

Steady state load transfer and aerodynamic loading

by Ryan James

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Steady State Load Transfer and Aerodynamic Loading

Vehicle Dynamics

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1 Introduction

1.1 Aims

To acquire accurate data from a vehicle simulator to gain an understanding of load transfer in longitudinal and lateral accelerations in steady state conditions.

1.2 Objectives

1.2.1 Lateral Corner Weight Transfer

To carry out steady state cornering tests on the universities BPS simulator. The steady state test type chosen is when the steering input condition is constant for a constant radius, to give an idea of dynamic stability (Dixon, 1991), at a variety of velocities according to the standard iso-4138 8.4.1 (ISO, 2012). During the test all the available data variables will be recorded and analysed after to determine the effects of load transfer.

1.2.2 Longitudinal Aero Load

To carry out a coast down test on the universities BPS simulator. The coast down test method will be used to estimate the drag and lift forces. By allowing the vehicle to decelerate from a set speed and monitor the loads applied to the tyres and the time to decelerate, the forces and coefficients can be calculated (SAE, 1995).

2 Steady state cornering weight transfer

2.1 Data gathering

Table 1 Test Setups

Test Setups		Setup 1	Setup 2	Setup 3
Front Spring Rate (N/mm)	K_{sf}	202	254	307
Rear Spring Rate (N/mm)	K_{sr}	307	254	202
Front Anti Roll Bar Wheel Rate (N/mm)	$K_{w_{arbf}}$	280	280	280
Rear Anti Roll Bar Wheel Rate (N/mm)	$K_{w_{arbr}}$	48	48	48

The setups in table 1 were provided. The spring rates were varied from soft front and rear hard in setup 1 to a medium spring rate all round in setup 2 then finally Hard Front soft Rear in setup 3 the anti-roll bar stiffness was not changed.

As in ISO 4138 a large known constant radius of 50m was selected, the vehicle is driven slowly around it and from the radius and steering data the ideal Ackerman steer angle is calculated at this neutral steer point (Ellis, 1994). The vehicle was then kept on the radius and accelerated to and held at 35k/h, 60k/h and 100k/h for at least 3 rotations. The 3 faster velocity tests were repeated for each setup.

If in each test the velocity and radius are identical in theory the lateral acceleration will be the same as $a_y = \frac{v^2}{r}$ (ISO, 2012). This should show the total weight transfer as constant as $WT = \frac{M \times a_y \times H}{L}$ (SAE J670, 2008). Therefore the change in spring rates front to rear should only change the load distribution as the proportion of sprung transfer moves across the axles thus changing the forces working the tyres affecting handling characteristics. Ideally the height of the centre of gravity would be at the floor and the cornering forces would cause no weight transfer and the cornering power of all four tyres would be at maximum (Barak, 1991).

The weight transfer distribution will be calculated using the equation front weight transfer/total weight transfer (Milliken, 1995). This “magic Number” can be used to predict under/oversteer characteristics caused by the tyre loadings from the different types of weight transfer (Barak, 1991). If all tyres have the same characteristics in theory as the magic number increases so does the understeer. Understeer is when the required steer angle needs to be increased as speed increases to maintain a radius oversteer is when the required steered angle needs to be decreased to maintain a radius as speed increases (Ellis, 1994).

As can be seen in the following equations if as previously stated the lateral acceleration is constant for the corner radius the sprung geometric and the unsprung geometric weight transfer will remain the same for each set up (as long as the roll centre does not move too much with body roll as this is taken as a constant). This means the move in weight distribution is caused by the sprung elastic element as this has a variable for roll stiffness for each setting.

The purpose of this study to gain an understanding of vehicle behaviour during cornering in the steady state this is mainly characterised as the lateral and vertical force each tyre receives. Unfortunately no tyre data was available as this would have given a spring rate and an idea of deformation/squish, pressure and the change in contact patch that would change the grip available and thus handling (Rowley, 2003).

2.2 Weight Transfer Equations

If the subscript z is seen this can be replaced with f,r and t to apply formulas to front rear or total as required.

2.2.1 Sim Model Spec

$$M_T = \frac{TL_{FR} + TL_{FL} + TL_{RR} + TL_{RL}}{g} \quad \text{Equation 1 Total Static Mass from Sim (kg)}$$

Where M_T = Total static Mass, Kg; TL = Tyre Load, N; g = Gravity, m/s/s.

$$WD = \left(\frac{SM_f}{TM} \right) \times Wb \quad \text{Equation 2 Weight Distance Distribution (m)}$$

Where WD = weight distribution, Kg; SM_f = Sim Mass Front, Kg; TSM = Total Sim Mass, Kg; Wb = Wheelbase, m.

2.2.2 Basic Prediction

$$LaWT = \frac{TM \times a_y \times COG}{T} \quad \text{Equation 3 Basic Weight transfer Prediction (N)}$$

Where LaWT = lateral Weight Transfer, N; a_y = Lateral Acceleration, M/s/s; COG = Centre of Gravity height, m.

2.2.3 Roll Stiffness Calculations

$$K_{WZ} = (K_{SZ} \times MR_z^2) + K_{warbz} \quad \text{Equation 4 Wheel Rate (N/mm)}$$

Where K_w = Wheel Rate, N/mm; K_s = Spring Rate, N/mm; MR = Motion Ratio; K_{warb} = Anti roll Bar Rate, N/mm.

$$K_{\theta z} = \frac{T_z^2 (K_{WZ} \times 1000)}{2} \quad \text{Equation 5 Roll Stiffness (NM/Rad)}$$

Where K_{θ} = Roll stiffness, NM/Rad; T = Track, m.

2.2.4 Roll angle

$$M_{ot} = M_s \times a_y \times H \quad \text{Equation 6 Overturning Moment (Nm)}$$

Where M_{ot} = Overturn moment, Nm; M_s = mass sprung, Kg; H = Distance Between Roll centre and COG, m.

$$\theta = \frac{M_{ot}}{K_{\theta z}} \quad \text{Equation 7 Roll Angle (Rad)}$$

Where θ = Roll angle, Rad.

$$\theta^\circ = \theta \times \left(\frac{180}{\pi}\right) \quad \text{Equation 8 Roll angle Degrees (°)}$$

Where θ° = Roll angle degrees, °.

$$\delta = \frac{T\theta}{2} \quad \text{Equation 9 Wheel Deflection (m)}$$

Where δ = Relative Wheel Deflection, m.

2.2.5 Predicted Weigh Transfers

$$WT_{sz} = \delta \times K_{WZ} \quad \text{Equation 10 Weight Transfer Sprung Forces (N)}$$

Where WT_s = Weight Transfer sprung elastic Force, N.

$$WT_{sRCz} = \frac{M_{sz} \times a_y \times h_z}{T_z} \quad \text{Equation 11 Sprung Mass Geometric Weight Transfer (N)}$$

Where WT_{sRC} = Sprung Mass Geometric Weight Transfer, N; h = Height of Roll Centre from roll axis, m.

$$WT_{usz} = \frac{M_{usz} \times a_y \times r_z}{T_z} \quad \text{Equation 12 Unsprung Mass Geometric Weight Transfer (N)}$$

Where WT_{us} = Unsprung Mass Geometric Weight Transfer, N; M_{us} = Mass Unsprung, Kg.
 r = Height of Wheel centre, m.

$$WT_z = WT_{sz} + WT_{sRCz} + WT_{usz} \quad \text{Equation 13 Weight Transfer Predicted (N)}$$

2.2.6 Actual Weight Transfer

$$WT_z = \frac{TireLoadZL - TireLoadZR}{2} \quad \text{Equation 14 Actual Weight Transfer (N)}$$

2.2.7 Magic Number

$$MN = \frac{Rear\ WT}{Front\ WT + Rear\ WT} \quad \text{Equation 15 Magic Number (Ratio)}$$

Where MN = Magic Number, Ratio. (can be used for actual and either predicted)

2.2.8 Understeer

$$r = \frac{v^2}{a_y} \quad \text{Equation 16 Corner Radius (m)}$$

Where r = Corner Radius, m; v = velocity, m/s.

$$RSA = \frac{Wb}{r} = \frac{Wb \times a_y}{v^2} \quad \text{Equation 13 Required Steer Angle (rad)}$$

Where RSA = Required Steer Angle, rad.

$$x = \frac{Steering\ Wheel\ Pct}{RSA} \quad \text{Equation 14 x ratio of wheel channel to road wheel angle (ratio)}$$

Where x = ratio of steering wheel channel to road wheel, ratio; Steering Wheel Pct = channel for steering input, %.

$$MSP = RSA \times x \quad \text{Equation 15 Minimum steer \%}$$

Where MSP = minimum Steer percent for corner, %.

$$Understeer = absolute(Steering\ Wheel\ Pct) - absolute(MSP) \quad \text{Equation 6 Understeer (ratio)}$$

Where Understeer = a ratio of understeer when positive and oversteer when negative.

$$U.S. = \frac{(Slide\ Pct\ FL + Slide\ Pct\ FR)}{(Slide\ Pct\ FR + Slide\ Pct\ FL + Slide\ Pct\ RR + Slide\ Pct\ RL)} \quad \text{Equation 7 Understeer Slip (Ratio)}$$

Where U.S. = understeer slip, Ratio (positive understeer negative oversteers); Slide Pct = percentage of slide on given tyre, %.

2.3 Results

All graphs not from Motec have the data taken as an average from the steadiest 314m (1 full circle) to smooth out errors. The maths channels and setup sheets used can be seen in the appendices 7.11.

2.3.1 Weight Transfer

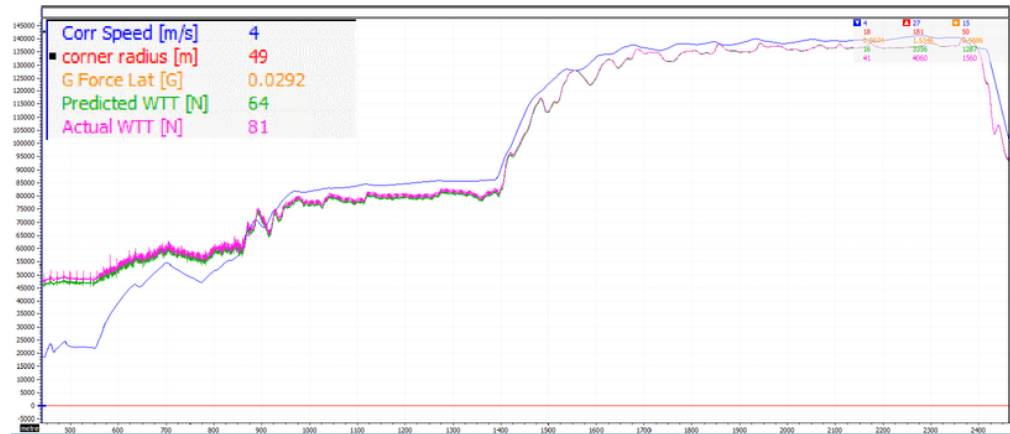


Figure 1 Weight transfer at different velocities

- Figure 1 shows as previously stated if the velocity is increased on a steady radius the lateral acceleration will increase increasing body roll and total weight transfer.

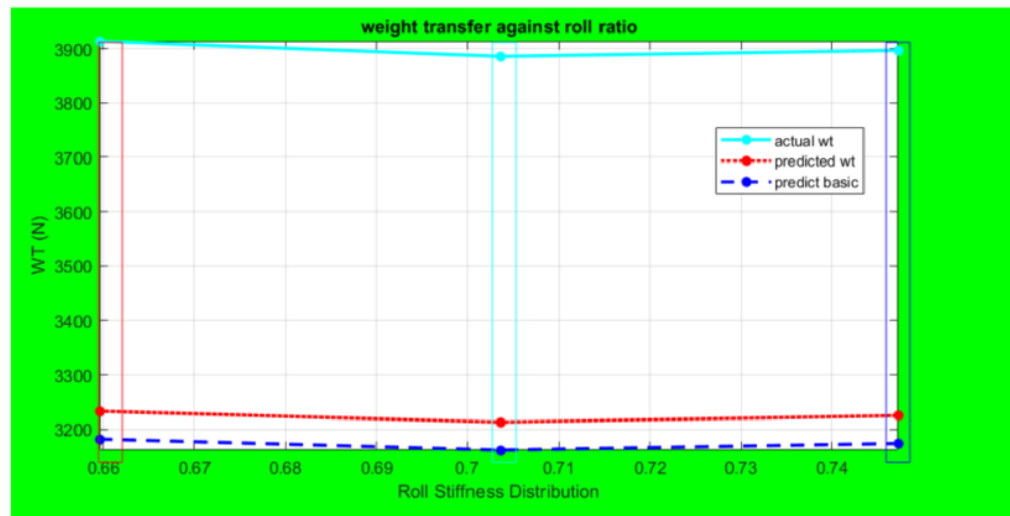


Figure 2 Weight Transfer at 100kph varying roll stiffness

- Figure 2 shows the total weight transfer at 100kph for setup 1 to 3 in the red, light blue and dark blue boxes respectively.
- Figure 2 shows total weight transfer at the same velocity is nearly the same across the 3 setups with a difference of less than 1% when looking at either actual predicted or basic.
- There is approximately 21% or 675 N Difference Between Predicted and Actual. This could be for the following reasons.
 1. Tyres have a spring rate that is not accounted for
 2. Tyre deflection results in increased body roll not accounted for
 3. Aero effect not taken into consideration in the calculations for predicted and basic.
 4. The roll centre may move with body roll.
 5. Very slight change in COG height with body roll (unlikely to have an effect as so small (PARCZEWSKI, 2017)).
 6. The sim model had 70l or 52kg of fuel. The mass was considered as static tyre loads were converted. The fuel mass was used as a sprung mass that moved as a fixed part with body roll in the predicted equations and the sim may use it dynamically as moving mass.

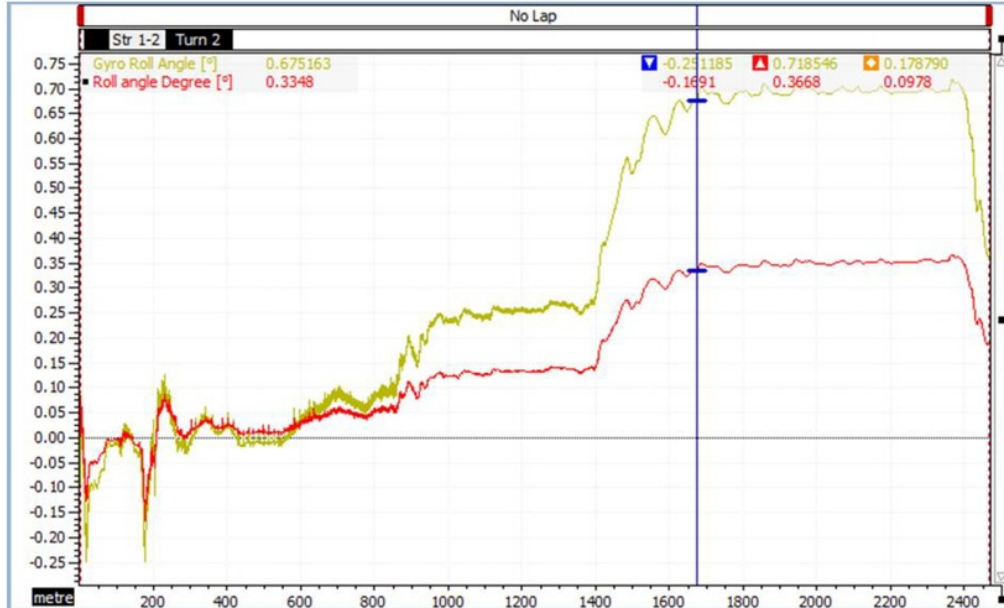


Figure 3 Sim Roll and Calculated Roll

- Figure 3 shows the difference in roll angle due to the tyre spring rate being neglected and the tyre deflection behaviour if that is accounted for by the sim.

2.3.2 Magic Number and Understeer

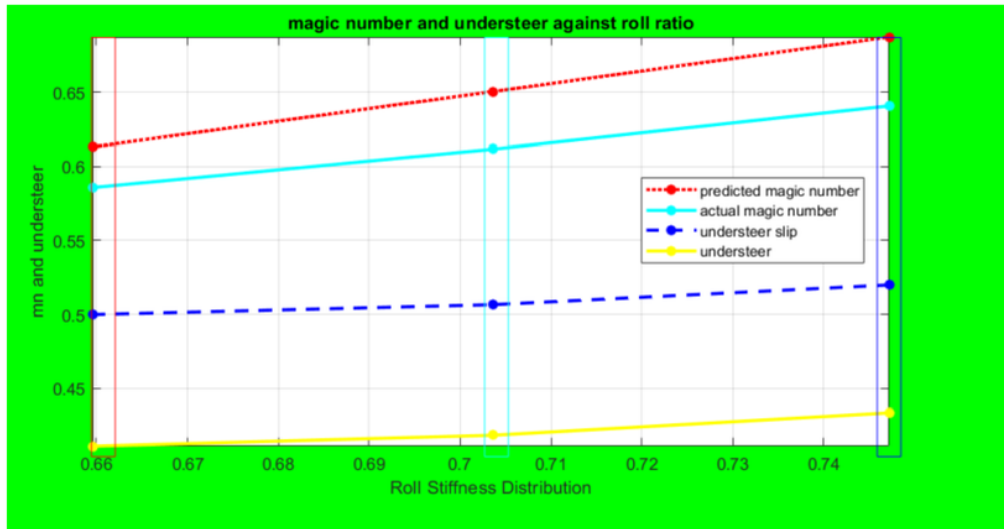


Figure 4 Magic Number and Understeer

- These results are all at 100kph as this was the fastest steady state and would show under or oversteer differences the best as they are proportional to speed.
- Understeers have been adjusted to decimal for correlation
- All show same Trend you get more understeer when the front axle becomes stiffer and the spring force works the tyre harder.
- Purple understeer (steering wheel difference to minimum Ackerman steer required) is the most accurate for understanding behaviour as this shows driver oversteering to compensate for understeer.
- Magic numbers and understeer slip all assume same tyre contact patch and same characteristics e.g. coefficient of friction. Therefore, if the rear tyres were twice the width the magic number would show a trend that had more oversteer in extreme cases when the understeer would show less as there would be more rear grip.

3 Straight Line Aerodynamic testing

3.1 Method and literature review

To calculate the proportion of force acting on the caused by aero dynamic loading a coast down test will be performed for a variety of aerodynamic settings.

Table 2 Aerodynamic settings.

		Front Splitter Setting		
		1	2	3
Rear Wing Setting	1	A7	A2	A6
	2			
	3			
	4			
	5			
	6	A8	A1	A5
	7			
	8		AB	
	9			
	10			
	11			
	12	A9	A3	A4

Table 2 shows the chosen settings tested for each coast down test from the range available. These had been chosen as they should show the full range of lift and drag available and if the change is linear. The first checked was AB (the base setting) then adjustments were made to the wing and those settings were checked then splitter and wing again for subsequent checks. This was done as in reality a wing is easier to adjust and this would result in fewer splitter adjustments.

To calculate the Coefficient of lift which is the ratio factor used to calculate the force that directly opposes a bodies weight due to its shape from passing through a fluid (Hall, n.d.). The vehicle is held at a constant velocity and the load difference to static is measured accounting for longitudinal Weight Transfer. The force is put through the CL equation to calculate it. As the forces are measured positive this gives a positive result for Lift which is incorrect as it is negative lift (downforce). The results have been kept as positive to aid comparison with Drag.

To calculate the balance the front aerodynamic load is divided by the total this gives the centre of pressure or the proportion that acts on the front axle. By altering the wing and splitter settings this can move its position about the wheel base. This is critical in determining handling characteristics of a car. Typically, the initial set up is approximately 45% acting on the front then this is adjusted for driver preference at the track (Totalsim, 2016).

To calculate the coefficient of Drag which is the ratio used to calculate the force that opposes the bodies motion due to its shape (frontal area) passing through fluid (Hall, n.d.). all the forces that resist motion need to be considered. There is a mechanical drag factor that when ignoring extra vertical force from downforce is essentially the force to tow the vehicle. The mechanical drag increases with velocity as the downforce increases but this can be contributed to the aerodynamic drag, so mechanical drag is calculated at a slow speed when there is thought to be nearly no aerodynamic drag as aerodynamic forces rise exponentially with velocity (Katz, 2006).

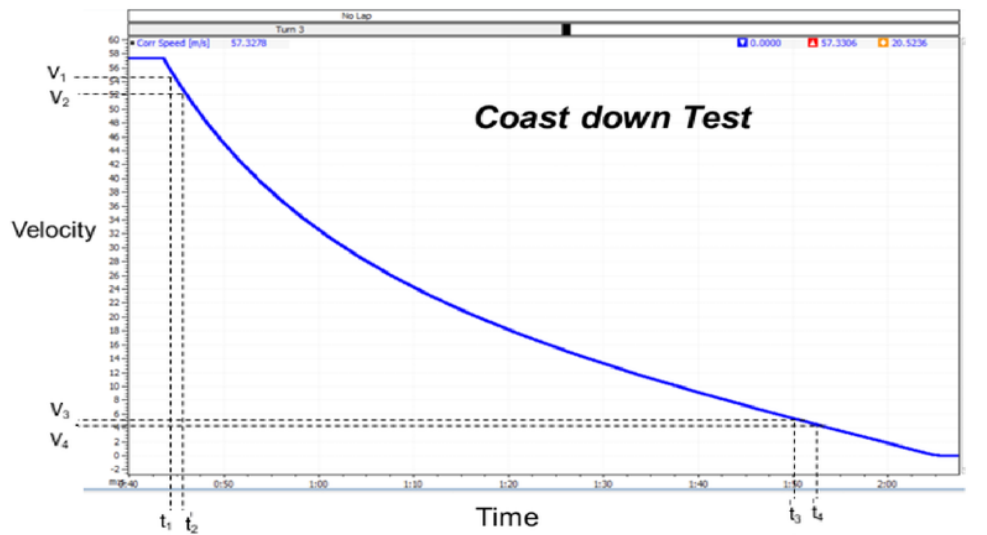


Figure 5 Graph showing coast down data points

Figure 5 shows the times and velocities used to calculate total resistance. The deceleration is performed by declutching from the maximum speed in 4th and letting only drag forces slow the vehicle. The times between t_1 and t_2 and then t_3 and t_4 were selected as 1 second this simplified the formulas to $\cdot 1s$ and using a shorter average to improve accuracy so only total resistance at t_1 - t_2 and mechanical at t_3 - t_4 would be

calculated. As $F=ma$ knowing the mass and the deacceleration from the graph the loads could be calculated (Katz, 2006).

To give an idea of aerodynamic performance the efficiency is calculated which is the lift/drag the higher the efficiency the more downforce per lift therefore the better aerodynamic performance (Quintarelli, 2018).

3.1.1 Equations

3.1.1.1 Coefficient of lift

$$LoWT = \frac{TSM \times a_x \times COG}{Wb} \quad \text{Equation 22 Longitudinal Weight Transfer (N)}$$

Where LoWT = longitudinal Weight Transfer, N; a_x = Longitudinal Acceleration, M/s/s.

$$CLf/r = \frac{2 \times [(F/R L + F/RR) - (F/RL0 + F/RR0)]}{\rho \times v^2} \pm LoWT \quad \text{Equation 22 CL Front/Rear (ratio)}$$

Where CL = Coefficient of Lift, Ratio; F/RL = Front/Rear left Tyre Load at Velocity, (N); F/RL0 = Front/Rear Left Tyre Load Static, (N); ρ = Density of Air, Kg/m³.

3.1.1.2 Total Resistance

$$TR = \left(\frac{(v_2 - v_1)}{(t_2 - t_1)} \right) \times TM \quad \text{Equation 23 Total Resistance (N)}$$

3.1.1.3 Mechanical Rolling Resistance

$$RR = \left(\frac{(v_4 - v_3)}{(t_4 - t_3)} \right) \times TM \quad \text{Equation 24 Rolling Resistance (N)}$$

3.1.1.4 Aerodynamic Resistance

$$AR = TR - RR \quad \text{Equation 25 Aerodynamic Resistance (N)}$$

3.1.1.5 Coefficient of Drag per m²

$$C_d A = \frac{2(AR)}{\rho v_m^2} \quad \text{Equation 26 Coefficient of Drag per m}^2$$

3.1.1.6 Aerodynamic Efficiency

$$AE = \frac{CLA}{CdA} \quad \text{Equation 27 Aerodynamic Efficiency}$$

3.1.1.7 Cop

$$AF F/R = [(F/R L + F/RR) - (F/RL0 + F/RR0)] \pm LoWT \quad \text{Equation 28 Aero Force (N)}$$

Where AF F/R= Aero Force Front/ Rear, N.

$$CoP = \frac{AF F}{(AF F + AF R)} \quad \text{Equation 29 Centre of Pressure (Ratio)}$$

3.1.2 Results

3.1.2.1 CL and CD

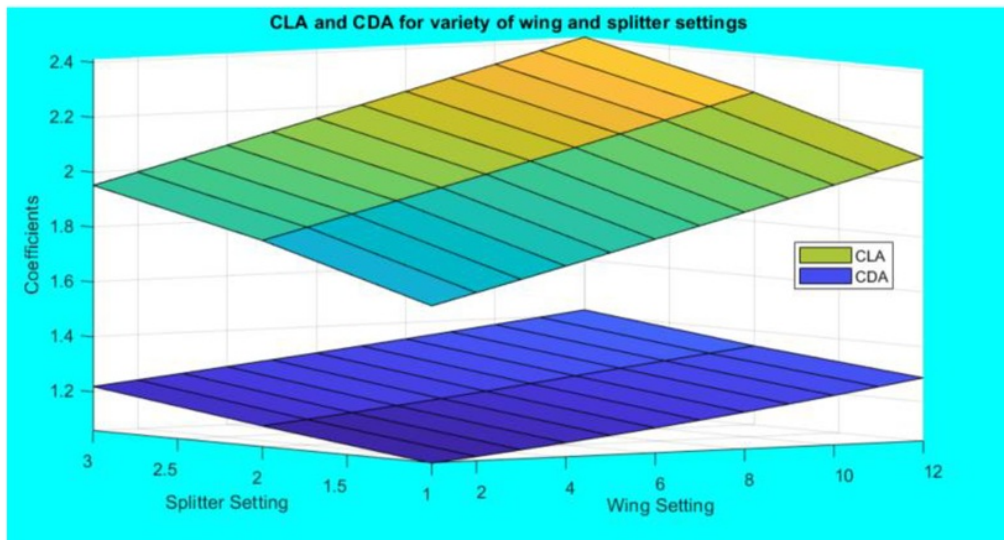
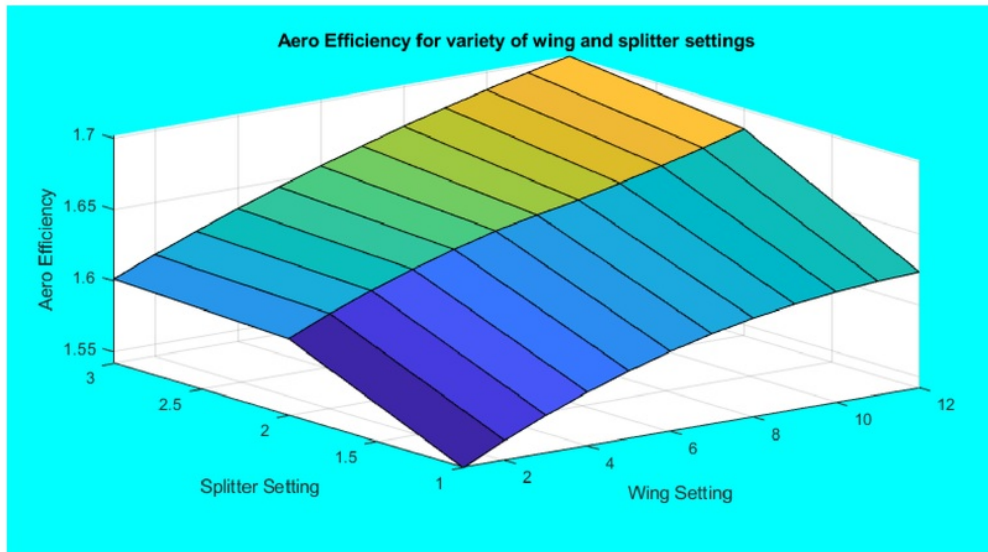


Figure 6 CLA and CDA for wing and splitter settings

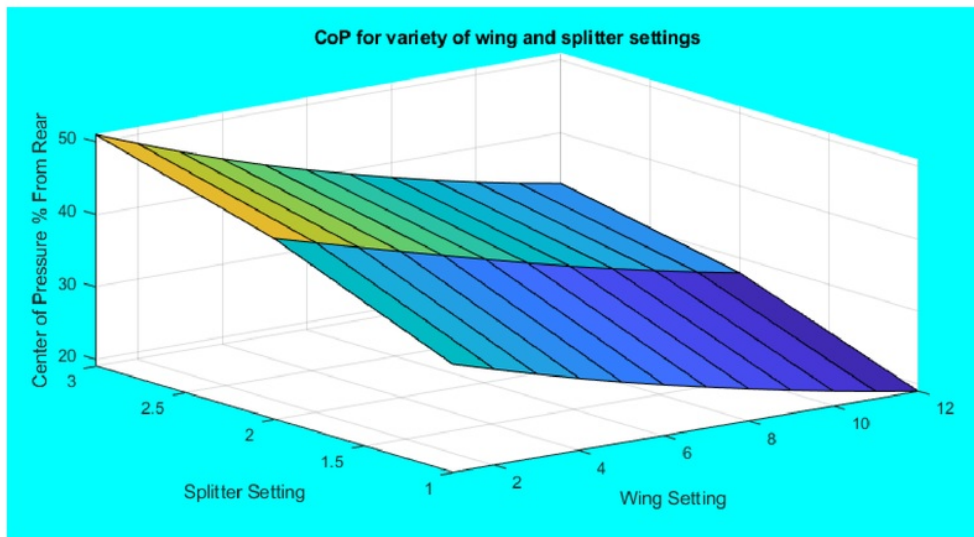
- Figure 6 shows the values for CL per m^2 (shown as positive representing downforce) and CD per m^2
- The initial results were interpolated on MATLAB to find the values for every possible setting.
- The interpolated results fit in a linear way which gives confidence in the calculations and predictions.
- Shows as CL increases so does drag but not at the same rate.
- The range on the devices is always in the working range with “attachment” as CL does not Drop towards maximum wing or splitter settings. Or the sim doesn't model flow separation. If it did it is possible that at the maximum wing setting the flow will not remain attached until the trailing edge which will cause a decrease in performance as the wing will enter a stage of stall. (Seetharam, 1978)

3.1.2.2 AE



- This graph better represents the rate of changes difference.
- As expected from previous graph the most efficient point is maximum settings as the drag does not increase as quickly.

3.1.2.3 Cop



- This graph shows the Aero Load distribution balance from the different settings
- If less understeer is required it shows that more splitter should be selected as this would increase the load on the front and move the centre of pressure forward.

- If less oversteer is required it shows that more wing should be selected as this would increase the load on the front and move the centre of pressure Backwards.
- Increasing the aero tyre load on any axle would in theory give more grip but it would result in a drag penalty.

3.1.2.4 Selecting Aero Balance

CoP		Front Splitter Setting			AE	Front Splitter Setting			
		1	2	3		1	2	3	
Rear Wing Setting	1	34	44	51	Rear Wing Setting	1	1.542	1.596	1.601
	2	32.23	42.34	48.74		2	1.556	1.608	1.613
	3	30.54	40.72	46.59		3	1.569	1.619	1.625
	4	28.93	39.12	44.57		4	1.58	1.629	1.635
	5	27.41	37.55	42.7		5	1.589	1.638	1.645
	6	26	36	41		6	1.598	1.646	1.655
	7	24.67	34.46	39.42		7	1.605	1.652	1.664
	8	23.39	33	37.93		8	1.611	1.657	1.673
	9	22.18	31.65	36.52		9	1.616	1.664	1.681
	10	21.04	30.35	35.22		10	1.619	1.671	1.688
	11	19.98	29.13	34.04		11	1.622	1.679	1.695
	12	19	28	33		12	1.623	1.687	1.702

- If it was desired to have a CoP of around 45% for initial test set up the tables above show the most efficient setting within 3% of that in green.
- As can be seen a setting of 3 Splitter and 5 Wing is the most efficient in that range.
- If a higher Cop is required it would be more efficient to move to 4 wing and bypass the next step in Cop of 2 splitter and 1 wing (although as previously stated if a drag reduction is required with higher CoP the latter less efficient CoP is better suited).

4 Discussion

4.1 Weight Transfer

The study proved increasing the spring rate on one axle increases the working of tyres on that axle, this will move the tyres faster to the point of maximum grip and increase slip when reaching critical speed (Ellis, 1994). This showed for the chosen settings the 'magic number' graph could be used to predict behaviour due to spring rate.

The difference in predicted could have been due to the many factors previously discussed, an additional check was made to see if there was a difference in front to rear roll from the wheel height channels these showed each axle to have the same roll angle. This showed there was no pitch during steady state and the chassis had no twist (these maths channels can be seen in the appendices 7.3)

You can approx. balance from spring and anti-roll bar rates if you know lateral g of corner and get a MN although it will be higher for previously discussed reasons.

To validate the maths channels the wheelbase was added to the details on Motec. This activated the Motec maths channels for oversteer this gave an additional yaw angle to compare with minimum steer calculated which was the same.

To set up the vehicle with different roll stiffness characteristic due to spring rate the following points need to be considered.

1. Position of the centre of gravity (mass distribution front to rear) see figures 7 and 8 below.
2. The driver's preference (under or oversteer).
3. The application.
4. The natural frequencies required from the wheel rate and chassis

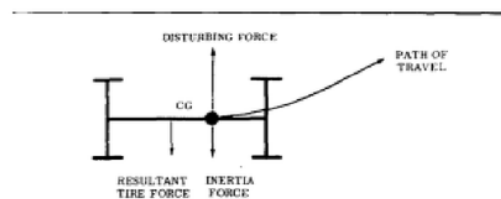


Fig. 20 - Effect of inertia force on understeering response

Figure 7 Effect of front centre of gravity (Bergman, 1965)

Figure 7 shows when the centre of gravity is forward this can create understeer therefore stiffening the rear or softening the front can balance out that effect (Bergman, 1965).

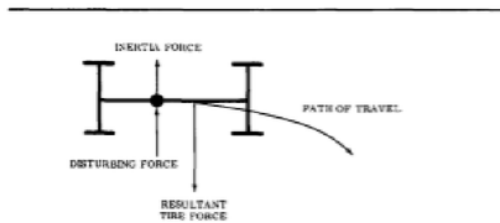


Fig. 21 - Effect of inertia force on oversteering response

Figure 8 Effect of Rear centre of gravity (Bergman, 1965)

Figure 8 shows when the centre of gravity is Rear this can create oversteer therefore stiffening the front or softening the rear can balance out that effect (Bergman, 1965).

As the roll stiffness distribution was taken across a steady total and without the effect of anti-roll bars a further study on more settings should be undertaken.

4.2 Aerodynamic

The aero results never appeared to reach max CL or pass the point of attachment where the CL rapidly drops off and the flow separates (Katz, 2006). This may be due to the fact the sim was only modelled with the aero dynamic devices in the working efficient range.

As adjusting the wing and splitter settings (unknown if its angle and length respectively) didn't give actual angles and positions it was not possible to conduct a study on for example wing angle of attack.

As the floor of the car is the largest aerodynamic surface a further study on rake should be undertaken.

4.3 Non-steady state

The results obtained do not by any means show the full picture for a vehicle around a lap. For cornering the following things should be considered for aerodynamic loading and lateral weight transfer

1. Entering a corner, the vehicle would pitch under braking. This would change the angle of attack of the aerodynamic devices affect and effect the rake. The car would experience longitudinal weight transfer from braking, an F1 car can

experience 5G's (Totalsim, 2016). During braking the dampers would experience a velocity which would create a resistive force.

2. As the car turns in under pitch it would experience roll from the lateral acceleration, this roll would have a velocity that would cause the dampers produce a force, the tyres would have higher loads in the non-steady state increasing under/oversteer and the aero devices would have a pitch and roll angle and they would pass through the air at a yaw angle effecting there performance.
3. Accelerating out of a corner the longitudinal weight transfer would move to the rear and the lateral acceleration would move back to straight again working against damper forces which will affect tyre contact.
4. If CoP for aero and the weight transfer distribution are central (not extreme over 1 axel) to give a balanced vehicle. The overall roll stiffness would play a part in behaviour as harder suspension would limit body roll allowing the vehicle to react faster to chicanes and fast directional changes. If the roll stiffness was softer more body roll would allow the wheels to move into camber (as usually designed) which would help maintain a better tyre contact patch.

5 Extra Data

5.1 Max and Min Roll Stiffness per Axle

5.1.1 Data Gathering

Table 3 Table for Known Roll Stiffness ratio's available

Roll Stiffness Distribution		Front Roll Stiffness (KNm/rad)							
		342822	375953	503412	525712	536543	570311	7E+05	730901
Rear Roll Stiffness (KNm/rad)	128702	0.7271	0.745	0.7964	0.8033	0.8065	0.8159	0.844	0.85028
	144761	0.7031	0.722	0.7767	0.7841	0.7875	0.7976	0.828	0.83468
	177893	0.6584	0.6788	0.7389	0.7472	0.751	0.7622	0.797	0.80425
	192938	0.6399	0.6609	0.7229	0.7315	0.7355	0.7472	0.783	0.79116
	199179	0.6325	0.6537	0.7165	0.7252	0.7293	0.7412	0.778	0.78585
	226069	0.6026	0.6245	0.6901	0.6993	0.7036	0.7161	0.755	0.76377
	258187	0.5704	0.5929	0.661	0.6706	0.6751	0.6884	0.73	0.73896
	259838	0.5688	0.5913	0.6596	0.6692	0.6737	0.687	0.728	0.73773
	291956	0.5401	0.5629	0.6329	0.6429	0.6476	0.6614	0.705	0.71457

- Table 3 shows the original values in blue text and how they increase as a linear ratio. The extra data taken is in red text. the yellow section running diagonally illustrates where the roll distribution is similar for big variations in total stiffness.

Table 4 Total roll Stiffness

total roll stiffness		Front Roll Stiffness (KNm/rad)							
		342822	375953	503412	525712	536543	570311	7E+05	730901
Rear Roll Stiffness (KNm/rad)	128702	471524	504655	632114	654414	665245	699013	8E+05	859603
	144761	487583	520714	648173	670473	681304	715072	8E+05	875662
	177893	520715	553846	681305	703605	714436	748204	9E+05	908794
	192938	535760	568891	696350	718650	729481	763249	9E+05	923839
	199179	542001	575132	702591	724891	735722	769490	9E+05	930080
	226069	568891	602022	729481	751781	762612	796380	9E+05	956970
	258187	601009	634140	761599	783899	794730	828498	1E+06	989088
	259838	602660	635791	763250	785550	796381	830149	1E+06	990739
	291956	634778	667909	795368	817668	828499	862267	1E+06	1022857

- The above Table shows all the original data had a similar total roll stiffness, so the ratio was distributing nearly the same total across the axels to give the linear trends seen in section 2.

5.1.2 Results

5.1.2.1 Weight Transfer

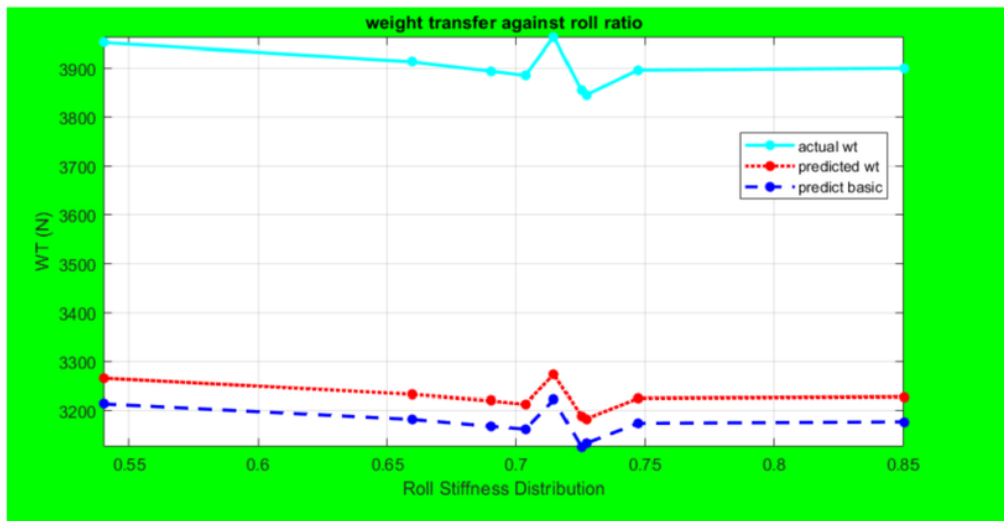


Figure 9 Weight Transfer for a larger setup range

- Figure 9 Graph appears to show anomaly between 0.71 and 0.73 this is only a variation of 3% along each line (predicted, basic and actual)

5.1.2.2 Magic Number and understeer

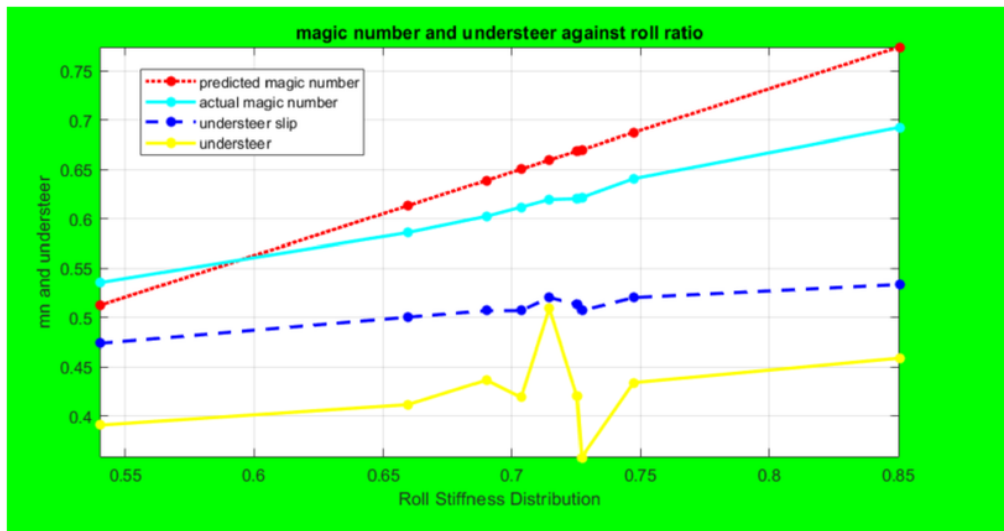


Figure 10 Magic Number and Understeer for Larger Roll Stiffness Distribution

- The under steer slip in figure 10 shows less of a deviation than the actual understeer this is because it is percentage of slip and does not account for the

larger rear contact patch this same tyre assumption also explains the magic number not having any noticeable spikes.

- The reason for the massive spike in understeer compared to understeer slip and magic number is the later two have same tyre on axel assumptions. This shows the limitations of the earlier analysis method.

5.1.3 Results to show for extreme cases

- As the roll stiffness distribution graph does not separate each axel it is not possible to predict for all cases what the behaviour would be.

WT Sim		Front Roll Stiffness (KNm/rad)							
		342822	375953	503412	525712	536543	570311	697133	730901
Rear Roll Stiffness (KNm/rad)	128702	3846							3901
	144761								
	177893								
	192938						3897		
	199179				3855				
	226069			3895		3886			
	258187								
	259838			3914					
	291956	3953							3965

- The above table shows the results taken for each axle roll stiffness to plot a 3d graph the blank yellow cells must be either tested or interpolated. As there are 72 different set ups the less accurate interpolation has been used to give an idea of weight transfer and other behaviour.

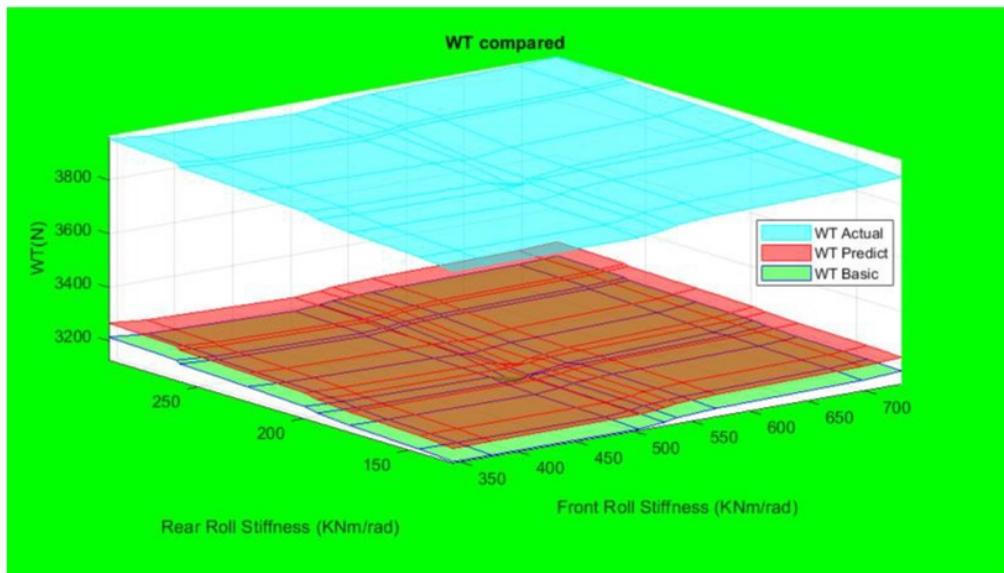


Figure 11 Graph for Interpolated Weight Transfer against each Axle stiffness

The Results in Figure 11 show only a 3% change again with each type which suggests the interpolation technique (Piecewise Cubic Hermite Interpolating Polynomial) did not introduce a new variable.

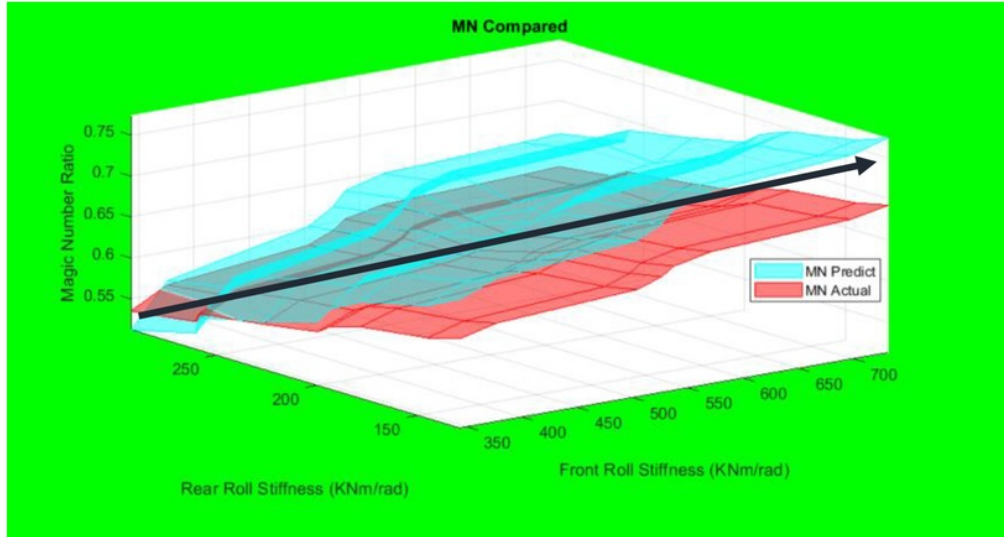


Figure 12 Graph for Interpolated Magic Number Transfer against each Axle stiffness

Figure 12 shows the magic number predicted and actual intersect at the same roll ratio and under steer increases with front roll stiffness and decreases with rear roll stiffness as previously predicted from the original 3 setups (under steer slip follows this trend too see appendices 7.10).

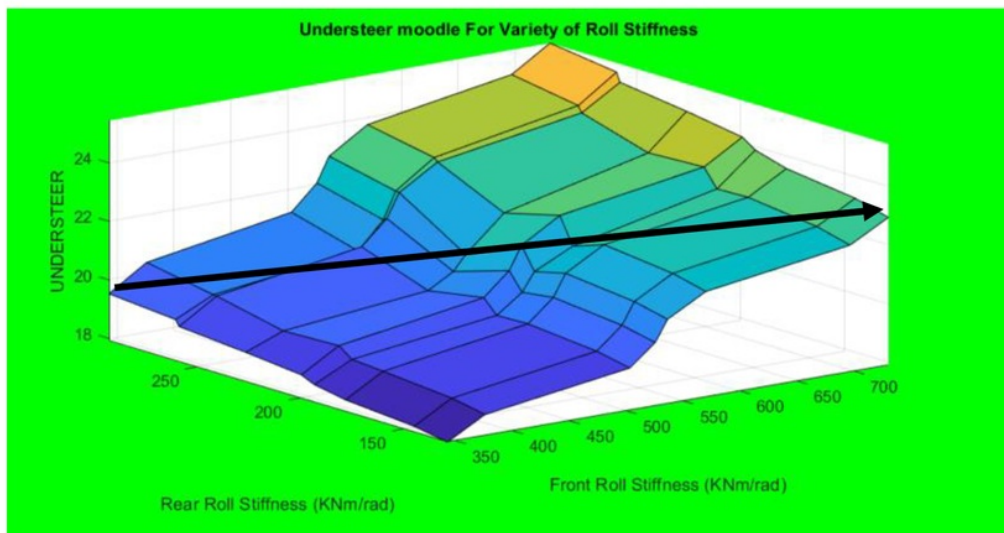


Figure 13 Understeer steering Ratio

- Figure 13 shows that because the rear has more grip, understeer increases with total roll stiffness and is the least with the lowest roll stiffness.
- The black arrows on figures 12 and 13 show the trend gradients for the original 3 data point this show how the magic number is steeper for those roll stiffnesses.
- This shows to get an accurate picture the magic number would only work on a vehicle with equal tyre characteristics all
- round and 50:50 weight distribution.
- This shows if there is more rear grip that increasing total roll stiffness increases understeer and vice versa.
- The spring rate would not be varied that much in reality as the body and wheel rate frequencies would define it and only minor adjustments would be made.

5.2 Adjust Ride and Rake

Table 5 Ride Heights Selected

angle calc		Front Ride (M)	
		0.046	0.7
Rear Ride (m)	0.056	0.20796925	-0.2911557
	0.062	0.33274852	
	0.8	0.70706265	0.20796925

Table 5 shows the setup heights chosen and the Rake angle calculated in degrees

5.2.1.1 Actual Rake

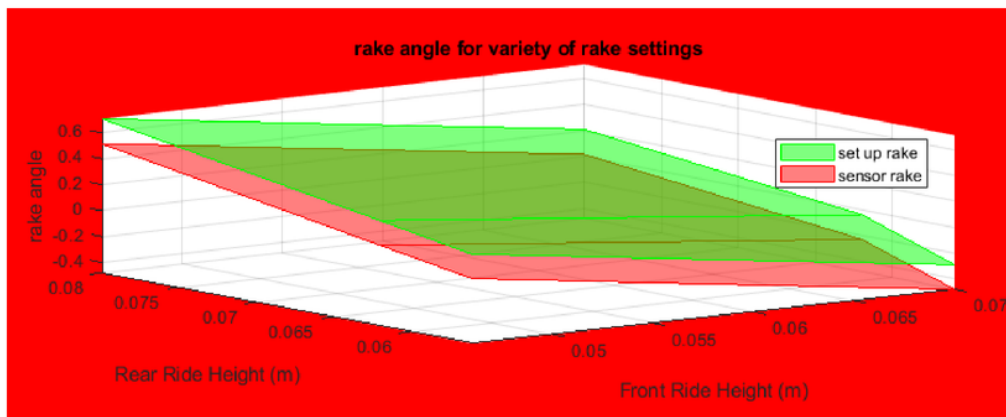


Figure 14 Setup Rake and Steady Velocity Rake

Figure 14 shows when the vehicle is steady at max speed in 4th gear the rake angle drops slightly (-0.2)

5.2.1.2 CL

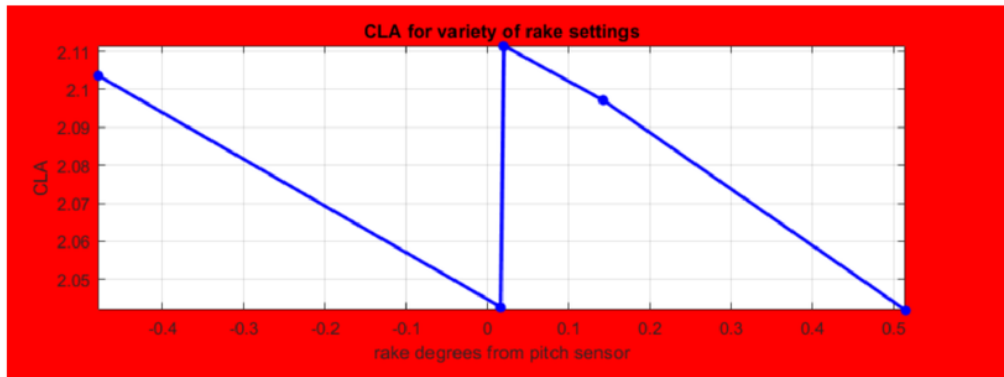


Figure 15 Rake against CL (positive is downforce)

Figure 15 shows when the rake is positive it still has a CL of over 1.9 this is incorrect as it should go negative (as positive is taken as downforce). This is because the floor is the largest aerodynamic surface and the air would not be squeezed at the splitter than expand and accelerated pulling the body down with lower pressure as happens with positive rake. Instead it would push up under the floor lifting the body. For this reason, CD and efficiency will not be looked into, the graphs are in appendices 7.12.

6 References

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7 Appendices

7.1 Setup sheet

[illegible][illegible]

MoTeC																											
Hide Values	Date	Time	Aero	Wing setting	Splice setting	Front Roll Height	Rear Roll Height	delta	V1	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18
Set						m	m	angle	m/s	m/s	m/s	m/s	N	N	N	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio	ratio
Set																											
Difference			0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
steady1 base	11-Feb-19	13:07:00	8	2	0.646	0.062	0.333																				
steady2 set1	11-Feb-19	13:12:00	8	2	0.646	0.062	0.333																				
steady3 set2	11-Feb-19	13:15:00	8	2	0.646	0.062	0.333																				
steady3 set3	11-Feb-19	13:18:00	8	2	0.646	0.062	0.333																				
steady5 redo1	11-Feb-19	13:21:00	8	2	0.646	0.062	0.333																				
aero Base	11-Feb-19	13:24:00	8	2	0.646	0.062	0.333	55.042	52.928	2.436	2.081	466.04	2709.9	2954.7	2.0572	1.2652	1.6576	33									
aero 1	11-Feb-19	13:27:00	6	2	0.646	0.062	0.333	54.794	52.747	1.956	1.597	460.17	2623.9	2163.7	2.0144	1.2238	1.646	36									
aero 2	11-Feb-19	13:29:00	1	2	0.646	0.062	0.333	55.25	53.3	1.95	1.594	456.33	2499.5	2043.2	1.8101	1.1342	1.5959	44									
aero 3	11-Feb-19	13:32:00	12	2	0.646	0.062	0.333	54.756	52.553	2.281	1.926	456.33	2823.8	2387.5	2.2885	1.3449	1.6888	28									
aero 4	11-Feb-19	13:34:00	12	3	0.646	0.062	0.333	54.472	52.194	2.408	2.053	456.04	2920	2464.9	2.4114	1.4172	1.7916	33									
aero 5	11-Feb-19	13:37:00	6	3	0.646	0.062	0.333	54.531	52.771	2.482	2.127	456.04	2768.1	2313.7	2.1593	1.3047	1.655	41									
aero 6	11-Feb-19	13:39:00	1	3	0.646	0.062	0.333	55.138	53.089	2.486	2.14	443.51	2626.4	2182.9	1.9521	1.2191	1.6913	51									
aero 7	11-Feb-19	13:41:00	1	1	0.646	0.062	0.333	56.384	53.53	2.625	2.267	458.09	2376.5	1917.6	1.6365	1.0574	1.6419	34									
aero 8	11-Feb-19	13:44:00	6	1	0.646	0.062	0.333	55.213	53.249	2.494	2.144	448.64	2514.9	2066.3	1.8361	1.149	1.598	26									
aero 9	11-Feb-19	13:46:00	12	1	0.646	0.062	0.333	54.958	52.811	2.439	2.075	446.58	2752.1	2285.5	2.0894	1.2872	1.6232	19									
B1	11-Feb-19	13:58:00	8	2	0.646	0.062	0.333																				
B2	11-Feb-19	14:02:00	8	2	0.646	0.062	0.333																				
B3	11-Feb-19	14:05:00	8	2	0.646	0.062	0.333																				
B4	11-Feb-19	14:08:00	8	2	0.646	0.062	0.333																				
C1	11-Feb-19	14:13:00	8	2	0.07	0.08	0.208	55.033	52.914	2.478	2.119	460.17	2713.5	2253.4	2.0427	1.265	1.6147	31									
C2	11-Feb-19	14:17:00	8	2	0.07	0.056	-0.291	55.036	52.900	2.603	2.247	456.33	2738	2281.6	2.1037	1.2811	1.6421	32									
C3	11-Feb-19	14:20:00	8	2	0.646	0.056	0.208	55.008	52.869	2.453	2.097	456.33	2741.8	2285.5	2.1116	1.2846	1.6436	33									
C4	11-Feb-19	14:23:00	8	2	0.646	0.08	0.707	54.900	52.756	2.431	2.075	456.33	2748.2	2291.9	2.0419	1.2935	1.5785	32									

7.2 Basic Predicted Weigh Transfer Maths Channels

- ☒ WTF latg [N] $((\text{Static mass FL} [\text{kg}] + \text{Static mass FR} [\text{kg}]) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{Center of Gravity} [\text{m}]) / ((\text{Track Front} [\text{mm}] / 1000))$
- ☒ WTR latg [N] $((\text{Static mass RL} [\text{kg}] + \text{Static mass RR} [\text{kg}]) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{Center of Gravity} [\text{m}]) / ((\text{Track Rear} [\text{mm}] / 1000))$
- ☒ WTT latg [N] $((\text{Mt mass total sim} [\text{kg}] * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{Center of Gravity} [\text{m}]) / ((\text{Track Front} [\text{mm}] / 1000))$
- ☒ magic number basic calc [ratio] $\text{WTF latg} [\text{N}] / \text{WTT latg} [\text{N}]$

7.3 Predicted Weigh Transfer Maths Channels

Expressions

- ☒ Mot overturning moment sim [Nm] $((\text{Mt mass total sim} [\text{kg}] * 9.8) * \text{G Force Lat} [\text{G}] * (\text{H RC to COG sim} [\text{m}] * \text{Gravity} [\text{m/s/s}]))$
- ☒ Roll angle [rad] $((\text{Mot overturning moment sim} [\text{Nm}] / \text{k? roll stiffness Total} [\text{Nm/rad}]))$
- ☒ Roll angle Degree [deg] $\text{Roll angle} [\text{rad}] * 57.3$
- ☒ wheel deflection calc [m] $((\text{Track Front} [\text{mm}] / 1000) * \text{Roll angle} [\text{rad}] / 2)$
- ☒ WTsf sprung elastic f [N] $\text{Kwf Front Wheel Rate} [\text{N/mm}] * 1000 * \text{wheel deflection calc} [\text{m}]$
- ☒ WTsr sprung elastic r [N] $\text{Kwr Rear Wheel Rate} [\text{N/mm}] * 1000 * \text{wheel deflection calc} [\text{m}]$
- ☒ WTsrcf sprung geo f [N] $((((\text{Static mass FL} [\text{kg}] + \text{Static mass FR} [\text{kg}] * (\text{Mus Brief mass unsprung any wheel} [\text{kg}] / 2)) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{hr Static Roll Centre Height Front} [\text{m}])) / ((\text{Track Front} [\text{mm}] / 1000))$
- ☒ WTsrcr sprung geo r [N] $((((\text{Static mass RL} [\text{kg}] + \text{Static mass RR} [\text{kg}] * (\text{Mus Brief mass unsprung any wheel} [\text{kg}] / 2)) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{hr Static Roll Centre Height Rear} [\text{m}])) / ((\text{Track Rear} [\text{mm}] / 1000))$
- ☒ WTuf unsprung geo f [N] $((\text{Mus Brief mass unsprung any wheel} [\text{kg}] / 2) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{Front Tyre Rolling Radius} [\text{m}]) / ((\text{Track Front} [\text{mm}] / 1000))$
- ☒ WTur unsprung geo r [N] $((\text{Mus Brief mass unsprung any wheel} [\text{kg}] / 2) * \text{G Force Lat} [\text{G}] * \text{Gravity} [\text{m/s/s}] * \text{Rear Tyre Rolling Radius} [\text{m}]) / ((\text{Track Rear} [\text{mm}] / 1000))$
- ☒ WTF s+ug+sg [N] $(\text{WTsf sprung elastic f} [\text{N}] + \text{WTsrcf sprung geo f} [\text{N}] + \text{WTuf unsprung geo f} [\text{N}] * \text{Long WT} [\text{N}])$
- ☒ WTR s+ug+sg [N] $(\text{WTsr sprung elastic r} [\text{N}] + \text{WTsrcr sprung geo r} [\text{N}] + \text{WTur unsprung geo r} [\text{N}] * \text{Long WT} [\text{N}])$
- ☒ Predicted WTT [N] $\text{WTF s+ug+sg} [\text{N}] + \text{WTR s+ug+sg} [\text{N}]$
- ☒ Magic Number Calc [ratio] $\text{WTF s+ug+sg} [\text{N}] / \text{WTT s+ug+sg} [\text{N}]$
- ☒ tyre press diff $((\text{Tire Press - FL} [\text{kPa}] * \text{Tire Press - RL} [\text{kPa}] - (\text{Tire Press - FR} [\text{kPa}] + \text{Tire Press - RR} [\text{kPa}])) * -1$
- ☒ front roll [deg] $(\text{atan}((\text{Ride Height FL} [\text{mm}] - \text{Ride Height FR} [\text{mm}]) / \text{Track Front} [\text{mm}])) * 57.3$
- ☒ rear roll [deg] $(\text{atan}((\text{Ride Height RL} [\text{mm}] - \text{Ride Height RR} [\text{mm}]) / \text{Track Rear} [\text{mm}])) * 57.3$

7.4 Actual Weight Transfer Maths Channels

Expressions

- ☒ motec WTr [N] $((\text{Tire Load - RL} [\text{N}] - \text{Tire Load - RR} [\text{N}]) / 2) * -1$
- ☒ motec WTr [N] $((\text{Tire Load - FL} [\text{N}] - \text{Tire Load - FR} [\text{N}]) / 2) * -1$
- ☒ Actual WTT [N] $(\text{motec wtr} [\text{N}] + \text{motec WTr} [\text{N}])$
- ☒ Magic Number sim [ratio] $\text{motec WTT} [\text{N}] / \text{Motec WTT} [\text{N}]$

7.5 Handling maths channels

☒ corner radius [m]	$\text{abs}((\text{'Corr Speed' [m/s]}^2)/(\text{'G Force Lat' [G]}*\text{'Gravity' [m/s/s]}))$
☒ theoretical steer angle [deg]	$((\text{'Wheelbase' [mm]}/1000)/\text{'corner radius' [m]})*57.3$
☒ Minimum Steering Pct [ratio]	$\text{'theoretical steer angle' [deg]}*\text{'x steer ratio' [ratio]}$
☒ understeer [ratio]	$\text{abs}(\text{'Steering Wheel Pct' [\%]}-\text{abs}(\text{'Minimum Steering Pct' [ratio]}))$
☒ vehicle yaw [deg/s]	$\text{'Gyro Yaw Velocity' [rad/s]}*57.3$
☒ yaw under [ratio]	$\text{abs}(\text{'Yaw Rate' [deg/s]}-\text{abs}(\text{'vehicle yaw' [deg/s]}))$
☒ understeer slide [ratio]	$(\text{'Slide Pct - FL' [\%]}+\text{'Slide Pct - FR' [\%]})/(\text{'Slide Pct - FL' [\%]}+\text{'Slide Pct - FR' [\%]}+\text{'Slide Pct - RL' [\%]}+\text{'Slide Pct - RR' [\%]})$
☒ required steer angle [rad]	$(\text{'Vehicle Wheelbase' [m]}*(\text{'G Force Lat' [G]}*\text{'Gravity' [m/s/s]}))/(\text{'Corr Speed' [m/s]}^2)$

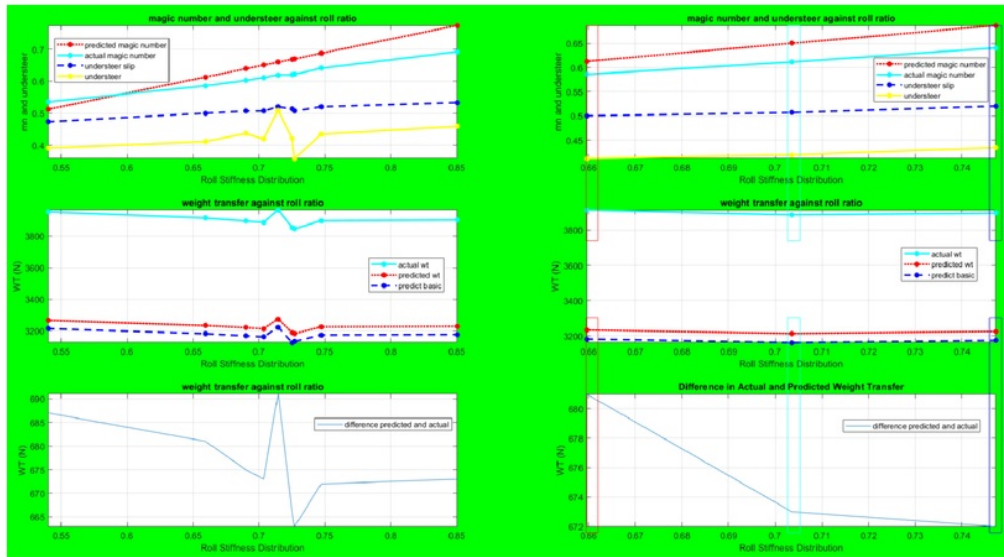
7.6 Aero maths channels

☒ corner radius [m]	$\text{abs}((\text{'Corr Speed' [m/s]}^2)/(\text{'G Force Lat' [G]}*\text{'Gravity' [m/s/s]}))$
☒ theoretical steer angle [deg]	$((\text{'Wheelbase' [mm]}/1000)/\text{'corner radius' [m]})*57.3$
☒ Minimum Steering Pct [ratio]	$\text{'theoretical steer angle' [deg]}*\text{'x steer ratio' [ratio]}$
☒ understeer [ratio]	$\text{abs}(\text{'Steering Wheel Pct' [\%]}-\text{abs}(\text{'Minimum Steering Pct' [ratio]}))$
☒ vehicle yaw [deg/s]	$\text{'Gyro Yaw Velocity' [rad/s]}*57.3$
☒ yaw under [ratio]	$\text{abs}(\text{'Yaw Rate' [deg/s]}-\text{abs}(\text{'vehicle yaw' [deg/s]}))$
☒ understeer slide [ratio]	$(\text{'Slide Pct - FL' [\%]}+\text{'Slide Pct - FR' [\%]})/(\text{'Slide Pct - FL' [\%]}+\text{'Slide Pct - FR' [\%]}+\text{'Slide Pct - RL' [\%]}+\text{'Slide Pct - RR' [\%]})$
☒ required steer angle [rad]	$(\text{'Vehicle Wheelbase' [m]}*(\text{'G Force Lat' [G]}*\text{'Gravity' [m/s/s]}))/(\text{'Corr Speed' [m/s]}^2)$

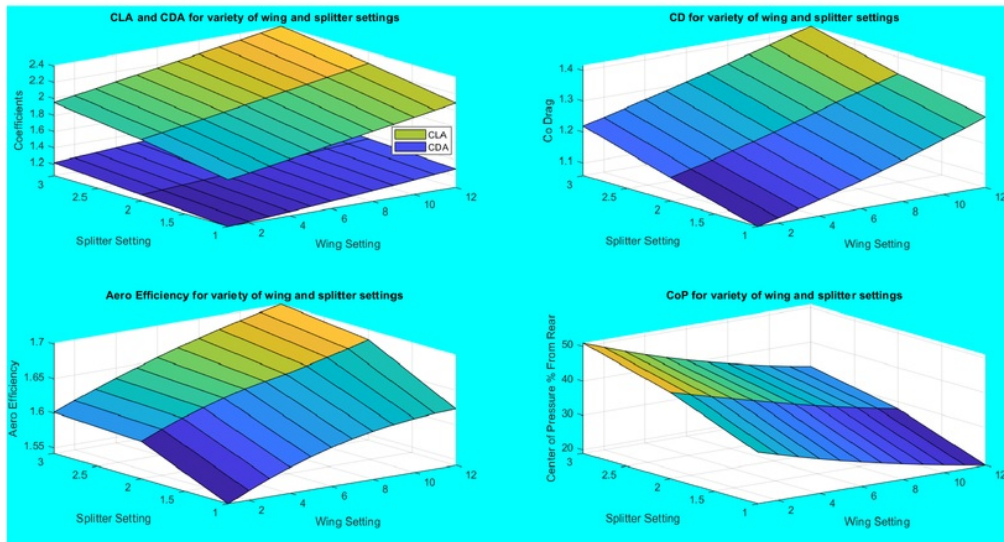
7.7 Steady state corner averaged results

	steady1 base1	steady2 set1	steady3 set 2	steady4 set3	steady5 redo1	b1	b2	b3	b4	Min	Max	% Diff
Roll Stiffness	0.73	0.66	0.7	0.75	0.69	0.85	0.71	0.54	0.73			
start dist	1774	1421	2075	2160	1744	2374	2165	2159	2155	1421	2374	67.06545
end dist	2088	1753	2389	2474	2056	2688	2479	2473	2469	1753	2688	53.33714
start time		01:40.2	02:13.9	02:17.6	01:44.7	02:36.4	02:11.2	02:03.3	02:12.9	0.00116	0.00181	56.05066
end time		01:51.8	02:25.5	02:29.3	01:56.2	02:48.0	02:22.9	02:14.8	02:24.6	0.001294	0.001945	50.24098
time	11.79	11.679	11.611	11.709	11.458	11.65	11.663	11.482	11.739	11.458	11.79	2.897539
yaw deg/s motec	30.6753	30.8223	30.4609	30.8013	30.5124	30.8358	31.1743	30.7021	30.559	30.4609	31.1743	2.342019
corner yaw calc	30.53435	30.82456	31.00508	30.74558	31.4191	30.90129	30.86684	31.35342	30.66701	30.53435	31.4191	2.897539
u-over	-0.14095	0.002257	0.544181	-0.05572	0.906696	0.065488	-0.30746	0.651323	0.108007	-0.30746	0.906696	-394.903
yaw sens	-30.78	-30.84	-30.47	-30.81	-30.52	-30.85	-31.17	-30.71	-30.57	-31.17	-30.47	-2.24575
un sens	-0.24565	-0.01544	0.535081	-0.06442	0.899096	0.051288	-0.30316	0.643423	0.097007	-0.30316	0.899096	-396.578
mns	0.6202	0.6023	0.6116	0.6406	0.5858	0.6923	0.6194	0.5121	0.6701	0.5121	0.6923	35.18844
mnc	0.6686	0.6389	0.6503	0.6872	0.6131	0.7743	0.6596	0.5121	0.6701	0.5121	0.7743	51.20094
us moodle	21.0328	21.8212	20.9403	21.6939	20.5719	22.942	25.4459	19.5274	17.9094	17.9094	25.4459	42.08125
wt sim	-3855	-3895	-3886	-3897	-3914	-3901	-3965	-3953	-3846	-3965	-3846	-3.00126
wt calc	3189	3220	3213	3225	3233	3228	3274	3266	3183	3183	3274	2.858938
mn lg	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0
wt lg	3126	3168	3162	3174	3182	3177	3222	3214	3133	3126	3222	3.071017
tire slip ratio	0.77	0.76	0.76	0.78	0.75	0.8	0.78	0.71	0.76	0.71	0.8	12.67606

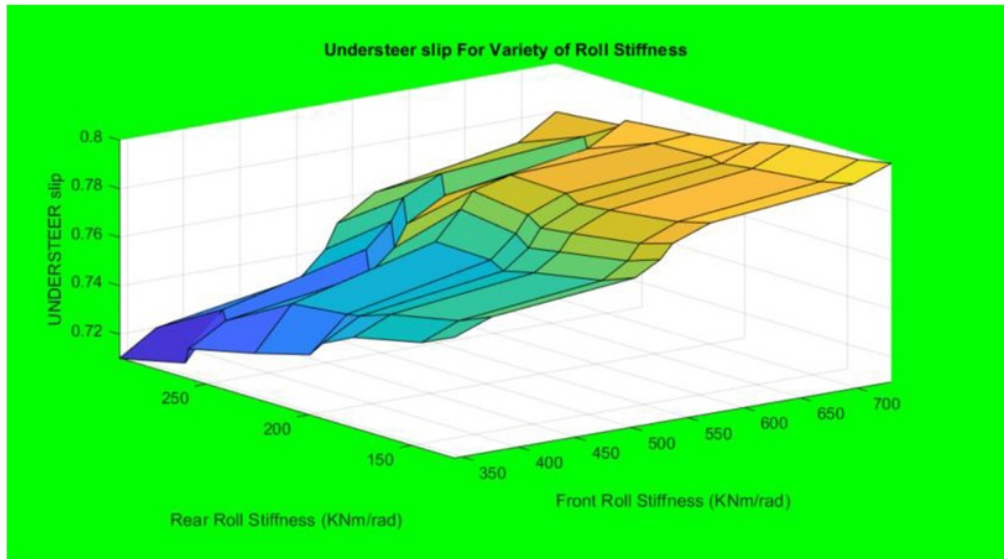
7.8 Steady state 2d



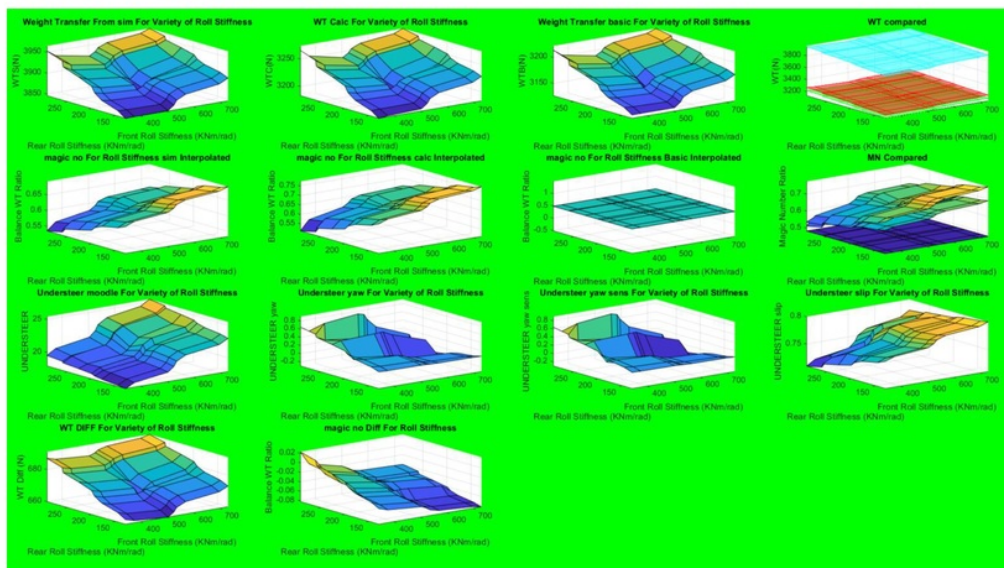
7.9 Aero Graphs



7.10 Understeer slip



7.11 3D Weight Transfer



7.12 Rake and Ride

