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An Investigation into the Characteristics of Bumpsteer & How These Can Be Altered/Reduced Through the Evaluation of Suspension Kinematics to Enhance the Handling of a Race Car



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Research Methods &
Project - M6X02206

Table of Contents

Table of Contents.....	1
List of Figures	3
List of Tables	4
Acknowledgements.....	5
Abstract.....	6
Chapter 1 - Introduction	7
1.1 - Nature of the Problem.....	7
1.2 - Background and Causes	8
1.3 - Aims and Objectives	8
Chapter 2 - Literature Review	10
2.1 - Scope of Chapter.....	10
2.2 - Wheel Toe	10
2.3 - Bump Steer	11
2.4 - Independent Multi-Link Suspension	12
2.5 - Roll Steer.....	14
2.6 - Camber and Caster	14
2.7 - Slip Angle.....	15
2.8 - Lateral Acceleration Force and Weight Transfer	16
2.9 - Understeer and Oversteer	16
2.10 - Steady-State and ISO 4138	17
2.11 - Computer-Aided Engineering and Suspension Software	18
Chapter 3 - Methodology.....	20
3.1 - Scope of Chapter.....	20
3.2 - Statement of Research aim	20
3.3 - Introduction	20
3.4 - Measuring Bumpsteer	21
3.4.1 - Outline of Experiment	21
3.4.2 - Experiment Control Measures.....	21
3.4.3 - Experiment Process	22
3.5 - Measuring Suspension Coordinates	23
3.5.1 - Outline of Experiment	23

3.5.2 - Experiment Control Measures	23
3.5.3 - Experiment Process	23
3.6 - WinGeo 3 Computer Simulation	24
3.6.1 - Outlines of Experiment	24
3.6.2 - Experiment Control Measures	25
3.6.3 - Experiment Process	27
3.7 - Manufacturing Adjustable Arms	29
3.7.1 - Outlines of Experiment	29
3.7.2 - Experiment Control Measures	29
3.7.3 - Experiment Process	29
3.8 - Track & Steady State Testing	32
3.8.1 - Outlines of Experiment	32
3.8.2 - Experiment Control Measures	32
3.8.3 - Experiment Process	33
3.9 - Summary of Chapter	35
Chapter 4 - Results & Analysis	36
4.1 - Scope of Chapter	36
4.2 - Measuring Bumpsteer	36
4.3 - WinGeo 3 Analysis	37
4.4 - Measuring Bumpsteer – Developed Set Up	42
4.5 - Track Testing Analysis	42
4.5.1 - Track Testing	43
4.5.2 - Steady-State Testing	47
4.5.3 - Driver Feedback & Test Data Sheet	48
4.6 - Summary of Chapter	49
Chapter 5 - Conclusion	50
5.1 - Scope of Chapter	50
5.2 - Discussion of Project Objectives	50
5.3 - Discussion of Project Aim	51
5.4 - Summary	51
5.5 - Limitations	52
5.6 - Further Work	53
Chapter 6 - Pandemic Impact	55

References	57
Bibliography	59
Appendix – 1	61
Bumpsteer Reduction Investigation Track & Steady-State Testing	61
Appendix - 2	65
WinGeo Tests and Bumpsteer Graphs.....	65

List of Figures

Figure 1- Toe In and Toe Out Diagram (Viking Tyres Bollincollog, 2020)	10
Figure 2 Bumpsteer Diagram (Competition X, 2020).....	11
Figure 3 The skeleton view of the Mercedes linkage in perspective requirements the corresponding front and side view and plan to be fully understood. (Bastow, et al., 2004)..	13
Figure 4- Mk3 Mx-5 Rear Subframe & Suspension (Japspeed, 2020)	14
Figure 5- Camber Diagram - (Viking Tyres Bollincollog, 2020) Figure 6- Caster Diagram (Viking Tyres Bollincollog, 2020)	15
Figure 7- Slip Angle vs Cornering Force (Suspension Secrets , 2017)	15
Figure 8- Effect of Slip Angles (Hillier, 2014)	17
Figure 9 - WinGeo 3 Multi-True-Five-Link-Suspension (Marshall, 2020)	19
Figure 10- Mx5 Suspension during string set-up on flatbed (Marshall, 2020)	21
Figure 11- Bumpsteer Experiment on Flatbed (Left- Side View Right- Rear View) (Marshall, 2020)	22
Figure 12- Measuring of XYZ Points (Marshall, 2020)	24
Figure 13 Mk3 Mx5 Suspension Model in WinGeo Software (Marshall, 2020)	25
Figure 14- Arm angle measurement of the suspension during Flatbed experiments (Marshall, 2020)	26
Figure 15 Check Sum angle of suspension in WinGeo model (Marshall, 2020)	26
Figure 16 WinGeo Iteration Settings (Marshall, 2020)	27
Figure 17 - 2D Paper Model of Suspension Coordinates (Marshall, 2020).....	28
Figure 18 Toe Arm Pins Technical Drawing (Marshall, 2020)	30
Figure 19 Mx5 Adjustable Toe Arm Pins (Marshall, 2020)	31
Figure 20- Adjustable Mx5 Toe Arms (Marshall, 2020)	31
Figure 21- Adjustable Toe Arm fitted on Mx5 Hub (Marshall, 2020)	31
Figure 22 - Mx5 Race Car Suspension Set-Up Using String Gauges and Set-up Strands (Marshall, 2020).....	32
Figure 23 - Graph of Bumpsteer of Standard Suspension	37
Figure 24-Standard Suspension Bumpsteer Results produced by WinGeo (Marshall, 2020) .	38
Figure 25 Test 5 Bumpsteer Graph - Tie Rod Lowered by 10mm (Marshall, 2020)	39
Figure 26 Test 8 Bumpsteer Graph - Lower A-arm shortened by 10mm (Marshall, 2020).....	39
Figure 27 Test 13 Bumpsteer Graph - Lower A-arm shortened by 80mm (Marshall, 2020)...	40

Figure 28 Test 21 Bumpsteer Graph - Upper A-arm Forward shortened by 100mm (Marshall, 2020)	40
Figure 29 Test 29 Bumpsteer Graph - Upper A-arm Rear shortened by 100mm (Marshall, 2020)	41
Figure 30 Test 31 Bumpsteer Graph - Combined Alterations (Marshall, 2020)	42
Figure 31 AIM Race Studio Analysis Example Data (Marshall, 2020)	43
Figure 32 Ackerman Angle Equation AIM Race Studio (Marshall, 2020)	44
Figure 33 Ackerman Steering Percentage Equation AIM Race Studio (Marshall, 2020)	45
Figure 34 Understeer Equation AIM Race Studio (Marshall, 2020)	45
Figure 35 Example Understeer Data Trace AIM Race Studio (Marshall, 2020)	45
Figure 36 Example Understeer vs Speed Scatter Plot (Marshall, 2020)	46
Figure 37 Example Understeer Data Trace (Marshall, 2020)	47

List of Tables

Table 1 ISO 4138 Test Conditions (ISO, 2012)	18
Table 2 - Combined Suspension Arm length for Bumpsteer reduction investigation	28
Table 3 - Understeer and Oversteer Matrix	33
Table 4 - Mx5 race car constant set-up for testing	34
Table 5 - Testing Set-up Schedule	34
Table 6 - Measured Toe change of standard suspension	36
Table 7 - Toe Steer of Standard Suspension from Bumpsteer Measuring Experiment and WinGeo	38
Table 8 - Combined Suspension Arm length for Bumpsteer reduction investigation	41

Acknowledgements

The completion of this dissertation would not have been possible without the advice and assistance of others; therefore, I would like to thank the following people for their contribution to this project.

Paul Sheard of Paul Sheard Autosport for loaning a complete subframe assembly for the complete duration of the project, the loan of an Mx5 race car, set-up equipment and transport. These items have assisted greatly, without these the dissertation would not have been possible.

Nigel and Nikki Greensall of Greensall Motorsport for helping to organise the use of Bruntingthorpe proving ground and in addition Nigel for offering to be the driver for track testing.

Clare Rees my learning support worker for her endless help with writing and completing my dissertation. And to my supervisor Kerry Tudor for her help and advice through the dissertation keeping me on track throughout.

Abstract

A Circuit race car desires to travel as fast as possible around a race circuit. To achieve this a race car must optimize its suspension kinematics. This dissertation's aim is to evaluate the suspension kinematics of a race car's performance highlighting any issues. Steering and suspension system must be designed and optimized properly to achieve good performance handling characteristics. Flaws in design will result in steering errors such as bumpsteer and roll steer (Kulkarni, et al., 2016).

Research provided insight to suspension characteristics and their relevance to a race car's handling. Through reviewing the literature, solutions were created for optimising the suspension kinematics, a selection of methods which have been employed throughout the industry. Creating a process of methods to optimise the suspension kinematics which can be applied to multiple race car applications.

Mazda Mx5 Nc race car's rear suspension will be evaluated in this dissertation through experiments, measurements and CAE analysis, a regression model of toe angle displacement during wheel travel were obtained (Suh, et al., 2000). A process of experiments will allow for the suspension design to be optimised to reduce bumpsteer and improve the race car's handling. The suspension development used CAE with the use of Mitchel WinGeo 3 software, allowing many suspension designs to be developed and analysed before the design is implemented on the race car. Track test will be used to evaluate and review if changes made to the suspension geometry have made a positive impact on the vehicle's handling performance.

Chapter 1 - Introduction

In motorsport many production cars are used for circuit racing, these cars and championships have proven very popular as a production car can be taken from standard with the addition of safety modifications and raced. This solution of modifying production cars is cheaper than building bespoke race cars, a production car is more desirable due to ease and reduced cost of maintenance, as standard production parts are readily available. The popularity of production car-based race cars has led to many one-make racing championships formed, (Did You Know Cars, 2020). Having said this with any motorsport application, development of the product will always be looked at to see how it can be made better, faster or stronger. This has led to the need for the development of the production car systems to improve them for their motorsport application.

The focus of this dissertation is to understand how the production suspension kinematics of Mazda NC Mk3 Mx 5 can be developed for its use in circuit racing. The dissertation will take the main focus into the vehicle multi-link system and how it induces bumpsteer. The optimization of the suspension geometry to reduce bumpsteer of the vehicle will be evaluated with a viable solution and conclusion drawn. Suspension geometry has a substantial role in the stability and control of a vehicle (Upadhyay, et al., 2008). Handling performance relies on the configuration of the vehicle kinematic characteristics; toe angle, camber and caster (Suh, et al., 2000). The paper will look mainly into toe angle and its relationship with bumpsteer relative to the vehicle handling and stability.

1.1 - Nature of the Problem

Bumpsteer is an issue of suspension kinematics which causes issues of vehicle dynamic handling behaviour, in motorsport the need for reduction of bumpsteer is even more prevalent than a road vehicle. With an Mk3 Mx 5 being a modified production car for circuit racing, it gives a need for the development of the suspension geometry to improve the handling performance of the car. The rear suspension geometry can benefit from optimization for the improvement of performance handling and control of the vehicle (Upadhyay, et al., 2008). In a discussion with Glen Long, owner of Long Road Racing, Long Road Racing is at the forefront of the development of NC and ND Mx 5 race cars, being the exclusive builder of the Global MX-5 Cup race car and a Mazda technical partner. After a

email discussion with Glen Long about improving the suspension geometry of an NC Mx 5 race car for circuit racing, Glen Long suggested 'looking at the rear bump steer curves and optimizing those.' (Glen Long 2019, personal communication, 16/05/2012)

1.2 - Background and Causes

Mk3 MX-5's is a popular vehicle for circuit racing with various national race championship including United kingdom based one-make series Supercup (BRSCC, 2019), and an American one makes series also features the NC Mx5 (Spec MX-5 Challenge, 2019). The popular use of the vehicle for track use has highlighted the importance of optimizing the handling of the vehicle's rear suspension geometry. The Mk3 Mx5 uses a multi-five-link independent suspension, this design from Mazda makes the vehicle very popular by its high handling performance for a production car. It has become apparent however, after years of these cars being raced that the standard rear suspension kinematics needs development to improve the dynamic handling behaviour of the car for circuit racing.

The dissertation is going to focus on how the bumpsteer affects the movement of the rear suspension and how this affects the dynamic handling behaviour of the race car. The Mx5 race car chosen for this dissertation uses a standard rear suspension system, an issue with this is a lowered ride height which changes the angles of the suspension arms when at static ride height. The change in the angle of the suspension arms drastically compromises the handling, this compromise is commonly produced due to bumpsteer induced from the change in ride height and suspension arm angle. A way to reduce this is to alter or change the angle and length of the suspension arms, (Harding, 2018). The mounting points height or position can also be changed to alter the suspension geometry but unfortunately, this is not possible with the Mazda Mk3 Mx5 due to its design.

1.3 - Aims and Objectives

The dissertation aims to investigate the suspension kinematics of a Mazda Mk3 NC Mx5 and how a race car set-up characteristic of producing bumpsteer: then identify solution and modifications to reduce the bumpsteer to improve the dynamic handling behaviour of the race car. To achieve the aim of the dissertation three objectives have been appointed for the project to work towards:

- Investigate how much bumpsteer is produced by a current Mx5 race car multi-link suspension geometry.
- Investigate how bumpsteer can be reduced by altering/evaluation of the geometry of the suspension kinematics.
- Investigate how the reduction/control of bumpsteer affects a race car's handling and lap times.

Chapter 2 - Literature Review

2.1 - Scope of Chapter

This Chapter begins by researching the Bumpsteer and suspension kinematics of multi-link suspension. Areas which hold key relevance to the dissertation were researched to develop an in-depth understanding of material being investigated. The chapter aims to give an overview of the subject and explain the field of the dissertation to give the project clarity.

2.2 - Wheel Toe

Toe or toe angle describes the change in the movement of the wheel from being vertical to the centreline of the vehicle. Toe angles are normally viewed from above, it is determined as a measurement of the movement of a wheel from the centerline of a vehicle across a single axle as seen in figure 1. Toe-in occurs when the wheel points inwards to the centreline of the vehicle; similarly, toe-out occurs when the wheel points outwards away from the centreline of the vehicle. Toe out is measured as a negative and Toe in as positive degrees or measurement, (Bastow, et al., 2004, Adams, 1992, Mavrigian, 2000).

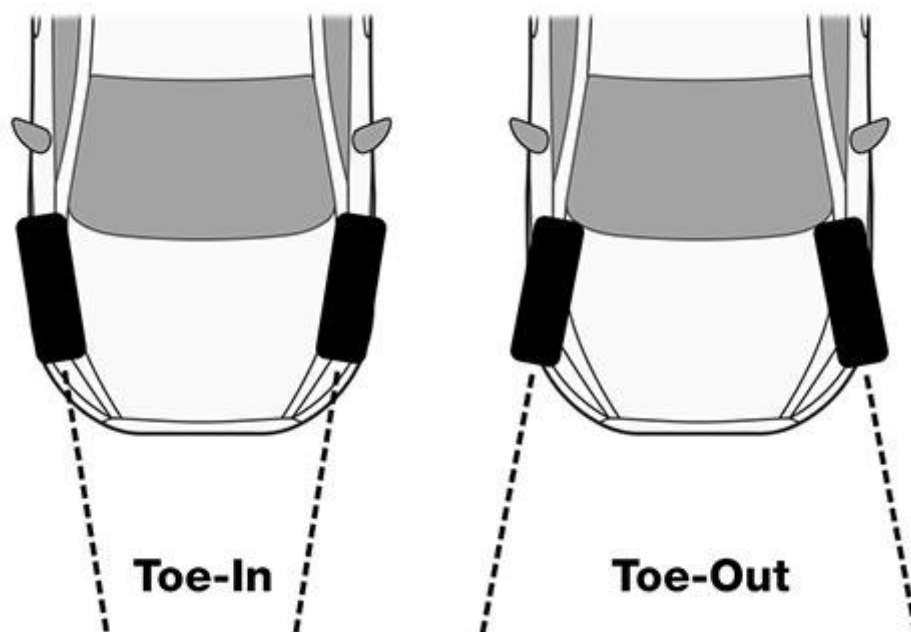


Figure 1- Toe In and Toe Out Diagram (Viking Tyres Bollincollig, 2020)

2.3 - Bump Steer

Bumpsteer is a relative measurement, not an absolute or linear measurement, 'Bumpsteer effect is changed with toe variation. The effect increased with greater toe variation' (Kulkarni, et al., 2016). Sharpio explains 'we are not interested in how much there is but interested in making it go away' (Smith, 1984). This supports the fact that the main focus of bumpsteer is reducing it as much as possible through suspension geometry optimisation. When completing an investigation of the suspension geometry, the measurement of bumpsteer is key, as the measurement allows for a comparison and evaluation of improvements. This allows the percentage change of parameters and their influence on vehicle behaviour to be evaluated throughout the investigation. When multiple changes are used to gain a result of suspension geometry and bumpsteer, it highlights the most desirable solution. All of these parameters can be used with the measurement of bumpsteer to evaluate its reduction through suspension geometry optimisation, (Upadhyay, et al., 2008).

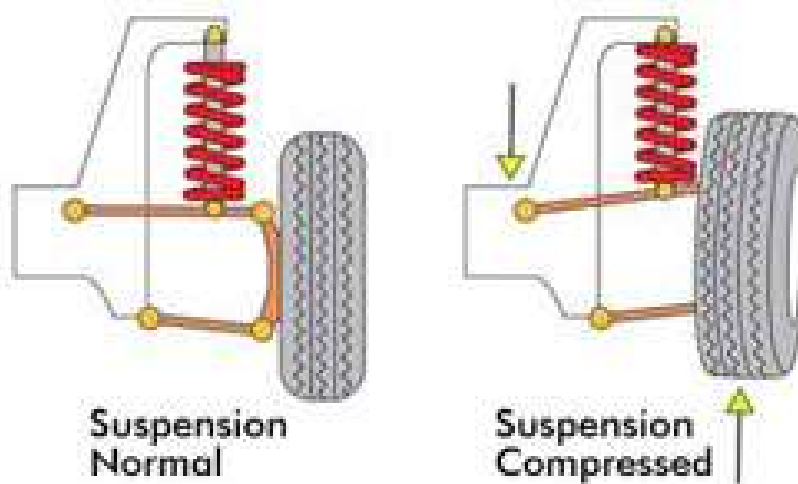


Figure 2 Bumpsteer Diagram (Competition X, 2020)

Bumpsteer is a steering error caused by the ride of the vehicle and the movement of the suspension through its travel. As the wheels move through bump and rebound, the wheel moves without driver input creating toe in or toe out as seen in figure 2 (Upadhyay, et al., 2008, Kulkarni, et al., 2016). Keeping wheel alignment constant through the motion of the vehicle's suspension is key for providing better handling performance, particularly during high-speed cornering (Suh, et al., 2000, Kulkarni, et al., 2016). The movement of the wheel

through bump and rebound is when bumpsteer occurs, this is a result of the toe arm or toe controlling suspension link changing its angle. The angle change of the toe arm will either extend or reduce the distance from the chassis to the hub relative to the suspension arms, this creates the variation of toe through bump and rebound (Upadhyay, et al., 2008). A toe arms angle change can be optimized to reduce bumpsteer. This is achieved by optimising its position to be perpendicular to the chassis with a matching movement of linear motion with the suspension arm between the hub and chassis, (Biswal, et al., 2017).

2.4 - Independent Multi-Link Suspension

The multi-link rear suspension has been used on production cars since the 1980s with Mercedes Benz being one of the first companies to implement this feature seen in figure 3. Multi-link allows for 'total flexibility of static geometry and geometry changes with vertical travel, longitudinal compliance without adverse effects on wheel geometry changes' (Bastow, et al., 2004:p224). These advantages demonstrate why manufacturers have chosen the design on many of their production cars. The particular example used in this dissertation is the Mazda Mk3 MX-5 seen in figure 4.

The multi-link system comprises of 5 links mounted to the chassis or sub-frame at one side, whilst the other end of the link mounts to the hub. The multi-link design forms two triangles when viewed from above with the addition of a stabiliser/ toe arm which forms the fifth link. Flexibility in the ball joints and bushes allow for some fore and aft movement. The compression of the front arm with the tension of the rear link induces a toe-in wheel action which is undesirable as this is a form of bumpsteer. The specific position of the links however can be changed so this toe-in can be reduced by an opposite effect. If the placement of the apices of the triangles is placed outwards from the middle of the contact patch, it will produce a toe-out wheel motion which counteracts the toe-in being produced.

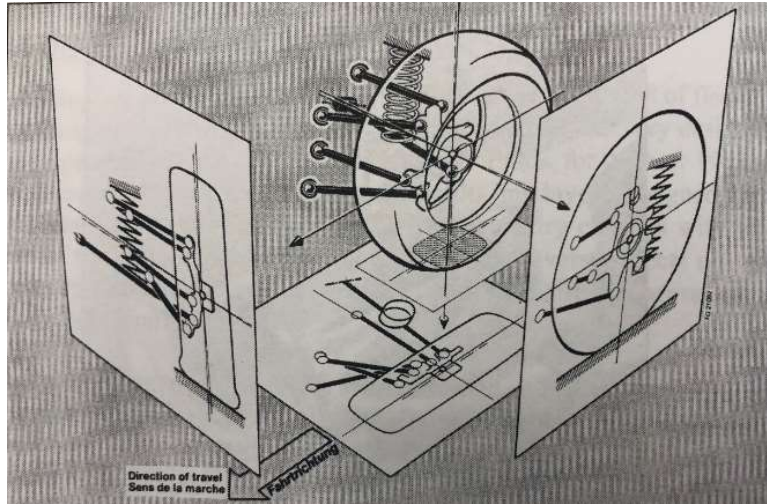


Figure 3 The skeleton view of the Mercedes linkage in perspective requires the corresponding front and side view and plan to be fully understood. (Bastow, et al., 2004)

Consideration of the apex points of the links at the chassis, hub and link length can be evaluated so the two tendencies cancel each other out to achieve a suspension geometry with minimal steering deflection through the wheel travel. This is aided by the fifth link; however, fore and aft compliance must still be obtained to eliminate/minimise steering deflection which includes bumpsteer, (Bastow, et al., 2004, Olley, 2002).

Multi-link is a popular application with race cars as there is no swing arm effect, therefore the wheels will lean with the vehicle roll. This allows the wheel to move independently with no external influence on camber change through compression; this means constant camber is present through the wheel travel which can be set to optimise the tyre contact patch with the track surface when cornering, (Bastow, et al., 2004, Olley, 2002).

According to Bastow et al. (2004) 'Incorrect relative lengths of the instantaneous radii of suspension and steering linkages, incorrect relative heights of the ends of the two effective radii' (p339) as the cause of steering geometry errors, bump and rebound. An Mk3 MX-5 race car has an altered suspension geometry from the factory including toe, camber and ride height. These changes mean the 'cancel out tendencies' of multi-link are altered, creating a variation in the steering deflection. This variation will allow bumpsteer to become more prominent; the aim being addressed in this investigation is how bumpsteer can be reduced, this is why the optimisation of the suspension geometry for an Mk3 MX-5 is key for improving the vehicle's dynamic handling performance in particular high-speed cornering (Suh, et al., 2000, Bastow, et al., 2004).

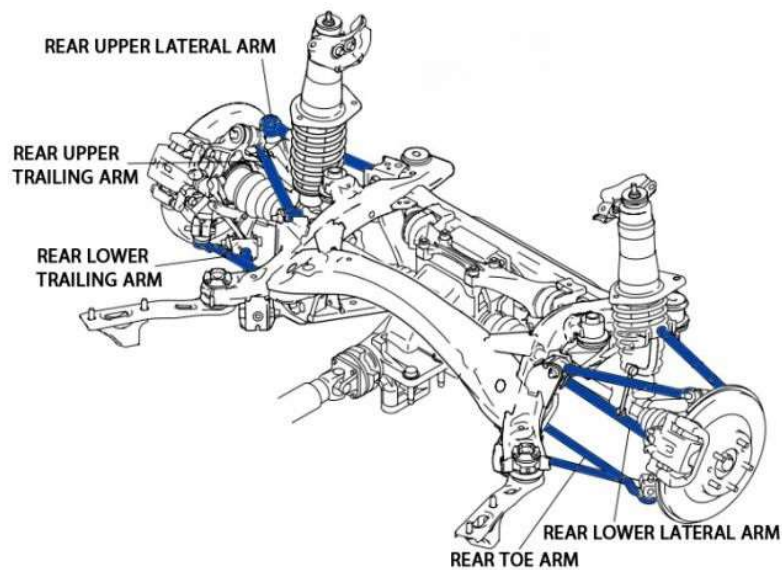


Figure 4- Mk3 Mx-5 Rear Subframe & Suspension (Japspeed, 2020)

2.5 - Roll Steer

Roll steer is an effect on the suspension kinematics altering the steer/toe of the wheels as the vehicle rolls and the suspension enters bump. Smith describes it as “the self-steering action of any automobile in response to lateral acceleration and consists of slip angle changes due to camber change, toe change and the inertias of the sprung mass.” (Smith, 1984). The principle is the same as bumpsteer, however, roll can be used to create either understeer or oversteer depending on which axle it has been designed on. Manufacturers use roll steer mainly to induce understeer on the front of a vehicle, as understeer is easy to manage for a conventional automotive driver however, this is not the case with a racing application, (Hillier, 2014, Olley, 2002).

2.6 - Camber and Caster

The terms Camber and Caster will be used throughout the dissertation, before using these terms it is important to understand their meaning. Camber is the measurement of the angle of the wheel from top to bottom, negative camber is the point when the top of the wheel is near to the centre of the car and positive camber is the point when the top of the wheel is further away from the centre of the car see figure 5. Camber helps keep a larger tyre contact patch during weight transfer during cornering, (Staniforth, 2006).

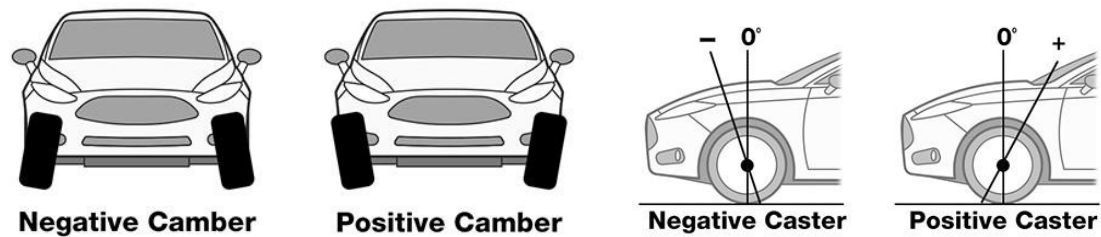


Figure 5- Camber Diagram - (Viking Tyres Bollincollog, 2020) Figure 6- Caster Diagram (Viking Tyres Bollincollog, 2020)

Looking at the wheel from the side, the suspension upright top pivot point is in line with the hub bottom pivot point at this point 0 caster is present. The top pivot point of the upright lies behind the bottom pivot point of the hub, this is positive caster. If the top pivot point of the upright lies in front of the bottom pivot point of the hub then this is negative caster. Caster angle changes how easily the steering self-centres itself when the vehicle accelerates out of a corner this can be seen in figure 6, (Staniforth, 2006).

2.7 - Slip Angle

Slip angle is the difference between the angle of which the steering wheel is pointing and the angle at which the wheels are pointing. Slip angles play a major role in the dynamic handling of a vehicle. The slip angle is created by the distortion of a tyre's contact patch, this distortion is caused by the loads acting on the tyre pushing it beyond its points of adhesion to the road surface, the slip angle can be seen in figure 7, (Suspension Secrets , 2017).

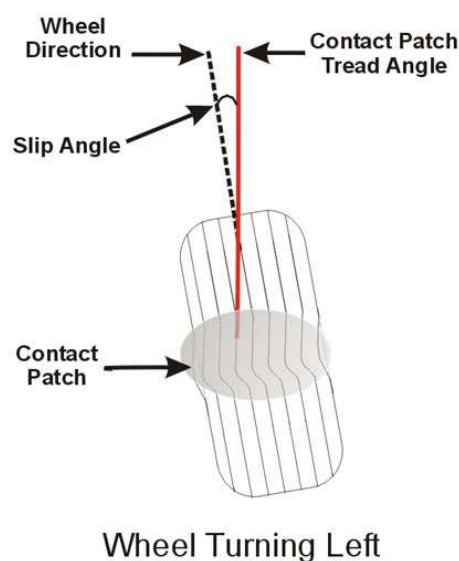


Figure 7- Slip Angle vs Cornering Force (Suspension Secrets , 2017)

2.8 - Lateral Acceleration Force and Weight Transfer

Lateral Force is perpendicular to the way the wheel is pointing, the lateral force has a linear relationship with slip angle- the larger the lateral force the larger the slip angle. As the lateral force is increased the slip angle increases, this will increase the corner radius or steering angle to keep the same corner radius. The increase in slip angle will result in the tyre starting to slip, which when the slip angle reaches a certain point will 'break free', this break free point is when the whole contact patch of the tyre slides resulting in either understeer or oversteer, (Santos, 2014).

Lateral weight transfer is the change in load from one tyre to the other across an axle, due to lateral acceleration imposed on the centre of gravity. It is the amount of load on the outer tyre which has been reduced from the inside tire, (Santos, 2015).

2.9 - Understeer and Oversteer

Understeer and oversteer, as defined by SAE J670e as cited by Bastow et al., (2004), is the change of steer angle with the change of lateral acceleration. ISO 4138 uses a steady-state where a vehicle is driven around a radius at different speeds, these allow for a definition of steer to be discussed. A set steering angle is needed to corner round the set radius, this neutral steer as the steering wheel is maintained in the same position as the vehicle's speed changes around the radius. If the steering input is required to be increased to maintain the vehicle's travels around the radius, this defines understeer. If the steering input is required to be decreased to maintain the vehicles travel around the radius, this defines oversteer as seen in figure 8. During transition conditions the handling behaviour may change, when cornering, change in braking or accelerating can cause the handling to change between understeer, oversteer or neutral steer, (Bastow, et al., 2004, Santos, 2014, Hillier, 2014).

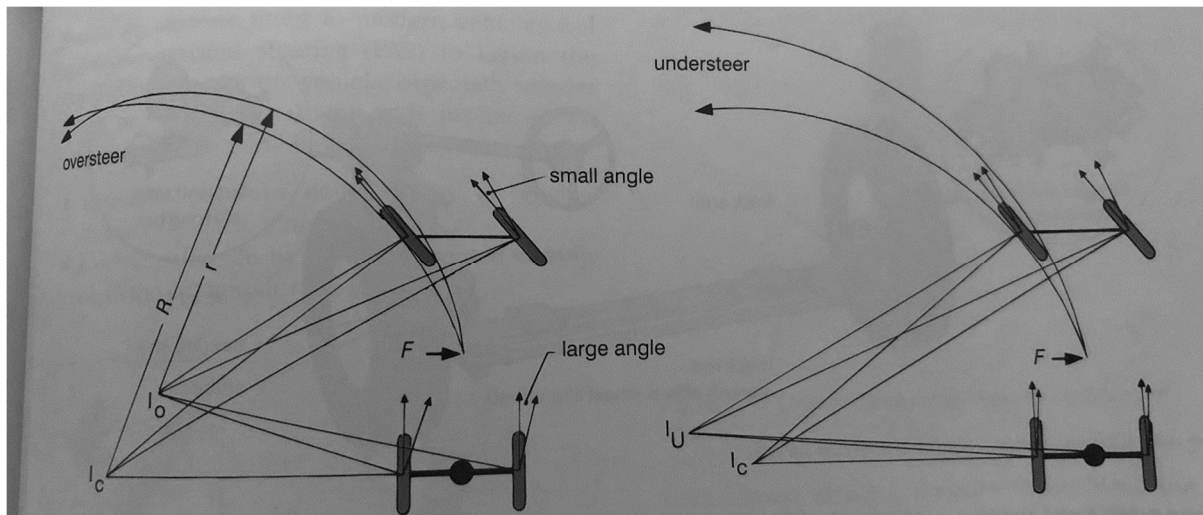


Figure 8- Effect of Slip Angles (Hillier, 2014)

2.10 - Steady-State and ISO 4138

The dynamic handling behaviour is an important aspect of a vehicle when combined with a driver and a changeable environment because it creates a unique closed-loop system. Evaluation of dynamic vehicle handling behaviour is very difficult due to variables in a driver, vehicle and environmental factors, therefore multiple different tests should be used to gain a complete understanding of a vehicle dynamic handling behaviour. Steady-state testing therefore should be used as part of dynamic handling behaviour evaluation however, the results gained from these tests allow an understanding of the vehicle behaviour to be evaluated and compared with other collected data, (ISO, 2012).

ISO 4138 specifies open-loop test methods which are designed for determining the steady-state circular cornering behaviour of a passenger vehicle, this behaviour comprises of vehicle dynamics and road-holding properties. The methods in ISO 4138 are not representative of real driving condition however, they are useful for obtaining measurements of vehicle steady-state behaviour due to controlled inputs which can closely be controlled in these test conditions, (ISO, 2012).

ISO 4138 specifies three different methods which allow steady-state results, each test has one constant and two variations, one which is controlled. The three different methods allow testing to be tailored to the exact requirement or conditions of testing. To obtain the desired set of steady-state results the following factors are key to each method speed, steering-wheel angle and turning radius. This means that method 1 has a constant corner

radius, method 2 a constant steering wheel angle and method 3 a constant speed. For each method, there will be a constant, controlled variable and a measured result. The tests can be seen in table 1, (ISO, 2012).

Test method	Constant	Varied	Measured or calculated
Constant radius	Radius	Speed	Steering-wheel angle
Constant steering-wheel angle	Steering-wheel angle	Speed	Radius
Constant speed with discrete turn radii	Speed	Radius	Steering-wheel angle
Constant speed with discrete steering-wheel angles	Speed	Steering-wheel angle	Radius

Table 1 ISO 4138 Test Conditions (ISO, 2012)

All three tests produce steady-state test data providing the same constant, varied and measure of either radius, speed or steering wheel angle as seen in Table 1. For each method, whichever one is chosen, three measures should be recorded: longitudinal velocity, lateral acceleration and steering-wheel angle. Control measure should also be followed to allow the results for the tests to be accurate these include consistent tyre temperature, same corner radius, same data acquisition equipment and operating temperature of the vehicle, (ISO, 2012).

2.11 - Computer-Aided Engineering and Suspension Software

The development of suspension kinematics using computer software has become prevalent, by the increasing development and design of computer-aided engineering (CAE) and computer-aided design (CAD) packages. Computer design packages allow for 3-D modelling of suspension where the suspension can be designed and developed at the same time. Bastow, et al (2004) goes on to say, 'CAD is essential to allow designers to investigate the integration and packaging of suspension layout into a proposed vehicle'(p283). The need for designing and developing suspension through CAD means accurate structure properties, vehicle dynamics and refinement can be altered with ease, saving time and costing as no prototype models are needed. A CAE package will allow for deeper analysis of the suspension geometry. CAE is essential for dynamical investigation, integration and development of a suspension layout with the need for producing multiple prototypes (Bastow, et al., 2004). WinGeo 3 figure 9 is a suspension package which is designed for development of motorsport suspension through its dynamics, with many features in the

package to investigate suspension kinematics including bumpsteer, roll, ride, camber etc. (Sharma, et al., 2015). Other CAE packages available include ADAMS, SolidWorks and DADS these can be used to optimize the suspension geometry, these packages have been developed for automotive manufactures to develop suspension models without producing prototypes, (Bastow, et al., 2004, Mohan, et al., 2008, Suh, et al., 2000, Upadhyay, et al., 2008).

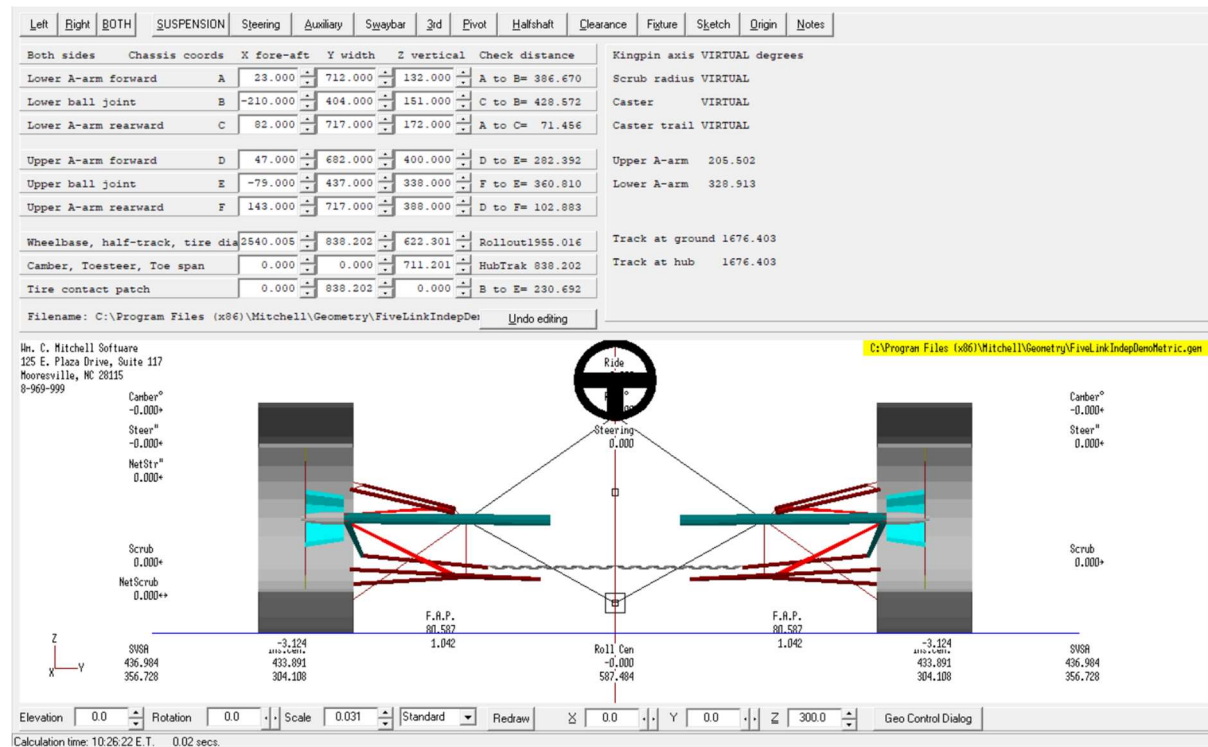


Figure 9 - WinGeo 3 Multi-True-Five-Link-Suspension (Marshall, 2020)

Chapter 3 - Methodology

3.1 - Scope of Chapter

This chapter explores the methods and experiments what are available to gain the necessary data for this dissertation. For accurate and relevant data to be collected, which is of most value to the project aims, the correct methods must be used. This chapter identifies the methods used, the reasoning behind each method, the method of data collection and how this data will aid in analysis.

3.2 - Statement of Research aim

The dissertation aims to investigate how bumpsteer can be reduced on a race car with multi-link suspension, methods will investigate how the reduction of bumpsteer can be achieved through the evaluation of suspension kinematics. The evaluation along with methods will conclude if the reduction and control of bumpsteer alters a race car's handling or lap time.

3.3 - Introduction

A variety of experiments were needed to address the aims of the dissertation which broke the project down into a process for research and development. The experiments which were undertaken are as follows.

- Measuring Bumpsteer
- Measuring Suspensions XYZ points
- Developing Suspension design using WinGeo 3
- Manufacturing Adjustable arms for developed designs
- Track Testing
 - Steady State Testing
 - Track Testing
 - Test Plan
 - Data Acquisition Collection
- Data Acquisition

Each method has been designed to achieve quantitative results which can be analysed. Each method section will demonstrate how the controlling variables have been reviewed to ensure the credibility of the results, human error, repeatability and limitations.

3.4 - Measuring Bumpsteer

3.4.1 - Outline of Experiment

A complete rear Mk3 Mx-5 subframe was used for the measuring of the bumpsteer. Using a flatbed to position the subframe for accurate measuring, a bumpsteer gauge, scissor jack, height gauge were all used in the experiment to gain results. The experiment set-up can be seen in figure 10. The experiment produced a set of results showing the change of toe as the wheel of the subframe is moved through its suspension travel.



Figure 10- Mx5 Suspension during string set-up on a flatbed (Marshall, 2020)

3.4.2 - Experiment Control Measures

A measuring flatbed was used to make sure any measurement is taken to have an accurate point of origin as they were taken with the floor being a reference, in this case, the flatbed. A calibrated height gauge was used as it was the most accurate method of measuring the height changes of the suspension, accompanied by a scissor jack allowed for steady accurate movements for height changes. A Bumpsteer gauge made by 'intercomp' was used with two dial test indicator (DTI) gauges, the experiment can be done with one DTI but two allowed for better accuracy when recording measurement, the set up can be seen in figure 11.



Figure 11- Bumpsteer Experiment on Flatbed (Left- Side View Right- Rear View) (Marshall, 2020)

3.4.3 - Experiment Process

The subframe was positioned on the flatbed in a way which replicated the identical set up found on an Mx-5 race car, a subframe was used rather than a complete race car as the space was not available for measuring. The subframe was raised 100mm from the base of the flatbed to replicate the ride height of a race car, this distance was measured directly from a race car on a flat floor so it could be replicated for accuracy during the experiment. Once the subframe was positioned, the suspension geometry was set to replicate a race car. Using a digital angle gauge, the camber was set to 2.8° negative camber. A string line was set parallel to the centre line of the car, then toe of the wheel was set to +1mm toe in by measuring the difference of distance between the rear and front of the wheel and changing the toe accordingly.

The method of measuring bumpsteer was used by both (Smith, 1984) and (Staniforth, 2006), who both argue using this method of measuring is the easiest and accurate method of measuring bumpsteer. The process starts with fitting a flat plate on the hub in place of the wheel, a bumpsteer gauge which consists of a stand with a DTI gauge which is positioned on each side of the plate then zeroed as seen in figure 11. A scissor gauge was placed under the hub and the hub height set to the static ride height of the race car 247mm; this was measured from the flatbed to shocker mount on the hub which can be seen in figure 11.

With the ride height set and the DTIs zeroed the ride height was risen by 50mm in 5mm increments with the DTIs reading taken down at each increment. The suspension was then zeroed at its static ride height and the process was repeated with the suspension being lowered through its rebound by 50mm at 5mm increments with the measurements of the DTIs recorded at each increment. The DTI's difference in change is the toe change of the wheel through its movement of bump and rebound, the results recorded allowed for analysis of the suspension's situation of bumpsteer before any changes were considered.

3.5 - Measuring Suspension Coordinates

3.5.1 - Outline of Experiment

To allow for a computer simulation of the subframe and suspension kinematics, the X, Y and Z coordinates of every suspension point, points must be measured from the X and Y centre line of the vehicle, and the Z which in the case of this experiment is the flatbed. The measurement was taken with the subframe on a flatbed with the wheel at static ride height and the subframe at static ride height (raised 100mm from flatbed) this was the same configuration as in the bumpsteer experiment.

3.5.2 - Experiment Control Measures

A measuring flatbed was used to make sure any measurements taken have an accurate point of origin as they were taken with the floor being a reference or in the case of the flatbed. Various measuring equipment was used to gain accurate measurements, these consisted of scale ruler and square, calibrated height gauge, Vernier callipers and a plumb bob. These tools allowed for the most accurate measurement which could be achieved measuring by hand on a flatbed.

3.5.3 - Experiment Process

This set-up process replicated the configuration of the bumpsteer measurement experiment. The subframe was positioned on the flatbed in a way which replicated the identical set up which would be found on an Mx-5 race car. The subframe was raised 100mm from the base of the flatbed. Once the subframe was positioned the suspension geometry was set to replicate a race car. The camber was set to 2.8° negative camber and the toe of the wheel set to +1mm toe in. A paper sheet was placed on the flatbed under the whole subframe and suspension assembly, a paper sheet was used to create a 2D drawing

of the suspension and assist the measurement of suspension point. This can be seen below in figure 12.

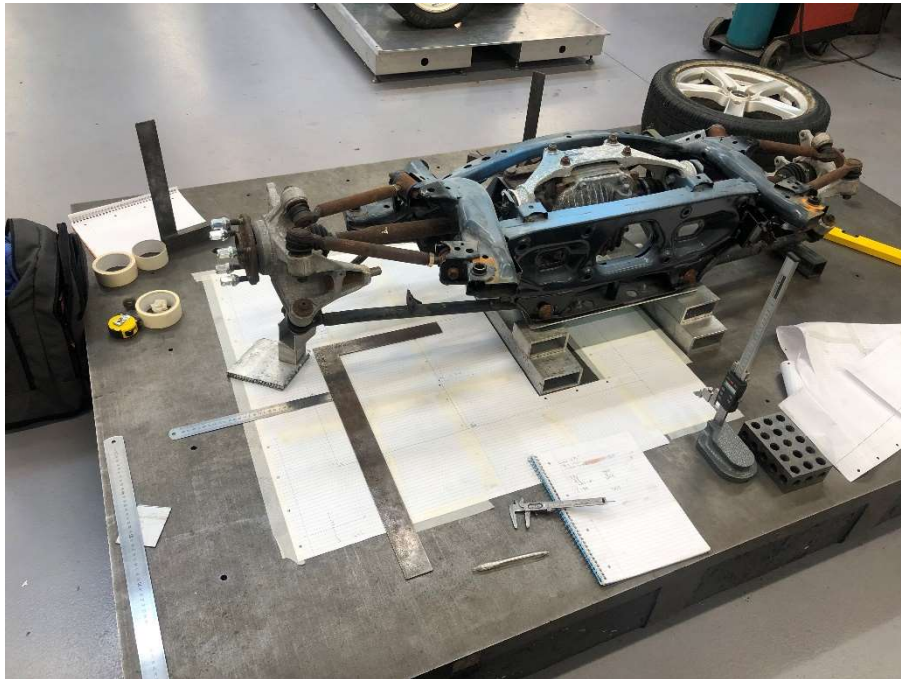


Figure 12- Measuring of XYZ Points (Marshall, 2020)

Firstly, the X and Y centre lines were marked on the drawing. The Y centre line was measured using the centre of the subframe using a measuring square, the X centre line was measured using a plumb bob from the centre of the drive shaft. Once these were drawn on the paper, they could be used as a datum for measuring each suspension point. Using the measuring equipment, the points at which the suspension mounts are positioned were marked on the paper; with the points being measured from X and Y then recorded. And the Z of each suspension mount was measured from the flatbed then recorded.

3.6 - WinGeo 3 Computer Simulation

3.6.1 - Outlines of Experiment

The development of suspension kinematics to reduce bumpsteer can be difficult to perfect, due to the adjustment of components requiring bumpsteer to be remeasured after each alteration. Measuring bumpsteer has proved to be a lengthy process so remeasuring after each alteration would take an unrealistic amount of time. Computer-aided software was therefore chosen to develop the alterations in suspension components and review the effect it has on the suspensions bumpsteer, whilst taking minimal time to complete and

producing accurate results. The software had to be able to support the design of a five-link independent suspension model which accurately represented the suspension kinematics of the Mx-5; the software also had to have the capability to examine/evaluate toe change through bump and rebound.

Mitchell's WinGeo 3 was chosen due to its capability to design an accurate model, easy adjustment of suspension components and its ability to produce bumpsteer graphs for each suspension design. WinGeo 3 has been the desired choice for suspension design and development used for many motorsport applications, Sharma, et al., (2015) and Mitchell, et al., (2008) discuss the benefits of using the program.

3.6.2 - Experiment Control Measures

The WinGeo model was created using the coordinates measured from the previous experiment; the software uses the coordinates to create a 2D suspension model.

The initial options were selected for the model, then the following setups were taken selecting the following tabs in WinGeo:

- New project
- 5-link independent
- True 5-Link

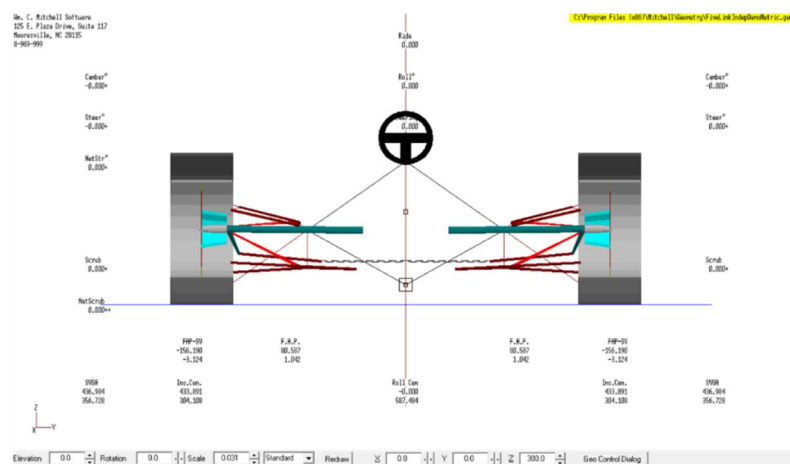


Figure 13 Mk3 Mx5 Suspension Model in WinGeo Software (Marshall, 2020)

Using the edit tab, 5-link independent was selected, here the coordinates of the suspension points were entered to create the model in figure 13. To validate the model, an angular

measurement was taken of an arm on the subframe, this angle is the same as the arm angle calculated by the WinGeo software for the same arm in figure 14 and figure 15. This validates that the suspension points measured have created an accurate model in the WinGeo software.



Figure 14- Arm angle measurement of the suspension during Flatbed experiments (Marshall, 2020)

Right	BOTH	Suspension	Steering	Auxiliary	Swaybar	3rd	Pivot	Halfshaft	Clea
sides	Chassis coords	X fore-aft	Y width	Z vertical	Check sums				
er A-arm forward	A	23.000	712.000	132.000	A - Am=	-2.817			
er A-arm forward mount	Am	-210.000	404.000	151.000	A to C=	-34.041			
er A-arm rearward	C	82.000	717.000	172.000	C - Cm=	2.992			
er A-arm rearward mount	Cm	151.000	205.000	145.000	Am- Cm=	0.834			
er A-arm forward	D	47.000	682.000	400.000	D - Dm=	12.683			
er A-arm forward mount	Dm	-79.000	437.000	338.000	D to F=	6.698			
er A-arm rearward	F	143.000	717.000	388.000	F - Fm=	12.454			
er A-arm rearward mount	Fm	182.000	439.000	326.000	Dm- Fm=	2.632			
re contact patch		0.000	838.202	0.000					

Figure 15 Check Sum angle of suspension in WinGeo model (Marshall, 2020)

3.6.3 - Experiment Process

Once the model was created using WinGeo's software feature, a bumpsteer graph menu was used to create a bumpsteer graph for the standard suspension, the iterations were

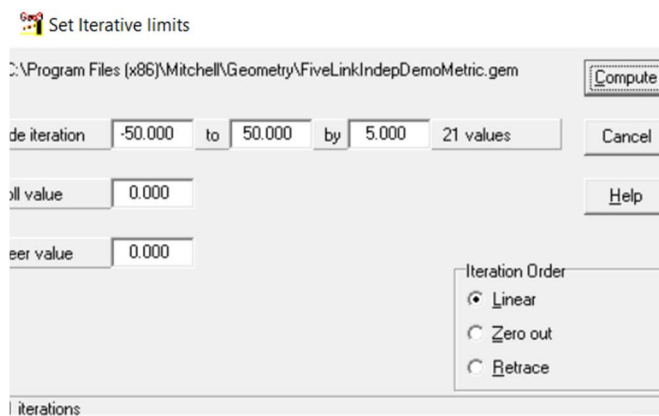


Figure 16 WinGeo Iteration Settings (Marshall, 2020)

changed to match the bumpsteer experiment completed at the beginning of the dissertation as seen in figure 16. To validate the graphs produced in WinGeo the standard suspension set-up produced a bumpsteer graph using WinGeo, the results and graphs were then compared against the results gained from the bumpsteer measuring

experiment; the correlation between these results will validate the accuracy of changes made in WinGeo. A series of changes were completed using the software, this produced a bumpsteer graph for each change and allowed what changes affected the reduction of bumpsteer the most.

Tests 1-7 investigated the effect of lowering or raising the toe arm. The first four tests used extreme changes in height - these allowed a view of where roughly the greatest effect was centred by lowering by 10mm. Three tests were then conducted with small changes of 1mm; this resulted in finding the largest reduction in bumpsteer by lowering the toe arm by 10mm.

Tests 8-13 investigated the effect of shortening the lower forward A-arm. These tests produced results for shortening the arm from 10mm up to 80mm.

Tests 14-21 investigated the effect of shortening the upper A-arm forward. These tests produced results for shortening the arm from 10mm up to 100mm. For each test, a bumpsteer graph was produced for analysis. As the arms did not run linear to either the X or Y axis, this resulted in both the X and Y coordinate needing to be changed when shortening the mounting of the arm. The 2D paper model was used to determine the X and Y of the arm when being shortening in increments, the 2D paper model can be seen under the subframe in figure 17.



Figure 17 - 2D Paper Model of Suspension Coordinates (Marshall, 2020)

Tests 22-29 investigated the effect of shortening the upper A-arm rearward. These tests produced results for shortening the arm from 10mm up to 100mm. For each test, a bumpsteer graph was produced for analysis. Using the same technique as for tests 14-21 the 2D paper model was used to calculate X and Y coordinates for changes of the arm.

Tests 30-37 investigated changing the toe arm, Upper A-arm forward and Upper A-arm rear in a combined test, below in table 2 the different arrangement of the arms for each test can be seen.

Test	Toe Arm Height	Upper A-arm Forward Length	Upper A-arm Rear Length
30	-10mm	-100mm	-100mm
31	-10mm	-50mm	-50mm
32	-10mm	-50mm	-100mm
33	-10mm	-80mm	-10mm
34	-10mm	-100mm	-50mm
35	-10mm	-100mm	-80mm
36	-10mm	-80mm	-80mm
37	0mm	-50mm	-100mm

Table 2 - Combined Suspension Arm length for Bumpsteer reduction investigation

3.7 - Manufacturing Adjustable Arms

3.7.1 - Outlines of Experiment

After conclusions were drawn from the development in WinGeo it posed the issue that the suspension arms would need modifying/ altering to minimise the bumpsteer. The development showed that 3 arms would need modification to achieve a reduction in bumpsteer. The top two arms needed adjustment to allow them to be shortened, the subframe used for the dissertation already had the availability for adjustable arms to be fitted. For previous tests, these arms were set to the standard length of a Mazda Mx-5 arm however, for track testing and reducing of bumpsteer these can be adjusted. A development from the WinGeo data showed a change in height of the toe arm was needed, this posed an issue as the standard toe arm was fixed and could not be adjusted. This meant a solution needed to be developed so the toe arm has the availability to have its pivot point changed on the Z-axis, this required manufacturing of a new component.

3.7.2 - Experiment Control Measures

The computer-aided design software was used to create a drawing which was an accurate representation of parts which required manufacturing, this meant that the parts were only manufactured once in order to perform their required function. Manufactured techniques of components were chosen as they produced the highest quality component which was fit for purpose.

3.7.3 - Experiment Process

After research of adjustable toe arms for Mx-5, it showed there were limited available to purchase, however they followed a design which could be manufactured with ease. The design consisted of an insert fitted into the hub with a thread on the end, this replaces the ball joint of the original arm as seen in figure 19. An insert with a thread was designed to be fitted into the standard arm, this allows for a rose joint to be fitted to the toe in place of the original ball joint. This design allows for the rose joints height to be varied on the hub insert with the use of spacers. Both inserts were designed in solid works using the measurement from the original ball joint and toe arm, the solid work parts were then produced into a technical drawing specifying sizes, thread sizes, radius and chamfers figure 18. A company then manufactured the inserts using computer-aided manufacturing on a CNC machine to

Technical drawing of a pin assembly. The drawing includes a side view with dimensions: 18.00, 13.00, 30.00, 10.00, 5.00, 35.00, and a callout for M14 x 2. A detail view shows a cross-section with dimensions 50.00, 6.00, 1.26, 14.00, 20.00, and 12.00. A note R3.26 is present. Two isometric views of the pin are shown to the right.

The design incorporated modifying the standard toe arm, the process required the arm being cut removing the standard ball joint, then 4 holes were drilled at the end of the arm to allow plug welding. Once the arm was prepped for welding, the insert was placed in the arm and welded. The insert was MIG welded in place around the collar and plug welded through the 4 holes on the arm, this makes sure the insert is attached to the toe arm in a way to increase strength and minimize the stress and fatigue of the joint. The finished assembly can be seen in figure 20. Figure 21 visualises how the hub insert fits with the rose joint allowing for adjustment, the rose joint is attached to the original toe arm with the attachment of the arm insert.



Figure 19 Mx5 Adjustable Toe Arm Pins (Marshall, 2020)



Figure 20- Adjustable Mx5 Toe Arms (Marshall, 2020)



Figure 21- Adjustable Toe Arm fitted on Mx5 Hub (Marshall, 2020)

3.8 - Track & Steady State Testing

3.8.1 - Outlines of Experiment

The aim for this experiment is to validate the changes developed from the WinGeo model, the testing will simulate real race conditions with the use of an Mx-5 race car around a selected racetrack and a steady-state loading test. The two tests will investigate differences of standard suspension set-up and selected developed set-ups which have shown to decrease bumpsteer. A test plan was developed to outline the process and order of the test, this was designed to maximise the credibility of results and usable data collected. This experiment was due to take place at Bruntingthorpe proving ground on 01/04/2020, however, due to the effects of Covid-19 pandemic this testing was unable to go forward.

3.8.2 - Experiment Control Measures

The experiment has many considerations and control measures to make sure the data recorded is accurate and credible. The test plan was designed with an A-B-C-A-D-E-A style, this means that the original set-up A is repeated throughout the day. Repeating set-up A shows in the data if the track conditions or time of day has any effect on the data, this will highlight data which may not be directly comparable with data collected at a different point. The race car will be running with the same suspension set-up, fuel and tyres throughout testing, the only changes will be those listed in the test plan. A level floor or corner pads will be used with set-up stands, string gauges and digital camber gauge as these are the most accurate measuring equipment available as highlighted in figure 22.



Figure 22 - Mx5 Race Car Suspension Set-Up Using String Gauges and Set-up Strands (Marshall, 2020)

All data will be recorded using an AIM Solo 2 DL, this will record all data needed for analysis, the data recorder will be positioned on the transmission tunnel, this allows for the g-force to be recorded at the centre of the car for every test. The driver will be driving the set-up changes blind, this ensures any feedback is impartial. Driver feedback will be recorded with a matrix for each corner this will allow quick and transferable driver feedback, a corner will be broken down into entry – 1 mid – 2 exit – 3, then understeer and oversteer will be scaled 5 for neutral, 0-4 for oversteer and 6-9 for understeer displayed in Table 3. The steady-state testing for each set-up will be completed around the same 25m radius, the tests will be completed straight after the track testing, this to ensure the tyres are warm for all tests, avoiding inconsistencies due to tyre temperature.

Corner Entry	Mid Corner	Corner Exit
1	2	3

Scale	Vehicle Handling
9	Excessive Understeer
8	High Understeer
7	Moderate Understeer
6	Slight Understeer
5	Neutral
4	Slight Oversteer
3	Moderate Oversteer
2	High Oversteer
1	Excessive Oversteer

Table 3 - Understeer and Oversteer Matrix

3.8.3 - Experiment Process

The car will be set up before the test using the set up listed in Table 4, this set is the standard base set up used by Mx-5 race cars. This set will stay the same throughout testing except for the alterations of developed bumpsteer set-ups.

	FL	FR	RL	RR
Toe	-1mm	-1mm	+1mm	+1mm
Camber	-2.5°	-2.5°	-2.8°	-2.8°
Corner Weight	276kg	298.5kg	264kg	284.5kg
Bump	8	8	8	8
Tyre Pressure Cold	24	25	24	25
Tyre Pressure Hot	30	30	30	30
Tyres	Avon ZZR	Avon ZZR	Avon ZZR	Avon ZZR

Table 4 - Mx5 race car constant set-up for testing

The testing will take place at Bruntingthorpe proving ground where track and steady-state testing will take place. A test plan is in place and can be seen in appendix 1, the plan documents the exact process of vehicle set-ups, controllable factors and data collection.

The car will be checked, and the driver briefed when arrived at the circuit, because of the nature of temperature and weather change throughout a day. A test plan has been chosen which retests the original set throughout the day, this is made to highlight any changes which might occur out of control of the test. Track testing will consist of 3 warm-up laps, after these laps the car will return to the pit lane so tyre pressures can be checked. After this 8-10 laps will be completed by the driver to collect data of the set-up.

Testing Set-ups Schedule-

Test	Toe Arm	Upper A-arm rearward	Upper A-arm forward
A	0mm	0mm	0mm
B	11mm	0mm	0mm
C	0mm	80mm	0mm
A	0mm	0mm	0mm
E	0mm	0mm	80mm
D	11mm	80mm	80mm
A	0mm	0mm	0mm

Table 5 - Testing Set-up Schedule

A test sheet has been attached to the test plan and a test sheet should be filled in for each test. These sheets will record the test conditions, driver feedback, and tyre conditions. The rest of the data collected will be done via the data logging system, the AIM Solo 2 DL will log lap times, longitudinal G-force, lateral G-force, steering angle, speed, rpm and Gyro force. A V-box data recording system will be used to monitor the video footage in order to monitor driver input and lap times for reference against other data recorded, this will help investigate certain data or anomalies.

Steady-State testing will be performed straight after the track testing this ensures the car and tyres are warmed up. A 50-metre cone circle will be marked out on an open flat patch of ground. The driver will drive around the circle clockwise, they will increase their speed until they find the car too difficult to keep at the same radius. This is a constant radius test as defined by ISO 4138 (ISO, 2012), this test aims to monitor the amount of steering angle input which will be recorded by the AIM data system. Ackerman data will be collected by the car travelling around the circle with the steering wheel at the same steering angle. The tests will display how the car's steady-state handling is affected by the different set-up, the tests will show how each set up influences understeer and oversteer of the car across a range of speeds. This will demonstrate which set-up allows the car to remain stable whilst moving around the radius.

3.9 - Summary of Chapter

The chapter concludes that a mixed-method approach was the best option for this dissertation; the mixed methods allowed validation, ease of development with the constraints of facilities and data recorded which can easily be compared against each other. Using both practical and computer-aided methods allowed for development to be analysed in greater detail compared to using either just practical or computer-aided methods.

Chapter 4 - Results & Analysis

4.1 - Scope of Chapter

This chapter explores the data collected from the mixed methods used and critically analyses them to create a greater understanding leading to a conclusion of how bumpsteer can be reduced by altering suspension kinematics. The chapter will analyse the data from mixed methods comparing and validating results against each other where possible. A full analysis of how designs of suspensions kinematics allow for a reduction of bumpsteer on an Mx-5 race car. The chapter will analyse each method separately referring to comparative data where necessary.

4.2 - Measuring Bumpsteer

Measuring the bumpsteer of the Mx5 as documented in the methodology produced a set of results which were used to create the table 6 and figure 23 below.

Bump			
<i>Ride Height (mm)</i>	DTI A	DTI B	Toe Steer (mm)
197	3.5	2.85	1.233
202	3.1	2.56	1.024
207	2.75	2.29	0.873
212	2.32	1.98	0.645
217	2.13	1.88	0.474
222	1.52	1.36	0.304
227	1.48	1.36	0.228
232	1.08	0.98	0.190
237	0.5	0.45	0.095
242	0.05	0.03	0.038
247	0	0	0.000
252	0.08	0.08	0.000
257	0.31	0.3	0.019
262	0.68	0.65	0.057
267	0.98	0.93	0.095
272	1.28	1.19	0.171
277	1.6	1.46	0.266
282	1.8	1.6	0.379
287	2	1.75	0.474
292	2.3	1.95	0.664
297	2.75	2.29	0.873

Table 6 - Measured Toe change of standard suspension

To calculate the change in toe with the use of 2 DTI gauges an equation was used. The whole equation is multiplied by 25.4 to convert the DTI value and span from Inch to millimetre.

$$\text{Toe change mm} = \frac{(A - B)}{\text{Span}} \times 25.4$$

The results from this experiment were gained to show the bumpsteer which is present on a standard Mx5 suspension with race-spec static ride height, camber, and toe. Table 6 was produced to achieve a clear presentation of the measurements recorded. As can be seen in Table 6 the values from DTI A are larger than DTI B throughout, this shows that the bumpsteer is creating toe-out. If DTI B was to be larger than DTI A than the result of bumpsteer would be positive toe. The graph shows that the largest change of toe is -1.233 mm at -50mm of ride height, with -0.873mm of the toe is present at +50mm of ride height.

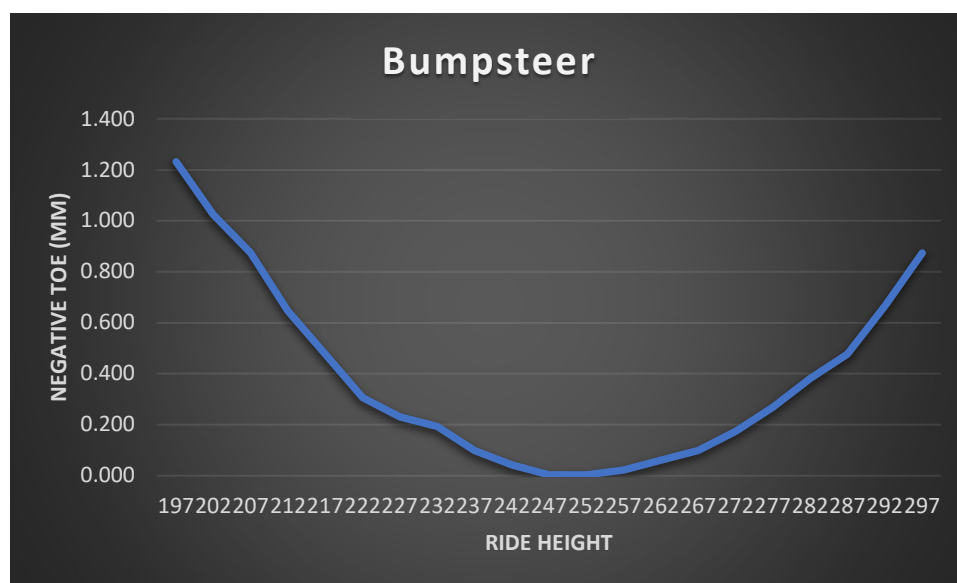


Figure 23 - Graph of Bumpsteer of Standard Suspension

4.3 - WinGeo 3 Analysis

WinGeo 3 software produced many results for analysis and comparison of bumpsteer. The software produced graphs and figure of bumpsteer for -50mm to +50mm of ride height at 5mm increments. The first test run in WinGeo was the standard Mx5 race set-up, a table of results and a graph was produced.

Bump		WinGeo			Steer_R
<i>Ride Height</i>	DTI A	DTI B	Toe Steer (mm)	Ride	Toe Steer (mm)
197	3.5	2.85	1.233	-50	1.266
202	3.1	2.56	1.024	-45	1.028
207	2.75	2.29	0.873	-40	0.816
212	2.32	1.98	0.645	-35	0.632
217	2.13	1.88	0.474	-30	0.472
222	1.52	1.36	0.304	-25	0.337
227	1.48	1.36	0.228	-20	0.225
232	1.08	0.98	0.190	-15	0.136
237	0.5	0.45	0.095	-10	0.07
242	0.05	0.03	0.038	-5	0.025
247	0	0	0.000	0	0
252	0.08	0.08	0.000	5	-0.004
257	0.31	0.3	0.019	10	0.011
262	0.68	0.65	0.057	15	0.045
267	0.98	0.93	0.095	20	0.097
272	1.28	1.19	0.171	25	0.167
277	1.6	1.46	0.266	30	0.255
282	1.8	1.6	0.379	35	0.359
287	2	1.75	0.474	40	0.479
292	2.3	1.95	0.664	45	0.616
297	2.75	2.29	0.873	50	0.768

Table 7 - Toe Steer of Standard Suspension from Bumpsteer Measuring Experiment and WinGeo

Table 7 shows the results gathered from the bumpsteer measurement experiment and the results produced from WinGeo (Steer_R), the results are not identical but follow very similar values producing near identical graphs of bumpsteer, emphasised in figure 24. This shows that the results produced from the WinGeo software are an accurate representation of the suspension, producing realistic results.

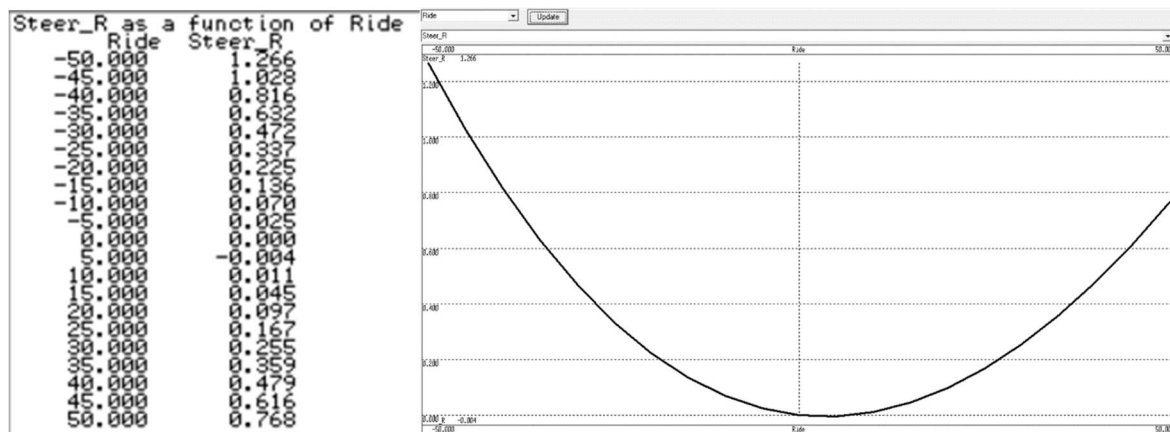


Figure 24-Standard Suspension Bumpsteer Results produced by WinGeo (Marshall, 2020)

Tests 1-7 performed were on the adjustment of height of the tie rod/toe arm, the position of this can be seen in figure 4. The height adjustment was changed at the hub end of the arm and was lowered and raised by various distances. Graphs were produced for the various measurements and can be seen in Appendix 2. Figure 25 shows the graph for test 5 lowering the tie rod by 10mm, this gave the largest reduction in overall bumpsteer, tests were also completed for 1mm each side of this height to make sure this measurement was the optimum height. Test 5 showed that the largest change of toe is -1.01 mm at -50mm of ride height, with -1mm of the toe is present at +50mm of ride height. This has an increased toe change as the ride height changes, however, this is only in the top range of figures and a significant decrease can be seen on the rebound of the suspension, overall a better value of bumpsteer across the ride height range is seen.

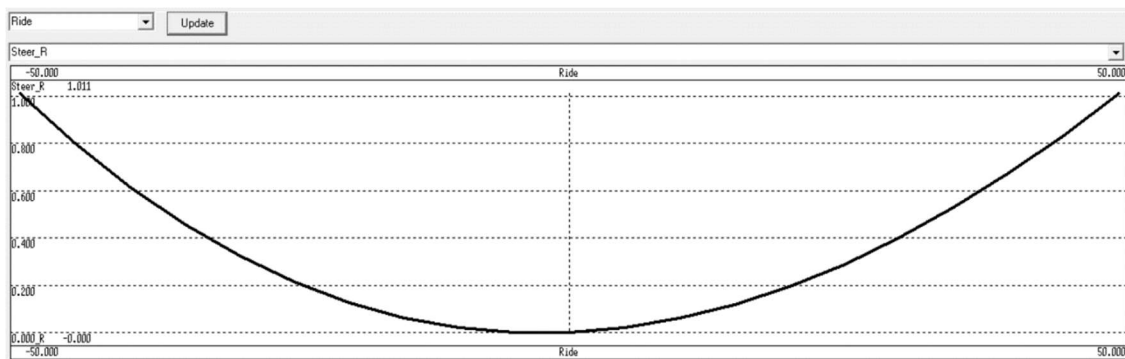


Figure 25 Test 5 Bumpsteer Graph - Tie Rod Lowered by 10mm (Marshall, 2020)

Tests 8-13 investigated the effect of shortening the Lower A-arm forward, these tests showed that there was no change in bumpsteer from altering the length of this arm. In figure 26 there was a 10mm change in length of the arm and in figure 27 there was an 80mm change in the arm's length, as you can see the bumpsteer graphs are identical. This was the same for the other tests and these graphs can be seen in appendix 2.

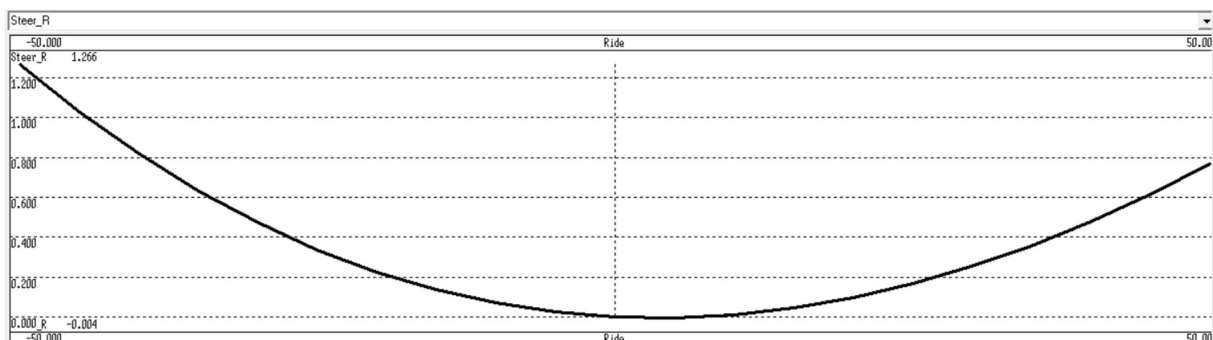


Figure 26 Test 8 Bumpsteer Graph - Lower A-arm shortened by 10mm (Marshall, 2020)

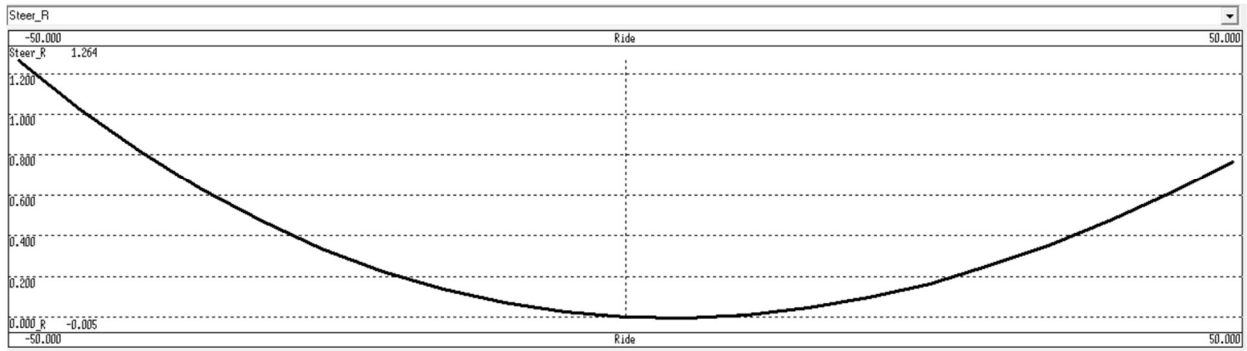


Figure 27 Test 13 Bumpsteer Graph - Lower A-arm shortened by 80mm (Marshall, 2020)

Tests 14-21 investigated the effect of shortening the Upper A-arm forward, these tests showed a reduction in bumpsteer. A continuous reduction in overall bumpsteer as the arm was shortened is shown by the graphs which can be seen in appendix 2, the largest reduction was test 21 where the arm was shortened by 100mm. Figure 28 the graph for test 21 shows that the largest change of toe is -1 mm at -50mm of ride height, with -0.95mm of the toe is present at +50mm of ride height. This has an increased toe change as the ride height changes however, this is only in the top range of ride height and significant decrease can be seen on the rebound of the suspension, overall a better value of bumpsteer across the ride height range is seen.

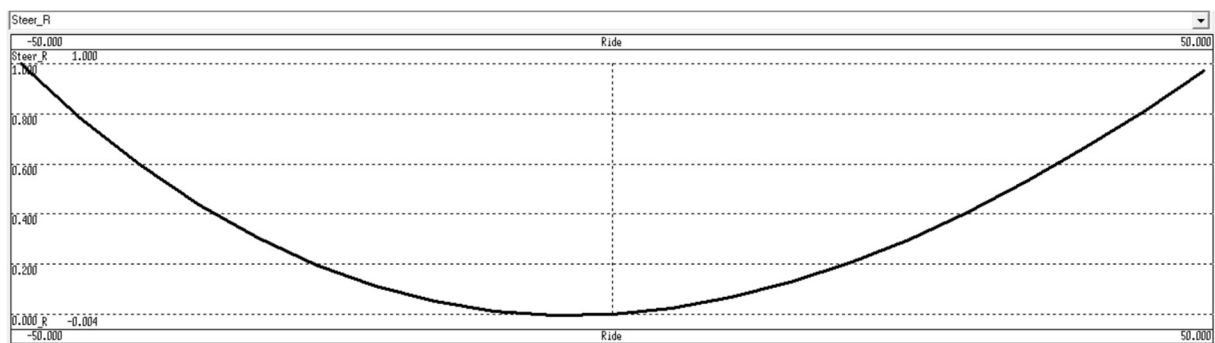


Figure 28 Test 21 Bumpsteer Graph - Upper A-arm Forward shortened by 100mm (Marshall, 2020)

Tests 22-29 investigated the effect of shortening the Upper A-arm rear, these tests showed a reduction in bumpsteer continuous reduction in overall bumpsteer as the arm was shortened the graphs can be seen in appendix 2, the largest reduction was test 29 where the arm was shortened by 100mm following a similar trend as the Upper A-arm forward. Figure 29 the graph for test 29 shows that the largest change of toe is -1.081 mm at -50mm of ride height, with -0.7mm of the toe is present at +50mm of ride height. The graph shows

that a reduction of overall bumpsteer has been achieved on both the bump and rebound of the suspensions travel.

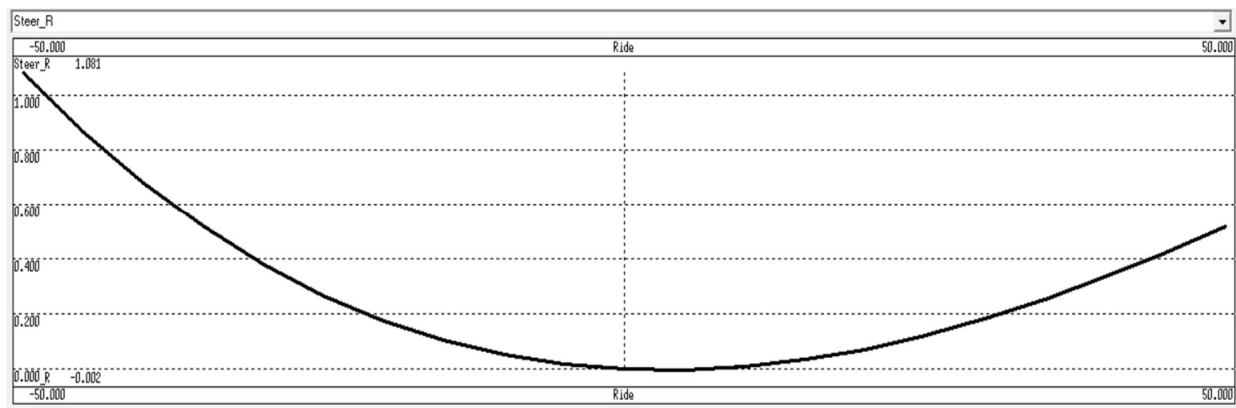


Figure 29 Test 29 Bumpsteer Graph - Upper A-arm Rear shortened by 100mm (Marshall, 2020)

Tests 30-37 investigated a combination of adjustment of the toe arm, Upper A-arm forward and Upper A-arm rear, table 8 lists the different combinations which were tested in WinGeo. Test 32 confirmed the best overall bumpsteer reduction, the other tests produced graphs which did not show any significant improvement these can be seen in appendix 2.

Test	Toe Arm Height	Upper A-arm Forward Length	Upper A-arm Rear Length
30	-10mm	-100mm	-100mm
31	-10mm	-50mm	-50mm
32	-10mm	-50mm	-100mm
33	-10mm	-80mm	-10mm
34	-10mm	-100mm	-50mm
35	-10mm	-100mm	-80mm
36	-10mm	-80mm	-80mm
37	0mm	-50mm	-100mm

Table 8 - Combined Suspension Arm length for Bumpsteer reduction investigation

Test 2 produced a bumpsteer graph figure 30 which shows that the largest change of toe is -0.746 mm at -50mm of ride height, with -0.72mm of toe is present at +50mm of ride height. The graph shows that a reduction of overall bumpsteer has been achieved on both the bump and rebound of the suspensions travel.

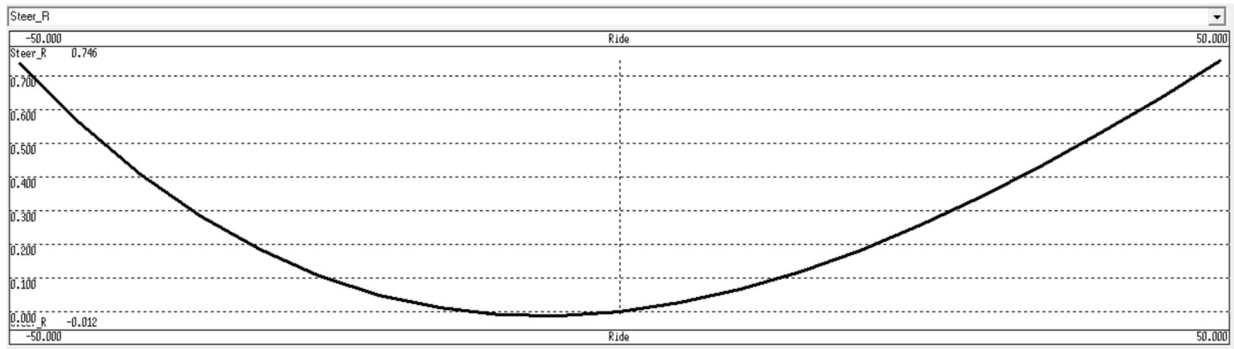


Figure 30 Test 31 Bumpsteer Graph - Combined Alterations (Marshall, 2020)

4.4 - Measuring Bumpsteer – Developed Set Up

After the results were gathered from the WinGeo the Mx5 subframe had the following modification changed:

- Toe arm lowered by 10mm using new developed adjustable toe arm.
- Upper A-arm forward shortened using adjustable arm supplied by Paul Sheard Autosport
- Upper A-arm rear shortened using adjustable arm supplied by Paul Sheard Autosport

Bumpsteer was to be measured in the same process as discussed previously in the dissertation using a flatbed, subframe and bumpsteer gauge. This experiment was not completed due to the effects of Covid-19 pandemic as University workshops were closed, therefore predictions of the results will be documented. Results of DTI A and DTI B would have been recorded to produce a figure of toe change through the wheels travel. The results would have allowed a graph of bumpsteer to be produced, this graph would have been compared against figure 23 to see the accuracy of the changes made. I would have expected to see very similar results between the WinGeo test 31 and the static subframe with modifications. The main purpose of gathering these results was to validate the results produced by the WinGeo software.

4.5 - Track Testing Analysis

Track testing was organised to have taken place on the 01/04/2020 at Bruntingthorpe proving ground, due to the Covid-19 pandemic this testing was unable to be completed. This section will document what the predicted results would have shown, the methods will explain how they would have been used for comparison of results.

The test plan which can be seen in appendix 1 documents each test set-up for track and steady-state testing. For each test, a results sheet would be produced with data including:

- Weather & Track Temperature
- Set-up & Laps Completed
- Driver feedback and Corner Feedback Matrix
- Tyre Temperature and Pressure

Data was also going to be recorded using an AIM Solo 2 DL, this records the following data needed for analysis plus other data:

- Corrective Speed
- Laps & Track Position
- Longitudinal and Lateral G-force
- Steering Angle

This would have produced data for both track and steady-state testing, allowing set-ups to be overlaid to analyse changes on the vehicle handling behaviour. An example of the AIM data analysis from a different test can be seen in figure 31.

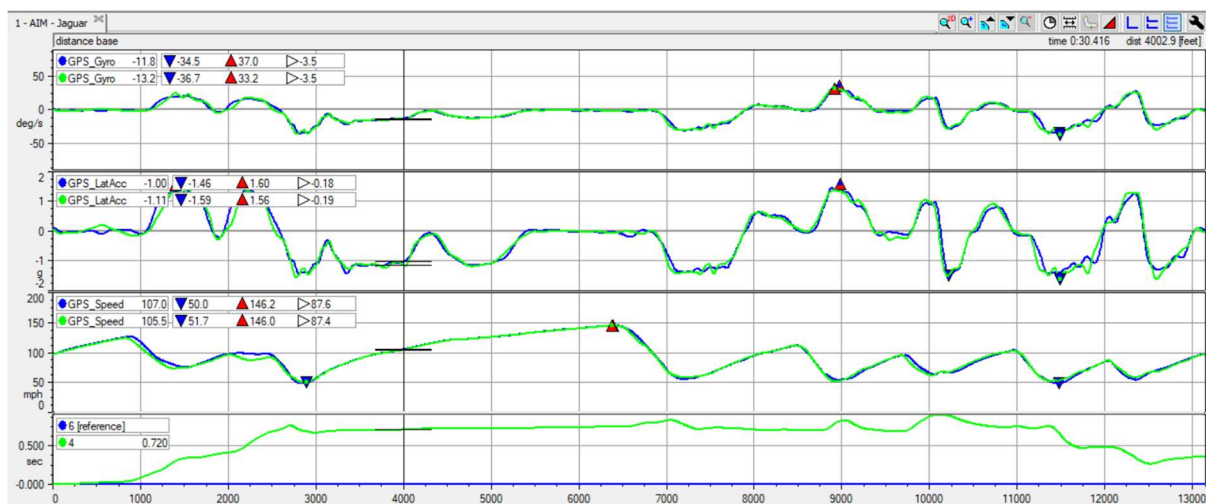


Figure 31 AIM Race Studio Analysis Example Data (Marshall, 2020)

4.5.1 - Track Testing

Track testing was predicted to show an improvement in corner speed and lap time mainly with set-up D when compared to the other set-ups; as this set-up had the largest bumpsteer reduction in comparison to the standard set-up. The fastest lap would have been taken from

each test for comparison, however, driver feedback would have taken the whole test into account. This is because a single lap may not demonstrate if the car presents undrivable conditions even with a single fast lap recorded.

Math channels were created in AIM race studio to analyse understeer and oversteer. The Maths channels calculate Ackerman angle as seen in figure 32. Ackerman Steering percentage which uses lateral g-force and steering percentage recorded from when the vehicle has travelled at 5mph round the corner radius of the steady-state test, this maths channel can be seen in figure 33. The understeer channel was then created by misusing the steering angle away from the Ackerman steering angle as seen in figure 34. This indicates how much more steering input is needed to achieve the desired corner radius.

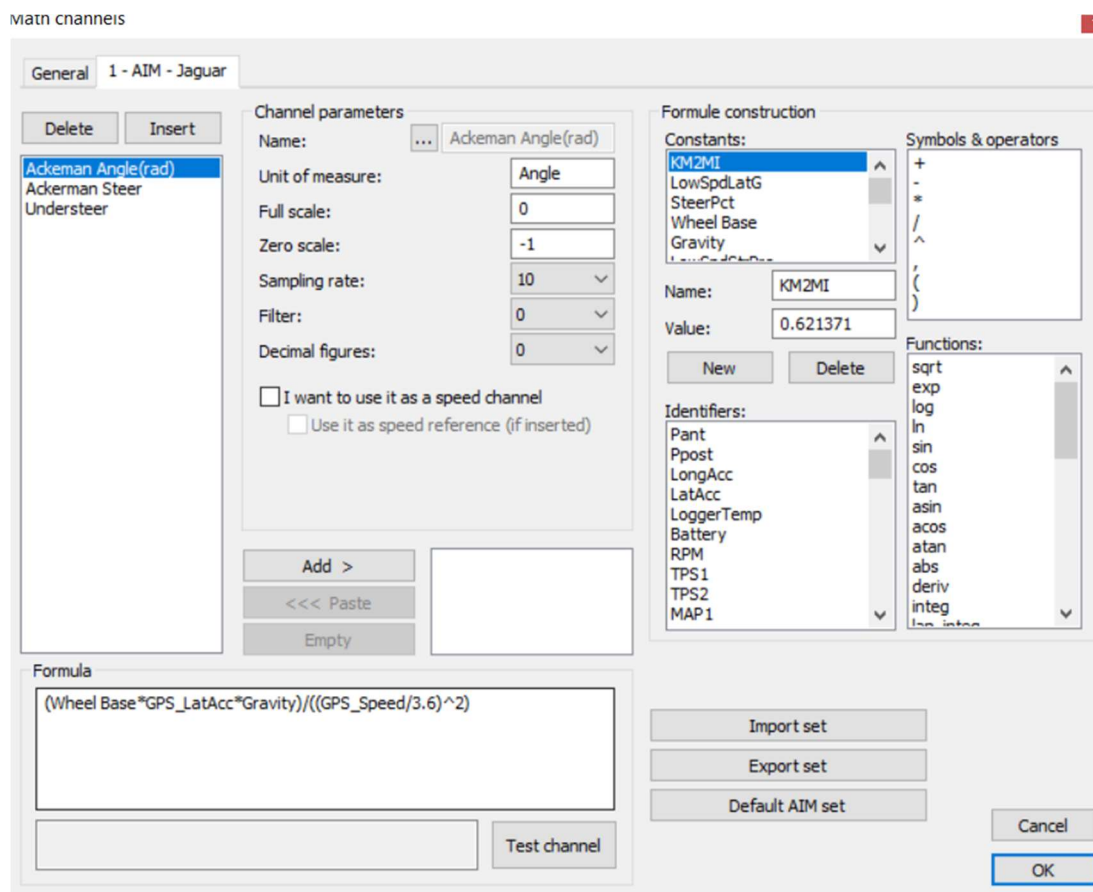


Figure 32 Ackerman Angle Equation AIM Race Studio (Marshall, 2020)



Figure 33 Ackerman Steering Percentage Equation AIM Race Studio (Marshall, 2020)

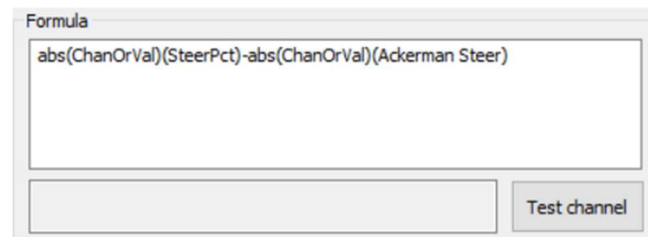


Figure 34 Understeer Equation AIM Race Studio (Marshall, 2020)



Figure 35 Example Understeer Data Trace AIM Race Studio (Marshall, 2020)

A scatter plot of understeer vs speed allowed for understeer and oversteer to be analysed against speed for different set-ups, an example of how this graph would have looked can be seen in figure 36. The example graph shows understeer plots against speed, as you can see the blue set-up shows less understeer at high speeds and black set-up experiences the most. This graph shows the oversteer that the car experiences by the negative understeer value shown in the graph, as can be seen, the green set-up experiences the most oversteer and the blue set-up the least. For data that would have been collected from testing, it is presumed that the data would have shown a reduction in high-speed oversteer and low-speed understeer across all the improved set-up against the standard set-up, set-up D has been predicted to show the largest reduction.

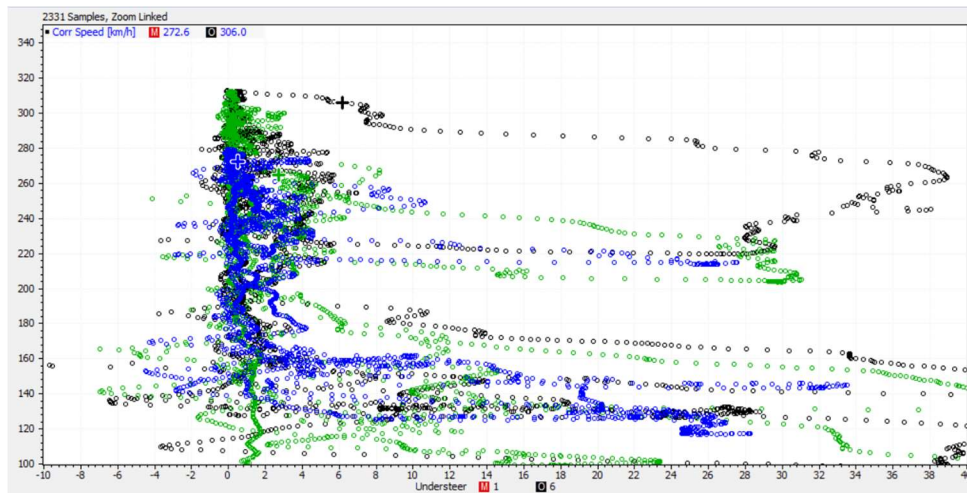


Figure 36 Example Understeer vs Speed Scatter Plot (Marshall, 2020)

Understeer and Oversteer can be analysed for a specific corner and against different setups. The data traces in Figure 37 below show the understeer and oversteer experienced by the vehicle at each point of the set-ups fastest lap. Figure 37 is an example of the data expected to be produced by track testing, however, was produced using Motec software from similar testing. AIM race studio was meant to be used for the whole analysis of the project however not having relevant data has meant it can not be used for the understeer analysis. However, an example of an AIM understeer trace can be seen in figure 35. The example data in figure 37 shows the green set-up experiences more understeer in turn 3 and 4 and experiences the most oversteer in the exit of turn 3. This data-trace is from example data however, the data that would have been collected from testing was predicted to show less oversteer in Set-up D than the Standard set-ups and a general reduction in entry and exit oversteer by all improved set-ups.

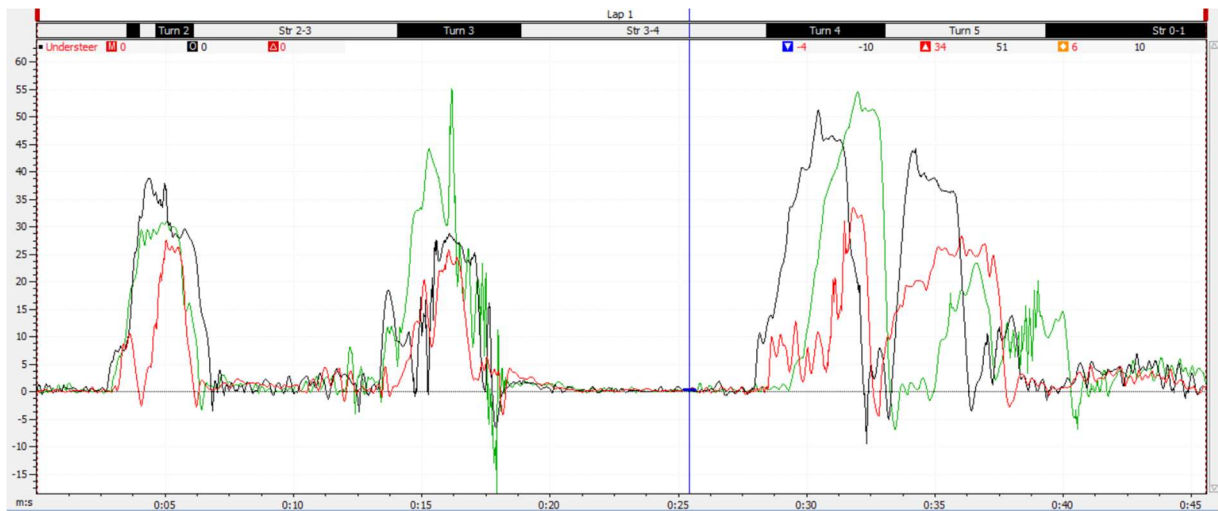


Figure 37 Example Understeer Data Trace (Marshall, 2020)

The AIM race studio would have been used to analyse the following data traces across the fastest laps of the different set-ups:

- Peak corner speed
- Exit corner speed
- Braking Longitudinal G-force
- Top speed

A prediction of these data channel comparisons would show an overall improvement of dynamic handling characteristics of the vehicle and improvement of lap time for the modified set-ups, in particular set-up D showing the most improvement against the standard set up.

The three different tests of the standard set-up would be compared to show any changes in the data during the day of testing, due to changes in track or weather conditions. The modified set-ups would be scrutinised against the standard set-up which was directly next to it in the running of the day. The amount of change between the modified set up and the standard set-up tested at the same point of the test day would have a large weighting on which modified set-up improved the dynamic handling characterises of the vehicle the most.

4.5.2 - Steady-State Testing

The data for the steady-state testing would have been recorded using the same equipment as the track testing therefore each set-up was compared using the majority of the same

channels to analyse the dynamic handling. The main channel which will be used for comparison of the set-up would be the understeer channel. This channel would demonstrate the extra steering input required as the speed increases, an improved set-up would show a lesser understeer value or steering input when compared to the original set-up at the same speed. The channel will show the point at which the vehicle breaks free and enters oversteer, whether this happens or what speed it happened at would be directly compared against other tests, an improved set up would not break free or enter oversteer at a higher speed. This information would be displayed on a scatter graph where speed is plotted against understeer as seen in the example figure 36. Data traces do not hold as much relevance for this test as they did for track testing, this is due to this test being relevant to speed rather than time or distance from which data traces are measured. Instead, the following scatter graphs would be analysed against to show an improvement gained by a set-up against the standard set-up.

- Speed vs Lateral G-force
- Speed vs Steering Wheel Percentage
- Speed vs Understeer Channel
- Speed vs Yaw

These graphs would allow a clear comparison of the understeer/oversteer for each speed across the set-ups, the lower the understeer and oversteer through the various speeds the better the dynamic handling of the vehicle. The graphs chosen above for a comparison of the set-ups are those which are specified by the ISO 4138 standard which the test is being run in accordance with (ISO, 2012).

4.5.3 - Driver Feedback & Test Data Sheet

Driver feedback would have been used to clarify the effect the set-up changes had on vehicle handling, these would have given a view on how the vehicle handling was affected from an operator's perspective which can have an impact on the lap time and how realistic the set-up is for a race situation. Tyre pressure and tyre temperature across the tyre gives a good indication of the weight loaded on a certain tyre; differences of tyre temperature will show how the load is distributed to each tyre, however, this must also be monitored along

with the number of laps completed as a tyre which has been exposed in the test for more laps may have an increased temperature. Overall tyre condition allows an understanding of tyre load differences between set-ups. Driver feedback gives reinforcement to the data explaining anomalies and how realistic the set-up is for improving the vehicles handling.

4.6 - Summary of Chapter

The results show that a Mazda Mx5 race car's rear suspension experiences a measured degree of bumpsteer, the use of a computer development software has shown to be accurate with a realistic model being created of the suspension kinematics. The alteration of suspension arm lengths and mounting points have shown a clear reduction of bumpsteer which can be seen clearly through the graphs produced. The WinGeo has shown to be key for allowing modification to the suspension easily and quickly through simulation, the software's capability to perform bumpsteer analysis has allowed for the development time of the project to be shortened drastically; allowing for more development of the suspension to be tested. The WinGeo software allowed for a conclusion to be drawn of modified suspension arm designs which allow a reduction in bumpsteer, these designs were then implemented on the Mx5 race car for deeper evaluation using track and steady-state testing.

The track and steady-state testing were to evaluate the effect that the reduction of bumpsteer has on the handling characteristics of the vehicle and how this effect its lap time. The testing allowed for ample data to be collected which is comparable across each set-up. AIM race studio software allowed a clear view of how the vehicles handing was affected by set-up changes, the graphs produced highlighted points of comparison and improvement between set-ups. This along with lap time data and driver feedback has allowed for a conclusion of how each set-up performed and whether the reduction of bumpsteer has changed/improved of the handling of an Mx5 race car. Due to the restriction of the Covid-19 pandemic, these conclusions were not drawn, however, an improvement of lap time and vehicle handling balance was expected from the set-up which showed the largest reduction in bumpsteer.

Chapter 5 - Conclusion

5.1 - Scope of Chapter

This chapter aims to conclude the dissertation with an appraisal of the aim and objectives. A discussion will evaluate the success of the research, methods, testing, and improvements that were made during the dissertation. Limitations and difficulties which occurred during the project will be evaluated to highlight any improvements for future work. A summary and suggestion for testing will be recommended for further work.

5.2 - Discussion of Project Objectives

The first objective was to investigate how much bumpsteer is produced by a current Mx5 race car multi-link suspension geometry. The methods of measuring bumpsteer was a design of experiment credited by (Smith, 1984) and (Staniforth, 2006), this experiment allowed for results to be collected which accurately documented the specific amount of bumpsteer present on the Mx5 rear suspension. This data allowed for a graph which allowed a clear representation of bumpsteer across the full suspension travel range. This measurement of bumpsteer allowed the project to progress with accurate documentation of improvement and changes in bumpsteer.

The second objective was to investigate how bumpsteer can be reduced by altering/evaluation of the geometry of the suspension kinematics. This objective was addressed by the methods of using computer-aided design to develop and design new suspension kinematics within the restriction of the factory suspension mounting points. The software allowed many designs and adjustment to be made to the suspension arms, each design or adjustment was then measured for bumpsteer using the computer software. The bumpsteer graphs allowed for each design or adjustment to be scrutinised on its benefit in reducing bumpsteer. These tests in the computer software allowed for four set-ups which improved on the standard suspension's amount of bumpsteer, one set-up, in particular, showed a large reduction in bumpsteer due to multiple adjustments of suspension arms. Once the best designs were concluded, relevant modifications to the arms physical design were made to allow these modifications to be trailed on the Mx5's suspension.

The third objective was to investigate how the reduction/control of bumpsteer affects a race car's handling and lap times. This objective aimed at gaining an understanding of how the reduction of bumpsteer can improve a race car in its ability to handle more positively for the driver and whether this gave an improvement in its ability to travel faster around a lap of a circuit. The method for understanding this was to implement the improvements of suspension design on to the Mx5 race car and then test the different designs against the standard design in a race circuit environment. This would ultimately show whether the reduction of bumpsteer developed during this project has a negative or positive effect on the circuit ability of the Mx5 race car. Unfortunately, due to the Covid-19 pandemic, this method was not completed even though it was planned to commence within the project's deadline. This means that the objective cannot be met and a prediction would be made on whether an improvement in the race car's handling would be present with the reduction of bumpsteer however, the degree of how much the handling and lap would be improved by cannot be known.

5.3 - Discussion of Project Aim

The aim was to investigate the characteristic of bumpsteer, how bumpsteer can be altered/reduced through the evaluation of suspension kinematics, and how a reduction/improvement of bumpsteer can enhance the handling of a race car. The research in the literature review gave a successful insight into the characteristics of bumpsteer and how it occurs and effect a race car. The methods of measuring bumpsteer and suspension design development using computer-aided design allowed a clear evaluation of the suspension kinematics. The evaluation showed a clear reduction of bumpsteer by altering the suspension arm designs. The project was planned to collect data to analyse how suspension kinematics with less bumpsteer than a standard suspension would enhance the handling of a race car when in a race circuit environment, a conclusion of this was very limited, however, the project has provided an opportunity for a conclusion to be further investigated with the processes used in the dissertation.

5.4 - Summary

Whilst the project used the research of relevant topics which gave an in-depth understanding of bumpsteer, documenting the exact industry views and methods of how it

affects a race car. Explaining how a reduction of bumpsteer can be achieved through the optimisation of suspension which will improve the handling characteristics of a race car. The research highlighted the positives of how computer-aided design and computer manufacturing can assist in the development of the suspension's design. The methods used in the dissertation meet all the objectives and the aim set, the methods provided a comprehensive solution for improving the bumpsteer of a race to improve the handling. The methods provided accurate validated data which allowed certain progressions to be made throughout the investigation. This progression allowed a solution to be created to reduce the bumpsteer of an Mx5 race car to improve its handling with relevant data supporting the solution. Bumpsteer was not completely eradicated during the project however it was dramatically reduced, it was done to the limitation of the standard mounting point of suspension arms giving a restriction of new suspension designs. This project has explored an area of suspension design development which has not been documented greatly, this project has developed a solution for analysis and developing bumpsteer found in a race car's multi-link rear suspension. The project was focused on a Mazda Mx5 race car, however, the solutions and methods used can be transferable to any race car supplication.

5.5 - Limitations

The main limitation for the project was the amount of secondary research surrounding the reduction of bumpsteer on a race car's rear multi-link suspension. Adequate research was found on individual topics and investigations using the same principles of the project. However, secondary research of bumpsteer reduction and suspension kinematic development of rear multi-link suspension was limited, this meant that validating results and a process for investigations was not scrutinised to a full extent.

The track testing was selected for validating the solutions found by CAD development, using track testing to validate developed suspension set-ups created limitations. The track is expensive and hard to organise; with the use of tack, race car, and the driver having to be organised together, this meant only one day of track testing was viable for the project. Multiple days of testing would allow for more data to be collected, more solutions to be tested, and track testing which is not designed around the time constraint of a single day test.

A limitation which was known from the start of the project which impacted certain designs of developed as part of the project, was the improving the suspension design whilst keeping the standard factory suspension arm mounting points of the Mx5 race car. Designing suspension modification to reduce bumpsteer was limited to a degree with using standard mounting points. If it were feasible to modify or change the suspension mounting point it would allow for different suspension designs, which may have aided in reducing bumpsteer further. For this specific project however, the suspension mounting points could not be changed, this could be an area of investigation for a future project.

5.6 - Further Work

The project has many aspects that could be taken further as suspension development is never truly complete. Given the timescale of the project, the results gained have shown an improvement of bumpsteer with an accurate and efficient method of improving suspension kinetics. However, given an unlimited timescale for development, there are many suspension developments which could be developed for improving a race car's handling.

Track and steady-state testing were meant to be completed as part of this project however due to circumstances outside the control of the project this was not completed. Testing would give validation of the developed suspension set-up which was created as a result of this project. An evaluation of how this compares to a standard set-up and how they enhance vehicle handling.

This project relied on the facility of track testing for validation of developed suspension set-ups. A simulation model using a race simulator would give the same data for analysis of suspension development as track testing. A simulation model would need to be developed using relevant software and comparison against the standard race car to validate the accuracy of the simulation car model. Once a simulation model is accurate and data recorded from a race simulator has a very close representation of a real race car on a race circuit, then the simulation model for the race car allows easy access to track testing and allowing newly developed suspension designs to be analysed for great accuracy using the simulator.

Bumpsteer effects the handling of a race car however, the rear suspension has many other aspects that could be optimised to give an improvement in handling characteristics. The

standard suspension mounting points have been a limitation during this project, a new subframe design may allow for greater improvement of suspension design; this could be developed using the same WinGeo computer-aided design software as used in the project. During this development, the weight transfer, roll centre, caster and camber optimisation of the suspension would aid in developing the race car's handling.

This project focused mainly on the bumpsteer generated by the rear suspension kinematics however, the front suspension has potential for development to reduce bumpsteer and optimise the suspension kinematics. The front suspension has plenty of areas that could be investigated as well as bumpsteer, for example, Ackerman angle, castor and camber optimisation, roll centre, and weight transfer.

Chapter 6 - Pandemic Impact

The Covid-19 pandemic has had a subsequent impact on the results and data collection for this dissertation. Where necessary in the report the effects Covid-19 have been discussed in relevance to this dissertation, listed below is everything in which the pandemic has changed or influenced the outcome of the dissertation.

Pandemic Timescale.

University Workshops Officially Closed	Measuring Experiment Planned Date	Covid-19 National Lockdown	Track Testing Experiment Planned Date
16/03/2020	20/03/2020	23/03/2020	01/04/2020

A measuring experiment was due to have taken place in the University workshops and was due to be completed, however, due to the closure of workshops this did not take place. This experiment aimed to measure the bumpsteer of a developed suspension set-up using a flatbed and bumpsteer measuring equipment. The results gained would have shown the change of the developed set and allowed for a bumpsteer graph to be created. The need for this graph was to validate the reduction of bumpsteer of developed D set-up designed in WinGeo. The graph would have directly compared against the graph created in WinGeo so the results could be compared, and any differences or similarities discussed to validate the graphs produced from the WinGeo computer software.

The main impact the pandemic had on the dissertation was the loss of the track and steady-state test day which was planned for 01/04/2020. The test day had been planned for a month in advance and took many items which had to arrange for the day including use of the circuit, use of the race car for testing and the race driver who was supporting the test; fortunately, the rental of test circuit was not paid in advance so there was no financial loss. The main purpose of the test day was to gain many different forms of data for the comparison of suspension set-up developed by using WinGeo computer software. This data included telemetry from the AIM solo for track and steady-state testing, tyre analysis sheets, and driver feedback. This data was needed to meet the dissertation aim and the last objective as this data provided a conclusion on the degree of how the reduction of bumpsteer improves the handling of a race car and improves its lap time. By not having this

data it was not possible to bring the dissertation to a solid conclusion, therefore a prediction was made of how the race car's handling would have responded to a developed suspension geometry set-up. A large section of results and analysis has not shown the true capabilities of the comparison of sets -ups and the technology used for this, instead, a vague example of the analysis has been given followed by a prediction which has no hard evidence to support it. Secondary research was considered to help validate the developed set-ups but unfortunately, the subject of this dissertation is very specific, and no research would help validate this section of the project.

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Appendix – 1

Bumpsteer Reduction Investigation Track & Steady-State Testing

- Bruntingthorpe Proving Ground – Sprint Circuit
- Driver - Nigel Greensall
- Car – Mk3 Mx-5 Race Car
- Date – 01.04.20

Aims of Test –

Investigate how different bumpsteer reduction set-ups effects a race car's handling and lap times against the standard set up of an Mx-5 Race Car.

Outlines of Testing –

The aim for this testing is to validate the changes developed from the WinGeo model, the testing will simulate real race conditions with the use of an Mx-5 race car around a selected racetrack and a steady-state loading test. The two tests will investigate differences of standard suspension set-up and selected developed set-ups which have shown to decrease bumpsteer.

Track Testing –

Track testing will consist of 3 warm-up laps, after these laps the car will return to the pit lane so tyre pressures can be checked. After this 8-10 laps will be completed by the driver to collect data of the set-up.

Steady-State Testing –

Steady-State testing will be performed straight after the track testing this ensures the car and tyres are warmed up. A 50-metre cone circle will be marked out on an open flat patch of ground. The driver will drive around the circle clockwise, they will increase their speed until they find the car too difficult to keep at the same radius. This is a constant radius test as defined by ISO 4138, this test aims to monitor the amount of steering angle input which will be recorded by the AIM data system. Ackerman data will be collected by the car travelling around the circle with the steering wheel at the same steering angle.

Testing Set-ups Schedule-

<i>Test</i>	Toe Arm	Upper A arm rearward	Upper A arm forward
A	0mm	0mm	0mm
B	10mm	0mm	0mm
C	0mm	100mm	0mm
A	0mm	0mm	0mm
E	0mm	0mm	100mm
D	10mm	50mm	100mm
A	0mm	0mm	0mm

Data Recording –

Data will be recorded with a paper test report for each set, AIM Solo 2 DL for data acquisition and V-box for video record of driver input of each lap.

Driver Feedback –

Driver feedback will be taken after each set-up test, this will comprise of two systems an overall/key verbal feedback which will be recorded and a scales feedback of understeer/oversteer for each corner. The understeer and oversteer corner matrix will use the scaling below.

Corner Entry	Mid Corner	Corner Exit
1	2	3

<i>Scale</i>	Vehicle Handling
9	Excessive Understeer
8	High Understeer
7	Moderate Understeer
6	Slight Understeer
5	Neutral
4	Slight Oversteer
3	Moderate Oversteer
2	High Oversteer
1	Excessive Oversteer

Constant Set-up –

	FL	FR	RL	RR
Toe	-1mm	-1mm	+1mm	+1mm
Camber	-2.5°	-2.5°	-2.8°	-2.8°
Corner Weight	276kg	298.5kg	264kg	284.5kg
Bump	8	8	8	8
Tyre Pressure Cold	24	25	24	25
Tyres	Avon ZZR	Avon ZZR	Avon ZZR	Avon ZZR

Test Sheet-

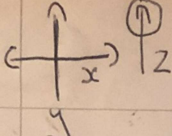
	Comments	Notes
Weather		
Set-Up		
Laps Completed		
Track Temperature		
Driver Feedback		

	FL			FR			RL			RR		
<i>Tyre Pressure After Warm-Up</i>												
<i>Tyre Pressure After Test</i>												
<i>Tire Temperature</i>	Out	Cen	In	In	Cen	Out	Out	Cen	In	In	Cen	Out

<i>Driver Feedback</i>	Entry – 1			Min – 2			Exit – 3		
<i>Corner 1</i>									
<i>Corner 2</i>									
<i>Corner 3</i>									
<i>Corner 4</i>									
<i>Corner 5</i>									
<i>Corner 6</i>									

Appendix - 2

WinGeo Tests and Bumpsteer Graphs

		$\begin{array}{r} 42 \quad 90 \\ 48 \quad 57 \\ \hline 33 \quad 31.5 \\ \text{BA13} \end{array}$
Test 1		
(180)	lower tie rod hub by 30 mm on Z	1.515
Test 2		
(195)	lower tie rod hub by 15 mm on Z	1.135
Test 3		
(160)	lower tie rod hub by 50 mm on Z	2.044
Test 4		
(250)	Raise tie rod hub by 40 mm on Z	2.262
Test 5		
(200)	Lower tie rod hub by 10 mm on Z	1.011
Test 6		
(199)	lower tie rod hub on Z	1.036
Test 7		
(201)	Lower tie rod hub on Z	1.037

Test 8

Lower A-arm forward Y shorter 10 mm 1.266

$$X = 18 \quad Y = 703 \quad Z = 132$$

Test 9

Lower A-arm forward Y shorter 20 mm 1.265

$$X = 10 \quad Y = 695 \quad Z = 132$$

Test 10

Lower A-arm forward Y shorter 30 mm 1.265

$$X = 5 \quad Y = 687 \quad Z = 132$$

Test 11

Lower A-arm forward Y shorter 40 mm 1.265

$$X = -1 \quad Y = 680 \quad Z = 132$$

Test 12

Lower A-arm forward Y shorter 60 mm 1.264

$$X = -14 \quad Y = 664 \quad Z = 132$$

Test 13

Lower A-arm forward Y shorter 80 mm 1.264

$$X = -28 \quad Y = 648 \quad Z = 132$$

Upper ball Joint E			-79
~~Lower~~ ~~Aspen~~ ~~Back~~			$x = 447$ $y = 437$
10mm	Test - 14		1.243
	$x = 74.5$	$y = 447$	
20mm	Test - 15		1.226
	$x = -69$	$y = 455$	
30mm	Test - 16		1.206
	$x = -64$	$y = 463$	
40mm	Test - 17		1.181
	$x = -60$	$y = 472$	
50mm	Test - 18		1.156
	$x = -55$	$y = 481$	
60mm	Test - 19		1.131
	$x = -51$	$y = 489$	
80mm	Test - 20		1.069
	$x = -41$	$y = 507$	
* 100mm	Test - 21		1.000
	$x = -31$	$y = 524$	

Second Upper Joint			¹⁸² $x = 182$ $y = 439$ $z = 326$
10mm	Test 22		
	$x = 1866$	$y = 447$	1.258
20mm	Test 23		
	$x = 1854$	$y = 454$	1.246
30mm	Test 24		
	$x = 182$	$y = 464$	1.230
40mm	Test 25		
	$x = 181$	$y = 474$	1.213
50mm	Test 26		
	$x = 179$	$y = 483$	1.196
60mm	Test 27		
	$x = 178$	$y = 495$	1.174
80mm	Test 28		
	$x = 175$	$y = 512$	1.137
800mm	Test 29		
	$x = 171$	$y = 534$	1.081

Test 30 Tie arm 10 lower
upper forward 100 short
upper Rear 100 short

Test 31 Tie arm 10
upper forward 50 s
upper Rear 50

Test 32 Tie arm 10
upper forward 50
upper Rear 100

Test 33 Tie arm 10
upper forward 80
upper Rear 100

Test 34 Tie arm 10
upper forward 100
upper Rear 50

Test 35 upper forward 100 Tie 10
upper Rear 80

Test 36 Tie 10
upper forward 80
upper Rear 80

Test 37 Tie 0
upper forward 50 upper Rear 100

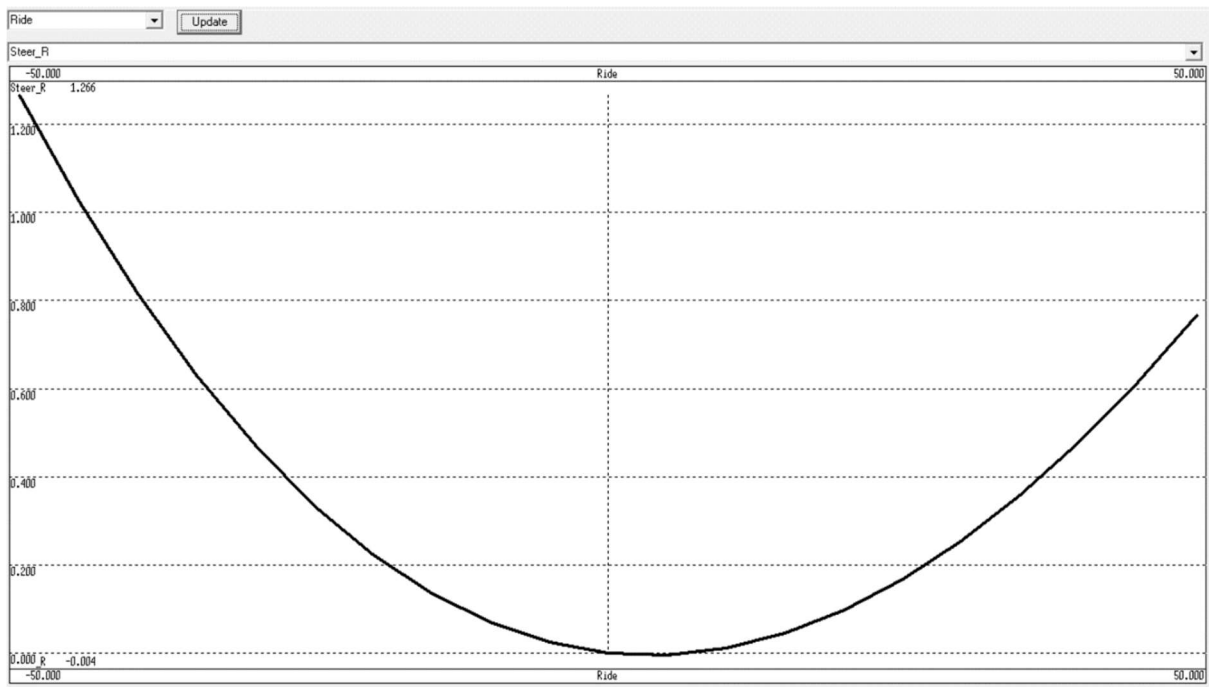


Figure 38 Standard Set-Up Bumpsteer Graph

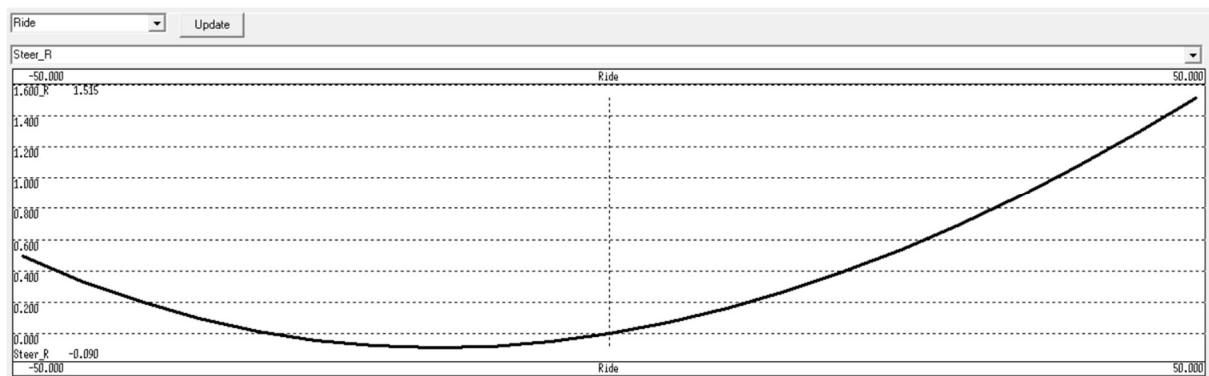


Figure 39 Test 1 Bumpsteer Graph

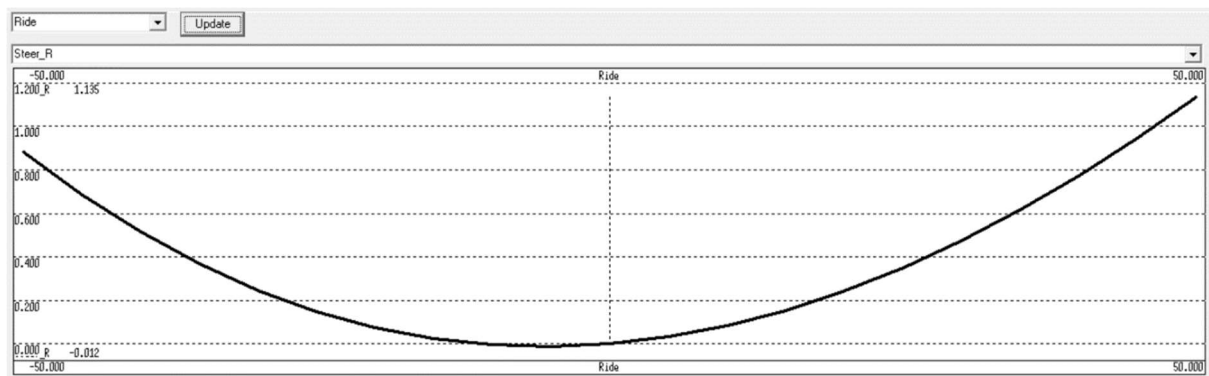


Figure 40 Test 2 Bumpsteer Graph

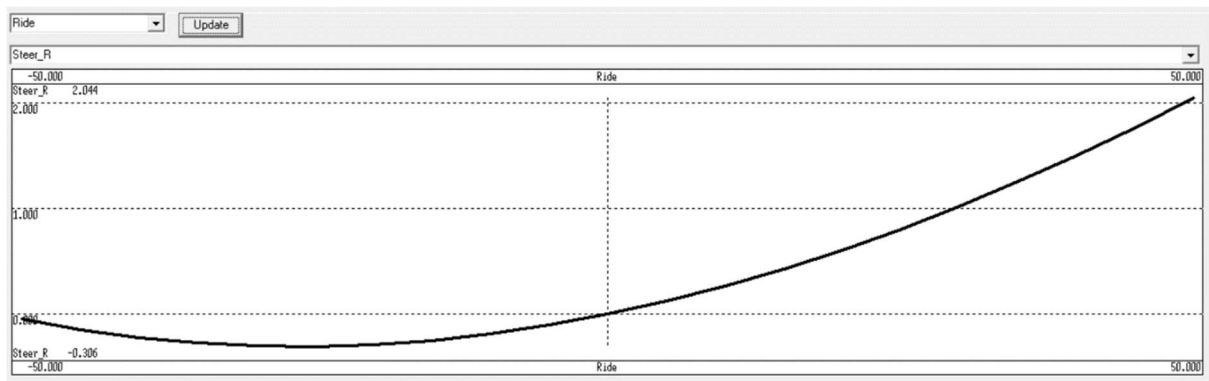


Figure 41 Test 3 Bumpsteer Graph

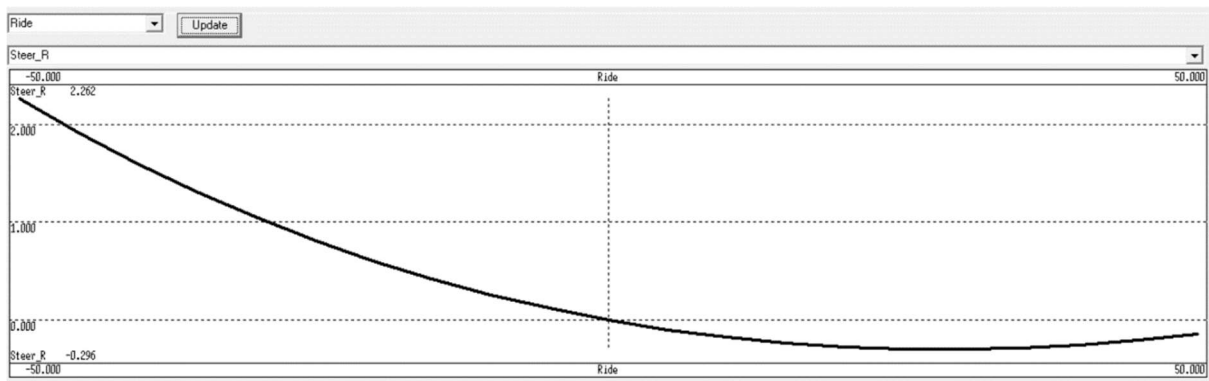


Figure 42 Test 4 Bumpsteer Graph

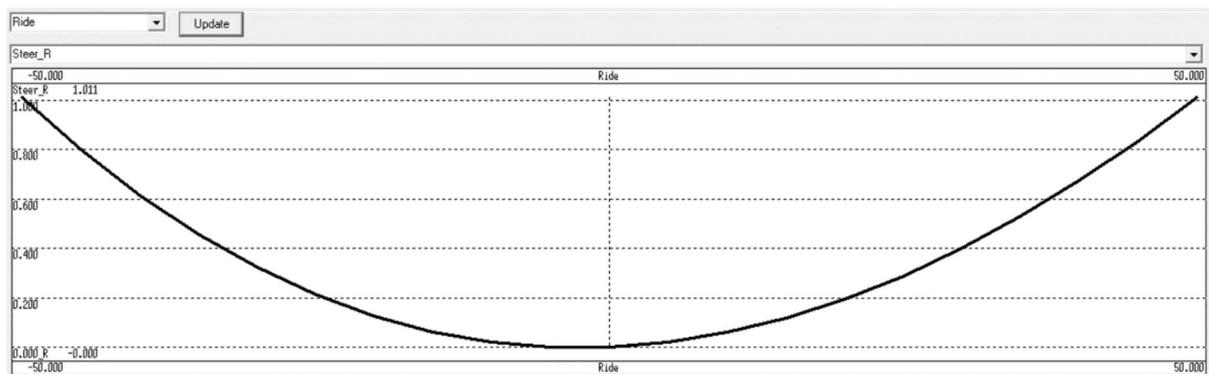


Figure 43 Test 5 Bumpsteer Graph

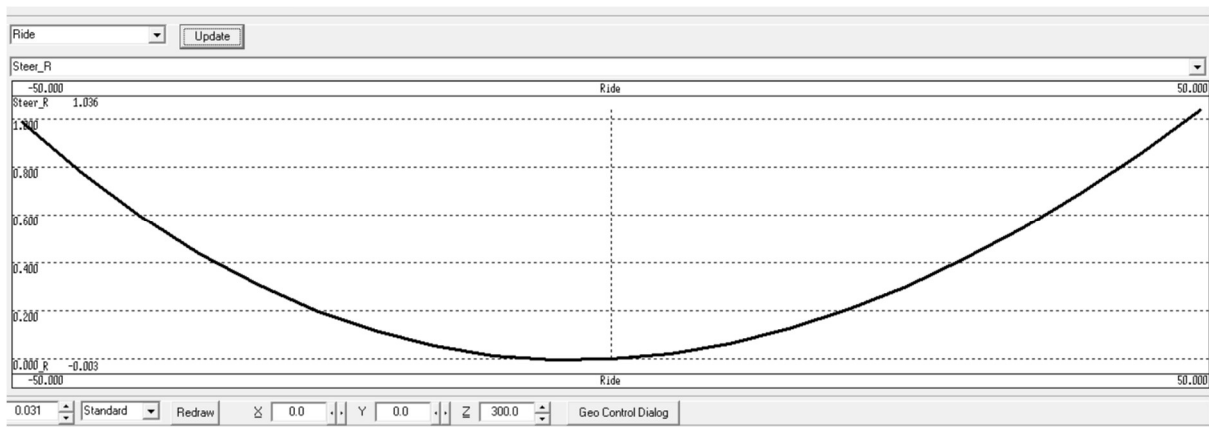


Figure 44 Test 6 Bumpsteer Graph

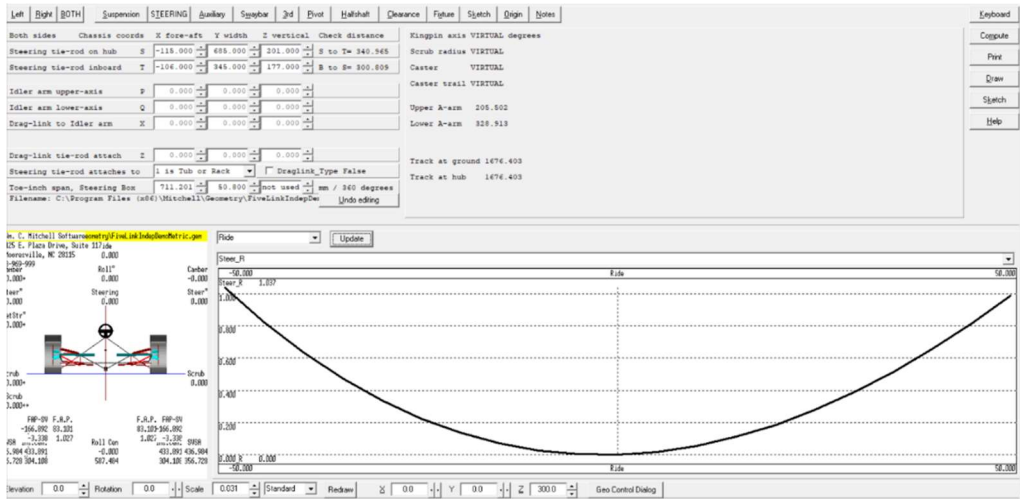


Figure 45 Test 7 Bumpsteer Graph

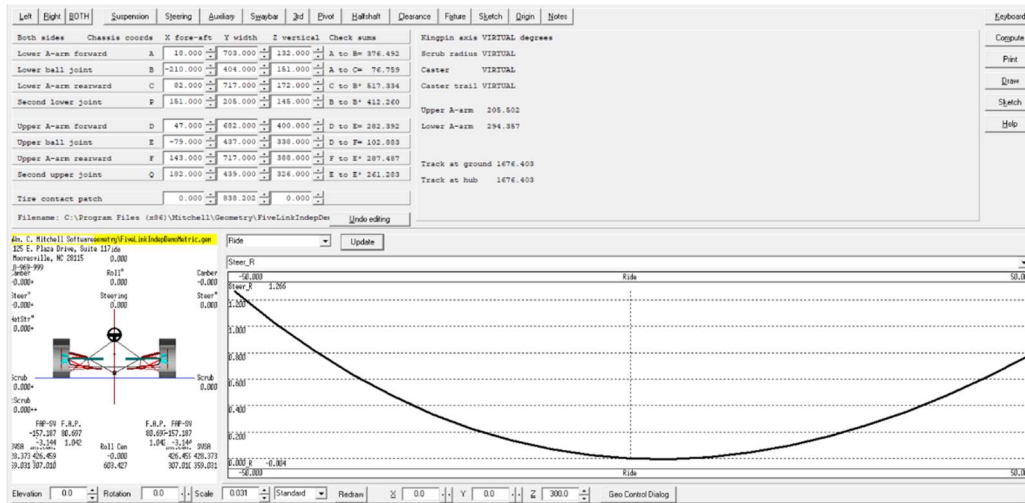


Figure 46 Test 8 Bumpsteer Graph

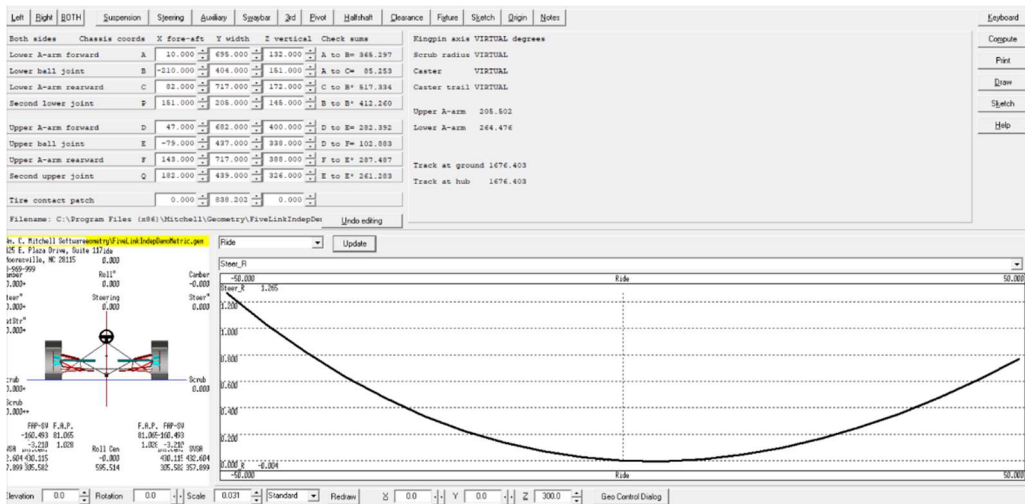
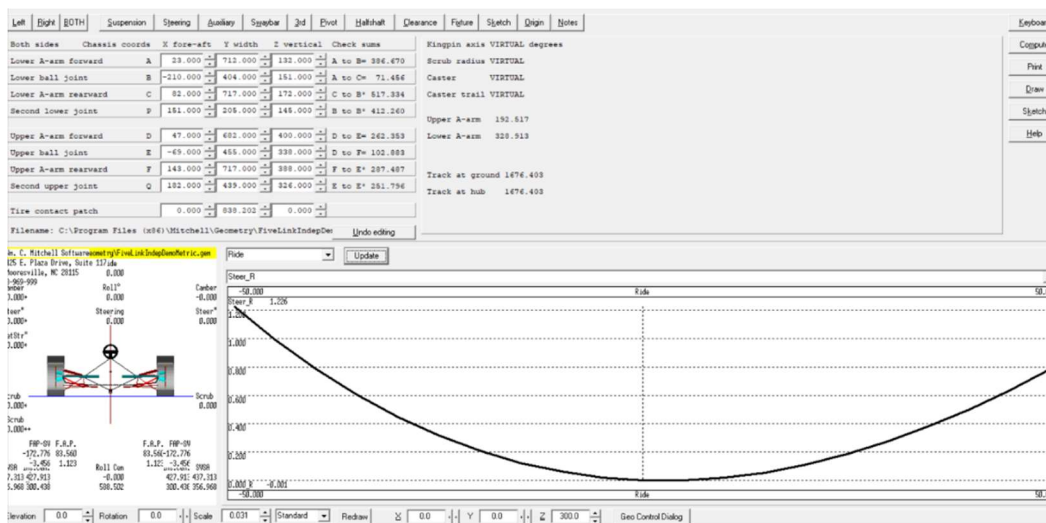
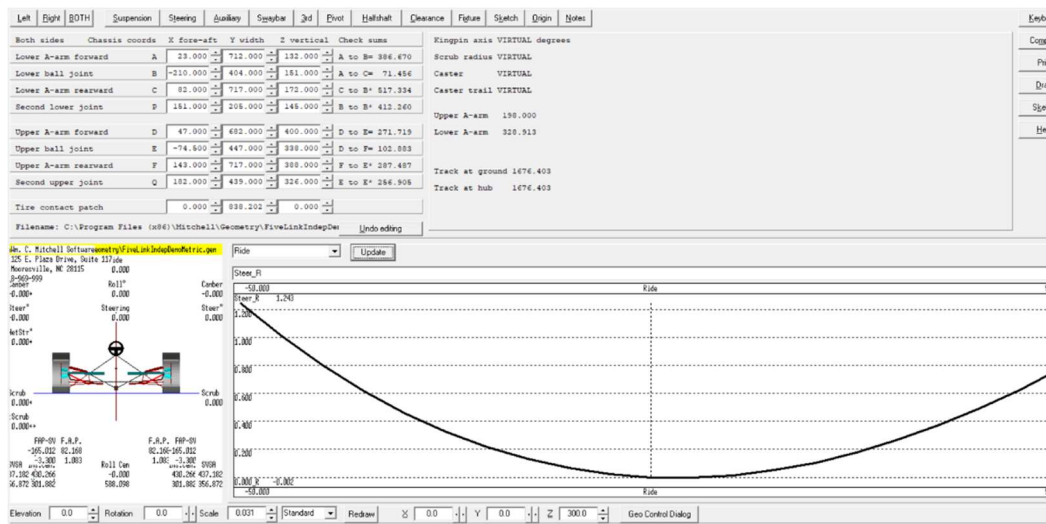
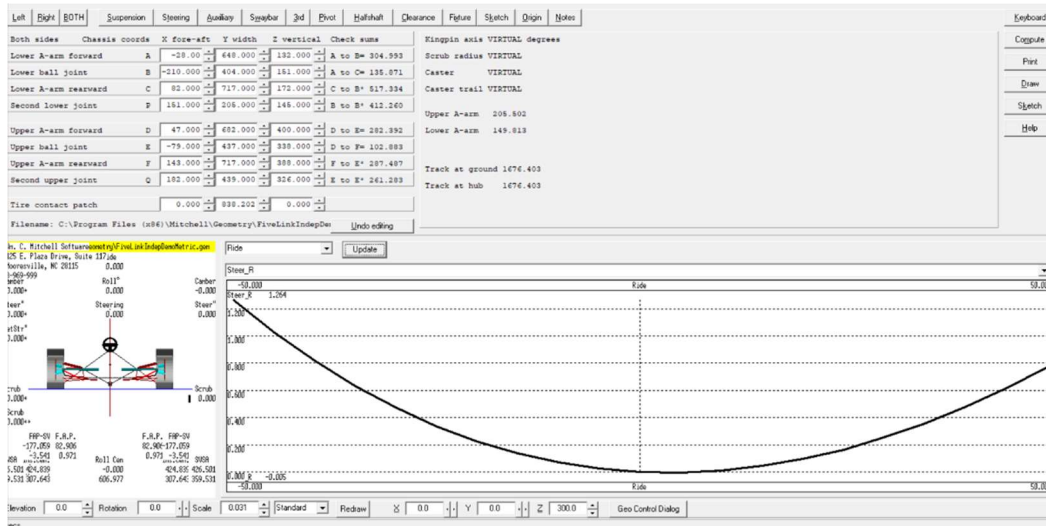


Figure 47 Test 9 Bumpsteer Graph





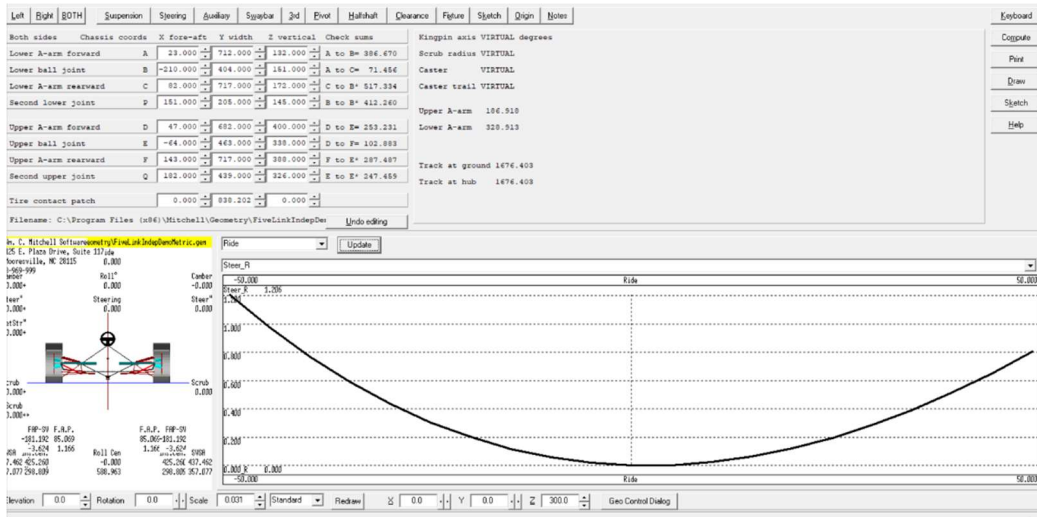


Figure 54 Test 16 Bumpsteer Graph

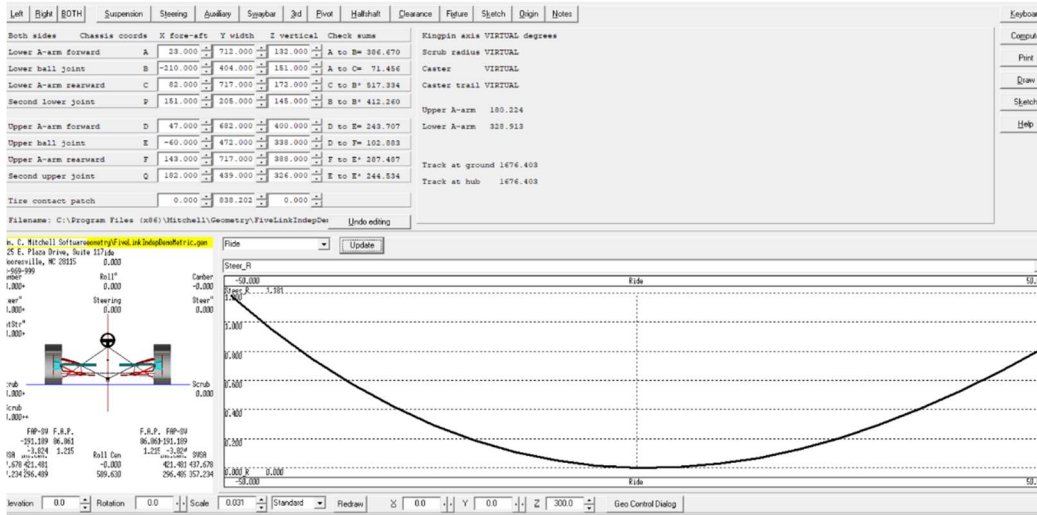


Figure 55 Test 17 Bumpsteer Graph

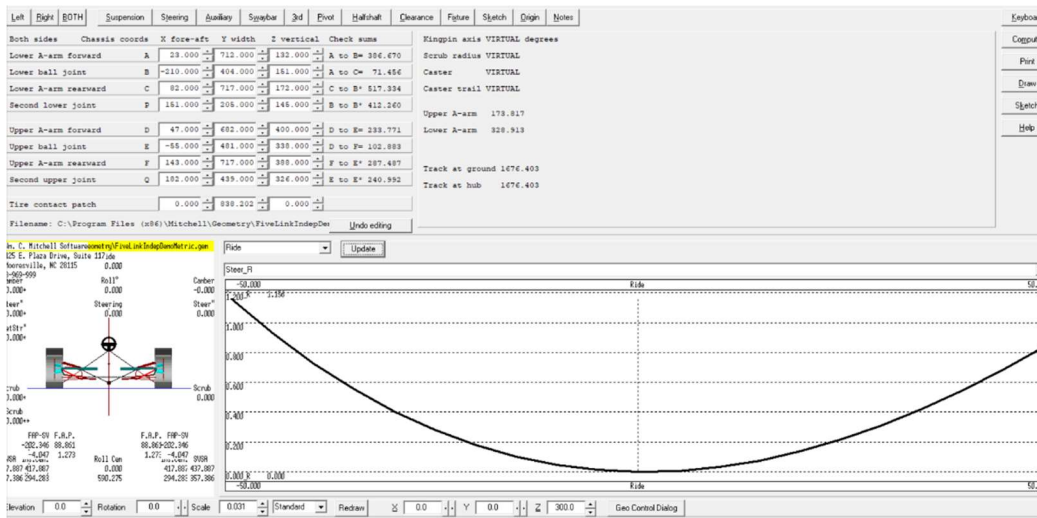


Figure 56 Test 18 Bumpsteer Graph

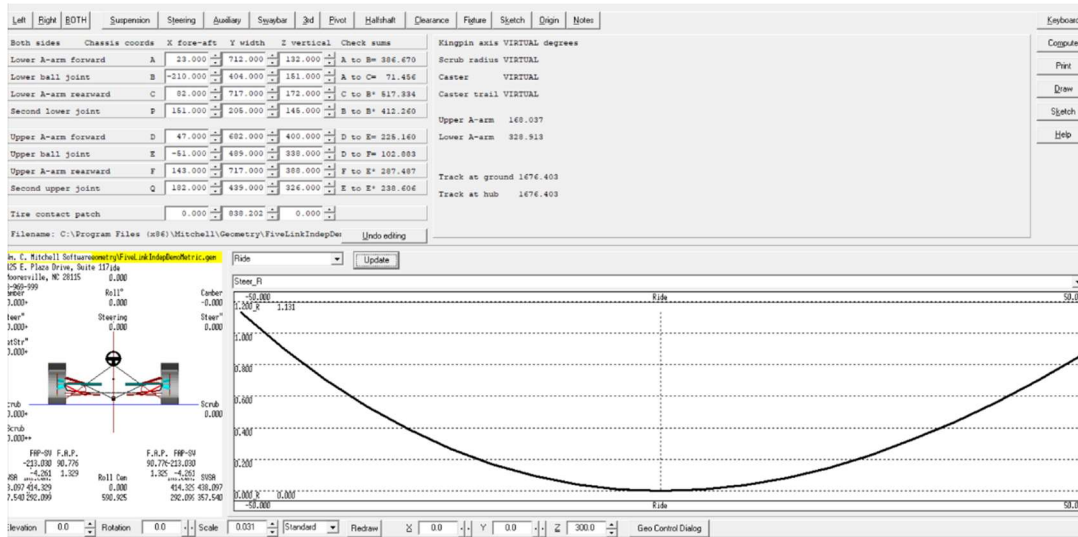


Figure 57 Test 19 Bumpsteer Graph

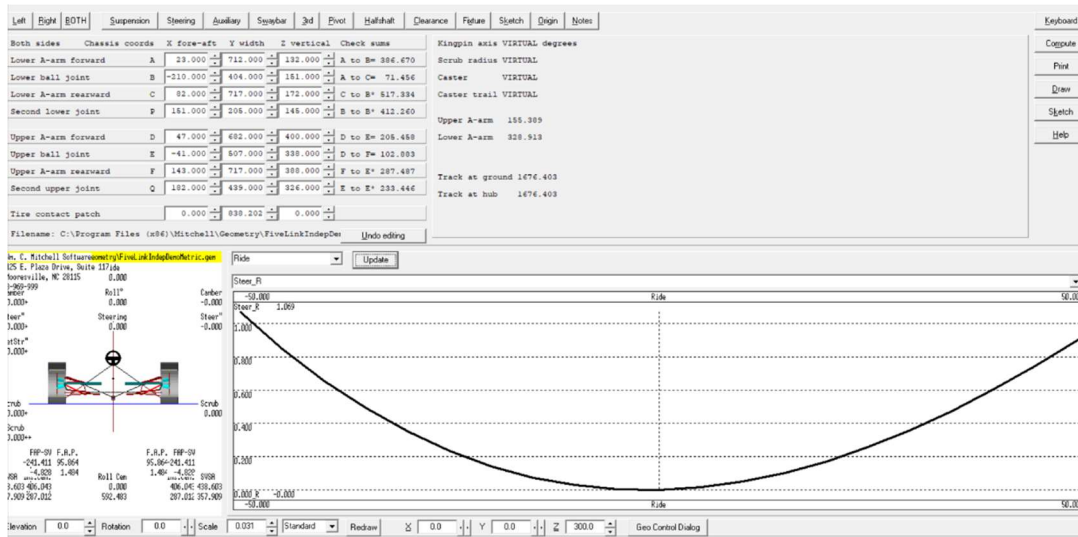


Figure 58 Test 20 Bumpsteer Graph

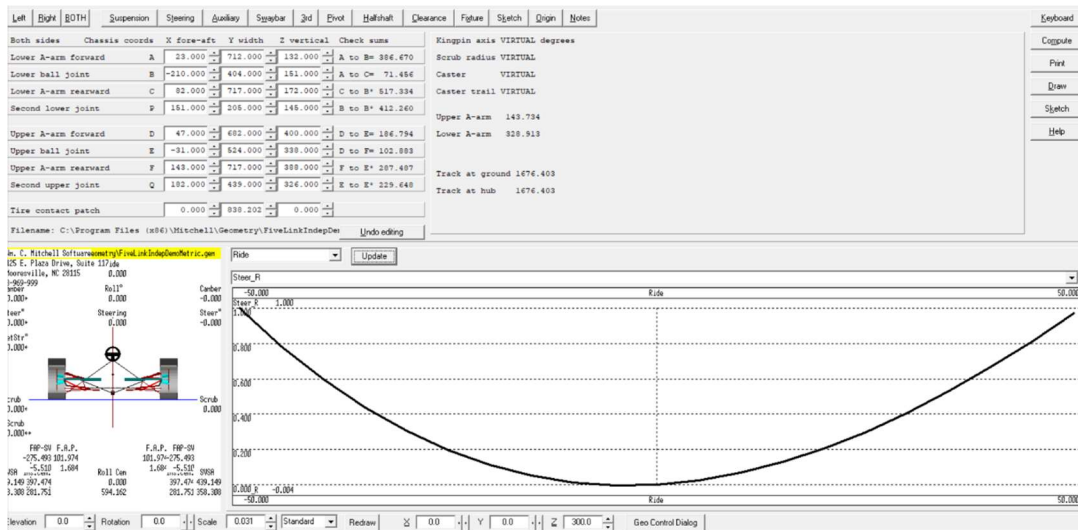


Figure 59 Test 21 Bumpsteer Graph

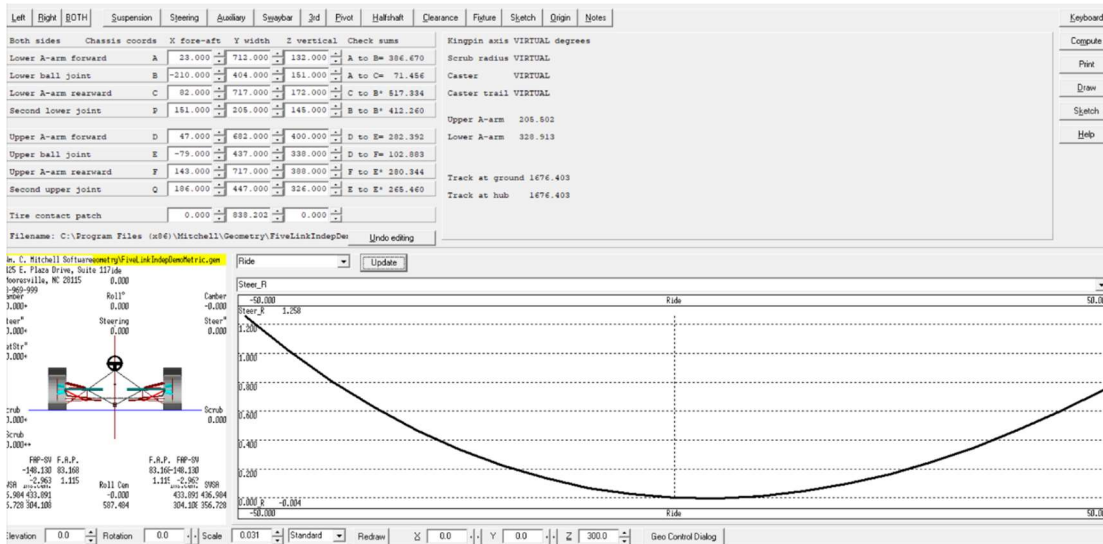


Figure 60 Test 22 Bumpsteer Graph

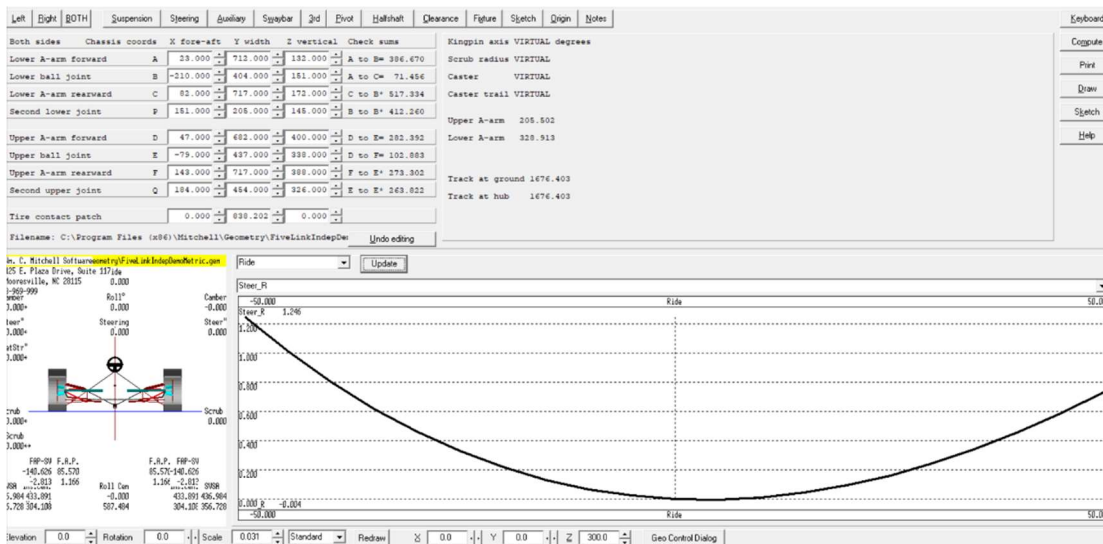


Figure 61 Test 23 Bumpsteer Graph

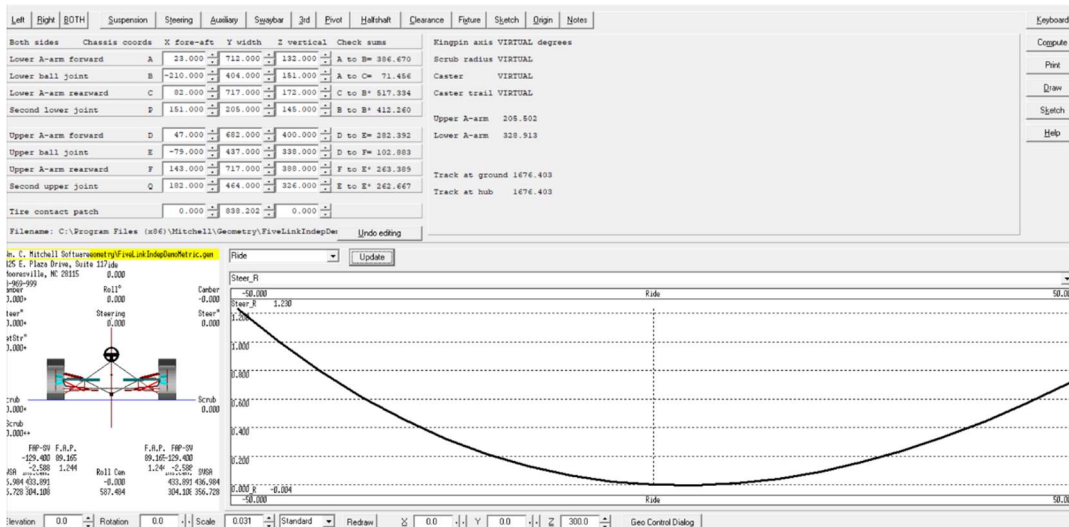


Figure 62 Test 24 Bumpsteer Graph

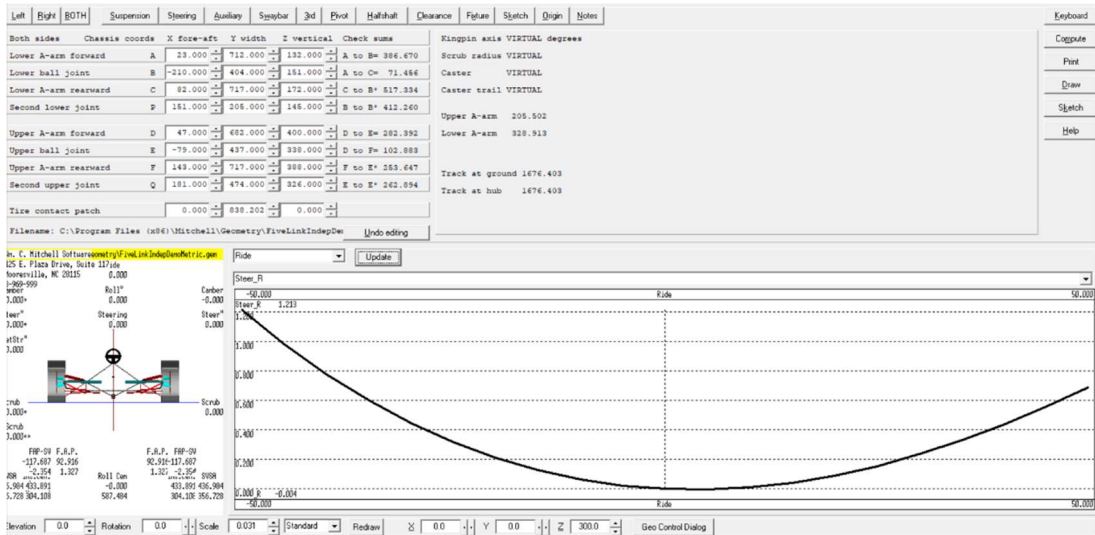


Figure 63 Test 25 Bumpsteer Graph

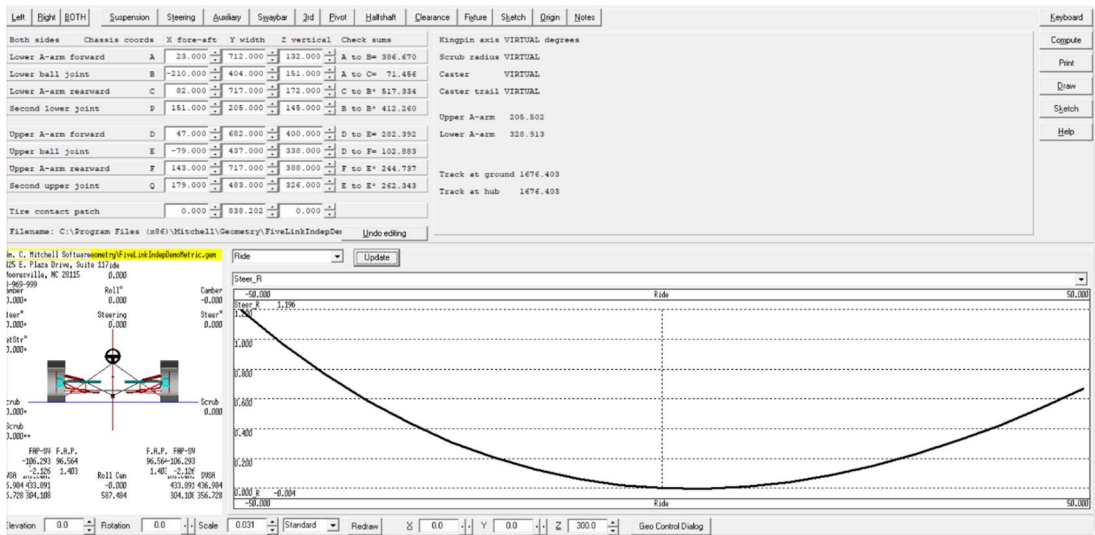


Figure 64 Test 26 Bumpsteer Graph

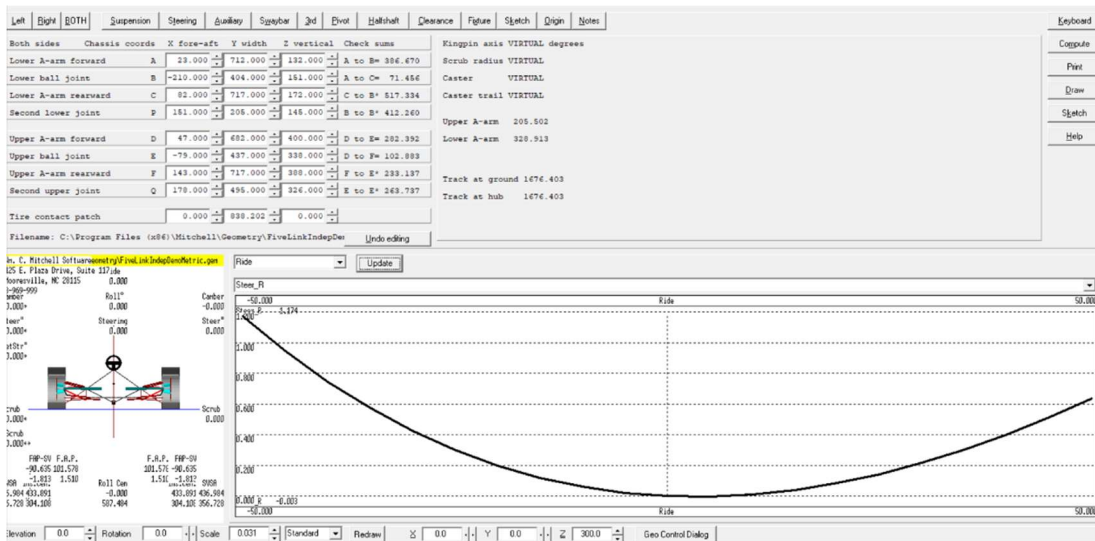


Figure 65 Test 27 Bumpsteer Graph

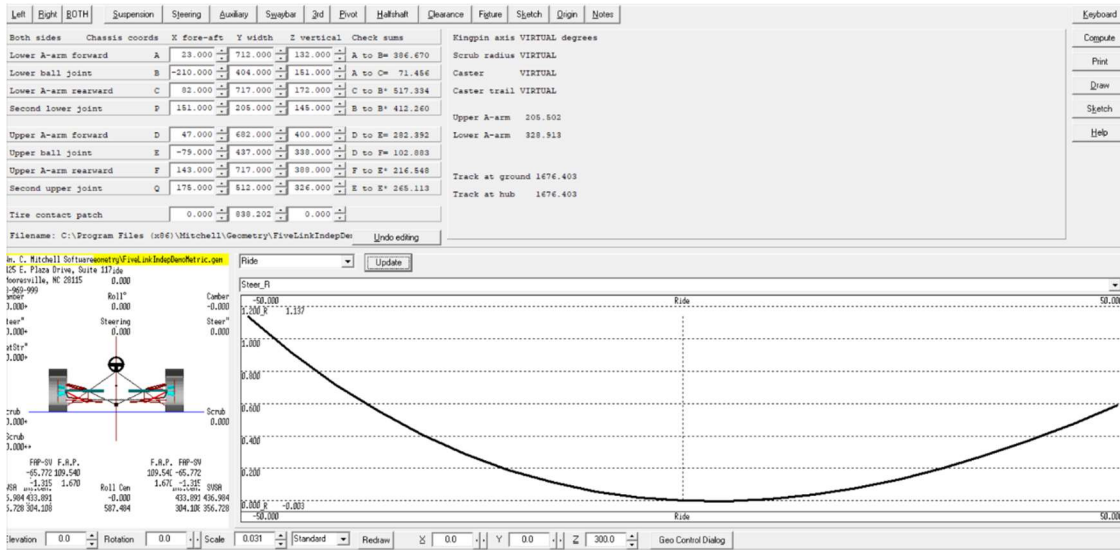


Figure 66 Test 28 Bumpsteer Graph

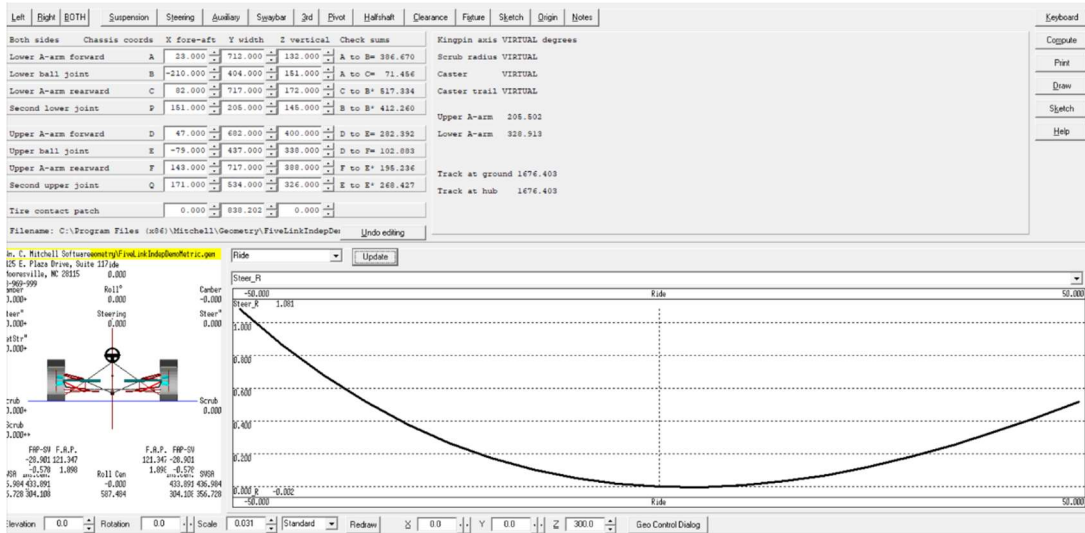


Figure 67 Test 29 Bumpsteer Graph

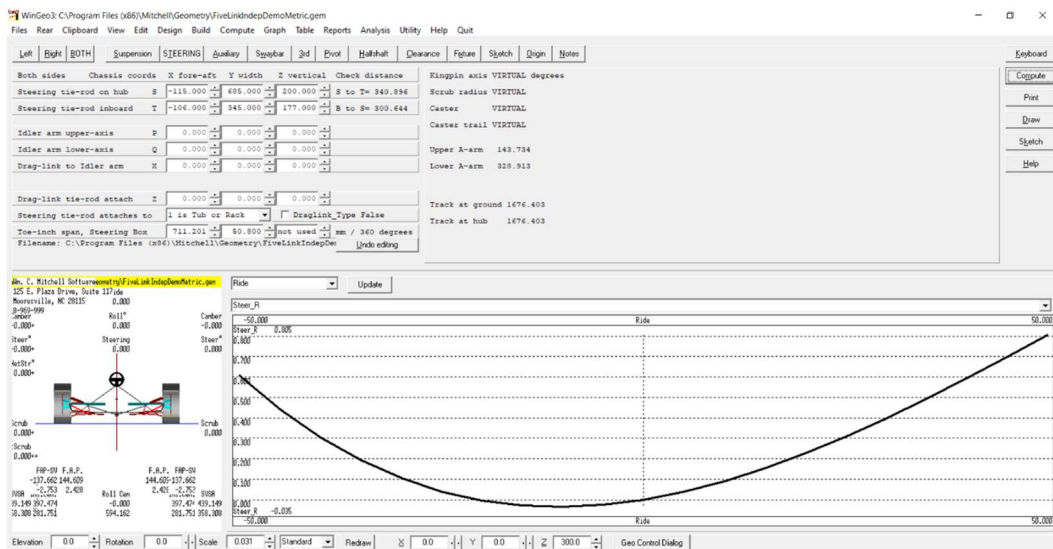


Figure 68 Test 30 Bumpsteer Graph

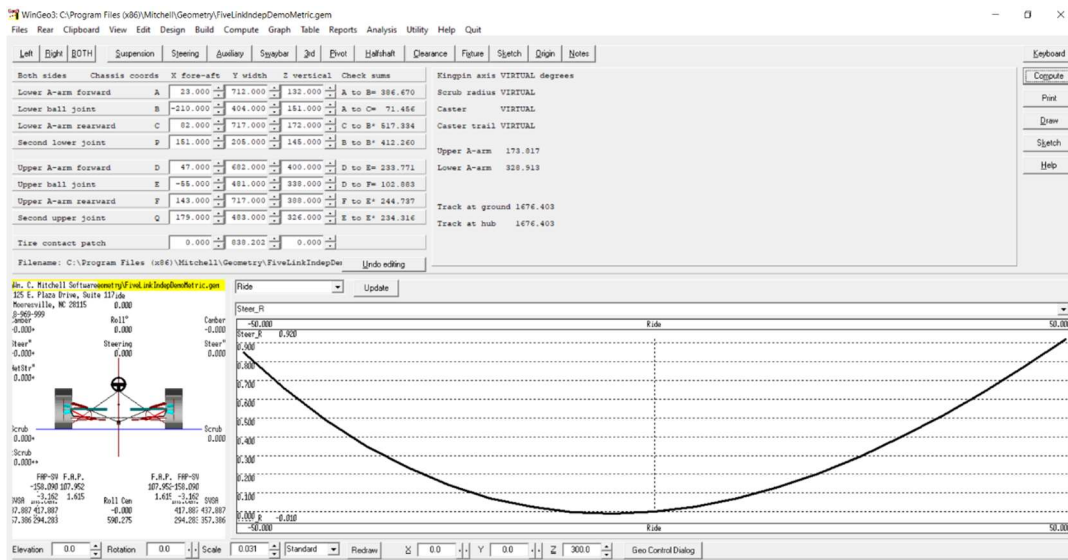


Figure 69 Test 31 Bumpsteer Graph

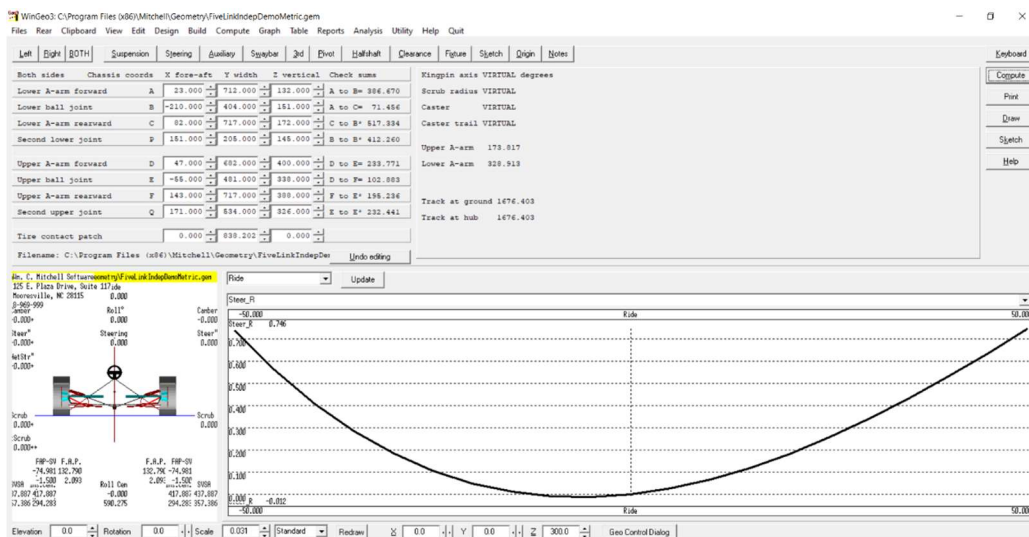


Figure 70 Test 32 Bumpsteer Graph

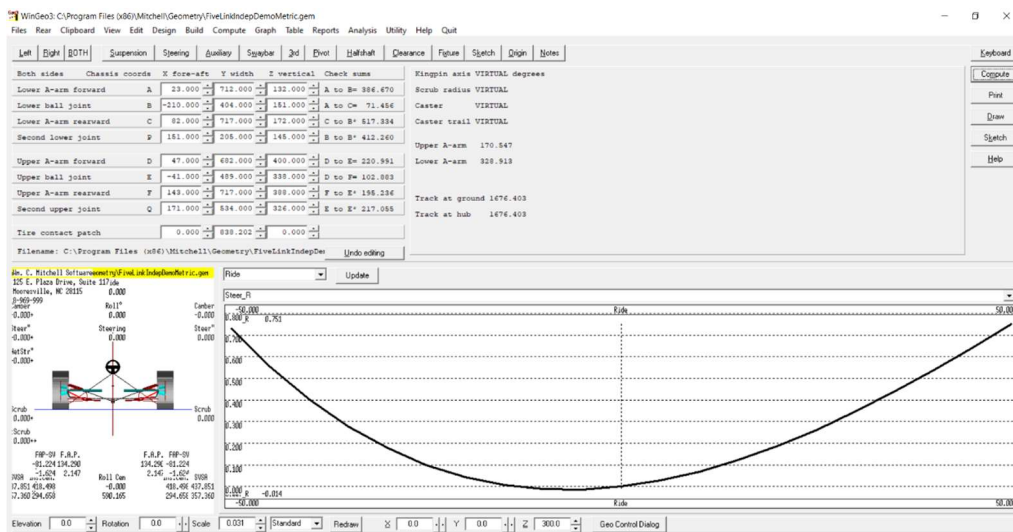


Figure 71 Test 33 Bumpsteer Graph

