

Harry Farnhill Vehicle dynamics assignment

by Harry Farnhill

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Steady state load transfer and aerodynamic loading through simulation

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Introduction

This paper will be about aerodynamic and mechanical set up changes during steady state testing. The car that used was an Aston martin DB9 GT1 which would take part in a coast down test in 6 different splitter lengths and wing angles varying from min downforce to max downforce whilst also studying the effects of varying the ride height. The lift value will be positive as it has been inversed to show downforce. The steady state cornering test that was conducted was varying the front and rear anti roll bar rates during constant velocity cornering, we would then compare predicted calculated weight transfer against actual weight transfer as well as explaining limitations to the experiments conducted.



Figure 1

Aero

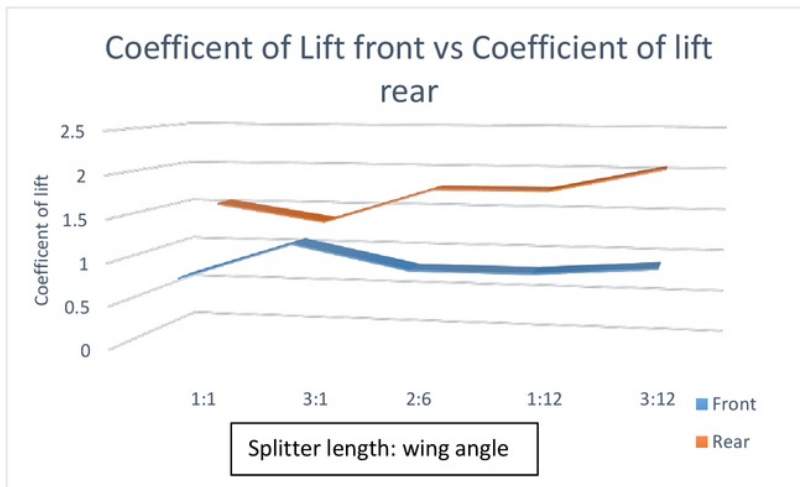


Figure 2

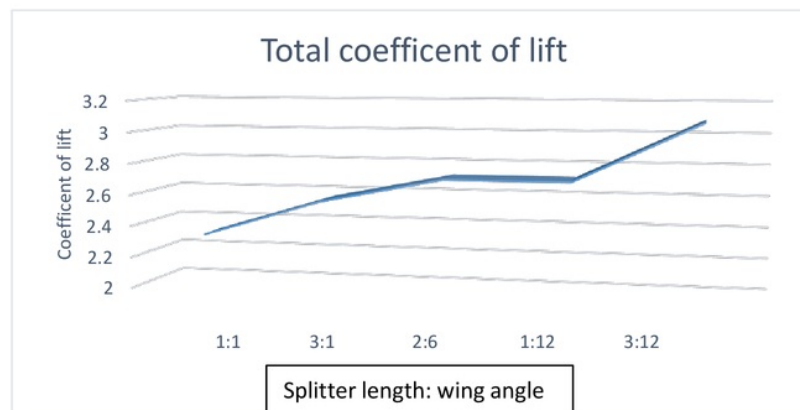


Figure 3

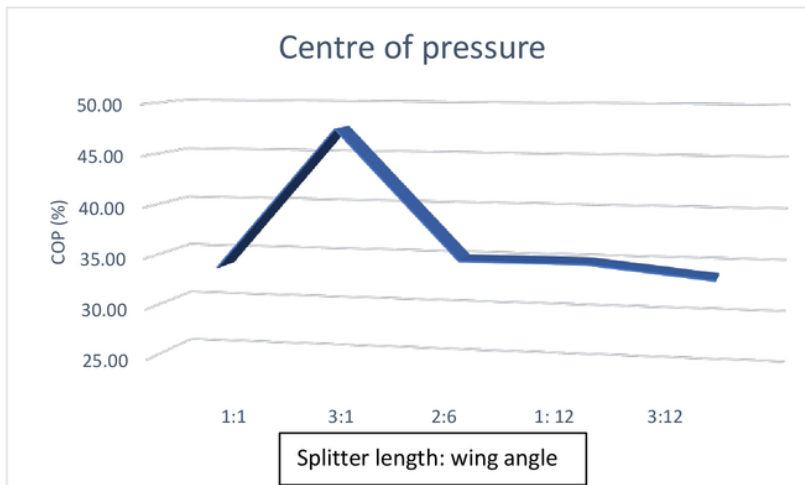


Figure 4

- The centre of pressure moves further forward the more the greater the splitter length.
- The less rear wing angle the centre of pressure moves further forward.
- The more rear wing angle the further the centre of pressure moves towards the rear.

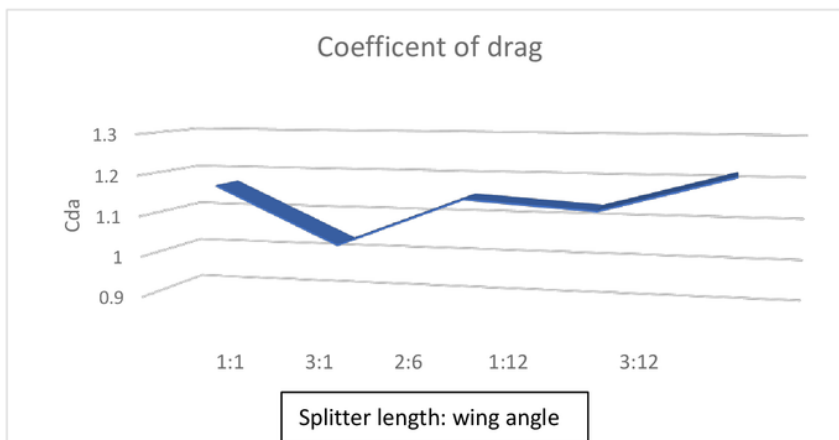


Figure 5

- The coefficient of drag increases the more aggressive the aerodynamics set up (ie more wing angle, longer splitter length)
- The splitter length has a smaller effect on drag as the rear wing angle increased the surface area, which causes more drag
- 1:1 set up there is an error because that should have the lowest coefficient of drag

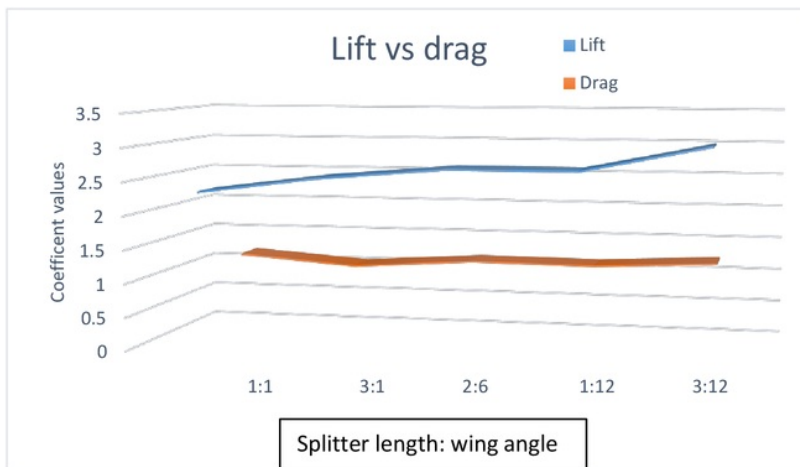


Figure 6

- The more downforce produced the greater the coefficient of drag
- The maximum splitter length and wing angle increases at a steeper gradient than the coefficient of drag, meaning it would be the most efficient set up.
- The error in the 1:1 setting be there should be a lower coefficient of drag.

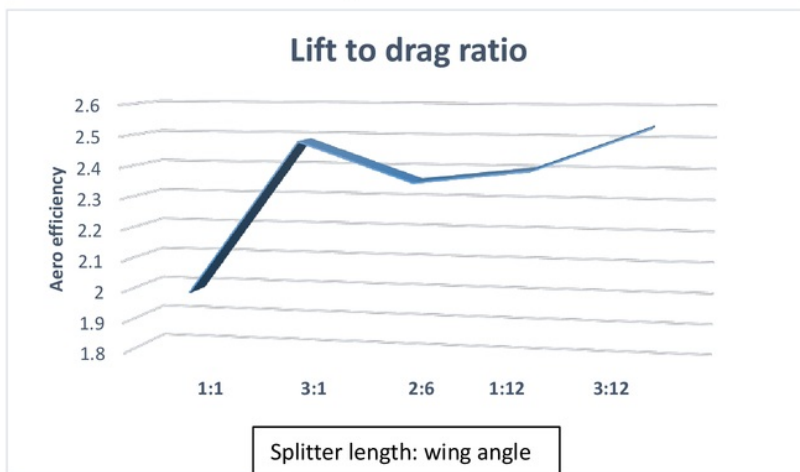


Figure 7

- The most inefficient aero set up would be 2:6 as the 1:1 set up there is an error so would be ignored.
- The most efficient set up would be 3:12 as it produces the greatest amount of lift for the smallest amount of drag.
- The 3:1 set up is efficient but could be unstable during braking and high speed cornering

Ride height affects lift and drag

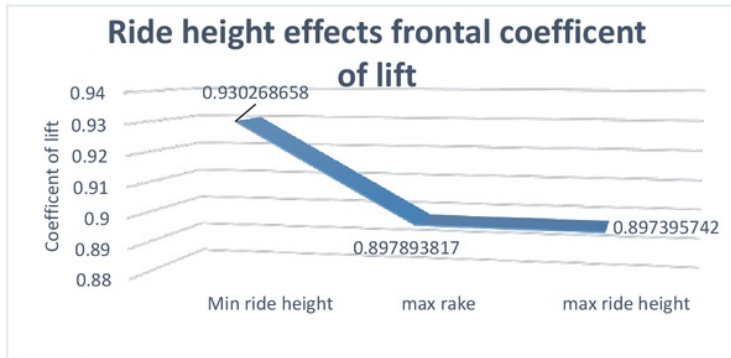


Figure 9

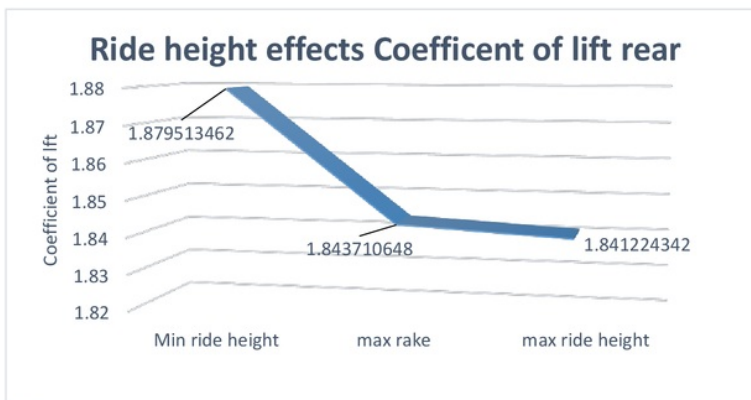
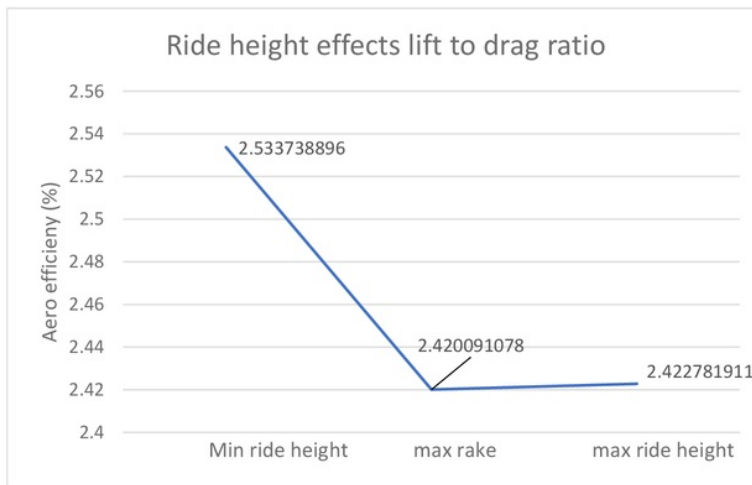


Figure 8



- The max rake angle would increase the surface area and have a very little benefit of increasing the diffuser length by increasing rake angle
- Running maximum ride height increases the velocity and decreases the pressure underneath causing the air flow to become turbulent which increases the drag coefficient.
 - The minimum ride height has the smallest coefficient of drag as the car is lower to the ground

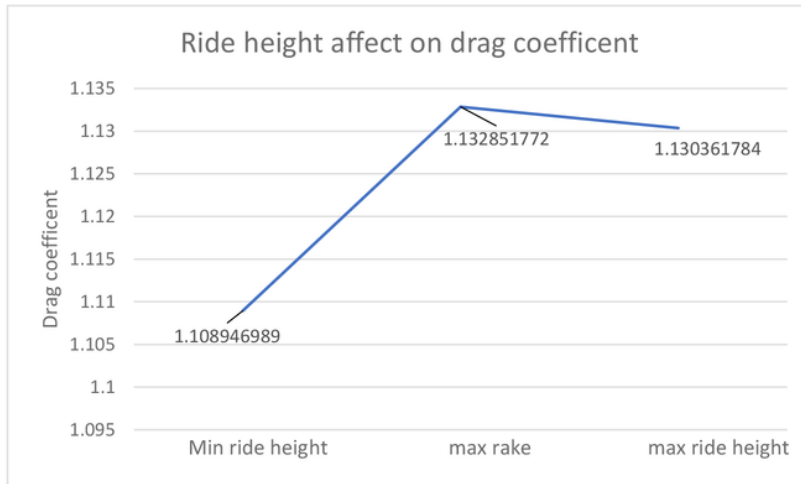


Figure 10

- The lowest ride height setting is the most efficient ride height setting with the wing angle in the 2:6 set up.
- The rake angle is not steep enough to affect the air flow into the diffuser.
- There would be no benefit of running a high ride height setting

Methodology

The coast down test involved leaving the car in 4th on the limiter for 5 seconds to find the steady state velocity. The car would then be put in neutral and steering would remain neutral until the car came to a standstill. All the equations can be seen in the appendices.

Analysis of the Lift and drag values

When the rear wing angle increases the angle of attack increases, the angle of attack is the angle of the wing when the air flow hits the wing. The steeper the wing angle the more aggressive the aerodynamic set up and can increase the downforce set up but also drag. Finding the most efficient angle will be a compromise between drag and downforce which will vary with circuit characteristics. The lift to drag ratio graph shows the best compromise. (Katz, 2006)

The two pictures below show variance in angle of attack:



Minimum angle of attack

Figure 12



Maximum angle of attack

Figure 11

What a splitter creates is a larger pressure difference for the air flow over the car, the air flow under the floor of the car would increase in velocity and drop in pressure and vice versa the air flow would slow down on top of the car and higher pressure flowing over the car creating more downforce. (engineering, 2009) Increasing splitter length would increase the effect. The air flow would attach to the underside of the splitter and the air would flow attached at the surface, this creates a boundary layer.

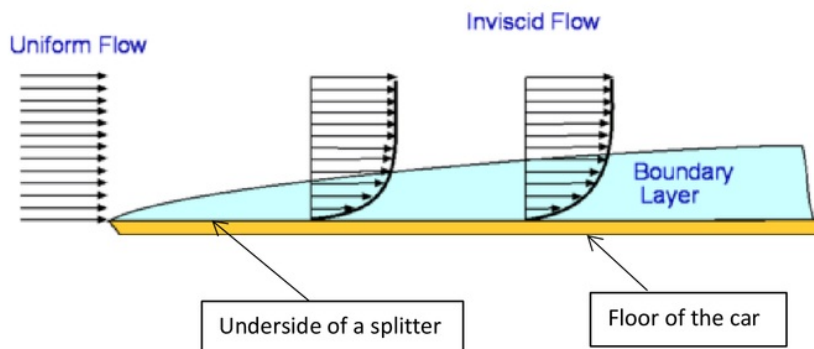


Figure 13

A boundary layer is air flow that is non turbulent laminar flow that is generally 1 inch thick that flows attached to the surface. The boundary layer on the underside of floor of the car will keep the air flow attached to the diffuser which increases downforce. Without a splitter or a very short splitter it will reduce effectiveness of the boundary layer and cause the airflow to become turbulent. (Katz, 2006)

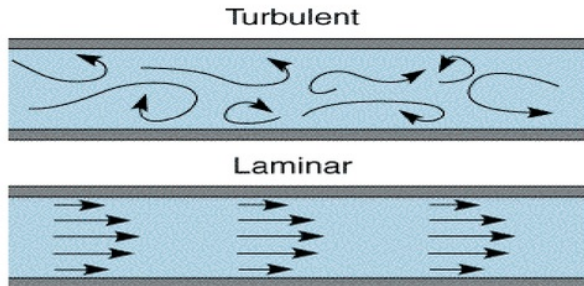


Figure 14

Turbulent air flow is very messy and has very low energy, the pressure increases and the velocity drops which is what you want into rear wing, however this would be very messy air flow and the rear wing would not be as efficient. Therefore, the importance of a splitter or a front wing is to divert all the turbulent air away from the diffuser and rear wing which could stall the device and be inefficient. (Mcbeath, 2015)

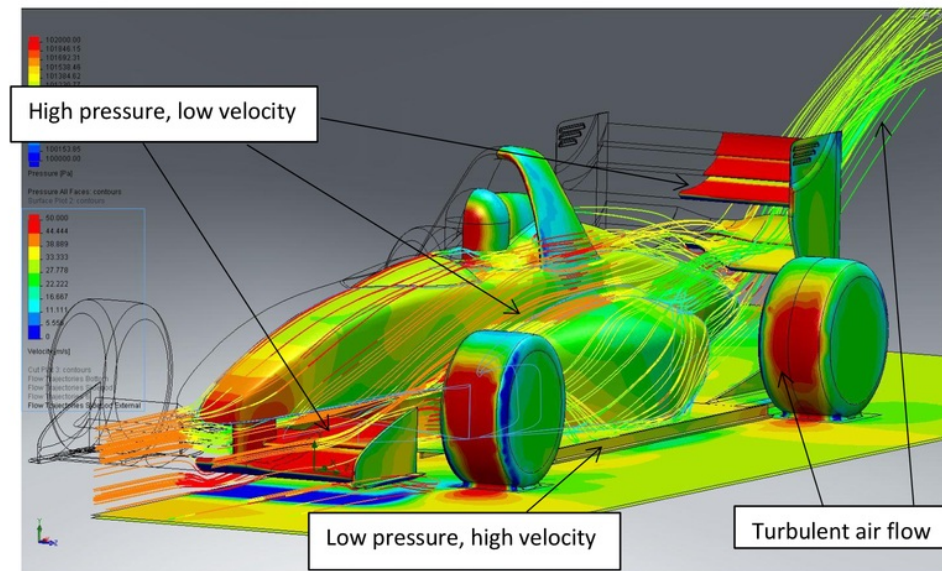


Figure 15

Centre of pressure

The centre of pressure is the point where the total sum of pressure acts on the vehicle, just like the centre of gravity of a vehicle. The greater splitter length the further the centre of pressure moves forward and the greater the wing angle the further the centre of pressure would be towards the rear. The picture below shows the best position for the centre of pressure to act on the vehicle

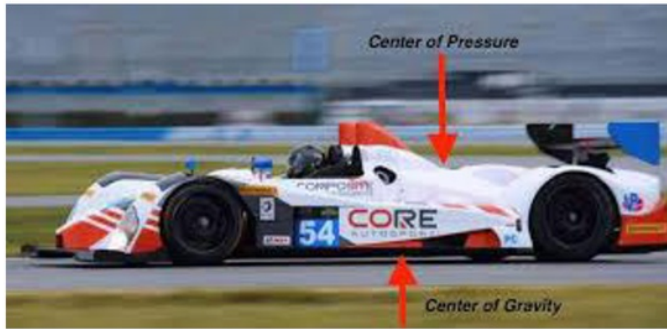


Figure 16

Ride height aerodynamic affects

Varying the ride height will influence lift and drag but not as great as varying the wing angle from testing we have conducted on Aston martin DB9 GT1. The lowest ride height setting was the highest coefficient of negative lift and lowest drag value, this is because it is increasing the velocity and decreasing the pressure underneath and vice versa on top of the car which creates a Venturi affect. (Newey, 2017)

Venturi affect

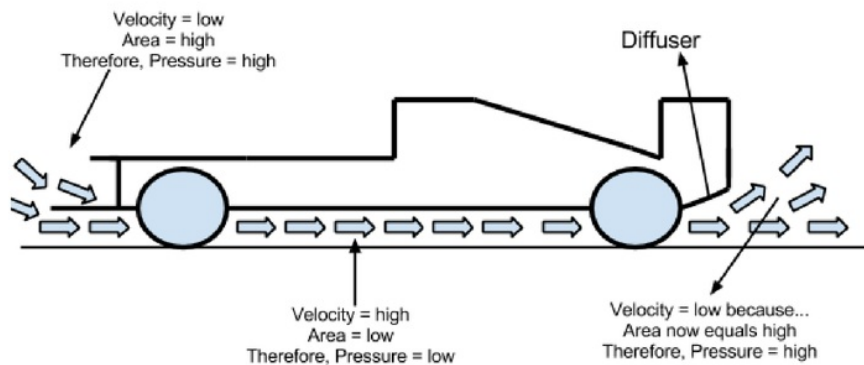


Figure 17

Increasing the ride height would slightly increase the area and decrease the velocity causing slightly more turbulence, reducing the effectiveness of the diffuser and air flow over the car. Therefore, the right height would want to be as low as possible without scraping the floor. (Nowlan, 2019)

Increasing the rake angle will accelerate the air flow around the front of the car because the area is greater behind the splitter than it is in front of it and airflow will want to fill the gap behind the splitter. This increases the Venturi affect. The shape of the car will also cause a very gentle diffuser at a small angle which makes the diffuser more efficient with the velocity slowly increasing further towards the diffuser but the boundary layer increases and there could be more turbulence on the underfloor of the car. Therefore, the rake angle would need to be controlled, the ideal angle for a diffuser would be 4 degrees before it starts to stall, and turbulence is increased. (Newey, 2017)The max rake angle that was run was 0.540 degrees which would not be enough to create a diffuser under the entire length of the car. Below is a Red Bull RB15 with a high rake angle.



Air flow stays laminar attached to the surface through to the diffuser

Velocity keeps increasing to fill the displacement of air, fill the gaps of a larger area behind the wing

Small frontal area, velocity increases

Figure 18

Limitations of the coast down test

Running the coast down test in BPS the wind speed is negligible which cannot factor in head wind, tailwind and cross winds which is very unlikely to happen which means assumptions would need to be made, for example in a tail wind the aero the negative lift would decrease and drag would decrease. The opposite would happen in a headwind. It could be hard to predict how the car would handle in a cross wind around a corner because it can't be simulated in BPS but also a coast down test is in a straight-line so it would be difficult to understand how the car would handle in a corner.

Trying to predict the air would flow around the tyres cornering would be difficult to predict as the coast down test is in a straight line. This would not have a significant effect on a car with enclosed wheels but in a single seater formula 1 car the wake flowing over the tyres rotating during cornering would be hard to predict where that air would flow.

A driver error during the first coast down test was the under the setup of a 1:1, the driver rode the brakes by 2.56% which caused the first result to be inaccurate for calculating the coefficient of drag. Therefore, the coast down test could be repeated to make sure that we can could get an accurate result for a low drag set up.

When running a high rake set up the air flow to the diffuser had a very insignificant affect as predicted and the coefficient of lift was lower than predicted. The centre of pressure was also further back than predicted which could be that:

- The rake angle was not steep enough
- The GT1 does not produce enough downforce to have a great enough effect
- The software is not developed enough for running high rake angles

My conclusion that it was the first 2 suggestions, maybe in a F1 car with a 4 degree rake angle would lead to a significant change in coefficient of lift values.

Weight transfer

Methodology

The setup that was investigated was by varying the anti-roll bar settings, the driver would then complete a 25m radius at 60km/h for at least 5 seconds of steady state driving. The anti-roll bar setting would then be changed, the driver would repeat each test. After anti roll bar set up had been completed the ride height setting was then adjusted from maximum rake, max ride height to minimum ride height. To see the full equations of how weight transfer graphs were created refer to the appendices.

Group 2 (ARB Investigation)		Setup 1	Setup 2	Setup 3
Front Spring Rate (N/mm)	K_{sf}	254	254	254
Rear Spring Rate (N/mm)	K_{sr}	254	254	254
Front Anti Roll Bar Wheel Rate (N/mm)	K_{warbf}	160	280	400
Rear Anti Roll Bar Wheel Rate (N/mm)	K_{warbr}	72	48	12

Weight transfer graphs

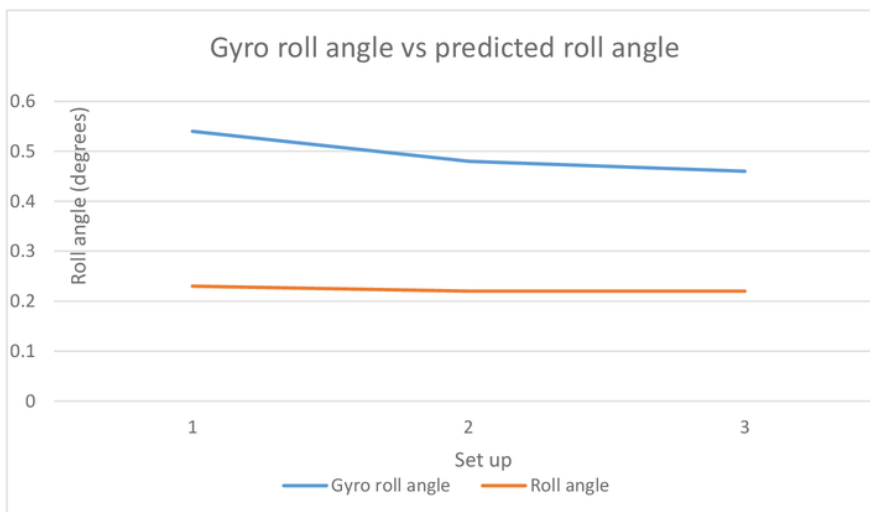


Figure 19

- Roll angle increases with the softer the anti-roll bar
- Predicted roll angle is less than measure roll angle, but at the same trend and underpredicted compared to measure roll angle

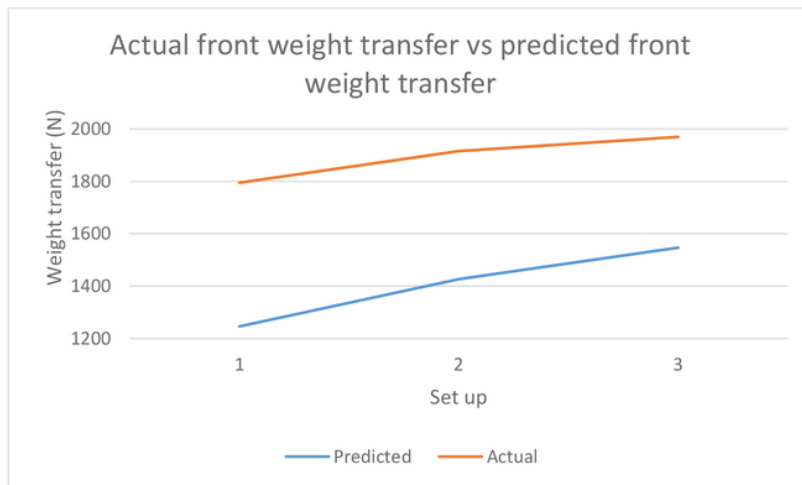


Figure 20

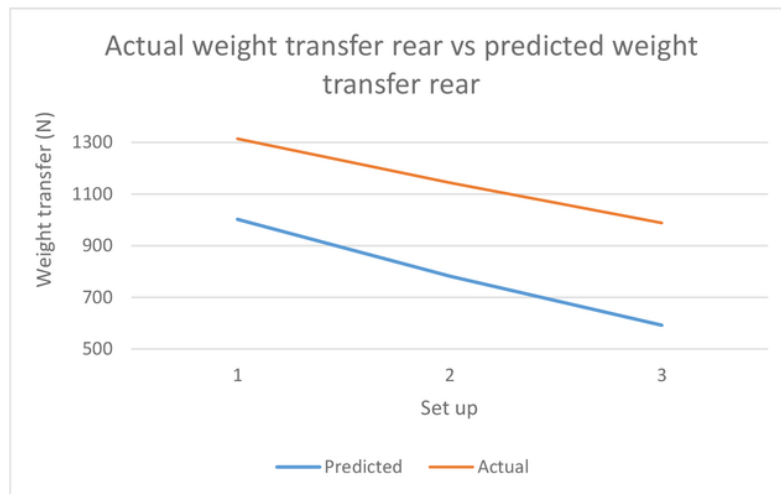


Figure 21

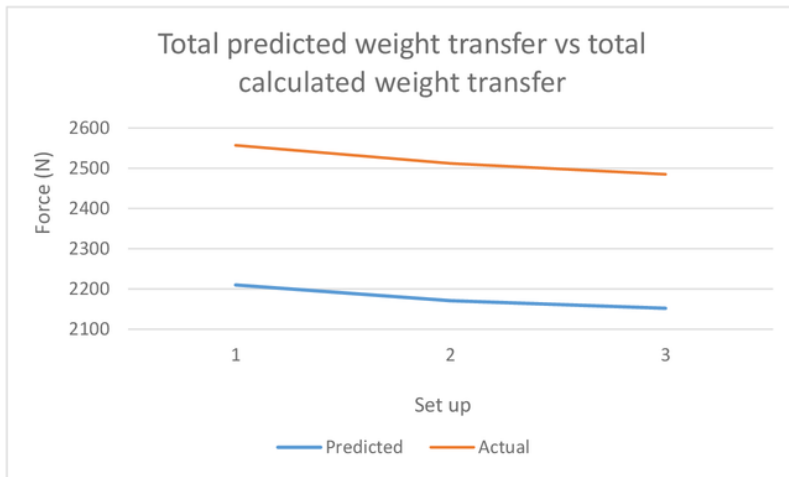


Figure 22

- Weight transfer decreases when the front anti roll bar is stiffer, and the rear anti roll bar is softer.
- Actual weight transfer increases with the stiffer the roll bar.
- The predicted weight transfer under predicts compared to actual weight transfer
- There predicted weight transfer is steeper than the actual weight transfer

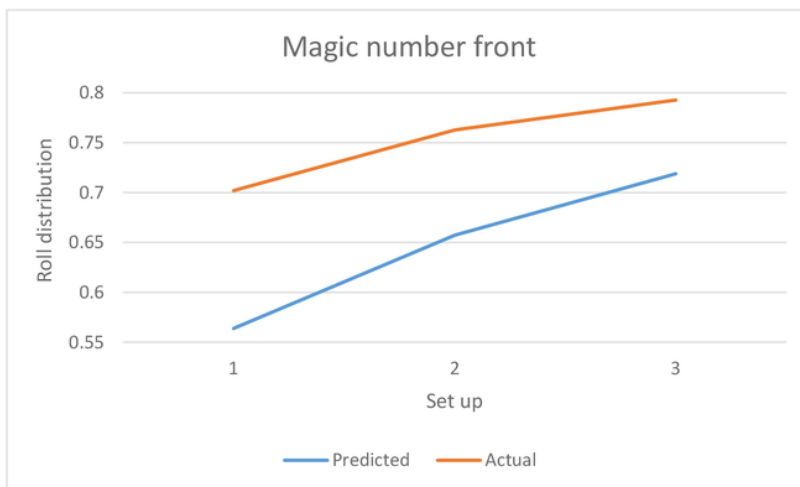


Figure 23

- The predicted magic number under predicts compared to the actual magic number
- The gradient of the predicted magic number is steeper than actual magic number

Ride height affects weight transfer

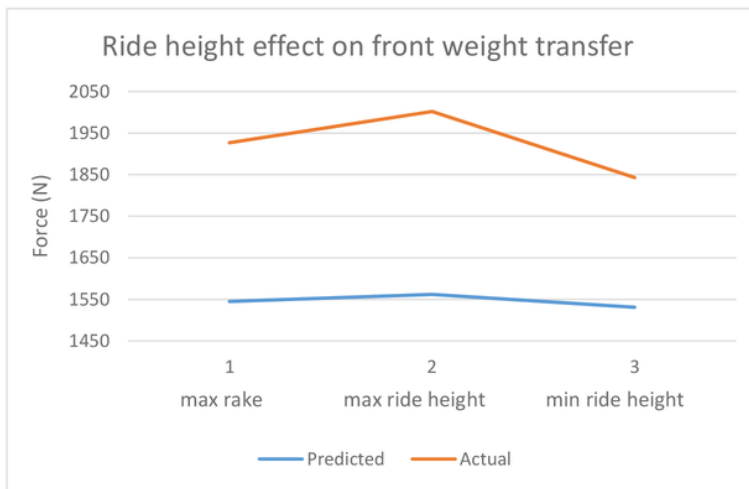


Figure 24

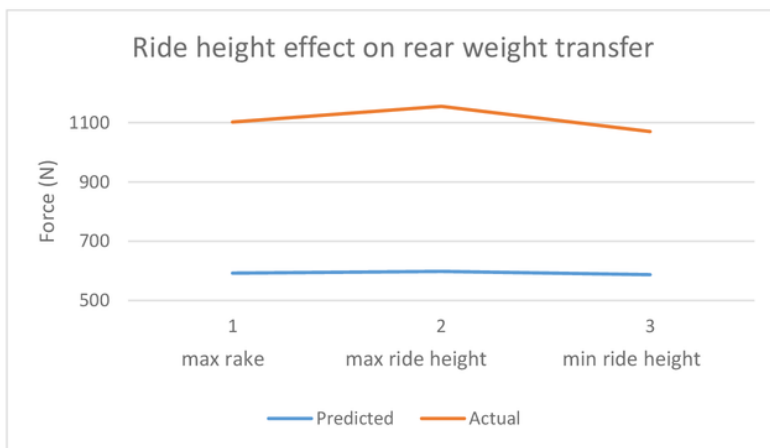


Figure 25

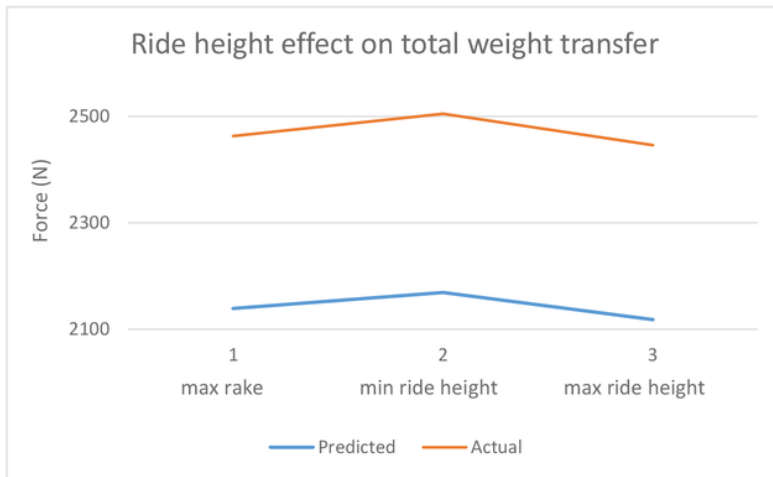


Figure 26

- Total weight transfer decreases the lower the ride height
- Running high rake value has very little effect on weight transfer

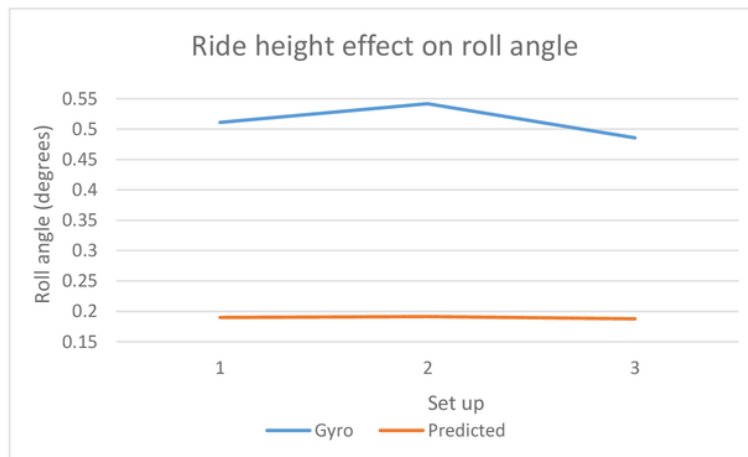


Figure 27

- The higher the ride height the greater the roll angle
- The lowest the ride height the smallest the roll angle

Analysis of results

An anti-roll bar increases roll stiffness and is designed to decrease body roll but not weight transfer. However, weight transfer decreases the softer the roll bar. (J.Rowley, 2003) (Rouelle, 2019)

Anti-roll bars also affect the balance of the car, if the car was understeering the anti-roll bar:

- Softer at the front
- Stiffer at the rear

If the car was oversteering:

- Stiffer at the front
- Softer at the rear

By softening the anti-roll bar, the roll angle decreases as it resist the body roll motion by increasing the roll stiffness, however this would not decrease overall weight transfer but does reduce elastic weight transfer based on the spring rate and suspension geometry. (William F.Milliken, 1995) (Staniforth, 2006)



Elastic weight transfer

Figure 29



Actual weight transfer

Figure 28

The more weight transfer the greater the load will be on the outside wheels when cornering compared to the inside tyre which means that the full contact patch will be used on the inside wheel and too much on the outside. (Smith, 1984) To maximise the inner contact patch as much as the outside the weight transfer would want to be reduced as much as possible so that there is equal load to maximise each contact patch, by softening the anti-roll bar this reduces the weight transfer and can allow more force being applied to the inside wheel providing more grip. (C.Dixon, 1991)

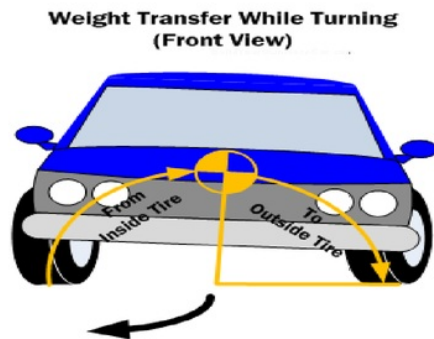


Figure 30

The graphs show that predicted weight transfer is lower than actual weight transfer and predicted at a steeper gradient than actual weight transfer. This is because the predicted weight transfer is based on roll angle, roll stiffness, spring rate and anti-roll bar settings which each setting is changed at a steeper gradient than actual weight transfer measures. The difference in anti-roll bar changes from a very low rate to a very high rate which predicts that the weight transfer will also increase at the rate which it doesn't but explains why the predicted weight transfer is at a steeper rate than actual weight transfer.

Ride height effect on weight transfer

The graphs show that the higher the ride height the increase in weight transfer, this is because the centre of gravity will be higher from the floor as the car will be higher from the floor. Ideally the centre of gravity height will want to be as low as possible as the weight transfer will be lower to the ground and the mass will be closer to the tyres and the inertia will be as low as possible. (Donald Bastow, 2004) This shows in the graphs as the lower the ride height the least amount of weight transfer. The image below shows the effect of increasing the COG height.

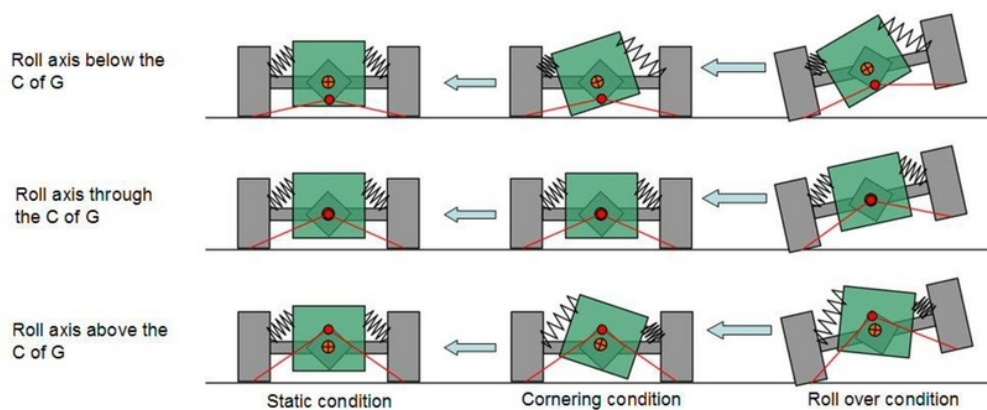


Figure 31

Running a high rake angle doesn't decrease the weight transfer as much at the front as predicted compared to minimum ride height. However, there is less weight transfer at the front compared to the rear which means the car is more likely to understeer than oversteer so the minimum ride height would be the most balanced set up.

Limitations to steady state cornering

The steady state cornering is useful for gathering data of the set up changes when cornering but applying to real life application is difficult because the driver and car are very rarely steady state when cornering so it can be hard to predict how the car will be handling but you would be able to get a good prediction of how the car will handle but not accurate enough for real life application.

The road surface that we used was a perfectly smooth surface with no bumps in a continuous corner, in real life application race tracks are very bumpy especially the fast circuits which means that the car could be set up for a smooth circuit but could be unstable on bumps meaning it may not be able to run any kerbs on the race circuit, which would be slower.

During testing only two variables were changed which was the anti-roll bar stiffness and ride height, factors like changing spring rate wasn't investigate, also changing camber, toe, rebound, bump and tyre pressure were not changed, however these were not part of the brief but more set up changes could be investigated in future testing as by softening the anti-roll bar, what camber and toe angle will be then run because of this change and what effect would that have?

During testing the driver only went anti clockwise for the whole testing set up changes, this means that running an unsymmetrical set up would improve the performance as the car would only doing 1 continuous left corner. If this logic was applied, then it wouldn't give a good indication of set up when the car would go around a race track and the engineer could be going down the wrong set up and not fully understand how the car should handles.

The steady state testing is one continuous corner so for a track that is very twisty with lots of chicanes the set up that worked in steady state testing may not work on a track with lots of very fast chicanes. For example, running the anti-roll bar very soft at front and stiff at the rear wouldn't become unstable at steady state but during fast change of direction the rear could be very unstable and difficult to drive.

The drivers input with steering and throttle could induce understeer or oversteer and maybe give a false impression of the car's performance, however maths channels can be created in MOTEC to show theoretical steer position vs actual to show if the driver is inducing understeer.

Conclusion

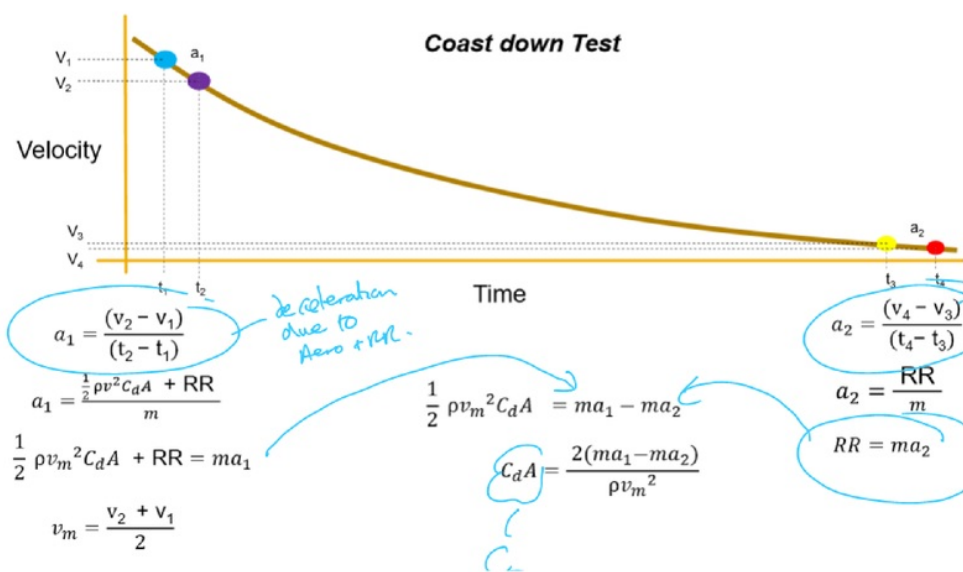
From the data gathered it can be seen that the coast down tests and steady state cornering were useful ways to gather data about the base performance of the car and starting point for developing the car, however it should not be fully used to evaluate the performance of the car and should be validated by real world testing of the same tests conducted, real life track data and driver feedback to rely on how the car should be performing.

Appendices

Aero calculations

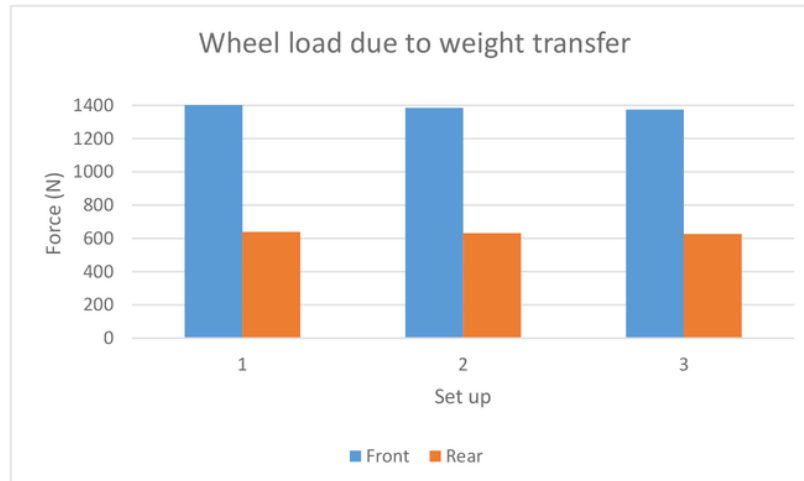
$$Lift_{front} = \frac{1}{2} \times CL_f \times \rho \times v^2$$

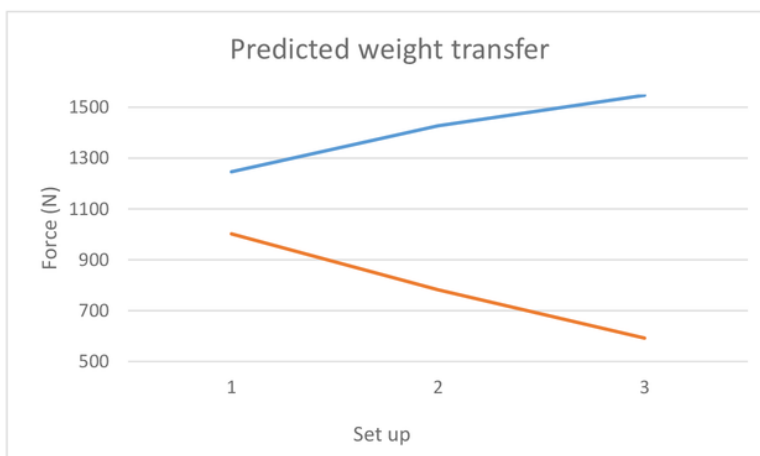
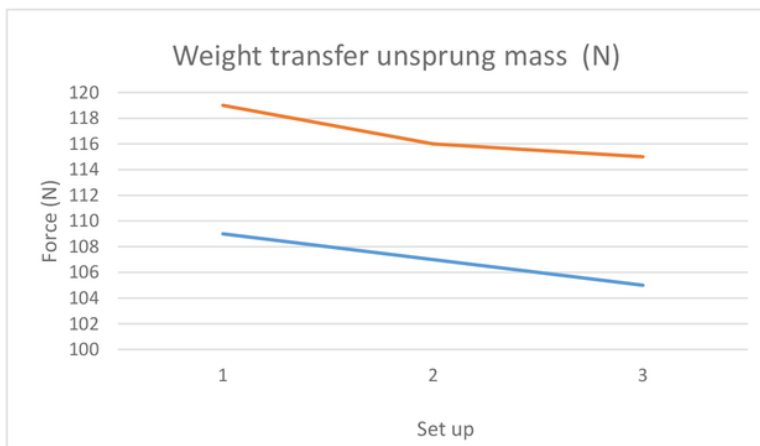
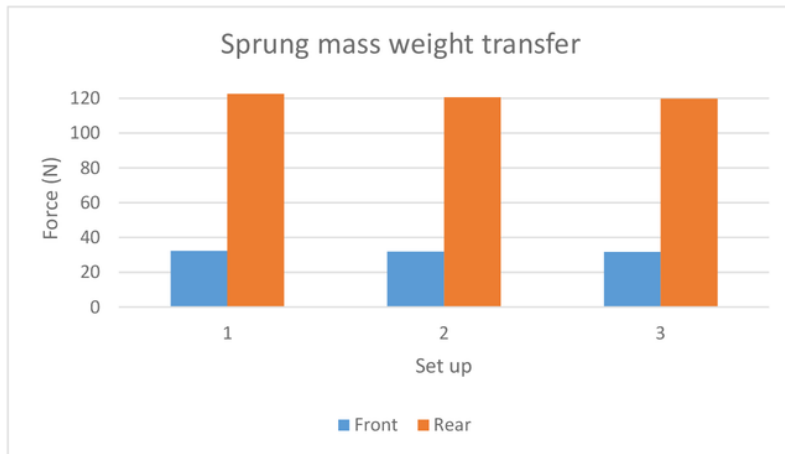
$$Lift_{rear} = \frac{1}{2} \times CL_r \times \rho \times v^2$$

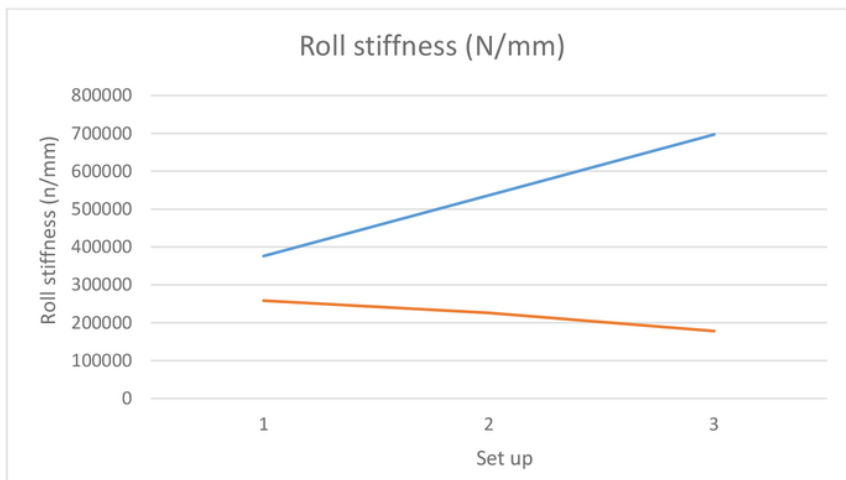


Maths channels

corner radius [m]	$(\text{'Ground Speed' [km/h]}/3.6)^2/2/\text{'G Force Lat' [g]}*9.81$
theoretical wheel steer [rad]	$\text{'Wheelbase' [m]}/\text{corner radius ' [m]}$
theoretical steer position [%]	$\text{'theoretical wheel steer ' [deg]}/(\text{'Steering Wheel Pct' [%]}/\text{'theoretical wheel steer ' [deg]})$
understeer [%]	$\text{abs}(\text{'theoretical steer position ' [%]})-\text{abs}(\text{'theoretical wheel steer ' [rad]})$
wheel rate front [Nm]	$(\text{'Spring Rate FL' [N/m]}*\text{'Motion Ratio FL'}^2)+\text{'Roll Bar Rate Front' [N/m]}$
wheel rate rear [Nm]	$(\text{'Spring Rate FL' [N/m]}*\text{'Motion Ratio FL'}^2)+\text{'Roll Bar Rate Rear' [N/m]}$
lateral acceleration [m/s/s]	$\text{'G Force Lat' [G]}*9.81$
wheel deflection	$((\text{'Track Front' [m]}^2)*\text{'Gyro Roll Angle' [rad]})/2$
anti roll moment front	$(\text{'Track Front' [m]}^2*\text{'Gyro Roll Angle' [rad]}*\text{'wheel rate front ' [N.m]})/2$
anti roll moment rear	$(\text{'Track Rear' [m]}^2*\text{'Gyro Roll Angle' [rad]}*\text{'wheel rate rear ' [N.m]})/2$
ride height front [mm]	$(\text{'Ride Height FL' [mm]}+\text{'Ride Height FR' [mm]})/2$
rear ride height [mm]	$(\text{'Ride Height RL' [mm]}+\text{'Ride Height RR' [mm]})/2$
roll stiffness front	$((\text{'Track Front' [m]}^2)*\text{'wheel rate front ' [N.m]})/2$
roll stiffness rear	$((\text{'Track Rear' [m]}^2)*\text{'wheel rate rear ' [N.m]})/2$
angle of roll centre [deg]	$\text{tanh}((\text{'RCr' [m]})-(\text{'RCr' [m]})/\text{'Wheelbase' [m]})$
Height of COG above roll centre [m]	$\text{tan}(\text{'angle of roll centre' [deg]})*(\text{'Wheelbase' [m]})/2$
overturning moment [Nm]	$(\text{'sprung mass ' [kg]})*\text{'lateral acceleration' [m/s/s]}*(\text{'cog height ' [m]}*\text{'Static Roll Centre Height Front' [m]}+\text{'Height of COG above roll centre' [m]})$
roll angle [rad]	$(\text{'overturning moment ' [N.m]})/(\text{'total roll stiffness ' [N.m]})$
wheel load due to wt front [N]	$((\text{'wheel rate front ' [N.m]})*(\text{'Track Front' [m]}))/\text{'roll angle ' [rad]}/2$
wheel load due to WT rear [N]	$((\text{'wheel rate rear ' [N.m]})*(\text{'Track Rear' [m]}))/\text{'roll angle ' [rad]}/2$
weight transfer sprung mass front [N]	$((\text{'sprung mass ' [kg]}/2)*\text{'lateral acceleration' [m/s/s]}*\text{'Static Roll Centre Height Front' [m]})/\text{'Track Front' [m]}$
weight transfer sprung mass rear [N]	$((\text{'sprung mass ' [kg]}/2)*\text{'lateral acceleration' [m/s/s]}*\text{'Static Roll Centre Height Rear' [m]})/\text{'Track Rear' [m]}$
unsprung weight transfer front [N]	$((\text{'unsprung corner mass' [kg]}^2)*\text{'lateral acceleration' [m/s/s]}*\text{'front tyre rolling radius ' [m]})/\text{'Track Front' [m]}$
unsprung weight transfer rear [N]	$((\text{'unsprung corner mass' [kg]}^2)*\text{'lateral acceleration' [m/s/s]}*\text{'rear tyre rolling radius ' [m]})/\text{'Track Rear' [m]}$
total weight transfer front [N]	$\text{'WTsf' [N]}+\text{'weight transfer sprung mass front ' [N]}+\text{'unsprung weight transfer front ' [N]}$
total weight transfer rear [N]	$\text{'unsprung weight transfer rear' [N]}+\text{'WTsr' [N]}+\text{'weight transfer sprung mass rear ' [N]}$
total weight transfer [N]	$\text{'total weight transfer front' [N]}+\text{'total weight transfer rear' [N]}$
WTF [N]	$(\text{'Tire Load - FR' [N]}+\text{'Tire Load - FL' [N]})/2$
WTr [N]	$(\text{'Tire Load - RR' [N]}+\text{'Tire Load - RL' [N]})/2$
WTt [N]	$((\text{'Tire Load - FL' [N]}+\text{'Tire Load - FR' [N]}+\text{'Tire Load - RL' [N]}+\text{'Tire Load - RR' [N]})/9.81)*\text{'lateral acceleration' [m/s/s]}*(\text{'cog height ' [m]})/\text{'Track Front' [m]}$
total roll stiffness [Nm]	$\text{'roll stiffness front ' [Nm]}+\text{'roll stiffness rear' [Nm]}$
Wt12 [N]	$\text{'WTF' [N]}+\text{'WTr' [N]}$
aero front [N]	$(\text{'Tire Load - FL' [N]}+\text{'Tire Load - FR' [N]}*((\text{'Static Weight FL' [kg]}*9.81)+(\text{'Static Weight FR' [kg]}*9.81))))$
aero rear [N]	$\text{'Tire Load - RL' [N]}+\text{'Tire Load - RR' [N]}*((\text{'Static Weight RL' [kg]}*9.81)+(\text{'Static Weight RR' [kg]}*9.81))))$







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