Norges miljø- og biovitenskapelige universitet

Master's Thesis 2019   30 ECTS
Faculty of Science and Technology

Front Suspension Design for an Electric Delivery Vehicle

Fredrik Lie Larsen
Mechanics and Process Technology

FRONT SUSPENSION DESIGN FOR AN ELECTRIC DELIVERY VEHICLE

Fredrik Lie Larsen

Norwegian University of Life Sciences

Preface

This master thesis will present the development process of the front suspension system for the Paxster Electric Delivery Vehicle. The development ranged from geometric suspension analysis and setup using Lotus Engineering Shark, to initial component design of the wishbone and steering mounting bracket using the selected geometry and off-the-shelf parts.
The thesis was written in spring of 2019 and is the final part of the Mechanics and Process Technology master program at the Faculty of Science and Technology at the Norwegian University of Life Sciences.

The author's motivation for writing this thesis is linked to my long-standing interest in vehicles and appreciation for the mechanical beauty of suspension systems. The thesis has also allowed me to work with the automotive industry, which has proved to be extremely educational and interesting.

I would like to extend my sincere appreciation to my master thesis counselor, Associate Professor Odd-Ivar Lekang for his valuable input during the writing process. Paxster AS and their lead mechanical engineer, Peer Toftner provided me with the thesis assignment, without their trust and their expertise this thesis would not exist, thank you.

I would also like to express my appreciation to my fellow classmates for valuable discussions during the thesis and our studies as a whole. I would also like to thank friends and family for all the support and motivation they have provided.

____

Fredrik Lie Larsen
Ås, 15. Mai 2019

Abstract

The Paxster EDV is a small Norwegian electric vehicle for delivery of mail and parcels. It is used by a number of companies, including the Norwegian Postal Service. The company wants to improve their front suspension, this wish is the basis of the thesis.

Several suspension types are used in the automotive industry. They all have different advantages and disadvantages making them more or less suited for different use cases. The suspension types are often split into independent and not independent suspensions, with various sub-categories. Typical examples of independent suspensions types are double wishbone and MacPherson setups. Dependent suspensions generally connect the two wheels with a solid axle, letting the wheels influence each other. Companies often develop the base MacPherson or double wishbone concepts further by adding elements to increase control. Paxster EDV currently utilizes a standard type of double wishbones. The system is easy to use but is still somewhat complex compared to a MacPherson setup.

Through discussions with Paxster, a choice of either an improved double wishbone setup or a MacPherson setup was deemed appropriate. This minimizes the development cost, as both suspension types are common and well known. The Paxster EDV is a utility vehicle that needs to be able to hit an aggressive price point, this rules out complex hi-per struts, active suspension components and other more complex systems. The overall goals of the project were to improve the driving characteristics, lower cost and increase the free lateral space.

The final product is an improved front suspension setup, specifically for the Paxster EDV, utilizing mostly standard components, except for the wishbone, steering bracket and the need to modify the chassis mounting points. The setup offers improved driving characteristics in several areas, for example by almost eliminating bump steer, a lower caster angle and more optimal negative camber gain during bump. The suspension system also offers lower complexity and cost due to fewer parts, as well as offering more free lateral space than the current solution . The wishbone exceeds the goals for strength and is designed to leverage welding, bending and cutting extrusions and sheet metal, a method Paxster already utilizes to a large extent.

Sammendrag

Paxster EDV er et lite norskprodusert elektrisk kjøretøy som benyttes til post- og vareleveranser av en rekke firmaer, blant annet Posten Norge. Selskapet ønsket en forbedring av sitt fremre hjuloppheng, som har vært basis for denne oppgaven.

Ulike typer hjuloppheng benyttes i bilindustrien, de har forskjellige fordeler og ulemper som også gir forskjellige bruksområder. Disse sorteres ofte i uavhengige eller solid aksel hjuloppheng, men hver kategori har flere underkategorier. Uavhengige hjuloppheng er for eksempel doble bærearmer eller MacPherson. Hjuloppheng med solide aksler kobler sammen hjulene på hver side, slik at de påvirker hverandre. Mange selskap videreutvikler en type hjuloppheng, ved å legge til flere elementer kan de oppnå større kontroll. Paxster EDV benytter i dag en standard type doble bærearmer i sitt hjuloppheng. Systemet er enkelt å benytte men er noe komplisert i forhold til et MacPherson oppheng og benytter flere deler.

Fra Paxster var det et ønske om at det nye hjulopphenget skulle ha bedre kjøreegenskaper, lavere kostnad og oppta mindre lateral plass. Samtidig ønsket Paxster å benytte oppsett med doble bærearmer eller MacPherson, dette minimerer utviklingskostnadene da disse typene er utbredt og godt kjent. Disse typene hjuloppheng vil også være billigere og enklere i produksjon enn et multilink system med langt flere komponenter. For et nyttekjøretøy som må treffe et aggressivt kostnadsnivå, vil kostnad være viktigere enn komfort.

Sluttresultatet representert i denne masteroppgaven er et forbedret fremre hjuloppheng, et MacPherson system spesielt tilpasset Paxster EDV. Oppsettet gir forbedrede kjøreegenskaper i form av blant annet nærmest eliminert uønsket styreutslag ved kompresjon og gunstigere økning av negativ cambervinkel ved kompresjon. Hjulopphenget benytter færre deler, dette medfører lavere innkjøp og sammenstillingskostnader. Valget av MacPherson hjuloppheng eliminerer den øvre bærearmen som brukes i doble bærearmer, dette medfører mer ledig lateral plass, slik Paxster ønsket. Hjulopphenget består i hovedsak av standardkomponenter, de to unike delene, bærearmen og styrebraketten benytter produksjonsmetoder som Paxster er godt kjent med.

Den nedre bærearmen og styrebraketten møter de oppgitte kravene til styrke. Oppgaven beskriver også potensielle produksjonsmetoder og delene er designet for å benytte selskapets erfaring med den valgte produksjonsmetoden.

Table of contents

PREFACE II

ABSTRACT IV

SAMMENDRAG VI

TABLE OF CONTENTS VIII

1 INTRODUCTION 1
- 1.1 Background 1
- 1.2 Current situation 1
- 1.3 Existing Solutions 2

2. THESIS OVERVIEW 3
- 2.1 Thesis Goals 3
- 2.2 Limitations 3

3. SOLUTION TOOLS & METHODS 4
- 3.1 Terminology 4
- 3.2 Equations 5
- 3.3 Parameter units 6
- 3.4 Methodology & Tools 6
- 3.5 Software 7

4. SUSPENSION THEORY 9
- 4.1 Coordinate System 9
- 4.2 Suspension Types 9
- 4.3 Suspension Nomenclature 11
  - *4.3.1 Bump steer 11*
  - *4.3.2 Roll 11*
  - *4.3.3 Camber 11*
  - *4.3.4 Sprung & Unsprung mass 12*
  - *4.3.5 Toe in & Toe out 12*
  - *4.3.6 Caster angle 13*
  - *4.3.7 Scrub Radius 13*
  - *4.3.8 Center of Gravity 14*
  - *4.3.9 Instant center 14*
  - *4.3.10 Roll center 15*
  - *4.3.11 Bump/Droop 15*
  - *4.3.12 Kingpin angle 15*
  - *4.3.14 Ackerman Steering & Percentage 16*
- 4.4 Springs 17
  - *4.4.1 Spring Rates 17*
  - *4.4.2 Hard & Soft Suspension 19*
- 4.5 Dampers 20
- 4.6 Static Forces 20
- 4.7 Dynamic Forces 22
  - *4.7.1 Shock Factor 22*
  - *4.7.2 Forces Summarized 23*

5. SPECIFICATIONS FOR PROPOSED SUSPENSION SETUP 24
- 5.1 Weighted Product Specifications 24
- 5.2 Size limitations 24

5.3 Driving Characteristics Goals 24
5.4 Analysis Scenarios 25
5.4.1 Static Analysis 25
5.4.2 Maximum bump and droop 25
5.4.3 Maximum steering angle and bump 25
5.4.4 Vehicle Roll in Steady State Cornering 26

6. ANALYSIS OF RELEVANT SUSPENSION CONCEPTS 27
6.1 Baseline Analysis Double Wishbone SLA 27
6.1.1 Baseline Analysis Setup 27
6.1.2 Baseline Analysis Results 30
6.1.3 Baseline Analysis Verification 33
6.2 Double Wishbone SLA Adjusted Track Rod Mounts 33
6.2.1 Double Wishbone SLA Adjusted Track Rod Mounts Setup 33
6.2.2 Double Wishbone SLA Adjusted Track Rod Mounts Results 34
6.3 Double Wishbone SLA Adjusted Pickup Points 37
6.3.1 Double Wishbone SLA Adjusted Pickup Points Setup 37
6.3.2 Double Wishbone SLA Adjusted Pickup Points Results 38
6.4 MacPherson Old Pickup Points 40
6.4.1 MacPherson Old Pickup Points Setup 40
6.4.2 Macpherson Old Pickup Points Results 41
6.5 MacPherson New Pickup Points 43
6.5.1 MacPherson New Pickup Points Setup 43
6.5.2 MacPherson New Pickup Points Results 44
6.6 Geometric Analysis Summary 46
6.7 Concept Selection 47

7. DEVELOPMENT OF THE CHOSEN CONCEPT 48
7.1 Reaction Forces 48
7.1.1 Wishbone Pothole Bump Loads 48
7.1.2 Wishbone Lateral Curb Strike Loads 50
7.1.3 Tie Rod Forces 51
7.2 Mounting Methods 52
7.3 Geometry & Design Envelope 54
7.4 Production Methods 55
7.4.1 Metal Stamping 55
7.4.2 Machining 55
7.4.3 Casting 55
7.4.4 Extrusions, Welding and Bending 56
7.5 Material Selection 56
7.6 Concept Development 57
7.7 Chassis Considerations 62
7.8 Manufacturing Considerations 63
7.9 Springs and Dampers 64
7.10 Final Product Specifications 66
7.11 Product Presentation 67

8. DISCUSSION 71

9. CONCLUSION 73

BIBLIOGRAPHY 74

LIST OF FIGURES 79

LIST OF TABLES **82**

ATTACHMENTS .... **I**

ATTACHMENT 1 VARIOUS RENDERS I
ATTACHMENT 2 BASELINE SUSPENSION ANALYSIS RESULTS MAXIMUM BUMP AND DROOP II
ATTACHMENT 3 BASELINE SUSPENSION ANALYSIS RESULTS 39 DEGREES OF STEERING TRAVEL VI
ATTACHMENT 4 BASELINE SUSPENSION ANALYSIS RESULT VEHICLE ROLL IN STEADY STATE CORNERING VIII
ATTACHMENT 5 DOUBLE WISHBONE SLA ADJUSTED TRACK ROD MOUNTS MAXIMUM BUMP & DROOP XI
ATTACHMENT 6 DOUBLE WISHBONE SLA ADJUSTED TRACK ROD MOUNTS MAXIMUM STEERING ANGLE AND BUMP XV
ATTACHMENT 7 DOUBLE WISHBONE SLA ADJUSTED TRACK ROD MOUNTS VEHICLE ROLL IN STEADY STATE CORNERING XVII
ATTACHMENT 8 DOUBLE WISHBONE SLA ADJUSTED PICKUP POINTS MAXIMUM BUMP & DROOP XX
ATTACHMENT 9 DOUBLE WISHBONE SLA ADJUSTED PICKUP POINTS MAXIMUM STEERING ANGLE AND BUMP . XXIII
ATTACHMENT 10 DOUBLE WISHBONE SLA ADJUSTED PICKUP POINTS VEHICLE ROLL IN STEADY STATE CORNERING XXV
ATTACHMENT 11 MACPHERSON OLD PICKUP POINTS MAXIMUM BUMP & DROOP XXVIII
ATTACHMENT 12 MACPHERSON OLD PICKUP POINTS MAXIMUM STEERING ANGLE AND BUMP XXXII
ATTACHMENT 13 MACPHERSON OLD PICKUP POINTS VEHICLE ROLL IN STEADY STATE CORNERING XXXIV
ATTACHMENT 14 MACPHERSON NEW PICKUP POINTS MAXIMUM BUMP AND DROOP XXXVII
ATTACHMENT 15 MACPHERSON NEW PICKUP POINTS MAXIMUM STEERING ANGLE & BUMP XLI
ATTACHMENT 16 MACPHERSON NEW PICKUP POINTS VEHICLE ROLL IN STEADY STATE CORNERING XLIII

1 Introduction

1.1 Background

This report is a master thesis for the Mechanics and Process Technology program at the Norwegian University of Life Sciences. The thesis is written for Paxster AS, a small-scale Norwegian developer and manufacturer of utility vehicles, aimed at delivery services like mail and smaller packages. The paper will present the development of a new front suspension system for their Generation 2.3 car with potential to be carried forward to further generations. The 2.3 version is an intermediary version between their second generation and the planned large-scale redesign for their third generation.

Paxster AS was founded in 2014 when it split from its mother company Lloyds Industries. The Paxster Electric Delivery Vehicle was developed upon request from the Norwegian Postal Service and development of the first generation started in 2011. It is currently in use in many countries around the world, amongst others, New Zealand and Germany. The vehicle focuses on the last portion of the delivery of mail and packages, where the distances are short, and the navigation can at times be troublesome for a regular size vehicle. The company and its production currently reside in Sarpsborg, Norway.

1.2 Current situation

Their second-generation car looks mostly similar to the previous edition; however, it features several improvements, most notably including a new suspension system and improved steering geometry. However, Paxster wishes to further improve their suspension setup. [1]
The car currently features a double wishbone suspension setup at the front, and a trailing link solid axle setup in the rear. Their double wishbone suspension is a typical SLA (Short Long Arm) style as shown in Figure 1.

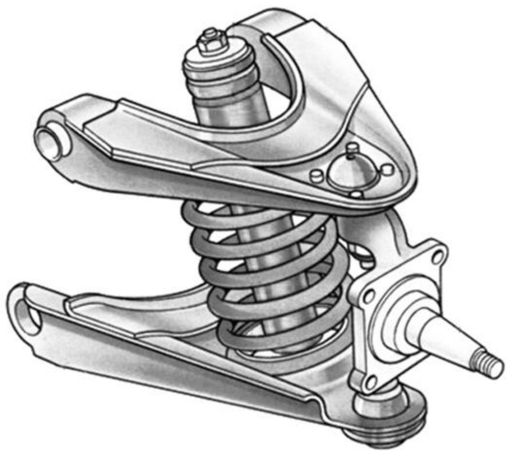

Figure 1. SLA Wishbone Configuration. [2]

Short Long Arm wishbone suspension is characterized by having a short and a long wishbone. Normally the lower wishbone is the longer of the two as this gives negative camber gain during bump travel. The springs can be attached in a variety of ways, directly or through pushrods or pullrods that allow the spring to be located elsewhere in the car of simply directly attached to the lower or upper wishbone.

Paxster is in a somewhat unique situation due to the large variation in weight it encounters during a route. This means the suspension must deal with a total weight of anything from 265kg to 535kg, depending on the configuration. Currently the suspension is optimized for a fully loaded vehicle, for the car to avoid fully compressing the springs with such a load they are stiff. In an unloaded vehicle this translates to a stiff and harsh ride, this is due to the forces now applied to the springs will not sufficiently compress the spring to follow the road. This solution does however work well with a fully laden car.

This thesis will focus on improving the front suspension system of the Paxster EDV.

1.3 Existing Solutions

The automotive sector has been around for well over a hundred years, this in turn has led to a large amount of progress and inventions in suspension technology, from the most basic mechanical leaf springs or torque tubes to the actively controlled and adaptive suspensions of many current high-end vehicles. All solutions have their pros and cons, “There is no single best geometry.” [3] [4]

During discussions with Paxster it became clear that double wishbone SLA and MacPherson suspension types were the most relevant for the vehicle. This is due to relatively low cost and complexity compared to other options like multilink or HiPer struts. The wish for a low-cost suspension setup also rules out any active or semi active suspension components. [5]

2. Thesis Overview

2.1 Thesis Goals

In order to achieve the desired results from the project several goals need to be completed.

- Develop a front suspension system with improved characteristics over the baseline. Utilize Lotus Engineering Shark to develop suspension geometry before further FEM analysis of a chosen concept.
    - Compare the car to the simulated baseline to verify the model
    - Geometrically develop a cloned setup.
    - Geometrically develop MacPherson suspension setups given a variety of input variables.
    - Geometrically develop double wishbone suspension setups for various input parameters.
    - Compare the results in various scenarios.
    - Design a wishbone for a selected production method, utilize FEM analysis to guide the design.

2.2 Limitations

- The thesis will not consider tire dynamics, the tires will be assumed rigid.
- The thesis will not determine the correct nuts and bolts.
- The project will not consider the effects of fatigue and will not verify the claims of part suppliers. Required weld dimensions will not be calculated, a representative weld size will be applied for FEM.

3. Solution Tools & Methods

This chapter outlines the use of terminology, symbols and formulas used in the thesis. The chapter also discusses the methods and software used.

3.1 Terminology

Table 1 Terminology

Concept	Description
Bump	Wheel travel upwards.
CAD	Computer Assisted Design.
Coilover	Component that combines the spring and damper.
CoG	Center of Gravity.
Droop	Wheel travel downwards.
EDV	Electric Delivery Vehicle.
FBD	Free Body Diagram.
FEM	Finite Element Analysis.
FWD	Front Wheel Drive.
Grnd	Lotus Engineering abbreviation for ground.
Kingpin offset	Same as scrub radius. Kingpin offset is used in Lotus Engineering Shark.
NMBU	Norwegian University of Life Sciences.
Pick up points	Attachment points between chassis and suspension components.
RWD	Rear Wheel Drive.
SAE	Society of Automotive Engineers
SLA	Short Long Arm, refers to a double wishbone setup of one short and one long wishbone.
Tie Rod	The linkage between the spindle and the steering rack. Normally connected using a swiveling joint at the ends, like a ball joint.
Trackwidth	Distance between the centerline of two tires (front-front or rear-rear).
Wheelbase	Center distance between front and rear tires.
W/C	Lotus Engineering abbreviation for wheel center.

Due to some aspects of suspension terminology being more complex than the explanation of short abbreviations, chapter *4.3 Suspension Nomenclature* will explain these in further detail.

3.2 Equations

Table 2 Equations

Name	Equation	Index
Ackerman Angle	$Ackerman = tan^{-1}\left(\frac{Wheelbase}{\frac{Wheelbase}{tan\delta_{Outside}} - track_{front}}\right)$	Equation 1
Hooke's Law	$F_s = k * x$	Equation 2
Linear Spring Stiffness	$k = \frac{G * d^4}{8 * n * D^3}$	Equation 3
Equivalent Spring Stiffness	$k_{eq} = k * (\frac{a}{b} * \cos(a))^2$ or $k_{eq} = MotionRatio * k$	Equation 4
Natural Frequency of a System	$f_n = \frac{1}{2\pi} * \sqrt{\frac{k}{m}}$	Equation 5
Optimal Spring Stiffness for Eight Car	$k_{eq} = 4\pi^2 * f_n^2 * m_{Front-1/8th} * MotionRatio^2$	Equation 6
Mass of Eighth Car Model	$m_{Front-1/8th} = \frac{TotalSprungMass}{4} - UnsprungMass$	Equation 7
Critical Damping Coefficient	$C_{cr} = 2\sqrt{k_{eq} * MotionRatio^2 * m_{Front-1/8th}}$	Equation 8
Damping Ratio	$\xi = \frac{C}{C_{cr}}$	Equation 9
Newtons First Law	$\sum F = 0 \ \& \ \sum M = 0$	Equation 10
Force Due to Mass and Gravity. Newtons Second Law	$G = m * g$	Equation 11
Front Weight Distribution	$FrontWD = \frac{F_{ZF}}{m * g} * 100$	Equation 12
Forces Due to Shock Loading	$F_{Max,Shock} = ShockFactor * F_{Max,Static}$	Equation 13
Damping Curve Initial Slope	$4\pi\xi f_n * m_{Front-1/8th}$	Equation 14
Front Vertical Tire Force	$F_{ZF} = m * g - \frac{m * g * x_1}{l}$	Equation 15
Rear Vertical Tire Force	$F_{ZR} = \frac{m * g * x_1}{l}$	Equation 16

3.3 Parameter units

Some parameters are not assigned symbols and are referred to by their full name in the thesis.

Table 3 Parameter units

Symbol	Parameter	Unit
SR	Scrub Radius	Mm
$BumpSteer$	Bump steer	Deg/mm
$Camber$	Camber or camber gain	Deg or deg/mm
$Toe\ Angle$	Toe in/ toe out	Deg
$Bump$	Bump / droop	Mm
$Kingpin\ Angle$	Kingpin angle	Deg
$Ackerman\%$	Ackerman percentage.	Relative (%)
$Wheelbase$	Wheelbase	mm
$TrackWidth$	Trackwidth	mm
m	Mass	Kg
g	Gravitational acceleration (-9.81)	m/s^2
G	Shear Modulus of Elasticity	N/mm^2
F	Force	N
F_Z	Force in Z-direction	N
F_{ZF}	Force in Z-direction, front wheels	N
F_{ZR}	Force in Z-direction, rear wheels	N
M_x	Moment around point x.	Nm
q	Pitch	$degrees$
p	Roll	$degrees$
r	Yaw	$degrees$
$FrontWD$	Front Weight Distribution	%
$RearWD$	Rear Weight Distribution	%
$Camber\ Angle$	Camber Angle	$degrees$
$Caster\ Angle$	Caster Angle	$degrees$
f_n	Natural frequency	Hz
ξ	Damping ratio	Relative

3.4 Methodology & Tools

The following chapter will present the utilized development methods, tools and software applied during the project. This is done in order to explain the process when these methods are used later as well as act as a toolbox during development.

Pugh's method

Selection method based on defining several weighted factors according to their importance, this is used further when grading several concepts. The result is a matrix that shows the weighted results and thus enables the user to find the best solution for the desired characteristics. [6]

SCAMPER
A creative thinking tool used to facilitate concept generation by forcing the user to ask a series of questions. This often leads to many variations of the initial concept. SCAMPER consists of the following steps. [7]

- Substitute – Substitute components with different ones whilst achieving a similar result.
- Combine – Combine components in new ways. This includes different mounting, simply joining two pieces or functions.
- Adapt – Adapt components to a new purpose.
- Magnify – Change the size of one or more components.
- Purpose – Change the purpose of certain components or the product itself. The product might be usable for an entirely different task.
- Eliminate – Simply remove components without losing functionality. Leaves the core functionality of the product without any frills.
- Elaborate – Adding functionality that the product was not intended to have originally.
- Rearrange – Change the assembly. Components can be placed differently and might change the function or complexity of the product.
- Reverse – Explore the product with reverse components or functionality.

Integrated Product Development
Integrated Product Development, also known as IPD is a development method with the intent of enabling the flow of data between divisions, such as development, production and economy. This is useful in order to balance the development work, as to not make a product that cannot be manufactured or may not economically viable.

Traditionally the model allows for dataflow between three divisions as mentioned above, however NMBU as added a fourth, Health, Security and Environment. This adds considerations of the products effect on its users as well as the environmental impact of the product itself. IPD is kept in mind during the development and selection process later in the thesis.

3.5 Software

Autodesk Fusion 360
A cloud enabled CAD program from Autodesk. Mostly used for rendering images. Version 2.0 5519

Autodesk Inventor Professional 2018
Traditional CAD software. Used for modelling, and measurements of the large assembly file supplied by Paxster. Build: 112, Release: 2018.

Lotus Engineering Shark
Suspension analysis software. Version 6.01b

Adobe Illustrator
Utilized for generating graphics and visualization tools.

Ansys Workbench
Used for FEM analysis. Release 19.2
CES EduPak
Material data

4. Suspension Theory

The overall goal of suspension systems in vehicles is to provide optimal contact between the tire and the road in order to maintain driving characteristics and safety. Assuming the suspension can provide adequate safety, ride comfort seems to often be a secondary objective.

4.1 Coordinate System

In order to define the location of various suspension components, which is important as their relative locations define many of the characteristics of the suspension system, a coordinate system is defined. This report will utilize a coordinate system as defined in the "Vehicle Dynamics Terminology" SAE J670e paper. The right-hand rule is valid for this system and the vehicle is assumed to have symmetry on either side of the XY-plane. Origin is defined at the center of gravity. The coordinate system also illustrates the positive direction of rotation as shown in Figure 2. [8]

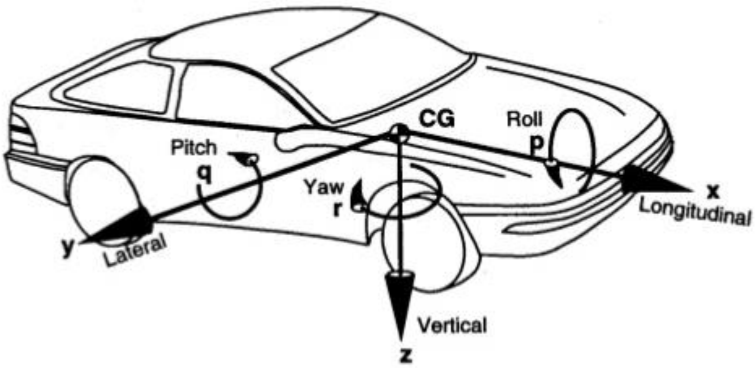

Figure 2. SAE Axis system. [9]

4.2 Suspension Types

MacPherson

One common suspension setup used in production cars. Especially useful in front suspension due to its relatively compact lateral size, which allows packaging an engine easier. A MacPherson setup consists of a lower wishbone with a strut on top, attached at the other end to a strut tower in the chassis. Steering is done either by allowing rotation between the strut and the chassis or between the strut and the spindle. (Figure 3.)

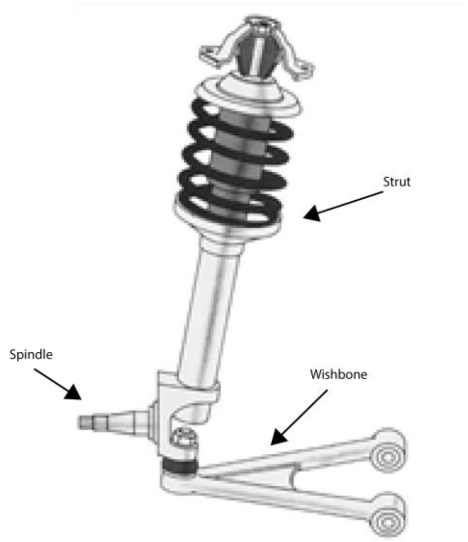

Figure 3. Typical MacPherson suspension setup. [2]

Double Wishbone

A very common suspension type for high-end and racing applications due to the desirable performance an optimized system can achieve. One notable benefit is a camber curve that is easier to control, this can lead to a better contact patch between the tire and the road. [10] The spring and shock assembly can be mounted in a few different ways in a double wishbone or SLA configuration as they are also referred to, the most notable are pushrods, pullrods or direct mounting. Direct mounting is the easiest and most basic method, the shocks are mounted directly to one of the wishbones, this is currently used in the Paxster EDV.(Figure 1) Race cars typically utilize pushrod or pullrod actuated shocks, these two types are the only types utilized in Formula 1 and are shown in Figure 4 and Figure 5 [11]

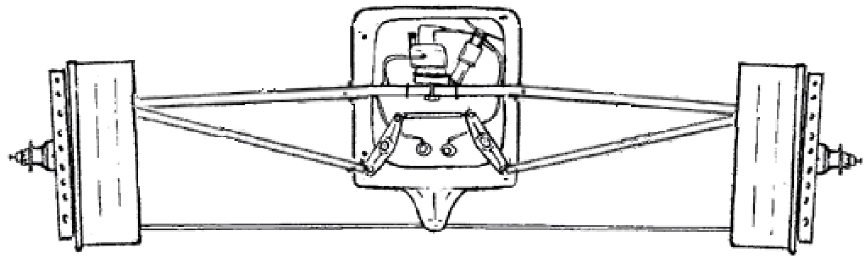

Figure 4. Pullrod setup in a Formula 1 car [11]

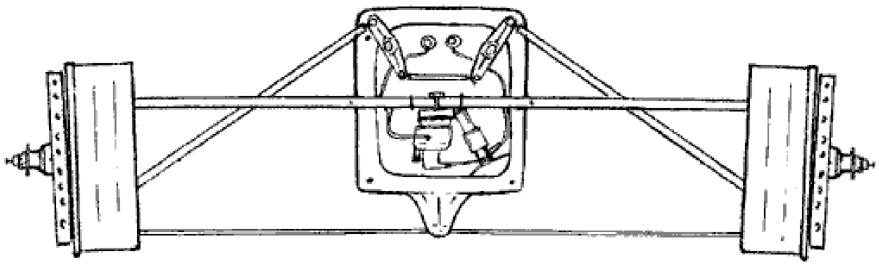

Figure 5. Pushrod setup in a Formula 1 car [11]

The difference between a regular SLA setup and a pushrod/pullrod SLA setup is how the shocks are actuated as the wheel travels up and down. A pushrod will push the rocker inwards or upwards while the pullrod will pull the rocker outwards or downwards. These setups often lead to great control over the behavior of the suspension.

4.3 Suspension Nomenclature

4.3.1 Bump steer

Bump steer is an unwanted effect where the actuation of the suspension during bump where the steering geometry pushes the wheels as if they were turning. This effect will make the leading edge of the wheels to point inwards or outwards, called toe in or toe out. Bump steer is normally made as small as possible. As shown in Figure 6 for the car to achieve zero bump steer the outer tie rod joint must achieve three conditions. [12]

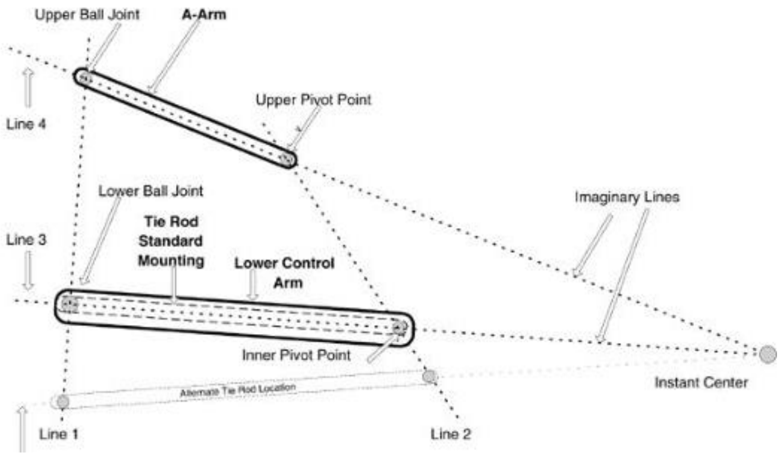

Figure 6. Illustrates the placement of the tie rod in relation to the upper and lower wishbone. [12]

The conditions shown in Figure 6 are listed below.

- Attach somewhere on the line between the outer upper and lower ball joints.
- The inner tie rod joint must intersect the line between the inner upper and lower pivot points.
- The imaginary line through the tie rods center must intersect the instant center.

If these criteria are achieved the wishbones and the tie rod rotate around the same center, resulting in zero bump steer. Bump steer is measured in degrees/mm.

4.3.2 Roll

Roll is the angle around the x axis as shown in Figure 2. This is normally caused during cornering as a result of the height difference between the center of gravity and the roll center. Roll can somewhat alter suspension geometry but is unlikely to be much of a concern in a slow-moving utility vehicle.

4.3.3 Camber

Camber can be wanted effect, depending on type and amount. Positive camber implies that the wheel leans outwards and away from the car at the top. Negative camber rotates the top of the wheel inwards at the top. (Figure 7)

Negative camber is normally used in cars, to some amount, larger values can be found in sportier cars as camber increases the tires contact patch on the outside wheels during cornering. Excessive camber will lead to uneven wear on the tire, due to the contact patch being smaller during regular driving. A smaller contact patch also reduces the cars ability to brake and accelerate in a straight line. The suspension geometry of the Paxster EDV will likely

try to achieve a relatively neutral value, with a preferred slight gain in negative camber during suspension bump.
Camber is measured in degrees, but degrees per unit of length is used to define camber gain.

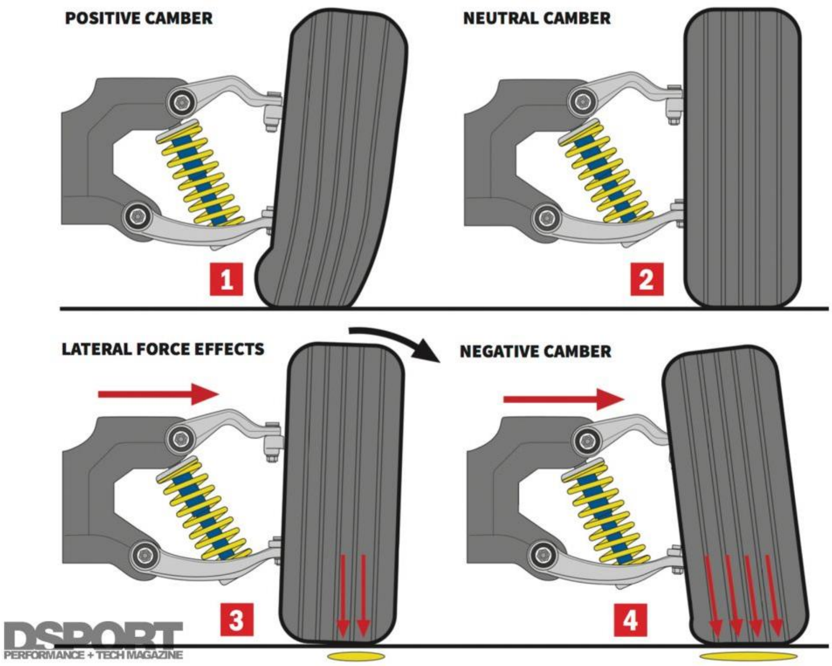

Figure 7.Positive, neutral and negative camber, as well as the advantage of negative camber. Note the contact patch below the tire for the various situations. [13]

4.3.4 Sprung & Unsprung mass

Sprung and unsprung mass are definitions that split the mass of the car into two distinct parts. The sprung mass is any mass of the vehicle that is supported by the springs of the car, typically this includes the chassis, bodywork and most of the car. The unsprung mass is any mass not supported by the springs of the car, like the wheels, brakes and most suspension components. [14]

4.3.5 Toe in & Toe out

Toe in and out refers to the leading edge of the front wheels both pointing away from the car, or towards the middle of the car, during a neutral steer situation. Away from the middle is toe out whilst toe in refers to the wheels pointing slightly inwards. Excessive amounts of toe angle are generally unwanted, however slight amounts offer certain advantages, at the cost of tire wear. This is shown in Figure 8. [15]

- Toe in can increase stability when driving in a straight line.
- Toe out improves the cars responsiveness during cornering.

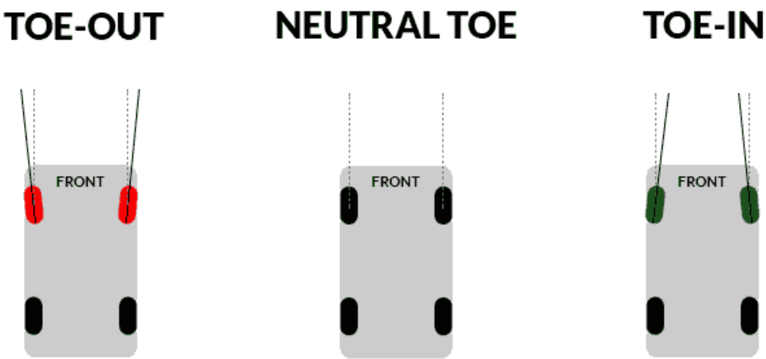

Figure 8. Toe angle illustrations. [15]

4.3.6 Caster angle

The caster angle is defined by the angle between the vertical and the line between the kingpins when viewed from a profile view. (Figure 9) [16]

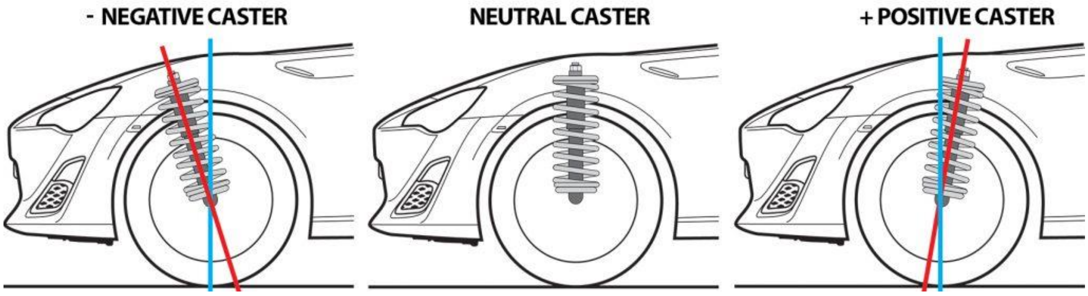

Figure 9. Illustrates caster angles for a McPherson setup. [13]

Positive caster leads to an increase in negative camber during turning which is generally wanted. It also contributes to self-centering but makes the car heavier to steer. Negative caster will make the car easier to steer, but also less stable. [13]

Caster angles for some common cars are shown in Table 4 below.

Table 4 Caster Angle for various vehicles [17].

Vehicle	Caster Angle (deg)
Citroën C5	3.1
Audi A4	3.4
Renault Clio II	2.1
Peugeot 307	4.6
Volkswagen Touran	7.5
Paxster EDV	5.5

4.3.7 Scrub Radius

Scrub radius is the distance from where the tire centerline and the kingpin axis intersect the ground plane, this is shown in Figure 10 below. Both positive and negative scrub radii are used. Ideally rear wheel-drive cars have a small scrub radius, this reduces the effect of one-wheel bumps on steering torque. [18]

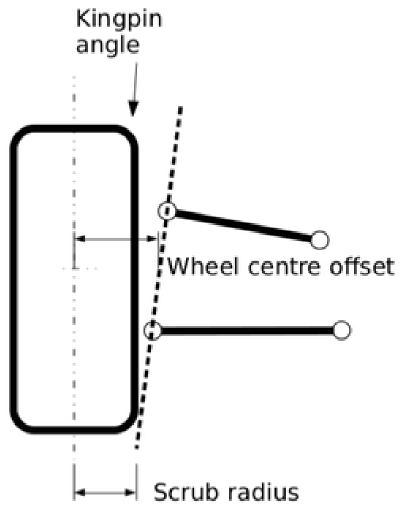

Figure 10. Scrub radius. [19]

Changing the where the wheel hub attaches to the wheel, in the y-direction will change the scrub radius. Essentially this may be an easy method for tuning the scrub radius slightly. (Table 5)

Table 5 Scrub radius for various vehicles [17].

Vehicle	Scrub Radius (mm)
Peugeot 406	+2
Audi A4	-8
Renault Mègane II	-2
Renault Mègane II RS	-14
Renault R18	+44
Paxster EDV	+25.7

4.3.8 Center of Gravity

"The center of gravity is the average location of the weight of an object" as formulated by the Glenn Research Center at NASA. Essentially this is the point at which an object can be balanced on the tip of a pencil. [20]

4.3.9 Instant center

The instant center refers to the center, effectively the pivot point of a set of linkages at an instant in time, the instant center a function of suspension travel. This is the pivot point the wheel rotates around during bump and droop. For small amounts of travel this movement can be approximately linear, this area is often called the linear range. As shown in Figure 11 the instant center is the point where the two-dimensional length axis of the wishbones intersects. The instant center is used to define the roll center. [21]

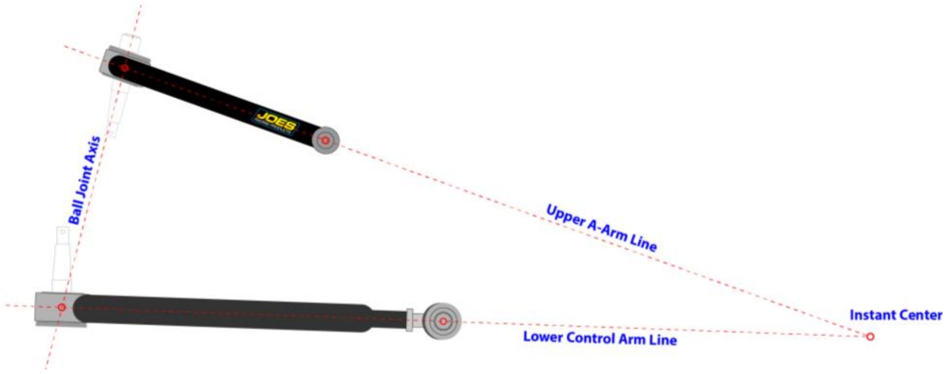

Figure 11. Illustrates the instant center for a double wishbone suspension setup. [22]

4.3.10 Roll center

The roll center is the center about which the vehicle rolls. The roll center is controlled by the location of the instant center and its distance from the tire contact patch. Together with the center of gravity the roll center produces a force coupling point between unsprung and sprung mass. This is important to control the body roll during cornering, where the centrifugal force will create a moment at the roll center with the force multiplied by the distance between the center of gravity and the roll center. The roll center can move in all directions on its 2D plane.

As shown in Figure 12 below, the roll center will heavily depend on the instant centers. A line is drawn from the instant center to the center of the tires contact patch on the same side, the point where these two lines intersect is the roll center. [23]

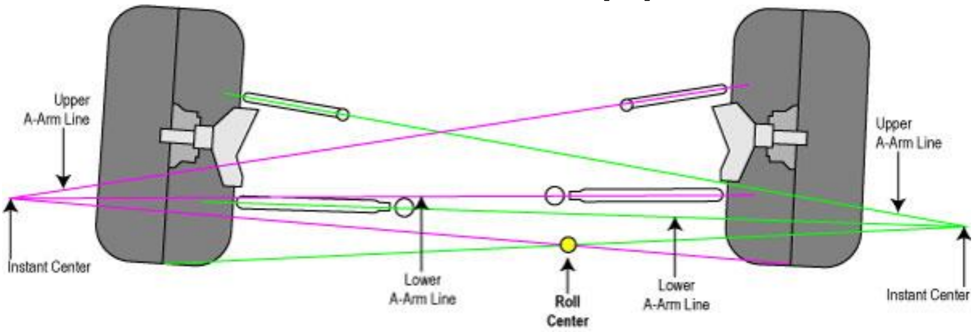

Figure 12. Illustrates how to find the instant centers and the roll center. [24]

4.3.11 Bump/Droop

Bump and droop refer to the upwards and downwards motion of the wheel, respectably. This is often used to describe other parameters of suspension. A 3-degree negative camber increase at 20mm bump is an example of this.

4.3.12 Kingpin angle

The kingpin angle is the angle between the kingpins on a spindle as seen from the front plane, this is shown in Figure 13 below. The angle is measured between the vertical line and the line that goes through the two kingpins, essentially the spindle to wishbone attachment points. This is important for stability as the kingpin angle will contribute to self-centering of the steering. This is an effect where the steering input returns to neutral if the steering wheel is released. Measured in degrees as viewed from the front plate. Examples of common kingpin angles are shown in Table 6 below. [25]

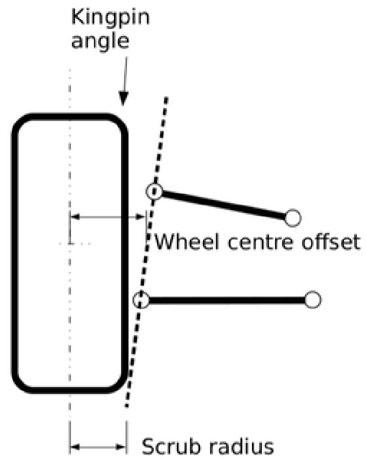

Figure 13. Kingpin angle. [19]

Table 6. Kingpin angle for various vehicles [17].

Vehicle	Kingpin Angle (deg)
Citroën C5	12.5
Audi A4	3.4
Renault Clio II	11.4
Peugeot 307	11.7
Mègane II RS	8.5
Volkswagen Touran	14.4
Paxster EDV	11.7

4.3.14 Ackerman Steering & Percentage

The Ackerman percentage, after Rudolf Ackerman, is the percentage that the outer and inner wheel travels along the correct path in a turn. This is wanted because the inner wheel will travel a tighter radius circle than the outer wheel, thus they must be angled differently. The percentage indicates to which degree this is achieved, 0% implies the angles are the same. Typically, 100% is the goal for Ackerman percentage. Ackermann can easily be observed by moving the steering on any passenger car to full lock, full steering input and viewing the toe angle of each wheel. [26]

Wheelbase and track front defined as in Table 1 and below in Figure 14. Wheelbase is defined as l, track front is defined as wf. [27]

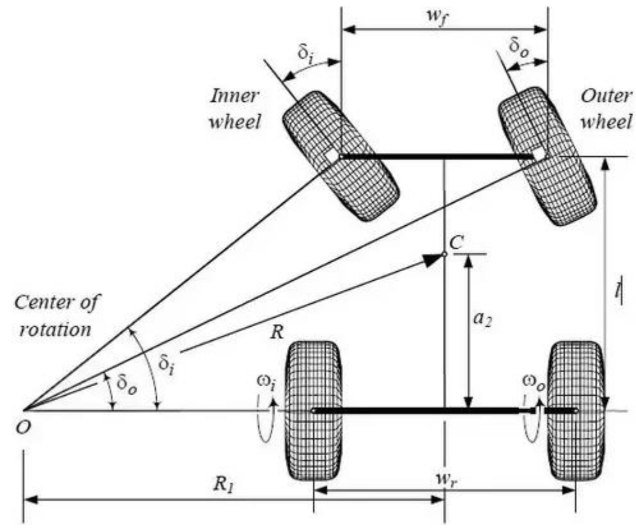

Figure 14. Measurements used in calculation of Ackerman percentage. [28]

$$Ackerman = tan^{-1}\left(\frac{Wheelbase}{\frac{Wheelbase}{tan\delta_{Outside}} - track_{front}}\right) \quad \text{Equation 1}$$

$$Ackerman_{percentage} = \frac{\delta_{inside}}{Ackerman} * 100$$

4.4 Springs

A suspension system typically consists of a spring and a damper for each wheel. The spring acts as an energy storage device and helps control the ride frequency.

4.4.1 Spring Rates

In traditional physics, Hooke's law defines the force acting on a linear spring as the equation.

$$F_{Spring} = k * x \quad \text{Equation 2}$$

Here k is the spring constant which expresses the amount of force needed to compress the spring a unit of length. Here x is the length the spring has been compressed from its unloaded state. The factor k is often referred to as a spring rate in the automotive world.
The stiffness of a linear spring can be calculated using the formula below, this is the spring constant. Adjusting these parameters at a given interval in a spring is a method of manufacturing progressive springs. [29]

$$k = \frac{G * d^4}{8 * n * D^3} \quad \text{Equation 3}$$

d = Wire diameter.
D = Mean coil diameter.
n = Number of coils being flexed.

However dual rate or progressive springs have a changing spring rate according to their compression. This allows the spring to compensate for extra load by having an increasing spring constant. [30]

A simplified model of a spring places the spring at the center of the wheel, as this is not viable in real world applications, an equivalent spring can be mathematically modeled using the equation. Illustrations of this is shown in Figure 15.

$$k_{eq} = (\frac{a}{b})^2 * k$$ *Equation 4*

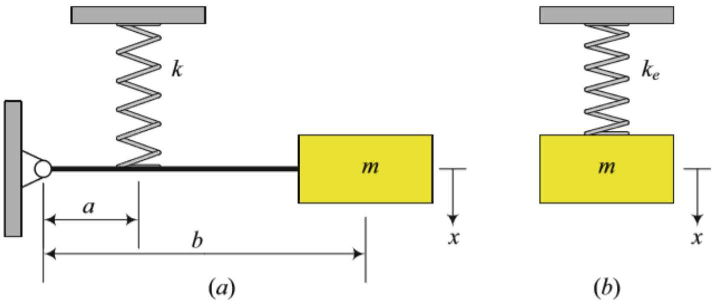

Figure 15. Spring constant and transformation. [31]

The equation assumes a very small compression $x \ll 1$ to ignore angle changes.
k_{eq} is the equivalent spring constant for a spring placed at the center of mass.
Most suspensions have the spring setup at an angle, for a MacPherson setup the equivalent spring constant may be calculated by the following equation. Relevant sizes and angles are shown in Figure 16. [32]

$$k_{eq} = k * (\frac{a}{b} * \cos(a))^2$$ *Equation 4*

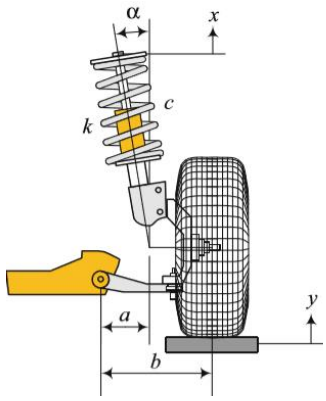

Figure 16. Equivalent spring constant calculation for MacPherson suspension. [33]

Lotus Engineering Shark outputs this directly for each interval of suspension travel.
The equivalent spring constant can be expressed using the spring ratio from Shark.

$$k_{eq} = MotionRatio * k$$ *Equation 4*

$SpringRatio$ indicates the Spring Ratio obtained from Lotus Engineering Shark for a given suspension setup. The natural frequency of a system may be expressed using the following equation.

$$f_n = \frac{1}{2\pi} * \sqrt{\frac{k}{m}} \qquad \text{Equation 5}$$

Here k and m represent the spring constant and mass, respectively.

4.4.2 Hard & Soft Suspension

Suspension is often referred to as being either hard or soft. For a comfortable ride the suspension must be made as soft as possible. A hard suspension will have less travel and thus need a higher acceleration level. This is felt as a harder ride by the user. [34]
The optimal spring constant can thus be expressed using the following equation. Optimal f_n, natural frequency for passenger cars where comfort is a priority should be in the ballpark of 0.5 - 1.5 Hz. [35]

$$k_{eq} = 4\pi^2 * f_n^2 * m_{Front-1/8th} * MotionRatio^2 \qquad \text{Equation 6}$$

In this mathematical model m is defined as the weight acting on all wheels. To simply the equation is altered to account for spring constant in only one wheel. This is often referred to as an eighth car model. It can be found by solving the following equation, assuming a total of 4 wheels. The $SpringRatio_n^2$ accounts for the difference in displacement at the wheel and at the spring.

$$m_{Front-1/8th} = \frac{TotalSprungMass}{4} - WheelMass \qquad \text{Equation 7}$$

Calculations show that the optimal spring constant more than double when the car is fully loaded. It is worth noting that the spring ratios will be affected by the spring and damper motion ratio as discussed in *4.4.1 Spring Rates* and depend on the suspension layout. [32] These results are confirmed in Spring & Dampers, Part One by OptimumG. (Figure 17) [35]

	Sprung Mass per corner							
	100	300	500	700	900	1100	lbs.	Motion Ratio:
Ride Frequency (Hz)	45	136	227	318	409	500	kg	1
1.0	10.3	30.8	51.4	72.0	92.5	113.1	lb/in	Spring Rates
	1.8	5.4	9.0	12.6	16.2	19.7	N/mm	
1.5	23.1	69.4	115.7	161.9	208.2	254.5	lb/in	
	4.0	12.1	20.2	28.3	36.3	44.4	N/mm	
2.0	41.1	123.4	205.6	287.9	370.1	452.4	lb/in	
	7.2	21.5	35.9	50.2	64.6	79.0	N/mm	
2.5	64.3	192.8	321.3	449.8	578.3	706.8	lb/in	
	11.2	33.6	56.1	78.5	100.9	123.4	N/mm	
3.0	92.5	277.6	462.6	647.7	832.7	1017.8	lb/in	
	16.2	48.5	80.8	113.1	145.4	177.7	N/mm	
3.5	125.9	377.8	629.7	881.6	1133.5	1385.3	lb/in	
	22.0	65.9	109.9	153.9	197.8	241.8	N/mm	
4.0	164.5	493.5	822.5	1151.5	1480.4	1809.4	lb/in	
	28.7	86.1	143.6	201.0	258.4	315.8	N/mm	
4.5	208.2	624.6	1040.9	1457.3	1873.7	2290.1	lb/in	
	36.3	109.0	181.7	254.4	327.0	399.7	N/mm	
5.0	257.0	771.1	1285.1	1799.1	2313.2	2827.2	lb/in	
	44.9	134.6	224.3	314.0	403.8	493.5	N/mm	

Figure 17. Optimal spring rates as a result of sprung mass and ride frequency from [35]

Optimizing for max load will lead to a car with very stiff suspension when driven with no load. Optimizing for no load will likely lead to a car that is too soft and will require very long suspension travel to absorb the extra weight, this extra travel may also upset the suspension geometry if not accounted for. The analysis shows that matching a progressive spring to the change in optimal spring constant may allow for optimal ride comfort at any given load. This is done for the final suspension setup.

4.5 Dampers

Modern automotive suspension uses dampers to limit the oscillations in the suspension system. This is intended to return the suspension to its resting state as quickly as possible after excitation. While a spring exerts force when it is displaced, a modern damper exerts force as a result of velocity. The critical damping coefficient can be found using the following formula.

$$C_{Cr} = 2\sqrt{k_s * MotionRatio^2 * m_{sprung}}$$ Equation 8

Here k_s is the spring rate and m is the systems sprung mass. It is important to note that in this case the system is for one wheel, spring, tire and a quarter of the cars mass. It is also worth mentioning that this is a one degree of freedom calculation that does not take time into account. After finding the critical damping coefficient the damping ratio can be found. [36]

$$\xi = \frac{C}{C_{cr}}$$ Equation 9

Essentially the ratio explains how well the system is damped. Here C is the damping coefficient of the system.

$$\xi < 1 \ Underdamped$$
$$\xi < 1 \ Critically\ damped$$
$$\xi > 1 \ Overdamped$$

Passenger cars usually have a damping ratio around $\xi = 0.2$, this ratio is used in further calculations. [36]

4.6 Static Forces

Static forces describe the forces acting on each wheel when the vehicle is at rest as shown in Figure 18. This is often described in terms of weight distribution. Weight distribution is normally presented as a percentage of weight taken up by the front and rear wheels. Weight distribution in a utility vehicle is subject to large changes as the payload changes significantly. Paxster, in a hardtop configuration, has an empty weight without a driver of roughly 335kg but can add 200 kg in payload. A driver weight of 102kg was utilized, this is the maximum weight of a 95th percentile man according to the Formula SAE rules. [37] Weight distribution is important both for the driving dynamics themselves and in selection of springs. This report assumes lateral CoG symmetry.

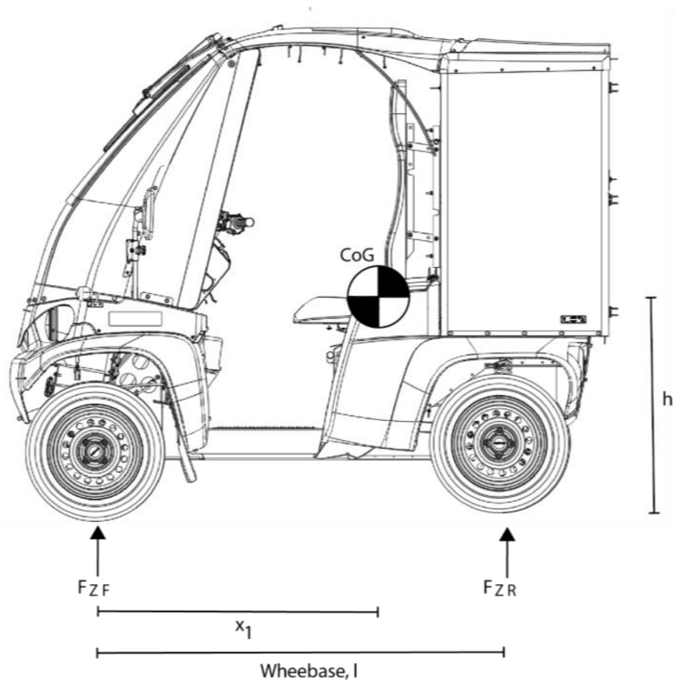

Figure 18. Displays static center of gravity (illustration) in relation to the weight carried by the front and rear tires as well as the distance between them. Only for x-direction.

The center of gravity location was found using the provided CAD model in Autodesk Inventor. This ensures accurate values despite not being able to physically weigh the car. (Table 7)

Table 7 Empty Vehicle Static Input Values

Parameter	Value
Wheelbase l	1700mm
Mass	335kg
CoG Height	653.703 mm
CoG X1	1008 mm

Assuming Fzf and Fzr as the normal reaction forces to the weight of the vehicle at the tires, acting in negative z direction. Using equilibrium equations, the forces acting on each pair of tires as a result of the center of gravity can be found.

$$\sum M_F = 0$$ *Equation 10*

$$G = m * g$$ *Equation 11*

$$F_{ZR} = \frac{m * g * x_1}{l}$$ *Equation 16*

$$\sum Fz = 0$$ *Equation 10*

$$F_{ZF} = m * g - \frac{m * g * x_1}{l}$$ *Equation 15*

This in turn implies that the front/rear weight distribution can be found by the following formulas. Results are shown in Table 8.

$$FrontWD = \frac{F_{ZF}}{m * g} * 100$$ Equation 12

$$RearWD = 100 - Front\ Weight\ Distribution$$

Table 8 Static Forces Results, Empty Car

Parameter	Value
F_{ZF}	$1337.7N$
F_{ZR}	$1948.6N$
$FrontWD$	40.7%

These results are for the unladen vehicle. Due to the placement of the additional cargo, the CoG will move backwards. Modelling and properly representing packages and letters in CAD is extremely difficult and time consuming, therefore it is assumed that the center of gravity remains the same. This will lead to a slightly higher front load than reality, making the results conservative. (Table 9)

Table 9 Static Forces Results, Fully Laden Car (535kg)

Parameter	Value
F_{ZF}	$2543.7N$
F_{ZR}	$3705.3N$
$FrontWD$	40.7%

4.7 Dynamic Forces

This chapter will discuss the forces acting on the vehicle during movement. As the extremes of these dynamic forces will only appear for small amounts of time, like when hitting a bump a common solution is to assume the vehicle experiences the forces in a steady state, essentially pretending it can maintain the forces forever. [38]

4.7.1 Shock Factor

The forces calculated so far in this chapter have been static. In reality this is highly unlikely, and the loads may act quickly. In order to approximate the dynamic forces a shock factor is often used to inflate the static forces. One method is using a shock factor based on the situation at hand, this factor is multiplied by the static load. The different shock factors are presented below in Table 10.

Table 10 Overview of shock factor for various load cases. [38]

Load Case	Load Factor		
	Longitudinal	Transverse	Vertical
Pothole Bump	3g at affected wheel	0	4g at affected wheel, 1g others.
Bump During Cornering	0	0	3.5g at affected wheel, 1g others.
Lateral Curb Strike	0	4g on front and rear wheels on side affected	1g on all wheels
Panic Braking	2g front wheels, 0.4g rear wheels	0	2g front wheels, 0.8g rear wheels

The maximal force experienced by the components due to shock loading can be expressed as.

$$F_{Max,Shock} = ShockFactor * F_{Max,Static}$$ *Equation 13*

4.7.2 Forces Summarized

This section summarizes the force acting on the suspension. The steering load scenario assumes the right front wheel to be the outside wheel. The forces with shock calculate the forces for any wheel experiencing load case, like hitting a pothole, even though only one wheel is likely to hit a pothole at a time. $F_{ZF,Per\ Wheel} = 1271.9N$ is used for the calculations, the results are presented in Table 11.

Table 11 Front Wheels Dynamic Loads, approx. [38]

Load Case Front	Load Factor		
	Longitudinal	**Transverse**	**Vertical**
Pothole Bump	$3815.7N$	$-$	$5087.6N\ Affected$ $1271.9\ Others$
Bump During Cornering	$-$	$-$	$4451.7N\ Affected$ $1271.9\ Others$
Lateral Curb Strike	$-$	$5087.6N$ $Affected\ side$	$1271.9N$
Panic Braking	$2543.6N\ Front\ Wheels$	$-$	$2543.6N\ Front\ Wheels$

5. Specifications for Proposed Suspension Setup

5.1 Weighted Product Specifications

The most vital attributes for the suspension setup are listed and given a weight according to their importance based on discussions with Paxster. The weight ranges from 1 to 5, 1 representing least important and 5 representing most important. (Table 12)

Table 12 Weighting factors for selection matrix.

Attribute	Description	Weighting
Available Space	Allowing more lateral space in the front of the car may allow for extra storage. This would achieve better weight distribution and a larger payload capacity.	4
Cost/Complexity	In order to reduce total cost both the component cost and assembly complexity must be minimized.	5
Driving Characteristics	The Paxster EDV is not a high-end luxury car, the driving characteristics will thus take a backseat to the more practical attributes.	3

Driving characteristics are ranked the least important. Due to low speed nature of the utility vehicle, there is no need for outstanding comfort or handling, it must simply be safe.
Cost is important in order to increase profit margin, although this will likely not make a huge impact, every little bit helps.

5.2 Size limitations

The suspension setup has a few size limitations, defined by the chassis and bodywork. Mostly these are used to limit the amount of redesign needed to adapt the setups to the vehicle. The chassis and bodywork make a design envelope, defining the available area.

5.3 Driving Characteristics Goals

In setting up analysis and comparing different suspension types some goals must be set when defining the suspension types. These are factors that directly affect the driving characteristics of the car and were chosen together with Paxster. (Table 13)

Table 13 Suspension Setup Goals.

Parameter	Goal	Min	Max
Static Camber	0 deg	-0.25 deg	0.25 deg
Bump steer	0 deg	-0.25 deg	0.25 deg
Camber–Max Bump	-1.25 deg	0 deg	-2 deg
Spring/Damper Rate	1.5	1	2
Static Caster	5	6	4
Toe in - Static	0 deg	-0.25 deg	0.25 deg
Kingpin Angle	10 deg	8 deg	14 deg

The suspension setups will aim to achieve the goal set for each parameter but will be accepted if they are within the maximum and minimum values.

A static camber of 0 degrees is preferred as it reduces the wear on the tire during normal, straight forward operations. Bump steer is as mentioned the toe in or toe out of the front tries when the suspension compresses or decompresses. This can lead to a car that is hard to control and suddenly moves in various directions as it travels over bumps. 0-degree bump steer is preferred but due to packaging some bump steer will be accepted.

5.4 Analysis Scenarios

In order to test the proposed suspension setups in a variety of situations a few different situations will be analyzed. This is done in order to verify that the setup achieves the goal parameters both for static and a variety dynamic situations. An example is to check that the toe angles remain within the acceptable range during bumps and turning.

5.4.1 Static Analysis

With the vehicle at rest the static suspension parameters are checked.

5.4.2 Maximum bump and droop

With zero steering angle the tires are moved through their entire vertical range of motion, this is done in order to check the effect on camber, toe angle, motion ratio, caster and kingpin inclination.

5.4.3 Maximum steering angle and bump

This check is done in order to quantify the bump steer of the vehicle when hitting a bump during a turn. In order to check this the, toe angles are compared, due to the steering angle the toe angle will never be zero, bump steer in this situation is the change of toe angle during bump. This needs to be done for both sides of the car as the value will not be the same.

In order to find the maximum steering input, the CAD assembly was used. The model was highly simplified and assembled using joints in Autodesk Fusion 360. Maximum steering input at the steering rack was found to be 39 degrees using the components shown in Figure 19.

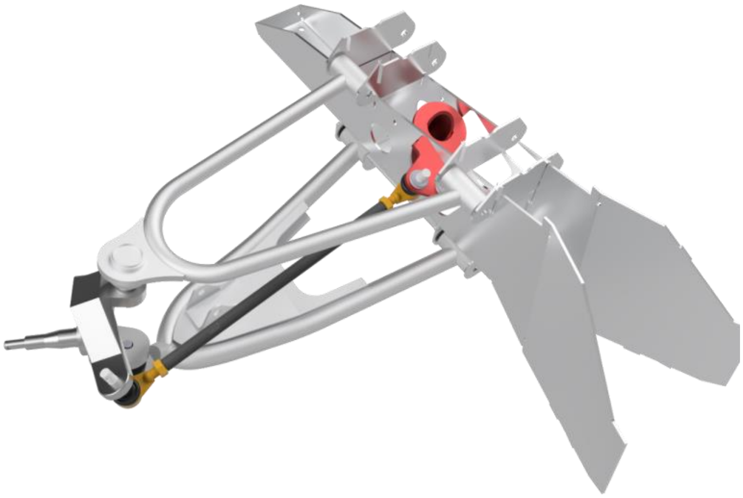

Figure 19. The steering plate, in red, has a notch that limits the maximum steering input to 39 degrees.

5.4.4 Vehicle Roll in Steady State Cornering

As a vehicle turns, the car will lean slightly towards the outside of the corner, this directly affects the vehicles suspension. Depending on which side of the vehicle the car will lose or gain camber as a result of roll, typically the outside wheel will gain negative camber and the inside wheel will gain positive camber. In order to maximize the grip, the tires must have a slight negative camber at the road. It is worth nothing that the camber on the outside wheel is more important than the camber on the inside wheel, as the outside wheel experiences added weight from the weight transfer and is thus able to maintain higher grip.
Lotus Engineering Shark allows comparison of the roll angle and the camber angle.

6. Analysis of Relevant Suspension Concepts

This chapter is dedicated to analyzing the various suspension setups, performed in Lotus Engineering Shark. The baseline is used to compare the suggested suspension setups with the existing car.

For the baseline suspension analysis to be useful beyond data collection a few other suspension types will be analyzed and compared. This will not only put the current suspension in perspective but will also help guide further development of the car into the next generation. The chosen suspension types are double wishbone SLA and MacPherson. There are other options, like hyperstrut or multilink suspensions, however these are more complex, advanced and solve problems beyond that of a lightweight delivery vehicle.

In order to gain a clear overview of the advantages of the different chosen suspension layout types, the typical advantages are laid out Table 14.

Table 14 Summary of advantages and disadvantages of the chosen suspension types. [39]

Suspension Type	Advantages	Disadvantages
Double Wishbone SLA	• Driving characteristics • Motion Ratio control • Vertical Space	• Cost • Complexity • Lateral Space
MacPherson	• Cost • Complexity • Lateral Space	• Vertical Space • Driving Characteristics

Double wishbones seem to generally be considered a better solution for high performance and control, however as mentioned driving characteristics take a back seat to cost and space considerations in this case.

6.1 Baseline Analysis Double Wishbone SLA

Based on CAD files obtained from Paxster AS the vital points where listed. These are known as hardpoints in Lotus Engineering Shark. These define components, for example 3 hardpoints could be used to define the three attachment points of a wishbone. Shark includes several pre-built and configurable suspension types, making the process of modelling the suspension setup as simple as selecting the right type and modifying the relative positions of the hardpoints. This process is repeated for each suspension setup.

6.1.1 Baseline Analysis Setup

The files supplied by Paxster AS were imported into Autodesk Inventor Professional 2018 where the hardpoints were identified. To ease this process the base model used contained only the chassis, front suspension setup and steering box. Utilizing a 3D sketch and projecting in the required geometry as well as finding various midpoints in tandem with Autodesk Inventors own measure tool the relative coordinates to the origin were found.

These points represent one half of the front suspension due to utilizing the symmetric suspension option and are summarized together with all other settings in *Attachment 2 Baseline Suspension Analysis Results.*

Hardpoints number 123-125 shown in Figure 20 and are specific for the steering case chosen to represent the system utilized in the car. As standard Lotus Shark assumes a steering rack, however the car uses a more rudimentary but functional method.
This system has the steering column connected to a hub, this hub is free to rotate around the same axis as the steering column, a small distance outwards the inner track rod ball joint is attached, this is essentially a lever system. The baseline front suspension setup is shown below in Figure 20.

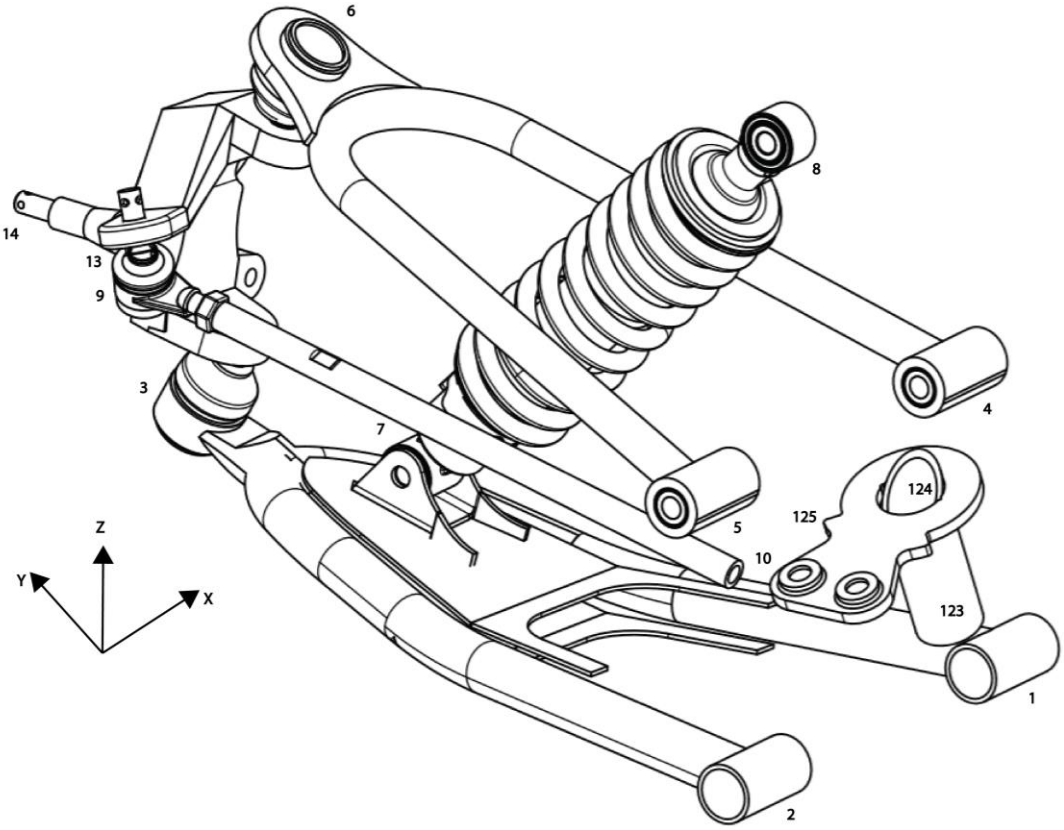

Figure 20. Hardpoint locations and numbers for the double wishbone setups.

The model was generated using the templates in Lotus Engineering Shark: Front Suspension type 1: Double Wishbone (Damper to lower wishbone corner) and steering box (typ2). Further the spring and damper components where merged to a single unit.

The current Kaifa coilovers provide 55mm of travel, from the analysis the mounting of the current suspension, the spring to wheel travel ratio is 1.65. The following calculations determine the overall wheel travel available with the current coilovers.

$$WheelTravel = SpringRatio * SpringTravel$$
$$WheelTravel = 1.65 * 55mm = 90.8mm$$

Utilizing a the 1/3 to 2/3 split rule of thumb as described by Paxster the available vertical travel from ride height is as follows. Note that due to the SAE axis system as defined in *4.1 Coordinate System* wheel travel in the negative Z direction corresponds to bump travel.

$$WheelTravel_{-Z} = 60mm$$
$$WheelTravel_{Z} = 30mm$$

These values are further utilized to define the limits of travel for the suspension analysis. Lotus Engineering Shark supplies easily configurable motion templates both in 2 and 3 dimensions. In analysis of the suspension 3D Bump, 3D Roll and 3D Steer was applied, this outputs data relevant to the situation and provides illustrative animations. The baseline setup in Lotus Engineering Shark is shown in Figure 21, Figure 22 and Figure 23.

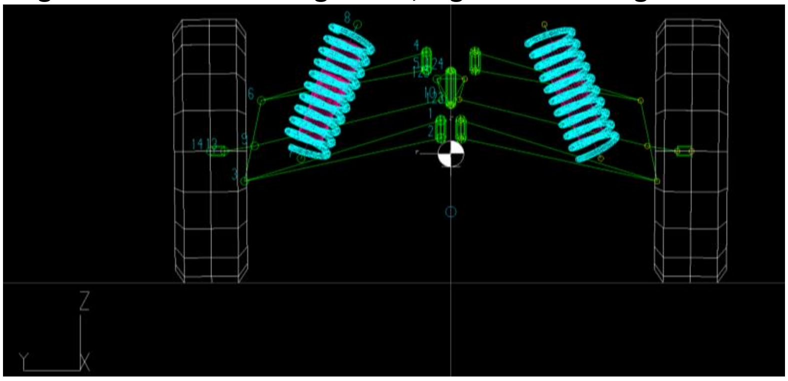

Figure 21. The completed suspension setup in Lotus Engineering Shark as seen from the front.

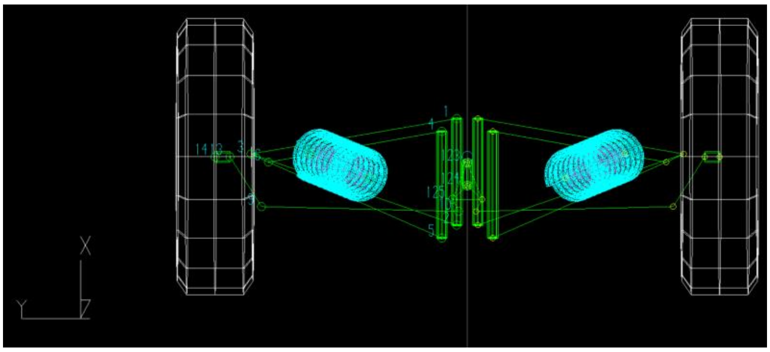

Figure 22. The completed suspension setup in Lotus Engineering Shark as seen from the top.

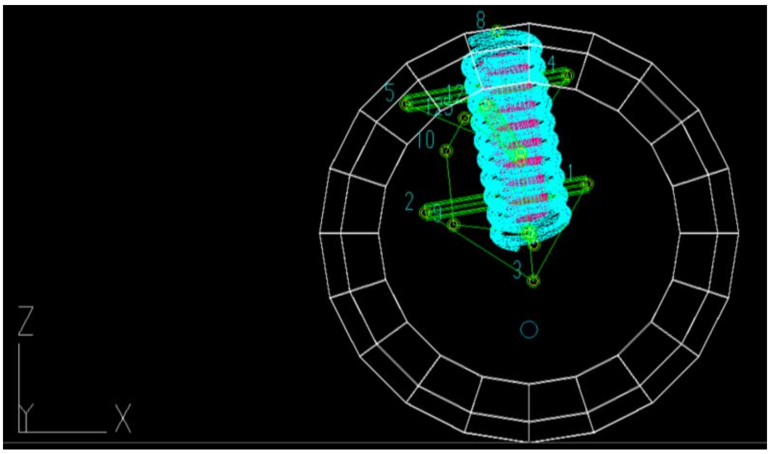

Figure 23. The completed suspension setup in Lotus Engineering Shark as seen from the side.

In order to achieve a static steering output for the cornering situation the 3D combined motion module in Lotus Engineering Shark must be utilized, with some alterations. The combine motion is based on a table of values the wheel will go through, for example at 10mm bump, a set steering travel is needed in this situation. The simulation is set to move between -30 to

60mm wheel travel, at a set 39 degrees of steering travel. These 39 degrees are at the typ2 steering box' axis of rotation.

6.1.2 Baseline Analysis Results

The results from the baseline analysis are displayed in *Attachment 2 Baseline Suspension Analysis Results.* A selection of graphs are shown for the 3 scenarios discussed in *5.4 Analysis*

Baseline Analysis - Static

The suspension values, statically at ride height is summarized in Table 15.

Table 15. Static suspension values baseline analysis.

Parameter	Value
Camber Angle (deg)	0
Toe Angle [Plane] (deg)	0
Toe Angle [SAE] (deg)	0
Caster Angle (deg)	5.52
Caster Trail (hub) (mm)	-0.480
Caster Offset (grnd) (mm)	-24.143
Kingpin Angle (deg)	11.68
Kingpin Offset (w/c) (mm)	78.439
Kingpin Offset (grnd) (mm)	25.708
Mechanical Trail (grnd) (mm)	-24.031
Roll Center Height (mm)	138.438

Baseline Analysis – Maximum Bump and Droop

The results for the baseline analysis in the maximum bump and droop scenario is shown below in Table 16, Figure 24 and Figure 25 below.

Table 16 Baseline Analysis Results, Maximum Bump and Droop.

Bump Travel(mm)	Camber Angle (deg)	Toe Angle (SAE)(deg)	Caster Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-) & Spring1 Ratio (-)	Half Track Change(mm)
60	-0.6654	0.6458	-5.5034	12.4112	1.662	13.9
50	-0.5138	0.5587	-5.5061	12.2512	1.664	12.1
40	-0.3777	0.4641	-5.5085	12.1059	1.6666	10.1
30	-0.2576	0.3651	-5.107	11.9759	1.666	7.9
20	-0.1541	0.2504	-5.5126	11.8617	1.666	5.5
10	-0.0679	0.1302	-5.5142	11.7639	1.666	2.9
0	0	0	-5.5155	11.6835	1.664	0
-10	0.0485	-0.1412	-5.5165	11.6214	1.661	-3.1
-20	0.0761	-0.2944	-5.5172	11.5792	1.657	-6.4
-30	0.0811	-0.4612	-5.5175	11.5583	1.652	9.9

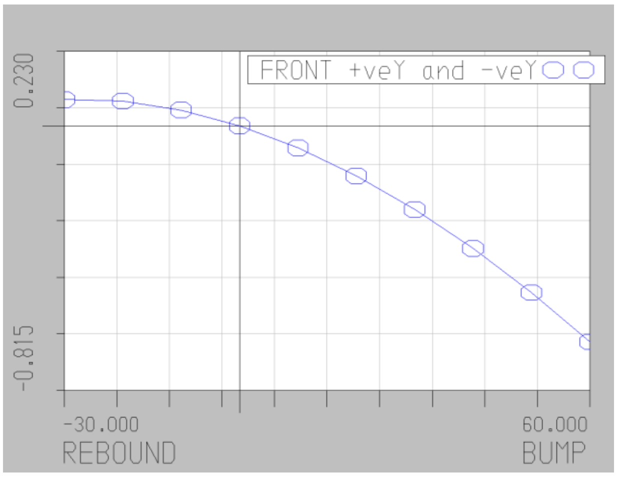

Figure 24. Wheel camber for the full range of vertical suspension movement. Camber (Y) vs Wheel Travel (X).

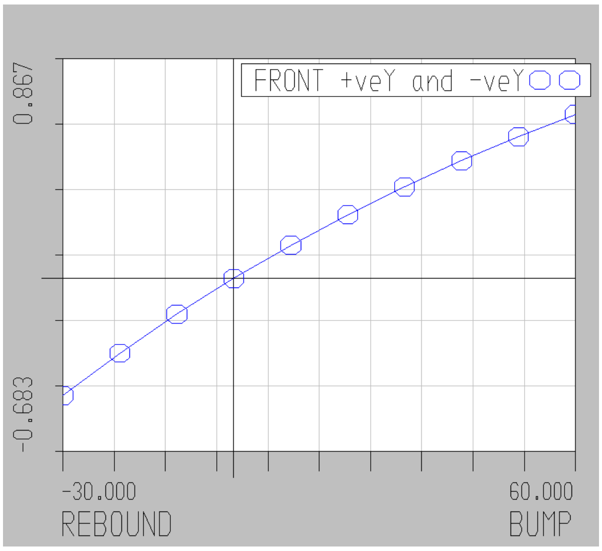

Figure 25. Toe Angle (PLANE) plotted for full bump/droop range of motion. Toe Angle (Y) vs Wheel Travel (X)

The full results can be found in *Attachment 2 Baseline Suspension Analysis Results*

Baseline Analysis – Maximum Steering Angle and Bump

In order to analyze the toe in and toe out during bump motion in a corner, the 3D combined motion module was run, at 39 degrees steering travel the result are shown in Figure 26 and Figure 27. The full results can be found in *Attachment 3 Baseline Suspension Analysis Results 39 degrees of* Steering Travel*.*

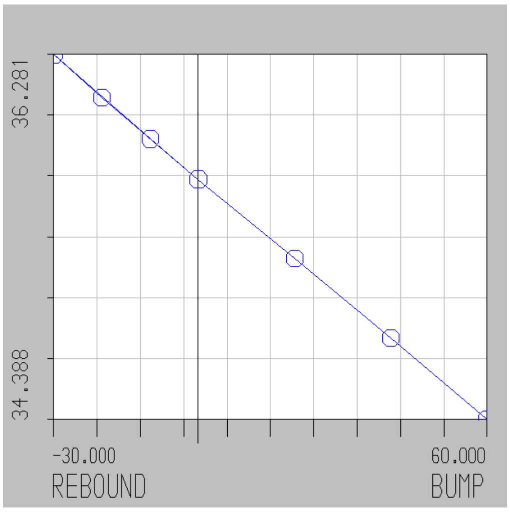

Figure 26. Toe angle for bump travel (-30mm to 60mm) at a static 42 degrees of steering travel. Outside wheel. Toe Angle (Y) vs Bump Travel (X).

Due to the placement of the tie rod and the steering box, the change in toe angle for each wheel will not be equal. Bump steer is essentially the result of a tie rod that does not rotate around the same center and with the same radius as the wishbones, thus pushing or pulling the wheels during bump movements.

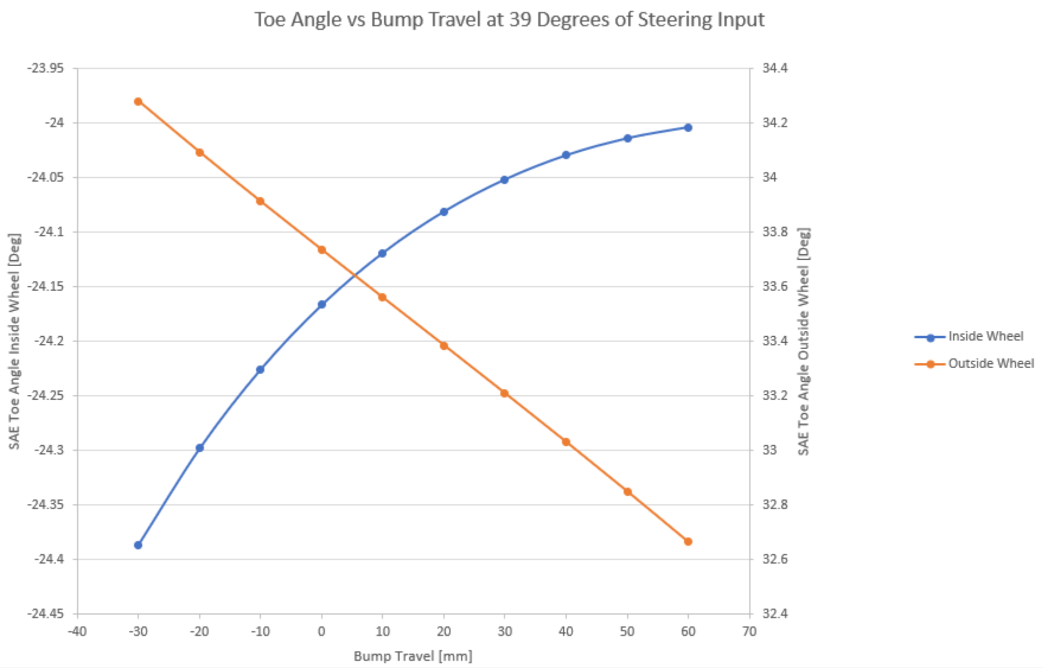

Figure 27. SAE Toe angle for bump travel (-30 to 60mm) at a static 39 degrees of steering input. Inside and outside wheel.

It is worthwhile noting that the toe angle will never be zero due to the static steering travel, however, ideally there would be no change in toe angle. The angle will also never be the same on both sides of the car due to Ackerman steering. The change as shown here implies that hitting bumps in a corner will alter the steering angle of the car, potentially leading to an unstable ride.

Baseline Vehicle Roll in Steady State Cornering

The result for the baseline analysis with the vehicle roll in steady state cornering is shown below in Figure 28. The full results can be viewed in *Attachment 4 Baseline Suspension Analysis Result Vehicle Roll in Steady State Cornering.*

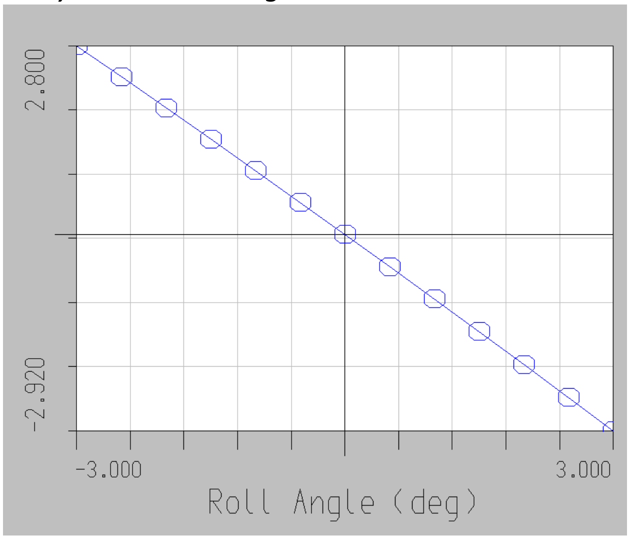

Figure 28. Roll vs Camber Angle. Minimum camber: 2.9 deg. Maximum camber: 2.8 deg. Camber Angle (Y) vs. Roll Angle (X)

6.1.3 Baseline Analysis Verification

In order to verify the accuracy of the input data and the setup itself the results need to be compared with the real car. In the same manner that displacement is often used to verify FEM results it is vital to verify the results from the analysis with easily measurable data from real life. In order to simplify this process, the chosen factors are ones that are easy to measure and regularly done during suspension setup.

This chapter is dedicated verifying both the CAD-model and the analysis setup. As the geometric data is taken from the manufacturer supplied CAD-model it is important to verify it with the real vehicle as there may be discrepancies. (Table 17)

Table 17 Analysis verification factors.

Factor	Shark – Baseline	Reality
Camber – Ride Height	0	0
Toe Angle -Ride Height	0	0

6.2 Double Wishbone SLA Adjusted Track Rod Mounts

In order to improve the current suspension without necessitating large chassis changes only minor details are changed for this analysis, as the suspension pickup points are made up brackets welded to the chassis these can easily be fine-tuned. The steering plate is also easily altered but must be viewed in relation to the chassis due to limited space.

6.2.1 Double Wishbone SLA Adjusted Track Rod Mounts Setup

The initial baseline analysis revealed a somewhat large toe in /toe out during bump, a difference of roughly 1.2 degrees between the maximum and minimum wheel travel, this

analysis aims to reduce this effect by altering the track rods mounting points while maintaining all other geometry the same as in 6. Analysis of Relevant Suspension Concepts.
The hardpoint coordinates can be found in *Attachment 5 Double Wishbone SLA Adjusted Track Rod Mounts Maximum Bump & Droop.* The Inner Track Rod Ball Joint was the only hardpoint altered, the following table compares the new coordinates to the current. Figure 29 shows the adjustments made. (Table 18)

Table 18. Comparing coordinates for hardpoint 10.

Hardpoint Label	X(mm)	Y(mm)	Z(mm)
Inner Track Rod Ball Joint Old	562.922	16	130.626
Inner Track Rod Ball Joint New	562.922	26	135.626

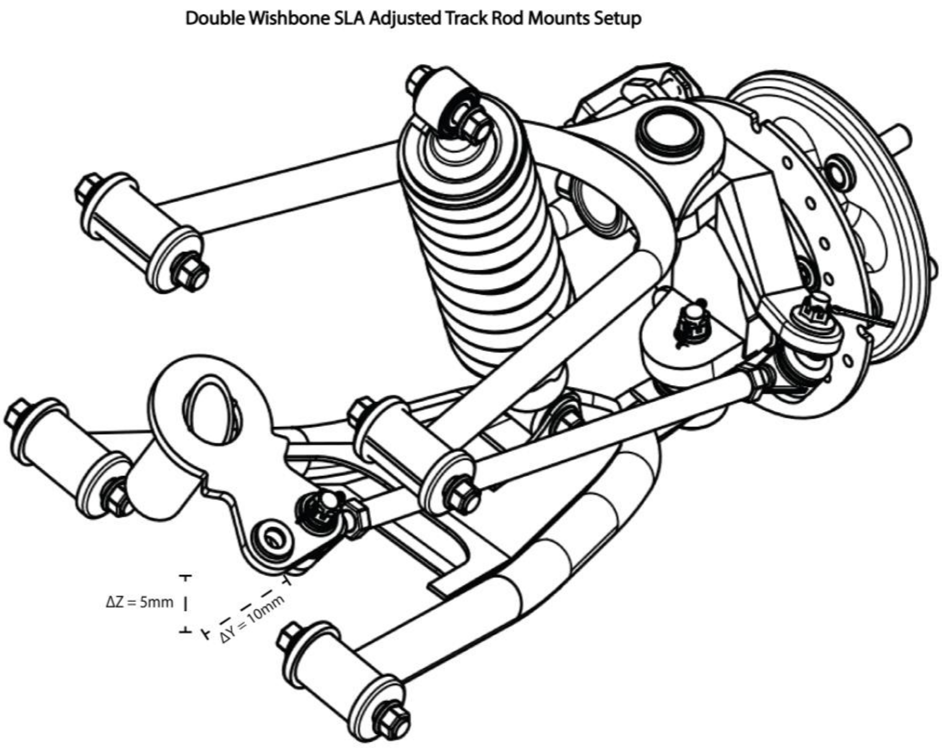

Figure 29. Difference in mounting between the baseline and the Double Wishbone SLA Adjusted Track Rod Mounts Setup, both track rod mounts are changed equally.

6.2.2 Double Wishbone SLA Adjusted Track Rod Mounts Results

The results presented in Figure 30, Figure 31 and Figure 32 are found during the maximum bump and droop scenario described in *5.4.2 Maximum bump and droop.* Testing the setup using the maximum steering angle scenario described in *5.4.3 Maximum steering angle and bump* provides the results shown in Figure 32.

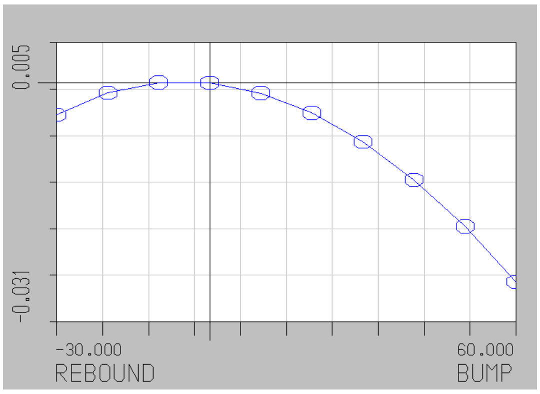

Figure 30. Bump steer graph for the new Track Rod Ball Joint mounting position. Toe Angle (Y) vs Wheel Travel (X).

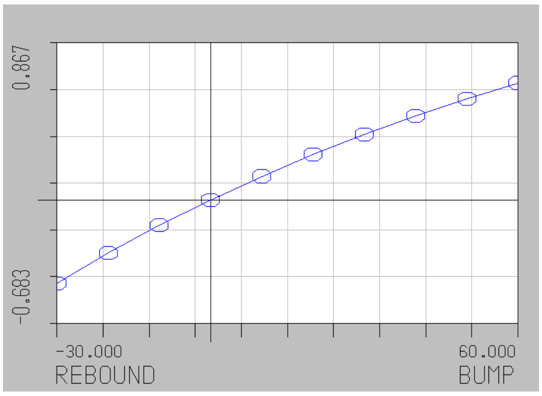

Figure 31. Bump steer graph for the old Track Rod Ball Joint mounting position. Toe Angle (Y) vs Wheel Travel (X).

Double Wishbone SLA Adjusted Track Rod Mounts Maximum Steering Angle and Bump

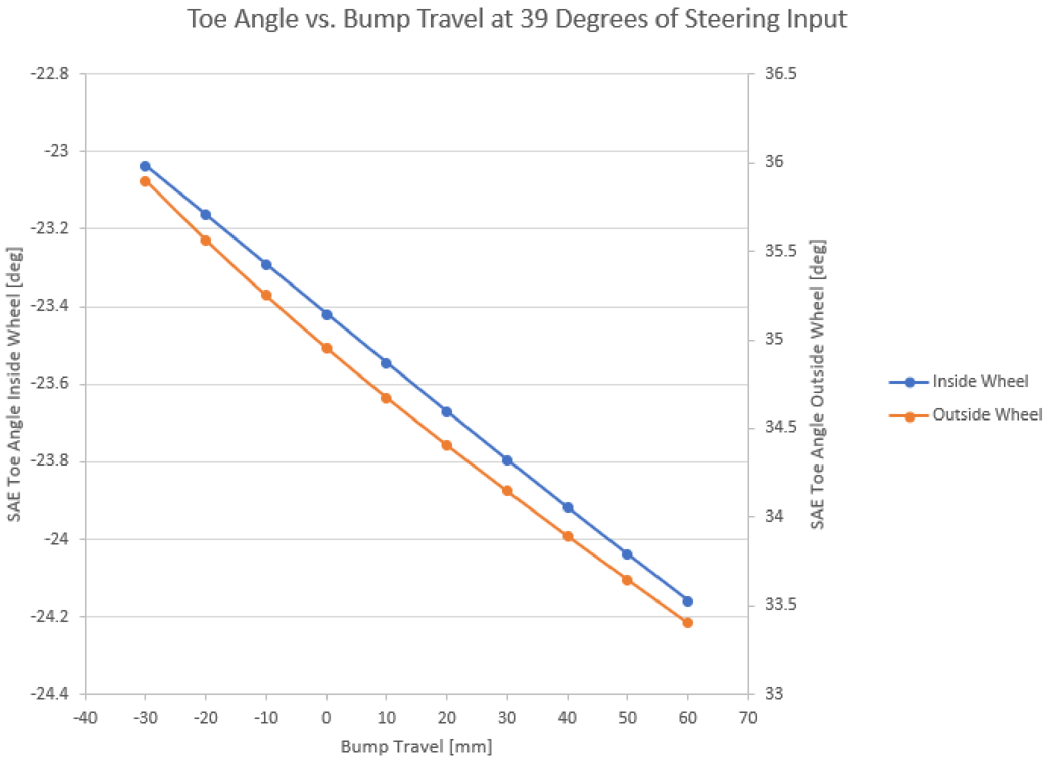

Figure 32. Toe Angle for maximum bump and steering angle for the Double Wishbone SLA Adjusted Track Rod Mounts setup.

These results show that slightly altering the mounting position of the track rod ball joints can greatly improve the bump steer with minimal effort. The full results can be view in *Attachment 6 Double Wishbone SLA Adjusted Track Rod Mounts Maximum Steering Angle and Bump.*

Double Wishbone SLA Adjusted Track Rod Mounts Pickup Points Vehicle Roll in Steady State Cornering

Figure 33 below shows the result of the analysis. The full result can be viewed in *Attachment 7 Double Wishbone SLA Adjusted Track Rod Mounts Vehicle Roll In Steady State Cornering.*

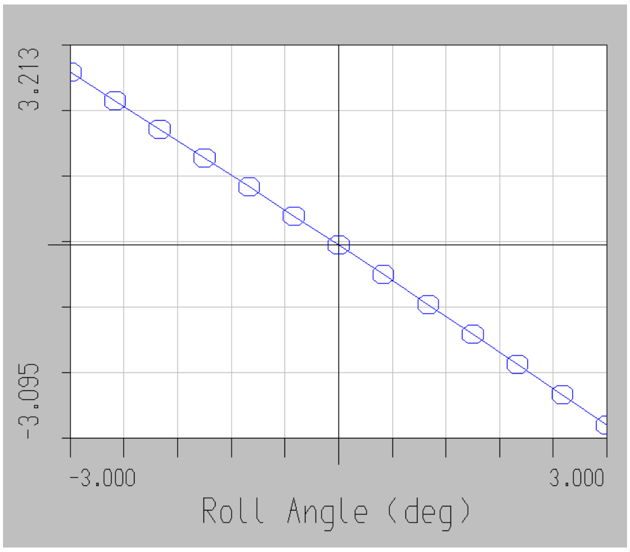

Figure 33. Camber Angle (Y) vs. Roll Angle(X). Minimum Camber: -2.88 deg. Maximum Camber: 2.77 deg.

6.3 Double Wishbone SLA Adjusted Pickup Points

Intended as an improvement in between the second and third generation Paxster EDV the intent is to keep the setup similar to the current, this is to ease the transition. These simulations will also alter the steering geometry in order to minimize bump steer.

6.3.1 Double Wishbone SLA Adjusted Pickup Points Setup

As mentioned, changes can easily be made to the suspension pickup points and the track rod position. Figure 34 below shows the placement of the relevant hardpoints and Table 19 list the difference between the adjusted pickups and the baseline.

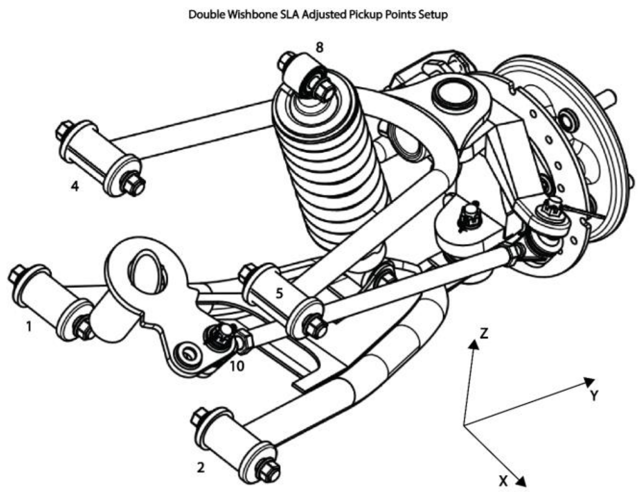

Figure 34. Double Wishbone SLA Adjusted Pickup Points and the changed hardpoints. Values in the table below.

Table 19. Hardpoint coordinate changes seen in relation to the baseline.

Hardpoint	ΔX	ΔY	ΔZ	Long Label
	(mm)	(mm)	(mm)	
1	0	19	-53	Lower Wishbone Front Pivot
2	0	19	-19	Lower Wishbone Rear Pivot
4	0	58	-48	Upper Wishbone Front Pivot
5	0	58	-14	Upper Wishbone Rear Pivot
8	0	2	0	Damper Body End
10	0	55.01	-35.24	Inner Track Rod Ball Joint

6.3.2 Double Wishbone SLA Adjusted Pickup Points Results

Static Values

The static values for the suspension setup are summarized in Table 20.

Table 20. Static Values for Double Wishbone SLA Adjusted Pickup Points.

Parameter	Value
Camber Angle (deg)	0
Toe Angle [Plane] (deg)	0
Toe Angle [SAE] (deg)	0
Caster Angle (deg)	5.52
Caster Trail (hub) (mm)	-0.480
Caster Offset (grnd) (mm)	-25.302
Kingpin Angle (deg)	11.68
Kingpin Offset (w/c) (mm)	78.439
Kingpin Offset (grnd) (mm)	23.226
Mechanical Trail (grnd) (mm)	-25.184
Roll Center Height (mm)	87.068

Maximum Bump and Droop

Results for maximum bump and rebound are shown in Figure 35 and Figure 36. The full result can be viewed in *Attachment 8 Double Wishbone SLA Adjusted Pickup Points Maximum Bump & Droop.*

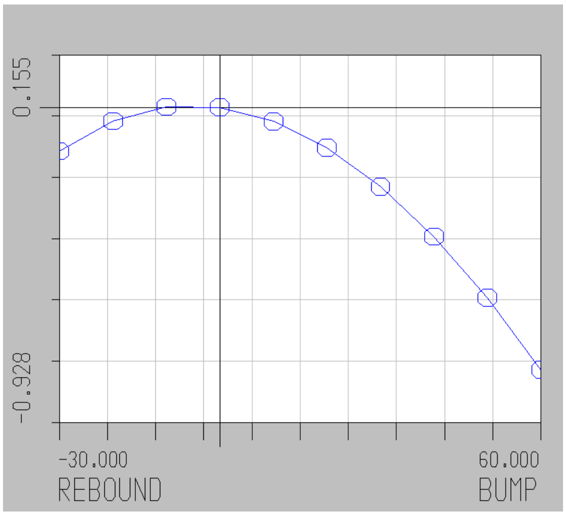

Figure 35. Double Wishbone SLA Adjusted Pickup Points. Camber Angle (Y) vs Wheel Travel (X).

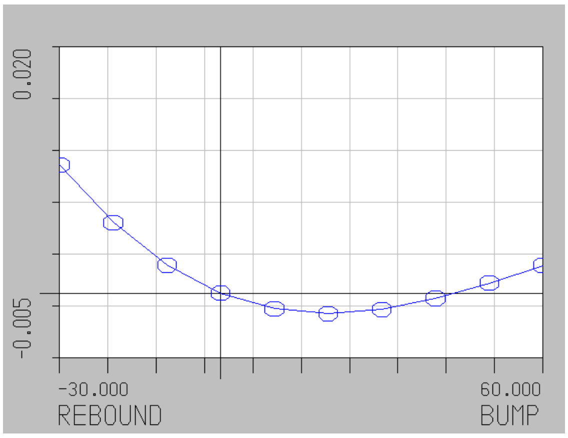

Figure 36. Toe Angle for Double Wishbone SLA Adjusted Pickup Points. Toe Angle (Y) vs Wheel Travel (X).

Maximum Steering Angle and Bump Travel
The result for the maximum steering angle and bump travel is shown below in Figure 37. The full result can be viewed in *Attachment 9 Double Wishbone SLA Adjusted Pickup Points Maximum Steering Angle and Bump.*

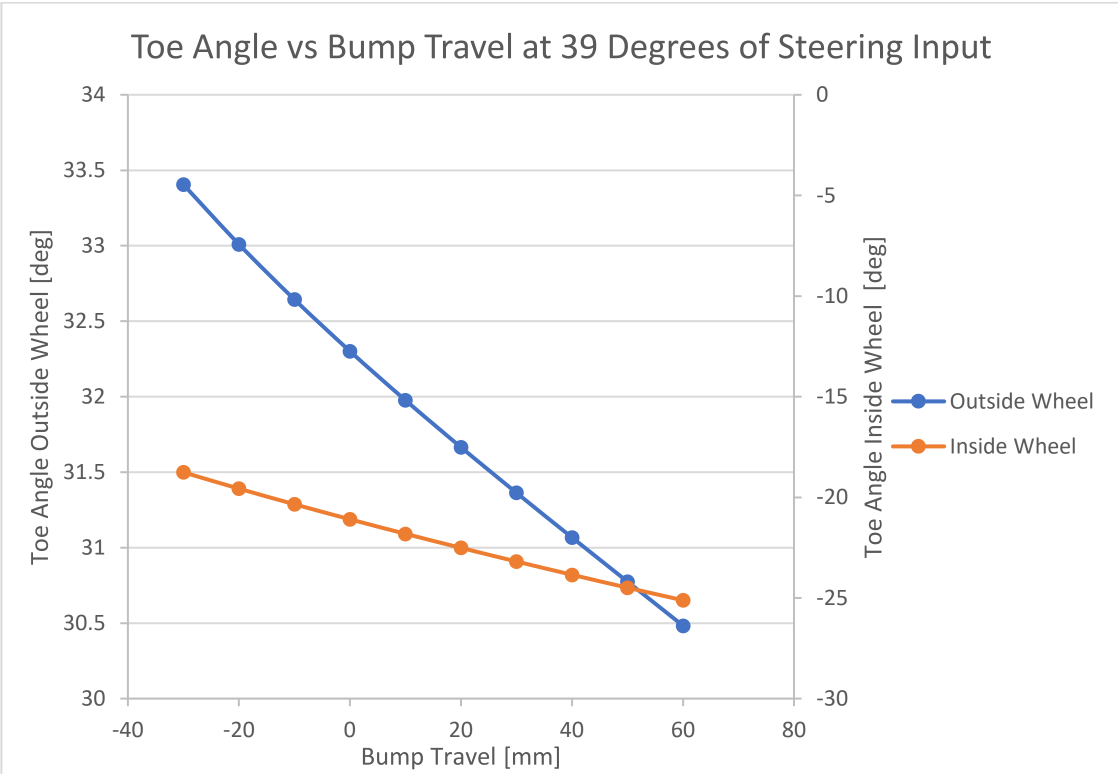

Figure 37. Toe Angle vs Bump Travel at 39 Degrees of Steering Input for Double Wishbone SLA Adjusted Pickup Points.

Double Wishbone SLA Adjusted Pickup Points Vehicle Roll in Steady State Cornering
The results for the vehicle roll in steady state cornering is shown in Figure 38. The full setup and results can be viewed in *Attachment 10 Double Wishbone SLA Adjusted Pickup Points Vehicle Roll In Steady State Cornering.*

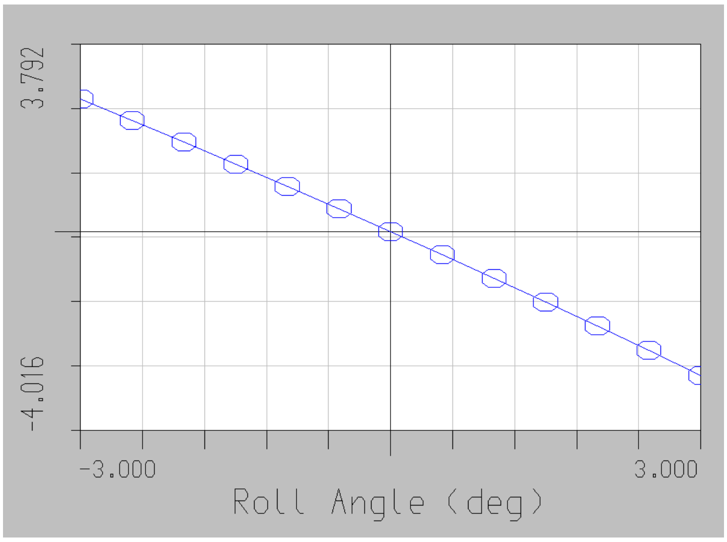

Figure 38. Camber Angle (Y) vs. Roll Angle (X). Minimum Camber: -2.9. Maximum Camber: 2.68 deg.

6.4 MacPherson Old Pickup Points

An extremely common suspension type for passenger cars, especially utilized in the front suspension. The main advantages are low cost and compact size. [40]
This version utilizes the existing suspension pickup points to minimize the changes needed for potential adoption. Some changes must be made to accommodate mounting of the strut tower.

6.4.1 MacPherson Old Pickup Points Setup

The setup was done using the old suspension pickup points, thus, the Lower wishbone pivots are identical to the baseline. The steering box typ2 definition was also copied. Paxster wishes to utilize a MacPherson upright from Comex and thus the suspension must be tailored to suit these mounting points. The standard components are shown in Figure 39.

Figure 39. Comex MacPherson upright, brake disc and wheel hub. Supplied by Paxster.

The hardpoint coordinates can be found in *Attachment 11 MacPherson Old Pickup Points Maximum Bump & Droop* and define a Lotus Engineering Shark model as shown in Figure 40 and Figure 41.

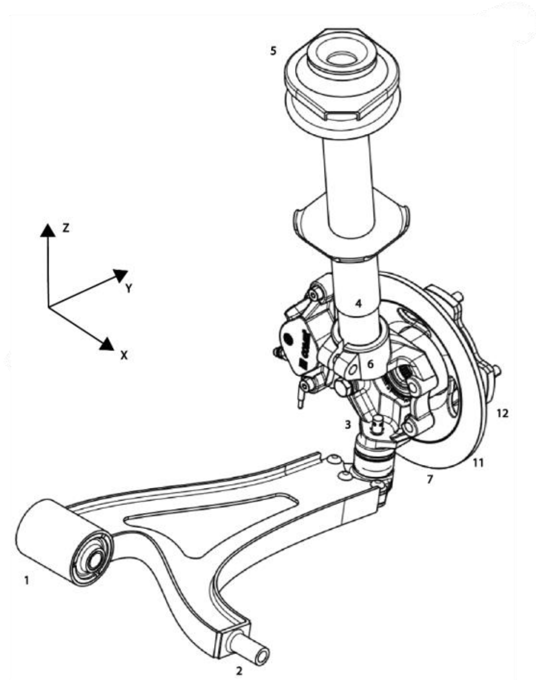

Figure 40. Illustration of a MacPherson setup and hardpoints.

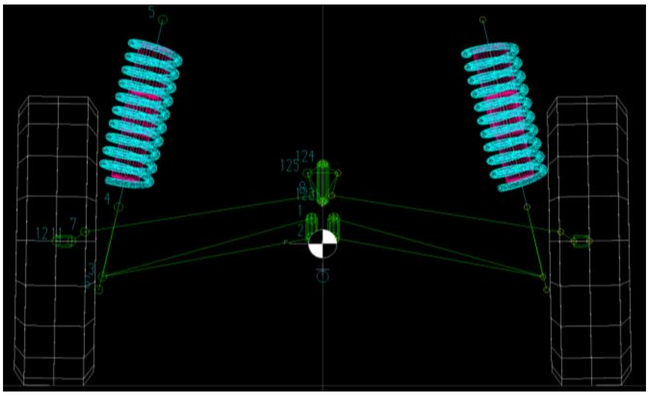

Figure 41. Front view of MacPherson Setup Old Pickup Points in Lotus Engineering.

6.4.2 Macpherson Old Pickup Points Results

Static Values

The static results are shown in Table 21.

Table 21 MacPherson Old Pickup Points Static Results

Parameter	Value
Camber Angle (deg)	0.00
Toe Angle [Plane] (deg)	-0.01
Toe Angle [SAE] (deg)	-0.01
Caster Angle (deg)	-7.02
Caster Trail (hub) (mm)	-3.014
Caster offset (grnd) (mm)	-28.392
Kingpin Angle (deg)	10.02
Kingpin Offset (w/c) (mm)	92.870
Kingpin Offset (grnd) (mm)	47.813
Mechanical Trail (grnd) (mm)	-28.179
Roll Center Height (mm)	174.043

Maximum bump and droop

The results for camber and toe as functions of bump travel are shown in Figure 42 and Figure 43. The full results can be viewed in *Attachment 11 MacPherson Old Pickup Points Maximum Bump & Droop.*

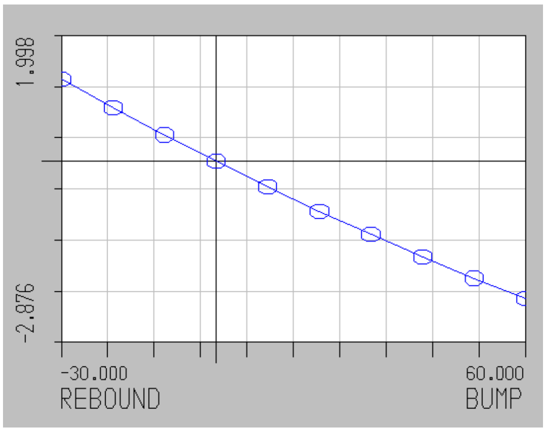

Figure 42. Camber Angle (Y) vs Bump Travel (X). Minimum Camber: -2.18deg. Maximum Camber: 1.3 deg.

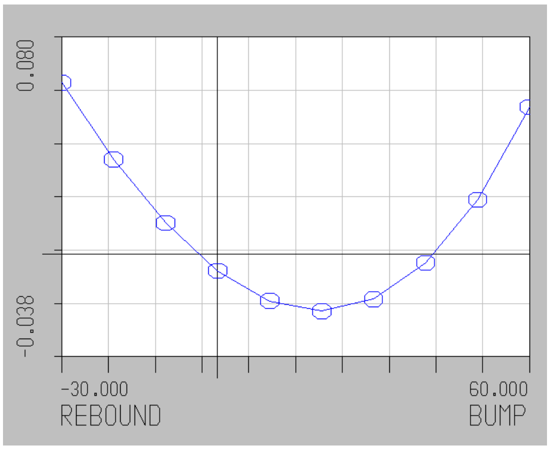

Figure 43. Toe Angle (Y) vs. Bump Travel (X). Minimum Toe Angle: -0.02deg. Maximum Toe Angle: 0.06deg.

Maximum steering angle and bump

Figure 44 below compares the toe angle of the outside and inside wheel at a static 39 degrees of steering input while traveling through the entire vertical range of motion. The full result can be viewed in *Attachment 12 MacPherson Old Pickup Points Maximum Steering Angle and Bump.*

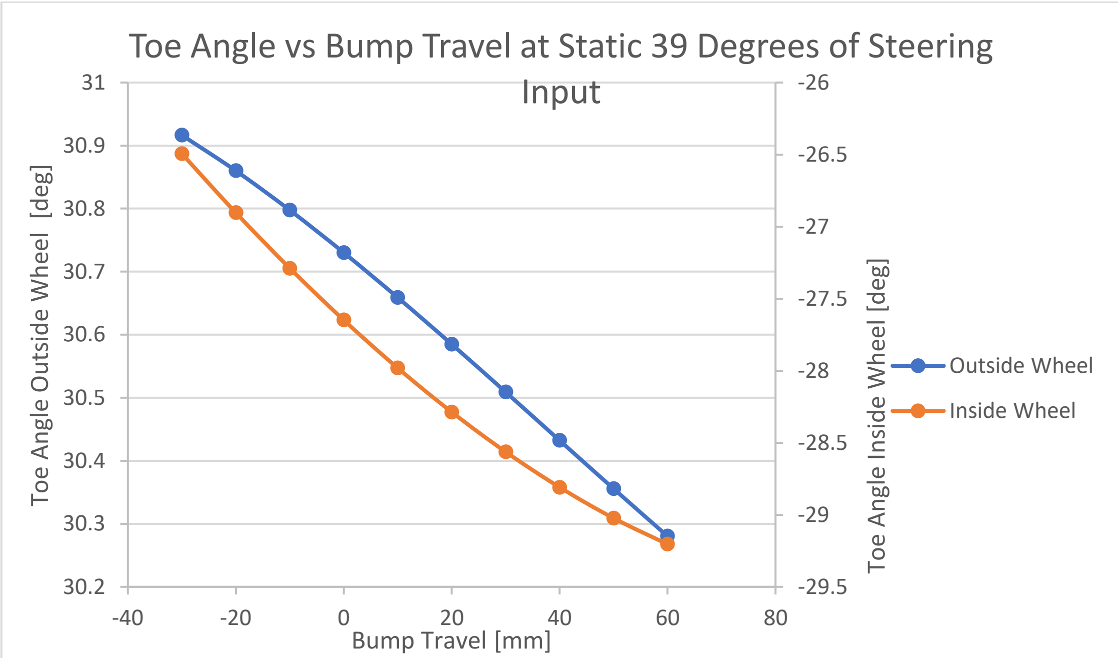

Figure 44. Graph showing the toe angle of both front wheels as a result of bump travel at 39 degrees of steering input.

MacPherson Old Pickup Points Vehicle Roll in Steady State Cornering

Figure 45 shows the results for the vehicle roll in steady state cornering. The full result is available in *Attachment 13 MacPherson Old Pickup Points Vehicle Roll In Steady State Cornering.*

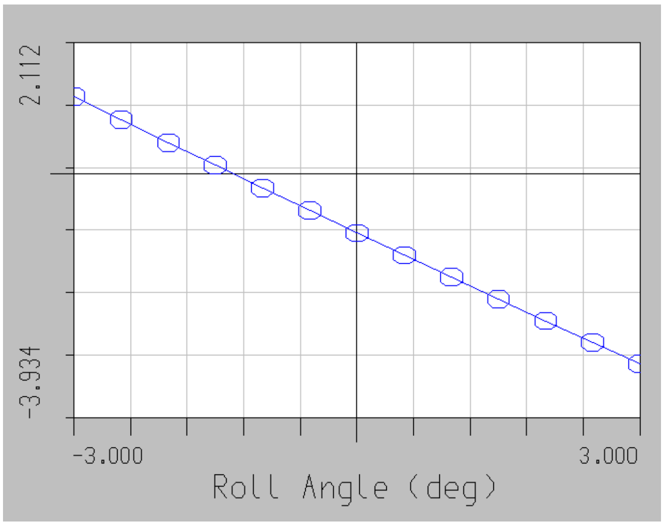

Figure 45. Camber Angle (Y) vs. Roll Angle (X). Minimum camber:-3.07 deg. Maximum camber: 1.25 deg.

6.5 MacPherson New Pickup Points

MacPherson suspension setup with pickup points adjusted in order to achieve the setup goals.

6.5.1 MacPherson New Pickup Points Setup

An illustration of the setup is shown below in Figure 46. The difference in hardpoint coordinates from *6.4 MacPherson Old Pickup Points* are shown in Table 22.

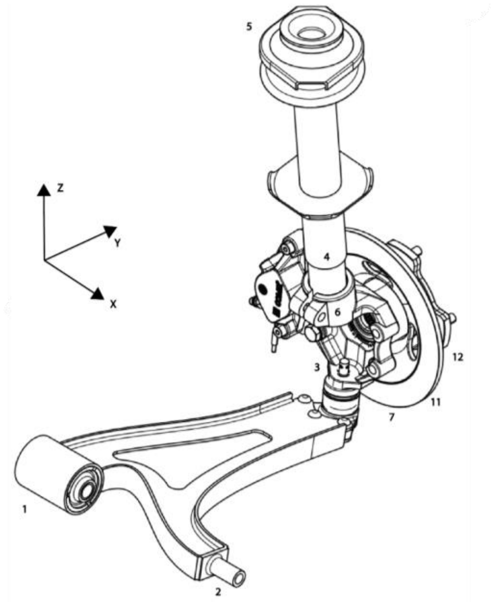

Figure 46. MacPherson Suspension Setup.

Table 22. Changes in hardpoint coordinates compared to MacPherson Old Pickup Points.

Hardpoint	ΔX(mm)	ΔY(mm)	ΔZ(mm)	Long Label
1	0	0	-34	Lower Wishbone Front Pivot
2	0	0	-16	Lower Wishbone Rear Pivot
4	0.414	6.392	-30.846	Strut Slider Upper Axis Point
5	15.085	49.416	-4.528	Strut Top Point
6	21.167	30.695	-294.423	Strut Slider Lower Axis Point
7	0	21	2-	Outer Track Rod Ball Joint
8	0	-3.391	-17.876	Inner Track Rod Ball Joint
11	4.671	4.046	-33.232	Wheel Spindle Point
12	4.668	9.779	-33.218	Wheel Center Point

6.5.2 MacPherson New Pickup Points Results

Static Values

The static results are shown in Table 23.

Table 23. MacPherson New Pickup Points Static Results

Parameter	Value
Camber Angle (deg)	0.02
Toe Angle [Plane] (deg)	0
Toe Angle [SAE] (deg)	0
Caster Angle (deg)	-4.8
Caster Trail (hub) (mm)	-2.446
Caster offset (grnd) (mm)	-18.965
Kingpin Angle (deg)	9.98
Kingpin Offset (w/c) (mm)	96.755
Kingpin Offset (grnd) (mm)	51.802
Mechanical Trail (grnd) (mm)	-18.899
Roll Center Height (mm)	140.460

It is worth pointing out that the scrub radius, called kingpin offset (grnd) by Lotus Engineering Shark is large in this setup. This is defined by the standard components from Comex and the standard tire used by Paxster. This can be adjusted to a lower value by adjusting the wheel geometry, which is needed anyway as the standard wheel used by Paxster and the Comex wheel hub utilizes different bolt patterns. Therefore, the large scrub radius is not much of a concern in this case.

Maximum Bump and Droop

The results for the maximum bump and droop scenario is shown below in Figure 47 and Figure 48. The full results can be found in *Attachment 14 MacPherson New Pickup Points Maximum Bump and Droop.*

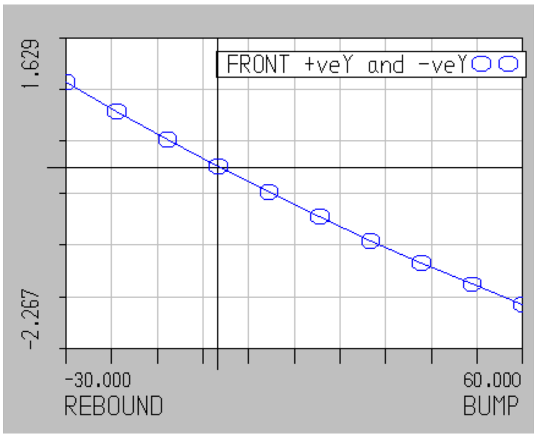

Figure 47. Camber Angle (Y) vs Bump Travel (X). Minimum Camber: -1.71deg. Maximum Camber: 1.07 deg.

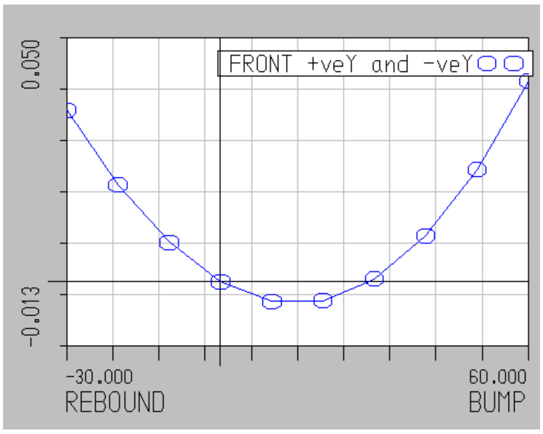

Figure 48. Toe Angle (Y) vs Bump Travel (X). Minimum Toe angle: -0.004 deg Maximum Toe Angle: 0.041 deg.

Maximum Steering Angle and Bump

Figure 49 shows the result from the maximum steering angle and bump scenario. The full setup and result can be view in *Attachment 15 MacPherson New Pickup Points Maximum Steering Angle & Bump.*

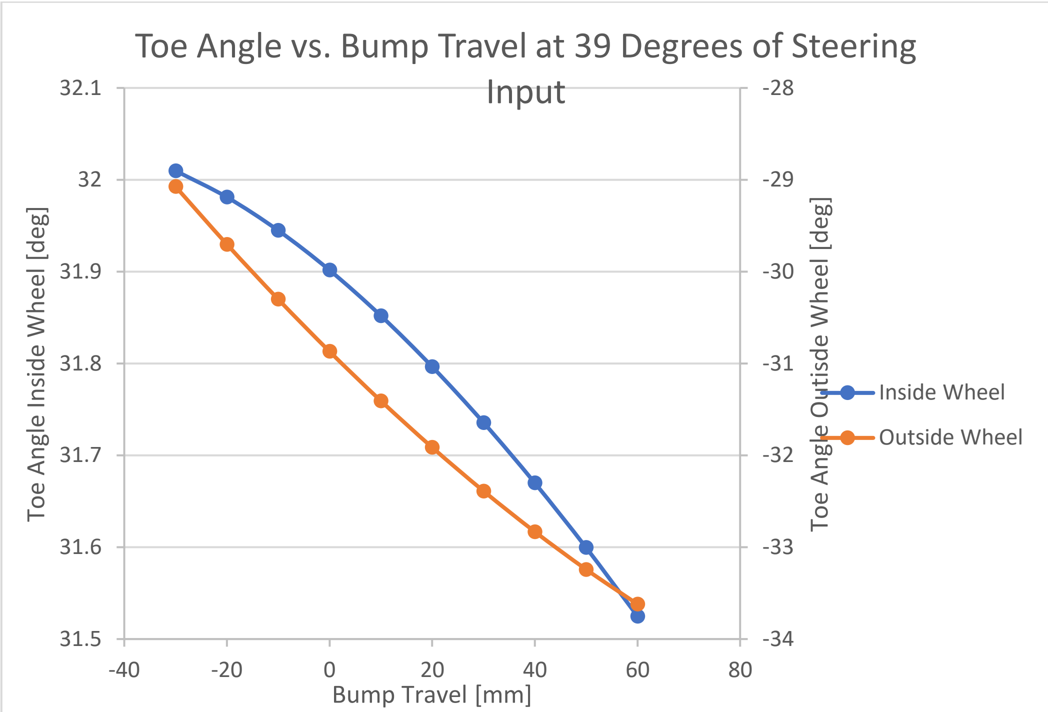

Figure 49. Graph showing the toe angle of both front wheels as a result of bump travel at 39 degrees of steering input.

MacPherson New Pickup Points Vehicle Roll in Steady State Cornering

The results from the vehicle roll in steady state cornering scenario are shown below in Figure 50. The full results are available in *Attachment 16 MacPherson New Pickup Points Vehicle Roll In Steady State Cornering.*

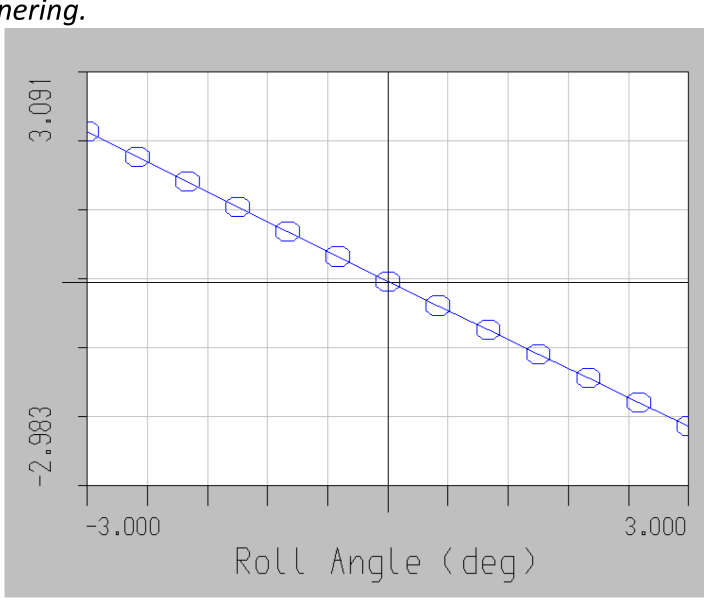

Figure 50. Camber Angle (Y) vs. Roll Angle (X). Minimum camber: -2.12 deg. Maximum camber: 2.22 deg.

6.6 Geometric Analysis Summary

The table below summarizes the various suspension setups. The results are used in order to later grade each setups performance during the concept selection. (Table 24)

Table 24. Summary of the geometric suspension analysis, the goal for the parameter is shown in parenthesis.

Suspension Concept (Goal)	Static Camber (0 deg)	Total Bump Steer (0 deg)	Camber-Max Bump (-1.25 deg)	Spring & Damper Rate (approx.) (1.5)	Static Caster (5 deg)	Toe Angle – Static (0 deg)	Kingpin Angle (10 deg)	Achieves Goals?
Baseline	$0\ deg$	$1.1\ deg$	$-0.665\ deg$	1.6	$5.52\ deg$	$0\ deg$	$11.7\ deg$	No
SLA Adjusted Track Rod	$0\ deg$	$0.046\ deg$	$-0.73\ deg$	1.6	$5.52\ deg$	$0\ deg$	$11.7\ deg$	Yes
SLA Adjusted Pickup Points	$0\ deg$	$0.011\ deg$	$-1.136\ deg$	1.6	$5.52\ deg$	$0\ deg$	$11.7\ deg$	Yes
MacPherson Old Pickup Points	$0.05\ deg$	$0.139\ deg$	$-1.65\ deg$	1.08	$7.09\ deg$	$-0.01\ deg$	$8.27\ deg$	Yes
MacPherson New Pickup Points	$0.02\ deg$	$0.061\ deg$	$-1.66\ deg$	1.07	$4.8\ deg$	$0\ deg$	$10.08\ deg$	Yes

6.7 Concept Selection

In order to select one suspension concept to develop further Pugh's method is used. The suspension concepts from *6.* Analysis of Relevant Suspension Concepts are scored according to the weighted characteristics found in *5.1 Weighted Product Specifications.* Cost/Complexity grading based on number of components and their perceived complexity. Ranked from 1-5 where 1 is the worst and 5 is the best.

The available space in the MacPherson setups are scored as 5 due to the lack of an upper wishbone, giving a large gain in free lateral space. The SLA setups are scored as 3 as they are neither especially bad nor good. An SLA setup adjusted to provide more free space, likely at the cost of driving characteristics could achieve a 4. (Table 25)

Table 25. Weighted Pugh's analysis of the various suspension setups.

Suspension Concept	Baseline	SLA Adjusted Track Rod	SLA Adjusted Pickup Points	MacPherson Old Pickup Points	MacPherson New Pickup Points
Available Space	3	3	3	5	5
Cost/Complexity	2	2	2	4	4
Driving Characteristics	3	4	5	3	4
Sum	8	9	10	12	13
Weighted Sum	10.3	11.3	12.3	15	17.3

The weighted sums show the reason MacPherson setups seem to be very common in regular cars, given that driving characteristics are not top priority. The MacPherson New Pickup Points setup is chosen and will be subject to further development. In a way, using the MacPherson setup is the combine component of SCAMPER in practice, as the MacPherson strut itself in a way acts as both spring/damper and upper wishbone.

7. Development of The Chosen Concept

The chosen concepts requires design of both a lower wishbone and a tie rod mounting bracket.

7.1 Reaction Forces

In order to setup the FEM analysis of the individual components the reactor forces must first be known. The forces acting on the tires are calculated in *4.7.2 Forces Summarized* and are shown below in Table 26.

Table 26. Front Wheels Dynamic Loads.

Load Case Front	Load Factor		
	Longitudinal	**Transverse**	**Vertical**
Pothole Bump	$3815.7N$	$-$	$5087.6N\ Affected$ $1271.9\ Others$
Bump During Cornering	$-$	$-$	$4451.7N\ Affected$ $1271.9\ Others$
Lateral Curb Strike	$-$	$5087.6N$ $Affected\ side$	$1271.9N$
Panic Braking	$2543.6N\ Front\ Wheels$	$-$	$2543.6N\ Front\ Wheels$

The suspension system is a statically indeterminate system. In order to calculate the lower wishbone, it is assumed that the reaction forces in the x-direction at the bushings are equal. Any vertical forces are carried by the MacPherson strut and not transmitted through the wishbone as the strut attaches directly to the upright and the bushings allows the wishbone to rotate in the roll direction. Using the simplified two dimensional FBD and the coordinate convention as described in *4.1 Coordinate System, t*he following calculations will focus on the Pothole Bump and Lateral Curb Strike scenarios as these will load the wishbones the most.

7.1.1 Wishbone Pothole Bump Loads

In order to ascertain the force acting on the ball joint in the wishbone the Macpherson strut and upright assembly is simplified as a beam between the two balljoints. The process is shown in Figure 51 and Figure 52.

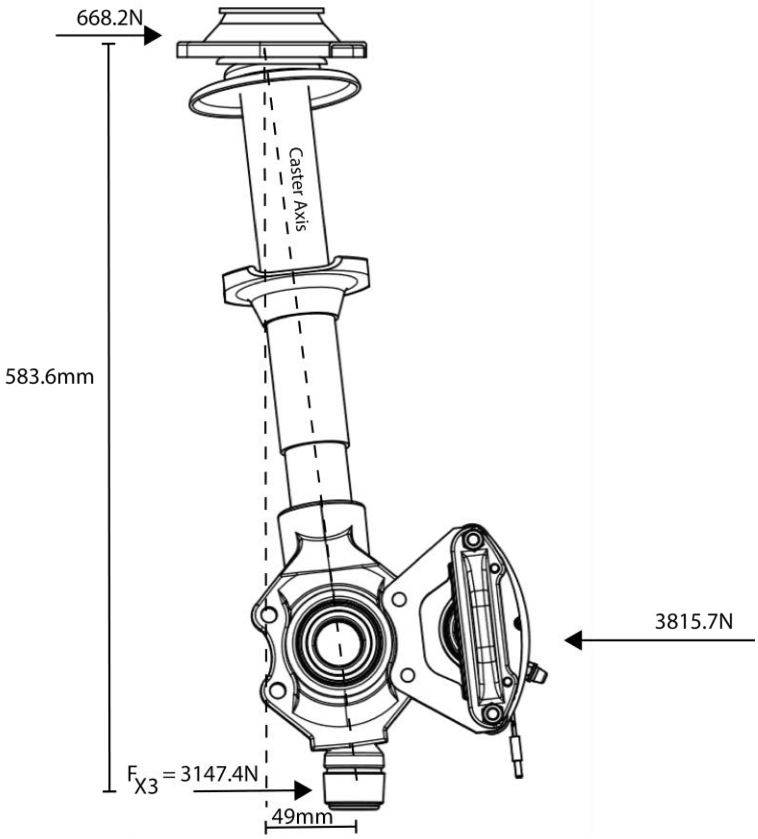

Figure 51. Simplified calculation of resulting forces in the wishbone and MacPherson Strut mount due to the longitudinal forces in the Wishbone FBD Pothole Bump Load scenario.

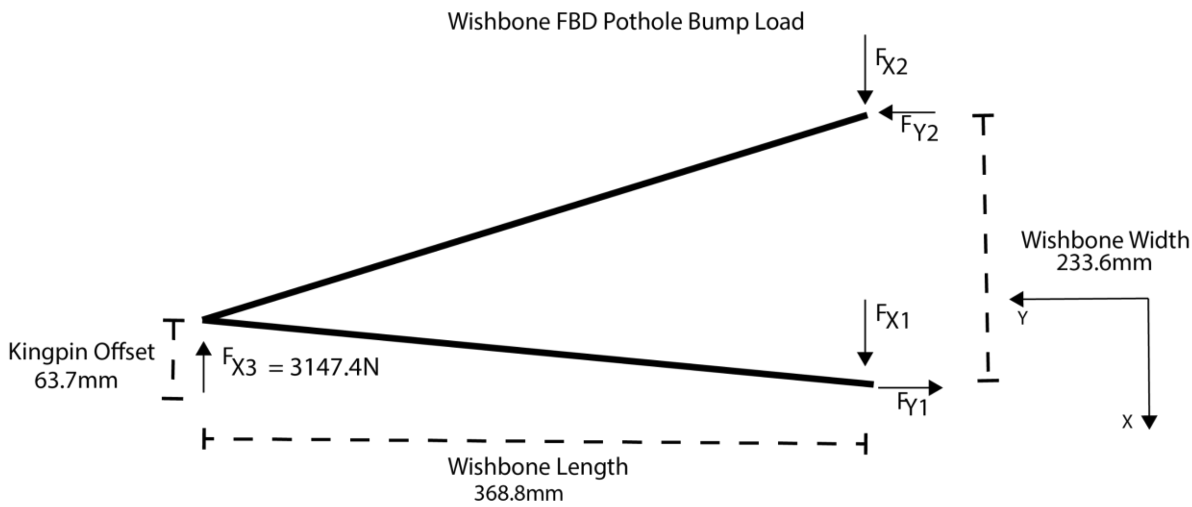

Figure 52. Wishbone FBD Pothole Bump Load.

Due to the assumption that the reaction forces at point 1 and 2 in the x-direction is equal.

$$\sum F_X = 0$$ *Equation 10*

$$F_{X3} = F_{X1} + F_{X2}$$

$$F_{X1} = F_{X2} = 1573.7N$$

Utilizing the moment and force equilibrium equations.

$$\sum M_2 = 3147.4N * 368.8mm + F_{Y1} * 233.6mm = 0$$ *Equation 10*

$$F_{Y1} = -4969N$$

$$\sum F_Y = 0$$ *Equation 10*

$$F_{Y2} = 4969N$$

7.1.2 Wishbone Lateral Curb Strike Loads

The situation to be calculated is illustrated using Figure 53 and Figure 54 below.

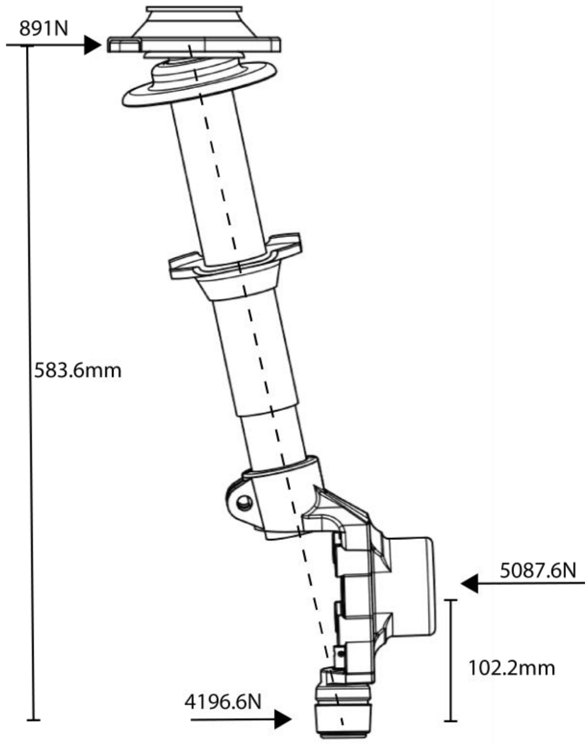

Figure 53. Simplified calculation of resulting forces in the wishbone and MacPherson Strut mount due to the transverse forces in the Wishbone Lateral Curb Load scenario.

The figure above shows the result of calculating the resulting forces at the balljoints due to the lateral curb strike, this data will be further utilized to calculate the reaction forces using the free body diagram below.

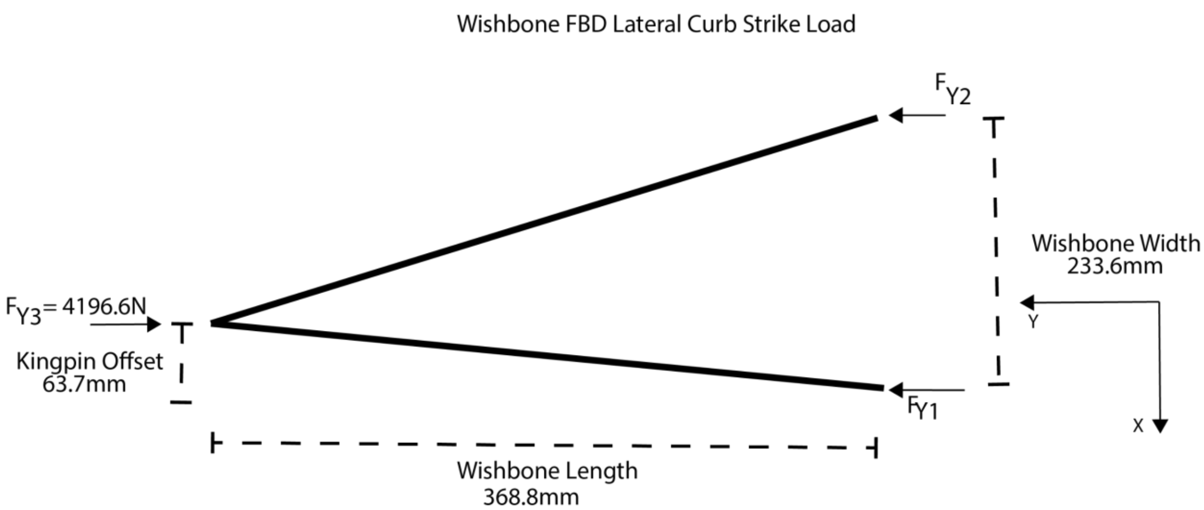

Figure 54. Wishbone FBD Curb Strike Load.

$$\sum M_1 = 4196.6N * 63.74mm - F_{Y2} * 233.6mm = 0$$ *Equation 10*

$$F_{Y2} = 1145N$$

$$\sum F_Y = 0$$

$$\sum F_Y = 1145N + F_{Y1} - 4196.6N = 0 => F_{Y1} = 2751.6N$$ *Equation 10*

7.1.3 Tie Rod Forces

Calculating the forces acting on the tie rod is complex, thus a few assumptions are made. These calculations ignore pneumatic trail and assume that the car turns with a max acceleration of 1G. During this steady state cornering situation, the steering axis is held still by the driver, through the wheel. If simplified down to a two-dimensional FBD, finding the forces acting on the tie rod mount is possible. (Figure 55, Figure 56) [41]

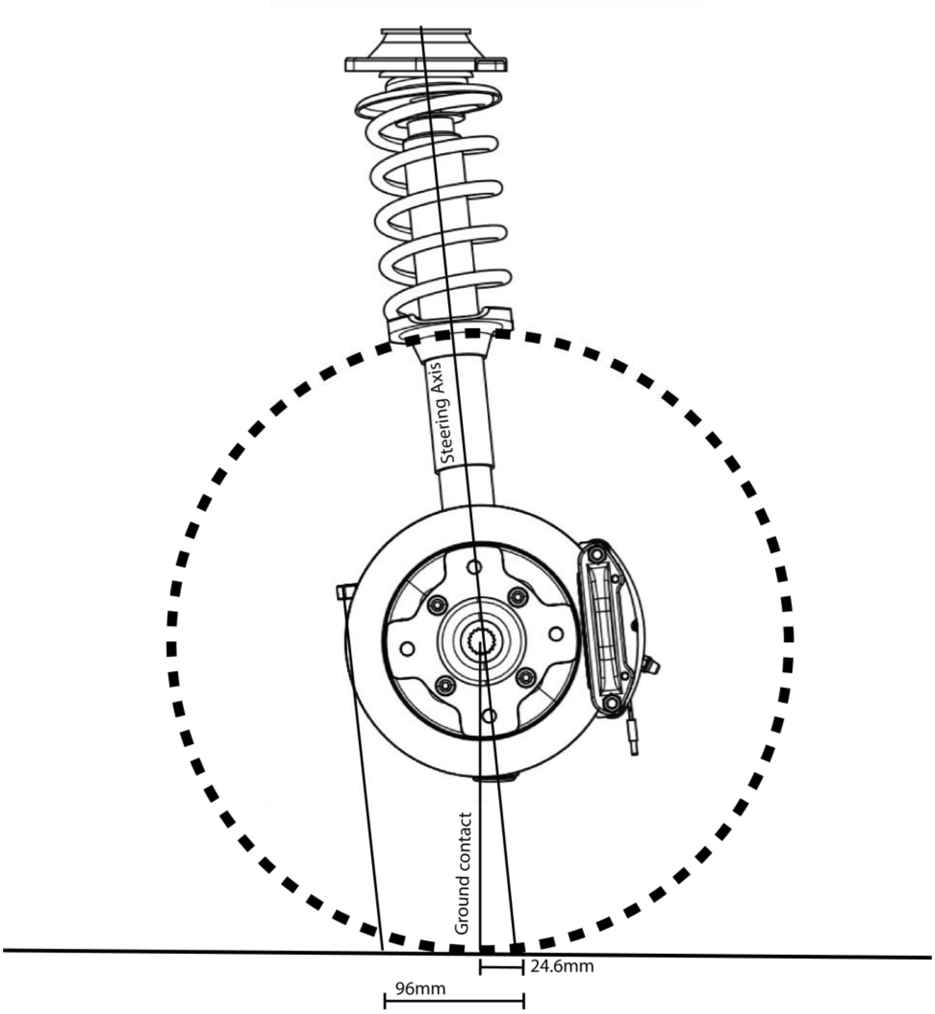

Figure 55. Sizes for tie rod force calculations.

The lateral force acting on the wheel during a 1G acceleration turn can be found using the following calculation. A full vehicle mass of 535kg is used. This assumes that half of the weight of the vehicle is concentrated on the front, and that the entire centripetal force acting on the front wheels is only taken up by the outside wheel, this wheel will take most of the forces. This is a conservative assumption.

$$F_{WC} = \frac{637kg * 9.81\, ^{m}/_{s^2}}{2} = 3124.5N$$

Equation 11

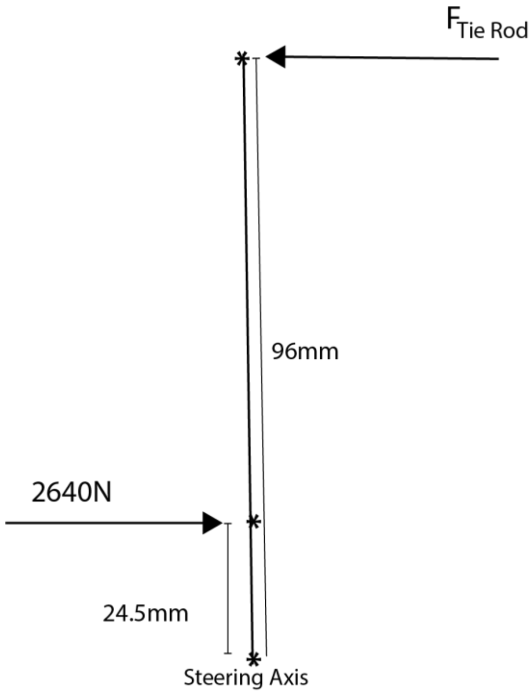

Figure 56. FBD for finding tie rod forces.

For the moment about the steering axis to be zero, the following force must act on the tie rod. The axes are projected to create a two-dimensional representation as view from above.

$$\sum M_{SteeringAxis} = 3124.5N * 24.5mm - F_{TieRod} * 96mm = 0$$

Equation 10

$$F_{TieRod} = \frac{3125.5N * 24.48mm}{96mm} = 797N$$

The F_{TieRod} force found is used during finite element analysis of the tie rod mounting bracket.

7.2 Mounting Methods

Several methods are regularly used for mounting suspension components, usually the wishbone mounting consists of either bushings or bearings. Seemingly most common is the use of bushings, however heim joints and needle bearings are also used in some applications. Examples of mounting methods are shown below in Figure 57. [42]

Figure 57. Double Wishbone utilizing Heim Joints (Left) and Double Wishbone utilizing bushings (Right) [43], [44].

An overview of the advantages and disadvantages of each mounting solution is given in Table 27 below.

Table 27. Comparison of various mounting interfaces. [45]

Mount Type	Advantages	Disadvantages
Bushing	Cost Complexity	Compliance Stiction
Heim Joint	Cost Adjustability	Rod ends in bending
Encapsulated Spherical Bearings	Low stiction Compliance	Production cost
Needle Bearings	Low stiction Compliance	Cost Complexity

Paxster utilizes needle bearings on their double wishbone suspension. Typically, a MacPherson setup incorporates various types of bushings, including a silent block, a type of bushing. A MacPherson suspension also utilizes a bearing on one side of the strut, allowing the wheel to rotate and steer the car. Choosing the bushing mounting interface will further guide the design of the lower wishbone. [46]

There are also several mounting methods for mounting the wishbone to the knuckle, most notably and common is a ball joint, as currently used in the Paxster EDV, shown below in Figure 58.

Figure 58. Ball joint for connecting a wishbone to an upright. [47]

7.3 Geometry & Design Envelope

The geometry and design envelope of the lower wishbone is defined by the geometric suspension analysis in *6.* Analysis of Relevant Suspension Concepts*.* Utilizing the selected suspension setup in Lotus Engineering Shark the toe angle of the tire at maximum and minimum steering input is found. This is done in order to verify that the wishbone will not intersect with the wheel during steering, illustrated below in Figure 59 and summarized in Table 28.

Table 28 Steering Input and resulting toe angles.

Steering Input [deg]	Toe Angle [deg]
$\mathbf{39}$	32.5
$\mathbf{-39}$	-34.5

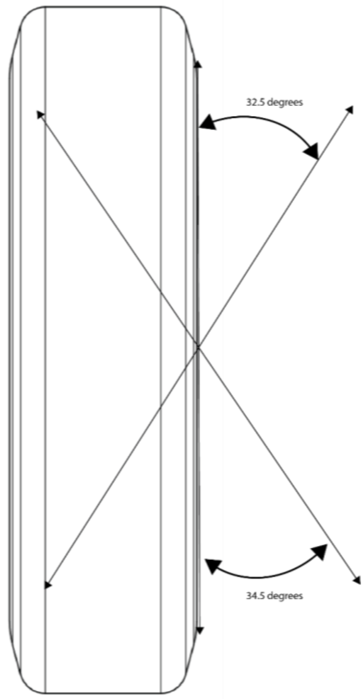

Figure 59. Single wheel turning envelope. [48]

The suspension analysis from Lotus Engineering Shark supplies the relative coordinates of the hardpoints for the lower wishbone, assuming the Lower Wishbone Front Pivot is centered at the origin. (Table 29)

Table 29. MacPherson Lower Wishbone Relative Coordinates.

X(mm)	Y(mm)	Z(mm)	Long Label
0	0	0	Lower Wishbone Front Pivot
-233.643	0	0	Lower Wishbone Rear Pivot
-68.764	-368.872	-68.744	Lower Wishbone Outer Ball Joint

7.4 Production Methods

The manufacturing process behind a component is a vital consideration during the design process. An example is the need for draft angles for casting, a feature that is not needed if milling from a billet of metal. Some common production methods used for suspension components include the following, these can also be combined in a multistage production process.

- Metal Stamping
- Machining
- Casting
- Extrusions, welding and bending

Each production method has advantages and disadvantages these are discussed underneath.

7.4.1 Metal Stamping

Metal stamping is a forming process where typically a metal sheet is pressed into specific shapes using high pressure, making the metal sheet take on the shape of the die. For wishbones and brackets this is often utilized for high production numbers, giving very low per unit costs. The wishbone is often stamped in two pieces and welded together. [49]

7.4.2 Machining

Machining is a production category consisting of several subtractive processes. This process is typically more expensive than stamping but allows for geometries that metal stamping might not. Machining is typically only viable for low production numbers or certain geometries.

7.4.3 Casting

Casting a component is done by filling a mold with a heated, liquid metal. Although relatively simple in concept, casting precision components require extensive knowledge. A metal will shrink and potentially warp as it cools from a liquid to a solid state. Depending on the mold type, the component may need a draft angle in order to extract it from the mold, shown in Figure 60.

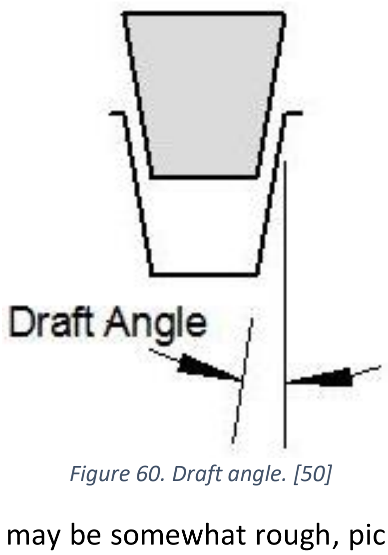

Figure 60. Draft angle. [50]

The surface finish from casting may be somewhat rough, picking up the texture of the mold. In many cases cast components have their mounting surfaces, where other critical components attach machined to achieve the desired dimensions or fitment. [51] [52]

7.4.4 Extrusions, Welding and Bending

A relatively common method for producing simple components in lower numbers is the utilization of extrusions and plates to bend and weld them into the desired shape. Paxster currently uses this production method to a large extent, their chassis, wishbones and numerous other parts of the vehicle is produced using this method. This production method is chosen as the basis of the wishbone design. The current lower front wishbone is produced using this method and is shown in Figure 61.

Figure 61. Current lower front wishbone.

7.5 Material Selection

The choice of material will influence the design, manufacturing and cost of the wishbone greatly. Seemingly most common in regular production car are various types of steel and aluminum, although a wishbone and steering mounting bracket may technically be made from any material strong enough.

Table 30. General overview of material properties for aluminum and steel and the chosen S355J2 steel obtained from CES EduPak.

Characteristic	Aluminum	Steel	S355J2
Density	$2.5e3 - 2.9e3\ kg/m^3$	$7.6e3 - 8.1e3\ kg/m^3$	$7.85e3\ kg/m^3$
Fracture Toughness	$22 - 35 MPa\sqrt{m}$	$62 - 150 MPa\sqrt{m}$	$43 - 62 MPa\sqrt{m}$
Fatigue Strength at 10^7 Cycles	$21.6 - 157 MPa$	$175 - 753 MPa$	$202 - 236 MPa$
Young's Modulus	$68 - 82 GPa$	$189 - 210 GPa$	$200 - 221\ GPa$
Yield Strength	$30 - 500 MPa$	$170 - 1e3\ MPa$	$350 - 435\ MPa$
Tensile Strength	$58 - 550 MPa$	$480 - 2.24e3\ MPa$	$430 - 550 MPa$

The suspension system in the Paxster EDV is currently manufactured from steel, including S355 for the rear. Aluminum is generally more expensive for a given component, to reduce cost, improve fatigue strength and utilize Paxster's experience with steel, steel is selected. The fatigue strength of S355J2 and Aluminum are noteworthy and important later. (Table 30) [53]

Operating temperature is a consideration when using steel, as it will become more brittle in cold weather conditions, therefore S355J2 is used, as it has better mechanical properties at low temperatures. [54]

7.6 Concept Development

Using the considerations earlier in this chapter the production method, mounting methods, rough dimensions can be selected. In order to adapt to low volume, low upstart cost welding, bending and cutting is chosen as the preferred production method. The concept will utilize the discussed mounting methods, one silent block, one T-pin bushing and a kingpin. The chosen design parameters are summarized in Table 31. The steering mounting bracket will be produced using the same material and manufacturing method.

Table 31. Overview of chosen design parameters.

Manufacturing method	Mounting methods	Welds	Plate thickness	Geometry
Welding, bending and cutting common sections.	Silent block, T-Pin bushing and ball joint.	Arbitrary size for initial FEM and appearance.	Selected as a result of FEM. Initially 3mm.	Mounting points defined by geometric analysis. Partially lead by FEM results.

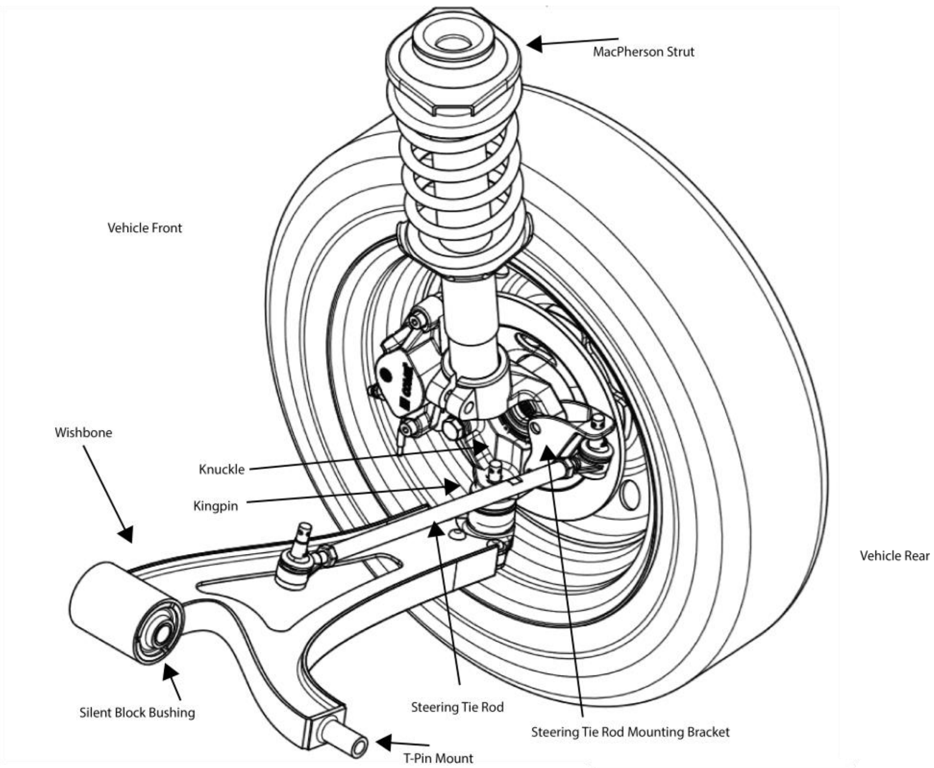

Figure 62. Overview of the vital components.

Using welding, bending and cutting as the intended production method has advantages and disadvantages, the process allows for almost zero upstart cost if done somewhat manually. The process also allows for cheap and simple prototyping of the finished wishbone. An important consideration is reducing the number of operations needed to complete the wishbone as this should reduce production cost.

Other than withstanding the shock loads described earlier, the wishbone will also aim to achieve other structural performance targets. These targets are borrowed from *Lightweight*

MacPherson Strut Suspension Front Lower Control Arm Design Development and are summarized in Table 32 below. [49]

Table 32. Additional structural performance metrics. Same coordinate system as described in 4.1 Coordinate System. [49]

Structural Performance Target	Goal
Longitudinal Buckling Strength	$> 25kN$
Static Stiffness x-direction	$\geq 2.9kN/mm$
Static Stiffness y-direction	$\geq 125kN/mm$

Although these parameters are for a slightly larger vehicle they will be used as the Paxster EDV is likely driven harder on its routes. Although the paper does not explicitly clarify the reason for the required x and y direction stiffness, it is assumed this is done in order to minimize compliance. High compliance will slightly alter the suspension geometry under load, potentially leading to an unpredictable ride.

The wishbone is FEM simulated using Ansys Workbench, the forces and displacements are applied at the balljoint socket in the housing and the two components are mounted using the modeled representative rivets and contact sets. As the balljoint housing and rivets are not part of the study, these are only used to transmit the forces. The simulation result for the pothole bump scenario is shown in Figure 63 and Table 33.

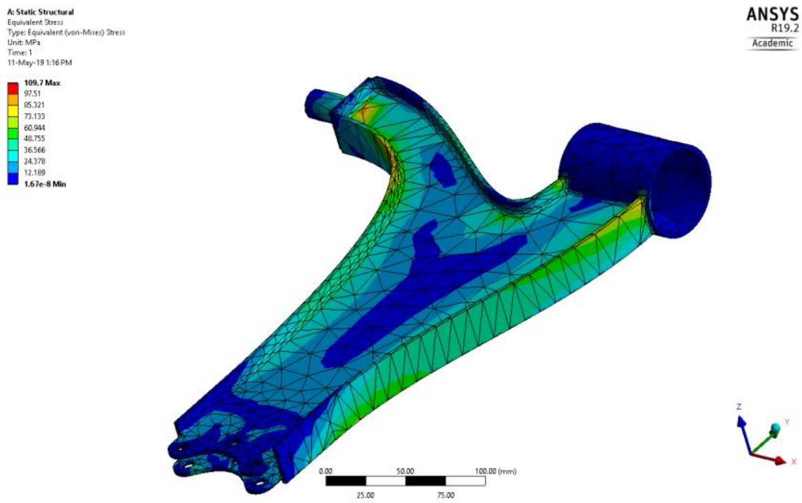

Figure 63. Welded Wishbone solid Von Mises equivalent stress for pothole bump scenario.

Table 33. Welded Wishbone Solid simulation results.

Load Scenario	Results
Pothole Bump scenario	$Maximum\ Von\ Mises\ Stress:\ 109.7MPa$ $Maximum\ Deformation: 0.39mm$
Lateral Curb Strike scenario	$Maximum\ Von\ Mises\ Stress: 47.5MPa$ $Maximum\ Deformation: 0.71mm$
Longitudinal Buckling Strength, 1st Mode	$32.451kN$
Static Stiffness X-direction	$14.110kN/mm$
Static Stiffness Y-direction	$148.69kN/mm$

The wishbone is constrained where it would contact the bushings, using cylindrical constraints and frictionless constrains on the appropriate surfaces. Force is applied at the balljoint housing, however the FEM results are scoped to only include the wishbone, as the balljoint housings will likely be purchased components.

Figure 63 above shows the stress concentrations during the pothole bump scenario, viewing the Von Mises Stress for the pothole bump and lateral curb strike scenarios in conjunction with each other reveals potential weight savings in the middle of the upper web. Removing material in the upper web would reduce weight and add drainage for potentially trapped water. A cutout was created with a 25mm distance from the nearest edge for the upper web. FEM analysis provides the following results shown in Figure 64 and Table 34.

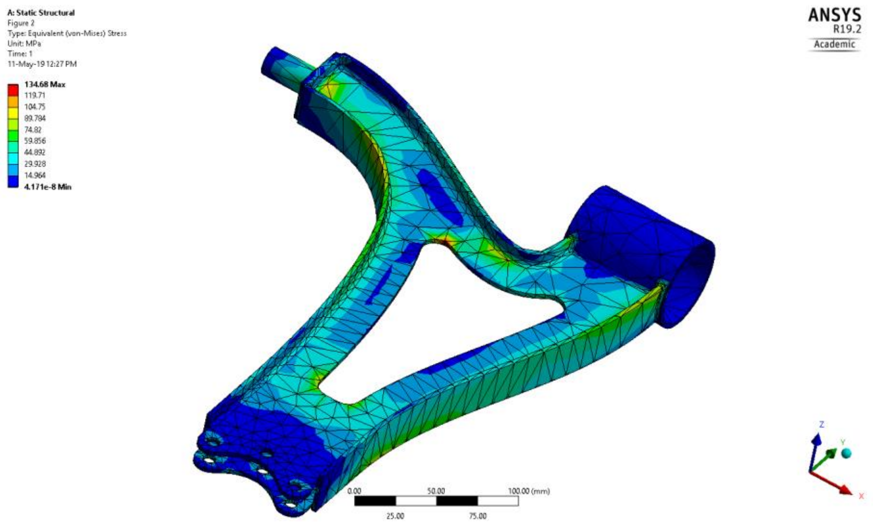

Figure 64. Welded Wishbone with 25mm offset cutout Von-Mises equivalent stress for pothole scenario.

Table 34. Welded Wishbone with 25mm offset cutout simulation results.

Load Scenario	Results
Pothole Bump scenario	$Maximum\ Von\ Mises\ Stress: 134.7MPa$ $Maximum\ Deformation: 0.56mm$
Lateral Curb Strike scenario	$Maximum\ Von\ Mises\ Stress: 74.4MPa$ $Maximum\ Deformation: 1.18mm$
Longitudinal Buckling Strength, 1st Mode	$28.366kN$
Static Stiffness X-direction	$10.694kN/mm$
Static Stiffness Y-direction	$102.46kN/mm$

A slight gain in deformation and maximum stresses along with the decrease in stiffness is to be expected. The revised wishbone with the 25mm offset cutout also reduces the weight by 242 grams, down to 2233.5 grams total including the balljoint and balljoint housing. For context the original double wishbone SLA lower wishbone weighs in at 2500g including the balljoint.

The proposed design is presented below in Figure 65 and Table 35 in its unwelded state. The flanges and webs are constructed from 3mm thick S355J2 steel, bent if needed and welded together. The proposed design is rendered and shown in context in Figure 74.

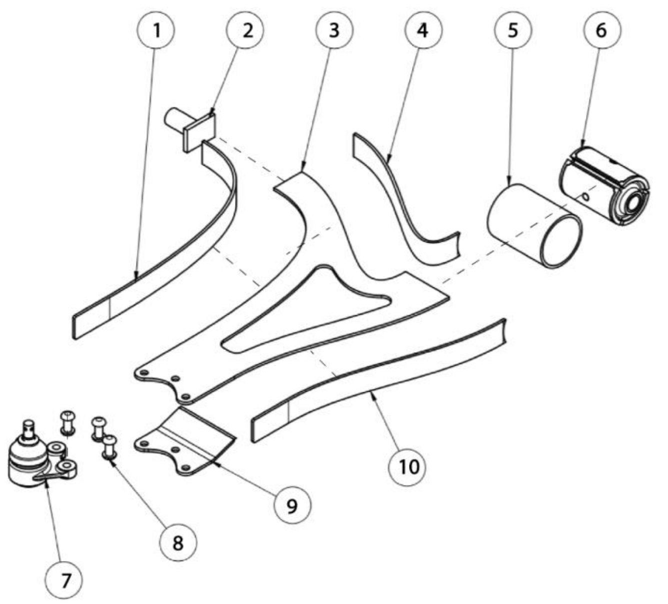

Figure 65. Welded Wishbone Version 1 explosion drawing.

Table 35. Welded Wishbone Version 1 component list.

Component Number	Description
1	Rear Flange
2	T-Pin
3	Upper Web
4	Inboard Flange
5	Silent Block Bushing Sleeve
6	Silent Block
7	Balljoint w/ housing
8	8mm Rivets
9	Lower Web
10	Forward Flange

The setup also requires a mount for the tie rod in order to steer. The location of the tie rod pickups are defined in the suspension analysis. The design follows the same main principle as the wishbone and is intended to be cut, bent and welded. It is bolted to the upright using a double shear connection. The steering tie rod mounting bracket weighs 133.6 grams. The FEM results are shown in Figure 66 and Table 36.

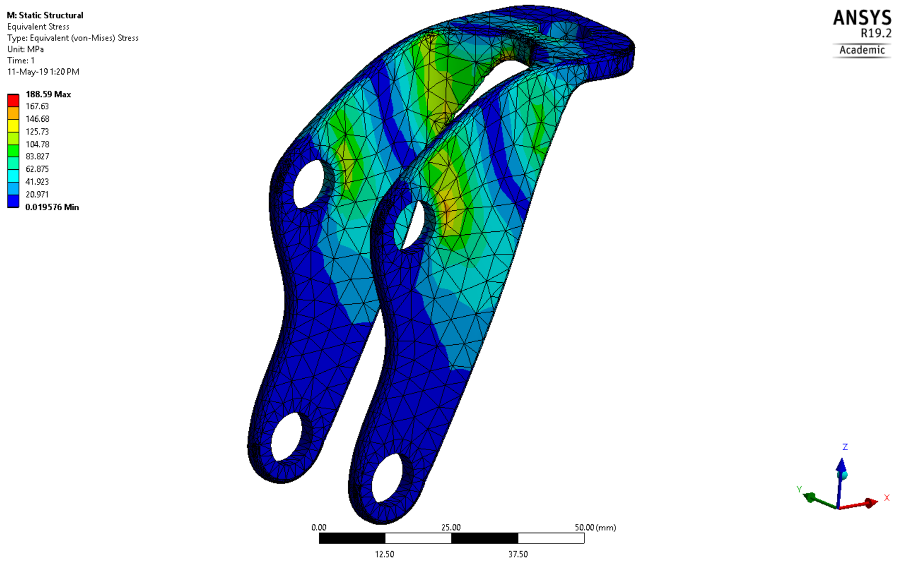

Figure 66 FEM Analysis results for the steering tie rod mounting bracket. Highest stress concentration at the mounting holes.

Table 36 FEM Analysis results for the steering tie rod mounting bracket.

Load Scenario	Results
Steady State Turning, Max.	$Maximum\ Von\ Mises\ Stress:\ 188.6MPa$ $Maximum\ Deformation: 0.13mm$
Static Stiffness Y-direction	8.272kN/mm

7.7 Chassis Considerations

The chassis will need to be adjusted to accommodate the new suspension setup. The wishbone is currently mounted to the chassis using simple, folded brackets, these can easily be altered to allow mounting of the new wishbone. (Figure 67)

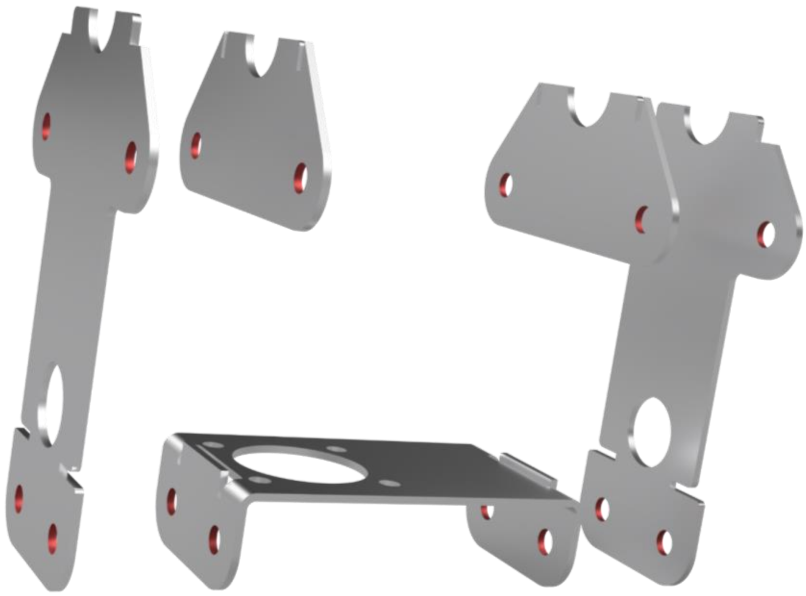

Figure 67. Existing wishbone to chassis mounting brackets.

The MacPherson strut must be attached to the chassis in what is often called a strut tower. This is a more complex adjustment but the space available should be adequate. This may allow for repurposing of the existing chassis structure. (Figure 68)

Figure 68. Location for wishbone and MacPherson Strut mounting.

The adjustments of the chassis and wishbone mounting falls under further work.

7.8 Manufacturing Considerations

The wishbone is a product of cut, bent and welded sheet metal, a tube and a rod. Various considerations must be taken into account during production in order to maintain functionality. The two bushing mounts must be, to a certain degree coaxial, depending on the final selected bushing. The six riveting holes for mounting the balljoint housing must also align. In order to achieve the somewhat accurate dimensions needed for the two bushing mounts lathe turning is a likely manufacturing method.

If the welding is done manually, which is likely for early prototypes a jig should be implemented in order to maintain the relative coordinates of the mounting points.
An overview of the example welded zones are shown below in Figure 69 using a dashed red line. Further work should evaluate if the welds need to be continuous all the way around or if using intermittent welds may decrease the potential for warping as well as manufacturing time and cost. [55] [56]

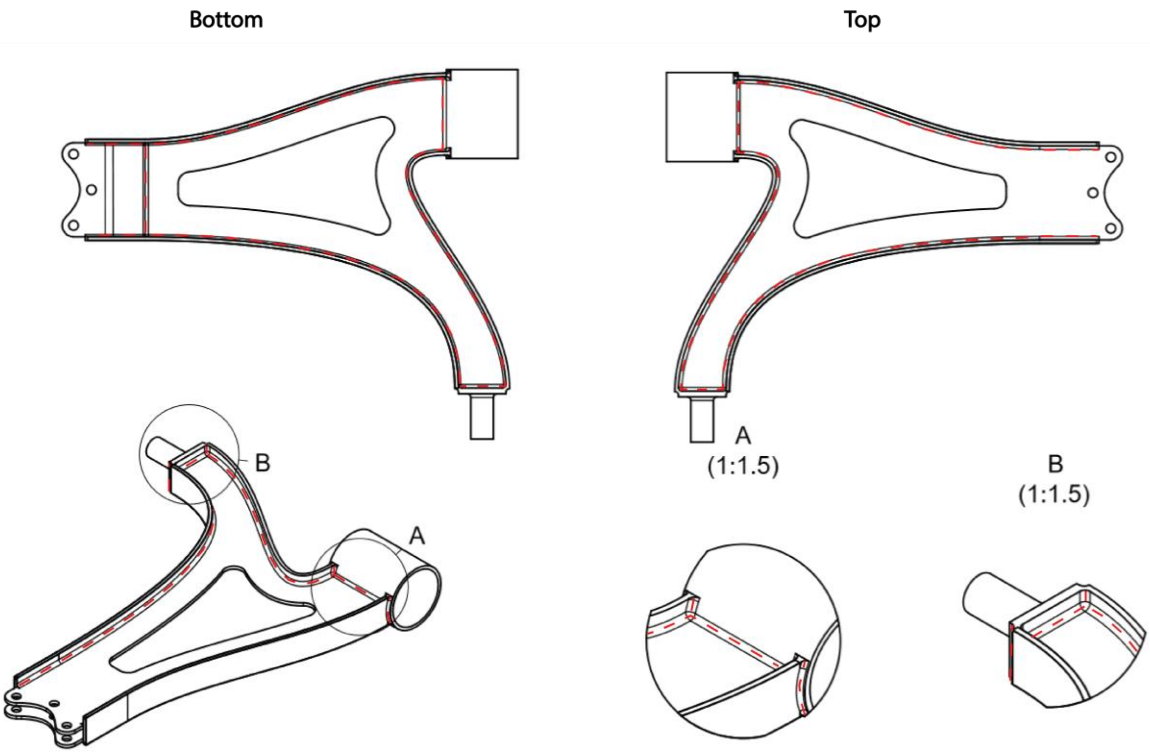

Figure 69. Overview of the example welds on the final welded wishbone shown in red.

7.9 Springs and Dampers

Once the suspension geometry has been defined the final spring and damper constants can be determined. During discussions with Paxster it was decided to go for progressive springs with the goal of achieving optimal spring stiffness regardless of the amount of payload in the car.

The optimal spring and damper constants are highly dependent on the sprung and unsprung mass, the unsprung mass in Table 37. Input parameters are shown in Table 38.

Table 37. Unsprung mass obtained from CAD model summarized.

Component	Weight
Wishbone (50%)	$1.12kg$
Tire	$3kg$
Wheel	$9kg$
Upright	$1.9kg$
Wheel Hub	$1.3kg$
Brake Caliper + Bracket	$2.2kg$
Bearing	$0.5kg$
Misc.	$0.5kg$
Total	$19.52kg$

Simplifying the unsprung mass is done by assumed to be equal on all four corners.

Table 38. Input parameters spring and damping constants.

Parameter	Value
$\boldsymbol{Unsprung\ Mass\ Per\ Wheel}$	$19.52kg$
$\boldsymbol{TotalSprungMass - Min}$	$256.9kg$
$\boldsymbol{TotalSprungMass - Max}$	$456.9kg$
$\boldsymbol{f_n}$	$1.5Hz$
$\boldsymbol{Weight\ Distribution}$	$40.7{:}\ 59.3$
$\boldsymbol{MotionRatio - MacPherson\ New}$	1.07
$\boldsymbol{Damping\ Ratio\ \xi}$	0.2

In order to find a suitable spring constant to guide the selection of a progressive spring, the optimal spring stiffness is calculated for the car in 15kg intervals from empty to fully loaded weight. The optimal spring stiffness is found using the following formula.

Equation 4

$$k_{eq} = 4\pi^2 f_n^2 * m_{SprungCorner} * MotionRatio^2$$

The critical damping is also calculated for the car at the 15kg intervals using the following formula.

Equation 8

$$C_{cr} = 2\sqrt{k_s * MotionRatio^2 * m_{sprung}}$$

To achieve their cost target the Paxster EDV will likely avoid using active dampers, thus the damper will be a simpler velocity damper, here the force from the damper is directly connected to the velocity of the compression or rebound, not the distance as in a spring.

Table 39. Optimal spring and damper constants at various loads, with 102kg driver.

Mass	Mass-Sprung	Corner Mass	keq (N/m)	Critical Damping	Damping
437	358.92	73.04	7420.47	1472.40	294.48
462	383.92	78.12	7937.33	1574.96	314.99
487	408.92	83.21	8454.19	1677.52	335.50
512	433.92	88.3	8971.05	1780.077	356.015
537	458.92	93.39	9487.91	1882.63	376.53
562	483.92	98.45	10004.78	1985.19	397.039
587	508.92	103.57	10521.64	2087.75	417.55
612	533.92	108.65	11038.5	2190.31	438.06
637	558.92	113.74	11555.36	2292.87	458.57

From Table 39 above a suitable combination of spring and damper constants can be chosen. After discussions with Paxster a combination of progressive springs that match the $\boldsymbol{K_{eq}}$ was deemed the optimal choice, as springs are easily altered to match the desired attributes, as discussed in *4.4.1 Spring Rates.* Paxster requested a damper constant in the middle of the suggested values above. The median damper constant is calculated.

$$C_{Median} = 376.5 \ \frac{N}{mm/s}$$

In order to define a damping curve for the desired damper a number of steps are followed as found in Optimum Gs guide to spring and damper setup. Finding a perfect damper is not expected, however this will act as a guideline for selecting a suitable damper at a reasonable cost. [57]

Modern dampers are developed to change their damping force as a result of the velocity, preferably reacting differently to low and high-speed bumps. Defining the initial slope of the damping curve is done using the following formula.

$$Initial\ Slope = \ 4\pi\xi f_n M_{1/8th} \ [\frac{N}{mm/s}] \qquad \text{Equation 14}$$

Solving the initial slope for the force in N allows the construction of a Force vs Velocity diagram. It is worth noting that the velocity in this case is the speed which the damper is being actuator of the damper is moving. Utilizing the method described in Optimum G's Technical Papers to find the suggested damping curve shown in Figure 70. [57]

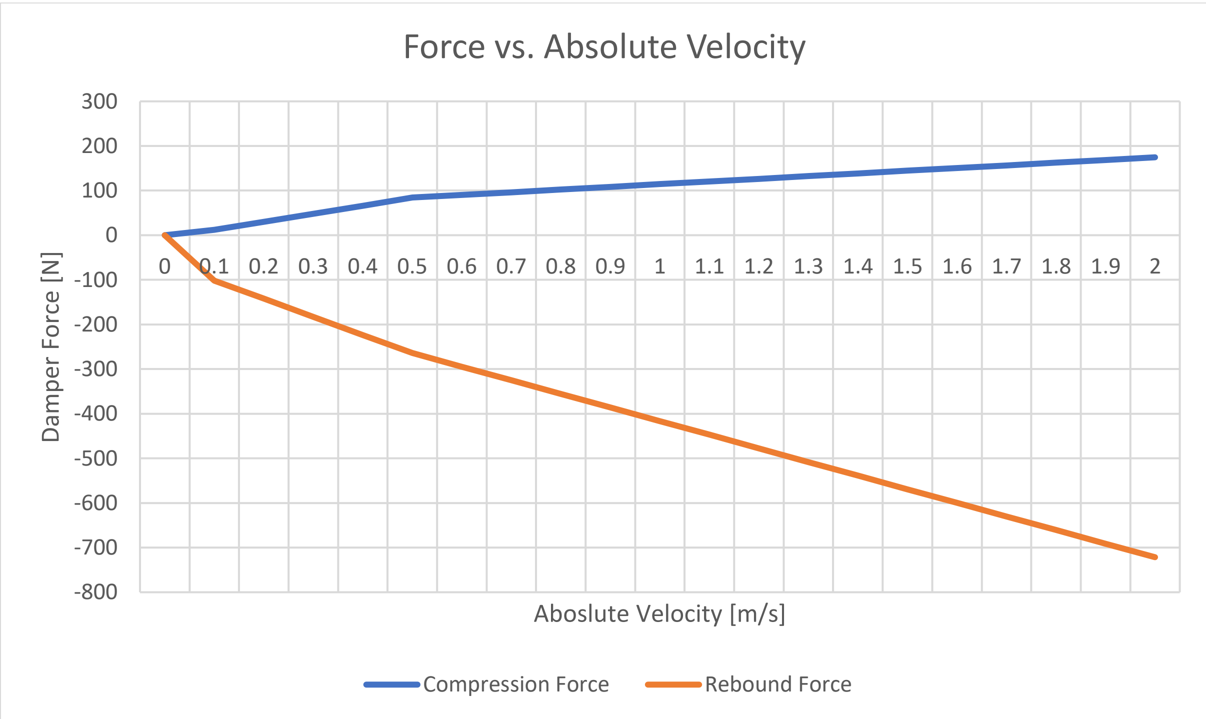

Figure 70. Final baseline Force vs. Absolute Velocity curve.

The damper curve above is a baseline and does not explicitly dampen roll or pitch movements. Roll and pitch dampening is most vital in race or sports cars in order to further control the vehicle movements and is not relevant here.

This completes the suggested spring and damper characteristics to be used as a guide during selection of the strut in further work.

7.10 Final Product Specifications

The final product is a list of geometric suspension recommendations and a wishbone setup for the selected suspension type. The wishbone is designed to fit the manufacturer components

suggested by Paxster, for ease of manufacturing and the be strong enough to survive the forces applied in extreme load cases.
The wishbone itself, excluding bushings and the kingpin weighs 1843 grams and is made of S355J2 steel. The kingpin and its housing are riveted to the upper and lower web of the wishbone to ensure a double shear connection.

The wishbone maintains hardpoint locations as defined is Lotus Engineering Shark. Coupled with high stiffness, the wishbone, together with the purchased components and appropriate chassis mounts should provide the expected driving characteristics.

7.11 Product Presentation

Figure 71. Steering bracket and wishbone shown in context, including purchased components.

Figure 72 Steering bracket and wishbone shown in context, including purchased components.

Figure 73. Wishbone shown in context, including purchased components.

Figure 74. Wishbone shown in context, including purchased components.

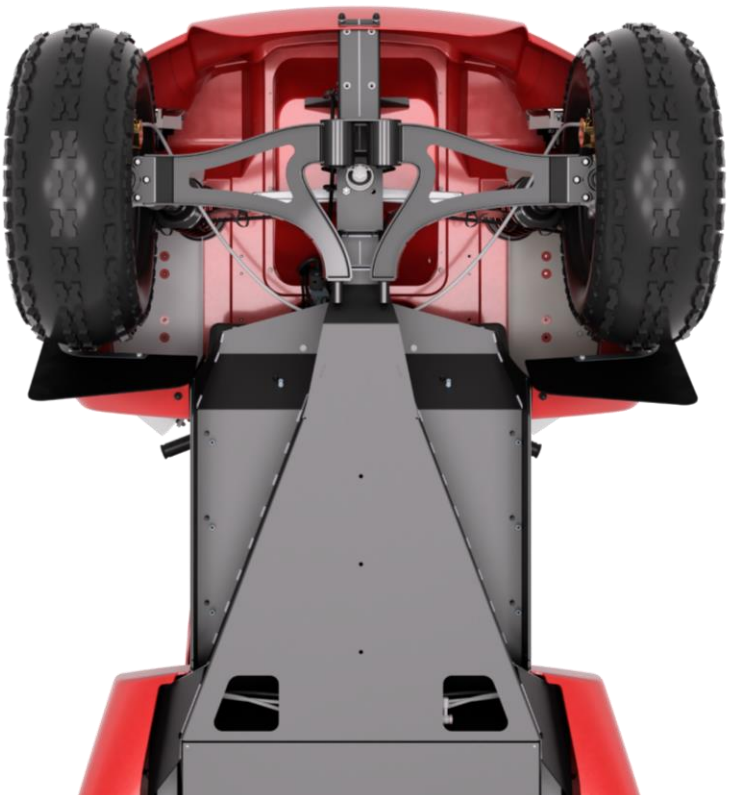

Figure 75. The suspension setup shown in context from below. ATV tires used for illustration. [58]

Figure 76. Front view of the suspension setup in context.

Figure 77. Same render as on the cover page. The new suspension setup needs to use different tires than currently being used. ATV Style tires used for illustration downloaded from [58]

8. Discussion

The geometric analysis in Lotus Engineering Shark analyses the suspension characteristics for a given displacement, like a certain amount of bump, this allows for quick analysis of various geometries. However, this will not achieve the same level of detail as a multi-body dynamics analysis, which would show the stresses in the components for a given movement type, like hitting a pothole, hand calculations and finite element analysis in Ansys Workbench were done to achieve similar results. Utilizing a multi-body dynamics software would likely provide better results, however no such software was available during the project.

The geometry of the suspension setup is done using the parameters suggested by Paxster. In order to compare the characteristics of each setup the same amounts of vertical travel is used, a total of 90mm. To achieve a smoother ride, utilizing a MacPherson strut with more travel is possible and realistic in the chosen MacPherson setup.

The chosen MacPherson suspension setup requires adjustments to be done to the chassis in order to mount the strut and the wishbone. The wishbone attachments are simple, these are simply plates that must be bent a little differently. Mounting the struts is more complex but possible as there should be adequate of free space, as shown earlier in the thesis.

The wishbone is meant to be produced using bending, cutting and welding, however the curves of some of the components are somewhat complex, the ease of bending this without using a press and a die is unclear and may need to be redesigned to achieve lower production cost.

Fatigue is commonly considered one of, if not the most common cause of failure in machines, as this was excluded in the project, it is vital this is done in further work. Failure from fatigue can occur even when the material is stressed significantly lower than its yield limit. Keeping this in mind an effort was made to keep the stress in the wishbone and steering mounting bracket significantly lower than the yield limit, at a cost of higher weight. [59]

Further work

Suspension and chassis development are large fields of work. Certain limitations have been placed on the report in order to maintain focus on the initial important aspects, as a result the report presents a suggested solution, upon which the viability of further development can be judged.

If the approach outlined in this thesis is selected for further development some areas of focus will be outlined.

- Calculating needed weld size and length if using intermittent welds. The thesis has attempted to use representative 3mm welds, although the underside of the upper web utilizes a 2mm weld due to space constraints. This space constraint may be solved by switching to taller flanges.
- Vehicles experience many varying loads as a result of uneven road surfaces and driver input, in order to make sure the wishbone has acceptable durability, fatigue studies must be done using a representative load range. This is especially vital as the

wishbones and steering brackets are welded and a failure may have dire consequences.

- The bushings used in the wishbone development are only used for representation and are not commercially available. Appropriate bushings and balljoints must be selected, and the wishbone may need some simple adjustments in order to fit these. Suppliers will also dictate the needed clearances for the bushings in order to obtain an appropriate fit.
- The wishbone and the selected suspension geometry does not utilize the existing chassis mounts. Further work will need to adjust the suspension mounting points and develop a mounting point for the MacPherson Strut.
- All FEM analysis was done using static approximations of the highest expected loads. Lotus Engineering Shark only provided a geometric analysis. A full multibody dynamics analysis may prove useful in further development.
- Verify the manufacturing feasibility for the steering bracket.
- Adjust the suspension setup to adopt a MacPherson strut with longer travel.
- Adjust and strengthen the chassis where needed to mount the MacPherson setup.

9. Conclusion

The thesis results are an improved suspension setup that allows for better space utilization in the front, lower amounts of bump steer and appropriate camber gain during bump. This setup also provides lower complexity and likely lower production costs. This setup requires some chassis modification to mount the strut and slight modification to the wishbone mounting locations.

Weight

The wishbone weighs in at 2346 grams in total, with the balljoint and bushing. The steering tie rod link adds an additional 133.6 grams. The total weight of the suspension setup per corner is dependent on the strut and chosen wheel and is currently unclear. The baseline wishbone weighs 2826 grams, however it is worth noting that the baseline setup requires two wishbones.

Functionality

0.061 degrees of bump steer, over 1 degree lower than the baseline.
90mm of suspension travel, 30mm droop and 60mm bump, however this may be increased using a MacPherson strut with longer travel.
The suspension system allows for 39 degrees of steering rotation.

Material Selection

The wishbone and steering tie rod mounting bracket are both intended to be manufactured using S355J2 steel, the J2 variant is selected in order to safeguard against impacts in colder conditions.

Production

Both the wishbone and the steering tie rod mounting bracket are meant to be produced by bending, cutting and welding sheet metal and common sections. This utilizes the experience and know-how of Paxster.

Strength and Safety Factor

The wishbone is subjected to a maximum of 134.7MPa of Von Mises stress, this implies a safety factor for yield of 2.59 with 0.56mm of maximum deformation.
The wishbone also achieves 28.366kN of first mode buckling strength, 10.694kN/mm of static stiffness in the x-direction and 102.46kN/mm stiffness in the y-direction.

The steering mounting bracket achieves a factor of safety for yield of 1.85 as a result of 188.6MPa Von Mises stress at one of the bolt connections. The steering mounting bracket has a maximum of 0.13mm deformation.

Bibliography

[1] Paxster A/S, "Paxster Generation 2," Paxster A/S, [Online]. Available: http://www.paxster.no/?ItemID=1224. [Accessed 13 08 2018].

[2] CARmag, "Technical: Understanding Suspension," [Online]. Available: http://www.carmag.co.za/technical/technical/technical-understanding-suspension/. [Accessed 13 08 2018].

[3] D. L. M. William F. Milliken, Race Car Vehicle Dynamics, Warrendale: Society of Automotive Engineers, 1995, p. 607.

[4] Daimler, "Company History - Benz Patent Motor Car: The first automobile (1885–1886)," [Online]. Available: https://www.daimler.com/company/tradition/company-history/1885-1886.html. [Accessed 29 04 2019].

[5] General Motors, "General Motors HiPer Strut Technology," [Online]. Available: http://gmauthority.com/blog/gm/general-motors-technology/gm-chassis-suspension-technology/gm-hiper-strut-chassis-suspension-technology/. [Accessed 29 04 2019].

[6] D. S. Burge, "The Systems Engineering Tool Box," [Online]. Available: https://www.burgehugheswalsh.co.uk/uploaded/1/documents/pugh-matrix-v1.1.pdf. [Accessed 07 01 2019].

[7] Mindtools, "SCAMPER- Improving products and services," [Online]. Available: https://www.mindtools.com/pages/article/newCT_02.htm. [Accessed 7 01 2019].

[8] Society of Automotive Engineers, "Vehicle Dynamics Terminology," Society of Automotive Engineers, Warrendale, PA, 1976.

[9] D. Steckelberg, "Development of an internal combustion engine fuel map model based on on-board acquisition," 11 2016. [Online]. Available: https://www.researchgate.net/publication/312577762_Development_of_an_internal_combustion_engine_fuel_map_model_based_on_on-board_acquisition. [Accessed 05 04 2019].

[10] D. L. M. William F. Miliken, Race Car Vehicle Dynamics, Warrendale: Society of Automotive Engineers, 1995, p. 627.

[11] Formula1 Dicitonary, "Pushrod-Pullrod," [Online]. Available: http://www.formula1-dictionary.net/pushrod_pullrod.html. [Accessed 14 08 2018].

[12] Longacre Racing Products, "Bump Steer," [Online]. Available: http://www.longacreracing.com/technical-articles.aspx?item=8162. [Accessed 02 10 2018].

[13] DSportMagazine, "Alignment Tech- Optimize Your Handling Performance," [Online]. Available: http://dsportmag.com/the-tech/extracting-handling-performance-alignment-settings/. [Accessed 25 09 2018].

[14] Formula1-Dictionary, "Unsprung Weight," [Online]. Available: http://www.formula1-dictionary.net/unsprung_weight.html. [Accessed 21 09 2018].

[15] Come and Drive It, "Learn camber,caster, toe," [Online]. Available: https://www.comeanddriveit.com/suspension/camber-caster-toe. [Accessed 21 01 2019].

[16] D. L. M. William F. Milliken, "Steering Systems," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 709-713.

[17] C. Constant, "Suspension design: definitions and effects on vehicle behavior," car engineer, 28 01 2013. [Online]. Available: www.car-engineer.com/suspension-design-and-effects-on-vehicle-behavior/. [Accessed 21 01 2019].

[18] D. L. M. William F. Milliken, "Chassis set-up," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 398-400.

[19] SuspensionDesigner, "KPI- Kingpin angle, scrub radius, wheel center offset.," [Online]. Available: http://www.suspensiondesigner.com/design-with-smbs/kpi-kingpin-angle-scrub-radius-wheel-centre-offset. [Accessed 25 09 2018].

[20] Glenn Research Center - NASA, "Center of gravity - cg," [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/cg.html. [Accessed 21 09 2018].

[21] D. L. M. William F. Milliken, "Instant Center Defined," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 610-612.

[22] Joes Racing Products, "Instant Center Adjustment," [Online]. Available: https://www.joesracing.com/rt-4197-instant-center-adjustment.html. [Accessed 21 09 2018].

[23] D. L. M. William F. Milliken, "Roll Center Height," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 613-614.

[24] Joes Racing Products, "Roll Center Magic," [Online]. Available: https://www.joesracing.com/rt-4179-roll-center-magic.html. [Accessed 21 09 2018].

[25] H. Heisler, "Learn more about Kingpins," ScienceDirect, 2002. [Online]. Available: https://www.sciencedirect.com/topics/engineering/kingpins/pdf. [Accessed 11 05 2019].

[26] D. L. M. William F. Milliken, "Ackerman Steering Geometry," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 713-716.

[27] P. A. &. A. R. Nitish Malik, "Design and Performance Optimisation of The Steering System of a Vehicle," International Journal of Automobile Engineering: http://www.tjprc.org/publishpapers/2-23-1509443168-1.IJAuERDDEC20171.pdf, Pradesh, 2017.

[28] P. Vijay, "How should I design for Ackermann geometry?," [Online]. Available: https://www.google.no/search?q=ackerman+percentage&source=lnms&tbm=isch&sa=X&ved=0ahUKEwi6-smco9jdAhXyw4sKHYidC8Y4HhD8BQgOKAE&biw=2560&bih=1368#imgrc=HOScCoD2MTkwIM:. [Accessed 26 09 2018].

[29] Engineers Edge, "Compression Spring Constant Equation and Calculator," [Online]. Available: https://www.engineersedge.com/spring_comp_calc_k.htm. [Accessed 27 10 2018].

[30] Steedablog, "Tech Tips Tuesday: Linear, Progressive and Dual Rate Springs Simplified," 09 01 2018. [Online]. Available: https://www.steedablog.com/2018/01/09/tech-tip-tuesday-linear-progressive-dual-rate-springs-simplified/. [Accessed 27 10 2018].

[31] R. N. Jazar, "Suspension Optimalization," in *Vehicle Dynamics : Theory and Application*, Springer International Publishing, 2018, p. 887.

[32] R. N. Jazar, "Suspension Optimization," in *Vehicle Dynamics: Theory and Application*, Springer International Publishing, 2017, pp. 893-943.

[33] R. N. Jazar, "Suspension Optimalization," in *Vehicle Dynamics: Theory and Application*, Springer International Publishing, 2017, p. 898.

[34] R. N. Jazar, "Suspension Optimalization," in *Vehicle Dynamics: Theory and Application*, Springer International Publishing, 2017, pp. 910-912.

[35] M. Giaraffa, "Springs and Dampers Tech Tip," [Online]. Available: http://www.optimumg.com/docs/Springs&Dampers_Tech_Tip_1.pdf. [Accessed 28 10 2018].

[36] J. Kasprzak, "Understanding your Dampers: A guide from Jim Kasprzak," Kaz Technologies, [Online]. Available: http://www.kaztechnologies.com/wp-content/uploads/2014/03/A-Guide-To-Your-Dampers-Chapter-from-FSAE-Book-by-Jim-Kasprzak.pdf. [Accessed 14 02 2019].

[37] Formula SAE / B. Riley, "Anthropometric Reference Data," 2016. [Online]. Available: https://www.fsaeonline.com/content/FSAE%20Rules95th_2016.pdf. [Accessed 11 05 2019].

[38] J. Happian-Smith, An Introduction to modern vehicle design., Oxford: Butterworth-Heinemann, 2002.

[39] S. Khan, "Comparative study between double wish-bone and," 2017. [Online]. Available: https://iopscience.iop.org/article/10.1088/1757-899X/263/6/062079/pdf. [Accessed 29 04 2019].

[40] P. K. S. P. &. V. D. S C Jain, "McPherson Suspension Systen - A Review," International Journal for Technological Research in Engineering, 2014.

[41] H. A. Garcia, Illinois Institute of Technology, [Online]. Available: https://addi.ehu.es/bitstream/handle/10810/19923/Steering%20System%20Design.pdf?sequence=1. [Accessed 17 04 2019].

[42] Koenigsegg Automotive AB, "Koenigsegg Automotive," Build 7128 - Subframe and Suspension, 13 12 2016. [Online]. Available: https://www.koenigsegg.com/build-7128-subframe-and-suspension/. [Accessed 12 03 2019].

[43] CarTechStuff, "Heim Joints," 18 08 2014. [Online]. Available: http://cartechstuff.blogspot.com/2014/08/heim-joints.html. [Accessed 12 03 2019].

[44] RideTech, "Why you need delrin the gold standard of suspension bushings," 29 03 2017. [Online]. Available: https://www.ridetech.com/info/why-you-need-delrin-the-gold-standard-of-suspension-bushings/. [Accessed 12 03 2019].

[45] A. S. /. MIT, "Fundamentals of Design," 2008. [Online]. Available: https://web.mit.edu/2.75/fundamentals/FUNdaMENTALs%20Book%20pdf/FUNdaMENTALs%20Topic%2010.PDF. [Accessed 02 05 2019].

[46] J. Ziobro, "ANALYSIS OF SUSPENSION ELEMENT OF CAR BODY ON THE EXAMPLE SILENTBLOCK," *Advances in Science and Technology Research Journal,* vol. 2015, no. Volume 9, Issue 28, pp. 125-129, 2015.

[47] Amazon, "Moog K778 Ball Joint," Amazon, [Online]. Available: https://www.amazon.com/Moog-K778-Ball-Joint/dp/B000C59Z0Y. [Accessed 15 03 2019].

[48] Amazon, "Track Control ARm," [Online]. Available: https://www.amazon.com/Lemf%C3%A3%C6%92-RDER-Lemf%C3%A3%C6%92%C3%A2-Track-Control/dp/B00WR2HMLE. [Accessed 15 03 2019].

[49] R. S. Hannes Fuchs, "Lightweight MacPherson Strut Suspension Front Lower Control Arm Design Development, 2011-01-0562," Society of Automotive Engineers, 2011.

[50] The Concrete Countertop Institute, "It's All in the Mold, Part 1: Mold Making Concepts," [Online]. Available: https://concretecountertopinstitute.com/free-training/its-all-in-the-mold-part-1-mold-making-concepts/. [Accessed 25 03 2019].

[51] S. R. S. Serope Kalpakjian, "Islamic University of Gaza," [Online]. Available: http://site.iugaza.edu.ps/aafeefy/files/2013/02/Ch-12-Metal-Casting-Design-Materials-and-Economics1.ppt. [Accessed 25 03 2019].

[52] Todays Machining World, "How It Works – Machining cast aluminum parts," 04 2008. [Online]. Available: https://todaysmachiningworld.com/magazine/how-it-works-machining-cast-aluminum-parts/. [Accessed 28 04 2019].

[53] Wenzel Metal Spinning, "Steel vs Aluminium," [Online]. Available: https://www.wenzelmetalspinning.com/steel-vs-aluminum.html. [Accessed 25 03 2019].

[54] MeadInfo, "Material Properties of S355 Steel - An overview," [Online]. Available: https://www.meadinfo.org/2015/08/s355-steel-properties.html. [Accessed 25 03 2019].

[55] Welding-Advisors, "Welding Distortion: How to prevent and avoid," [Online]. Available: https://www.welding-advisers.com/Welding-distortion.html. [Accessed 29 03 2019].

[56] Lincoln Electric, "Weld Distortion," [Online]. Available: https://www.lincolnelectric.com/en-gb/support/welding-how-to/Pages/weld-distortion-detail.aspx. [Accessed 29 03 2019].

[57] Optimum G, "Technical Papers," Optimum G, [Online]. Available: http://www.optimumg.com/technical/technical-papers/. [Accessed 14 03 2019].

[58] E. Araujo, "ATV Font tire/wheel set," GrabCad, 29 10 2016. [Online]. Available: https://grabcad.com/library/atv-font-tire-wheel-set-1. [Accessed 03 04 2019].

[59] Curtis Wright IMR Test Labs, "EXPLORING DIFFERENT TYPES OF FATIGUE FAILURE," [Online]. Available: https://www.imrtest.com/blog/exploring-different-types-fatigue-failure. [Accessed 22 04 2019].

[60] D. L. M. William F. Miliken, Race Car Vehicle Dynamics, Warrendale: Society of Automotive Engineers, 1995, p. 632.

[61] RacingAspirations, "Suspension Calculator," 18 09 2018. [Online]. Available: https://www.racingaspirations.com/apps/suspension-geometry-calculator/.

[62] RcTek, "Ackerman Steering Principle," [Online]. Available: http://www.rctek.com/technical/handling/ackerman_steering_principle.html. [Accessed 21 09 2018].

[63] ProWiringDiagram, "Wheel Hub Diagram," [Online]. Available: http://prowiringdiagram.today/wheel-hub-diagram.html. [Accessed 25 09 2018].

[64] Department of Mechanical & Aerospace Engineering, University of Florida, "Steering (differential steering, rack & pinion and front vs. rear wheel steering.," [Online]. Available: http://www2.mae.ufl.edu/designlab/Class%20Projects/Background%20Information/Steering.htm. [Accessed 02 10 2018].

[65] T. Parry, "Turnology," 09 April 2018. [Online]. Available: https://www.turnology.com/tech-stories/brakes-suspension/appeal-pushrod-suspension/. [Accessed 17 10 2018].

[66] United Nations Economic Commision for Europe, "Determination of Vehicle's CG Position," 20 10 2000. [Online]. Available: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29grsg/grsginf/79/GRSG79_inf11.pdf. [Accessed 17 01 2019].

[67] Mitt Dekkvalg, "Alternative Dimensjoner," [Online]. Available: http://www.mittdekkvalg.no/dekkinformasjon/alternative-dimensjoner/. [Accessed 24 01 2019].

[68] D. L. M. William F. Milliken, "Slip Angle Clarified," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 2019, pp. 18-19.

[69] J. H. Hanssen, "Dolphin Duo 1+1: Development of wheelbase," IMT/NMBU, Ås, 2014.

[70] The Technical World of F1 Explained, "F1 Tires... Part 2," 22 10 2012. [Online]. Available: http://technicalf1explained.blogspot.com/2012/10/f1-tirespart-2.html. [Accessed 5 02 2019].

[71] T. K. U. L. M. Kiumars Jalali, "Development of an Advanced Torque Vectoring Control System for an Electric Vehicle with In-Wheel Motors using Soft Computing Techniques," 4 2013. [Online]. Available: https://www.researchgate.net/publication/256422220_Development_of_an_Advanced_Torque_Vectoring_Control_System_for_an_Electric_Vehicle_with_In-Wheel_Motors_using_Soft_Computing_Techniques . [Accessed 05 02 2019].

[72] Skandinavisk Veibetong, "Betongkantstein og lave profiler.," [Online]. Available: http://www.veibetong.no/betongkantstein_lave_profiler.php. [Accessed 06 02 2019].

[73] Racing Car Dynamics, "A Discussion on Steady-State Lateral Weight Transfer and How To Use It In Setup," [Online]. Available: http://racingcardynamics.com/weight-transfer/. [Accessed 07 02 2019].

[74] AutoCarIndia, "Car Suspension System," AutoCarIndia, 07 12 2017. [Online]. Available: http://autocarindia.in/apollotyres/car-suspension-system/. [Accessed 14 08 2018].

[75] D. L. M. William F. Milliken, "Two Types of Axis Systems," in *Race Car Vehicle Dynamics*, Warrendale, Society of Automotive Engineers, 1995, pp. 114-118.

[76] R. Ledesma, "Slideshare," 10 03 2015. [Online]. Available: https://www.slideshare.net/RagnarLedesaPEPhD/vehicle-dynamics-45667777. [Accessed 02 10 2018].

[77] Atlas Tool Inc., "Services," [Online]. Available: http://www.atlastool.com/services.html. [Accessed 18 03 2019].

[78] J. Fox, "Grabcad Silent Block," 13 03 2015. [Online]. Available: https://grabcad.com/library/silent-block-1. [Accessed 25 03 2019].

[79] G. Terjesen, Skrueforbindelser, Ås: REALTEK/NMBU, 2018.

List of Figures

Figure 1. SLA Wishbone Configuration. [2] 1
Figure 2. SAE Axis system. [9] 9
Figure 3. Typical MacPherson suspension setup. [2] 10
Figure 4. Pullrod setup in a Formula 1 car [11] 10
Figure 5. Pushrod setup in a Formula 1 car [11] 10
Figure 6. Illustrates the placement of the tie rod in relation to the upper and lower wishbone. [12] 11
Figure 7.Positive, neutral and negative camber, as well as the advantage of negative camber. Note the contact patch below the tire for the various situations. [13] 12
Figure 8. Toe angle illustrations. [15] 13
Figure 9. Illustrates caster angles for a McPherson setup. [13] 13
Figure 10. Scrub radius. [19] 14
Figure 11. Illustrates the instant center for a double wishbone suspension setup. [22] 15
Figure 12. Illustrates how to find the instant centers and the roll center. [24] 15
Figure 13. Kingpin angle. [19] 16
Figure 14. Measurements used in calculation of Ackerman percentage. [28] 17
Figure 15. Spring constant and transformation. [31] 18
Figure 16. Equivalent spring constant calculation for MacPherson suspension. [33] 18
Figure 17. Optimal spring rates as a result of sprung mass and ride frequency from [35] 19
Figure 18. Displays static center of gravity (illustration) in relation to the weight carried by the front and rear tires as well as the distance between them. Only for x-direction. 21
Figure 19. The steering plate, in red, has a notch that limits the maximum steering input to 39 degrees. 25
Figure 20. Hardpoint locations and numbers for the double wishbone setups. 28
Figure 21. The completed suspension setup in Lotus Engineering Shark as seen from the front. 29
Figure 22. The completed suspension setup in Lotus Engineering Shark as seen from the top. 29
Figure 23. The completed suspension setup in Lotus Engineering Shark as seen from the side. 29
Figure 24. Wheel camber for the full range of vertical suspension movement. Camber (Y) vs Wheel Travel (X). 31
Figure 25. Toe Angle (PLANE) plotted for full bump/droop range of motion. Toe Angle (Y) vs Wheel Travel (X) 31
Figure 26. Toe angle for bump travel (-30mm to 60mm) at a static 42 degrees of steering travel. Outside wheel. Toe Angle (Y) vs Bump Travel (X). 32
Figure 27. SAE Toe angle for bump travel (-30 to 60mm) at a static 39 degrees of steering input. Inside and outside wheel. 32
Figure 28. Roll vs Camber Angle. Minimum camber: 2.9 deg. Maximum camber: 2.8 deg. Camber Angle (Y) vs. Roll Angle (X) 33
Figure 29. Difference in mounting between the baseline and the Double Wishbone SLA Adjusted Track Rod Mounts Setup, both track rod mounts are changed equally. 34

Figure 30. Bump steer graph for the new Track Rod Ball Joint mounting position. Toe Angle (Y) vs Wheel Travel (X)........ 35
Figure 31. Bump steer graph for the old Track Rod Ball Joint mounting position. Toe Angle (Y) vs Wheel Travel (X)........ 35
Figure 32. Toe Angle for maximum bump and steering angle for the Double Wishbone SLA Adjusted Track Rod Mounts setup........ 36
Figure 33. Camber Angle (Y) vs. Roll Angle(X). Minimum Camber: -2.88 deg. Maximum Camber: 2.77 deg........ 37
Figure 34. Double Wishbone SLA Adjusted Pickup Points and the changed hardpoints. Values in the table below........ 37
Figure 35. Double Wishbone SLA Adjusted Pickup Points. Camber Angle (Y) vs Wheel Travel (X)........ 38
Figure 36. Toe Angle for Double Wishbone SLA Adjusted Pickup Points. Toe Angle (Y) vs Wheel Travel (X)........ 39
Figure 37. Toe Angle vs Bump Travel at 39 Degrees of Steering Input for Double Wishbone SLA Adjusted Pickup Points........ 39
Figure 38. Camber Angle (Y) vs. Roll Angle (X). Minimum Camber: -2.9. Maximum Camber: 2.68 deg........ 40
Figure 39. Comex MacPherson upright, brake disc and wheel hub. Supplied by Paxster........ 40
Figure 40. Illustration of a MacPherson setup and hardpoints........ 41
Figure 41. Front view of MacPherson Setup Old Pickup Points in Lotus Engineering........ 41
Figure 42. Camber Angle (Y) vs Bump Travel (X). Minimum Camber: -2.18deg. Maximum Camber: 1.3 deg........ 42
Figure 43. Toe Angle (Y) vs. Bump Travel (X). Minimum Toe Angle: -0.02deg. Maximum Toe Angle: 0.06deg........ 42
Figure 44. Graph showing the toe angle of both front wheels as a result of bump travel at 39 degrees of steering input........ 43
Figure 45. Camber Angle (Y) vs. Roll Angle (X). Minimum camber:-3.07 deg. Maximum camber: 1.25 deg........ 43
Figure 46. MacPherson Suspension Setup........ 44
Figure 47. Camber Angle (Y) vs Bump Travel (X). Minimum Camber: -1.71deg. Maximum Camber: 1.07 deg........ 45
Figure 48. Toe Angle (Y) vs Bump Travel (X). Minimum Toe angle: -0.004 deg Maximum Toe Angle: 0.041 deg........ 45
Figure 49. Graph showing the toe angle of both front wheels as a result of bump travel at 39 degrees of steering input........ 46
Figure 50. Camber Angle (Y) vs. Roll Angle (X). Minimum camber: -2.12 deg. Maximum camber: 2.22 deg........ 46
Figure 51. Simplified calculation of resulting forces in the wishbone and MacPherson Strut mount due to the longitudinal forces in the Wishbone FBD Pothole Bump Load scenario........ 49
Figure 52. Wishbone FBD Pothole Bump Load........ 49
Figure 53. Simplified calculation of resulting forces in the wishbone and MacPherson Strut mount due to the transverse forces in the Wishbone Lateral Curb Load scenario........ 50
Figure 54. Wishbone FBD Curb Strike Load........ 50
Figure 55. Sizes for tie rod force calculations........ 51
Figure 56. FBD for finding tie rod forces........ 52

Figure 57. Double Wishbone utilizing Heim Joints (Left) and Double Wishbone utilizing bushings (Right) [43], [44]. 53
Figure 58. Ball joint for connecting a wishbone to an upright. [47] 54
Figure 59. Single wheel turning envelope. [48] 54
Figure 60. Draft angle. [50] 56
Figure 61. Current lower front wishbone. 56
Figure 62. Overview of the vital components. 58
Figure 63. Welded Wishbone solid Von Mises equivalent stress for pothole bump scenario.59
Figure 64. Welded Wishbone with 25mm offset cutout Von-Mises equivalent stress for pothole scenario. 60
Figure 65. Welded Wishbone Version 1 explosion drawing. 61
Figure 66 FEM Analysis results for the steering tie rod mounting bracket. Highest stress concentration at the mounting holes. 62
Figure 67. Existing wishbone to chassis mounting brackets. 62
Figure 68. Location for wishbone and MacPherson Strut mounting. 63
Figure 69. Overview of the example welds on the final welded wishbone shown in red. 64
Figure 70. Final baseline Force vs. Absolute Velocity curve. 66
Figure 71. Steering bracket and wishbone shown in context, including purchased components. 67
Figure 72 Steering bracket and wishbone shown in context, including purchased components. 68
Figure 73. Wishbone shown in context, including purchased components. 69
Figure 74. Wishbone shown in context, including purchased components. 69
Figure 75. The suspension setup shown in context from below. ATV tires used for illustration. [58] 69
Figure 76. Front view of the suspension setup in context. 70
Figure 77. Same render as on the cover page. The new suspension setup needs to use different tires than currently being used. ATV Style tires used for illustration downloaded from [58] 70
Figure 78 Front-end render of baseline suspension setup. I
Figure 79 Isometric view render of baseline suspension setup. I

List of Tables

Table 1 Terminology 4
Table 2 Equations 5
Table 3 Parameter units 6
Table 4 Caster Angle for various vehicles [17]. 13
Table 5 Scrub radius for various vehicles [17]. 14
Table 6. Kingpin angle for various vehicles [17]. 16
Table 7 Empty Vehicle Static Input Values 21
Table 8 Static Forces Results, Empty Car 22
Table 9 Static Forces Results, Fully Laden Car (535kg) 22
Table 10 Overview of shock factor for various load cases. [38] 22
Table 11 Front Wheels Dynamic Loads, approx. [38] 23
Table 12 Weighting factors for selection matrix. 24
Table 13 Suspension Setup Goals. 24
Table 14 Summary of advantages and disadvantages of the chosen suspension types. [39] . 27
Table 15. Static suspension values baseline analysis. 30
Table 16 Baseline Analysis Results, Maximum Bump and Droop. 30
Table 17 Analysis verification factors. 33
Table 18. Comparing coordinates for hardpoint 10. 34
Table 19. Hardpoint coordinate changes seen in relation to the baseline. 37
Table 20. Static Values for Double Wishbone SLA Adjusted Pickup Points. 38
Table 21 MacPherson Old Pickup Points Static Results 41
Table 22. Changes in hardpoint coordinates compared to MacPherson Old Pickup Points. .. 44
Table 23. MacPherson New Pickup Points Static Results 44
Table 24. Summary of the geometric suspension analysis, the goal for the parameter is shown in parenthesis. 46
Table 25. Weighted Pugh's analysis of the various suspension setups. 47
Table 26. Front Wheels Dynamic Loads. 48
Table 27. Comparison of various mounting interfaces. [45] 53
Table 28 Steering Input and resulting toe angles. 54
Table 29. MacPherson Lower Wishbone Relative Coordinates. 54
Table 30. General overview of material properties for aluminum and steel and the chosen S355J2 steel obtained from CES EduPak. 56
Table 31. Overview of chosen design parameters. 57
Table 32. Additional structural performance metrics. Same coordinate system as described in 4.1 Coordinate System. [49] 58
Table 33. Welded Wishbone Solid simulation results. 59
Table 34. Welded Wishbone with 25mm offset cutout simulation results. 60
Table 35. Welded Wishbone Version 1 component list. 61
Table 36 FEM Analysis results for the steering tie rod mounting bracket. 62
Table 37. Unsprung mass obtained from CAD model summarized. 64
Table 38. Input parameters spring and damping constants. 65
Table 39. Optimal spring and damper constants at various loads, with 102kg driver. 65

Attachments

Attachment 1 Various Renders

Figure 78 Front-end render of baseline suspension setup.

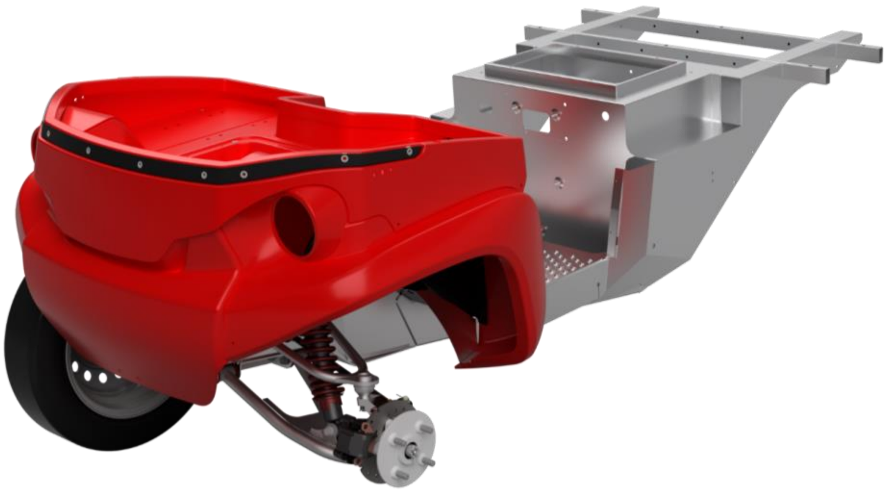

Figure 79 Isometric view render of baseline suspension setup.

Attachment 2 Baseline Suspension Analysis Results Maximum Bump and Droop

```
*********************************************************************************
*
    18/01/2019                                                         15:13:16
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                           Default Bump/Rebound
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: D:\lesoft\Paxster.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                             STATIC VALUES
          X         Y         Z
        (mm)      (mm)      (mm)
    734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
    537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
    668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
    710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
    513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
    653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
    669.847   290.614    16.399    POINT:7          Damper Wishbone End
    624.910   181.127   275.958    POINT:8          Damper Body End
    571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
    562.922    16.000   130.626    POINT:10         Inner Track Rod Ball Joint
    663.844   439.000    30.456    POINT:13         Wheel Spindle point
    663.844   466.481    30.456    POINT:14         Wheel Centre Point
   4030.000   440.000   195.000    POINT:15         Part 1 C of G
   4170.000   520.000   450.000    POINT:16         Part 2 C of G
   4230.000   525.000   220.000    POINT:17         Part 3 C of G
   4130.000   720.000   275.000    POINT:18         Part 4 C of G
    652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
    610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
    563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -5.52
               Castor Trail (hub)   (mm):   -0.480
             Castor Offset (grnd)   (mm):  -24.143
                    Kingpin Angle  (deg):    11.68
             Kingpin Offset (w/c)   (mm):   78.439
            Kingpin Offset (grnd)   (mm):   25.708
          Mechanical Trail (grnd)   (mm):  -24.031
               ROLL CENTRE HEIGHT   (mm):  138.438

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
       BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       10.000
    REBOUND TRAVEL    (mm):       30.000          INCREMENT    (mm):       10.000
        ROLL ANGLE   (deg):         3.00     ROLL INCREMENT   (deg):         0.50
 STEERING ROTATION   (deg):     30.000    STEERING INCREMENT  (deg):        5.000
```

****
*
18/01/2019 15:13:16
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****
*

FRONT SUSPENSION - BUMP TRAVEL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-0.6654	0.6458	-5.5034	12.4112	1.662	1.662	13.9
50.00	-0.5138	0.5587	-5.5061	12.2512	1.664	1.664	12.1
40.00	-0.3777	0.4641	-5.5085	12.1059	1.666	1.666	10.1
30.00	-0.2576	0.3615	-5.5107	11.9759	1.666	1.666	7.9
20.00	-0.1541	0.2504	-5.5126	11.8617	1.666	1.666	5.5
10.00	-0.0679	0.1302	-5.5142	11.7639	1.666	1.666	2.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.664	1.664	0.0
-10.00	0.0485	-0.1412	-5.5165	11.6214	1.661	1.661	-3.1
-20.00	0.0761	-0.2944	-5.5172	11.5792	1.657	1.657	-6.4
-30.00	0.0811	-0.4612	-5.5175	11.5583	1.652	1.652	-9.9

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	126.53	0.00	142.39	82.39	13.85	11.33	-36.03	-36.03
50.00	120.52	0.00	141.71	91.71	12.08	9.48	-30.02	-30.02
40.00	115.09	0.00	141.04	101.04	10.09	7.61	-24.01	-24.01
30.00	110.17	0.00	140.39	110.39	7.90	5.73	-18.01	-18.01

20.00	105.71	0.00	139.74	119.74	5.49	3.84	-12.01	-12.01
10.00	101.64	0.00	139.10	129.10	2.85	1.93	-6.01	-6.01
0.00	97.92	0.00	138.44	138.44	0.00	0.00	0.00	0.00
-10.00	94.52	0.00	137.76	147.76	-3.08	-1.94	6.02	6.02
-20.00	91.41	0.00	137.06	157.06	-6.39	-3.91	12.04	12.04
-30.00	88.57	0.00	136.32	166.32	-9.94	-5.90	18.09	18.09

****
18/01/2019 15:13:17
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****

FRONT SUSPENSION - BUMP TRAVEL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-0.6654	0.6458	-5.5034	12.4112	1.662	1.662	13.9
50.00	-0.5138	0.5587	-5.5061	12.2512	1.664	1.664	12.1
40.00	-0.3777	0.4641	-5.5085	12.1059	1.666	1.666	10.1
30.00	-0.2576	0.3615	-5.5107	11.9759	1.666	1.666	7.9
20.00	-0.1541	0.2504	-5.5126	11.8617	1.666	1.666	5.5
10.00	-0.0679	0.1302	-5.5142	11.7639	1.666	1.666	2.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.664	1.664	0.0
-10.00	0.0485	-0.1412	-5.5165	11.6214	1.661	1.661	-3.1
-20.00	0.0761	-0.2944	-5.5172	11.5792	1.657	1.657	-6.4
-30.00	0.0811	-0.4612	-5.5175	11.5583	1.652	1.652	-9.9

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel	Anti Dive	Anti Squat	Roll Centre	Roll Centre	Half Track	Wheelbase Change	Damper1 Travel	Spring1 Travel

(mm)	(%)	(%)	Height {to Body} (mm)	Height {to Grnd} (mm)	Change (mm)	(mm)	(mm)	(mm)
60.00	126.53	0.00	142.39	82.39	13.85	11.33	-36.03	-36.03
50.00	120.52	0.00	141.71	91.71	12.08	9.48	-30.02	-30.02
40.00	115.09	0.00	141.04	101.04	10.09	7.61	-24.01	-24.01
30.00	110.17	0.00	140.39	110.39	7.90	5.73	-18.01	-18.01
20.00	105.71	0.00	139.74	119.74	5.49	3.84	-12.01	-12.01
10.00	101.64	0.00	139.10	129.10	2.85	1.93	-6.01	-6.01
0.00	97.92	0.00	138.44	138.44	0.00	0.00	0.00	0.00
-10.00	94.52	0.00	137.76	147.76	-3.08	-1.94	6.02	6.02
-20.00	91.41	0.00	137.06	157.06	-6.39	-3.91	12.04	12.04
-30.00	88.57	0.00	136.32	166.32	-9.94	-5.90	18.09	18.09

Attachment 3 Baseline Suspension Analysis Results 39 degrees of Steering Travel

```
*********************************************************************************
*
    26/02/2019                                                     15:20:56
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                     Default Combined Mode
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: Paxster.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                                 STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
   537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
   513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    16.000   130.626    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                                 STATIC VALUES
                      Camber Angle  (deg):     0.00
                 Toe Angle {Plane}  (deg):     0.00
                   Toe Angle {SAE}  (deg):     0.00
                      Castor Angle  (deg):    -5.52
                Castor Trail (hub)   (mm):   -0.480
              Castor Offset (grnd)   (mm):  -24.143
                     Kingpin Angle  (deg):    11.68
              Kingpin Offset (w/c)   (mm):   78.439
             Kingpin Offset (grnd)   (mm):   25.708
           Mechanical Trail (grnd)   (mm):  -24.031
                ROLL CENTRE HEIGHT   (mm):  138.438

                             GENERAL DATA VALUES
               TYRE ROLLING RADIUS   (mm):  255.000
                         WHEELBASE   (mm): 2240.000
                     C OF G HEIGHT   (mm):  250.000
            BREAKING ON FRONT AXLE    (%):    60.00
               DRIVE ON FRONT AXLE    (%):     0.00
              WEIGHT ON FRONT AXLE    (%):    40.00
                    OUTBOARD FRONT BRAKES:
             INDEPENDENT FRONT SUSPENSION:
           STEERING BOX TYPE ARTICULATION:

                                   RUN DETAILS
                    FRONT SUSPENSION ONLY:
     BUMP TRAVEL    (mm):       60.000          INCREMENT   (mm):       10.000
  REBOUND TRAVEL    (mm):       30.000          INCREMENT   (mm):       10.000
      ROLL ANGLE   (deg):         3.00     ROLL INCREMENT  (deg):         0.50
```

STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
*
26/02/2019 15:20:56
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
60.00	-39.00	-1.852	-24.004	-5.504	12.382	1.662	1.662
50.00	-39.00	-1.710	-24.014	-5.507	12.225	1.665	1.665
40.00	-39.00	-1.582	-24.029	-5.509	12.082	1.667	1.667
30.00	-39.00	-1.468	-24.051	-5.511	11.955	1.668	1.668
20.00	-39.00	-1.368	-24.081	-5.513	11.844	1.668	1.668
10.00	-39.00	-1.282	-24.119	-5.514	11.749	1.667	1.667
0.00	-39.00	-1.213	-24.166	-5.516	11.672	1.666	1.666
-10.00	-39.00	-1.161	-24.226	-5.517	11.613	1.663	1.663
-20.00	-39.00	-1.126	-24.298	-5.517	11.574	1.659	1.659
-30.00	-39.00	-1.111	-24.386	-5.518	11.557	1.654	1.654

****
*
26/02/2019 15:20:56
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
60.00	-39.00	4.181	32.665	-5.502	12.515	1.653	1.653
50.00	-39.00	4.363	32.851	-5.504	12.346	1.657	1.657
40.00	-39.00	4.531	33.032	-5.507	12.191	1.660	1.660
30.00	-39.00	4.686	33.210	-5.509	12.052	1.662	1.662
20.00	-39.00	4.826	33.386	-5.512	11.928	1.664	1.664
10.00	-39.00	4.952	33.561	-5.513	11.820	1.665	1.665
0.00	-39.00	5.063	33.736	-5.515	11.729	1.666	1.666
-10.00	-39.00	5.159	33.913	-5.516	11.656	1.665	1.665
-20.00	-39.00	5.241	34.094	-5.517	11.602	1.664	1.664
-30.00	-39.00	5.306	34.281	-5.517	11.568	1.662	1.662

Attachment 4 Baseline Suspension Analysis Result Vehicle Roll in Steady State Cornering

```
*********************************************************************************
*
    10/04/2019                                                      12:07:02
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                                Default Roll
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterAdjustedTrackRod.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
   537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
   513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    16.000   130.626    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -5.52
               Castor Trail (hub)   (mm):   -0.480
             Castor Offset (grnd)   (mm):  -24.143
                    Kingpin Angle  (deg):    11.68
             Kingpin Offset (w/c)   (mm):   78.439
            Kingpin Offset (grnd)   (mm):   25.708
          Mechanical Trail (grnd)   (mm):  -24.031
               ROLL CENTRE HEIGHT   (mm):  138.438

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                  OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                  FRONT SUSPENSION ONLY:
      BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       20.000
   REBOUND TRAVEL    (mm):       60.000          INCREMENT    (mm):       20.000
```

ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

FRONT SUSPENSION - ROLL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	-2.9189	-0.3636	-5.5844	14.5676	1.683	1.683
2.50	-2.4235	-0.2981	-5.5719	14.0785	1.680	1.680
2.00	-1.9318	-0.2347	-5.5599	13.5928	1.677	1.677
1.50	-1.4437	-0.1733	-5.5482	13.1106	1.674	1.674
1.00	-0.9591	-0.1138	-5.5369	12.6316	1.670	1.670
0.50	-0.4779	-0.0560	-5.5260	12.1560	1.667	1.667
0.00	0.0000	0.0000	-5.5155	11.6835	1.664	1.664
-0.50	0.4746	0.0543	-5.5053	11.2141	1.660	1.660
-1.00	0.9460	0.1071	-5.4955	10.7478	1.657	1.657
-1.50	1.4142	0.1583	-5.4859	10.2845	1.654	1.654
-2.00	1.8793	0.2080	-5.4768	9.8242	1.650	1.650
-2.50	2.3413	0.2562	-5.4679	9.3668	1.647	1.647
-3.00	2.8003	0.3030	-5.4593	8.9123	1.643	1.643

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-5.53	138.40	0.02	-4.83	14.59	14.59
2.50	663.84	-4.59	138.41	0.01	-4.01	12.17	12.17
2.00	663.84	-3.66	138.42	0.01	-3.20	9.75	9.75
1.50	663.84	-2.74	138.43	0.01	-2.39	7.32	7.32
1.00	663.84	-1.82	138.43	0.00	-1.59	4.88	4.88
0.50	663.84	-0.91	138.44	0.00	-0.79	2.44	2.44
0.00	663.84	0.00	138.44	0.00	0.00	0.00	0.00
-0.50	663.84	0.91	138.44	0.00	0.78	-2.45	-2.45
-1.00	663.84	1.82	138.43	0.00	1.56	-4.90	-4.90
-1.50	663.84	2.74	138.43	0.00	2.34	-7.36	-7.36
-2.00	663.84	3.66	138.42	0.01	3.11	-9.83	-9.83
-2.50	663.84	4.59	138.41	0.01	3.88	-12.30	-12.30
-3.00	663.84	5.53	138.40	0.02	4.64	-14.77	-14.77

****
10/04/2019 12:07:02
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****

FRONT SUSPENSION - ROLL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	2.8003	0.3030	-5.4593	8.9123	1.643	1.643
2.50	2.3413	0.2562	-5.4679	9.3668	1.647	1.647
2.00	1.8793	0.2080	-5.4768	9.8242	1.650	1.650
1.50	1.4142	0.1583	-5.4859	10.2845	1.654	1.654
1.00	0.9460	0.1071	-5.4955	10.7478	1.657	1.657
0.50	0.4746	0.0543	-5.5053	11.2141	1.660	1.660
0.00	0.0000	0.0000	-5.5155	11.6835	1.664	1.664
-0.50	-0.4779	-0.0560	-5.5260	12.1560	1.667	1.667
-1.00	-0.9591	-0.1138	-5.5369	12.6316	1.670	1.670
-1.50	-1.4437	-0.1733	-5.5482	13.1106	1.674	1.674
-2.00	-1.9318	-0.2347	-5.5599	13.5928	1.677	1.677
-2.50	-2.4235	-0.2981	-5.5719	14.0785	1.680	1.680
-3.00	-2.9189	-0.3636	-5.5844	14.5676	1.683	1.683

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-5.53	138.40	0.02	4.64	-14.77	-14.77
2.50	663.84	-4.59	138.41	0.01	3.88	-12.30	-12.30
2.00	663.84	-3.66	138.42	0.01	3.11	-9.83	-9.83
1.50	663.84	-2.74	138.43	0.00	2.34	-7.36	-7.36
1.00	663.84	-1.82	138.43	0.00	1.56	-4.90	-4.90
0.50	663.84	-0.91	138.44	0.00	0.78	-2.45	-2.45
0.00	663.84	0.00	138.44	0.00	0.00	0.00	0.00
-0.50	663.84	0.91	138.44	0.00	-0.79	2.44	2.44
-1.00	663.84	1.82	138.43	0.00	-1.59	4.88	4.88
-1.50	663.84	2.74	138.43	0.01	-2.39	7.32	7.32
-2.00	663.84	3.66	138.42	0.01	-3.20	9.75	9.75
-2.50	663.84	4.59	138.41	0.01	-4.01	12.17	12.17
-3.00	663.84	5.53	138.40	0.02	-4.83	14.59	14.59

Attachment 5 Double Wishbone SLA Adjusted Track Rod Mounts Maximum Bump & Droop

```
***********************************************************************************
*
    26/02/2019                                                  15:35:02
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                    Default Bump/Rebound
***********************************************************************************
*

     FRONT SUSPENSION       FILENAME: Paxster.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
    734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
    537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
    668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
    710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
    513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
    653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
    669.847   290.614    16.399    POINT:7          Damper Wishbone End
    624.910   181.127   275.958    POINT:8          Damper Body End
    571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
    562.922    26.000   135.000    POINT:10         Inner Track Rod Ball Joint
    663.844   439.000    30.456    POINT:13         Wheel Spindle point
    663.844   466.481    30.456    POINT:14         Wheel Centre Point
   4030.000   440.000   195.000    POINT:15         Part 1 C of G
   4170.000   520.000   450.000    POINT:16         Part 2 C of G
   4230.000   525.000   220.000    POINT:17         Part 3 C of G
   4130.000   720.000   275.000    POINT:18         Part 4 C of G
    652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
    610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
    563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -5.52
               Castor Trail (hub)   (mm):   -0.480
             Castor Offset (grnd)   (mm):  -24.143
                    Kingpin Angle  (deg):    11.68
             Kingpin Offset (w/c)   (mm):   78.439
            Kingpin Offset (grnd)   (mm):   25.708
          Mechanical Trail (grnd)   (mm):  -24.031
               ROLL CENTRE HEIGHT   (mm):  140.727

                         GENERAL DATA VALUES
                TYRE ROLLING RADIUS   (mm):  255.000
                          WHEELBASE   (mm): 2240.000
                      C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE      (%):    60.00
              DRIVE ON FRONT AXLE      (%):     0.00
             WEIGHT ON FRONT AXLE      (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
        BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       10.000
     REBOUND TRAVEL    (mm):       30.000          INCREMENT    (mm):       10.000
```

ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
26/02/2019 15:35:02
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****

FRONT SUSPENSION - BUMP TRAVEL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-0.7253	0.0155	-5.5034	12.4098	1.664	1.664	14.1
50.00	-0.5654	0.0164	-5.5061	12.2500	1.666	1.666	12.3
40.00	-0.4204	0.0160	-5.5086	12.1051	1.668	1.668	10.3
30.00	-0.2907	0.0142	-5.5107	11.9754	1.669	1.669	8.0
20.00	-0.1770	0.0109	-5.5126	11.8614	1.669	1.669	5.6
10.00	-0.0798	0.0062	-5.5142	11.7638	1.668	1.668	2.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.667	1.667	0.0
-10.00	0.0612	-0.0079	-5.5165	11.6215	1.664	1.664	-3.1
-20.00	0.1026	-0.0176	-5.5172	11.5793	1.660	1.660	-6.5
-30.00	0.1224	-0.0293	-5.5175	11.5584	1.655	1.655	-10.1

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	123.71	0.00	143.90	83.90	14.11	10.42	-35.98	-35.98
50.00	117.65	0.00	143.35	93.35	12.30	8.70	-29.97	-29.97
40.00	112.17	0.00	142.81	102.81	10.27	6.97	-23.98	-23.98

30.00	107.18	0.00	142.28	112.28	8.04	5.24	-17.98	-17.98
20.00	102.64	0.00	141.76	121.76	5.58	3.50	-11.99	-11.99
10.00	98.48	0.00	141.25	131.25	2.90	1.75	-6.00	-6.00
0.00	94.66	0.00	140.73	140.73	0.00	0.00	0.00	0.00
-10.00	91.14	0.00	140.19	150.19	-3.13	-1.76	6.01	6.01
-20.00	87.89	0.00	139.64	159.64	-6.50	-3.53	12.02	12.02
-30.00	84.89	0.00	139.06	169.06	-10.10	-5.30	18.05	18.05

****
*
26/02/2019 15:35:03
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****
*

FRONT SUSPENSION - BUMP TRAVEL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-0.7253	0.0155	-5.5034	12.4098	1.664	1.664	14.1
50.00	-0.5654	0.0164	-5.5061	12.2500	1.666	1.666	12.3
40.00	-0.4204	0.0160	-5.5086	12.1051	1.668	1.668	10.3
30.00	-0.2907	0.0142	-5.5107	11.9754	1.669	1.669	8.0
20.00	-0.1770	0.0109	-5.5126	11.8614	1.669	1.669	5.6
10.00	-0.0798	0.0062	-5.5142	11.7638	1.668	1.668	2.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.667	1.667	0.0
-10.00	0.0612	-0.0079	-5.5165	11.6215	1.664	1.664	-3.1
-20.00	0.1026	-0.0176	-5.5172	11.5793	1.660	1.660	-6.5
-30.00	0.1224	-0.0293	-5.5175	11.5584	1.655	1.655	-10.1

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump	Anti	Anti	Roll	Roll	Half Wheelbase	Damper1	Spring1

Travel (mm)	Dive (%)	Squat (%)	Centre Height {to Body} (mm)	Centre Height {to Grnd} (mm)	Track Change (mm)	Change (mm)	Travel (mm)	Travel (mm)
60.00	123.71	0.00	143.90	83.90	14.11	10.42	-35.98	-35.98
50.00	117.65	0.00	143.35	93.35	12.30	8.70	-29.97	-29.97
40.00	112.17	0.00	142.81	102.81	10.27	6.97	-23.98	-23.98
30.00	107.18	0.00	142.28	112.28	8.04	5.24	-17.98	-17.98
20.00	102.64	0.00	141.76	121.76	5.58	3.50	-11.99	-11.99
10.00	98.48	0.00	141.25	131.25	2.90	1.75	-6.00	-6.00
0.00	94.66	0.00	140.73	140.73	0.00	0.00	0.00	0.00
-10.00	91.14	0.00	140.19	150.19	-3.13	-1.76	6.01	6.01
-20.00	87.89	0.00	139.64	159.64	-6.50	-3.53	12.02	12.02
-30.00	84.89	0.00	139.06	169.06	-10.10	-5.30	18.05	18.05

Attachment 6 Double Wishbone SLA Adjusted Track Rod Mounts Maximum Steering Angle and Bump

```
********************************************************************************
*
    10/04/2019                                                      12:09:48
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                       Default Combined Mode
********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterAdjustedTrackRod.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                                STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
   537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
   513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    26.000   135.626    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                                STATIC VALUES
                        Camber Angle  (deg):     0.00
                   Toe Angle {Plane}  (deg):     0.00
                     Toe Angle {SAE}  (deg):     0.00
                        Castor Angle  (deg):    -5.52
                  Castor Trail (hub)   (mm):   -0.480
                Castor Offset (grnd)   (mm):  -24.143
                       Kingpin Angle  (deg):    11.68
                Kingpin Offset (w/c)   (mm):   78.439
               Kingpin Offset (grnd)   (mm):   25.708
             Mechanical Trail (grnd)   (mm):  -24.031
                  ROLL CENTRE HEIGHT   (mm):  140.936

                            GENERAL DATA VALUES
                 TYRE ROLLING RADIUS   (mm):  255.000
                           WHEELBASE   (mm): 2240.000
                       C OF G HEIGHT   (mm):  250.000
               BREAKING ON FRONT AXLE   (%):    60.00
                  DRIVE ON FRONT AXLE   (%):     0.00
                WEIGHT ON FRONT AXLE   (%):    40.00
                    OUTBOARD FRONT BRAKES:
               INDEPENDENT FRONT SUSPENSION:
             STEERING BOX TYPE ARTICULATION:

                                  RUN DETAILS
                    FRONT SUSPENSION ONLY:
         BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       20.000
      REBOUND TRAVEL    (mm):       60.000          INCREMENT    (mm):       20.000
          ROLL ANGLE   (deg):         3.00     ROLL INCREMENT   (deg):         0.50
```

STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
*
10/04/2019 12:09:48
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
60.00	-39.00	-1.851	-24.172	-5.504	12.382	1.662	1.662
50.00	-39.00	-1.710	-24.052	-5.507	12.225	1.665	1.665
40.00	-39.00	-1.582	-23.929	-5.509	12.082	1.667	1.667
30.00	-39.00	-1.467	-23.805	-5.511	11.955	1.668	1.668
20.00	-39.00	-1.366	-23.679	-5.513	11.844	1.668	1.668
10.00	-39.00	-1.280	-23.552	-5.514	11.749	1.667	1.667
0.00	-39.00	-1.209	-23.425	-5.516	11.672	1.666	1.666
-10.00	-39.00	-1.155	-23.297	-5.517	11.613	1.663	1.663
-20.00	-39.00	-1.119	-23.169	-5.517	11.574	1.660	1.660
-30.00	-39.00	-1.103	-23.042	-5.518	11.557	1.655	1.655

****
*
10/04/2019 12:09:48
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
60.00	-39.00	4.351	33.514	-5.502	12.518	1.654	1.654
50.00	-39.00	4.547	33.768	-5.504	12.349	1.658	1.658
40.00	-39.00	4.730	34.026	-5.507	12.194	1.662	1.662
30.00	-39.00	4.900	34.289	-5.509	12.054	1.665	1.665
20.00	-39.00	5.058	34.559	-5.511	11.930	1.667	1.667
10.00	-39.00	5.204	34.838	-5.513	11.822	1.668	1.668
0.00	-39.00	5.338	35.128	-5.515	11.731	1.669	1.669
-10.00	-39.00	5.460	35.433	-5.516	11.658	1.669	1.669
-20.00	-39.00	5.570	35.756	-5.517	11.603	1.669	1.669
-30.00	-39.00	5.667	36.101	-5.517	11.569	1.667	1.667

Attachment 7 Double Wishbone SLA Adjusted Track Rod Mounts Vehicle Roll In Steady State Cornering

```
*********************************************************************************
*
    10/04/2019                                                     12:13:29
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                               Default Roll
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterAdjustedTrackRod.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    90.195    POINT:1          Lower Wishbone Front Pivot
   537.815    19.500    55.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784    47.000   222.291    POINT:4          Upper Wishbone Front Pivot
   513.822    47.000   187.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    26.000   135.626    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -5.52
               Castor Trail (hub)   (mm):   -0.480
             Castor Offset (grnd)   (mm):  -24.143
                    Kingpin Angle  (deg):    11.68
             Kingpin Offset (w/c)   (mm):   78.439
            Kingpin Offset (grnd)   (mm):   25.708
          Mechanical Trail (grnd)   (mm):  -24.031
               ROLL CENTRE HEIGHT   (mm):  140.936

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
      BUMP TRAVEL    (mm):       60.000           INCREMENT    (mm):       20.000
   REBOUND TRAVEL    (mm):       30.000           INCREMENT    (mm):       20.000
```

ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
*
10/04/2019 12:13:29
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****
*

FRONT SUSPENSION - ROLL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	-2.8835	0.0073	-5.5844	14.5678	1.687	1.687
2.50	-2.3944	0.0067	-5.5719	14.0786	1.684	1.684
2.00	-1.9089	0.0058	-5.5599	13.5930	1.681	1.681
1.50	-1.4267	0.0047	-5.5482	13.1107	1.677	1.677
1.00	-0.9479	0.0033	-5.5369	12.6317	1.674	1.674
0.50	-0.4723	0.0018	-5.5260	12.1560	1.670	1.670
0.00	0.0000	0.0000	-5.5155	11.6835	1.667	1.667
-0.50	0.4692	-0.0020	-5.5053	11.2141	1.663	1.663
-1.00	0.9353	-0.0042	-5.4955	10.7477	1.660	1.660
-1.50	1.3984	-0.0067	-5.4859	10.2843	1.656	1.656
-2.00	1.8585	-0.0093	-5.4768	9.8239	1.653	1.653
-2.50	2.3157	-0.0122	-5.4679	9.3665	1.649	1.649
-3.00	2.7700	-0.0153	-5.4593	8.9119	1.645	1.645

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-4.25	140.93	0.02	-4.23	14.56	14.56
2.50	663.84	-3.53	140.93	0.01	-3.53	12.15	12.15
2.00	663.84	-2.82	140.93	0.01	-2.82	9.73	9.73
1.50	663.84	-2.11	140.93	0.00	-2.12	7.30	7.30
1.00	663.84	-1.40	140.93	0.00	-1.41	4.87	4.87
0.50	663.84	-0.70	140.94	0.00	-0.71	2.44	2.44
0.00	663.84	0.00	140.94	0.00	0.00	0.00	0.00
-0.50	663.84	0.70	140.94	0.00	0.71	-2.44	-2.44
-1.00	663.84	1.40	140.93	0.00	1.42	-4.90	-4.90
-1.50	663.84	2.11	140.93	0.00	2.13	-7.35	-7.35
-2.00	663.84	2.82	140.93	0.01	2.84	-9.81	-9.81
-2.50	663.84	3.53	140.93	0.01	3.55	-12.28	-12.28
-3.00	663.84	4.25	140.93	0.01	4.27	-14.75	-14.75

****
*
10/04/2019 12:13:29
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****
*

FRONT SUSPENSION - ROLL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	2.7700	-0.0153	-5.4593	8.9119	1.645	1.645
2.50	2.3157	-0.0122	-5.4679	9.3665	1.649	1.649
2.00	1.8585	-0.0093	-5.4768	9.8239	1.653	1.653
1.50	1.3984	-0.0067	-5.4859	10.2843	1.656	1.656
1.00	0.9353	-0.0042	-5.4955	10.7477	1.660	1.660
0.50	0.4692	-0.0020	-5.5053	11.2141	1.663	1.663
0.00	0.0000	0.0000	-5.5155	11.6835	1.667	1.667
-0.50	-0.4723	0.0018	-5.5260	12.1560	1.670	1.670
-1.00	-0.9479	0.0033	-5.5369	12.6317	1.674	1.674
-1.50	-1.4267	0.0047	-5.5482	13.1107	1.677	1.677
-2.00	-1.9089	0.0058	-5.5599	13.5930	1.681	1.681
-2.50	-2.3944	0.0067	-5.5719	14.0786	1.684	1.684
-3.00	-2.8835	0.0073	-5.5844	14.5678	1.687	1.687

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-4.25	140.93	0.01	4.27	-14.75	-14.75
2.50	663.84	-3.53	140.93	0.01	3.55	-12.28	-12.28
2.00	663.84	-2.82	140.93	0.01	2.84	-9.81	-9.81
1.50	663.84	-2.11	140.93	0.00	2.13	-7.35	-7.35
1.00	663.84	-1.40	140.93	0.00	1.42	-4.90	-4.90
0.50	663.84	-0.70	140.94	0.00	0.71	-2.44	-2.44
0.00	663.84	0.00	140.94	0.00	0.00	0.00	0.00
-0.50	663.84	0.70	140.94	0.00	-0.71	2.44	2.44
-1.00	663.84	1.40	140.93	0.00	-1.41	4.87	4.87
-1.50	663.84	2.11	140.93	0.00	-2.12	7.30	7.30
-2.00	663.84	2.82	140.93	0.01	-2.82	9.73	9.73
-2.50	663.84	3.53	140.93	0.01	-3.53	12.15	12.15
-3.00	663.84	4.25	140.93	0.02	-4.23	14.56	14.56

Attachment 8 Double Wishbone SLA Adjusted Pickup Points Maximum Bump & Droop

```
*********************************************************************************
*
    10/04/2019                                                        12:16:39
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                           Default Bump/Rebound
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: Paxster - DoubleWishboneSLAAdjusted13.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                             STATIC VALUES
        X         Y         Z
      (mm)      (mm)      (mm)
   734.458    38.500    37.195    POINT:1          Lower Wishbone Front Pivot
   537.815    38.500    36.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784   105.000   169.291    POINT:4          Upper Wishbone Front Pivot
   513.822   105.000   169.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    70.000    93.000    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -5.52
               Castor Trail (hub)   (mm):   -0.480
             Castor Offset (grnd)   (mm):  -25.302
                    Kingpin Angle  (deg):    11.68
             Kingpin Offset (w/c)   (mm):   78.439
            Kingpin Offset (grnd)   (mm):   23.226
          Mechanical Trail (grnd)   (mm):  -25.184
               ROLL CENTRE HEIGHT   (mm):   97.725

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  267.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
         BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       20.000
      REBOUND TRAVEL    (mm):       30.000          INCREMENT    (mm):       20.000
```

ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
10/04/2019 12:16:39
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****

FRONT SUSPENSION - BUMP TRAVEL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-1.1365	0.0105	-5.4359	12.8190	1.649	1.649	9.8
40.00	-0.6294	0.0045	-5.4593	12.3120	1.651	1.651	7.2
20.00	-0.2478	0.0004	-5.4858	11.9306	1.652	1.652	3.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.649	1.649	0.0
-20.00	0.0994	0.0051	-5.5485	11.5853	1.642	1.642	-4.5
-40.00	0.0263	0.0176	-5.5853	11.6603	1.629	1.629	-9.6

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	6.78	0.00	116.66	56.66	9.83	0.11	-36.34	-36.34
40.00	6.18	0.00	110.39	70.39	7.16	0.07	-24.23	-24.23
20.00	5.66	0.00	104.15	84.15	3.88	0.03	-12.12	-12.12
0.00	5.21	0.00	97.73	97.73	0.00	0.00	0.00	0.00
-20.00	4.80	0.00	90.84	110.84	-4.49	-0.03	12.15	12.15
-40.00	4.45	0.00	83.06	123.06	-9.59	-0.04	24.38	24.38

****

****

FRONT SUSPENSION - BUMP TRAVEL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-1.1365	0.0105	-5.4359	12.8190	1.649	1.649	9.8
40.00	-0.6294	0.0045	-5.4593	12.3120	1.651	1.651	7.2
20.00	-0.2478	0.0004	-5.4858	11.9306	1.652	1.652	3.9
0.00	0.0000	0.0000	-5.5155	11.6835	1.649	1.649	0.0
-20.00	0.0994	0.0051	-5.5485	11.5853	1.642	1.642	-4.5
-40.00	0.0263	0.0176	-5.5853	11.6603	1.629	1.629	-9.6

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	6.78	0.00	116.66	56.66	9.83	0.11	-36.34	-36.34
40.00	6.18	0.00	110.39	70.39	7.16	0.07	-24.23	-24.23
20.00	5.66	0.00	104.15	84.15	3.88	0.03	-12.12	-12.12
0.00	5.21	0.00	97.73	97.73	0.00	0.00	0.00	0.00
-20.00	4.80	0.00	90.84	110.84	-4.49	-0.03	12.15	12.15
-40.00	4.45	0.00	83.06	123.06	-9.59	-0.04	24.38	24.38

Attachment 9 Double Wishbone SLA Adjusted Pickup Points Maximum Steering Angle and Bump

```
*******************************************************************************
    10/04/2019                                                      12:17:38
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                         Default Combined Mode
*******************************************************************************
*

     FRONT SUSPENSION       FILENAME: Paxster - DoubleWishboneSLAAdjusted13.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                                 STATIC VALUES
         X          Y          Z
       (mm)       (mm)       (mm)
   734.458     38.500     37.195    POINT:1          Lower Wishbone Front Pivot
   537.815     38.500     36.521    POINT:2          Lower Wishbone Rear Pivot
   668.989    400.089    -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784    105.000    169.291    POINT:4          Upper Wishbone Front Pivot
   513.822    105.000    169.561    POINT:5          Upper Wishbone Rear Pivot
   653.896    367.767    128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847    290.614     16.399    POINT:7          Damper Wishbone End
   624.910    181.127    275.958    POINT:8          Damper Body End
   571.909    380.650     40.619    POINT:9          Outer Track Rod Ball Joint
   562.922     70.000     93.000    POINT:10         Inner Track Rod Ball Joint
   663.844    439.000     30.456    POINT:13         Wheel Spindle point
   663.844    466.481     30.456    POINT:14         Wheel Centre Point
  4030.000    440.000    195.000    POINT:15         Part 1 C of G
  4170.000    520.000    450.000    POINT:16         Part 2 C of G
  4230.000    525.000    220.000    POINT:17         Part 3 C of G
  4130.000    720.000    275.000    POINT:18         Part 4 C of G
   652.967      0.000    119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628      0.000    186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922     17.000    131.626    POINT ( 125 ) = PITMAN ARM JOINT

                                 STATIC VALUES
                        Camber Angle  (deg):     0.00
                   Toe Angle {Plane}  (deg):     0.00
                     Toe Angle {SAE}  (deg):     0.00
                        Castor Angle  (deg):    -5.52
                  Castor Trail (hub)   (mm):   -0.480
                Castor Offset (grnd)   (mm):  -25.302
                       Kingpin Angle  (deg):    11.68
                Kingpin Offset (w/c)   (mm):   78.439
               Kingpin Offset (grnd)   (mm):   23.226
            Mechanical Trail (grnd)   (mm):  -25.184
                  ROLL CENTRE HEIGHT   (mm):   97.725

                             GENERAL DATA VALUES
                 TYRE ROLLING RADIUS   (mm):  267.000
                           WHEELBASE   (mm): 2240.000
                       C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):     60.00
              DRIVE ON FRONT AXLE    (%):      0.00
             WEIGHT ON FRONT AXLE    (%):     40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                                   RUN DETAILS
                   FRONT SUSPENSION ONLY:
```

BUMP TRAVEL (mm): 60.000 INCREMENT (mm): 20.000
REBOUND TRAVEL (mm): 30.000 INCREMENT (mm): 20.000
ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
10/04/2019 12:17:38
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****

FRONT SUSPENSION - COMBINED MOTION

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	-39.00	-1.091	-18.761	-5.569	11.606	1.638	1.638
-20.00	-39.00	-1.085	-19.571	-5.551	11.584	1.643	1.643
-10.00	-39.00	-1.117	-20.348	-5.534	11.607	1.647	1.647
0.00	-39.00	-1.182	-21.095	-5.518	11.669	1.649	1.649
10.00	-39.00	-1.279	-21.818	-5.503	11.769	1.650	1.650
20.00	-39.00	-1.406	-22.517	-5.488	11.905	1.650	1.650
30.00	-39.00	-1.559	-23.197	-5.474	12.074	1.650	1.650
40.00	-39.00	-1.739	-23.858	-5.461	12.276	1.648	1.648
50.00	-39.00	-1.944	-24.504	-5.449	12.510	1.646	1.646
60.00	-39.00	-2.172	-25.135	-5.438	12.775	1.643	1.643

****
10/04/2019 12:17:38
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****

FRONT SUSPENSION - COMBINED MOTION

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	-39.00	5.172	33.560	-5.556	11.586	1.655	1.655
-20.00	-39.00	5.073	33.156	-5.539	11.597	1.654	1.654
-10.00	-39.00	4.947	32.782	-5.522	11.649	1.654	1.654
0.00	-39.00	4.793	32.429	-5.507	11.739	1.652	1.652
10.00	-39.00	4.613	32.093	-5.492	11.865	1.650	1.650
20.00	-39.00	4.405	31.770	-5.478	12.025	1.648	1.648
30.00	-39.00	4.171	31.456	-5.465	12.219	1.645	1.645
40.00	-39.00	3.909	31.148	-5.452	12.445	1.642	1.642

50.00	-39.00	3.620	30.843	-5.441	12.703	1.638	1.638
60.00	-39.00	3.304	30.539	-5.430	12.992	1.635	1.635

Attachment 10 Double Wishbone SLA Adjusted Pickup Points Vehicle Roll In Steady State Cornering

```
*********************************************************************************
*
    10/04/2019                                                        12:19:03
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                                  Default Roll
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: Paxster - DoubleWishboneSLAAdjusted13.shk

     TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

                                  STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    38.500    37.195    POINT:1          Lower Wishbone Front Pivot
   537.815    38.500    36.521    POINT:2          Lower Wishbone Rear Pivot
   668.989   400.089   -27.802    POINT:3          Lower Wishbone Outer Ball Joint
   710.784   105.000   169.291    POINT:4          Upper Wishbone Front Pivot
   513.822   105.000   169.561    POINT:5          Upper Wishbone Rear Pivot
   653.896   367.767   128.502    POINT:6          Upper Wishbone Outer Ball Joint
   669.847   290.614    16.399    POINT:7          Damper Wishbone End
   624.910   181.127   275.958    POINT:8          Damper Body End
   571.909   380.650    40.619    POINT:9          Outer Track Rod Ball Joint
   562.922    70.000    93.000    POINT:10         Inner Track Rod Ball Joint
   663.844   439.000    30.456    POINT:13         Wheel Spindle point
   663.844   466.481    30.456    POINT:14         Wheel Centre Point
  4030.000   440.000   195.000    POINT:15         Part 1 C of G
  4170.000   520.000   450.000    POINT:16         Part 2 C of G
  4230.000   525.000   220.000    POINT:17         Part 3 C of G
  4130.000   720.000   275.000    POINT:18         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   563.922    17.000   131.626    POINT ( 125 ) = PITMAN ARM JOINT

                                  STATIC VALUES
                          Camber Angle  (deg):     0.00
                     Toe Angle {Plane}  (deg):     0.00
                       Toe Angle {SAE}  (deg):     0.00
                          Castor Angle  (deg):    -5.52
                    Castor Trail (hub)   (mm):   -0.480
                  Castor Offset (grnd)   (mm):  -25.302
                         Kingpin Angle  (deg):    11.68
                  Kingpin Offset (w/c)   (mm):   78.439
                 Kingpin Offset (grnd)   (mm):   23.226
               Mechanical Trail (grnd)   (mm):  -25.184
                    ROLL CENTRE HEIGHT   (mm):   97.725

                              GENERAL DATA VALUES
                   TYRE ROLLING RADIUS   (mm):  267.000
                             WHEELBASE   (mm): 2240.000
                         C OF G HEIGHT   (mm):  250.000
                BREAKING ON FRONT AXLE    (%):    60.00
                   DRIVE ON FRONT AXLE    (%):     0.00
                  WEIGHT ON FRONT AXLE    (%):    40.00
                     OUTBOARD FRONT BRAKES:
                 INDEPENDENT FRONT SUSPENSION:
               STEERING BOX TYPE ARTICULATION:

                                    RUN DETAILS
```

FRONT SUSPENSION ONLY:

BUMP TRAVEL	(mm):	60.000	INCREMENT	(mm):	20.000
REBOUND TRAVEL	(mm):	30.000	INCREMENT	(mm):	20.000
ROLL ANGLE	(deg):	3.00	ROLL INCREMENT	(deg):	0.50
STEERING ROTATION	(deg):	30.000	STEERING INCREMENT	(deg):	5.000

****
*
10/04/2019 12:19:03
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****
*

FRONT SUSPENSION - ROLL

RHS WHEEL (+ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	-2.9007	0.0071	-5.6236	14.5857	1.658	1.658
2.50	-2.4004	0.0053	-5.6040	14.0851	1.657	1.657
2.00	-1.9071	0.0037	-5.5851	13.5915	1.656	1.656
1.50	-1.4206	0.0024	-5.5668	13.1047	1.654	1.654
1.00	-0.9406	0.0013	-5.5491	12.6245	1.652	1.652
0.50	-0.4672	0.0005	-5.5320	12.1508	1.651	1.651
0.00	0.0000	0.0000	-5.5155	11.6835	1.649	1.649
-0.50	0.4610	-0.0003	-5.4995	11.2223	1.647	1.647
-1.00	0.9159	-0.0004	-5.4840	10.7673	1.644	1.644
-1.50	1.3648	-0.0003	-5.4690	10.3182	1.642	1.642
-2.00	1.8079	0.0000	-5.4545	9.8751	1.640	1.640
-2.50	2.2451	0.0005	-5.4405	9.4377	1.637	1.637
-3.00	2.6767	0.0011	-5.4269	9.0061	1.635	1.635

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-38.99	96.83	0.22	-0.03	14.77	14.77
2.50	663.84	-32.35	97.11	0.15	-0.02	12.31	12.31
2.00	663.84	-25.79	97.34	0.10	-0.02	9.86	9.86
1.50	663.84	-19.29	97.51	0.05	-0.02	7.40	7.40
1.00	663.84	-12.83	97.63	0.02	-0.01	4.93	4.93
0.50	663.84	-6.41	97.70	0.01	-0.01	2.47	2.47
0.00	663.84	0.00	97.73	0.00	0.00	0.00	0.00
-0.50	663.84	6.41	97.70	0.01	0.01	-2.47	-2.47
-1.00	663.84	12.83	97.63	0.02	0.01	-4.94	-4.94
-1.50	663.84	19.29	97.51	0.05	0.02	-7.42	-7.42
-2.00	663.84	25.79	97.34	0.09	0.03	-9.90	-9.90
-2.50	663.84	32.35	97.11	0.14	0.03	-12.39	-12.39
-3.00	663.84	38.99	96.83	0.21	0.04	-14.88	-14.88

****
*
10/04/2019 12:19:04
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b

Default Roll

****
*

FRONT SUSPENSION - ROLL

LHS WHEEL (-ve Y)

TYPE 1 Double Wishbone, Damper to Lower Wishbone [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	2.6767	0.0011	-5.4269	9.0061	1.635	1.635
2.50	2.2451	0.0005	-5.4405	9.4377	1.637	1.637
2.00	1.8079	0.0000	-5.4545	9.8751	1.640	1.640
1.50	1.3648	-0.0003	-5.4690	10.3182	1.642	1.642
1.00	0.9159	-0.0004	-5.4840	10.7673	1.644	1.644
0.50	0.4610	-0.0003	-5.4995	11.2223	1.647	1.647
0.00	0.0000	0.0000	-5.5155	11.6835	1.649	1.649
-0.50	-0.4672	0.0005	-5.5320	12.1508	1.651	1.651
-1.00	-0.9406	0.0013	-5.5491	12.6245	1.652	1.652
-1.50	-1.4206	0.0024	-5.5668	13.1047	1.654	1.654
-2.00	-1.9071	0.0037	-5.5851	13.5915	1.656	1.656
-2.50	-2.4004	0.0053	-5.6040	14.0851	1.657	1.657
-3.00	-2.9007	0.0071	-5.6236	14.5857	1.658	1.658

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	663.84	-38.99	96.83	0.21	0.04	-14.88	-14.88
2.50	663.84	-32.35	97.11	0.14	0.03	-12.39	-12.39
2.00	663.84	-25.79	97.34	0.09	0.03	-9.90	-9.90
1.50	663.84	-19.29	97.51	0.05	0.02	-7.42	-7.42
1.00	663.84	-12.83	97.63	0.02	0.01	-4.94	-4.94
0.50	663.84	-6.41	97.70	0.01	0.01	-2.47	-2.47
0.00	663.84	0.00	97.73	0.00	0.00	0.00	0.00
-0.50	663.84	6.41	97.70	0.01	-0.01	2.47	2.47
-1.00	663.84	12.83	97.63	0.02	-0.01	4.93	4.93
-1.50	663.84	19.29	97.51	0.05	-0.02	7.40	7.40
-2.00	663.84	25.79	97.34	0.10	-0.02	9.86	9.86
-2.50	663.84	32.35	97.11	0.15	-0.02	12.31	12.31
-3.00	663.84	38.99	96.83	0.22	-0.03	14.77	14.77

Attachment 11 MacPherson Old Pickup Points Maximum Bump & Droop

```
*******************************************************************************
*
    14/03/2019                                                   13:07:26
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                     Default Bump/Rebound
*******************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterM.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                             STATIC VALUES
         X          Y          Z
       (mm)       (mm)       (mm)
    734.458     19.500     90.195    POINT:1          Lower wishbone front pivot
    537.815     19.500     55.521    POINT:2          Lower wishbone rear pivot
    665.694    388.372    -12.549    POINT:3          Lower wishbone outer ball joint
    659.843    355.551    117.027    POINT:4          Strut slider upper axis point
    601.609    296.431    507.794    POINT:5          Strut top point
    687.662    383.793    -69.649    POINT:6          Strut slider lower axis point
    569.252    421.646     69.367    POINT:7          Outer track rod ball joint
    562.922     23.989    140.382    POINT:8          Inner track rod ball joint
    661.023    442.744     49.824    POINT:11         Wheel spindle point
    661.026    470.221     49.824    POINT:12         Wheel centre point
   1882.003    498.488    347.784    POINT:13         Part 1 C of G
   1769.217    659.474    299.118    POINT:14         Part 2 C of G
    299.118      0.000    325.000    POINT:15         Part 3 C of G
   1770.000    660.000    285.000    POINT:16         Part 4 C of G
    652.967      0.000    119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
    610.628      0.000    186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
    585.312     27.189    170.267    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.00
                Toe Angle {Plane}  (deg):    -0.01
                  Toe Angle {SAE}  (deg):    -0.01
                     Castor Angle  (deg):    -7.02
               Castor Trail (hub)   (mm):   -3.014
             Castor Offset (grnd)   (mm):  -28.392
                    Kingpin Angle  (deg):    10.02
             Kingpin Offset (w/c)   (mm):   92.870
            Kingpin Offset (grnd)   (mm):   47.813
          Mechanical Trail (grnd)   (mm):  -28.179
               ROLL CENTRE HEIGHT   (mm):  172.702

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
             INDEPENDENT FRONT SUSPENSION:
           STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
         BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       10.000
      REBOUND TRAVEL    (mm):       30.000          INCREMENT    (mm):       10.000
          ROLL ANGLE   (deg):         3.00     ROLL INCREMENT   (deg):         0.50
   STEERING ROTATION   (deg):     30.000    STEERING INCREMENT   (deg):        5.000
```

```
********************************************************************************
*
   14/03/2019                                                    13:07:26
  LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                    Default Bump/Rebound
********************************************************************************
*
```

FRONT SUSPENSION - BUMP TRAVEL

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-2.1391	0.0543	-6.6532	12.3232	1.079	1.079	16.5
50.00	-1.8238	0.0201	-6.7210	11.9750	1.085	1.085	14.5
40.00	-1.4912	-0.0033	-6.7860	11.6120	1.091	1.091	12.2
30.00	-1.1420	-0.0167	-6.8483	11.2346	1.097	1.097	9.6
20.00	-0.7768	-0.0212	-6.9082	10.8434	1.101	1.101	6.7
10.00	-0.3960	-0.0174	-6.9658	10.4386	1.106	1.106	3.5
0.00	0.0000	-0.0062	-7.0211	10.0204	1.109	1.109	0.0
-10.00	0.4109	0.0114	-7.0745	9.5889	1.112	1.112	-3.8
-20.00	0.8367	0.0349	-7.1259	9.1443	1.115	1.115	-8.0
-30.00	1.2770	0.0632	-7.1754	8.6864	1.117	1.117	-12.5

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	131.79	0.00	150.14	90.14	16.45	9.85	-54.76	-54.76
50.00	124.05	0.00	154.46	104.46	14.48	8.16	-45.52	-45.52
40.00	117.12	0.00	158.52	118.52	12.20	6.49	-36.33	-36.33
30.00	110.90	0.00	162.36	132.36	9.61	4.85	-27.19	-27.19
20.00	105.28	0.00	165.99	145.99	6.72	3.22	-18.09	-18.09

10.00	100.18	0.00	169.43	159.43	3.52	1.60	-9.03	-9.03
0.00	95.55	0.00	172.70	172.70	0.00	0.00	0.00	0.00
-10.00	91.32	0.00	175.81	185.81	-3.83	-1.59	9.00	9.00
-20.00	87.45	0.00	178.78	198.78	-7.98	-3.17	17.98	17.98
-30.00	83.90	0.00	181.61	211.61	-12.45	-4.75	26.94	26.94

```
*********************************************************************************
   14/03/2019                                                   13:07:26
  LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                     Default Bump/Rebound
*********************************************************************************
```

FRONT SUSPENSION - BUMP TRAVEL

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-2.1391	0.0543	-6.6532	12.3232	1.079	1.079	16.5
50.00	-1.8238	0.0201	-6.7210	11.9750	1.085	1.085	14.5
40.00	-1.4912	-0.0033	-6.7860	11.6120	1.091	1.091	12.2
30.00	-1.1420	-0.0167	-6.8483	11.2346	1.097	1.097	9.6
20.00	-0.7768	-0.0212	-6.9082	10.8434	1.101	1.101	6.7
10.00	-0.3960	-0.0174	-6.9658	10.4386	1.106	1.106	3.5
0.00	0.0000	-0.0062	-7.0211	10.0204	1.109	1.109	0.0
-10.00	0.4109	0.0114	-7.0745	9.5889	1.112	1.112	-3.8
-20.00	0.8367	0.0349	-7.1259	9.1443	1.115	1.115	-8.0
-30.00	1.2770	0.0632	-7.1754	8.6864	1.117	1.117	-12.5

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)

60.00	131.79	0.00	150.14	90.14	16.45	9.85	-54.76	-54.76
50.00	124.05	0.00	154.46	104.46	14.48	8.16	-45.52	-45.52
40.00	117.12	0.00	158.52	118.52	12.20	6.49	-36.33	-36.33
30.00	110.90	0.00	162.36	132.36	9.61	4.85	-27.19	-27.19
20.00	105.28	0.00	165.99	145.99	6.72	3.22	-18.09	-18.09
10.00	100.18	0.00	169.43	159.43	3.52	1.60	-9.03	-9.03
0.00	95.55	0.00	172.70	172.70	0.00	0.00	0.00	0.00
-10.00	91.32	0.00	175.81	185.81	-3.83	-1.59	9.00	9.00
-20.00	87.45	0.00	178.78	198.78	-7.98	-3.17	17.98	17.98
-30.00	83.90	0.00	181.61	211.61	-12.45	-4.75	26.94	26.94

Attachment 12 MacPherson Old Pickup Points Maximum Steering Angle and Bump

```
*********************************************************************************
    14/03/2019                                                          13:14:20
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                    Default Combined Mode
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterM.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                              STATIC VALUES
        X         Y         Z
      (mm)      (mm)      (mm)
   734.458    19.500    90.195    POINT:1          Lower wishbone front pivot
   537.815    19.500    55.521    POINT:2          Lower wishbone rear pivot
   665.694   388.372   -12.549    POINT:3          Lower wishbone outer ball joint
   659.843   355.551   117.027    POINT:4          Strut slider upper axis point
   601.609   296.431   507.794    POINT:5          Strut top point
   687.662   383.793   -69.649    POINT:6          Strut slider lower axis point
   569.252   421.646    69.367    POINT:7          Outer track rod ball joint
   562.922    23.989   140.382    POINT:8          Inner track rod ball joint
   661.023   442.744    49.824    POINT:11         Wheel spindle point
   661.026   470.221    49.824    POINT:12         Wheel centre point
  1882.003   498.488   347.784    POINT:13         Part 1 C of G
  1769.217   659.474   299.118    POINT:14         Part 2 C of G
   299.118     0.000   325.000    POINT:15         Part 3 C of G
  1770.000   660.000   285.000    POINT:16         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   585.312    27.189   170.267    POINT ( 125 ) = PITMAN ARM JOINT

                              STATIC VALUES
                      Camber Angle  (deg):     0.00
                 Toe Angle {Plane}  (deg):    -0.01
                   Toe Angle {SAE}  (deg):    -0.01
                      Castor Angle  (deg):    -7.02
                Castor Trail (hub)   (mm):   -3.014
              Castor Offset (grnd)   (mm):  -28.392
                     Kingpin Angle  (deg):    10.02
              Kingpin Offset (w/c)   (mm):   92.870
             Kingpin Offset (grnd)   (mm):   47.813
           Mechanical Trail (grnd)   (mm):  -28.179
               ROLL CENTRE HEIGHT    (mm):  172.702

                          GENERAL DATA VALUES
             TYRE ROLLING RADIUS    (mm):  255.000
                       WHEELBASE    (mm): 2240.000
                   C OF G HEIGHT    (mm):  250.000
            BREAKING ON FRONT AXLE   (%):    60.00
               DRIVE ON FRONT AXLE   (%):     0.00
              WEIGHT ON FRONT AXLE   (%):    40.00
                    OUTBOARD FRONT BRAKES:
              INDEPENDENT FRONT SUSPENSION:
            STEERING BOX TYPE ARTICULATION:

                                RUN DETAILS
                    FRONT SUSPENSION ONLY:
         BUMP TRAVEL    (mm):      60.000          INCREMENT    (mm):      10.000
      REBOUND TRAVEL    (mm):      30.000          INCREMENT    (mm):      10.000
          ROLL ANGLE   (deg):        3.00     ROLL INCREMENT   (deg):        0.50
   STEERING ROTATION   (deg):    30.000    STEERING INCREMENT  (deg):       5.000
```

****
*
14/03/2019 13:14:20
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	39.00	8.553	31.303	-7.131	9.101	1.088	1.088
-20.00	39.00	8.126	31.208	-7.078	9.557	1.087	1.087
-10.00	39.00	7.709	31.110	-7.024	9.999	1.085	1.085
0.00	39.00	7.303	31.009	-6.967	10.427	1.083	1.083
10.00	39.00	6.907	30.908	-6.909	10.840	1.081	1.081
20.00	39.00	6.522	30.806	-6.848	11.239	1.077	1.077
30.00	39.00	6.148	30.704	-6.784	11.622	1.074	1.074
40.00	39.00	5.786	30.605	-6.718	11.990	1.070	1.070
50.00	39.00	5.436	30.507	-6.649	12.343	1.065	1.065
60.00	39.00	5.100	30.413	-6.577	12.678	1.060	1.060

****
*
14/03/2019 13:14:20
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****
*

FRONT SUSPENSION - COMBINED MOTION

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	39.00	-0.901	-26.497	-7.192	8.524	1.114	1.114
-20.00	39.00	-1.286	-26.911	-7.143	8.988	1.111	1.111
-10.00	39.00	-1.653	-27.301	-7.092	9.439	1.107	1.107
0.00	39.00	-2.002	-27.667	-7.039	9.878	1.103	1.103
10.00	39.00	-2.333	-28.007	-6.984	10.304	1.098	1.098
20.00	39.00	-2.647	-28.320	-6.927	10.716	1.093	1.093
30.00	39.00	-2.944	-28.604	-6.867	11.116	1.088	1.088
40.00	39.00	-3.224	-28.859	-6.805	11.501	1.082	1.082
50.00	39.00	-3.486	-29.082	-6.740	11.872	1.075	1.075
60.00	39.00	-3.731	-29.272	-6.672	12.229	1.068	1.068

Attachment 13 MacPherson Old Pickup Points Vehicle Roll In Steady State Cornering

```
*********************************************************************************
*
    10/04/2019                                                    12:21:37
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                              Default Roll
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterM.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                              STATIC VALUES
        X          Y          Z
      (mm)       (mm)       (mm)
   734.458    19.500    90.195    POINT:1          Lower wishbone front pivot
   537.815    19.500    55.521    POINT:2          Lower wishbone rear pivot
   665.694   388.372   -12.549    POINT:3          Lower wishbone outer ball joint
   659.843   343.551   117.027    POINT:4          Strut slider upper axis point
   601.609   313.431   502.794    POINT:5          Strut top point
   688.008   358.118   -69.551    POINT:6          Strut slider lower axis point
   569.252   419.646    66.367    POINT:7          Outer track rod ball joint
   562.922    26.989   141.382    POINT:8          Inner track rod ball joint
   661.023   442.744    49.824    POINT:11         Wheel spindle point
   661.026   470.221    50.284    POINT:12         Wheel centre point
  1882.003   498.488   347.784    POINT:13         Part 1 C of G
  1769.217   659.474   299.118    POINT:14         Part 2 C of G
   299.118     0.000   325.000    POINT:15         Part 3 C of G
  1770.000   660.000   285.000    POINT:16         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   585.312    27.189   170.267    POINT ( 125 ) = PITMAN ARM JOINT

                              STATIC VALUES
                     Camber Angle  (deg):    -0.96
                Toe Angle {Plane}  (deg):    -0.01
                  Toe Angle {SAE}  (deg):    -0.01
                     Castor Angle  (deg):    -7.09
               Castor Trail (hub)   (mm):   -3.146
             Castor Offset (grnd)   (mm):  -28.560
                    Kingpin Angle  (deg):     8.27
             Kingpin Offset (w/c)   (mm):   90.986
            Kingpin Offset (grnd)   (mm):   58.178
          Mechanical Trail (grnd)   (mm):  -28.341
               ROLL CENTRE HEIGHT   (mm):  164.707

                          GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                       WHEELBASE   (mm): 2240.000
                   C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                  OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                                RUN DETAILS
                  FRONT SUSPENSION ONLY:
    BUMP TRAVEL    (mm):       60.000          INCREMENT    (mm):       10.000
 REBOUND TRAVEL    (mm):       30.000          INCREMENT    (mm):       10.000
```

ROLL ANGLE (deg): 3.00 ROLL INCREMENT (deg): 0.50
STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
*
10/04/2019 12:21:37
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****
*

FRONT SUSPENSION - ROLL

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	-3.0707	0.0564	-7.2729	10.2382	1.116	1.116
2.50	-2.7247	0.0424	-7.2426	9.9151	1.111	1.111
2.00	-2.3764	0.0297	-7.2122	9.5903	1.106	1.106
1.50	-2.0257	0.0184	-7.1815	9.2639	1.100	1.100
1.00	-1.6727	0.0086	-7.1507	8.9357	1.095	1.095
0.50	-1.3172	0.0004	-7.1197	8.6057	1.090	1.090
0.00	-0.9591	-0.0062	-7.0886	8.2740	1.086	1.086
-0.50	-0.5984	-0.0111	-7.0572	7.9402	1.081	1.081
-1.00	-0.2350	-0.0143	-7.0257	7.6046	1.076	1.076
-1.50	0.1313	-0.0156	-6.9939	7.2668	1.071	1.071
-2.00	0.5005	-0.0149	-6.9620	6.9270	1.067	1.067
-2.50	0.8727	-0.0123	-6.9299	6.5850	1.062	1.062
-3.00	1.2479	-0.0075	-6.8976	6.2407	1.058	1.058

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	661.03	28.66	163.17	-0.26	-3.91	22.57	22.57
2.50	661.03	23.82	163.65	-0.18	-3.27	18.85	18.85
2.00	661.03	19.01	164.03	-0.12	-2.63	15.12	15.12
1.50	661.03	14.23	164.33	-0.07	-1.98	11.37	11.37
1.00	661.03	9.48	164.54	-0.03	-1.33	7.59	7.59
0.50	661.03	4.73	164.66	-0.01	-0.67	3.81	3.81
0.00	661.03	0.00	164.71	0.00	0.00	0.00	0.00
-0.50	661.03	-4.73	164.66	-0.01	0.67	-3.82	-3.82
-1.00	661.03	-9.48	164.54	-0.03	1.35	-7.66	-7.66
-1.50	661.03	-14.23	164.33	-0.07	2.03	-11.52	-11.52
-2.00	661.03	-19.01	164.03	-0.13	2.72	-15.39	-15.39
-2.50	661.03	-23.82	163.65	-0.20	3.41	-19.28	-19.28
-3.00	661.03	-28.66	163.17	-0.29	4.11	-23.19	-23.19

****
*
10/04/2019 12:21:37
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Roll
****
*

FRONT SUSPENSION - ROLL

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	1.2479	-0.0075	-6.8976	6.2407	1.058	1.058
2.50	0.8727	-0.0123	-6.9299	6.5850	1.062	1.062
2.00	0.5005	-0.0149	-6.9620	6.9270	1.067	1.067
1.50	0.1313	-0.0156	-6.9939	7.2668	1.071	1.071
1.00	-0.2350	-0.0143	-7.0257	7.6046	1.076	1.076
0.50	-0.5984	-0.0111	-7.0572	7.9402	1.081	1.081
0.00	-0.9591	-0.0062	-7.0886	8.2740	1.086	1.086
-0.50	-1.3172	0.0004	-7.1197	8.6057	1.090	1.090
-1.00	-1.6727	0.0086	-7.1507	8.9357	1.095	1.095
-1.50	-2.0257	0.0184	-7.1815	9.2639	1.100	1.100
-2.00	-2.3764	0.0297	-7.2122	9.5903	1.106	1.106
-2.50	-2.7247	0.0424	-7.2426	9.9151	1.111	1.111
-3.00	-3.0707	0.0564	-7.2729	10.2382	1.116	1.116

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	661.03	28.66	163.17	-0.29	4.11	-23.19	-23.19
2.50	661.03	23.82	163.65	-0.20	3.41	-19.28	-19.28
2.00	661.03	19.01	164.03	-0.13	2.72	-15.39	-15.39
1.50	661.03	14.23	164.33	-0.07	2.03	-11.52	-11.52
1.00	661.03	9.48	164.54	-0.03	1.35	-7.66	-7.66
0.50	661.03	4.73	164.66	-0.01	0.67	-3.82	-3.82
0.00	661.03	0.00	164.71	0.00	0.00	0.00	0.00
-0.50	661.03	-4.73	164.66	-0.01	-0.67	3.81	3.81
-1.00	661.03	-9.48	164.54	-0.03	-1.33	7.59	7.59
-1.50	661.03	-14.23	164.33	-0.07	-1.98	11.37	11.37
-2.00	661.03	-19.01	164.03	-0.12	-2.63	15.12	15.12
-2.50	661.03	-23.82	163.65	-0.18	-3.27	18.85	18.85
-3.00	661.03	-28.66	163.17	-0.26	-3.91	22.57	22.57

Attachment 14 MacPherson New Pickup Points Maximum Bump and Droop

```
*********************************************************************************
*
    16/03/2019                                                        12:29:49
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                          Default Bump/Rebound
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: D:\lesoft\PaxsterMacPhersonNewMounts.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    56.195    POINT:1          Lower wishbone front pivot
   537.815    19.500    56.195    POINT:2          Lower wishbone rear pivot
   665.694   388.372   -12.549    POINT:3          Lower wishbone outer ball joint
   665.823   373.543    89.641    POINT:4          Strut slider upper axis point
   616.694   285.673   571.019    POINT:5          Strut top point
   709.175   451.079  -335.132    POINT:6          Strut slider lower axis point
   569.252   440.646    64.367    POINT:7          Outer track rod ball joint
   562.922    41.051   119.500    POINT:8          Inner track rod ball joint
   665.694   446.790    16.592    POINT:11         Wheel spindle point
   665.694   480.000    16.582    POINT:12         Wheel centre point
  1882.003   498.488   347.784    POINT:13         Part 1 C of G
  1769.217   659.474   299.118    POINT:14         Part 2 C of G
   299.118     0.000   325.000    POINT:15         Part 3 C of G
  1770.000   660.000   285.000    POINT:16         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   585.312    27.189   170.267    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.02
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -4.80
               Castor Trail (hub)   (mm):   -2.446
             Castor Offset (grnd)   (mm):  -18.965
                    Kingpin Angle  (deg):     9.98
             Kingpin Offset (w/c)   (mm):   96.755
            Kingpin Offset (grnd)   (mm):   51.802
          Mechanical Trail (grnd)   (mm):  -18.899
               ROLL CENTRE HEIGHT   (mm):  147.460

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
    BUMP TRAVEL   (mm):       60.000          INCREMENT   (mm):       10.000
  REBOUND TRAVEL   (mm):       30.000          INCREMENT   (mm):       10.000
      ROLL ANGLE  (deg):         3.00      ROLL INCREMENT  (deg):         0.50
```

STEERING ROTATION (deg): 30.000 STEERING INCREMENT (deg): 5.000

****
*
16/03/2019 12:29:49
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****
*

FRONT SUSPENSION - BUMP TRAVEL

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-1.7106	0.0406	-5.3178	11.6845	1.076	1.076	12.9
50.00	-1.4611	0.0227	-5.2233	11.4384	1.083	1.083	11.5
40.00	-1.1954	0.0094	-5.1323	11.1764	1.090	1.090	9.8
30.00	-0.9141	0.0005	-5.0447	10.8991	1.096	1.096	7.8
20.00	-0.6180	-0.0039	-4.9601	10.6071	1.102	1.102	5.5
10.00	-0.3074	-0.0040	-4.8785	10.3009	1.107	1.107	2.9
0.00	0.0172	0.0000	-4.7996	9.9810	1.112	1.112	0.0
-10.00	0.3556	0.0079	-4.7234	9.6474	1.116	1.116	-3.2
-20.00	0.7074	0.0196	-4.6496	9.3006	1.120	1.120	-6.8
-30.00	1.0724	0.0348	-4.5782	8.9407	1.124	1.124	-10.6

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel (mm)	Anti Dive (%)	Anti Squat (%)	Roll Centre Height {to Body} (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
60.00	-29.52	0.00	120.91	60.91	12.94	0.38	-54.77	-54.77
50.00	-27.16	0.00	126.00	76.00	11.55	0.29	-45.51	-45.51
40.00	-25.10	0.00	130.79	90.79	9.85	0.21	-36.31	-36.31
30.00	-23.29	0.00	135.31	105.31	7.84	0.14	-27.16	-27.16

20.00	-21.69	0.00	139.58	119.58	5.53	0.09	-18.06	-18.06
10.00	-20.26	0.00	143.62	133.62	2.92	0.04	-9.01	-9.01
0.00	-18.98	0.00	147.46	147.46	0.00	0.00	0.00	0.00
-10.00	-17.83	0.00	151.11	161.11	-3.23	-0.03	8.97	8.97
-20.00	-16.79	0.00	154.58	174.58	-6.76	-0.05	17.92	17.92
-30.00	-15.85	0.00	157.90	187.90	-10.60	-0.07	26.83	26.83

****
16/03/2019 12:29:49
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Bump/Rebound
****

FRONT SUSPENSION - BUMP TRAVEL

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)	Half Track Change (mm)
60.00	-1.7106	0.0406	-5.3178	11.6845	1.076	1.076	12.9
50.00	-1.4611	0.0227	-5.2233	11.4384	1.083	1.083	11.5
40.00	-1.1954	0.0094	-5.1323	11.1764	1.090	1.090	9.8
30.00	-0.9141	0.0005	-5.0447	10.8991	1.096	1.096	7.8
20.00	-0.6180	-0.0039	-4.9601	10.6071	1.102	1.102	5.5
10.00	-0.3074	-0.0040	-4.8785	10.3009	1.107	1.107	2.9
0.00	0.0172	0.0000	-4.7996	9.9810	1.112	1.112	0.0
-10.00	0.3556	0.0079	-4.7234	9.6474	1.116	1.116	-3.2
-20.00	0.7074	0.0196	-4.6496	9.3006	1.120	1.120	-6.8
-30.00	1.0724	0.0348	-4.5782	8.9407	1.124	1.124	-10.6

INCREMENTAL SUSPENSION PARAMETER VALUES

Bump Travel	Anti Dive	Anti Squat	Roll Centre	Roll Centre	Half Track	Wheelbase Change	Damper1 Travel	Spring1 Travel

(mm)	(%)	(%)	Height {to Body} (mm)	Height {to Grnd} (mm)	Change (mm)	(mm)	(mm)	(mm)
60.00	-29.52	0.00	120.91	60.91	12.94	0.38	-54.77	-54.77
50.00	-27.16	0.00	126.00	76.00	11.55	0.29	-45.51	-45.51
40.00	-25.10	0.00	130.79	90.79	9.85	0.21	-36.31	-36.31
30.00	-23.29	0.00	135.31	105.31	7.84	0.14	-27.16	-27.16
20.00	-21.69	0.00	139.58	119.58	5.53	0.09	-18.06	-18.06
10.00	-20.26	0.00	143.62	133.62	2.92	0.04	-9.01	-9.01
0.00	-18.98	0.00	147.46	147.46	0.00	0.00	0.00	0.00
-10.00	-17.83	0.00	151.11	161.11	-3.23	-0.03	8.97	8.97
-20.00	-16.79	0.00	154.58	174.58	-6.76	-0.05	17.92	17.92
-30.00	-15.85	0.00	157.90	187.90	-10.60	-0.07	26.83	26.83

XL

Attachment 15 MacPherson New Pickup Points Maximum Steering Angle & Bump

```
*********************************************************************************
    10/04/2019                                                        12:27:42
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                    Default Combined Mode
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterMacPhersonNewMounts.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
   734.458    19.500    56.195    POINT:1          Lower wishbone front pivot
   537.815    19.500    56.195    POINT:2          Lower wishbone rear pivot
   665.694   388.372   -12.549    POINT:3          Lower wishbone outer ball joint
   665.823   373.543    89.641    POINT:4          Strut slider upper axis point
   616.694   285.673   571.019    POINT:5          Strut top point
   709.175   451.079  -335.132    POINT:6          Strut slider lower axis point
   569.252   440.646    64.367    POINT:7          Outer track rod ball joint
   562.922    41.051   119.500    POINT:8          Inner track rod ball joint
   665.694   446.790    16.592    POINT:11         Wheel spindle point
   665.694   480.000    16.582    POINT:12         Wheel centre point
  1882.003   498.488   347.784    POINT:13         Part 1 C of G
  1769.217   659.474   299.118    POINT:14         Part 2 C of G
   299.118     0.000   325.000    POINT:15         Part 3 C of G
  1770.000   660.000   285.000    POINT:16         Part 4 C of G
   652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
   610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
   585.312    27.189   170.267    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.02
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -4.80
               Castor Trail (hub)   (mm):   -2.446
             Castor Offset (grnd)   (mm):  -18.965
                    Kingpin Angle  (deg):     9.98
             Kingpin Offset (w/c)   (mm):   96.755
            Kingpin Offset (grnd)   (mm):   51.802
          Mechanical Trail (grnd)   (mm):  -18.899
               ROLL CENTRE HEIGHT   (mm):  147.460

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
        BUMP TRAVEL   (mm):       60.000          INCREMENT   (mm):       10.000
     REBOUND TRAVEL   (mm):       30.000          INCREMENT   (mm):       10.000
         ROLL ANGLE  (deg):         3.00     ROLL INCREMENT  (deg):         0.50
   STEERING ROTATION  (deg):     30.000    STEERING INCREMENT  (deg):        5.000

*********************************************************************************
*
    10/04/2019                                                        12:27:42
```

LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****

FRONT SUSPENSION - COMBINED MOTION

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	39.00	4.763	32.134	-4.617	9.142	1.097	1.097
-20.00	39.00	4.487	32.091	-4.692	9.502	1.094	1.094
-10.00	39.00	4.222	32.042	-4.769	9.849	1.090	1.090
0.00	39.00	3.969	31.987	-4.848	10.181	1.086	1.086
10.00	39.00	3.728	31.928	-4.931	10.499	1.081	1.081
20.00	39.00	3.500	31.863	-5.016	10.802	1.076	1.076
30.00	39.00	3.284	31.794	-5.104	11.090	1.071	1.071
40.00	39.00	3.082	31.721	-5.196	11.362	1.065	1.065
50.00	39.00	2.895	31.645	-5.291	11.618	1.058	1.058
60.00	39.00	2.723	31.565	-5.390	11.856	1.052	1.052

****
10/04/2019 12:27:42
LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
Default Combined Mode
****

FRONT SUSPENSION - COMBINED MOTION

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Bump Travel (mm)	Steer Travel (mm)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
-30.00	39.00	0.031	-29.074	-4.567	8.882	1.123	1.123
-20.00	39.00	-0.316	-29.703	-4.638	9.245	1.119	1.119
-10.00	39.00	-0.650	-30.303	-4.712	9.594	1.115	1.115
0.00	39.00	-0.971	-30.874	-4.788	9.930	1.111	1.111
10.00	39.00	-1.279	-31.416	-4.866	10.253	1.106	1.106
20.00	39.00	-1.575	-31.927	-4.948	10.562	1.101	1.101
30.00	39.00	-1.859	-32.408	-5.032	10.856	1.096	1.096
40.00	39.00	-2.130	-32.857	-5.119	11.136	1.090	1.090
50.00	39.00	-2.390	-33.275	-5.210	11.401	1.084	1.084
60.00	39.00	-2.638	-33.660	-5.304	11.649	1.078	1.078

Attachment 16 MacPherson New Pickup Points Vehicle Roll In Steady State Cornering

```
*********************************************************************************
    10/04/2019                                                        12:28:37
      LOTUS SUSPENSION ANALYSIS - SHARK v6.01b
                                                                  Default Roll
*********************************************************************************
*

     FRONT SUSPENSION       FILENAME: PaxsterMacPhersonNewMounts.shk

     TYPE 3 Steerable Macpherson Strut [corner]

                             STATIC VALUES
         X         Y         Z
       (mm)      (mm)      (mm)
    734.458    19.500    56.195    POINT:1          Lower wishbone front pivot
    537.815    19.500    56.195    POINT:2          Lower wishbone rear pivot
    665.694   388.372   -12.549    POINT:3          Lower wishbone outer ball joint
    665.823   373.543    89.641    POINT:4          Strut slider upper axis point
    616.694   285.673   571.019    POINT:5          Strut top point
    709.175   451.079  -335.132    POINT:6          Strut slider lower axis point
    569.252   440.646    64.367    POINT:7          Outer track rod ball joint
    562.922    41.051   119.500    POINT:8          Inner track rod ball joint
    665.694   446.790    16.592    POINT:11         Wheel spindle point
    665.694   480.000    16.582    POINT:12         Wheel centre point
   1882.003   498.488   347.784    POINT:13         Part 1 C of G
   1769.217   659.474   299.118    POINT:14         Part 2 C of G
    299.118     0.000   325.000    POINT:15         Part 3 C of G
   1770.000   660.000   285.000    POINT:16         Part 4 C of G
    652.967     0.000   119.936    POINT ( 123 ) = STEERING BOX AXIS POINT
    610.628     0.000   186.395    POINT ( 124 ) = STEERING BOX AXIS POINT
    585.312    27.189   170.267    POINT ( 125 ) = PITMAN ARM JOINT

                             STATIC VALUES
                     Camber Angle  (deg):     0.02
                Toe Angle {Plane}  (deg):     0.00
                  Toe Angle {SAE}  (deg):     0.00
                     Castor Angle  (deg):    -4.80
               Castor Trail (hub)   (mm):   -2.446
             Castor Offset (grnd)   (mm):  -18.965
                    Kingpin Angle  (deg):     9.98
             Kingpin Offset (w/c)   (mm):   96.755
            Kingpin Offset (grnd)   (mm):   51.802
          Mechanical Trail (grnd)   (mm):  -18.899
               ROLL CENTRE HEIGHT   (mm):  147.460

                         GENERAL DATA VALUES
              TYRE ROLLING RADIUS   (mm):  255.000
                        WHEELBASE   (mm): 2240.000
                    C OF G HEIGHT   (mm):  250.000
           BREAKING ON FRONT AXLE    (%):    60.00
              DRIVE ON FRONT AXLE    (%):     0.00
             WEIGHT ON FRONT AXLE    (%):    40.00
                   OUTBOARD FRONT BRAKES:
            INDEPENDENT FRONT SUSPENSION:
          STEERING BOX TYPE ARTICULATION:

                               RUN DETAILS
                   FRONT SUSPENSION ONLY:
        BUMP TRAVEL    (mm):       60.000          INCREMENT   (mm):      10.000
     REBOUND TRAVEL    (mm):       30.000          INCREMENT   (mm):      10.000
         ROLL ANGLE   (deg):         3.00     ROLL INCREMENT  (deg):        0.50
   STEERING ROTATION  (deg):     30.000     STEERING INCREMENT  (deg):       5.000

*********************************************************************************
*
    10/04/2019                                                        12:28:37
```

LOTUS SUSPENSION ANALYSIS - SHARK v6.01b

Default Roll

****
*

FRONT SUSPENSION - ROLL

RHS WHEEL (+ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	-2.1153	0.0266	-4.6597	12.1258	1.143	1.143
2.50	-1.7644	0.0207	-4.6816	11.7728	1.138	1.138
2.00	-1.4118	0.0153	-4.7040	11.4181	1.132	1.132
1.50	-1.0574	0.0105	-4.7270	11.0616	1.127	1.127
1.00	-0.7011	0.0064	-4.7506	10.7033	1.122	1.122
0.50	-0.3429	0.0028	-4.7748	10.3431	1.117	1.117
0.00	0.0172	0.0000	-4.7996	9.9810	1.112	1.112
-0.50	0.3794	-0.0022	-4.8251	9.6168	1.107	1.107
-1.00	0.7437	-0.0036	-4.8512	9.2506	1.102	1.102
-1.50	1.1101	-0.0044	-4.8779	8.8823	1.098	1.098
-2.00	1.4788	-0.0044	-4.9054	8.5117	1.093	1.093
-2.50	1.8497	-0.0036	-4.9335	8.1389	1.089	1.089
-3.00	2.2231	-0.0021	-4.9623	7.7638	1.084	1.084

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	665.69	30.85	146.03	-0.23	-0.06	22.29	22.29
2.50	665.69	25.64	146.47	-0.16	-0.05	18.62	18.62
2.00	665.69	20.47	146.83	-0.10	-0.05	14.93	14.93
1.50	665.69	15.32	147.10	-0.06	-0.04	11.22	11.22
1.00	665.69	10.20	147.30	-0.03	-0.03	7.50	7.50
0.50	665.69	5.10	147.42	-0.01	-0.01	3.76	3.76
0.00	665.69	0.00	147.46	0.00	0.00	0.00	0.00
-0.50	665.69	-5.10	147.42	-0.01	0.02	-3.77	-3.77
-1.00	665.69	-10.20	147.30	-0.03	0.03	-7.56	-7.56
-1.50	665.69	-15.32	147.10	-0.06	0.05	-11.37	-11.37
-2.00	665.69	-20.47	146.83	-0.11	0.07	-15.19	-15.19
-2.50	665.69	-25.64	146.47	-0.18	0.09	-19.03	-19.03
-3.00	665.69	-30.85	146.03	-0.26	0.12	-22.88	-22.88

****
*

10/04/2019 12:28:37

LOTUS SUSPENSION ANALYSIS - SHARK v6.01b

Default Roll

****
*

FRONT SUSPENSION - ROLL

LHS WHEEL (-ve Y)

TYPE 3 Steerable Macpherson Strut [corner]

INCREMENTAL GEOMETRY VALUES

Roll Angle (deg)	Camber Angle (deg)	Toe Angle {SAE} (deg)	Castor Angle (deg)	Kingpin Angle (deg)	Damper1 Ratio (-)	Spring1 Ratio (-)
3.00	2.2231	-0.0021	-4.9623	7.7638	1.084	1.084
2.50	1.8497	-0.0036	-4.9335	8.1389	1.089	1.089
2.00	1.4788	-0.0044	-4.9054	8.5117	1.093	1.093
1.50	1.1101	-0.0044	-4.8779	8.8823	1.098	1.098
1.00	0.7437	-0.0036	-4.8512	9.2506	1.102	1.102
0.50	0.3794	-0.0022	-4.8251	9.6168	1.107	1.107
0.00	0.0172	0.0000	-4.7996	9.9810	1.112	1.112
-0.50	-0.3429	0.0028	-4.7748	10.3431	1.117	1.117
-1.00	-0.7011	0.0064	-4.7506	10.7033	1.122	1.122
-1.50	-1.0574	0.0105	-4.7270	11.0616	1.127	1.127
-2.00	-1.4118	0.0153	-4.7040	11.4181	1.132	1.132
-2.50	-1.7644	0.0207	-4.6816	11.7728	1.138	1.138
-3.00	-2.1153	0.0266	-4.6597	12.1258	1.143	1.143

INCREMENTAL SUSPENSION PARAMETER VALUES

Roll Angle (deg)	Roll Centre X (mm)	Roll Centre Y (mm)	Roll Centre Height {to Grnd} (mm)	Half Track Change (mm)	Wheelbase Change (mm)	Damper1 Travel (mm)	Spring1 Travel (mm)
3.00	665.69	30.85	146.03	-0.26	0.12	-22.88	-22.88
2.50	665.69	25.64	146.47	-0.18	0.09	-19.03	-19.03
2.00	665.69	20.47	146.83	-0.11	0.07	-15.19	-15.19
1.50	665.69	15.32	147.10	-0.06	0.05	-11.37	-11.37
1.00	665.69	10.20	147.30	-0.03	0.03	-7.56	-7.56
0.50	665.69	5.10	147.42	-0.01	0.02	-3.77	-3.77
0.00	665.69	0.00	147.46	0.00	0.00	0.00	0.00
-0.50	665.69	-5.10	147.42	-0.01	-0.01	3.76	3.76
-1.00	665.69	-10.20	147.30	-0.03	-0.03	7.50	7.50
-1.50	665.69	-15.32	147.10	-0.06	-0.04	11.22	11.22
-2.00	665.69	-20.47	146.83	-0.10	-0.05	14.93	14.93
-2.50	665.69	-25.64	146.47	-0.16	-0.05	18.62	18.62
-3.00	665.69	-30.85	146.03	-0.23	-0.06	22.29	22.29

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway