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Suspension Kinematics Investigation

Motorsport Technology – ACHA4012

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1 Introduction

This report details an investigation into the front suspension system of a Van Diemen RF 96 (VD96) chassis. This chassis is a lightweight, mid-engine, open wheel vehicle designed for track use and is used in many different formula-style, hillclimb, and sprint events around the world, most notably Formula Ford. This Chassis uses double A-arm inboard push rod suspension.

Characteristics of the front suspension are investigated through laboratory testing and through simulation using WinGeo suspension software. The data obtained is evaluated individually and combined to further understand the characteristics of the suspension system.



Figure 1 - Example of a Van Diemen RF96 Chassis (Wood, 2021)

2 Laboratory Sessions

2.1 Equipment

- Van Diemen RF 96 Chassis (Figure 2)
- Digital height gauge – Measures to 0.01mm (Figure 4)
- Adjustable mock spring/damper (Figure 3)
- Vernier calliper – A digital calliper would be more accurate but was not available during the test. (Figure 5)
- Dial test indicator (DTI) – Measures to 0.001in. A digital dial gauge would be more accurate but was not available during the test. (Figure 6)
- Surface Table (+/- 0.1µm/m) – Good for maintaining a datum. (Figure 8)
- Digital Inclinator– Measures to 0.01°. More Accurate than analogue inclinometer. (Figure 7)
- Bump steer gauge (Figure 9)
- Corner Weight Scales – Measures to 0.1kg (Figure 10)
- Coil spring test rig – Measures to 0.1Kg (Figure 11)
- Tyre deflection test rig – Measures to 0.1Kg (Figure 12)

Figures shown on next two pages.



Figure 2 - Van Diemen RF96 Chassis



Figure 3 - Mock Spring/Damper



Figure 4 - Height Gauge

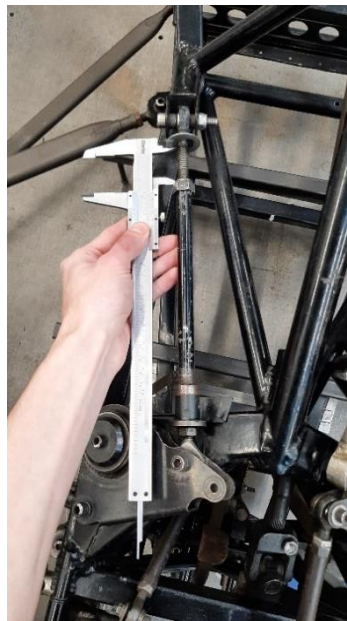


Figure 5 - Vernier Calliper



Figure 6 - DTIs



Figure 7 - Digital Inclinator



Figure 8 -Surface Plate



Figure 9 - Bump Steer Gauge



Figure 10 - Example of Corner Weight Scale (Demon-Tweeks, 2021)



Figure 11 - Coil Spring Tester

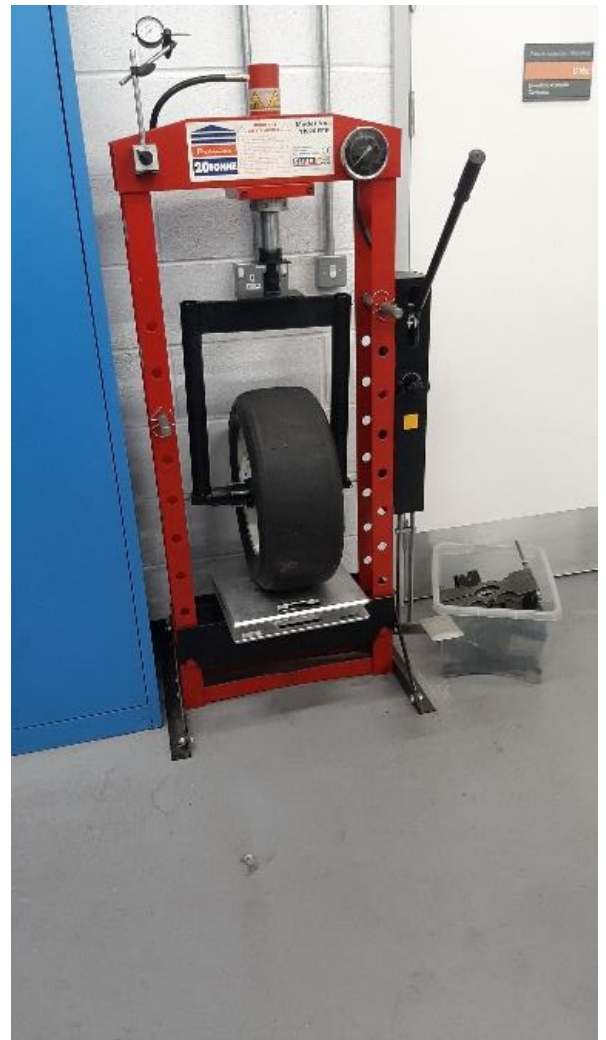


Figure 12 - Tyre Deflection Tester

2.2 Methodology

2.2.1 Wheel Position Tests

In order to establish a good zero position for the test a surface plate was used. The VD96 chassis was placed on the surface plate and the measuring equipment setup as follows. The spring/damper was replaced with the mock damper (Figure 3), this provides the controlled variable for this experiment allowing the suspension system to be changed by regular intervals. To achieve this movement the nut on the mock spring was turned two full rotations, to ensure this test was accurate it was important to ensure the nut was not over rotated and the turned back as this could introduce a slight error into the readings. To prevent this extra care was taken and one face of the nut was marked black to provide a visual reference. A vernier calliper was used to measure the distance between the nut and the top of the mock spring to record a measurement for spring displacement.

A height gauge was placed at the top right edge of the bump steer gauge (Figure 4), this provides a measurement for ride height change during the experiment. A digital inclinometer was attached to the brake disk using a G-clamp, this provides a measurement for camber change during the experiment (Figure 7). Two DTIs were placed against the bump steer gauge at a toe span of 341mm (Figure 6).

To take measurements the mock springs were adjusted as previously mentioned, this was done eight times from the zero-position giving nine sets of results. Each time the mock springs were adjusted measurements were taken for wheel position, camber, spring displacement, and change of distance for both DTIs. In order to maintain accuracy all readings taken from an analogue scale were taken at while at eye level to that scale. Repeating this test three times and taking an average result at each stage would have been more accurate but due to time constraints this was not possible.

2.2.2 Unsprung Mass Test

To obtain the unsprung mass of the suspension components they were weighed on a corner weight scale and again when detached from the car. The value obtained when off the car will be used during analysis as it represents the true mass of the components when not being supported by the chassis.

2.2.3 Tyre and Spring Stiffness Tests

The tyres vertical stiffness was tested using the rig with a tyre a corner weight scale (Figure 12). The tyre was compressed by 2mm increments and the force on the scale recorded. This was repeated to obtain eight results (including zero position). The tyre width and height were also recorded using a tape measure.

Spring stiffnesses were tested using a Coil Spring Tester (Figure 11) by deflecting the spring by 0.1 inches and measuring the force applied. This was repeated to include 11 results (including zero position).

2.3 Results and Analysis

The following data was recorded from the laboratory tests.

Table 1 - Wheel Position Test Data

Wheel Position	Approx. Ride Height	Measured Camber	Zeroed Camber	DTI A	DTI B	Calculated Toe	Zeroed Toe	Spring / Damper Length	Spring Compression
(mm)	(mm)	(Degrees)	(Degrees)	(Inches)	(Inches)	(Degrees)	(Degrees)	(mm)	(mm)
0.00	26	-1.32	0.31	0.000	0.000	0.00	-0.20	48.9	0.0
6.33	20	-1.39	0.24	0.021	0.013	0.03	-0.17	46.0	2.9
12.90	13	-1.47	0.16	0.043	0.021	0.09	-0.11	43.0	5.9
19.34	7	-1.55	0.08	0.062	0.027	0.15	-0.05	40.0	8.9
25.93	0	-1.63	0.00	0.079	0.032	0.20	0.00	37.0	11.9
32.22	-6	-1.72	-0.09	0.095	0.035	0.26	0.06	34.0	14.9
38.53	-13	-1.81	-0.18	0.095	0.035	0.26	0.06	30.9	18.0
44.77	-19	-1.90	-0.27	0.108	0.035	0.31	0.11	28.1	20.8
51.05	-25	-1.99	-0.36	0.127	0.032	0.41	0.20	24.9	24.0

Table 2 - Unsprung Mass Test Data

Total Corner Mass (Kg)	115
Unsprung Mass on car (Kg)	22
Unsprung Mass off car (Kg)	23.5

Table 3 - Tyre Vertical Stiffness Test Data

Tyre Vertical Deflection	Scale Reading	Applied Force
(mm)	(kg)	(N)
0	30.5	299.10
2	58.0	568.79
4	74.5	730.60
6	102.0	1000.28
8	133.5	1309.19
10	168.0	1647.52
12	193.0	1892.68
14	215.5	2113.33

Table 4 - Spring Stiffness Test Data

Spring Deflection	Spring Deflection	Measured Force	Measured Force
(inches)	(mm)	(lbs)	(N)
0	0.00	0	0.00
0.1	2.54	38	169.03
0.2	5.08	78	346.96
0.3	7.62	119	529.34
0.4	10.16	160	711.72
0.5	12.70	199	885.20
0.6	15.24	239	1063.12
0.7	17.78	278	1236.61
0.8	20.32	318	1414.53
0.9	22.86	358	1592.46
1	25.40	399	1774.84

Table 5 - Additional Laboratory Data

Motion Ratio (MR)	0.4689
Spring Rate (Ks) - (N/mm)	69.923
Spring Rate (Ks) - (N/m)	69923
Sprung Mass (Ms) - (Kg)	91.5
Tyre Stiffness - (N/mm)	133.21
Tyre Stiffness (Kt) - (N/m)	133210
Tyre Radius - (mm)	270
Tyre Width - (mm)	220
Toespan - (Inches)	13.4252
Toespan - (mm)	341

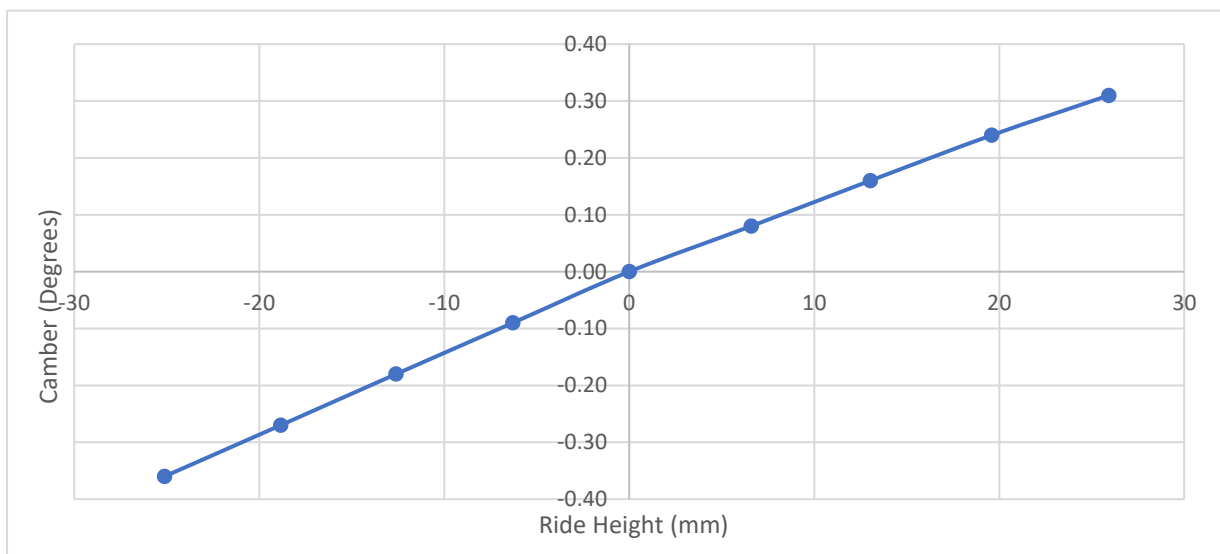


Figure 13 - Camber Against Ride height

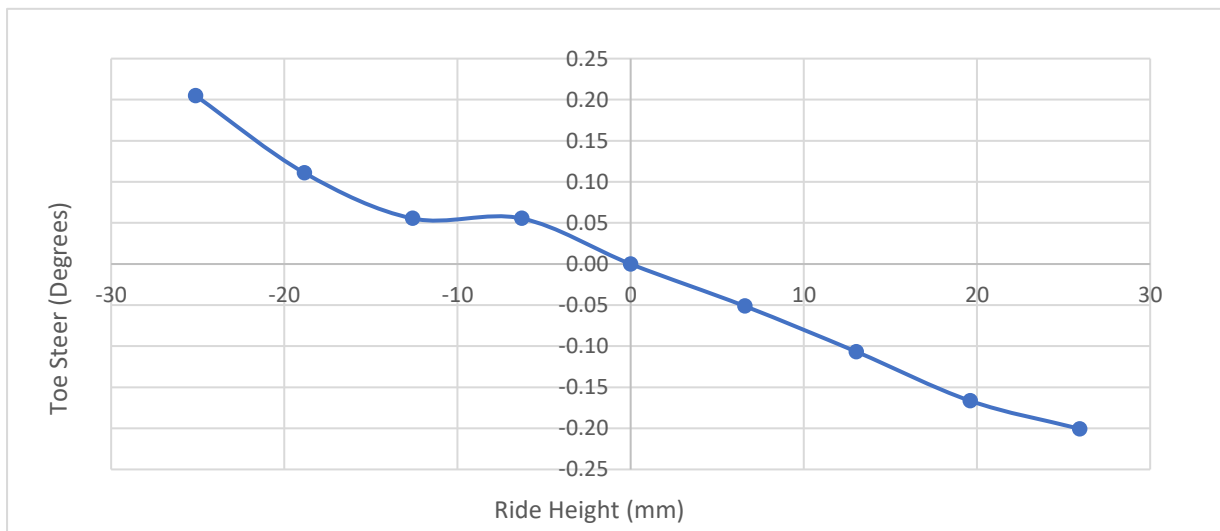


Figure 14 - Toe Steer Against Ride Height

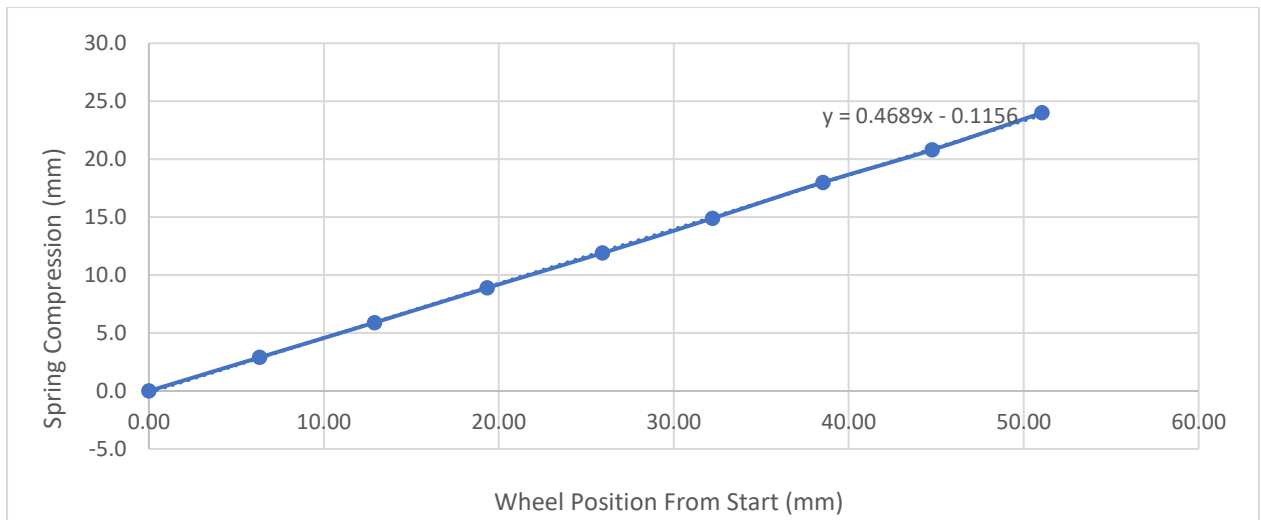


Figure 15 - Spring compression Against Wheel Position

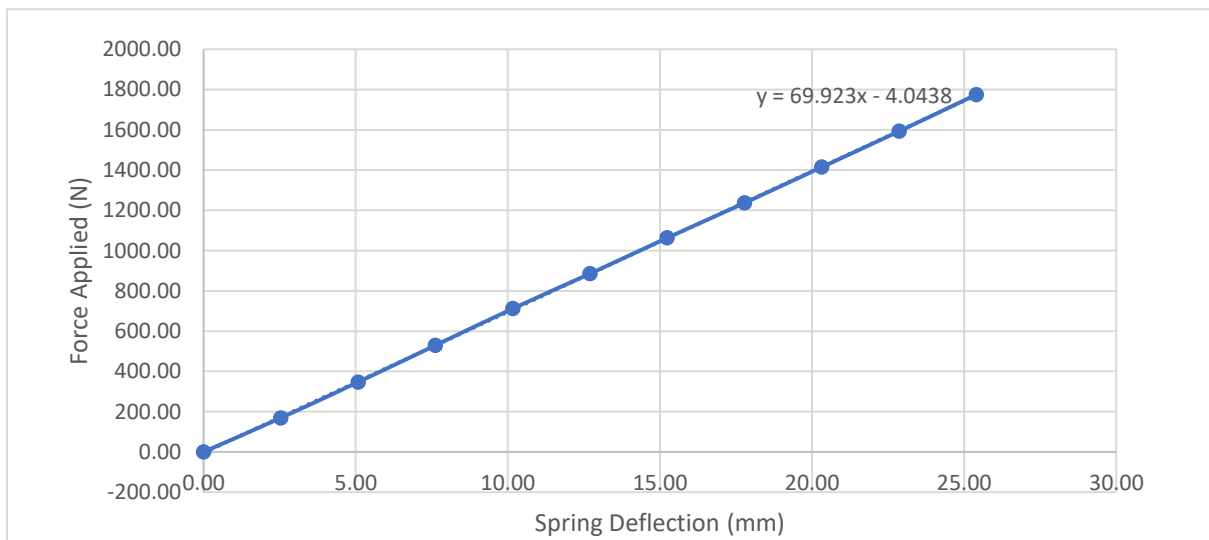


Figure 16 - Spring Defection Against Spring Load

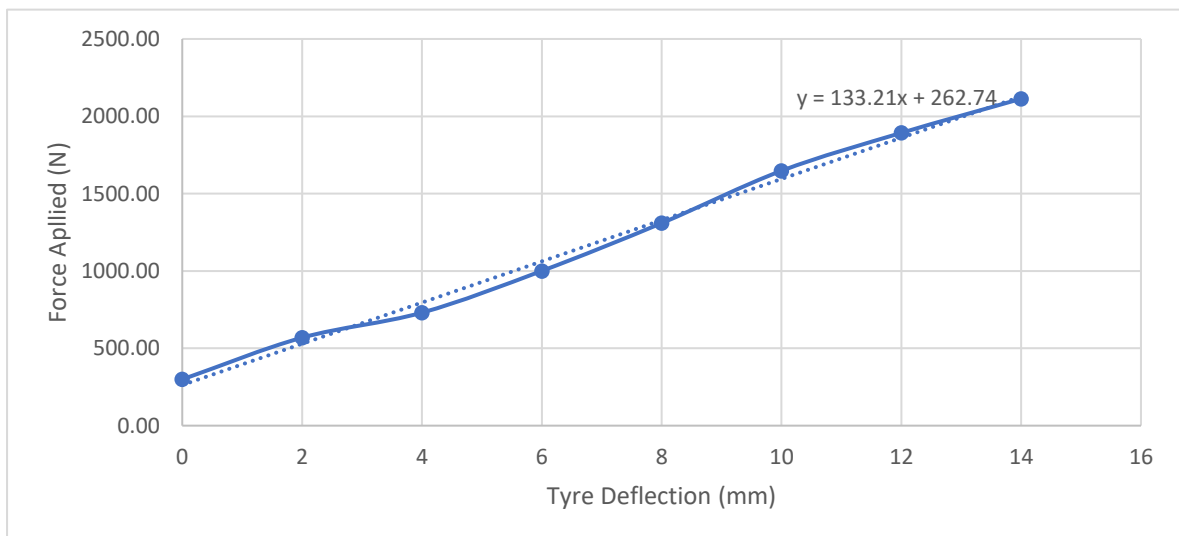


Figure 17 - Tyre Defection Against Tyre Load

The calculated toe (Table 1) was calculated using the following equation.

$$\frac{(DTI A - DTI B) \times 180}{Toespan(inches) \times \pi}$$

The units of inches on the DTIs and the Toespan cancel giving an answer in degrees.

The force applied on the tyre (Table 3) was calculated using the following.

$$F = ma$$

Where the value for acceleration (a) is gravity, the value of gravity for this experiment is 9.80665m/s² (Dachi and Setiawan, 2018).

As shown in Figure 13 camber becomes more negative as ride height becomes more negative as the wheels are moving through an arc defined by the instant centre (IC). As the chassis moves down the wheel moves up and leans in as it follows this arc the opposite is true for positive ride height. The instant centre is a theoretical point in space defined as where the upper and lower a-arms would meet if extended and is measured in mm defining the radius of the arc of wheel movement.

Figure 14 shows that when ride height decreases the front tyre increase in positive toe angle, this can be useful in racing applications as it helps with initial turn in. Additionally negative toe angle when the ride height may help to stabilise the front end on corner exit when the car leans back due to acceleration.

Figure 15 shows how the motion ration (Table 5) of the suspension was calculated. The gradient of the trendline is the motion ratio as the graph compares spring movement to wheel movement. The Motion ration is the ration of movement between the wheel and what is transferred to the spring and is set by the geometry of the pushrod rocker.

Figure 16 was used to calculate the spring rate as the gradient of the trend line is the value of the spring rate once the units are corrected. The spring rate defines how much the spring will deflect for a given load. The tyre vertical stiffness was calculated using the same method in figure 17. The tyre vertical stiffness defines how much the tyre will deflect vertically when under a given load.

3 WinGeo Kinematic Simulation

3.1 Methodology

3.1.1 Kinematics Simulation

The supplied model (RF 96) was used to obtain data in suspension simulation software.

Measurement of different suspension variables (Table 7/8) were measured between +/- 25mm ride height at 5mm increments. In addition to this further measurements of suspension variables (Table 9/10) were measured between 0° - 2° roll angle at 0.1° increments. WinGeo measures toe angle as toe-in angle so it was necessary to correct all data affected by this. WinGeo Model shown below.

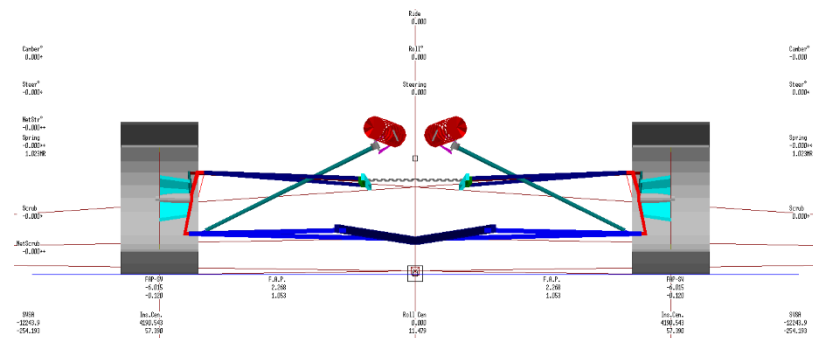


Figure 18 - WinGeo Model Rear View

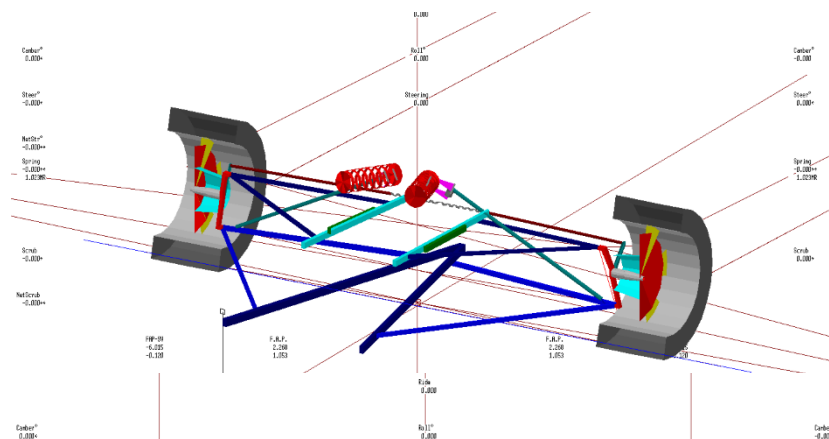


Figure 19 - WinGeo Model Offset View

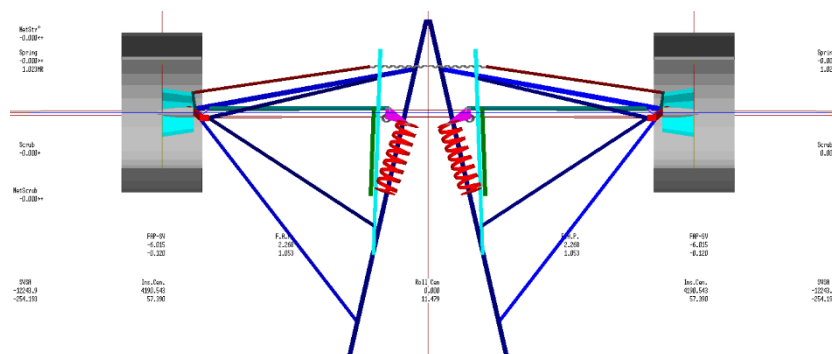


Figure 20 - WinGeo Model Top View

3.1.2 Roll Centre Migration

In order to investigate the roll centre migration, the model was manipulated through various stages with ride height and roll angle changes representative of a cornering scenario. The stages are as follows. The resulting roll centre movement will be plotted on a graph.

Table 6 - Roll Centre Stages of Corner

Stage of Corner		Ride	Roll
1	Zero Position	0	0
2	Full Braking	-20	0
3	Half Braking, Half Cornering	-10	0.75
4	Full Cornering	0	1.5
5	Half Acceleration, Half Cornering	10	0.75
6	Full Acceleration	20	0

3.2 Kinematics Results and Analysis

Table 7 - WinGeo Data 1

Ride	Roll	Steer	Camber Right	Camber Left	Toe Right	Toe Left	Toe-in Angle	Spring Right	Spring Left
25	0	0	0.239	0.239	0.537	0.537	1.073	24.758	24.758
20	0	0	0.195	0.195	0.431	0.431	0.861	19.926	19.926
15	0	0	0.15	0.15	0.324	0.324	0.648	15.039	15.039
10	0	0	0.102	0.102	0.217	0.217	0.433	10.091	10.091
5	0	0	0.052	0.052	0.109	0.109	0.217	5.079	5.079
0	0	0	0	0	0	0	0	0	0
-5	0	0	-0.055	-0.055	-0.109	-0.109	-0.219	-5.15	-5.15
-10	0	0	-0.112	-0.112	-0.22	-0.22	-0.439	-10.371	-10.371
-15	0	0	-0.171	-0.171	-0.331	-0.331	-0.661	-15.666	-15.666
-20	0	0	-0.233	-0.233	-0.442	-0.442	-0.885	-21.033	-21.033
-25	0	0	-0.297	-0.297	-0.555	-0.555	-1.11	-26.468	-26.468

Table 8 - WinGeo Data 2

Ride	Roll	Steer	Motion Ratio Right	Motion Ratio Left	Corrected Toe	Wheel Position	Zeroed Spring Compression
25	0	0	0.961	0.961	-1.073	0	-24.758
20	0	0	0.972	0.972	-0.861	5	-19.926
15	0	0	0.983	0.983	-0.648	10	-15.039
10	0	0	0.996	0.996	-0.433	15	-10.091
5	0	0	1.009	1.009	-0.217	20	-5.079
0	0	0	1.023	1.023	0	25	0
-5	0	0	1.037	1.037	0.219	30	5.15
-10	0	0	1.052	1.052	0.439	35	10.371
-15	0	0	1.066	1.066	0.661	40	15.666
-20	0	0	1.08	1.08	0.885	45	21.033
-25	0	0	1.093	1.093	1.11	50	26.468

Table 9 - WinGeo Roll Data 1

When Rolling Right								
Roll	Steer	Camber Right	Camber Left	Toe Right	Toe Left	Toe-in Angle	Spring Right	Spring Left
0	0	0	0	0	0	0	0	0
0.1	0	0.084	-0.084	-0.032	0.032	0	-1.499	1.493
0.2	0	0.168	-0.169	-0.064	0.064	0	-3.005	2.981
0.3	0	0.252	-0.254	-0.096	0.095	-0.001	-4.516	4.462
0.4	0	0.336	-0.339	-0.128	0.127	-0.001	-6.034	5.937
0.5	0	0.419	-0.424	-0.16	0.159	-0.002	-7.558	7.407
0.6	0	0.502	-0.51	-0.193	0.19	-0.002	-9.088	8.871
0.7	0	0.586	-0.595	-0.225	0.222	-0.003	-10.625	10.33
0.8	0	0.668	-0.681	-0.257	0.253	-0.004	-12.167	11.783
0.9	0	0.751	-0.767	-0.29	0.285	-0.005	-13.716	13.23
1	0	0.833	-0.853	-0.322	0.316	-0.006	-15.271	14.672
1.1	0	0.916	-0.94	-0.355	0.347	-0.008	-16.832	16.109
1.2	0	0.998	-1.026	-0.388	0.379	-0.009	-18.4	17.541
1.3	0	1.08	-1.113	-0.42	0.41	-0.011	-19.973	18.968
1.4	0	1.161	-1.2	-0.453	0.441	-0.012	-21.552	20.39
1.5	0	1.243	-1.287	-0.486	0.472	-0.014	-23.137	21.807
1.6	0	1.324	-1.375	-0.519	0.503	-0.016	-24.728	23.219
1.7	0	1.405	-1.462	-0.552	0.534	-0.018	-26.323	24.627
1.8	0	1.486	-1.55	-0.585	0.565	-0.02	-27.924	26.03
1.9	0	1.566	-1.638	-0.618	0.596	-0.023	-29.53	27.429
2	0	1.647	-1.726	-0.651	0.626	-0.025	-31.14	28.824

Table 10 - WinGeo Roll Data 2

When Rolling Right						
Roll	Steer	Motion Ratio Right	Motion Ratio Left	Corrected Toe Right	Corrected Toe Left	Corrected Toe
0	0	1.023	1.023	0	0	0
0.1	0	1.027	1.019	0.032	-0.032	0
0.2	0	1.031	1.015	0.064	-0.064	0
0.3	0	1.035	1.011	0.096	-0.095	0.001
0.4	0	1.04	1.007	0.128	-0.127	0.001
0.5	0	1.044	1.003	0.16	-0.159	0.002
0.6	0	1.048	0.999	0.193	-0.19	0.002
0.7	0	1.052	0.995	0.225	-0.222	0.003
0.8	0	1.057	0.991	0.257	-0.253	0.004
0.9	0	1.061	0.988	0.29	-0.285	0.005
1	0	1.065	0.984	0.322	-0.316	0.006
1.1	0	1.069	0.981	0.355	-0.347	0.008
1.2	0	1.073	0.977	0.388	-0.379	0.009
1.3	0	1.077	0.974	0.42	-0.41	0.011
1.4	0	1.081	0.97	0.453	-0.441	0.012
1.5	0	1.085	0.967	0.486	-0.472	0.014
1.6	0	1.089	0.964	0.519	-0.503	0.016
1.7	0	1.092	0.961	0.552	-0.534	0.018
1.8	0	1.096	0.958	0.585	-0.565	0.02
1.9	0	1.099	0.955	0.618	-0.596	0.023
2	0	1.102	0.952	0.651	-0.626	0.025

Table 11 - Suspension Characteristics at Zero Position

MR	IC (mm)	Roll Centre Height (mm)	Roll Centre Width (mm)
1.023	4190.543	11.479	0

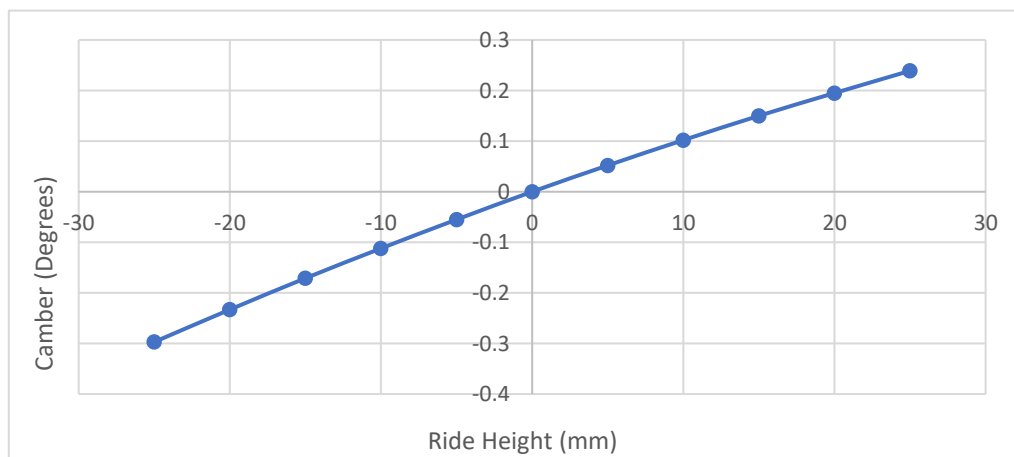


Figure 21 - WinGeo Camber Against Ride Height

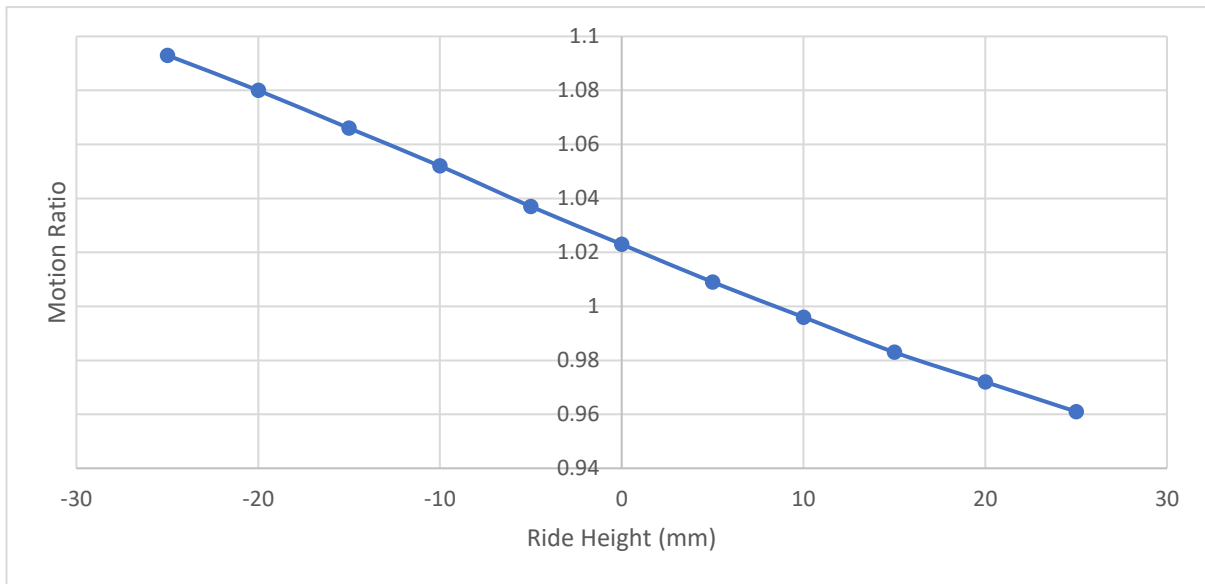


Figure 22 – WinGeo Motion Ratio Against Ride Height

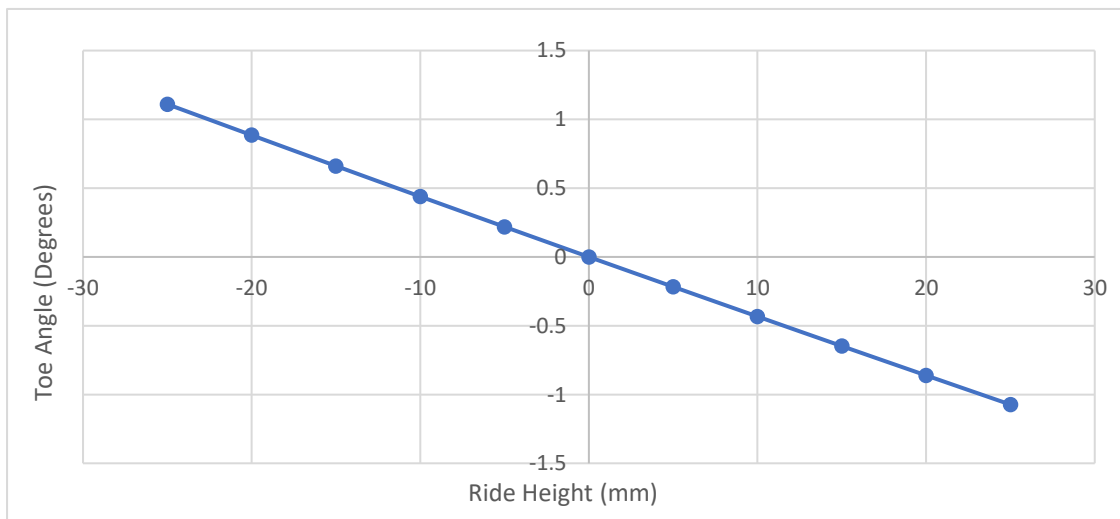


Figure 23 - WinGeo Toe Angle Against Ride Height

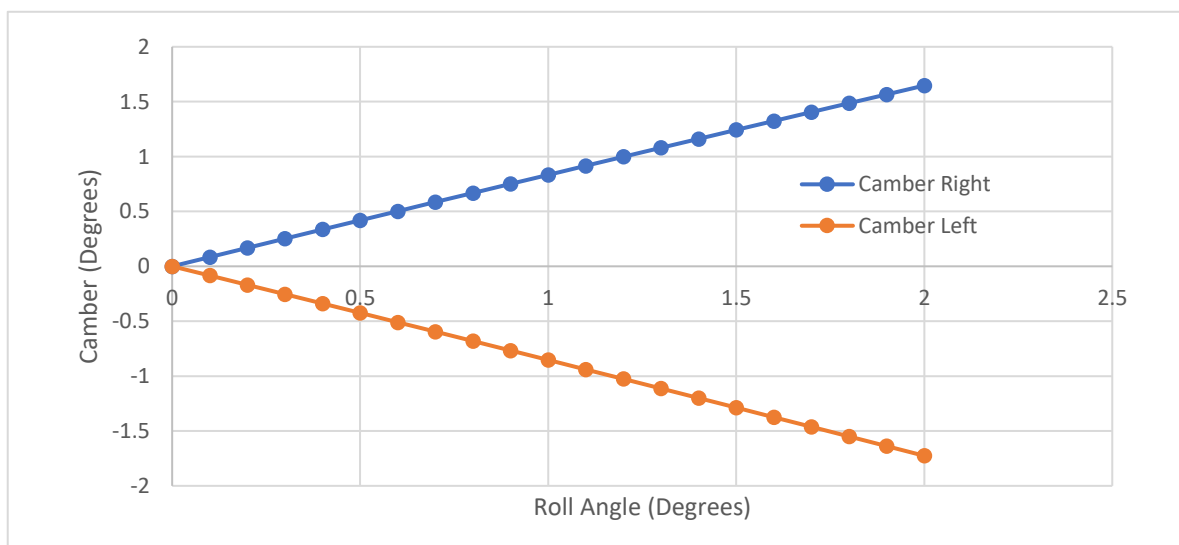


Figure 24 - WinGeo Camber Against Roll Angle

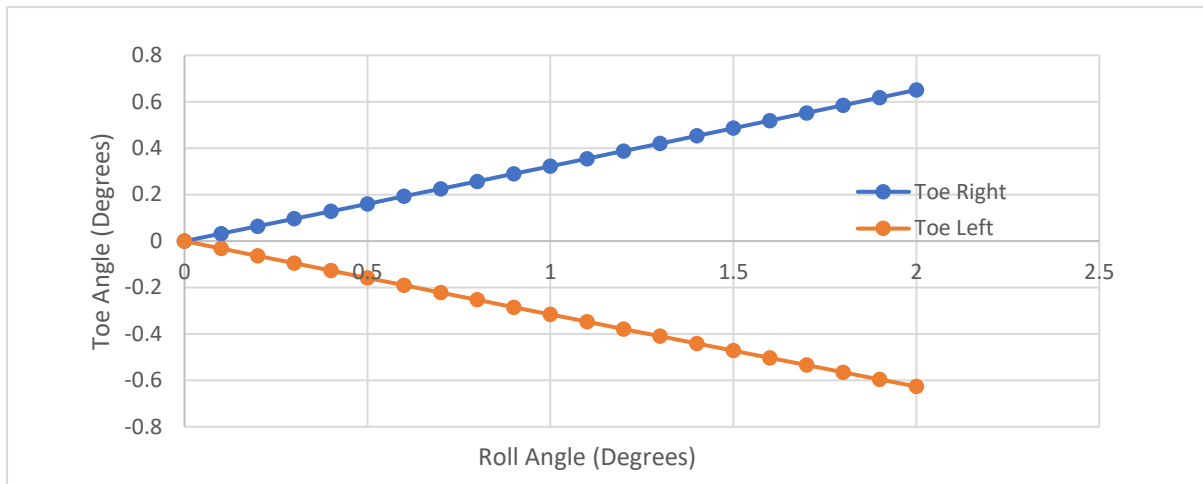


Figure 25 - WinGeo Toe Angle Against Roll Angle

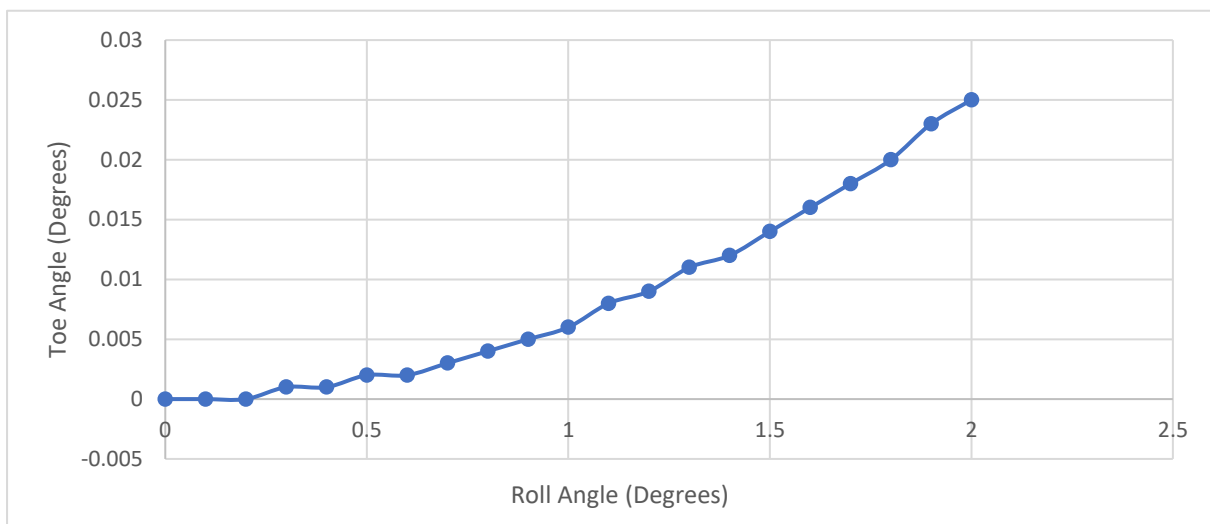


Figure 26 - WinGeo Net Toe Angle Against Roll Angle

From Figure 22 it can be observed that the motion ratio of this suspension system changes as the ride height changes this may be because the spring is not 90° to the angle of the motion of the wheel due to the rocker and push rod not being perpendicular to the wheel hub assembly. Due to this some of the movement of the wheel is being transferred to the chassis not the spring. In addition to this these angles are further changing over the course of the test as the camber of the wheel changes.

It can be seen in the above graph (Figure 26) that the toe angle increases as the roll angle increases, this can be beneficial in lightweight mid-engine cars to help counter some of the mid-corner understeer inherent to this layout.

3.3 Roll Centre Migration

The roll centre is a key aspect of any vehicles handling characteristics as it is the effective point around which the whole suspension system, of one end of the car, pivots. It is also the point of rotation for that axle. As a car travels and lateral and vertical loads are applied to it the roll centre will move, this is important as this is the effective point at which the sprung mass of the vehicle is applied to the suspension and therefore the wheels.

The height of the roll centre is important to the setup of a car as described by Lee *et al.* (2001) decreasing the height of the roll centre will reduce the severity of camber changes from bumps when traveling in a straight line and raising the height will introduce more camber change as such the roll centre of a vehicle must always be considered when deciding on a setup for any given vehicle.

The roll centre has many different applications in racing as described by Mitchell (1998) cars that race on ovals have a left biased roll centre as the cars only turn left. This allows the roll centre to be central to both tyres when the car is under cornering load evening out the load of both tyres allowing for more efficient use of grip.

Stage of Corner		Ride	Roll	Steer	Camber Right	Camber Left	Toe Right	Toe Left	Spring Right	Spring Left
1	Zero Position	0	0	0	0	0	0	0	0	0
2	Full Braking	-20	0	0	-0.233	-0.233	- 0.442	- 0.442	- 21.033	- 21.033
3	Half Braking, Half Cornering	-10	0.75	0	0.505	-0.74	- 0.464	0.021	- 22.083	0.993
4	Full Cornering	0	1.5	0	1.243	-1.287	- 0.486	0.472	- 23.137	21.807
5	Half Acceleration, Half Cornering	10	0.75	0	0.74	-0.546	- 0.021	0.451	-0.995	20.867
6	Full Acceleration	20	0	0	0.195	0.195	0.431	0.431	19.926	19.926

Table 12 - Roll Centre Migration Data 1

Table 13 - Roll Centre Migration Data 2

Stage of Corner		Motion Ratio Right	Motion Ratio Left	Toe-in Angle	Corrected toe	Toe Left	Toe Right
1	Zero Position	1.023	1.023	0	0	0	0
2	Full Braking	1.08	1.08	-0.885	0.885	0.442	0.442
3	Half Braking, Half Cornering	1.083	1.02	-0.443	0.443	-0.021	0.464
4	Full Cornering	1.085	0.967	-0.014	0.014	-0.472	0.486
5	Half Acceleration, Half Cornering	1.026	0.969	0.43	-0.43	-0.451	0.021
6	Full Acceleration	0.972	0.972	0.861	-0.861	-0.431	-0.431

Table 14 - Roll Centre Migration Data 3

Stage of Corner		IC Right	IC Left	Roll Centre Height	Roll Centre Width	Zeroed Roll Centre Height
1	Zero Position	4190.543	4190.543	11.479	0	0
2	Full Braking	3687.023	3687.023	-9.039	0	-20.518
3	Half Braking, Half Cornering	3665.875	4219.001	1.158	-194.439	-10.321
4	Full Cornering	3644.422	4935.075	11.539	-47.52	0.06
5	Half Acceleration, Half Cornering	4161.877	4895.201	21.819	-14.303	10.34
6	Full Acceleration	4855.331	4855.331	32.166	0	20.687

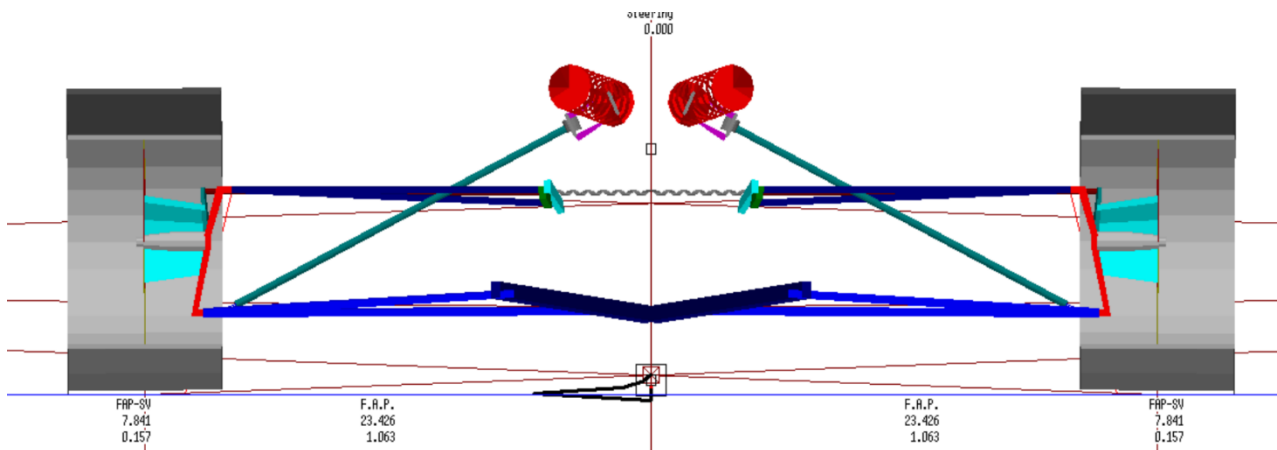


Figure 27 - WinGeo Roll Centre Migration

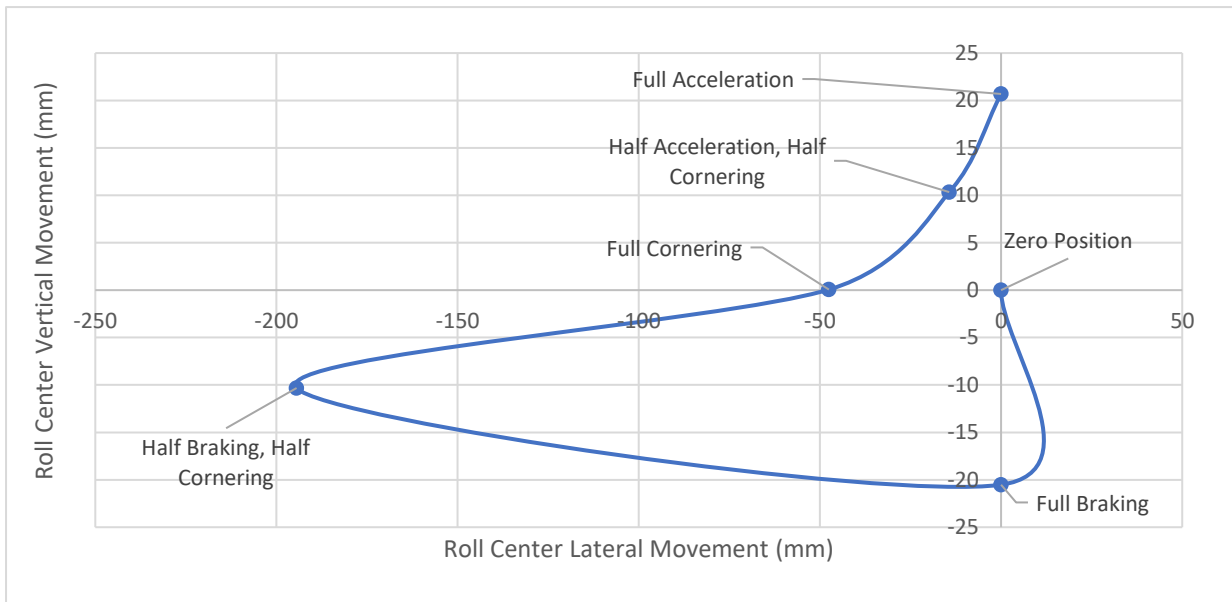


Figure 28 – Roll Centre Movement Through Corner

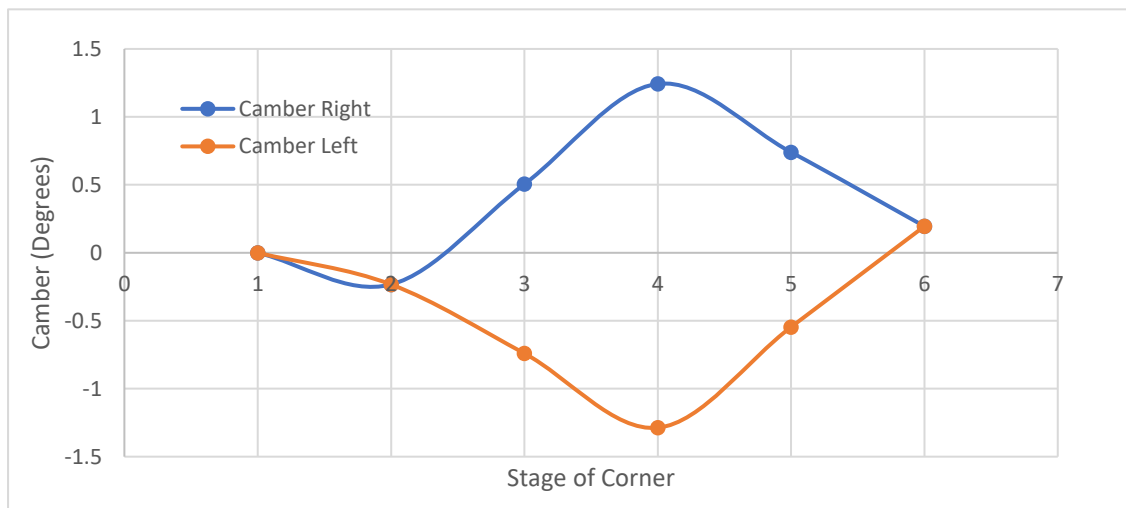


Figure 30 - Camber Change During Cornering

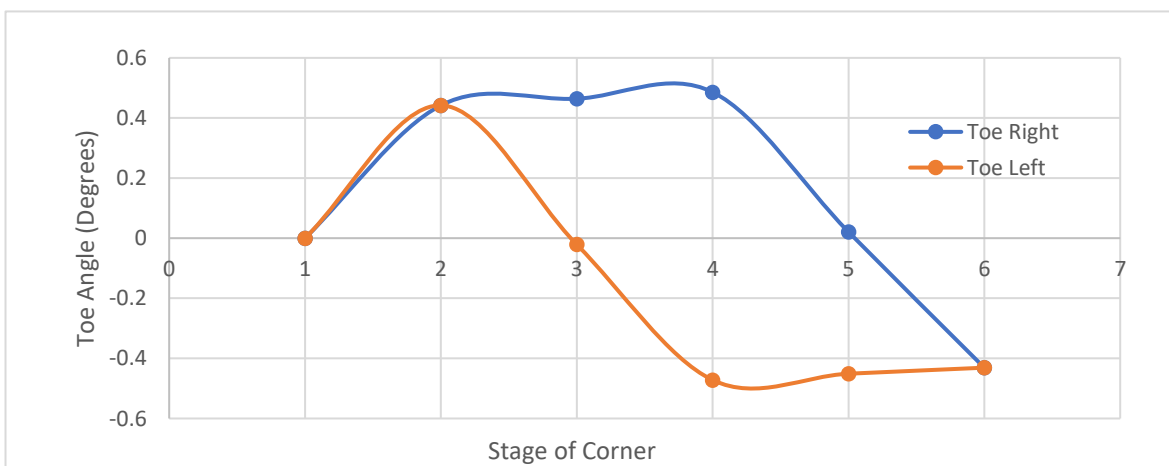


Figure 29 - Toe Angle Change During Cornering

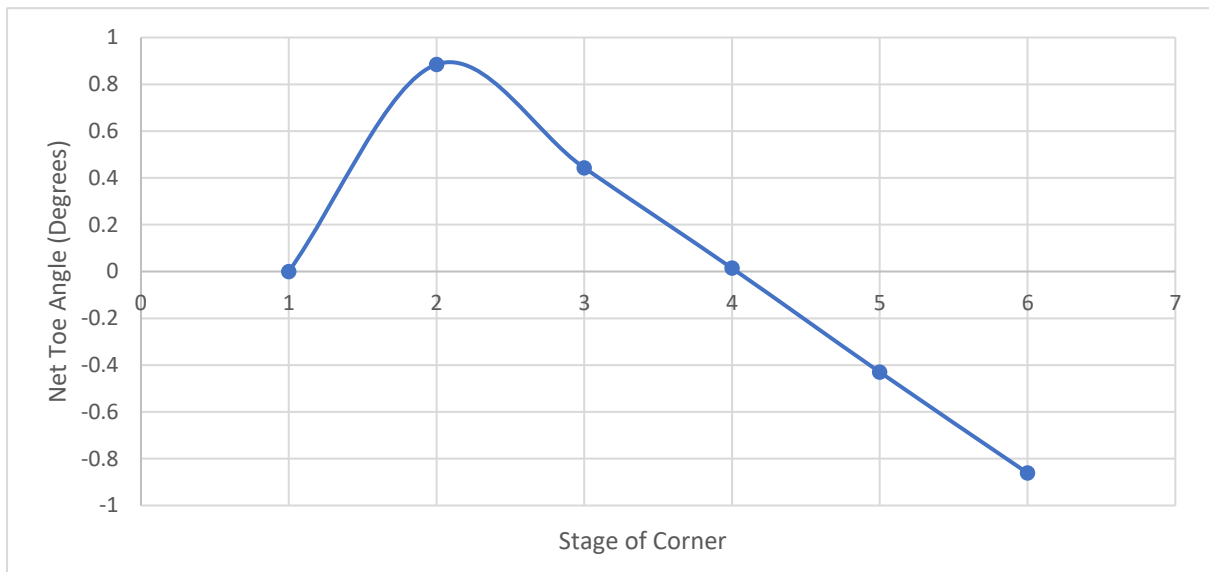


Figure 31 - Net Toe Angle During Cornering

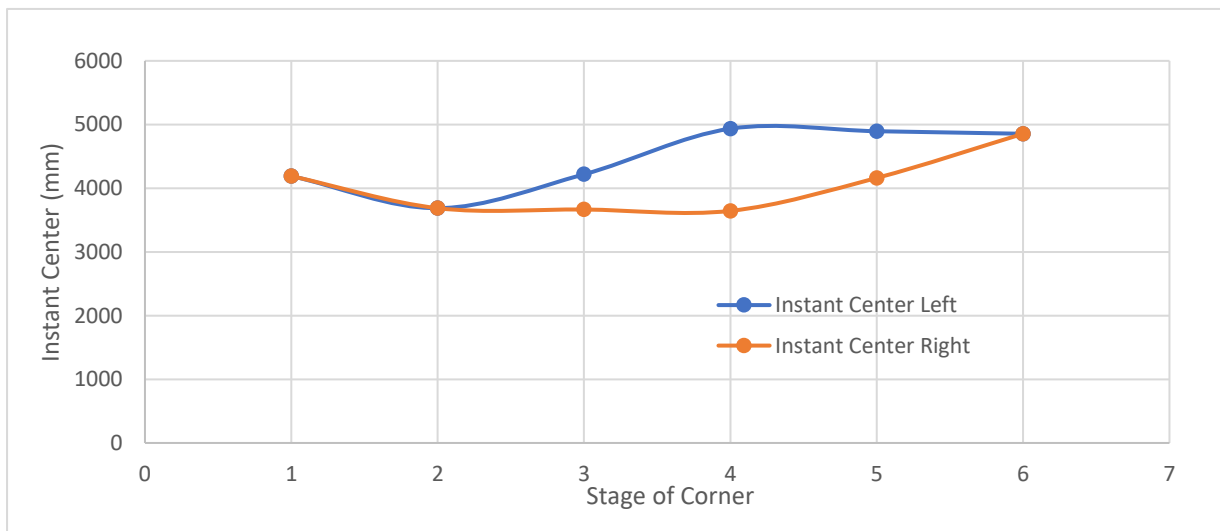


Figure 32 - Instant Centre During Cornering

The diagram shown in Figure 28 is significant as it depicts the transfer of load of the sprung mass of a car during a corner for example the tyres are under the most lateral load and the tyres are loaded more asymmetrically during “half braking, half cornering” than at any other point during the test. The diagram shows the roll centre moving into positive horizontal movement at the beginning of the test, this is a mistake from the way the trend line was generated, the true movement is shown in figure 27.

4 Suspension Calculations

Table 15 - Suspension Calculation Results

Wheel Rate (N/m)	15373.77492
Front Suspension Ride Frequency (Hz)	2.063002595
Front Unsprung Mass Natural Frequency (fus) (Hz)	12.65528396

The above values were calculated using the method detail in the sub-sections below.

The ride frequency of this car suggests that it was designed for track use as it would be relatively stiff. This is further supported when considering the low ride height of the vehicle. A frequency around 2Hz is also suitable for a small amount of downforce. If the car was designed for road use the ride frequency would be lower, for example 1 to 1.5 Hz (Barak, 1991). This suspension would not be suited for road use as it would be too stiff to be comfortable while absorbing bumps in the road, these are not issues on a smooth track. However, this style of suspension can be seen in some road cars but only in specialised sports vehicles.

4.1 Wheel Rate

The wheel rate was calculated using the following formula.

$$K_w = K_s \times MR^2$$

Where K_w is Wheel Rate (N/m), K_s is spring rate (N/m), and MR is the motion ratio.

K_s (N/m) = 69923 (Table 5)

MR = 0.4689 (Table 5)

Therefore,

Wheel Rate (N/m) = $69923 \times 0.4689^2 = 15373.77492$

4.2 Unsprung Mass Natural Frequency

The unsprung mass natural frequency was calculated using the following formulae.

$$M_s = M_t - M_{us}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{K_w}{M_s}}$$

Where M_s is sprung mass (Kg), M_t is Total corner mass (Kg), M_{us} is unsprung mass (Kg), and f is ride frequency (Hz).

The mass of the unsprung components when off the car was used for these calculations as previously noted.

Therefore,

$$\text{Ride Frequency (Hz)} = \frac{1}{2\pi} \sqrt{\frac{15373.77492}{91.5}} = 2.063002595$$

4.3 Front Unsprung Mass Natural Frequency

The front unsprung mass was calculated using the following formula.

$$f_{us} = \frac{1}{2\pi} \sqrt{\frac{K_w + K_t}{M_{us}}}$$

Where f_{us} is front unsprung mass natural frequency (Hz).

Therefore,

$$\text{Front Unsprung Mass Natural Frequency (Hz)} = \frac{1}{2\pi} \sqrt{\frac{15373.77492+133210}{23.5}} = 12.65528396$$

5 Validation

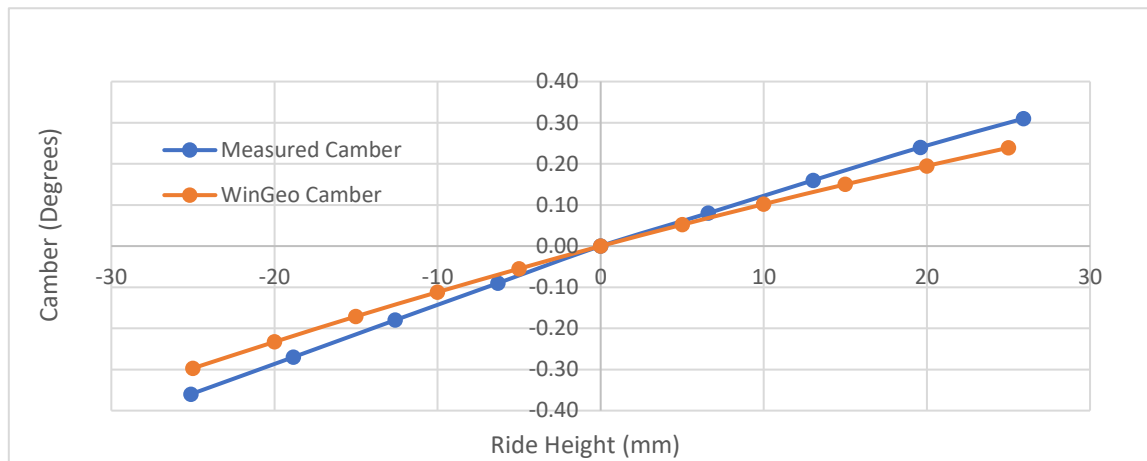


Figure 33 - Comparative Camber Against Ride Height

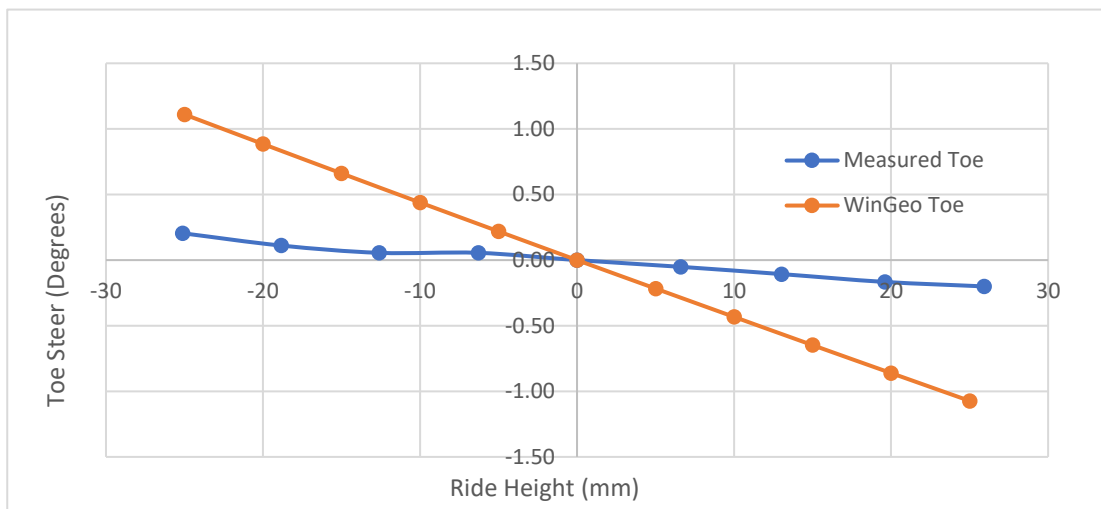


Figure 34 - Comparative Toe Angle Against Ride Height

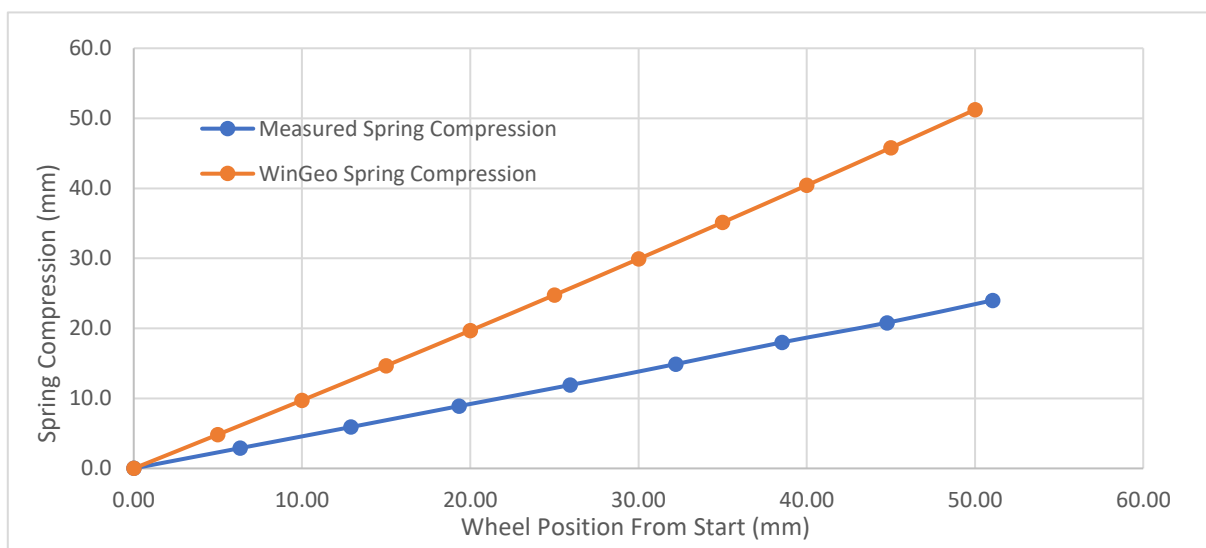


Figure 35 - Comparative Spring Compression Against Wheel Position

The above graphs (Figures 33-35) show that the data recorded in the lab does not correlate perfectly with the WinGeo data. The data trends the same way showing that the characteristics of the suspension system are correctly shown, and all data point meet the trend line showing laboratory data is consistent therefore reliable. However, the difference in the results may be because the motion ratio of the WinGeo model used does not match the motion ration of the chassis the tests were conducted on.

Laboratory Chassis MR = 0.4689 (Table 5)

WinGeo Zero Position MR = 1.023 (Table 11)

6 Conclusion

The methodology of this test could be improved using previously mentioned changes however it was sufficiently accurate for this investigation. The suspension system was designed for track use only as the ride frequency is too high and the ride height too low for road use. WinGeo can be useful for checking data recorded in laboratory tests, for visualising suspension movement and running repeated calculations providing the model is accurate.

7 References

Barak, P. (1991) 'Magic numbers in design of suspensions for passenger cars', *SAE Technical Papers*. doi: 10.4271/911921.

Dachi, R. and Setiawan, I. (2018) 'Measurement of gravitational acceleration with the leak tank method', *Journal of Physics: Theories and Applications*, 2(1), p. 19. doi: 10.20961/jphystheor-appl.v2i1.29000.

Demon-Tweeks (2021). Available at: <https://www.demon-tweeks.com/uk/longacre-modular-billet-scale-pad-levellers-lon72840/> (Accessed: 29 November 2021).

Lee, U. and Han, C. (2001) 'A suspension system with a variable roll centre for the improvement of vehicle handling characteristics', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 215(6), pp. 677–696. doi: 10.1243/0954407011528266.

Mitchell, W. C. (1998) 'Asymmetric roll centers', *SAE Technical Papers*. doi: 10.4271/983085.

Wood, I. (2021) *Formula Scout*. Available at: <https://formulascout.com/when-webber-ruled-the-world-25-years-since-the-1996-ford-festival/85397> (Accessed: 29 November 2021).