

p150613 Weight transfer and Aerodynamics report

by Simon Ellis-Williams

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*Steady State Load Transfer
and
Aerodynamic Loading*

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1) Introduction

The aim of this report is to ascertain how weight transfer is affected by the stiffness of the chassis and the amount of roll experienced by the car. The car used for the experiment was an Aston Martin DBR9 GT1 and data was collected from a base performance simulator, running R factor Pro software.

The data will then be used to find aerodynamic and weight transfer values for differing suspension and aero setups using coast down and steady state testing. Once the data is recorded and processed via excel and results graphs are produced, an analysis will be made to see how each set up affects the cars behaviour.

2) Background Research

Aerodynamic coast down testing

Coast down testing is used to find several aerodynamic forces on a car such as lift and coefficient of drag. The rolling resistance of the tyres can also be calculated via coast down testing. Using data taken from real test examples can also help calibrate dynamometers and validate simulation runs. (Emtage, 1983)

Emtage states for a coast down test to happen, there needs to be a smooth, flat, straight surface. A vehicle is then accelerated to a velocity of preference; once the velocity is achieved, a timer is started. The car then holds velocity for several seconds before disengaging the drivetrain from the engine and letting the car roll to a stop naturally. A graph of the velocity and time taken is created, which is then used to take readings to find acceleration by using:

$$Acceleration = \frac{\text{difference in velocity}}{\text{difference in time}}$$

This can then be used to find other aerodynamic forces acting on the car.

Splitters and wings

A splitter is a modification adding an extension to the bottom edge of the bumper of a car usually made of a composite material. A splitter serves to trap the air against the front of the bumper and the top of the splitter. This creates an area of high pressure on top of the splitter as air passes below at a lower pressure, thereby adding downforce to the front of the vehicle and balancing the downforce on the car between the front and back axles.

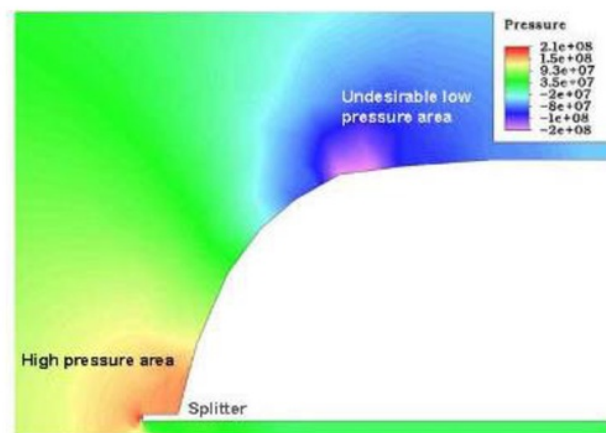


Figure 1 - picture showing pressure distribution around a splitter.
(<http://www.formula1-dictionary.net/splitter.html>)

Aerofoils work in a similar way by splitting the airflow, forcing it to travel over the top and bottom surfaces of the aerofoil profile. This creates an area of high pressure, slow moving air above and an area of low pressure, fast moving air underneath which must travel further to meet with the rest of

the airflow at the end of the aerofoil. The curved profile of the underside of an aerofoil ensures that no separation occurs, maximising its potential. (NASA, 2010)

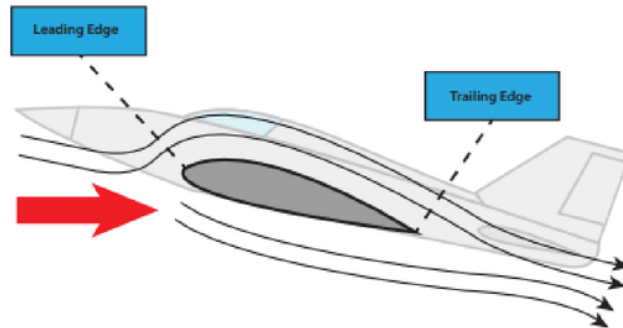


Figure 2 - picture showing the air flow around an aerofoil. An aerofoil for use on a vehicle is inverted but uses the same principles to create negative lift or downforce. (NASA, 2010)

Steady state testing

To measure a vehicle's understeer or oversteer characteristics, steady state or constant speed testing is carried out. This technique can also be used to analyse lateral acceleration of the vehicle, which dictates how much weight transfer and body roll the sprung and unsprung mass experiences depending on the suspension and chassis set up. Harder roll stiffness will increase weight transfer, whereas a softer set up will lessen the weight transfer. (D.A. Panke, 2014)

The heavier the front of a vehicle is, the more the vehicle tends to naturally understeer. Whereas the heavier the rear of the vehicle is, the vehicle will naturally oversteer. This is down to the weight transfer happening at each axle. Basic weight transfer can be found with the following equation:

$$WT_{lat} = \frac{Mass \times Lateral\ acceleration \times Height\ of\ COG}{Track\ width}$$

To conduct the steady state testing of a vehicle in the simulator, as per ISO 4138:2012, the vehicle must be driven at a singular speed on circular paths of a different radii so that several different steering wheel angles are used throughout the test. The circles driven around must provide 0.5m/s² of lateral acceleration increments at the speeds tested. (British Standards Publication, 2012)

3) Methodology

Setup sheet

For MoTeC to calculate each individual run with different setups, a setup sheet was used detailing specific details of the car necessary for making the appropriate calculations; for example: wheelbase, track length, different weight values and changes to the car's suspension settings. MoTeC reads the date and time of specific runs, then correlates it to the matching run listed in the setup sheet, using the setup values from the appropriate row to calculate equations made using maths channels. Below is a screenshot of the setup sheet, the full version can be found in the appendix.

Figure 3 - setup sheet used for the simulation runs, detailing any changes to vehicle setup.

To collect the necessary data, a simulation was run on base performance simulator using the Aston Martin DBR9 GT1 car. Eighteen runs were made in total, consisting of steady state and coast down runs. Below is the order in which the runs were made, also detailing the different setups tested.

Steady state runs:

Table 1- Table displaying the different anti roll bar settings used for each steady state run.

Set up	Front ARB	Rear ARB
1 slow speed	160	72
1	160	72
2	280	48
3	400	12
3 – radius 50m, and 75m	400	12

Coast downs:

Table 2 - Table displaying the different splitter and wing set ups for each coast down test.

Coast down test	Splitter angle	Wing angle
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

Rake angle runs

Table 3 - table displaying the rake angle runs, where the height of suspension was adjusted between the front and rear axles.

Run number	Front height	Rear height
Rake angle 1	max	max
Rake angle 2	min	max
Rake angle 3	min	min
Rake angle 4	max	min

From the data collected, calculations for finding aerodynamic forces acting on the car were made and recorded in a spreadsheet using the equations below:

$$Front\ aero = (F_{front\ right} + F_{front\ left}) - (F_{static\ front\ right} + F_{static\ front\ left})$$

$$Rear\ aero = (F_{rear\ right} + F_{rear\ left}) - (F_{static\ rear\ right} + F_{static\ rear\ left})$$

$$Coefficient\ of\ lift = \frac{total\ aero}{0.5 \times air\ density \times velocity^2}$$

$$Centre\ of\ pressure = \left(\frac{front\ aero}{total\ aero} \right) \times 100$$

To find rolling resistance, aerodynamic drag, mean velocity, and CdA values, velocity and time values from the coast down velocity/time graphs were taken at four points. Two points just after the engine was disengaged, and two points just before the car became stationary. As seen in figure 4.

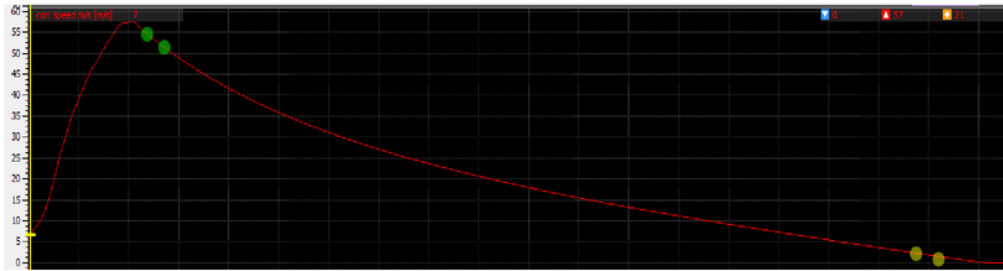


Figure 4 - A velocity/time graph taken from one of the simulator coast down runs. The green and yellow points marked showing where velocity and time data was taken.

The values from the points in green were used to find acceleration rate one, and yellow acceleration rate two. Acceleration values were then used in the following formulas to find the remaining forces on the vehicle.

$$\text{Rolling resistance} = \text{acceleration}_2 \times \text{total mass}$$

$$\text{Aerodynamic drag} = (\text{mass} \times \text{acceleration}_1) - (\text{mass} \times \text{acceleration}_2)$$

$$\text{Mean velocity} = \frac{(\text{velocity}_2 + \text{velocity}_1)}{2}$$

And finally CdA was calculated using:

$$\text{CdA} = \frac{2 \times (\text{ma}_1 - \text{ma}_2)}{\text{air density} \times \text{velocity}^2}$$

4) Results

Coast down results

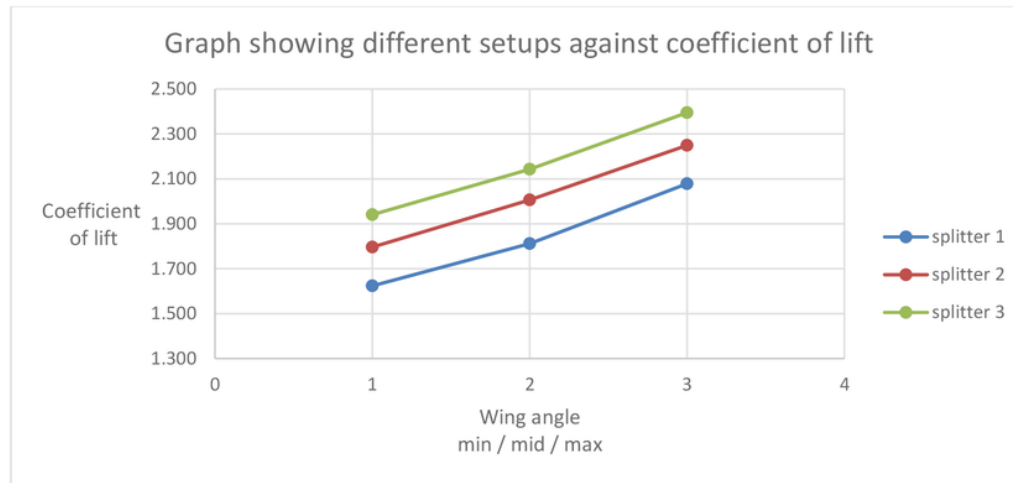


Figure 5 - Graph displaying the coefficient of lift data taken from the experiment. the maximum amount of downforce created is with splitter 3, and wing at maximum angle.

Expected outcome: Each splitter variation will see an initial higher coefficient of lift as there will be more downforce at the front of the vehicle and each wing angle increase will see a higher value of downforce. (R Tarulescu, 2017)

Outcome: In the above graph, the data shows a strong trend between all three setups. With each change in wing angle causing an increase in the coefficient of lift. The graph also shows that keeping the wing angle at minimum and changing splitter length also increases downforce. The initial points for each series starting at a higher value show this. These changes increase tyre loadings when the car is in motion, adding to the amount of grip available. The positive correlation of the graph proves the theory that increasing the wing angle increases the amount of downforce, as predicted.

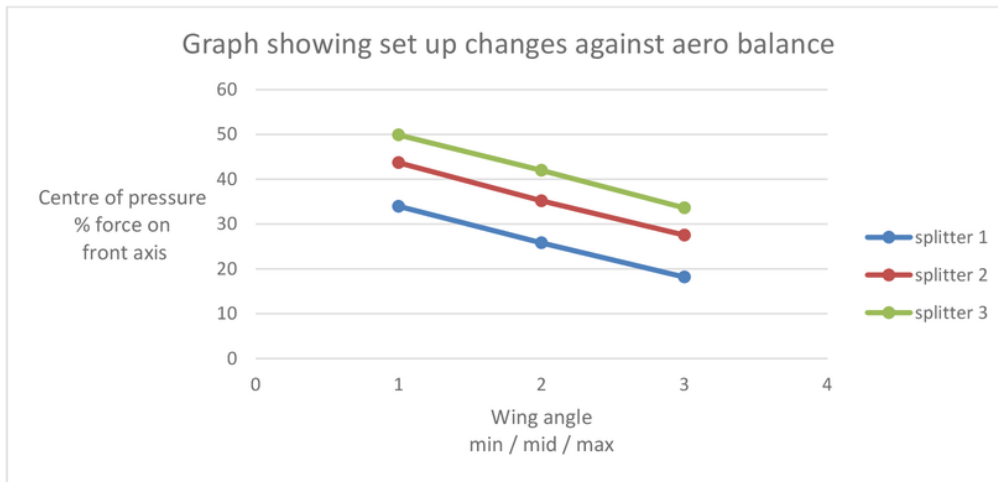


Figure 6 - Graph displaying how adjusting the wing and splitter angles affects the percentage of force acting upon the front axle of the vehicle.

Expected outcome: It is anticipated the effect of increasing the rear wing angle will lessen the amount of force acting upon the front axle, as it acts as a moment on the car. The same should stand true for the increase in splitter length, as more force on the front is added, bringing the pressure forward. (Mcbeath, 2016) Shifting the centre of pressure so it rests just behind the centre of gravity will lead the car to be more stable when cornering, whereas having the centre of pressure closer to the front will make the car handle in a more unpredictable way. (F1 dictionary, 2019)

Outcome: The graph data shows that as wing angle increases, the percentage of force on the front axle drops, the coefficient of lift is increasing with each wing angle adjustment and therefore a higher percentage is acting on the rear overall, giving the car stable handling with a tendency to understeer. The graph also displays that the increase in splitter length increases the amount of downforce at the front, even when wing angle moves the centre of pressure backward. This fits the expected outcome above.

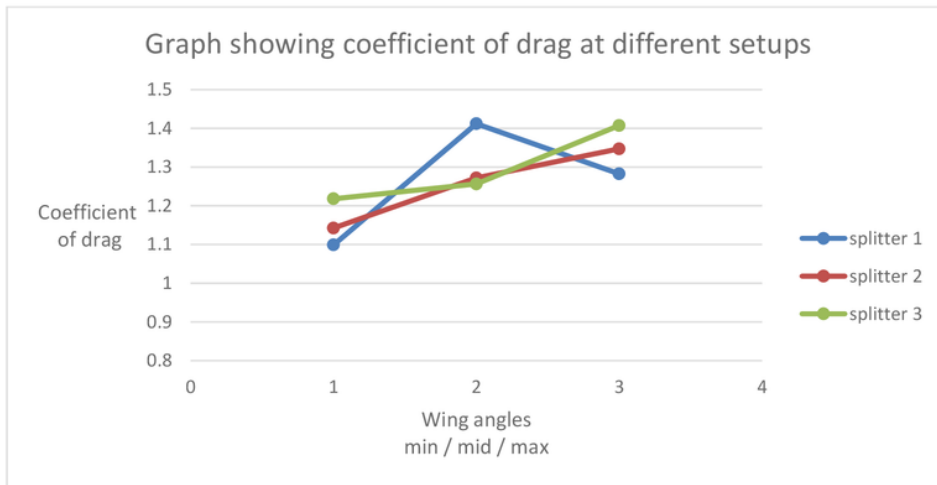


Figure 7 - graph displaying the change in drag coefficient values for each increase in splitter and wing angle.

Expected outcome: As wing angle and lift increases, drag will also increase somewhat as the resultant force from the wing changes angle closer to horizontal instead of downward. Increasing the splitter length will create a larger area of higher pressure at the front of the vehicle also resulting in more drag. (Katz, 1995)

Outcome: Splitter length two and three show some correlation, and an increase in drag with each set up, although setup 'splitter 3, wing 2' increases from its initial value, it does not increase as much as expected, showing a lower value than 'splitter 2, wing 2'. Although for splitter 1 wing angles one and three see an increase that follows the general expected curve, the value displayed for 'splitter 1, wing 2' doesn't follow the trend in any way and appears a lot higher than expected.

It is obvious that there is an error in the data for this point, so looking into the data behind this point it is noticed that the ma1 value is higher than expected, whereas the ma2 value is lower, this may be the reason the datapoint is so far out of trend.

Rake angle coast down results

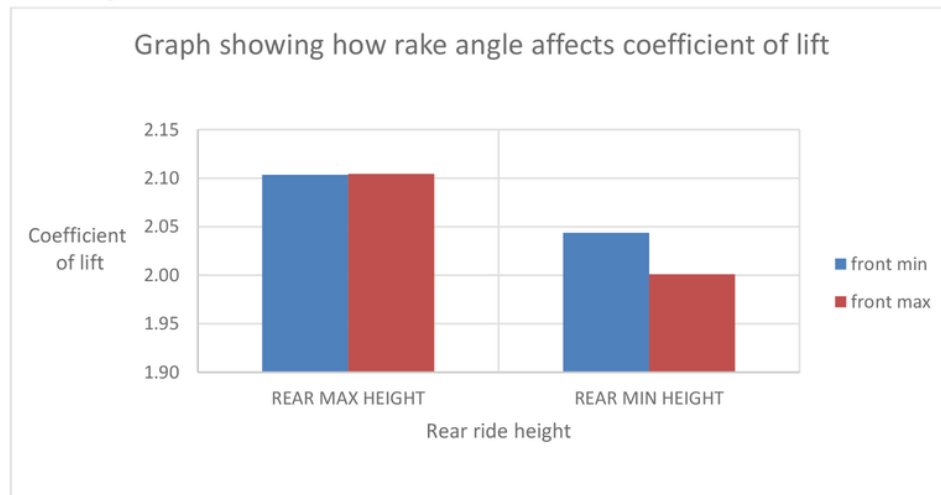


Figure 8 - Graph displaying how rake angle effects coefficient of lift.

Expected outcome: Increasing the ride height at the rear of a vehicle while the front stays at minimum height would create a venturi effect on the underside of the car, so an increase in downforce is expected. Increasing the front height and lowering the rear will reverse this effect, so a drop in downforce is expected. (Tudor, 2019)

Actual outcome: Lowering the rear of the car shows a small drop in downforce of the vehicle as expected, due to the venturi effect lessening. Increasing the front height with the rear low increases the lift further as this would cause high pressure to build under the car, increasing drag. This is demonstrated in the next results graph.

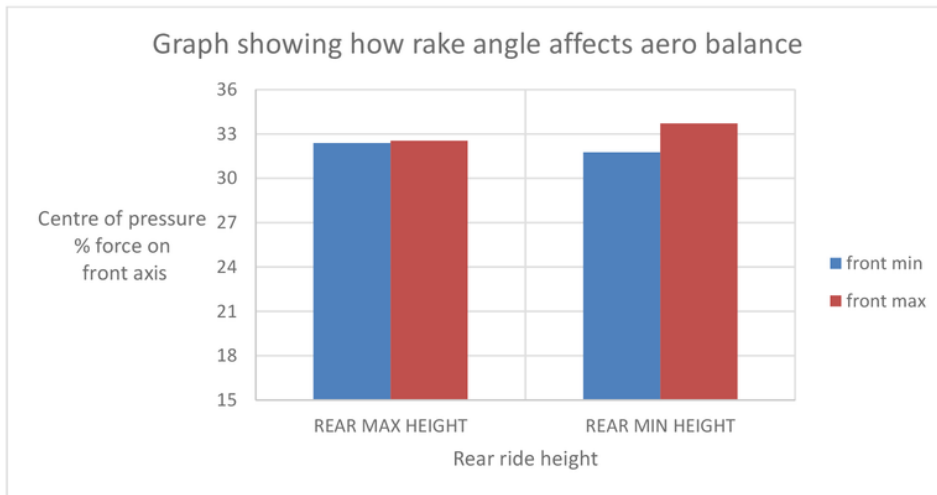


Figure 9 – graph displaying the effects of rake angle on aero balance.

Expected outcome: For positive rake angle, the results of the test should show a high percentage of force as pressure on the splitter will be most active, whereas there will be a low area of pressure under the car due to the venturi effect created. Negative rake angle should see a lower percentage acting on the front as pressure build up underneath the vehicle would cause the front to lift acting with rear downforce and in extreme cases cause the car to flip.

Actual outcome: The graph shows small changes in percentage of pressure acting on the front axle for each setup, but nothing significant. The largest value is shown for the negative rake set up, going against the predicted theory; but the simulator does not show the effect.

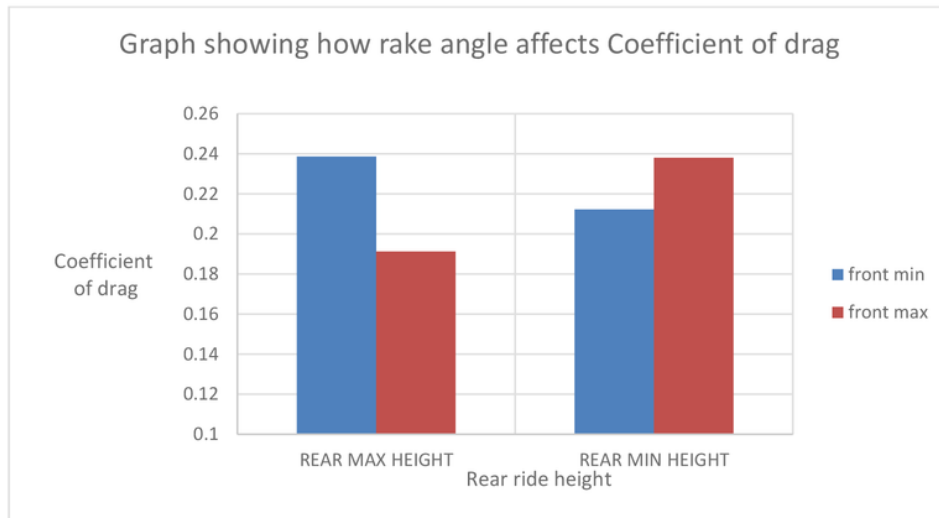
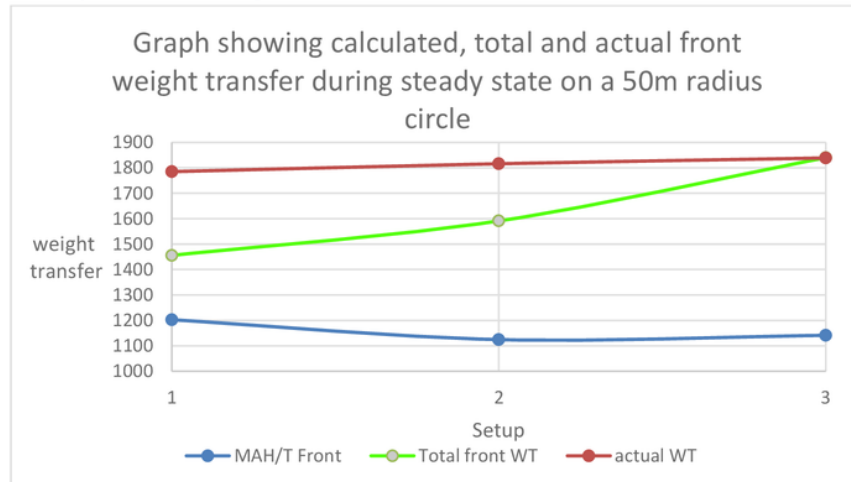


Figure 10 - Graph displaying how ride height setups affect the coefficient of drag of the vehicle

Expected outcome: An increase in positive rake angle should see a slight increase in coefficient of drag due to the frontal area of the car increasing slightly. The same is expected to happen for reverse rake as the underside of the car would be exposed, also increasing frontal area. (NASA, 2014)

Actual outcome: As predicted with the rake at both negative and positive positions create the highest amount of drag, seeing results that are very close to each other. The lowest value is seen with the car at maximum height at both axles. In this position the smallest frontal area is on show, and air passes under and over the car easily due to less airflow restriction underneath.

Steady state handling results

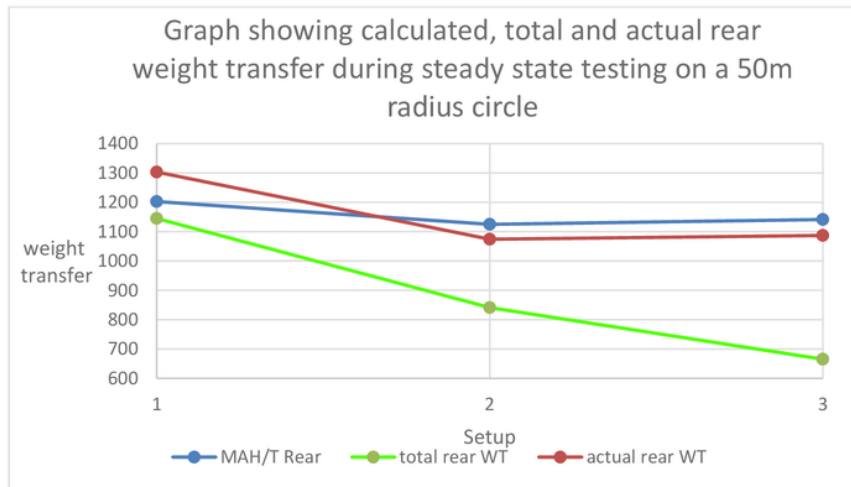


Expected outcome: Front weight transfer will increase as the front anti roll bar gets stiffer.

Actual outcome: The graph shows that for the basic weight transfer (MAH/T) the weight transfer decreases between setups one and two. This is not as expected as the front end gets stiffer with each setup. The reason the weight transfer value is low is due to the speed of the vehicle when the values were recorded. The car was traveling at a slightly lower velocity therefore lateral acceleration was not as strong.

Total weight transfer shows a positive trend, with each setup showing an increase in weight transfer, this fits with expectations as the front of the car gets stiffer, and the equation considers more variables, such as the sprung and unsprung masses.

Actual weight transfer is almost linear, only displaying a small increase in weight transfer between set ups. The reason an almost linear trend for actual weight transfer is seen is due to the rear setup being softer and influencing the front weight transfer via the chassis.

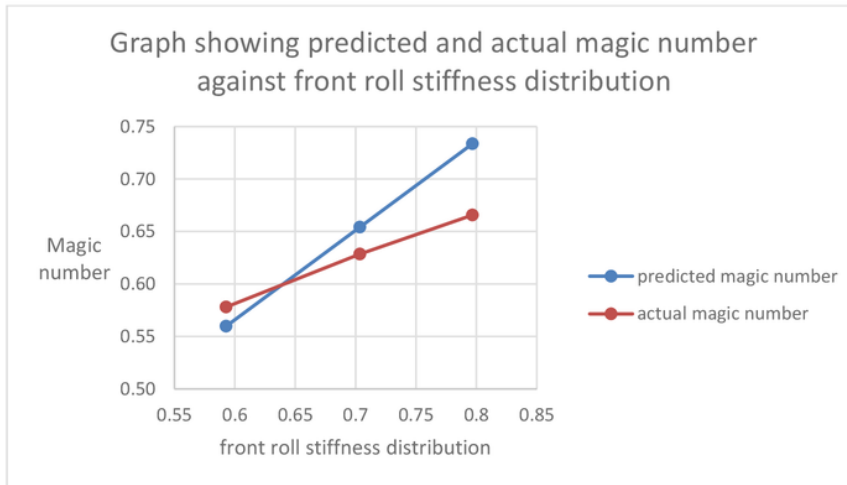


Expected outcome: As roll stiffness gets softer at the rear, a decrease in weight transfer should be perceived.

Actual outcome: Basic weight transfer shows the same trend and values as in the front weight transfer graph, as the vehicle has a 50/50 weight distribution and the same track width between front and rear so the only variable between each setup in the equation is the lateral acceleration.

Total weight transfer shows that, as the setups get softer at the rear less weight transfer occurs which is what was expected. Actual weight transfer follows this trend but deviates from it at set up three, which doesn't fit the expected outcome. Taking both front and rear into account at setup three there is more stiffness at the front of the car which is having an influence on the rear weight transfer via the chassis stiffness.

Roll centre distribution



The magic number is a ratio of how much oversteer or understeer the vehicle experiences, the lower the value the more oversteer the car experiences; whereas the higher the value the greater the understeer.

The above graph shows as the setups increase in stiffness the magic number increases, meaning the car will tend toward understeer. This proves that the stiffer the front axle the more weight transfer takes place at the front of the vehicle, increasing the amount of understeer.

5) Conclusion

The work undertaken in this report has covered how aerofoils and splitters can be used to affect a cars downforce, and how coast down testing is used to find how these devices affect the performance of the car. Coast down testing has also been investigated to find how great a part weight transfer plays in the handling of a vehicle with different anti roll bar settings. It is clear to see that roll stiffness and weight distribution do affect how a car handles as regards to under or oversteer, with stiffer setups creating more weight transfer in turn leading to understeer and softer set ups leading to oversteer.

Although the trends in the graphs show an expected result in some cases, there is no way to validate these results. The wing angles used in the simulator are not quantifiable angular values for angle of attack, neither are the splitter lengths, thus making it difficult to replicate in real life.

A simulator is only as good as the computer code it runs on, which in turn is only as good as the programmer who created it who will not have taken certain nuances into account that can affect a cars performance.

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8) Appendix

Appendix 1

Name	Summary
☒ WT long [N]	$(M_{s\text{ tot}} \cdot [kg]) \cdot (G \text{ Force Long} \cdot [G] \cdot 9.81) \cdot \text{'center of gravity' [m]} / \text{'Wheelbase' [m]}$
☒ WT latitudinally front	$((M_{s\text{ tot}} \cdot [kg]) / 2) \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'center of gravity' [m]} / \text{'Track Front' [m]}$
☒ WT latitudinally rear	$(M_{s\text{ tot}} \cdot [kg]) / 2 \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'center of gravity' [m]} / \text{'Track Rear' [m]}$
☒ roll angle [rad]	$\text{'sprung mass' [kg]} \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'roll centre at CoG' [m]} / ((\text{'roll stff front' [N/rad]} + \text{'roll stff rear' [N/rad]})$
☒ sprung mass elastic WT front	$(\text{'wheel rate front' [N/rad]} \cdot \text{'Track Front' [m]} \cdot \text{'roll angle 2' [deg]} / 2$
☒ sprung mass elastic rear WT	$(\text{'wheel rate rear' [N/rad]} \cdot \text{'Track Rear' [m]} \cdot \text{'roll angle 2' [deg]} / 2$
☒ WT sprung mass roll centre front	$((0.5 \cdot \text{'sprung mass' [kg]}) \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'Static Roll Centre Height Front' [m]} / \text{'Track Front' [m]}$
☒ WT sprung mass roll centre rear	$((0.5 \cdot \text{'sprung mass' [kg]}) \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'Static Roll Centre Height Rear' [m]} / \text{'Track Rear' [m]}$
☒ Mus geo WT front	$((\text{'front corner unsprung mass' [kg]} / 2) \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'front tyre rolling radius' [m]} / \text{'Track Front' [m]}$
☒ Mus geo WT rear	$((\text{'rear corner unsprung mass' [kg]} / 2) \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'rear tyre rolling radius' [m]} / \text{'Track Rear' [m]}$
☒ total weight transfer front	$\text{'sprung mass elastic WT front' + WT sprung mass roll centre front' + Mus geo WT front'}$
☒ total weight transfer rear	$\text{'sprung mass elastic rear WT' + WT sprung mass roll centre rear' + Mus geo WT rear'}$
☒ pnt WT (magic no)	$\text{total weight transfer front} / (\text{total weight transfer front} + \text{total weight transfer rear})$
☒ sum weight transfer	$\text{total weight transfer front} + \text{total weight transfer rear}$
☒ corner radius [m]	$\text{'corr speed m/s' [m/s]}^2 / (G \text{ Force Lat} \cdot [G] \cdot 9.81)$
☒ corr speed m/s [m/s]	$\text{'Corr Speed' [km/h]} \cdot 1000 / 3600$
☒ required steering angle [rad]	$(\text{'Wheelbase' [m]} \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81)) / \text{'corr speed m/s' }^2$
☒ theoretical wheel steer [rad]	$\text{'Wheelbase' [m]} / \text{'corner radius' [m]}$
☒ X	$\text{'Steering Wheel Pct' [\%]} / \text{'theoretical wheel steer' [deg]}$
☒ theoretica steer percent	$\text{'theoretical wheel steer' [deg]} \cdot X$
☒ understeer	$\text{abs}(\text{'Steering Wheel Pct' [\%]} - \text{abs}(\text{'theoretical wheel steer' [deg]}))$
☒ actual front wt	$(\text{'Tire Load - FL' [N]} - \text{'Tire Load - FR' [N]}) / 2$
☒ actual rear wt	$(\text{'Tire Load - RL' [N]} - \text{'Tire Load - RR' [N]}) / 2$
☒ roll angle 2 [deg]	$(\text{'sprung mass' [kg]} \cdot (G \text{ Force Lat} \cdot [G] \cdot 9.81) \cdot \text{'center of gravity' [m]}) / ((\text{'Track Front' [m]}^2 \cdot \text{'wheel rate front' [N/rad]} / 2) + (\text{'Track Rear' [m]}^2 \cdot \text{'wheel rate rear' [N/rad]} / 2)$
☒ lot accel	$G \text{ Force Lat} \cdot [G] \cdot 9.81$
☒ wheel rate front	$(\text{'Spring Rate FL' [N/mm]} \cdot \text{'Motion Ratio FL' }^2) + \text{'Roll Bar Rate Front' [N/mm]}$
☒ wheel rate rear	$(\text{'Spring Rate RL' [N/mm]} \cdot \text{'Motion Ratio RL' }^2) + \text{'Roll Bar Rate Rear' [N/mm]}$
☒ roll stiffness distribution front	$\text{'roll stiffness front' / total roll stiffness'}$
☒ roll stiffness front	$(\text{'Track Front' [m]}^2 \cdot \text{'wheel rate front' [N/rad]} / 2$
☒ roll stiffness rear	$(\text{'Track Rear' [m]}^2 \cdot \text{'wheel rate rear' [N/rad]} / 2$
☒ total roll stiffness	$\text{'roll stiffness front' + 'roll stiffness rear'}$
☒ roll stiffness distribution rear	$\text{'roll stiffness rear' / total roll stiffness'}$
☒ actual magic number	$\text{'actual front wt' / (actual front wt' + actual rear wt')}$

Figure 11 - Maths channels used in Motec, displaying syntax and equations used.

[illegible]

Car Anti Squat	Driveline	Diff Ratio	Gear Ratio 1	Gear Ratio 2	Gear Ratio 3	Gear Ratio 4	Gear Ratio 5	Gear Ratio 6	Gear Ratio 7	Aero	Splitter Angle Front	Rear Wing Angle	Splitter height front	Other	Fuel Level Initial
										deg	deg	mm			l
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
										1	1				
										1	1				
										1	6				
										1	12				
										2	1				
										2	6				
										2	12				
										3	1				
										3	6				
										3	12				

Figure 12 - Full version of the Motec setup sheet, detailing each setup change per run.