigned Formulas list and the scope according to the Group selected are not available. The assignment of interested focus part of the curve behaviour determines the nature of the formula. The figure below describes the target functions formula before optimisation procedure to be carried out.

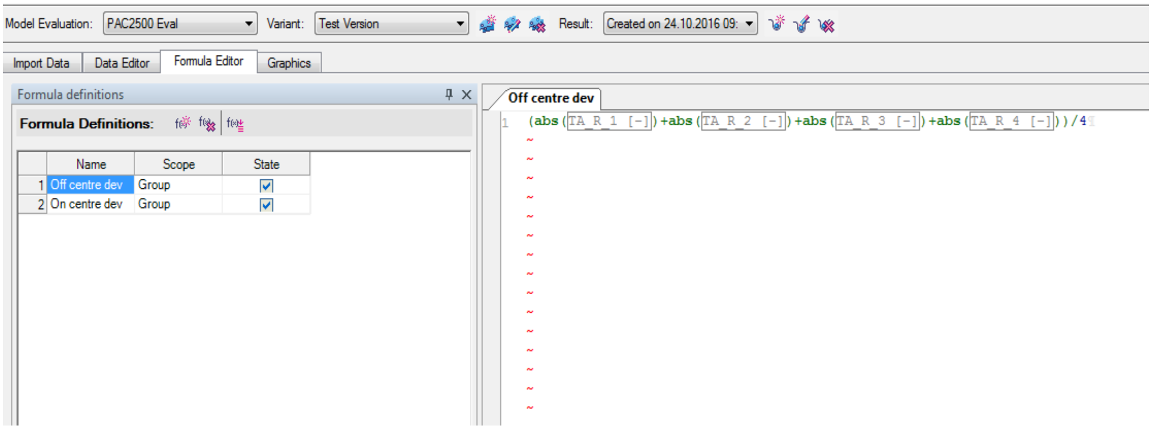


Figure 4.7: Assigning target functions in equations for Optimisation

Before evaluating the model after the modelling procedure, it is necessary to understand the nature of the measurement data along the model data. The graphic displays measured values over the values of the model generated along the 45 degrees line through the zero point. The dispersed points around the line allows the user to understand and analyse the well-build measured values that fits the model values which have been calculated. The points are very close to the model line, and then the model fits to the measured values very well. More the scattered points from the line (Outliers), the model behaviour is poorer. However, the graphic does not give sufficient information to evaluate the model quality.

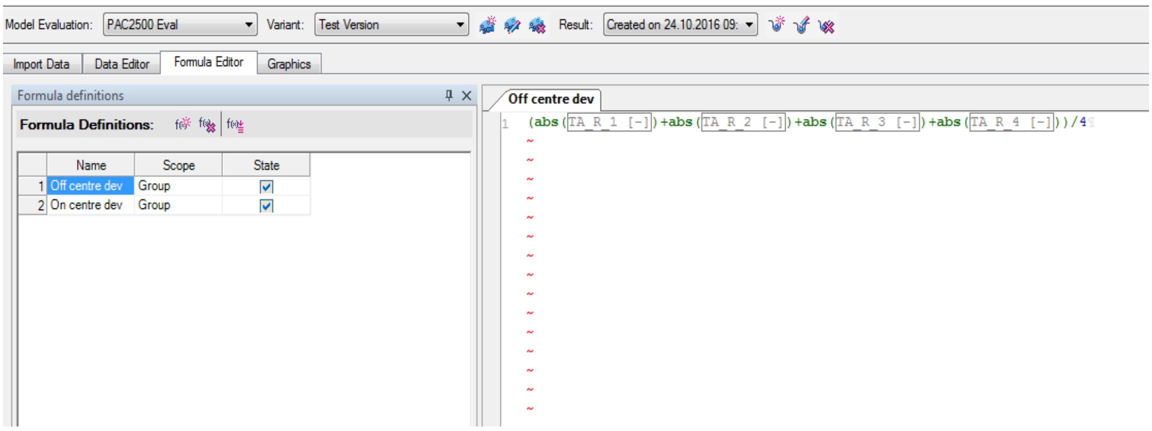


Figure 4.8: Assigning target functions in equations for Optimisation

The graphic displays the need for assigning the target functions for which the responses are modelled. Depending on which optimisation the user wish to run, the specification according to the selected optimisation type is executed. For a single objective optimisation the procedure shown below is enough to work on, otherwise for a multi objective target optimisation until 10 target functions could be added.

The procedure to assign the target functions:

1. Click the Create Target Function option on top of the Target function table.

2. In the Channel column, select the target function created already (also modelled).

3. In the Type column, set the optimisation target values.

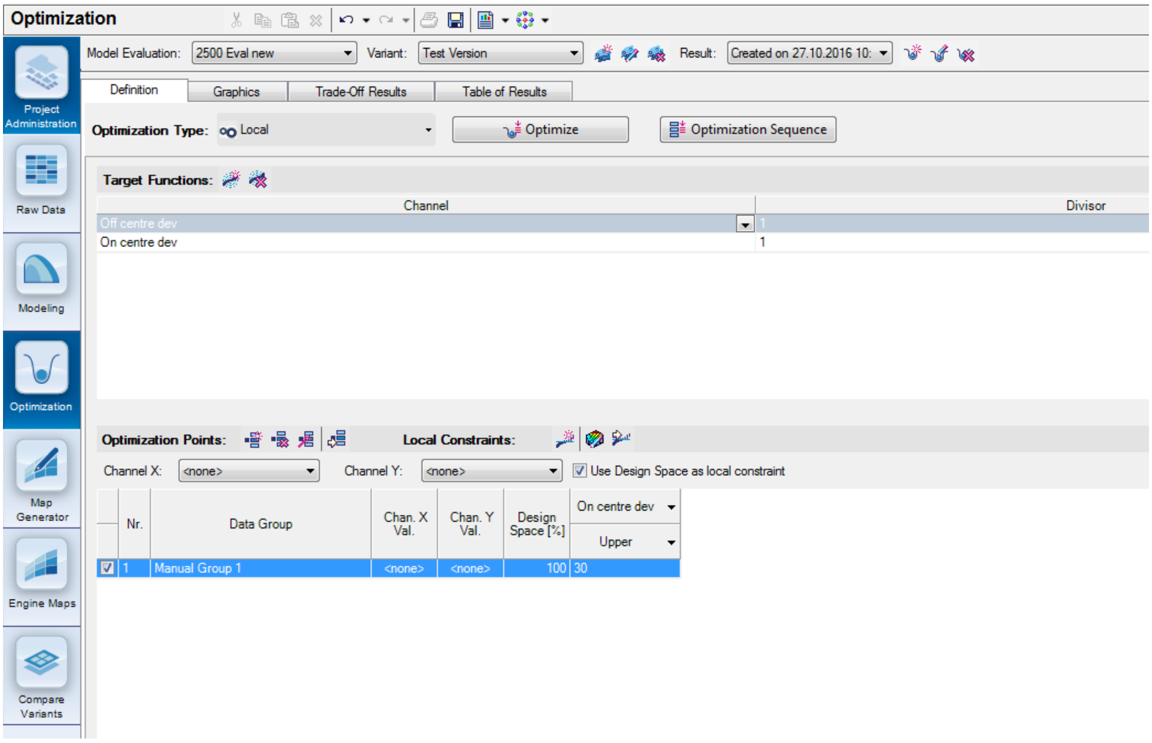


Figure 4.9: Typical Optimisation window with the option to assign the target functions

5 Results and Discussions

In this chapter the results from the model based tuning method and comparison of the examined tyre models have been discussed.

5.1 Comparison and comments

The comparison between the tyre models parametrised and optimised using AVL Cameo^{TM} is been discussed in this section and results are produced for explanation.

5.1.1 Comparison on qualities of the tyre models

In order to determine the necessary tyre properties, the tyre models are meant to be parametrised with the measurement data under the defined reproducible conditions. The start points of the variation ranges are the results of the parametrisation of different tyre models as mentioned in the Table 5.1, Table 5.2, and Table 5.3. The qualities of the extrapolation of values of these tyre models are also considered to evaluate the manual tuning method in order to validate the models used. For the lateral (cornering) steady state behaviour of the tyres,

- steady-state lateral force
- lateral stiffness

are realised after parametrisation. Depending on the type of tyre models viz., semi-empirical or physical, the meaning of interpretation differed with respect to the parameters used. This helps to extrapolate the experimental conditions for wide range of values because the test bench setup has limitations for range for obvious experimental reasons.

The measurement data produced at FTG[1] research facility are performed at 60 km/h. The extension of the measurement program could be modelled for higher

[1]Das Institut für Fahrzeugtechnik an der TU Graz

ranges of velocities, so that the tyre behaviour could be investigated. Similarly, when the measurement data is available for different wheel velocities, the models could be validated.

The measurements have been performed at dry asphalt. Nevertheless, it is also necessary to understand the behaviour of the tyre at the wet, snowy and icy conditions. If the tyre models are represent the physical behaviour, this evaluation is essential to understand how the tyre is behaving at several other environmental conditions and the dynamic friction qualities of the tyre models.

The exclusion of the camber effect is not included and the tyre models are also modelled at 0° camber angle (γ). The influence of the temperature and the dependency of the inflation pressure are also not taken into account to validate the pure lateral characteristics.

5.1.2 Potential improvements of the existing tyre models

After the study on several tyre models it can be commented that various suggestions could be adopted:

- In semi-physical tyre models, the friction coefficient and the rolling resistance coefficient are constant throughout the operating tyre. The normal pressure along the lateral direction is generally assumed by an uniform distribution. The identification of model parameters that determines the linear and the non-linear properties are simpler. but lower the number of parameters the higher the sensitivity of the model. The steady-state characteristics are mainly studied thus leaving an opportunity to study the dynamic[2] lateral characteristics of the tyre.

- In the semi-empirical tyre model like Magic Formula Tyre model, no influence of the environmental factors are included. The gradient changes of the temperature and pressure could also be reflected for the better understanding of the tyre model.

The suggestions have been put forth for further improvement of the tyre models,

- TM Simple:
  This is one of the simplest form of tyre models available on present day. The approach used for parametrisation is way simpler than other existing models. As the friction coefficient and the rolling resistance coefficient are constant throughout the tyre model, along with the 0% influence of camber angle, this

[2] depended on time as a factor

posses a potential area to expand by including these parameters into the model. This would make it into one of the simplest and efficient tyre models known till date.

- Magic Formula:
  For the given modelling environment, especially for one particular measurement condition, the steady-state characteristics are well defined in the Magic Formula. The simpler version of the original Magic Formula have been used, to reduce the complexity of dealing with multiple number of tyre parameters to increase the accuracy of the tyre characteristics. However, the large number of parameters determine the highest accuracy rate in studying the complete tyre behaviour. As described in the TM Simple Tyre model, the inclusion of the environmental factors influences are one of the important suggestions to improve this model, so that the model accuracy can be improved.

- Dugoff tyre:
  This model has a heavy dependency on the friction coefficient used. Thus making it as a friction tyre model. For the lateral tyre characteristics, there existed the possibility to investigate for the higher ranges of slip angle. The maximum friction coefficient (μ_{max}) value have been estimated at higher accuracy than other models as well as helped in the identification of the type of road. The extrapolated values of the slip qualities have also become a good outcome of this model.

5.1.3 Evaluation of TM Simple model

Evaluation of TM simple model begins with the definition of the input parameters in the design space. The variations are distributed in the space of minimum to the maximum ranges of values assigned in the DoE procedure with respect to the manual parameter tuning. The following Table 5.1 gives the overview of the design setup with respect to the experimental data.

The DoE is performed with the set of procedures described in the previous chapter. The Test results are stored in the corresponding project sub folder and further used for the Modelling and Optimisation sub-routine.

All the variation parameters of the TM Simple model which have been selected in the Data Editor are arranged in a two dimensional space along XY axis. The representation of the variations vs variations shows the opportunity to analyse the screening of the DoE design in the design space. The variations have been checked for the second time to set correctly on the test procedure as well as the ranges that could be possibly run. The six varying design parameters with the respective ranges

Table 5.1: Variations setup in the DoE – TM Simple Model

Typical range of variation parameters (input channels) used in tuning task			
Design Variables	From	To	Start
F_{ymax1}	3755	4555	4155
dY_{01}	615	815	715
$Y_{\infty 1}$	3545	4345	3945
F_{ymax1}	4855	5555	5255
dY_{02}	820	1220	1020
$Y_{\infty 2}$	4755	5555	5155

are compared with the modelled output on Cameo^{TM}.

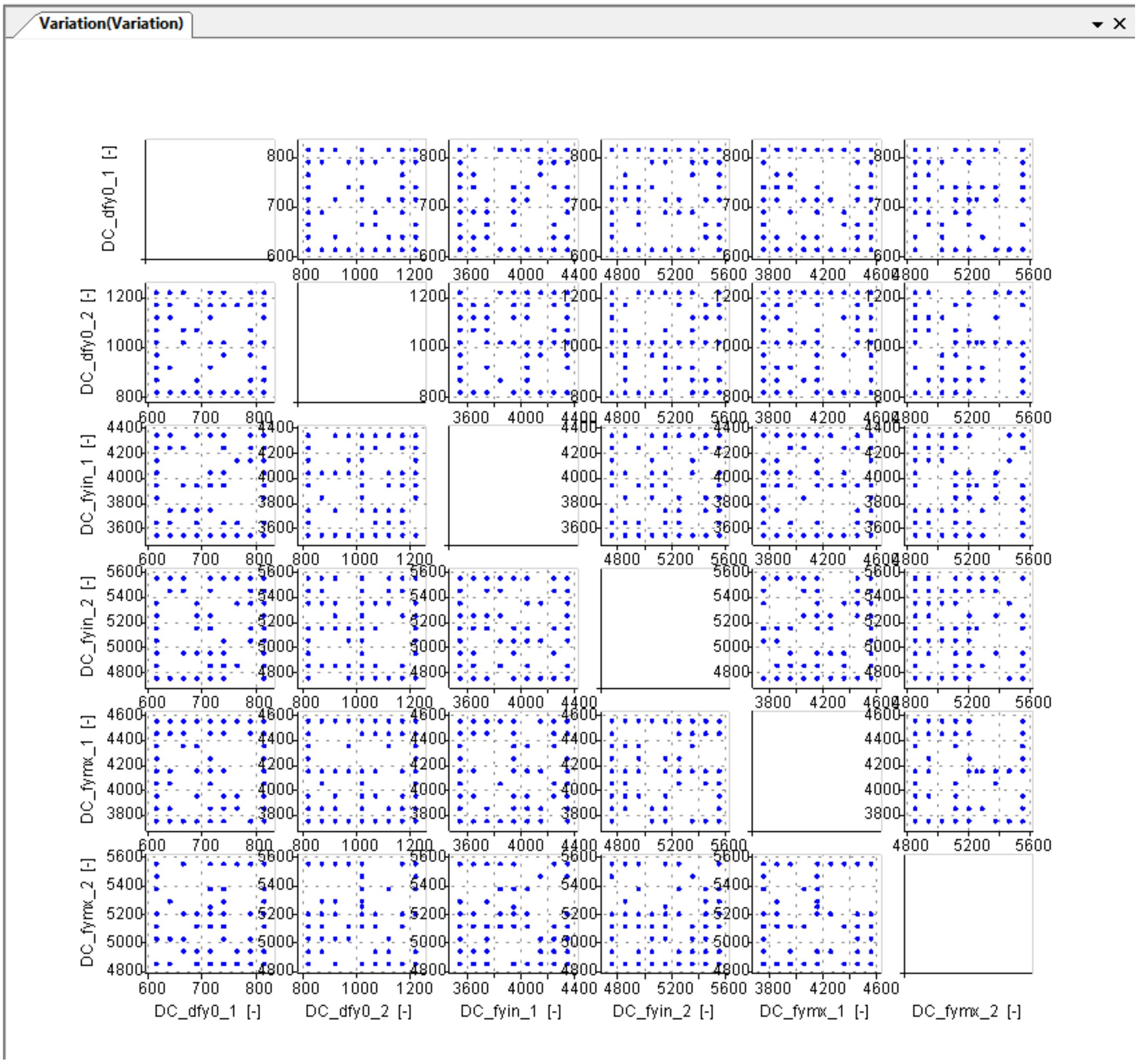


Figure 5.1: Variation distribution in the design space for Fz = 3400 N

In the figure 5.1, the distribution of the design space with the input variation

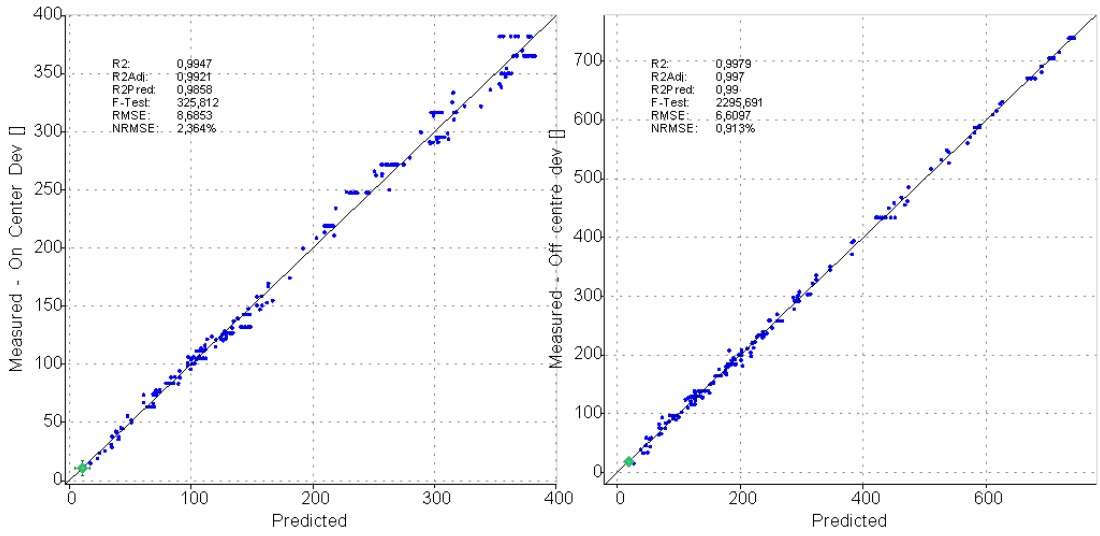


Figure 5.2: Measured vs Predicted graph of the On-Centre and Off-Centre – TM Simple

interactions have been shown. In the figure **??**, the behaviour of the variations of the test data and the predicted model has been evaluated. The independent and the dependent influences of the input parameters gives the idea on what the test DoE data has been distributed over the range of values given for the vertical load F_z = 3400 N.

The Figure 5.3 (On-Centre) and Figure 5.4 (Off-Centre) describes the cross sectional view of the six dimensional design space of the input channels (input parameters) and expanded over the XY axis (two dimensional) to get an overview of how strong the interaction of the model are. influences changes are happening during the selection of the specific points on one of the channels.

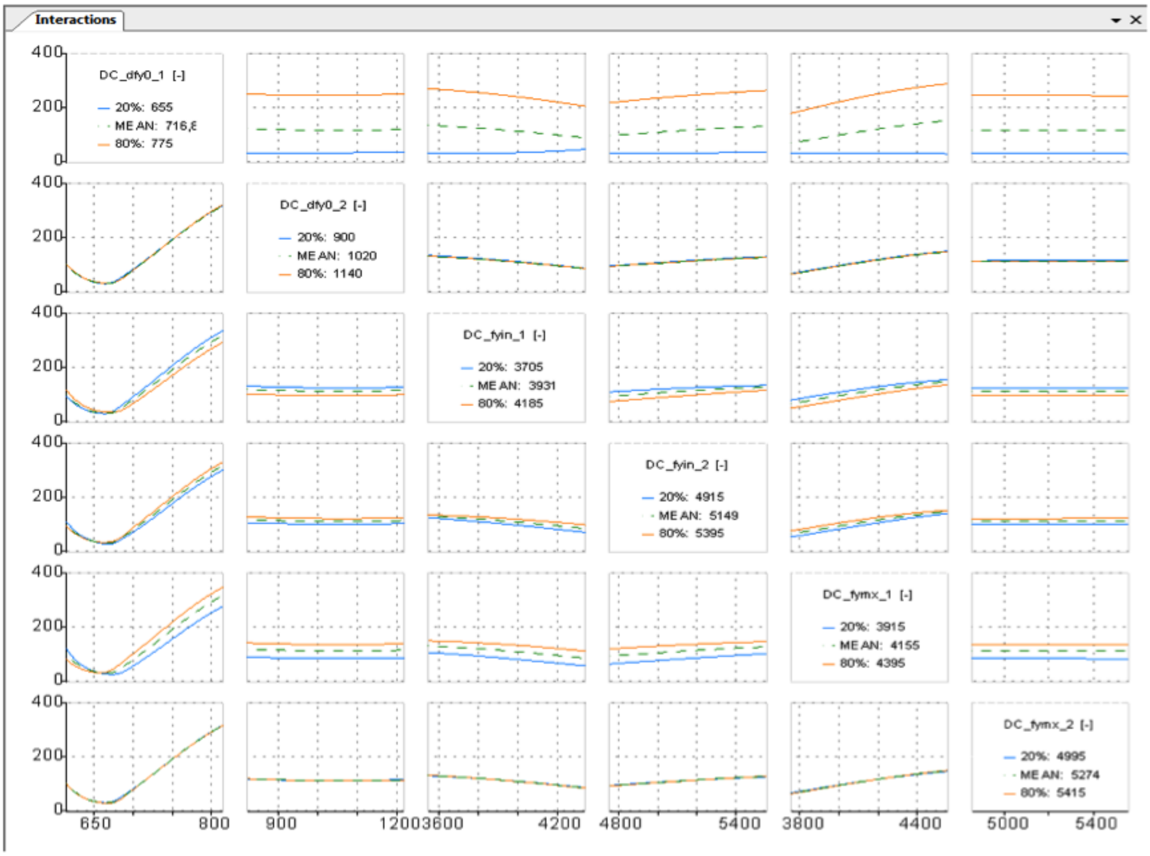


Figure 5.3: Interaction of the variation parameters in the On-Centre – TM Simple

Both from the manual tuning and the Cameo model tuning approaches it is clear that the influence of dy01 is more than the dy02. This could be easily identified by this interaction graphics. Similarly, the values of fyin1 and the fymx1 are more influencing than the fyin2 and the fymx2 respectively. The higher the variation of these values could alter the model behaviour greatly so that the model is not parameterised properly. This is a great advantage over the manual processing where it takes a lot of time to perform this procedure.

In the Figure 5.5, the results of the residual window show of the variation parameters in the On-Centre and Off-Centre deviations. The graphic displays individual residuals with respect to the TM Simple Response model (On-Centre and Off-Centre deviation models). The model fit quality can be found out where the outliers are denoted in the blue coloured points. The confidence area intersects the model zero line. The orange line with the green points shown are the points that deviate from the intersect line but lies close to it, and the red points are the gross outliers because the confidence area does not intersect the zero line as it is far from it. From this feature the user could interpret the cornering residuals and mathematically calculate while building the regression model to study the deviations of the measured value from the modelled values. These points are the actual reflection according to the

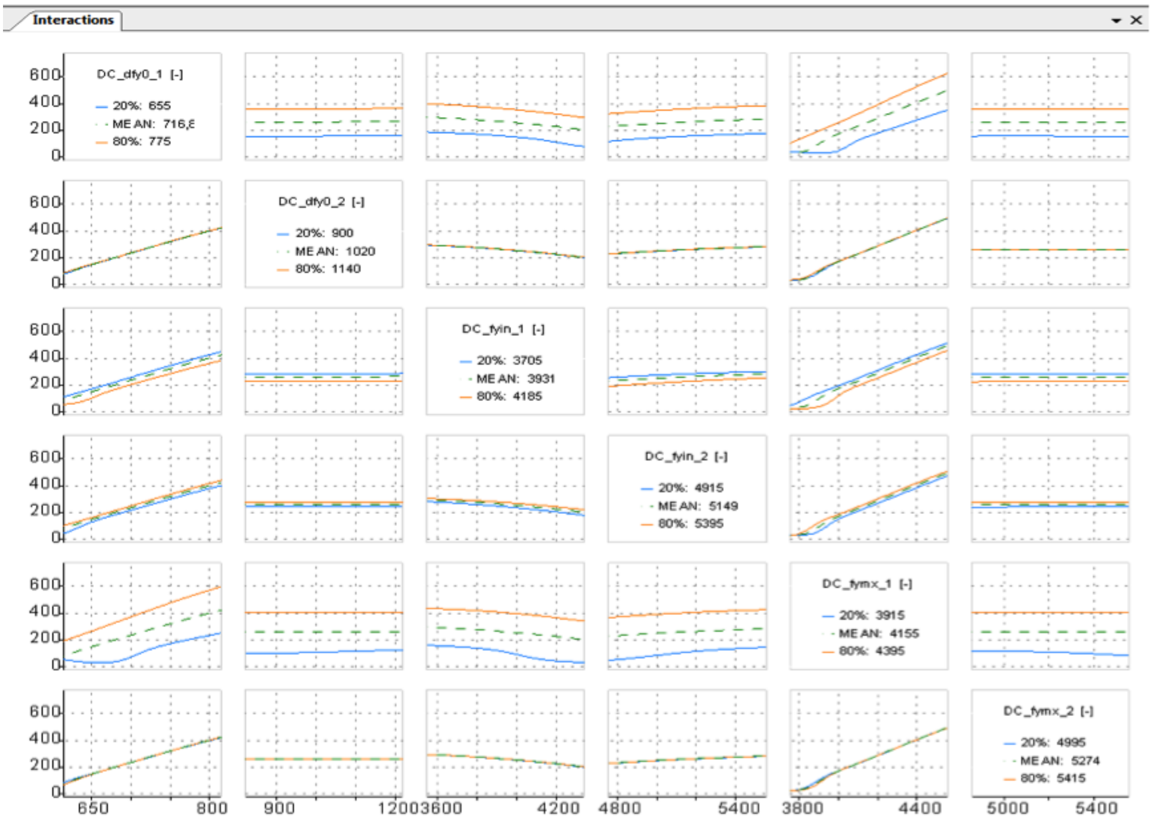


Figure 5.4: Interaction of the variation parameters in the Off-Centre – TM Simple

Gaussian distribution. The number of points are more along the model line represent s the model fit is very good with few exceptional points as indicated. This directly influences the prediction of the input parameters accurately and one of the advantages of using the model based tuning approach.

The optimisation is performed based on the inbuilt modelling algorithm and the optimisation window allows the user to save the results and validated the desired optimal points with respect to the parameterised values. By keeping one set of parameters in the data set it is simple to identify the response in other data sets.

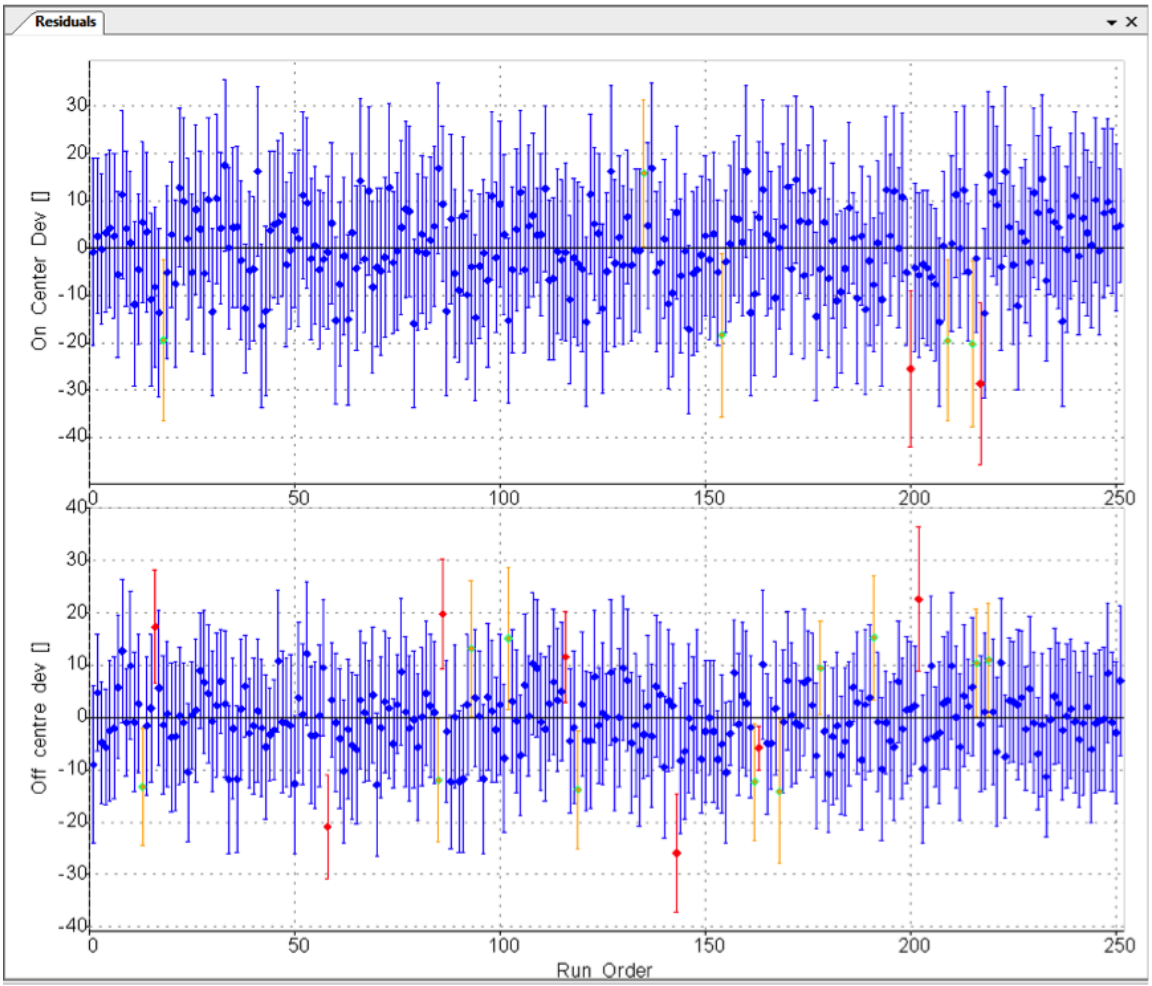


Figure 5.5: The residual window shows the variation parameters in the On-Centre and Off-Centre – TM Simple

The Figures 5.6 show the identified optimal points in the curve both responses namely, the On-Centre and the Off-Centre where the variation of the absolute value is minimised to zero. The is the response obtained using an optimal Pareto front and thus saves time to identify the parameters and ease the manual parameterisation time. The maximum and the minimum values of the variation parameters have been displayed. The reliability of the model can be known from the confidence area and the prediction area. The design space gives the operating range of the values represented by the green line at the bottom. The aim of this procedure is to find the ultimate point that is close to zero line i.e., the variation is close to zero. The prediction area allows validating the model in verification to the experimental data. The confidence interval area determines the uncertainty of the response variable along the Y-axis at the measured point along X-axis.

After taking a close look on the intersection graphics, TM Simple first three parameters dy01, fyin1, fymx1 are the most influencing when compared to the dy02,

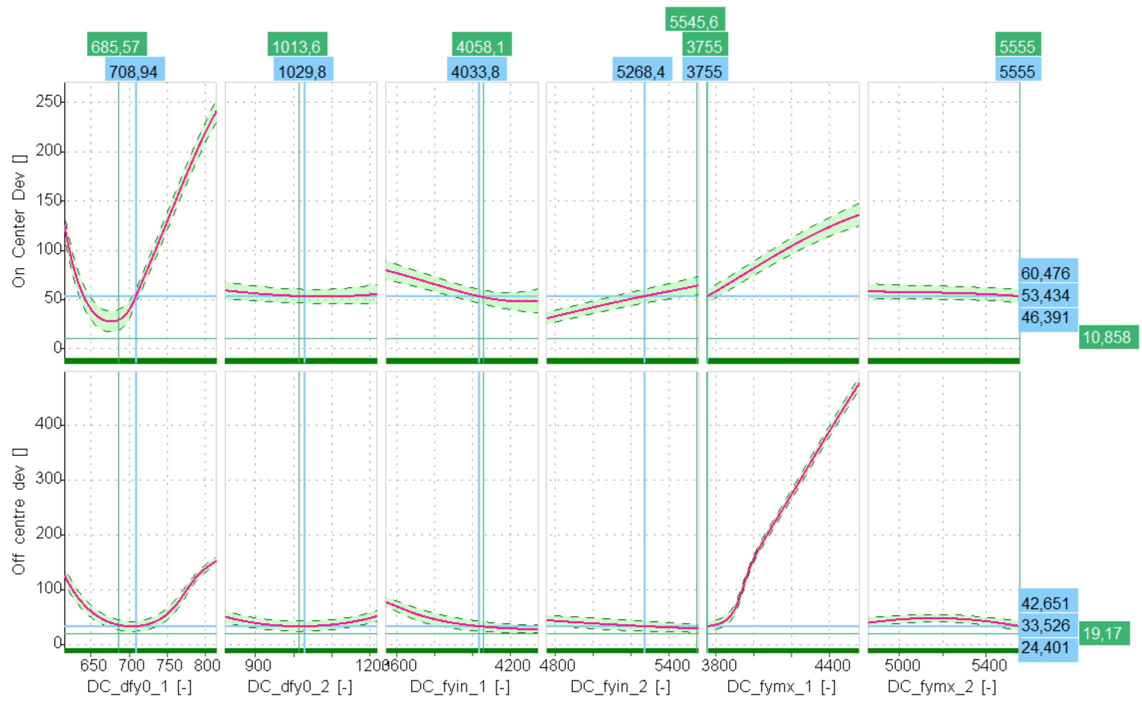


Figure 5.6: Intersection plot of the responses at Fz = 3400 N – TM Simple

fyin2 and fymx2.

By considering the optimal points in all three Fz values, the optimal points. The optimal points in the Pareto front graph is indicated by dark green (feasible points) and light grey (not feasible points). The Pareto points are represented by the steel blue points, which are feasible. The other random distribution points are represented by the dark grey.

The Figure 5.6 also gives an interpretation of the optimal points for all the loads which are parameterised for a single nominal force value of 3400 N. The 0-0 coordinates gives the ultimate optimal point for which Cameo™ is optimising the model responses close to that point. Thus reducing the variation values to zero gives the better quality output in parameter identification.

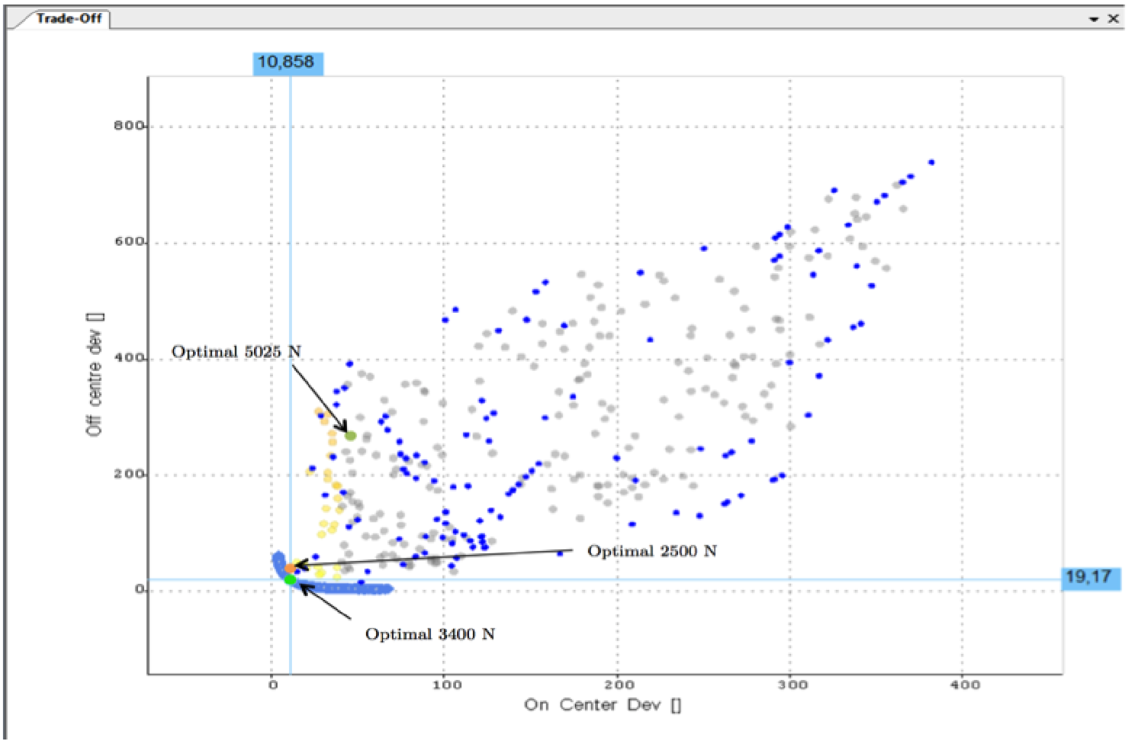


Figure 5.7: TM Simple - Pareto front plot on Fz =3400 N data with the indication of optimum points of 2500 N and 3400 N

The Figure 5.7 shows how the results from the optimisation procedure in Cameo™ fits with the manual tuning results which is visualised in MATLAB®. This result shows that the input parameters that influence the tyre model behaviour are performing well at the On-Centre than the Off-Centre. This means at the lower slip angles the model behaviour is very good than at the higher slip quantities.

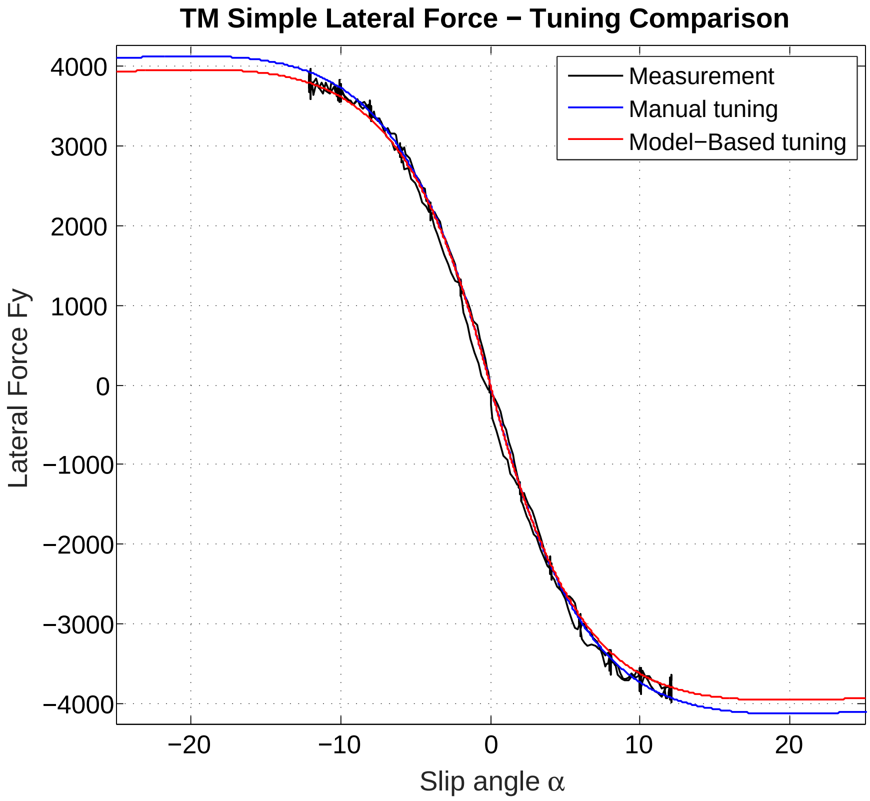


Figure 5.8: Comparison of results - manual tuning and Cameo™ model based tuning

The figure 5.9 gives the quality of extrapolation characteristics and the comparison of the model-based tuning and the manual results of the TM Simple model. The table 5.4 gives us the elucidation of how the manual and the model based tuning are compared and the time and quality of the methods are the primary factors to evaluate the comparison task. The initial set up of the model is the inevitable process which has taken much time in both manual and model based tuning. The values of R2 and NRMSE gives the prediction on the quality and the time taken in days for a non-expert describes the duration of paramterisation.

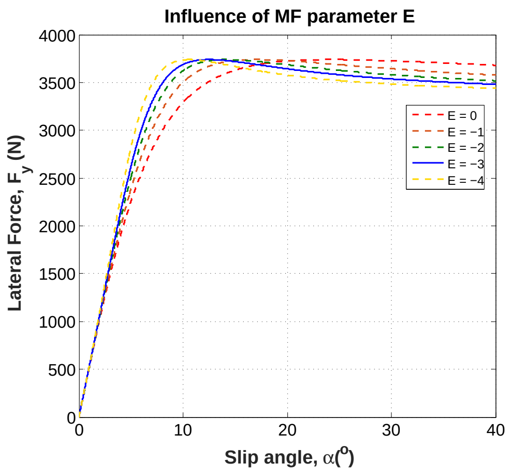
5.1.4 Evaluation of Magic Formula model

The evaluation of the Magic formula model depends on the range of input parameters to generate the design space. the variations with maximum and the minimum values indicate the limits of the design space as shown in the Table 5.2

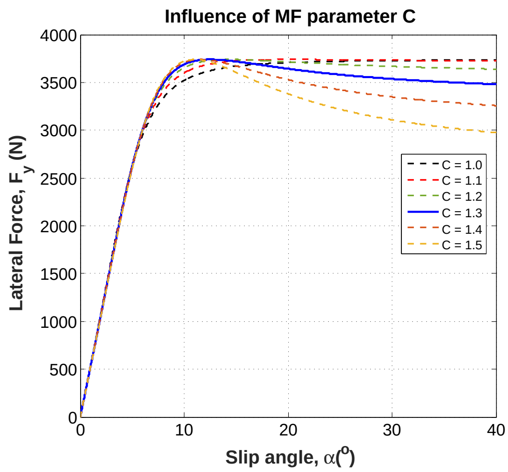
Table 5.2: Variations setup in the DoE – Standard Pacejka Model

Typical range of variation parameters (input channels) used in tuning task			
Design Variables	From	To	Start
C	1	1.5	1.3
C_1	31500	41500	36500
C_2	5400	7400	6400
E	-5	-1	-3
μ	0.8	1.4	1.1

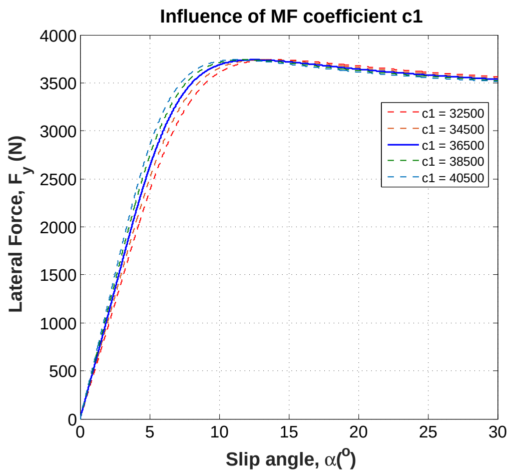
In the Figure 5.9, the subfigure (a) gives the representation of the influence of the curvature factor E values in the model. Similarly, the influence of the shape factor C, and the stiffness coefficients c_1 and c_2 are shown in the subfigures (b), (c) and (d) gives their respective influence over the model. With the higher E, C and c_1 values, the model behaves proportional to the increase in the lateral forces. But tot he contrary, the c_2 values the model is indirectly proportional.



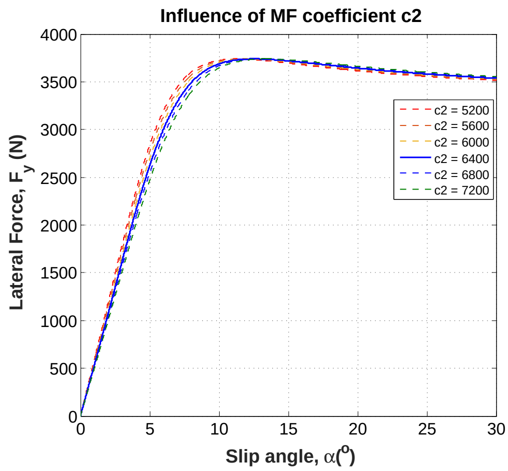
(a) Influence of E in MF model



(b) Influence of C in MF model



(c) Influence of $c1$ in MF model



(d) Influence of $c2$ in MF model

Figure 5.9: Influence of various MF model parameters

In the figure 5.10, the influence of the friction coefficient μ on the lateral behaviour of the tyre is shown. It is understood that the increased value of the μ denotes the increased response in the values of F_y. For lower values of μ, indicates that the surface is icy and wet (slippery) and for the higher values the surface is rough and friction performance is doing good.

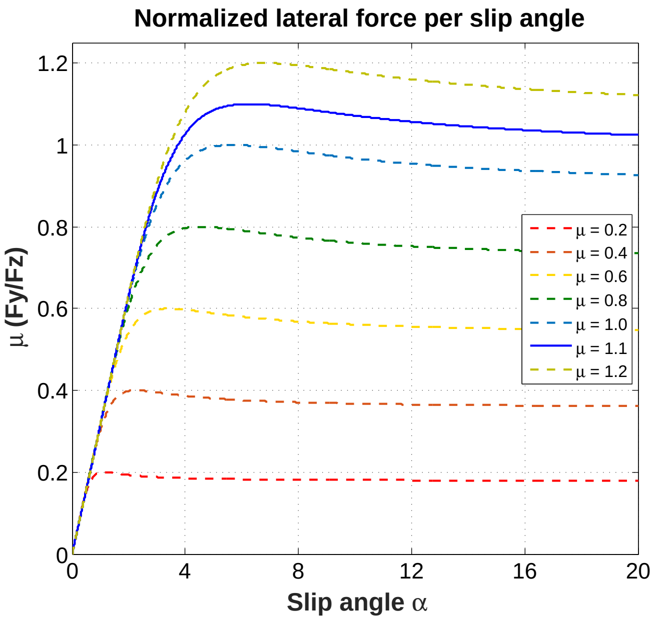


Figure 5.10: Influence of mu in MF model

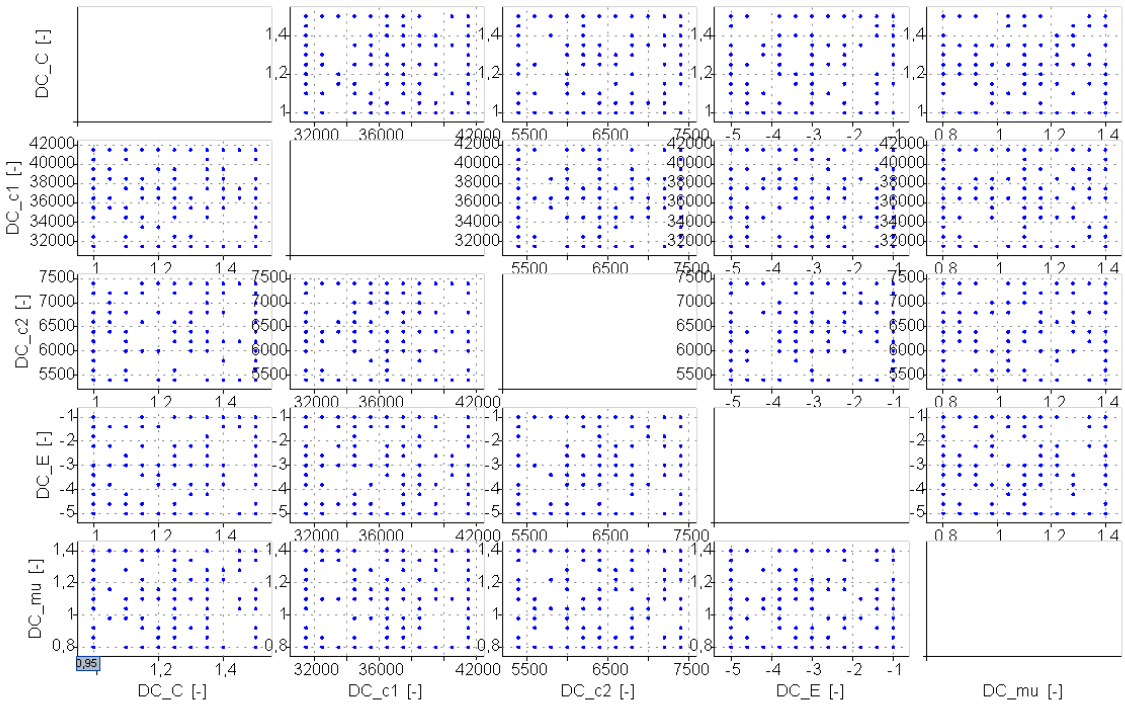


Figure 5.11: Variation vs variation distribution in the design space for Fz = 3400 N – Pacejka MF Tyre

In the figure 5.11, the distribution of the design space with the input variation interactions have been shown. In the figure 5.12, the behaviour of the variations of the measured data and the predicted model is evaluated. The independent and the mutual influences of the input parameters gives the idea on what the measurement DoE data has been distributed over the range of values given for the vertical load F_z = 3400 N.

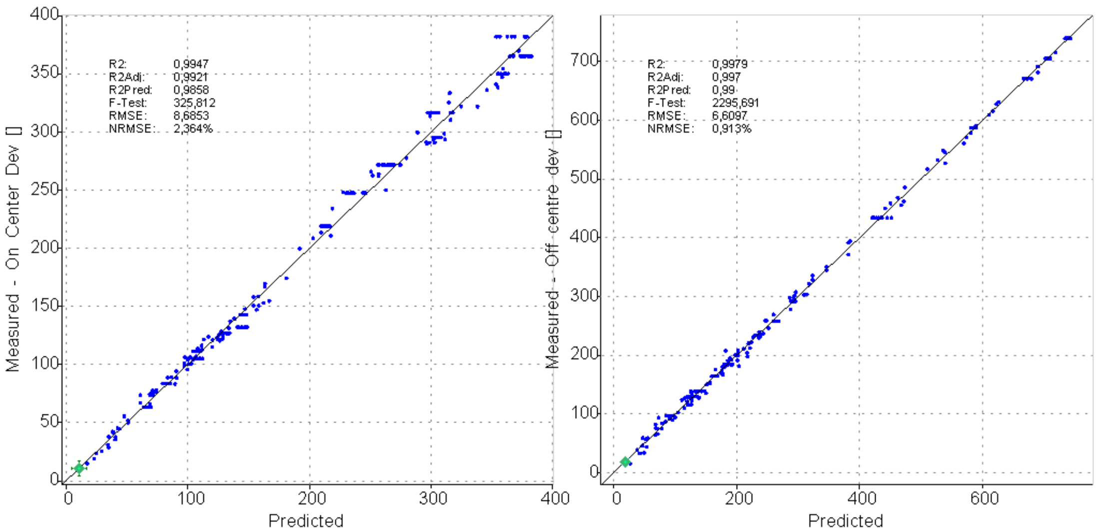


Figure 5.12: Measured vs Predicted graph of the On-Centre and Off-Centre – Pacejka MF Tyre

In the figure 5.12, the plot shows how the predicted model has been built based on the key goal to make the model that accurately predicts the interested target values of the measurement data. This is evaluated with the accuracy measurement of the model error values displayed. The 45 degree line running across is closely populated by both the points of measurement and prediction, shows that the model behaves with good accuracy and the error is minimised to a good level of R^2 value is 0.9979 on the On-centre and 0.9947 on the Off-Centre deviations. Similarly, the values of NRSME of On-Centre is 2.364% and the Off-Centre is 0.913% shows the predicted vs measured values are good performing.

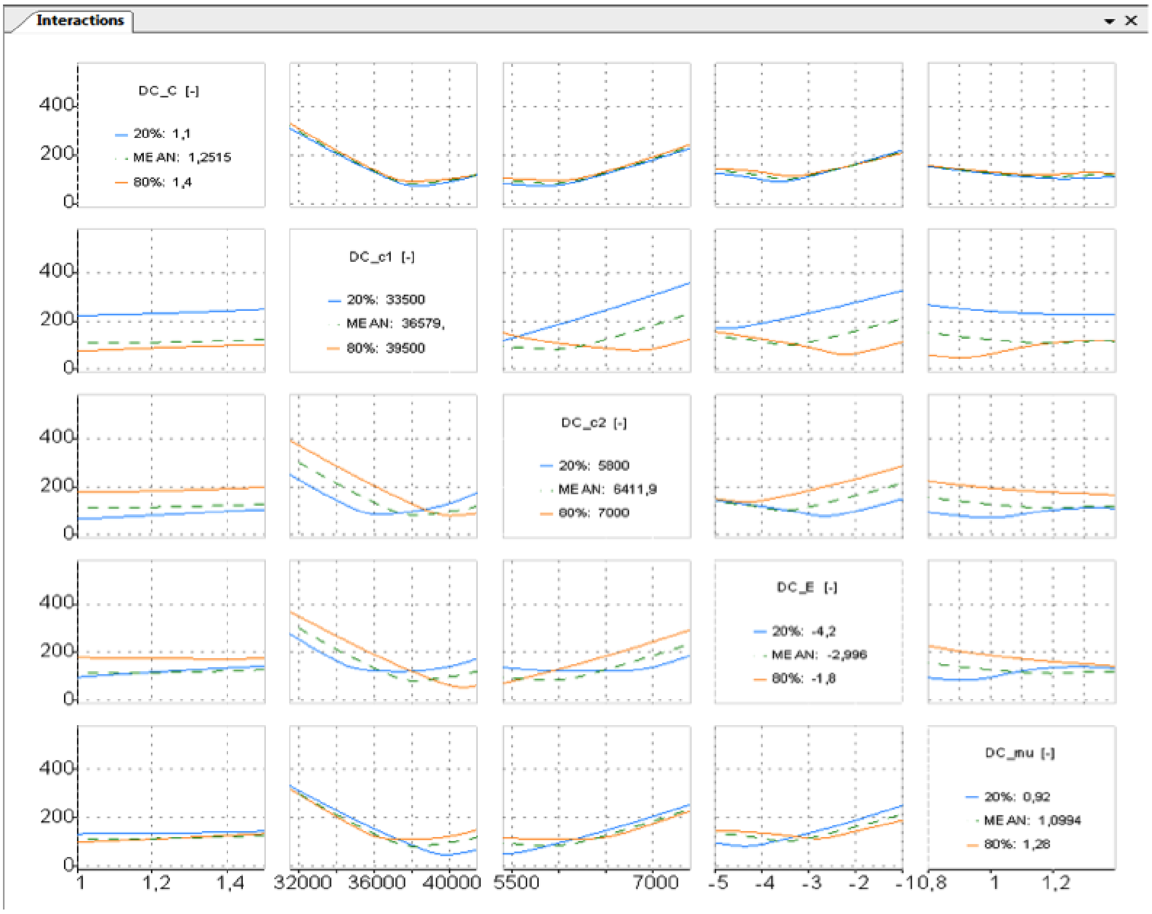


Figure 5.13: Interaction of the variation parameters in the On-Center – Pacejka MF Tyre

In the figures 5.12 and 5.13, the interaction graphs show the effects of the influences of independent variables and their depended variables. Here the five input parameters (including two coefficients) and their interactions are studied. For example, in the On-Centre 5.13, the interaction of the μ with the mean value is sparsely interacting with the shapefactor C. Then the mean value of the curvature factor E is strongly influences the coefficients c_1 and c_2. Similarly, the mean value effects of the interaction between the stiffness coefficient values c_1 and c_2 are independently interacting.

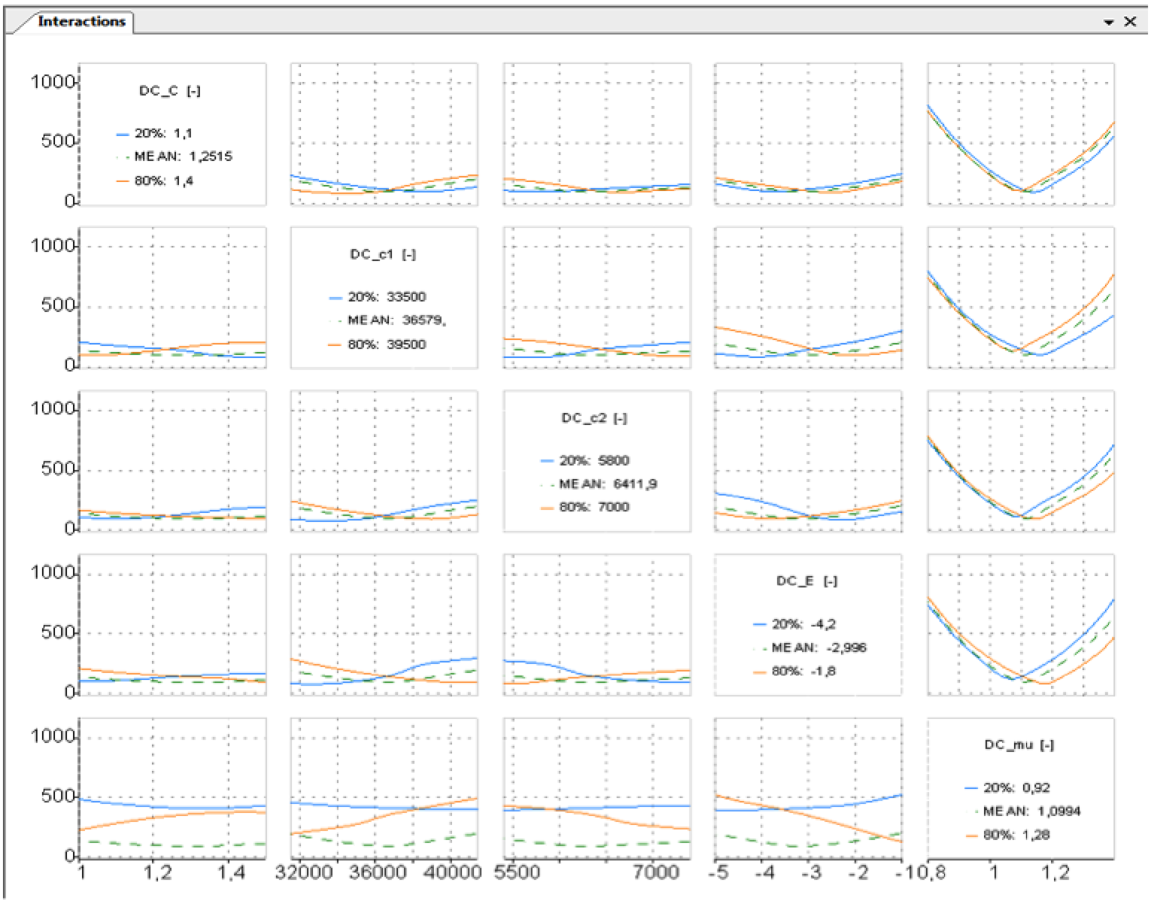


Figure 5.14: Interaction of the variation parameters in the Off-Center – Pacejka MF Tyre

In the figure 5.15, the residual plot shows the responses vs the run order (200 points) of the MF Tyre DoE test generated data. The residuals show that the responses are closely distributed along the horizontal axis, the linear regression model is relevant for the given data. The points and confidence intervals with red colour are randomly distributed along the horizontal axis that signifies the points are non-linear to the regression.

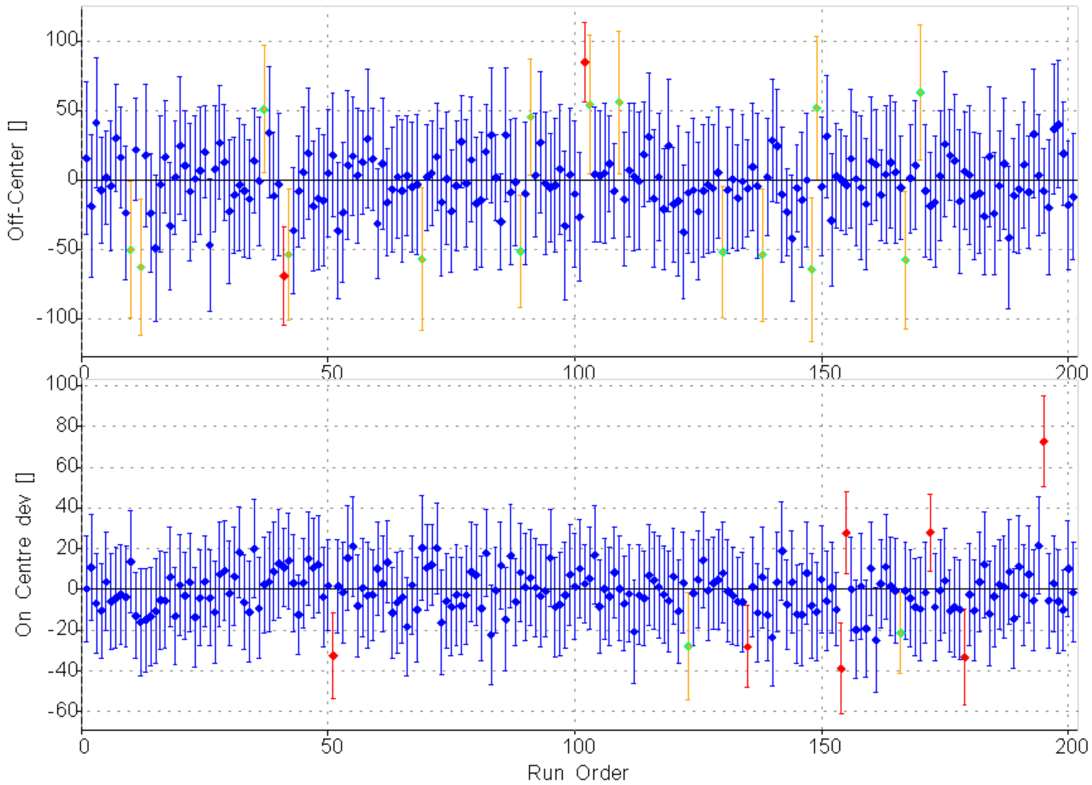


Figure 5.15: The residual window shows of the variation parameters in the On-Centre and Off-Centre – Pacejka MF Tyre

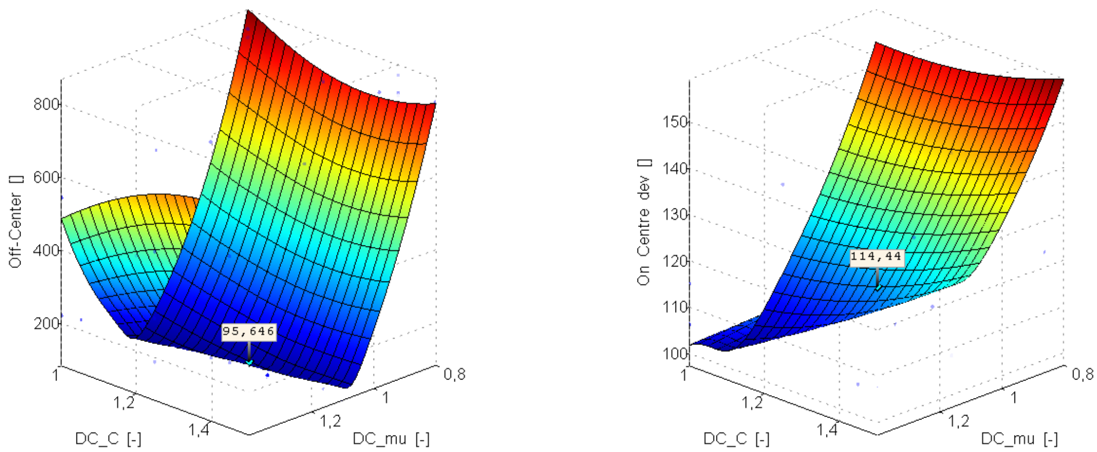


Figure 5.16: Intersection plot of the responses at Fz = 3400 N – Pacejka MF Tyre

In the figure 5.16, the input parameters are influences the responses in the three dimensional DoE space. The Off-Centre response is shown on the left graph and the

On-Centre is on the right. The range of variations can be varied in order to see the immediate change in the behaviour of the On-Centre and the Off-Centre deviations.

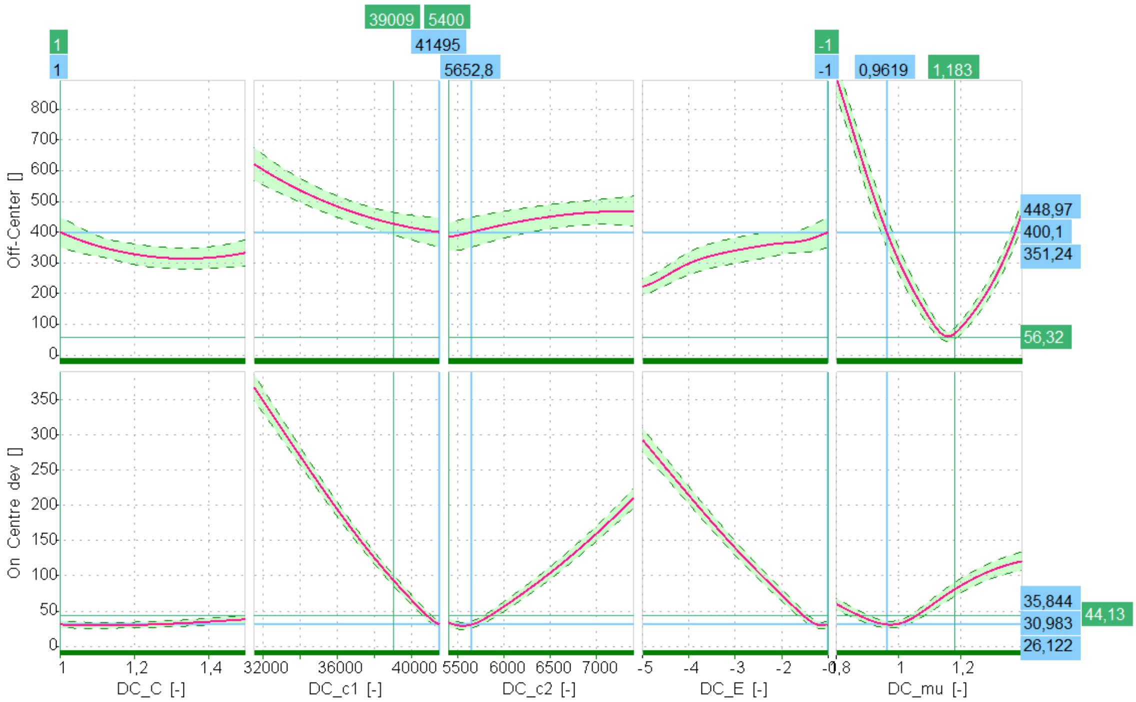


Figure 5.17: Intersection plot of the responses – Pacejka MF Tyre

In the figure 5.17 of MF tyre model, for the optimal points where the deviation variance in the On-Centre and the Off-centre responses are minised to zero and instantaneously show the corresponding input parameters. This gives the user to decide on the desired input values of the inputs which is falling into the operating range of input values. The indication of the operating range is shown as the dark green line at the bottom of the graph.

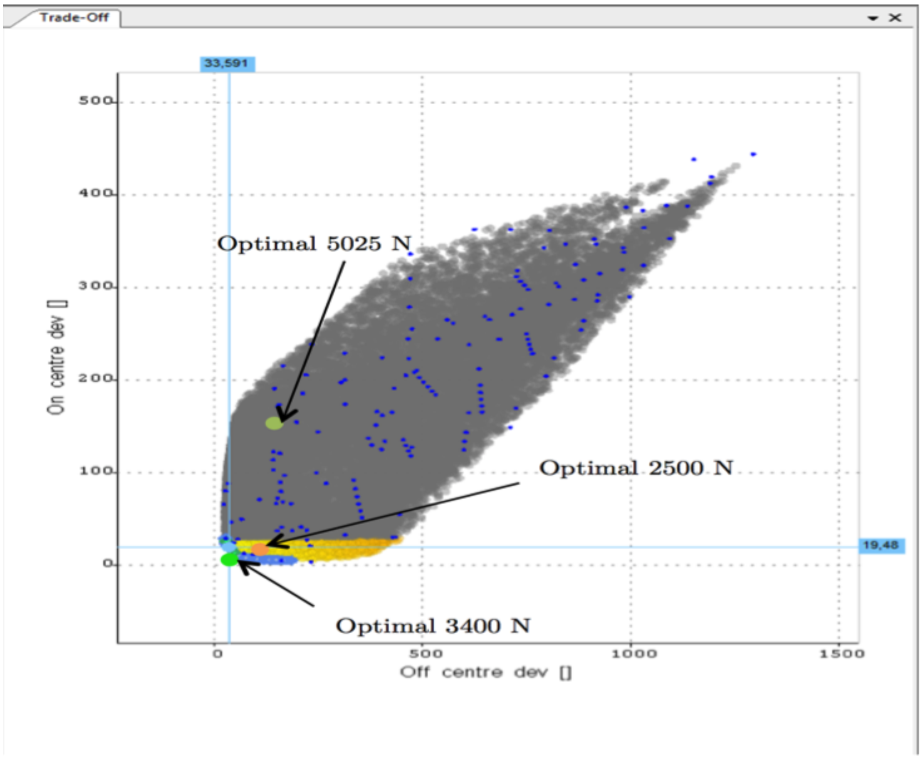


Figure 5.18: Pareto front plot on Fz =3400 N data with the indication of optimum points of 2500 N and 5025 N – Pacejka MF Tyre

The figure 5.18 gives the opportunity to find the optimal points which are close to zero. These points are identified as the Pareto points where the responses are greatly traded off between them and gives us the optimised input parameter values. the constraint is given to the On-Centre deviation response of 40 N, where the Pareto front is restricted to find the optimal point within this limitation. the random points are also distributed along with test data. For this particular setup the optimal points for the dataset of vertical forces F_z 2500 N and 5025 N are also indicated. The results are stored in order to compare with the manual tuning method.

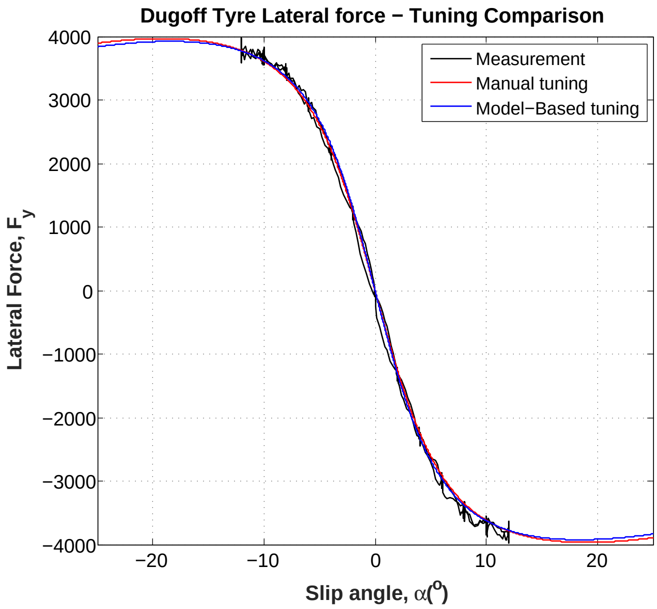


Figure 5.19: Comparison of results - MF manual tuning and Cameo^{TM} model based tuning

The figure 5.19 gives the comparison of the manual and model-based tuning results of the MF model. the extrapolation capability of the model based tuning method shows the quality is less due the number of points restricted is from +12 degrees to -12 degrees of the slip angle values. The model cannot predicted beyond this limitation. But the mathematical model could be much stronger in this prediction. The table 5.4 gives us the elucidation of how the manual and the model based tuning are compared and the time and quality of the methods are the primary factors to evaluate the comparison task. The initial set up of the model is the inevitable process which has taken much time in both manual and model based tuning. The values of R2 and NRMSE gives the prediction on the quality and the time taken in days for a non-expert describes the duration of paramterisation.

5.1.5 Evaluation of Dugoff model

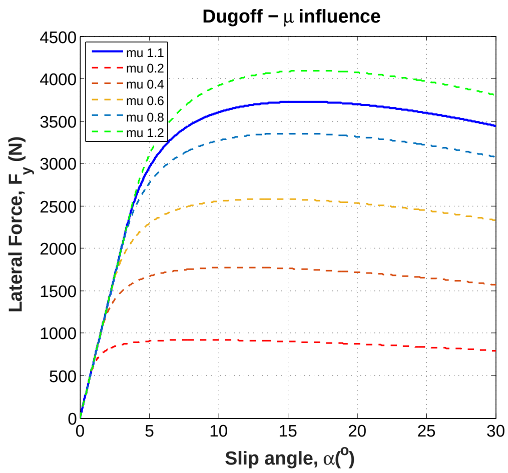
The assignment of the range of DoE values of the input parameters determine the possiblity of the desired parametrisation of Dugoff model. the Table 5.3 gives the overview of the design setup with the range of influencing input parameters.

Table 5.3: Variations setup in the DoE – Dugoff Tyre Model

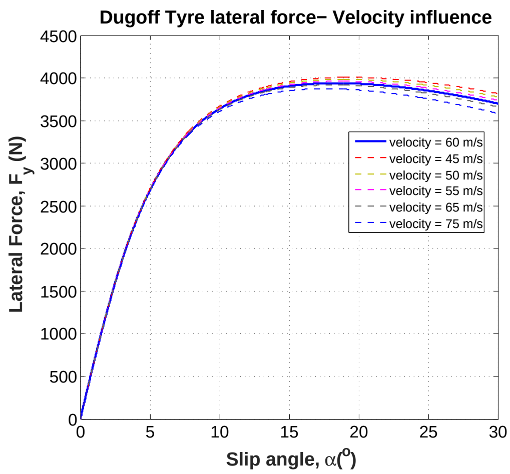
Typical range of variation parameters (input channels) used in tuning task			
Design Variables	From	To	Start
C_s	41500	51500	46500
C_s	31500	41500	36500
μ_0	0.8	1.3	1.115

In the Figure 5.20, the subfigure (a) gives the representation of the influence of the friction coefficient values in the model. Similarly, the influence of velocity, influence of longitudinal stiffness c_l and the lateral stiffness C_s are shown in the subfigures (b), (c) and (d) gives their respective influence over the model. With the higher friction coefficient values the model behaves proportional to the increase in the lateral forces. Similarly, the longitudinal stiffness and the velocity influences the increase of lateral force output with the increased values. But to the contrary, the lateral stiffness influences the lateral curve inversely. That is, the lower the laeral stiffness values higher the lateral force response.

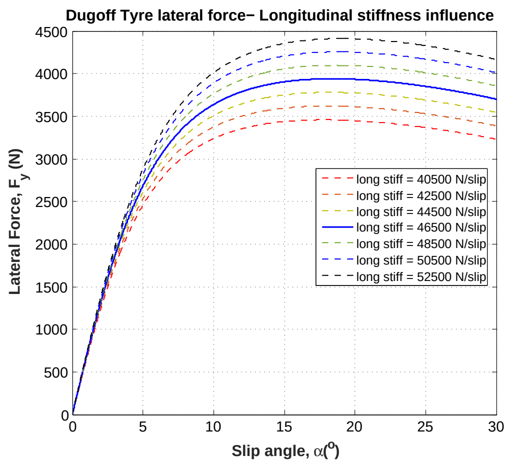
In the figure 5.21, the distribution of the design space with the variations interaction has been shown. The mutual influences of the input parameters gives the idea on what the measurement DoE data has been distributed over the range of values given for the vertical load $F_z = 3400$ N.



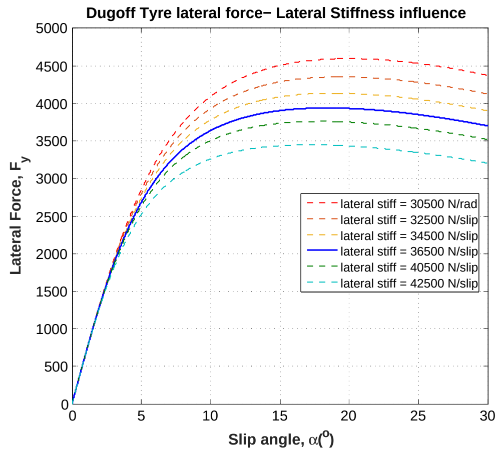
(a) Influence of μ in Dugoff model



(b) Influence of v in Dugoff model



(c) Influence of C_l in Dugoff model



(d) Influence of C_s in Dugoff model

Figure 5.20: Influence of various Dugoff friction model parameters

In the figure 5.22, the graphic shows how the predicted model has been built based on the key goal to make the model that accurately predicts the interested target values of the measurement data. This is evaluated with the model error values displayed. The 45 degree line is closely populated by both the points of measurement and prediction, shows that the model behaves with high accuracy and the error is minimised to a great level of R^2 value is close to 1 (0.9984) on the On-centre and (0.9997) on the Off-Centre deviations.

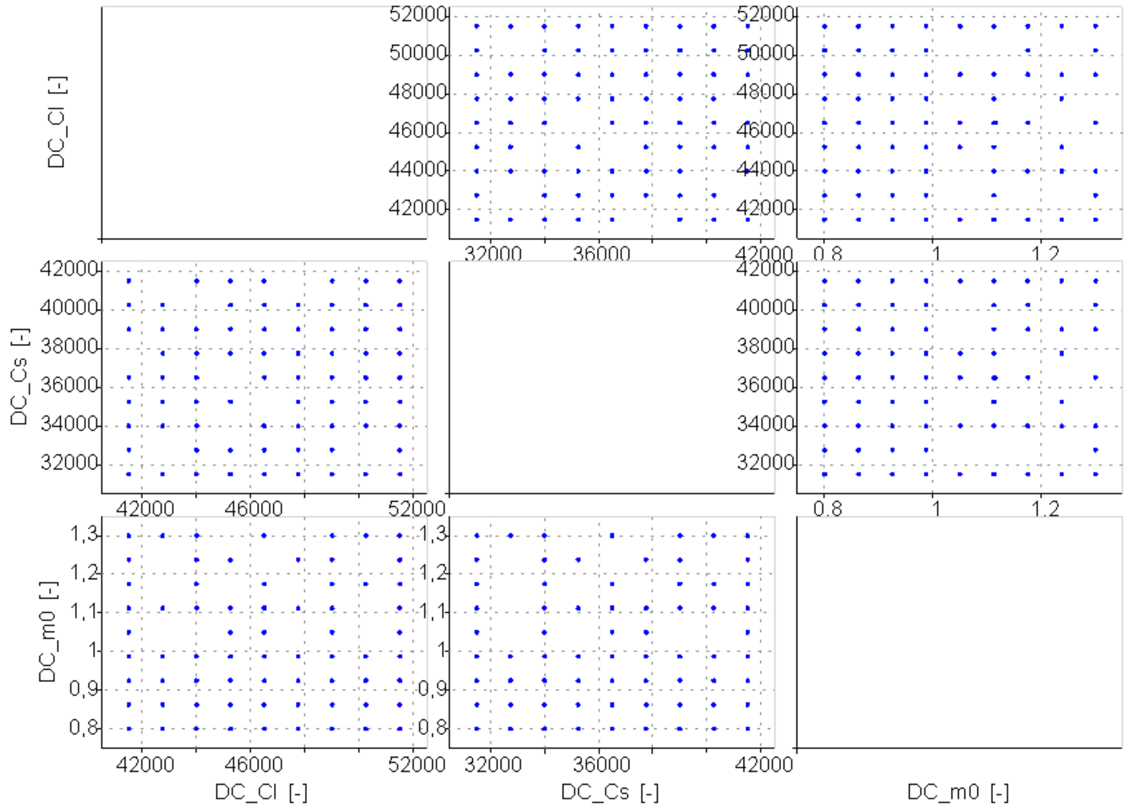


Figure 5.21: Variation vs variation distribution in the design space for Fz = 3400 N – Dugoff Tyre

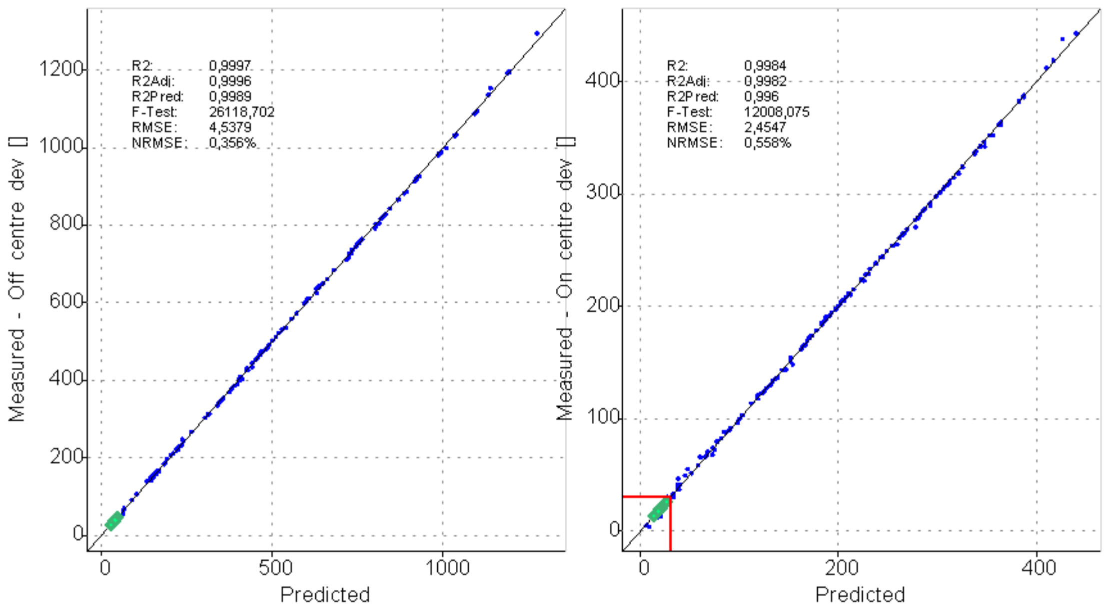


Figure 5.22: Measured vs Predicted graph of the On-Centre and Off-Centre – Dugoff Tyre

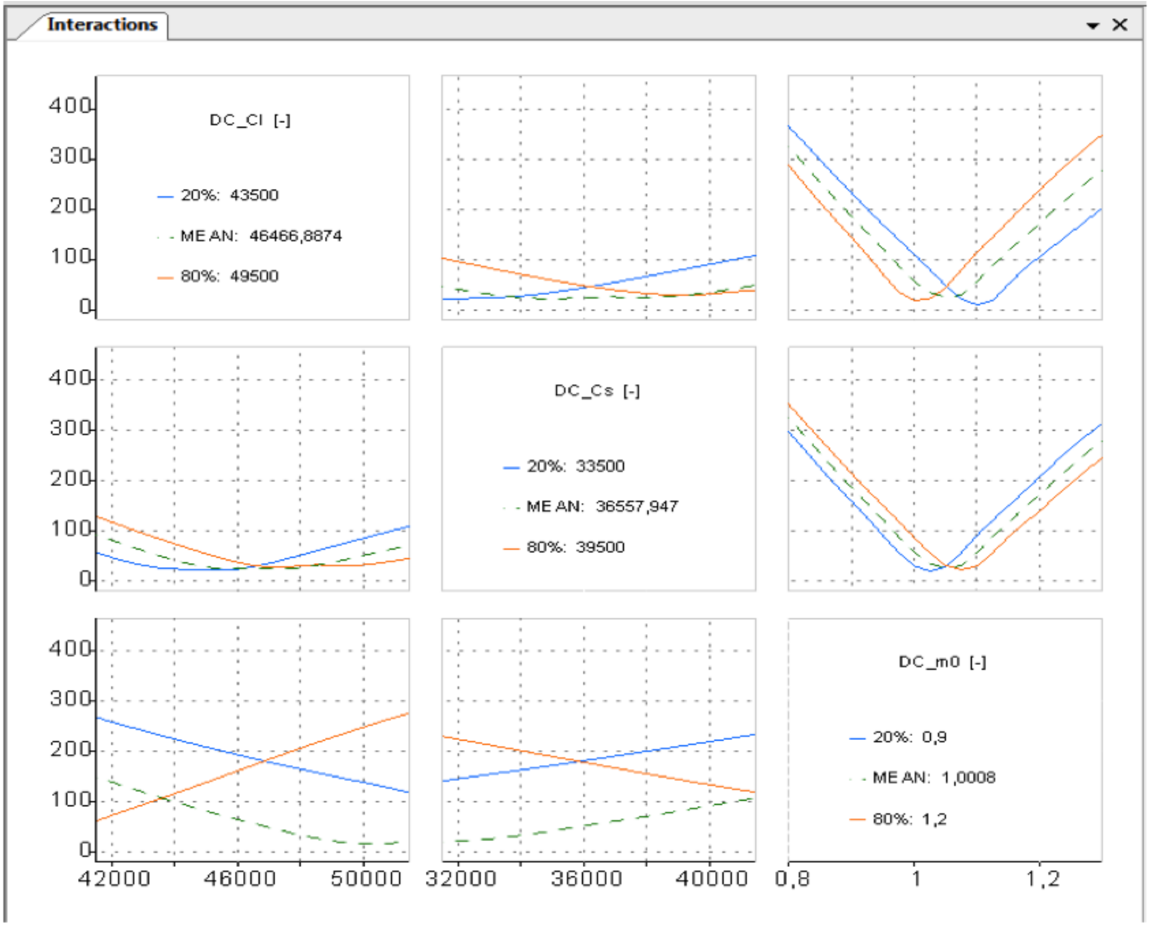


Figure 5.23: Interaction of the variation parameters in the On-Center – Dugoff Tyre

In the figures 5.23 and 5.24, the interaction graphs show the effects of the influences of a independent variable and the depended variable. Here the three input parameters and their interactions are studied. For example, in the Off-Centre, the interaction of the initial friction coefficient values strongly interacting with the lateral and longitudinal stiffness values in which the effect of the *mu* is more. Similarly, the mean value effects of the interaction between the lateral stiffness C_s and the longitudinal stiffness C_l is independently interacting.

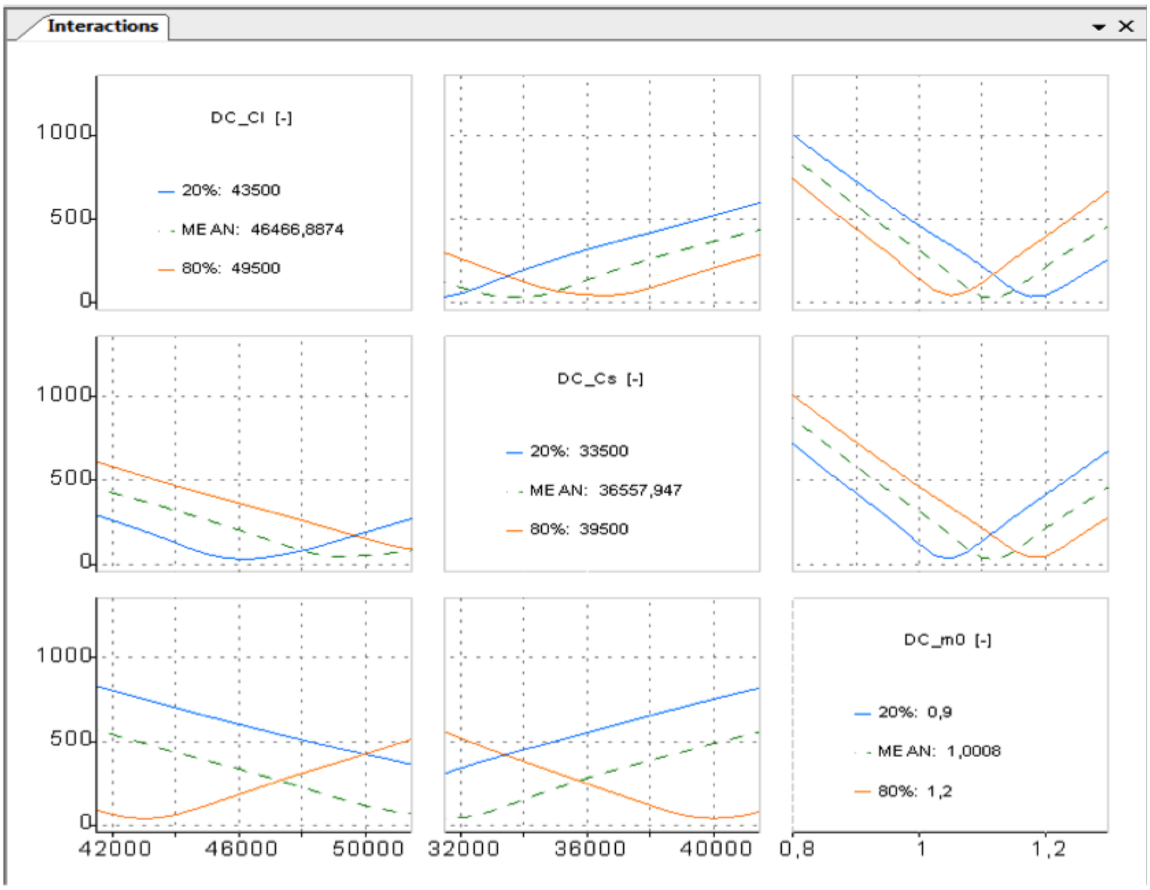


Figure 5.24: Interaction of the variation parameters in the Off-Center – Dugoff Tyre

In the figure 5.25, the residual plot shows the responses vs the run order of the test generated data. The residuals show that the responses are closely distributed along the horizontal axis, the linear regression model is relevant for the given data. Very few points are randomly distributed along the horizontal axis that signifies the points are non-linear to the regression.

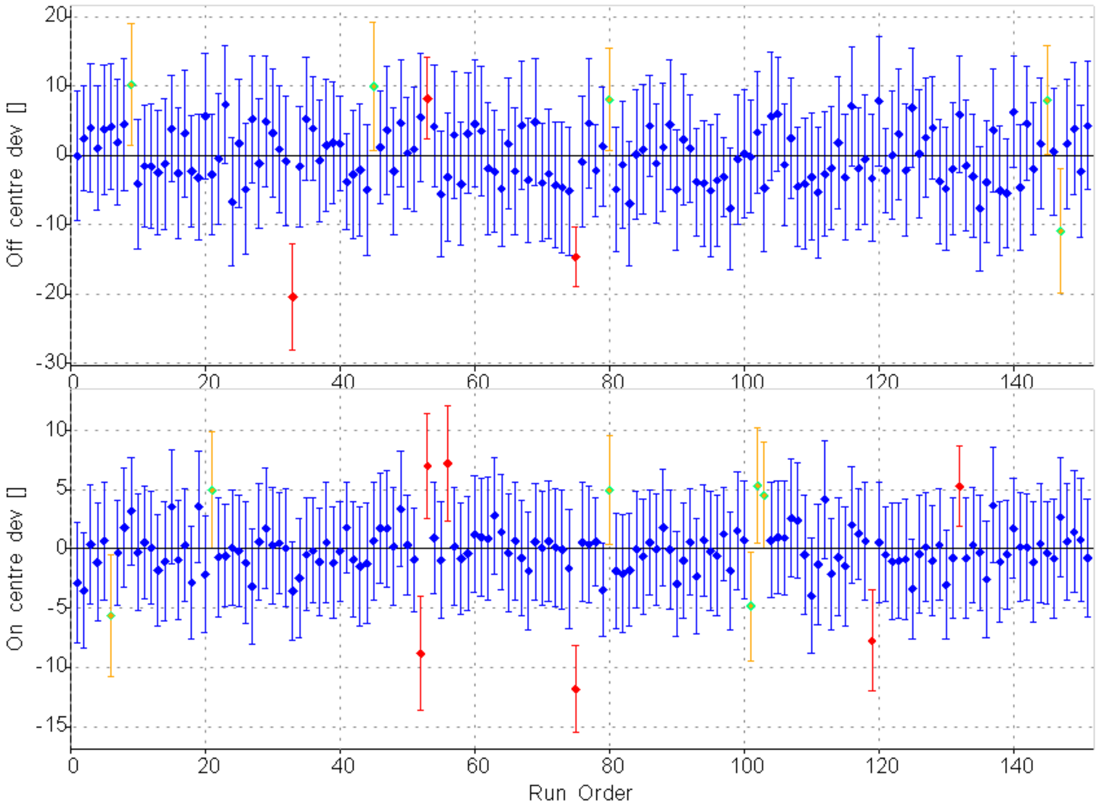


Figure 5.25: The residual window shows of the variation parameters in the On-Centre and Off-Centre – Dugoff Tyre Model

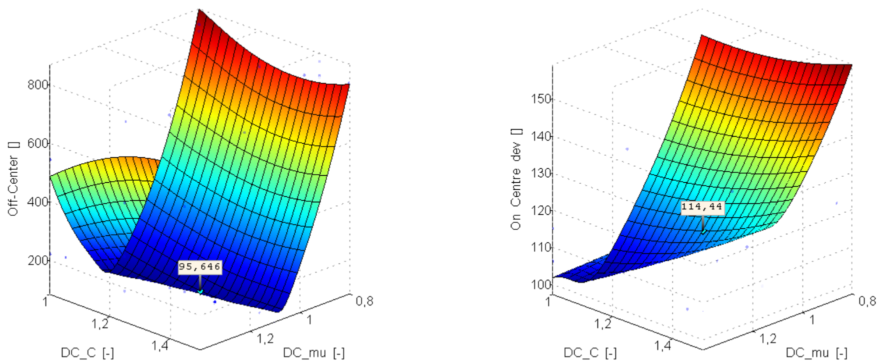


Figure 5.26: 3D plot of the responses at Fz = 3400 N – Dugoff Tyre

In the figure 5.26, the input parameters are influences the responses in the three dimensional space. The Off-Centre response is shown on the left graph and the On-Centre is on the right.

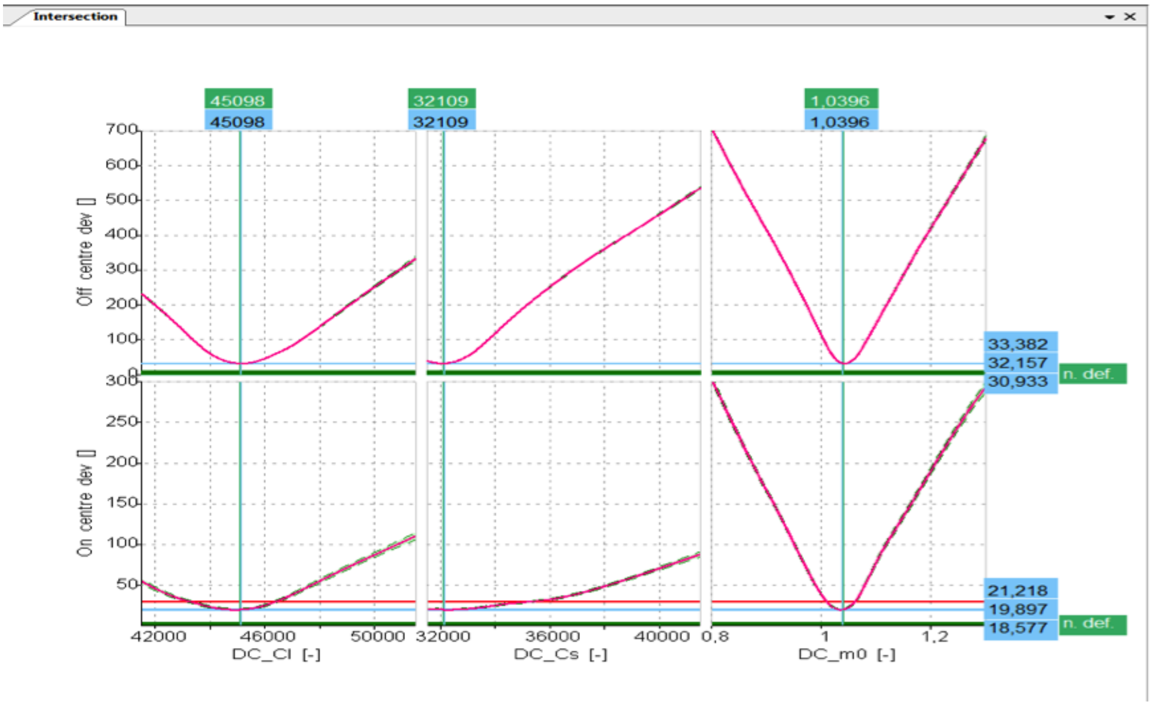


Figure 5.27: Intersection plot of the responses for Fz = 3400N – Dugoff Tyre

In the figure 5.27, for the optimal point where the deviations in the On-Centre and the Off-centre responses are minised to zero and instantaneously show the corresponding input parameters. This gives the user to decide on the desired input values of the inputs which is falling into the operating range of input values. The indication of the operating range is shown as the dark green line at the bottom of the graph.

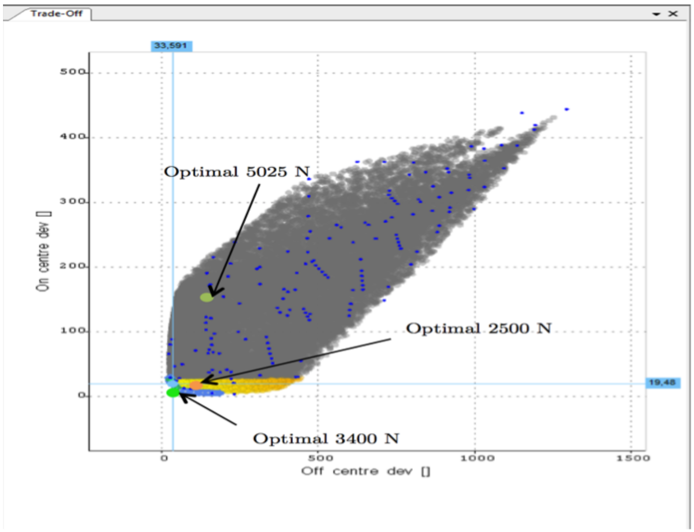


Figure 5.28: Dugoff Tyre - Pareto front plot on Fz =3400 N data with the indication of optimum points of 2500 N and 5025 N

The figure 5.28 gives the possibility to find the optimal points which are close to zero. These points are identified as the Pareto points where the responses are greatly traded off between them and gives us the optimised input parameter values. the constraint is given to the On-Centre deviation response of 40 N, where the Pareto front is restricted to find the optimal point within this limitation. the random points are also distributed along with test data. For this particular setup the optimal points for the dataset of vertical forces F_z 2.5kN and 5kN are also shown. This is the result of parameterisation using the Pareto front. The results are stored in order to compare with the manual tuning method.

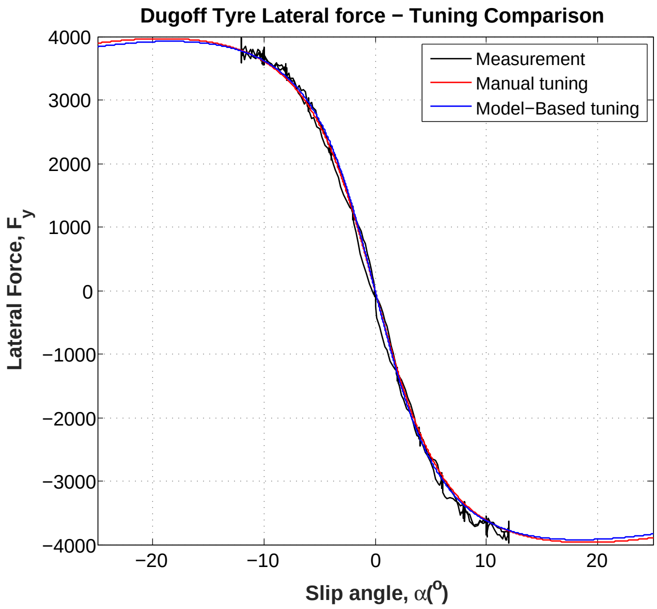


Figure 5.29: Comparison of results - Dugoff tyre manual tuning and Cameo™ model based tuning

The figure 5.29 gives the the details of extrapolation and the comparison of the manual and model-based tuning results of the Dugoff model. The table 5.4 gives us the elucidation of how the manual and the model based tuning are compared and the time and quality of the methods are the primary factors to evaluate the comparison task. The initial set up of the model is the inevitable process which has taken much time in both manual and model based tuning. The values of R2 and NRMSE gives the prediction on the quality and the time taken in days for a non-expert describes the duration of paramterisation.

Table 5.4: Comparison of all the three tyre models with respect to Manual and Model-based tuning

S.No	Models			Quality		Time for parameterisation
				R2	NRMSE[a] (%)	(days)
1	TM Simple Model	Manual tuning	On-Centre	0.9917	4.387	8
			Off-Centre	0.9879	8.465	
		Model-based tuning	On-Centre	0.9947	2.364	5
			Off-Centre	0.9979	0.913	
2	Magic Formula Model	Manual tuning	On-Centre	0.9741	3.534	5
			Off-Centre	0.9876	1.766	
		Model-based tuning	On-Centre	0.9868	2.271	3
			Off-Centre	0.9894	2.233	
3	Dugoff Friction Model	Manual tuning	On-Centre	0.9947	3.384	4
			Off-Centre	0.9812	9.356	
		Model-based tuning	On-Centre	0.9984	0.558	2
			Off-Centre	0.9997	0.356	

[a]Normalised Root Mean square Error

6 Conclusions and Recommendations

6.1 Conclusions

The tyre modelling and its applications in optimising the procedure to reduce the experimentation time have been discussed in detail. The parameterisation is the most important task in determining the influencing inputs to the mathematical models, which in turn consumes much of the expert's time. The model based tuning approach provides an ease and comfortable means to identify the parameters with high level of accuracy. The virtual calibration technique of the tyre modelling developed in the MiL (Model in the Loop) environment in AVL Cameo^{TM} using an optimisation tool can be the most efficient and powerful method for the development of the tyre model applications and experimental system setups. The traditional approach on an experimental design, which is supported by using the simulated environment, is improved and the outputs are well defined in the methodology used in this thesis. Using DoE methods used by AVL Cameo^{TM} is mainly having a potentiality to increase the number of the tuning combinations and tests compared to a manual parameterisation and tuning and also the number of target parameters and tests required to match closely them. The extrapolation of the modelling curves and the relevant data points are also determined by using the interaction plots to give an idea of how the model is behaving in both the realistic and theoretical basis. MBT approach gives a higher accuracy in the semi-physical models and supports experts to find the best trade-off decision in case of conflicting targets. The varied DoE range has given the possibility to study the real influence of input parameter over a wide spectrum. This method had reduced the time of parameterisation for a non-expert. With respect to the modelling error, the values of R^2 and $NRMSE$ have given significant improvement in Model-Based Tuning method results. This also have given opportunity to include the expert's pre-knowledge.

The feasibility to separately handle the alternate study on the tyre model use cases is one of the important achievements in this project. Also this approach is highly robust and reproducible for other tyre models as well. The control over multiple data sets at the same time has been produced to reduce the efforts. The comparison of different variants o fthe tyre are also possible. Independent of the complexity this method is applicable. The software and the tuning data has been properly explained and studied in detail. The independent validation process for each data set has given the reader to clearly understand the in depth influence of all input parameters and the modelling out responses how they behave in different modelling environment. The model based tuning approach can be very much helpful as the real time test procedures and experimentation process is both expensive and complicated with to obtain the desired outcome. This method could be extrapolated to further experimentation data points that may be useful for the engineer to test the characteristics of the tyre with much flexibility and freedom. The robustness of the output responses (KPI's) that are appropriate can be estimated.

6.2 Recommendations

The further steps in this project and the scope lays in the simulation part where the model based tuning system would be connected to a simulation environment to study the dynamic behaviour of the tyre models discussed. It is however possible to analyse various other tyre models that have been experimentally investigated and the model performance which might have a greater applicability for the same agenda of this thesis such as LuGre Model, TMeasy Tyre Model. Due to time and computational constraints, these simulations could not be performed. More studies can be performed for different input parameters of other physical or semi-empirical models as well. In this project, three different tyre models have been investigated in detail and its applications are very much realised after the parameterisation procedures and by knowing influence in varying tyre-modelling aspects. Furthermore, it is better to perform experiments and simulations with other external and environmental parameters such as temperature influence, type or road surface and so on. The modelling and simulations would tend to get slower as time proceeds. So it is better to speeding up the code by improving the structure of the complex mathematical models with large set of parameters.

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