

University of Wales Trinity Saint David School of Engineering

Vehicle Testing and Analysis
Advanced Vehicle Dynamics M6X00415

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1 Introduction

Analysing data in motorsport has become increasingly important through its history. This is true more now than ever with almost every parameter monitored for each session and then analysed to gain a competitive advantage. In this report the author will run a simulator to investigate changes to springs, dampers, aerodynamics, and anti-roll bars. This will be done using the roll stiffness model.

In this analysis an Aston Martin Lagonda DB9 racecar (2010 GT1 class) is used. It uses a V12 engine which produced 625 BHP using a double bonded aluminium body and double wishbone suspension featuring KONI dampers (Koni, 2019) and EIBACH springs (Eibach, 2019). It also features a rear wing, rear diffuser, and a splitter (Aston Martin, 2011).

The simulator the author used was a Base Performance Simulator (Base Performance, 2019). The benefit of using a simulator is that the conditions are consistent. So rather than the track having a change in wind direction or temperature it stays consistent. Thus, the data can be compared much more easily as the changes in environment does not need to be considered. It also means that any setup changes which are made can be done by a click of a button rather than having to spend half an hour between runs to make the change. There can also be a cost saving as you do not need to pay for fuel, track time and tyres.

On the other hand, because it is a simulator there will always be correlation issues with real life. It can be very useful though to find trends in changes e.g. understeer or aerodynamic load. But there are alternatives to find trends in aerodynamics by using wind tunnels and CFD (Ansys, 2019). Some suspension parameters can be investigated through vehicle modelling such as (MSC Software, n.d.) and through shaker rigs (L & Scott, 1994).

2 Test Plan

As a group they produced a test plan to cover as broad a range as possible within the time limit. To do this they decided it was best to run standard settings then running with maximum and minimum and variations of, which can be seen below.

R0

COAST DOWN 1 - std

CD2

COAST DOWN 2 - R4

CD1

UNDERSTEER COEFF

R1

R2

R3

R4

R5

Aero

Splitter

Wing

Standard

Standard

Min

Min

Min

Max

Max

Max

Min

R6

R7

R8

R9

Ride Height

Front

Rear

Standard

Standard

Min

Min

Min

Max

Max

Max

Min

R10

R11

R12

R13

R1b

ARB

Front

Rear

Standard

Standard

Min

Min

Min

Max

Max

Max

Min

STANDARD RE-DO

R14

R15

R16

R17

Dampers

Front BUMP

Rear BUMP

SLOW

FAST

SLOW

FAST

Standard

Standard

Standard

Standard

Min

Min

Min

Max

Max

Max

Max

Max

Min

Max

Min

Max

R18

R19

R20

R21

Dampers

Front RBOUND

Rear RBOUND

SLOW

FAST

SLOW

FAST

Standard

Standard

Standard

Standard

Min

Min

Min

Min

Max

Max

Max

Max

Max

Min

Max

Min

Max

R22

R23

R24

R25

Dampers

Front BUMP

Rear BUMP

SLOW

FAST

SLOW

FAST

Min

Standard

Max

Standard

Max

Standard

Min

Standard

Standard

Min

Standard

Max

Min

Standard

Max

Standard

Min

R26

R27

R28

R29

Dampers

Front RBOUND

Rear RBOUND

SLOW

FAST

SLOW

FAST

Min

Standard

Max

Standard

Max

Standard

Min

Standard

Standard

Max

Standard

Max

Min

Standard

Max

Standard

Min

R30

R31

R32

R33

Dampers

Front RBOUND

Rear RBOUND

SLOW

FAST

SLOW

FAST

Min

Standard

Max

Standard

Max

Standard

Min

Standard

Standard

Max

Standard

Max

Min

Standard

Max

Standard

Min

Table 1-Table of All Setups

The group also gave individual roles to ensure that the test ran as smoothly as possible so that all the data can be gained as quickly as possible to give the opportunity to gain extra runs.

<u>JOBS</u>
<u>Ainsley</u> Driver
<u>Max</u> Setup change
<u>Nick</u> Setup change
<u>Sam</u> Data organisation
<u>Simon</u> Setup photos
<u>Ewan</u> Data feed supervisor

Figure 1-List of Job Roles

Driver is an obvious role, but the setup change was one person reading out the setup and another changing it (author). Then there needed a to be a person to organise the data while a run was on going such as naming it so that they knew what the setup was during the run. To add to that, to know the exact setting a person was also needed to take a picture of the setup for future reference. Finally, as the simulator can be sometimes temperamental therefore it was needed for a person to check if the data was recording during the run (data feed supervisor).

3 Aerodynamics

To gain the coefficient of drag the author used previous data gained from other straight line tests made on the car (Thomas, 2019). From this for each setup the author could get a value for the coefficient of drag. However, these are just averages, and in reality, would change depending on pitch and ride height.

3.1 Wing and splitter settings

3.1.1 Drag

As can be seen the drag decreases as speed decreases. This is as expected as the air velocity is decreased so therefore from the equations, so does the drag force. This can be seen more clearly from the graph below.

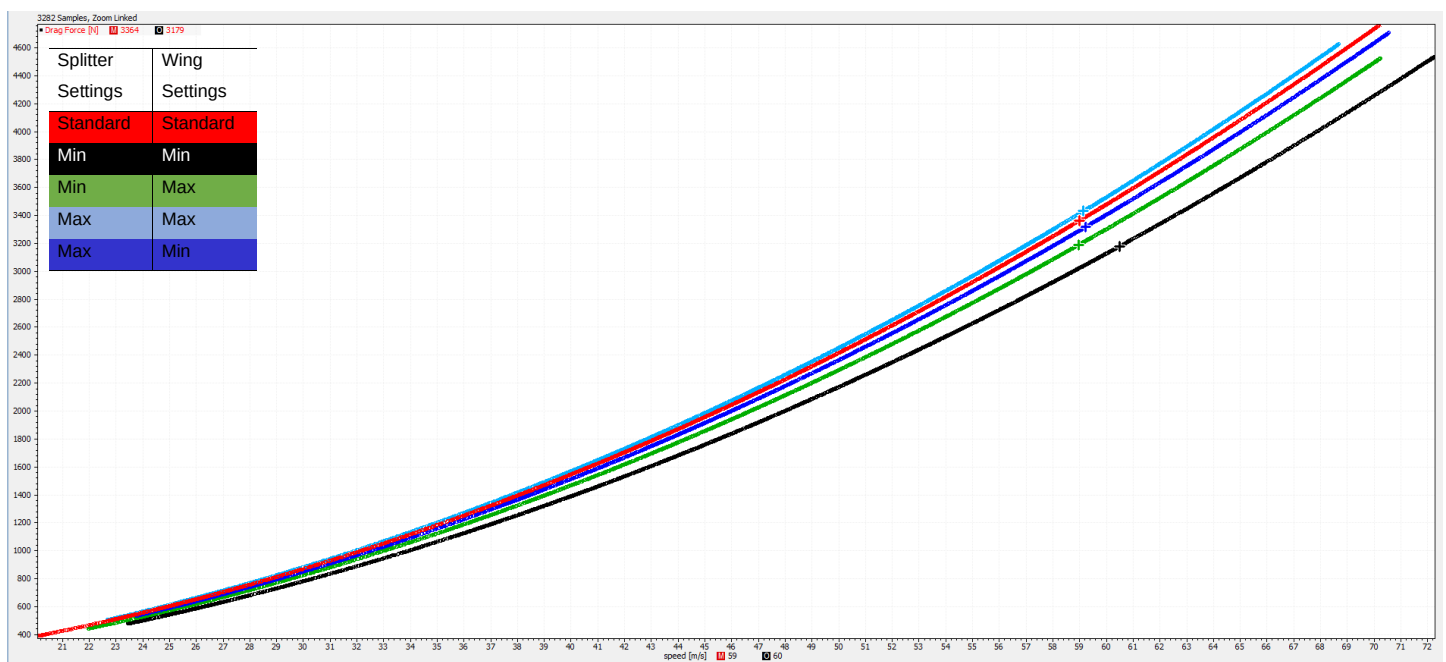


Figure 2-Graph of Drag Vs Speed for wing and Splitter changes

This happens because as the wing is changed and the frontal area becomes greater. This means that there is a larger area for there to be a velocity difference as the molecules needed to be moved further to get around the object (Hall, 2015). As there will be a gap behind the device this will leave an area of negative pressure behind it. This will mean that the high pressure will then bleed into that area and start to rotate. This will create turbulence which will then again increase the frontal area. The turbulence will also then again slow down the air which is going around the wing. The actual value may vary though as this is using an estimate for the coefficient therefore the value will be constantly changing hence why the graph above is so smooth.

3.1.2 Lift

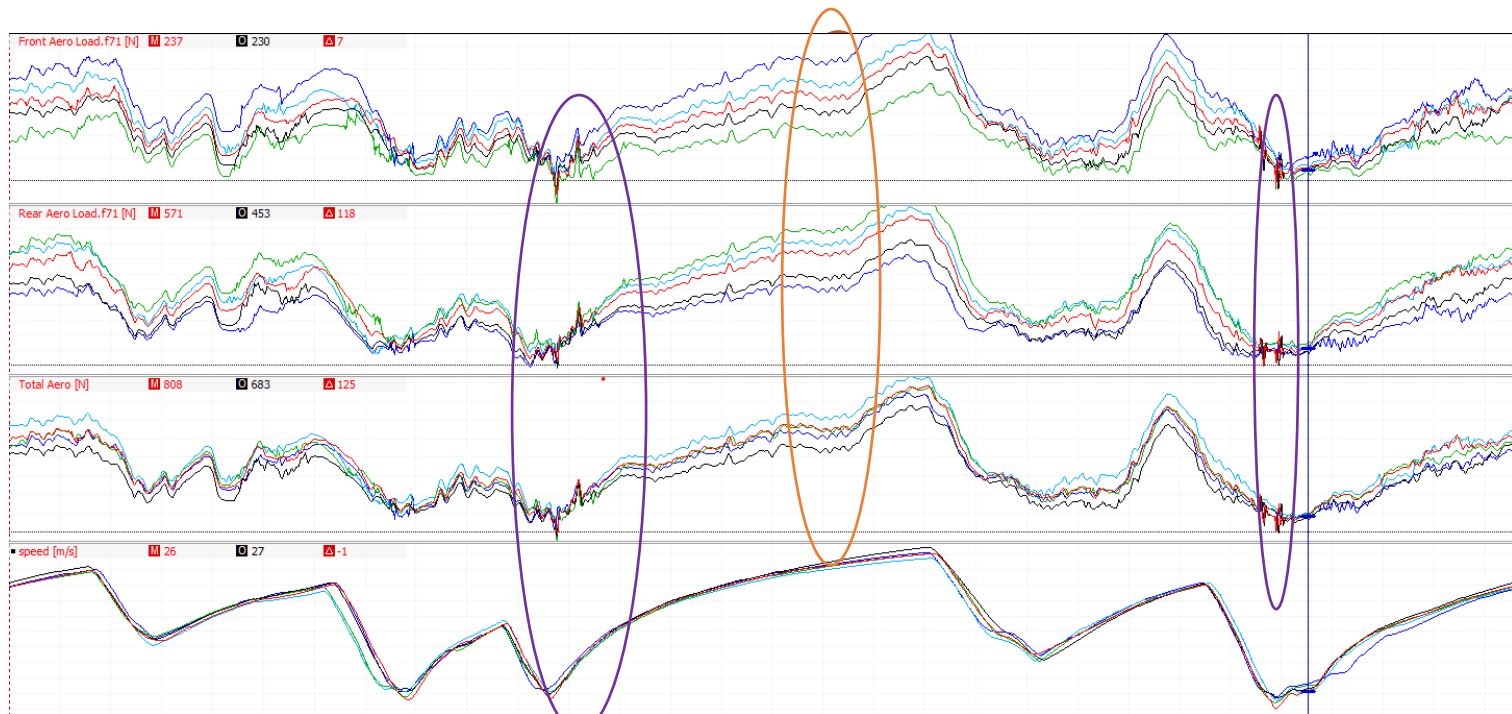


Figure 4-Aero force Around a Lap Comparing Wing and Setup Changes

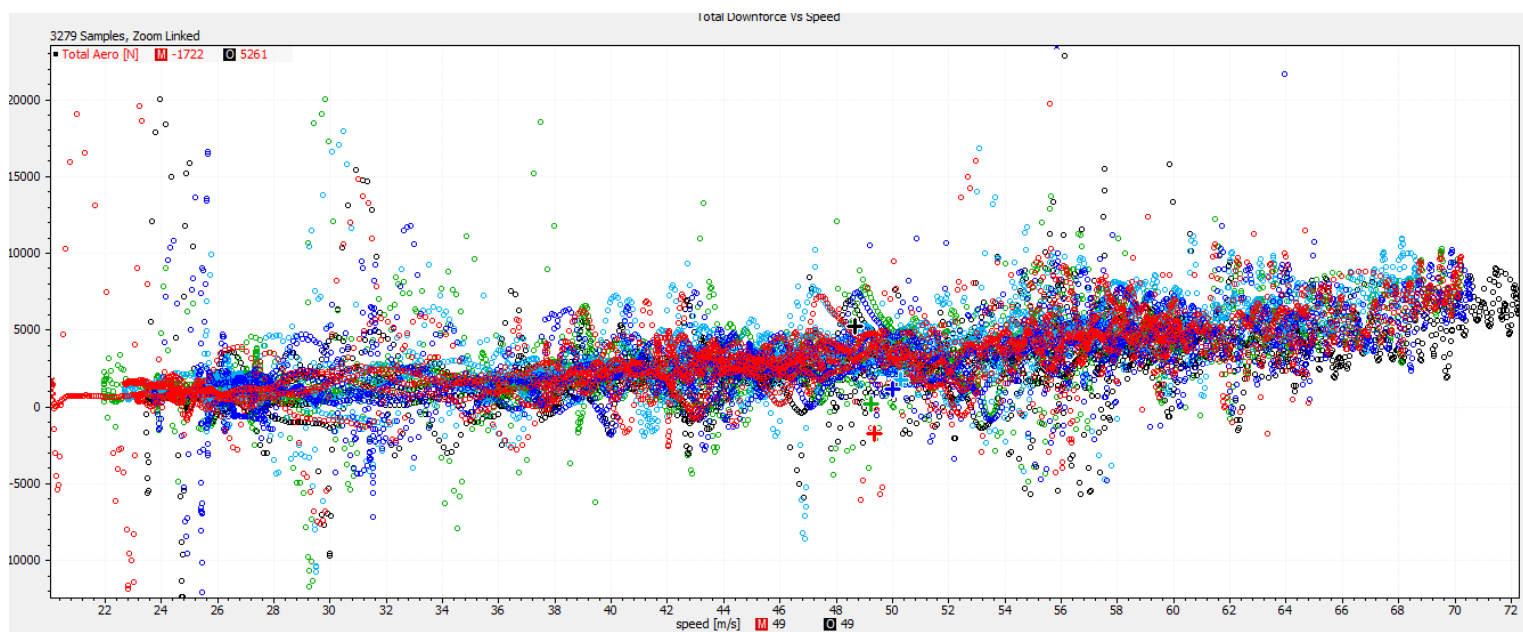


Figure 3-Graph of Lift vs Speed

The lift is calculated from removing the static load from the tyre load. To take pitch into account the longitudinal weight transfer is added to the front and removed from the rear. When a filter is applied to reduce noise (unfiltered can be found in appendices), a clear trend can be seen. The faster the car is traveling the greater the aerodynamic load is acting on the

car. Interestingly though the wing is producing more down force as the average load on the rear is around a minimum of 200N more than on the front. There are some peculiar spikes when the car goes below around 25m/s (circled purple above). This could be down to the fact that at this speed the aerodynamics are no longer taking effect. An unexpected part is when the car is accelerating along the track at the same point on the circuit there is a dip in the load (orange circle). This happens on all the runs, so it may be that this is a brow of a hill, so the car is slightly unloading.

Another interesting point is that as the car first comes out of a corner the value of lift wavers. This could be down to as the car pitches upwards under acceleration the front pitches up. This will cause a slight amount of lift as the air hits under the car. This can be seen from the suspension positioning data as the cars ride height lifts. Assuming that the ride height is taken at the wheels the author calculated the rake using the suspension positions.

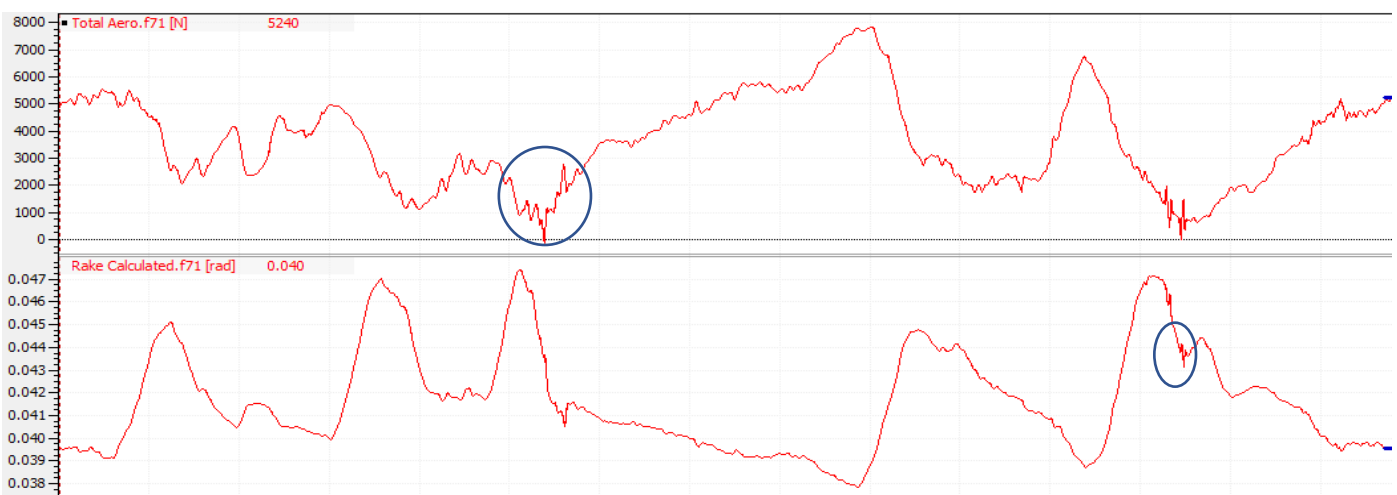


Figure 5-Graph of Total Aero and Rake Angle

As can be seen as the car is under braking the lift drops but the rake also increases. But, at first acceleration the rake snaps up then goes back to normal. The author believes this is down to the air briefly catching under the car and lifting it temporarily.

If we look at individual corners the change in aerodynamics load can be seen at each point around the corner. If we look at club corner which is quite a slow left-hand corner.

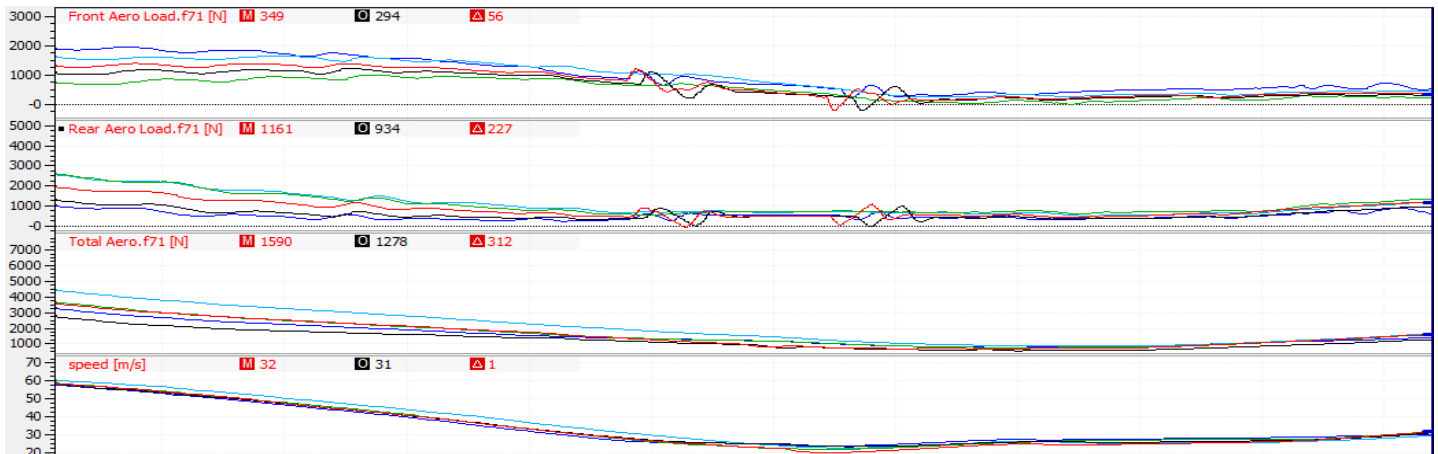


Figure 6-Aero Load around Club Corner

The aerodynamic force decreases until the car reaches the apex of the corner. Interestingly the rear aero load drops much quicker than the front aero load. This could be down to as when the car breaks it pitches forward. This causes the gap between the road and the splitter to decrease which suggests that ground effect is taking place as it is able to still create downforce. This could be a benefit in the grand scheme of things as it means that there is more grip going to the front wheels which helps with steering. However, this may cause too much front-end grip and cause the car to oversteer (Auto Express, 2017).

Similarly, on the exit of the corner as the car accelerates and the front lifts slightly the rear aero load increases quicker than the front. This will be down to that the rear being closer to the ground so ground effect will be taking place on the diffuser. Ground effect happens as the bottom of the car gets closer to the ground the air speeds up through the smaller gap because of the venturi effect and drops the pressure underneath making a large pressure difference causing downforce.

3.1.3 Centre of Pressure

The centre of pressure is also an important consideration within design of an aerodynamic package. It is essentially the distribution of the downforce being produced. For a correctly designed aerodynamic package the centre of pressure should complement the centre of gravity, as the aim is to balance out the centre of gravity with the centre of pressure. This has a number of effects such as the handling of the car and straight-line stability. The centre of pressure in a race car is generally acting behind the centre of gravity. This generally means that the vehicle is more stable (oversteer and understeer) when it is a mid-engine car like the car being used (Total Sim, 2016).

If we look at Hanger straight, we can get an overall view of the centre of pressure as it is at reasonably constant acceleration.

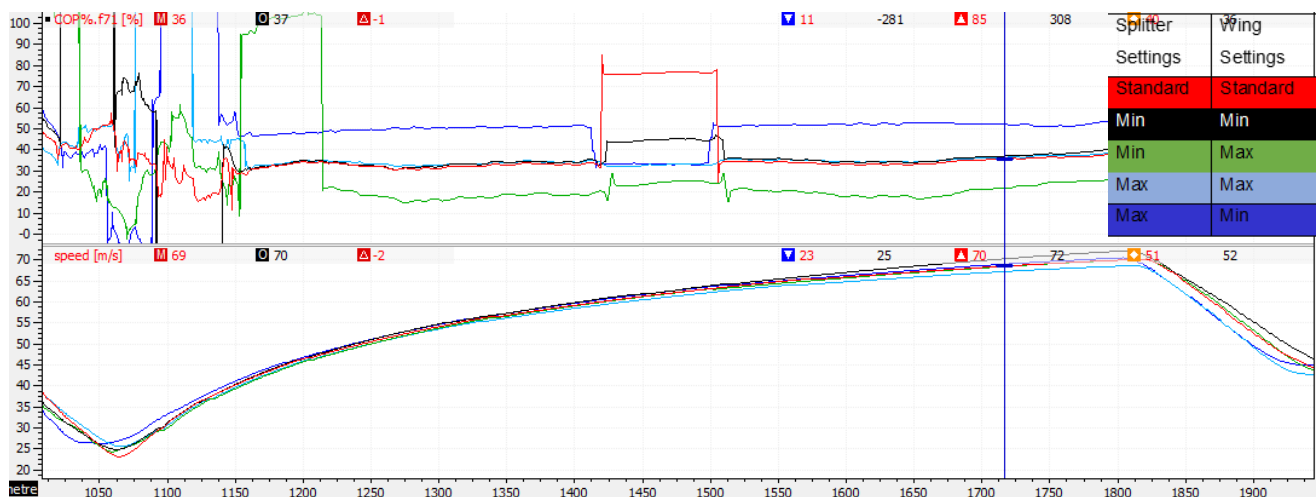


Figure 7-Centre of Pressure on Hanger Straight

As can be seen the centre of pressure is at its highest when the splitter is at its lowest setting and the wing is at maximum. This is expected as it this brings the centre of pressure much closer to the front as the splitter is producing comparatively more lift at the front than the rear. Interestingly though that the cars centre of pressure does not change much (only about 0.1%) when changing from maximum on both ends and minimum. This may be due to the way the simulator models the aerodynamic settings as generally the wing will not change at the same rate as the splitter.

If we then look at the centre of pressure across a lap, we can get a good indication of how balanced the car is around the lap.

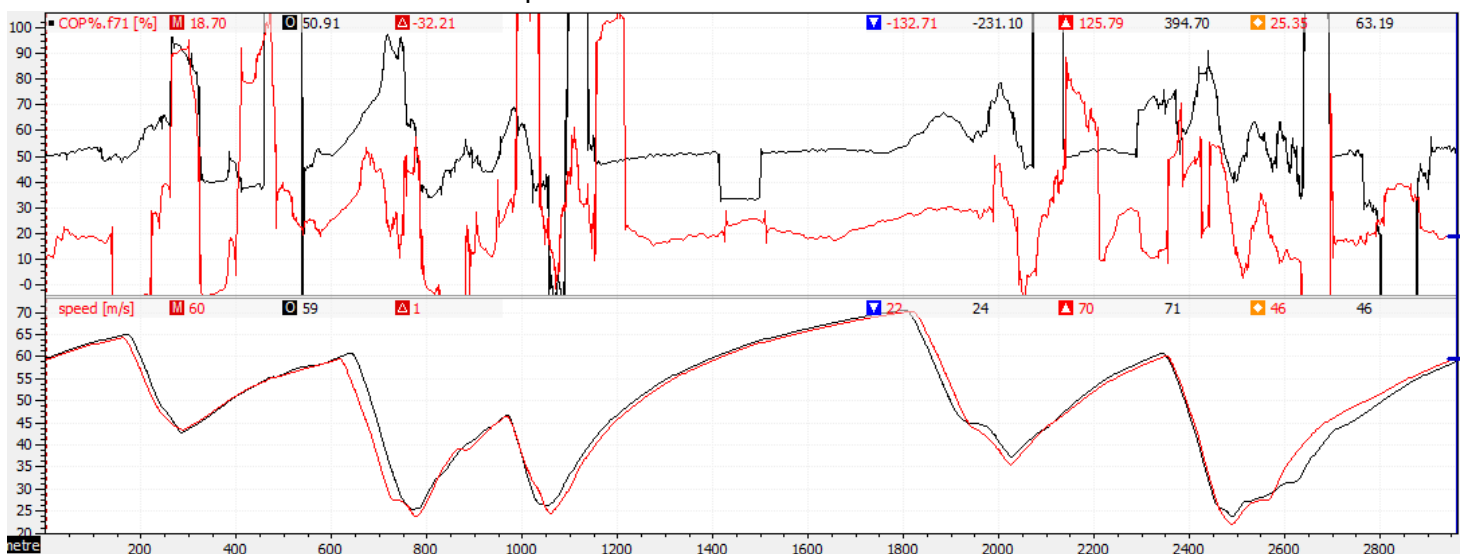


Figure 8-Centre of pressure around a lap

This is quite a telling plot of how the vehicles aerodynamics are behaving under acceleration/ deceleration and in cornering. It tells us that under deceleration the centre of pressure moves forward. This backs up the premise that as the car is tilting toward the front

end and is producing more downforce which is expected, so the centre of pressure will increase. Then as the car begins to accelerate the centre of pressure shoots right down (moves rearward) as the car tilts back again and the front no longer produces as much downforce and the rear produced more again as it is closer to the ground. When the car is at the apex the centre of pressure is longitudinally stable as there is very little acceleration or deceleration.

3.2 Rake changes

Research shows that rake has a significant effect on the aerodynamics of a vehicle (Dzijan, et al., 2018). The rake is essentially the angle of the car is at. The idea of raking the car is to make the whole underside of the car like a venturi tunnel mentioned earlier. Although this could be taken too far as if the rear is too high then the diffuser is too high to interact with the ground. Adversely if the front of the car gets too close to the ground then it could choke and the flow under the car could be stopped completely. This is why there is a balancing act between rake and ride height. Despite this as mentioned earlier it is not known whether the simulator is able to model near ground aerodynamics accurately or at all.

	Ride Height	
	Front	Rear
R1	46mm	62mm
R6	46mm	56mm
R7	46mm	80mm
R8	70mm	80mm
R9	70mm	56mm

This test uses the maximum possible sweep for the shortest amount of time by using the maximum and minimum settings on the front and rear. As can be seen to save even more time we used the same standard test as there is no point repeating the same setup when the data is already gained.

3.2.1 Drag

Theoretically the drag should not change a huge amount for the gain in downforce when changing rake. This is due to the air going to the wing having less turbulent air going towards it and the splitter being closer to the ground. Therefore, a well set up car will have the correct rake angle with the aerodynamic devices also being changed to suite the new rake angle.

This can be seen as the standard set up has the highest downforce. But, in this test because of the length of test the group kept the wing and splitter setting as standard so as to keep the tests comparable.

Looking at the value for drag at 66m/s an easy comparison can be made.

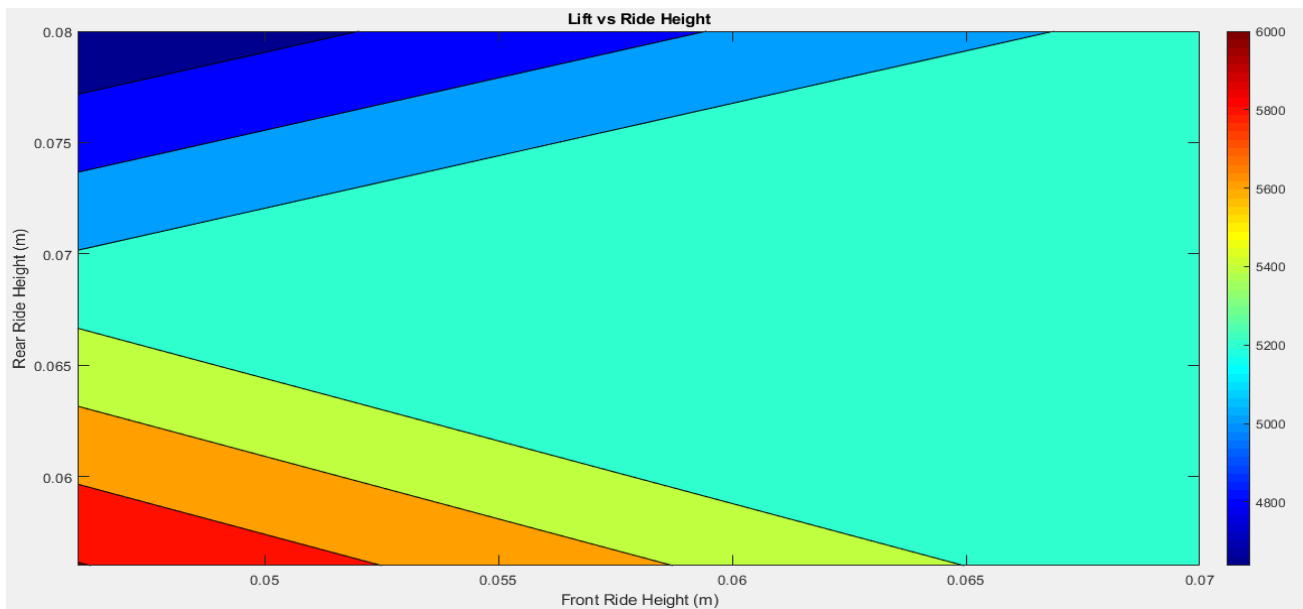


Figure 9-Graph of Drag against Ride Height

One thing this graph tells us is that the front ride height does not have such a large effect on the overall drag of the car than the rear. This can be seen as when the rear is constant, and the front is increased there is little to no effect on the drag. This is interesting as you would expect the drag to increase because of the extra frontal area but because there is less air getting to the wing this is producing less turbulence so therefore producing less drag. This is also the reason of why the drag increases as the angle of the rake gets much steeper as the frontal area becomes greater.

3.2.2 Lift

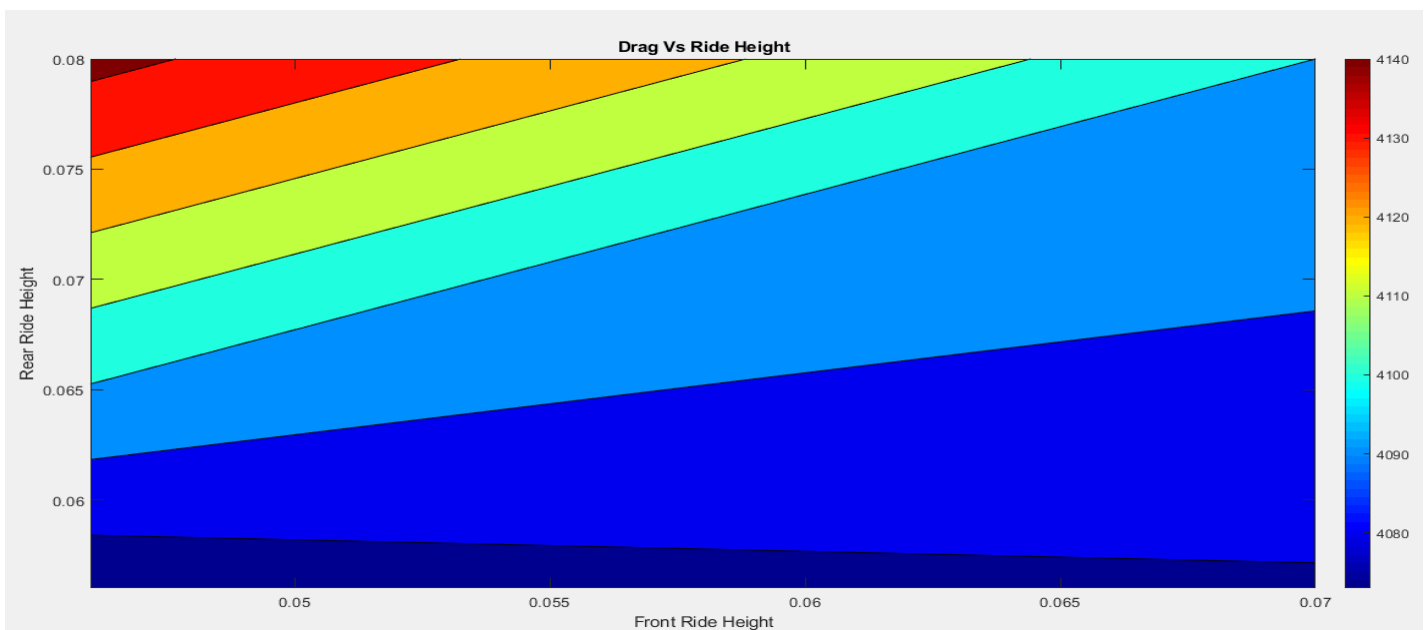


Figure 10-Graph of Lift against Ride Height

This shows us that when the car is at its lowest it produces the most downforce which is confirmed with (Katz, 2006). This is because the ground effect is stronger as it gets closer to the ground as discussed earlier. But what is very interesting is that the car produces the least down force when the rear is highest, and front is lowest. This may suggest that the diffuser produces a large amount of the overall downforce and when it is not close to the ground it is not working. However, it could just mean that the simulator does not model rake angle very well which is supported by others findings (Hart, 2019). If it were modelled accurately the author would expect to see the highest downforce produced when the rear is at its highest and the front at its lowest. This is because at this point the static rake is around 0.7° which is not that steep but should still mean that the rear of the car is getting clean flow and that the splitter is low enough so that ground effect can take place.

4 Weight Transfer

Once the aerodynamic set up changes were finished the group then went on to change springs, Anti-roll bar (ARB's) and then damper setups. Weight transfer occurs when a lateral G force is applied at the centre of gravity which then creates a moment around the centre of rotation which in turn causes the vehicle to have roll and weight transfer (Abe, 2015).

4.1 Roll Stiffness Setup Changes

The group initially started with investigating the effect of changing the ARB rate.

	ARB					
	Front	Rear	Front (N/mm)	Rear (N/mm)	Front roll Stiffness	Rear Roll Stiffness
	Standard	Standard	280	36	525711.5899	199179.0779
	Min	Min	160	0	365121.8299	151002.1499
	Min	Max	160	72	365121.8299	247356.0059
	Max	Max	400	72	686301.3499	247356.0059
	Max	Min	400	0	686301.3499	151002.1499

Table 2-Different ARB Settings

They then went onto spring setups.

	Springs						
	Front	Rear	Front (N/mm)	Rear (N/mm)	Front Roll Stiffness	Rear Roll Stiffness	
	Stand-ard	Stand-ard	237	237	525711.5899	199179.078	
	R14	Min	Min	202	202	503411.6943	176879.182
	R15	Min	Max	202	307	503411.6943	243778.869
	R16	Max	Max	307	307	610451.1929	176879.182
	R17	Max	Min	307	202	610451.1929	243778.869

Table 3-Different Spring Settings

When the rate is 0 then the ARB is completely disconnected. First the roll angle had to be calculated as this is the basis for the different weight transfers. Using this, the author then calculated the weight transfer in a number of different ways. First is the long method which calculates each individual weight transfer then adds them together. This is useful as it means that each type of weight transfer can be found out, but because they are each calculated this can introduce errors within the equations. The three types are, unsprung geometric, sprung geometric and elastic weight transfer. Adapting the springs, dampers and ARB's just change the ratio between elastic and geometric weight transfer. The next method is the short method where the equations use the lateral acceleration, track, mass, and centre of gravity height. Then there is also using the MOTEC tyre loads which finds the

difference in force from one side then divides it by two. To compare the different setups the roll stiffness was also calculated. This is convenient as this gives a solid value to compare the different setup changes.

If we first look at the standard setup, we can compare the effectiveness of the predictive equations before any analysis is done.

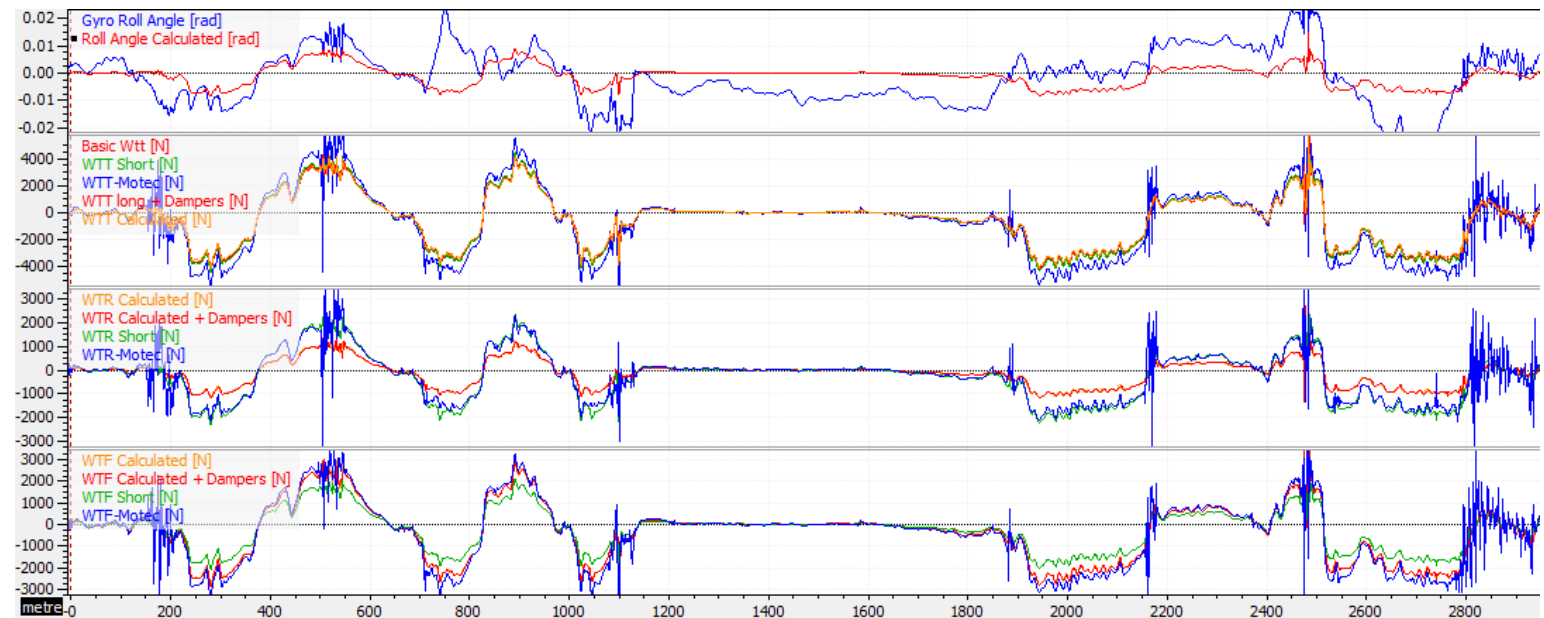


Figure 11 Comparison of the different Weight transfers

On the actual channels there is a little bit more noise than the others but this is expected as the equations do not take everything into account so there is something that the sim is modelling that the equations do not take into account. One thing the prediction equation do not consider are the tyres. The tyres change over the lap with variations in temperature and therefore pressure. The prediction equations also do not model tyre deformation which could make a quite a large difference. What is interesting is that the shorthand method of calculating weight transfer is the closest to the real value, especially on the rear. This could be down to calculation errors with the lengthier methods of calculation. Intriguingly the weight transfer is much closer at slow speed corners than at high speed corners.

One variable that is very different is the roll angle. This could be down to the tyre deformation, but it could also be down to the chassis. These equations assume that the chassis is infinitely rigid. In real circumstances the chassis flexes and twists so this may cause a difference (Time Attack, 2014). As the roll angle is wrong this may give another reason why there is a big difference between the weight transfers as well as some methods of calculating weight transfer uses the roll angle as its basis. So, to investigate the author

changed the equations to use the gyro roll angle instead of the calculated to see if the values get any closer.

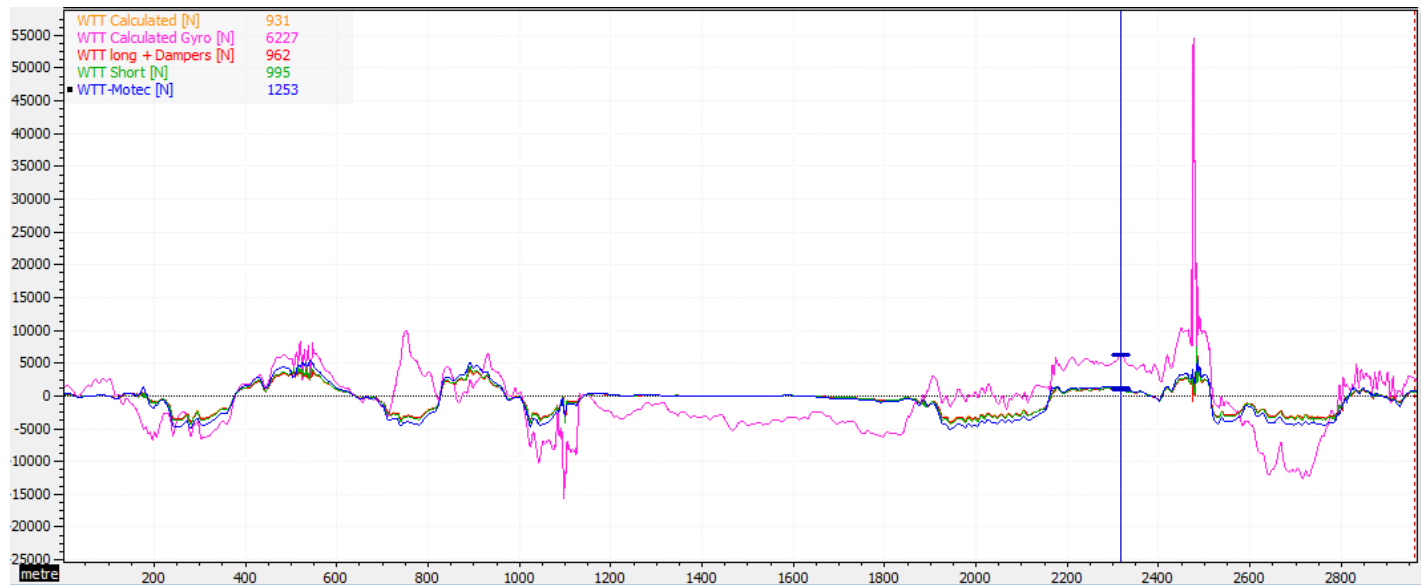


Figure 12-Comparison of adding the Gyro Roll Angle to the Weight Transfer Equations

However, doing this did not improve the weight transfer and made it much worse. This is interesting as this suggests that the gyro roll angle is incorrect and the calculated is actually much closer to real life.

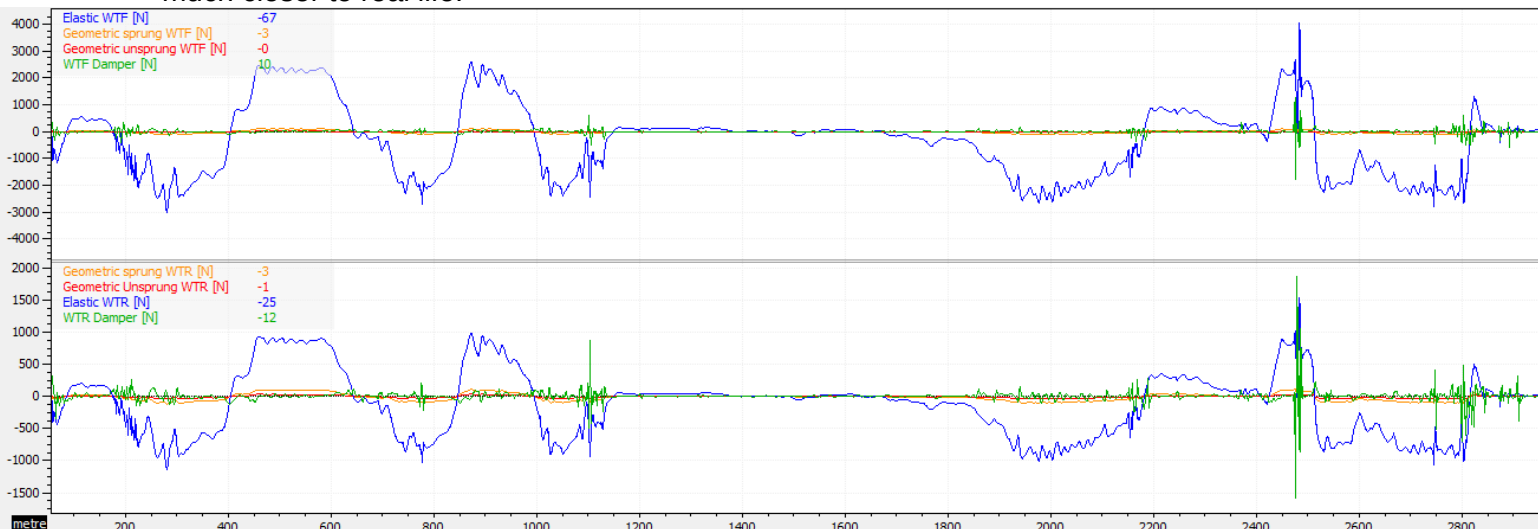


Figure 13-Comparing Different Types of Weight Transfer

If we look at the different weight transfer, we can see that elastic has the most effect on overall weight transfer and geometric unsprung has the least. This is expected as the unsprung parts of the car are the wheels, breaks and some of the suspension, so they are relatively light compared to the rest so do not have a huge effect. To add to that the elastic has the most, as all the weight from the sprung parts must go through the springs and suspension parts hence why elastic has such an effect. Because unsprung geometric has such little effect on total weight transfer and it is not something that can be changed so it will be left out of this analysis.

4.1.1 ARB's

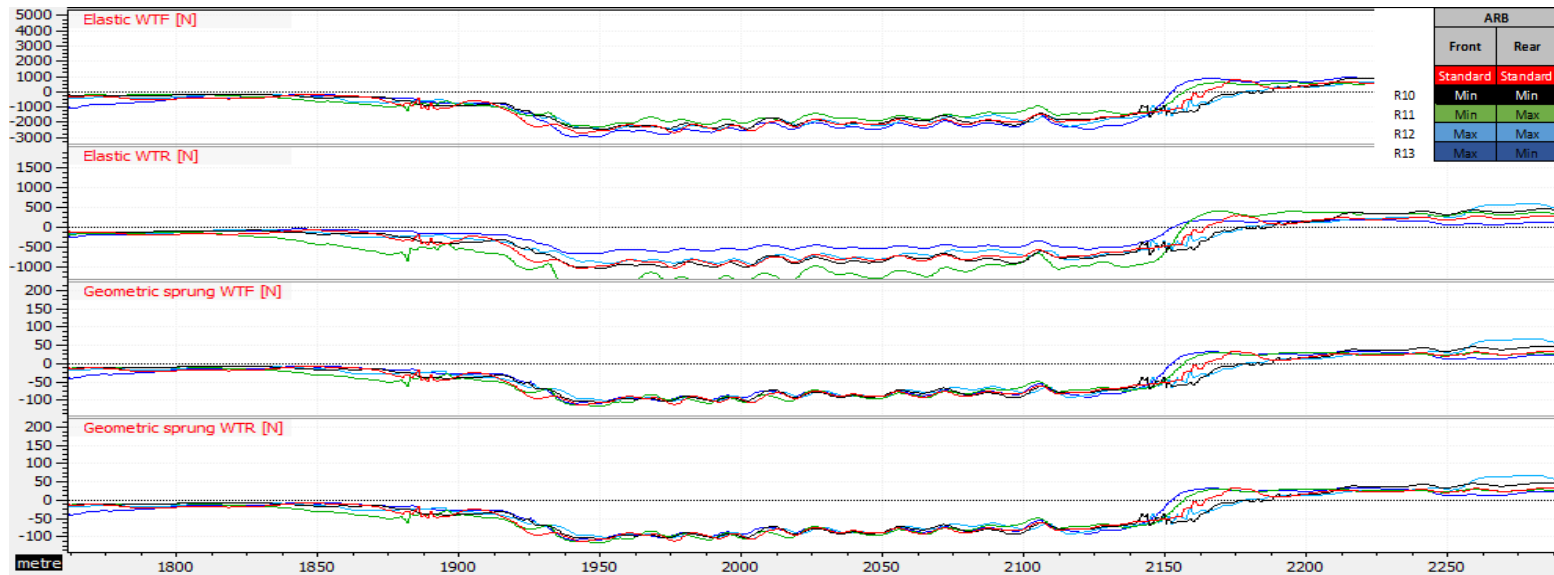


Figure 14-Different Weight Transfer Around Stowe Corner

If we look at Stowe corner, we can compare how the ARB's effect the weight transfer. There is a small difference at corner entry and a much larger difference at the exit of the corner. Looking at the individual axles can also give us an indication of what is happening at each end as well. This shows that when the ARB is on its softest setting the more elastic weight transfer is occurring. This is expected as when the ARB's are softer it does not transfer the weight to the inside wheel as much.

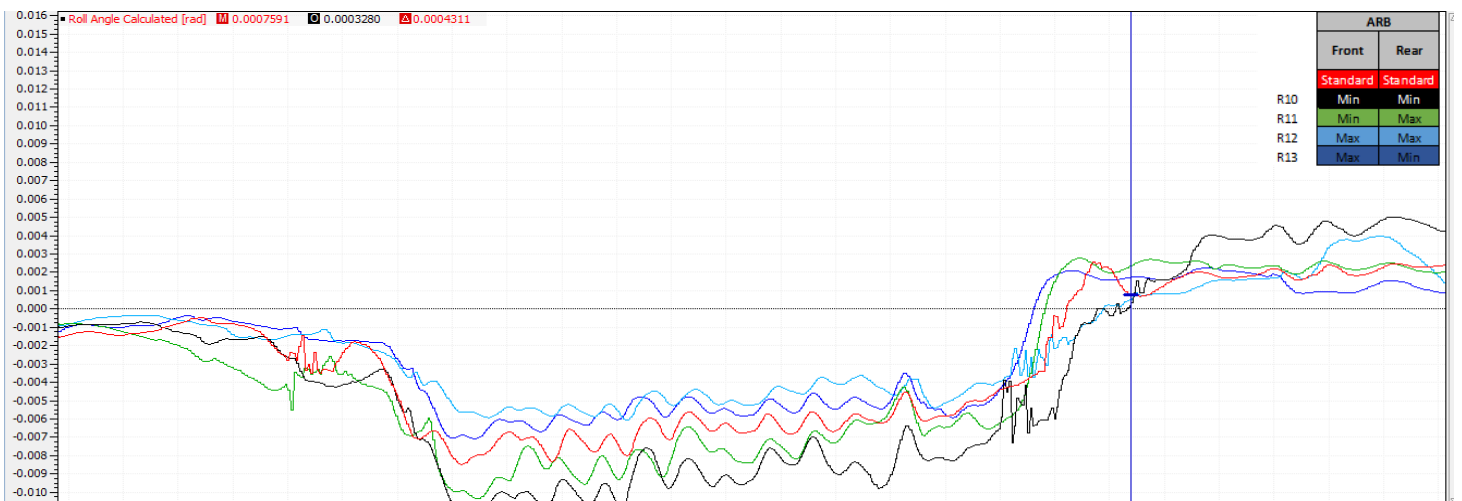


Figure 15-Roll Angle Around Stow When Changing ARB Setting

This shows it has a clear effect on it the roll angle of the vehicle. When the ARB's are at there minimum setting the greater the car rolls. This is entirely expected, as the name implies, they prevent the car from rolling, so the stiffer the ARB the less roll there is.

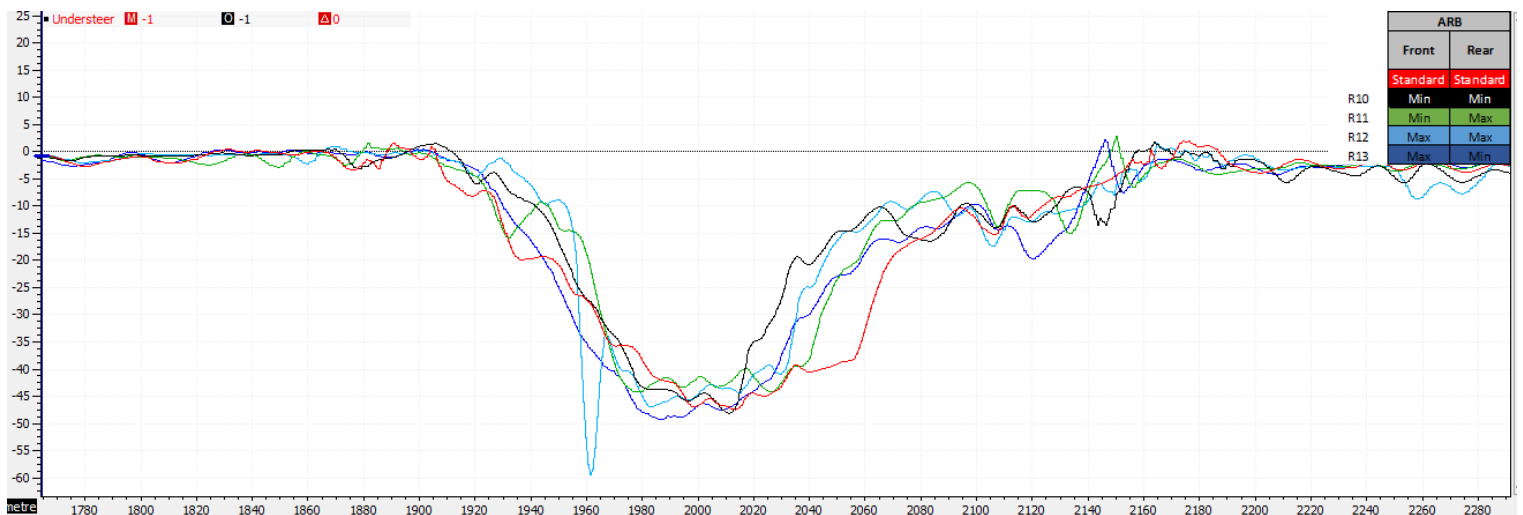


Figure 17-Understeer around Stowe corner Changing ARB Setting

What this graph shows is how much the car understeers. As the value goes more negative the more the car is understeering. In general, the stiffer the ARB the less understeer the car is creating. But what else is expected is that when the front is stiffer than the rear the more understeer occurs. This is because there is more weight transfer occurring at the front which means that there is less of a load on the front and therefore understeers (Gomez & Starkey, 2006).

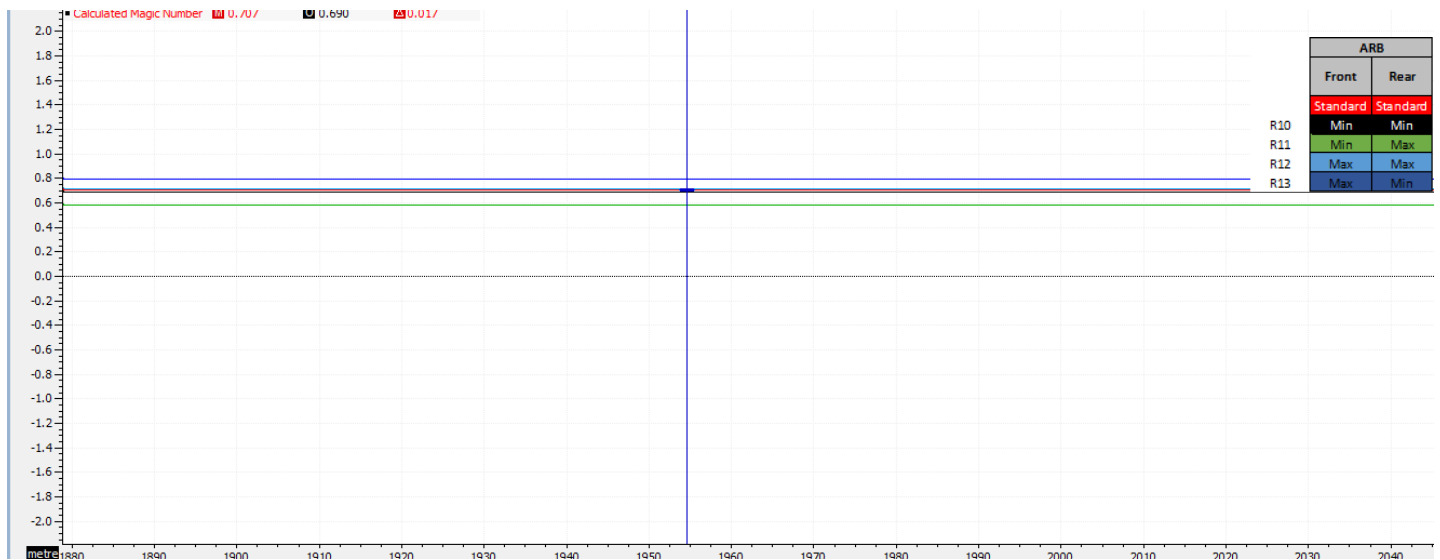


Figure 16-Weight Transfer Distribution, ARB Settings

If we look at the weight transfer distribution or “magic number”, we can see how the ARB’s effect that. What can be seen when there is a large difference between values on each end the greater the magic number. This is expected as one end has more weight transfer than the other. The dark blue line is the highest as this is where the front is stiffest. This makes sense as there is more weight transfer occurring at the front than the rear so as a percentage of how close it is to the front it is going to be higher.

Now if we look at a slower corner such as Village, we can compare the effects in a slower turn.

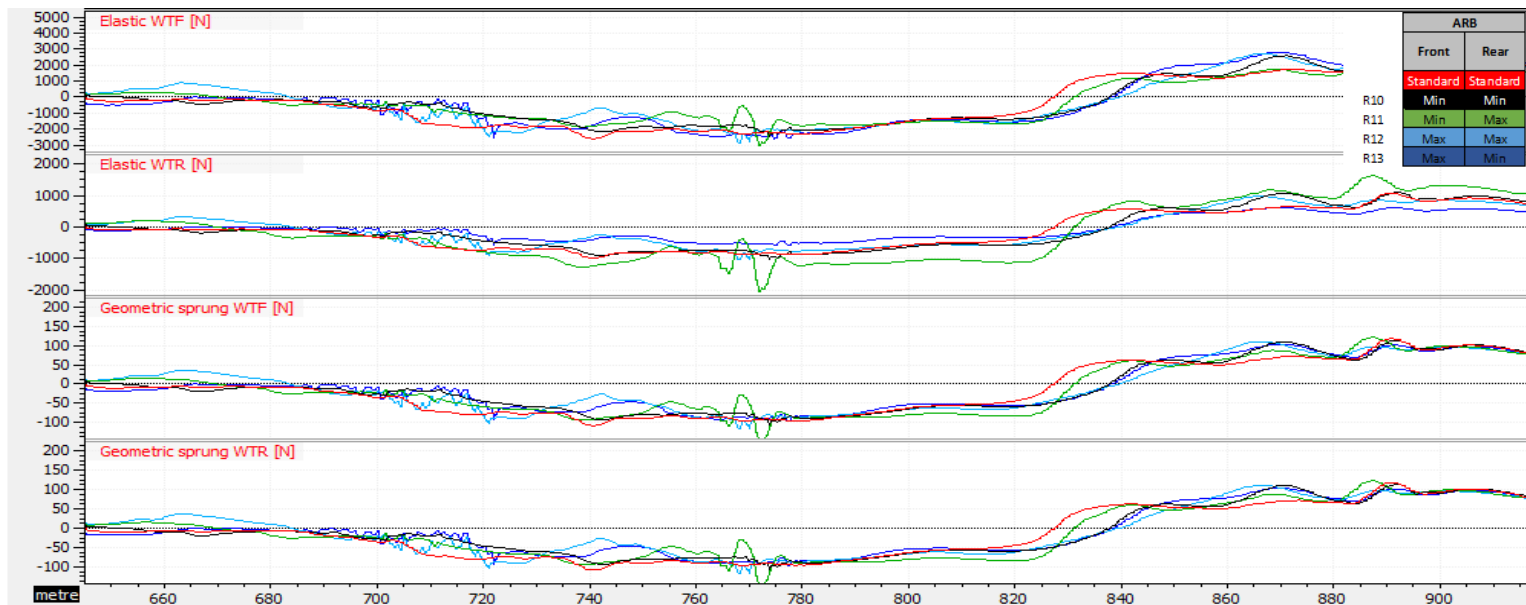


Figure 18-Different Weight Transfer around Village Changing Weight Transfer

There is actually greater weight transfer and a greater roll angle in village than in Stowe.

This is interesting as there is a greater lateral G force at Stowe. This maybe due to that village is a much smaller corner than Stowe so it has not got time for the suspension to level out as much, so the dampers have not had enough time to fully settle perhaps. What else is interesting is that the least weight transfer is occurring on the standard on exit and the most on entry which is in contrast to the rest. Other than this the rest of the weight transfer follows the same pattern as Stowe corner.

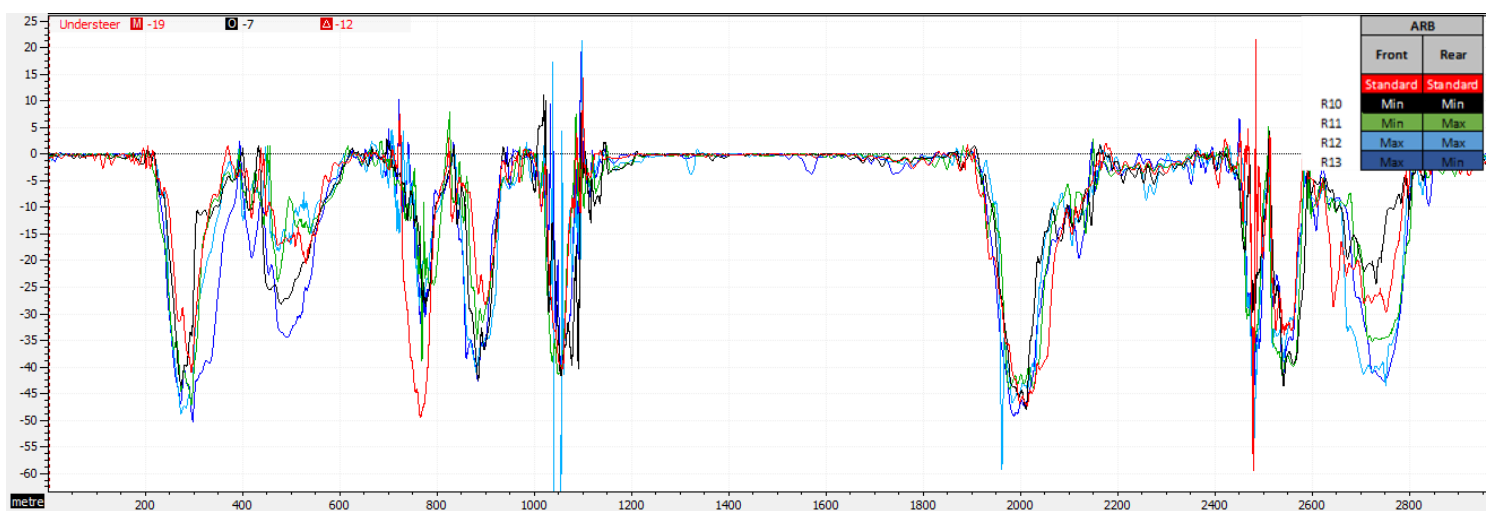
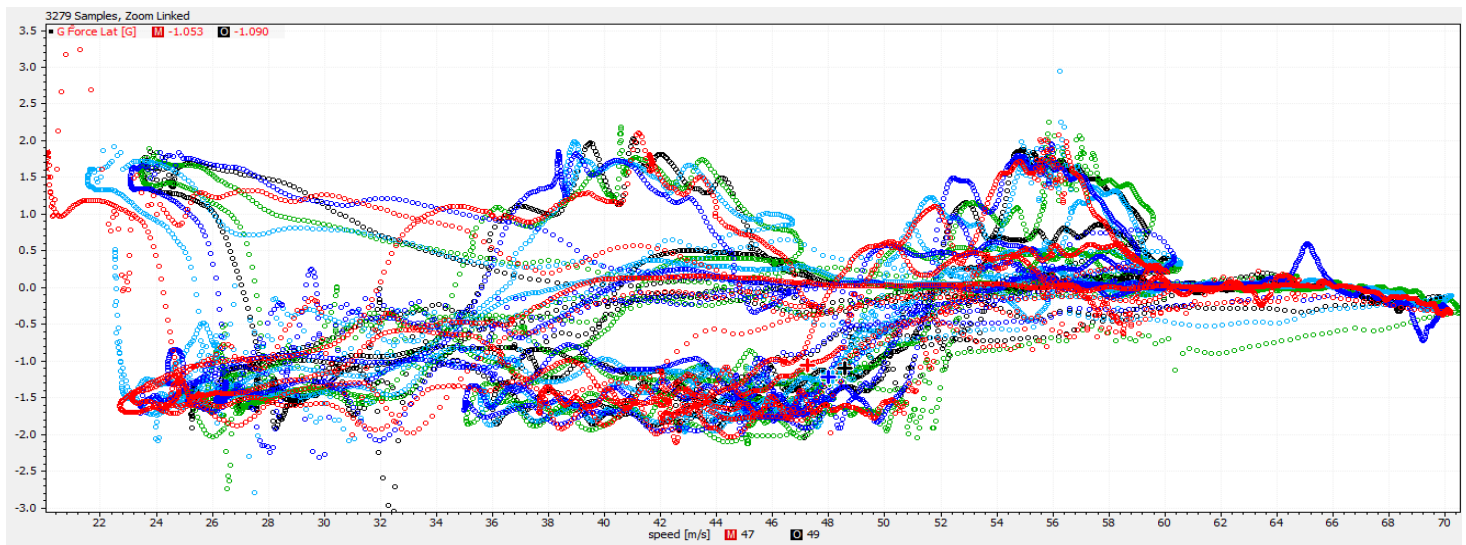


Figure 19-Understeer Around Village, ARB Settings

What else is interesting is that the car in general understeer less in village than Stowe. This is because it is a slower corner and therefore there is less of a side force on the tyre so they are able to grip better.



This shows the lateral G Force against speed. As it shows there is no coloration between the two as the g force is affected by the steering angle as well as speed.

4.1.2 Springs

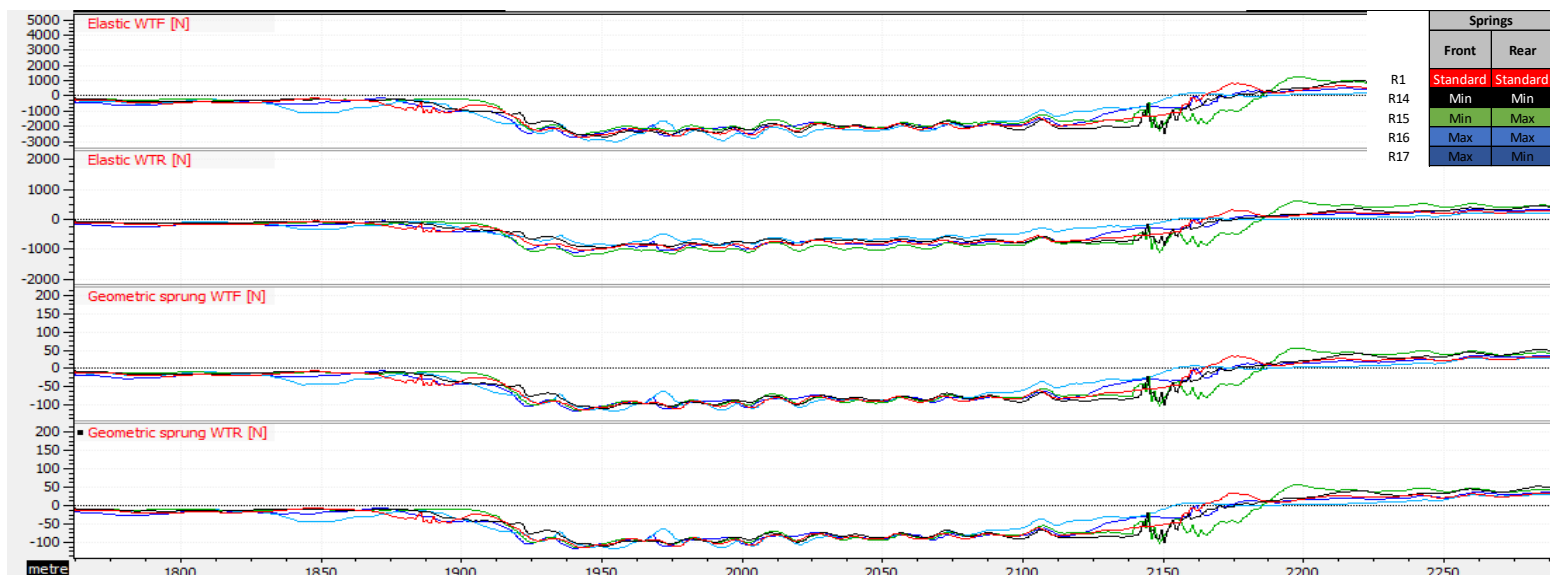


Figure 20-Different Weight Transfer around Stowe, Spring Settings

When the springs are hardest is when the least elastic weight transfer is occurring. However, this is when the most geometric weight transfer is occurring. This is still a very small change; it is only on corner exit where the car is going back to its neutral position where we see a big difference. This makes sense as the harder springs can push back more.

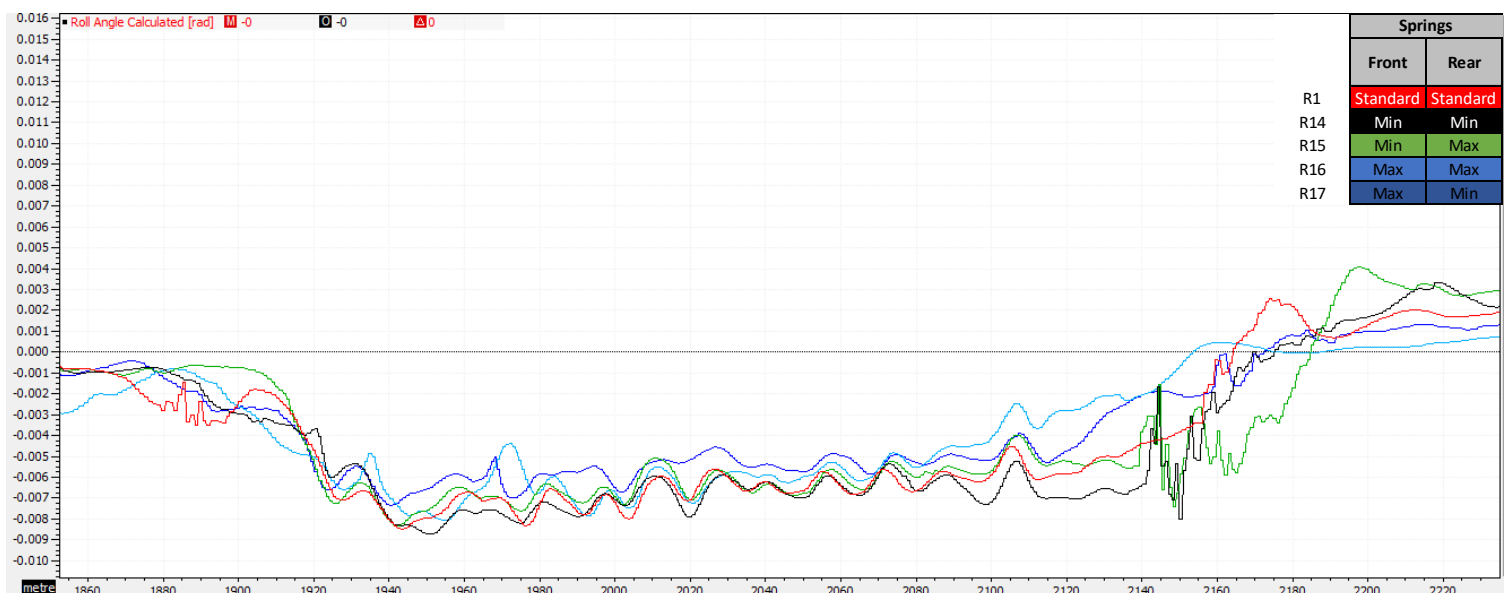


Figure 21-Roll Angle around Stowe, Spring Settings

This shows what is expected with the roll angle that the softer the springs, the more roll there is. This is because the springs are not able to put as much of a reaction force against the roll of the body. But this also follows the trend of the corner exit is different from corner entry. These may be down to if the spring is stiffer it will be more reluctant to roll and will then go back to neutral quicker than if the springs were softer.

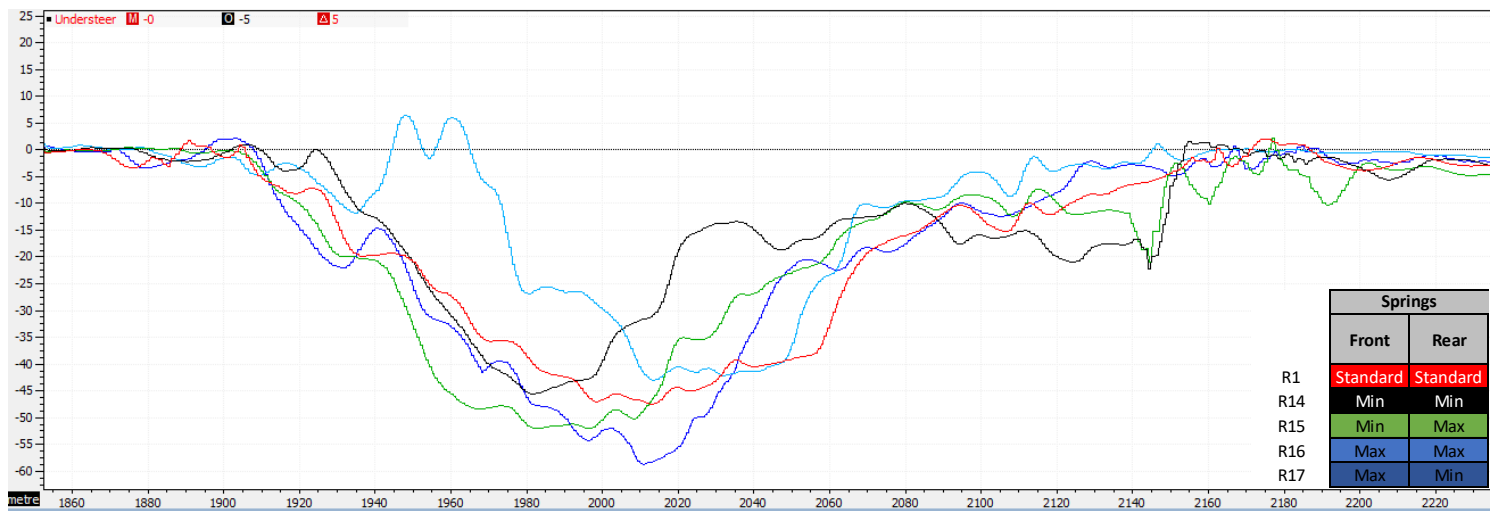


Figure 22-Understeer around Stowe, Spring Settings

As expected when the front is stiffer than the rear the car understeers more. This is because it causes a different weight transfer between the two axle which then means that there is a different slip angle. This will mean that the tyres grip less on the front so it will understeer more. However, there is error in the data (light blue line) as the driver took an odd line through the corner, so it is hard to compare that run with the rest. So, if this test were to be done again the author would do multiple runs with the same setup to get an average to make sure the data was more accurate.



Figure 23-Weight Transfer Distribution, Spring Settings

This follows suite with the ARB when the front is stiffer and the rear is softer, the distribution is further forward. What is interesting though is when both ends are the same, they are the highest values. This is down to that the rest of the settings are at standard and the car is set up to have a distribution closer to the front of the car which is potentially used to balance out

the aerodynamics, as the rear aerodynamics are stronger than the front as mentioned earlier.

4.2 Dampers

The use of a damper is to control the suspension to optimising the grip by keeping the contact patch load consistent (Hatton, 2018). They also have the job of controlling the weight transfer. These are used often as they are quick and easy ways to change variables at the track rather than taking springs out and changing the shape of the suspension. It does this by varying the size of hole oil gets pushed through and how much the shims flex (Clemens, n.d.). Dampers only work when they are moving so on corner entry, exit, acceleration, and deceleration. In theory they should not be having that much affect when at steady state.

The initial calculations previously analysed (Thomas, 2019) did not include any dampers. This meant that there was a huge gap in the values which may have been to the lack of dampers included into the equations. The author predicts that there will still be a difference as the equations still do not consider other factors like tyre deflection. If we concentrate on slow bump and rebound as this has the most effect on how the car pitches and rolls therefore on the weight transfer.

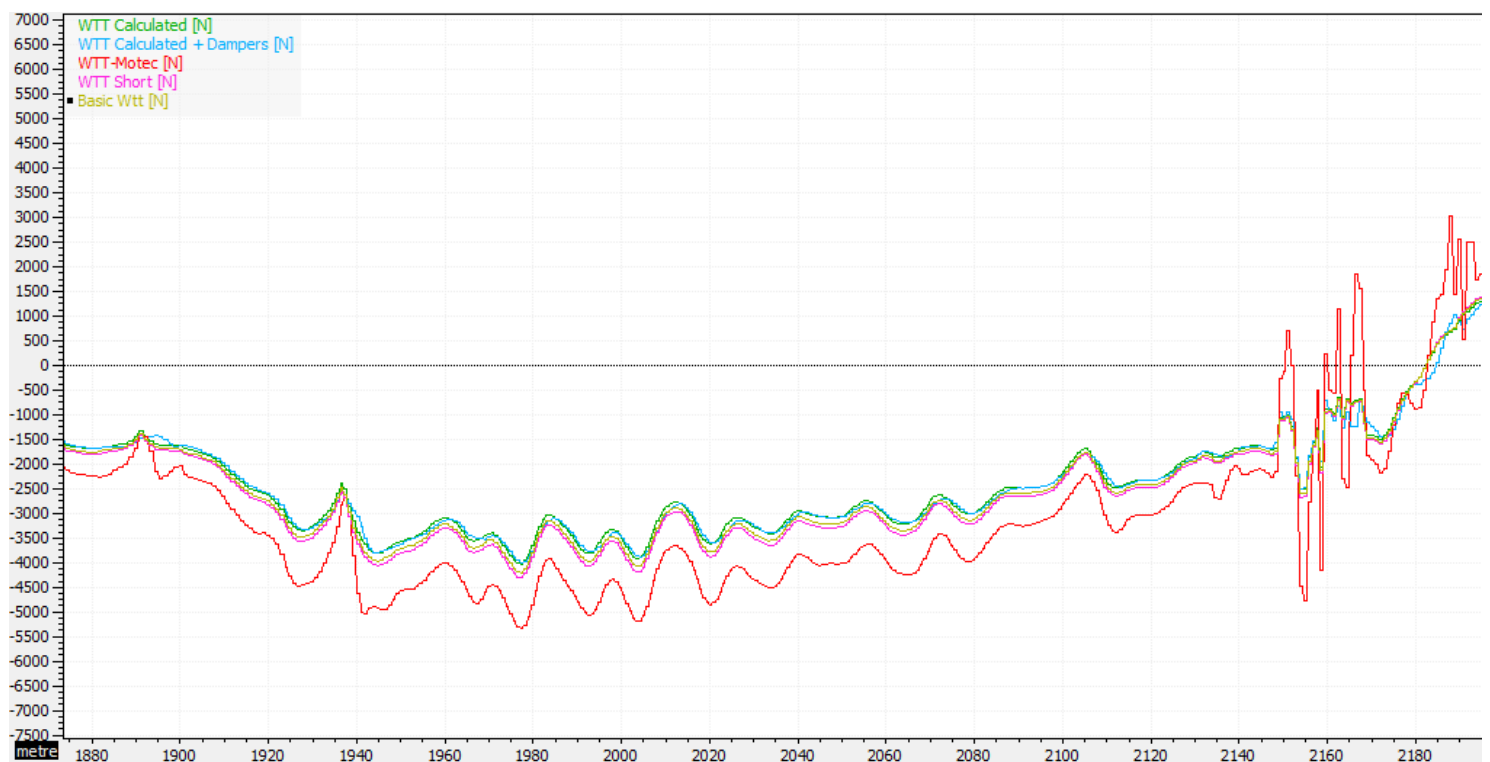


Figure 24-Comparison adding Dampers to Weight Transfer Predictions

The adding the dampers made a slight difference to the weight transfer but there is still a large difference. However, the shorter methods are still closer. This is again down to errors in calculations and the equations still not taking tyres into account. But with the shorter methods you cannot get the individual type of weight transfer to see how they affect things.

4.2.1 Bump

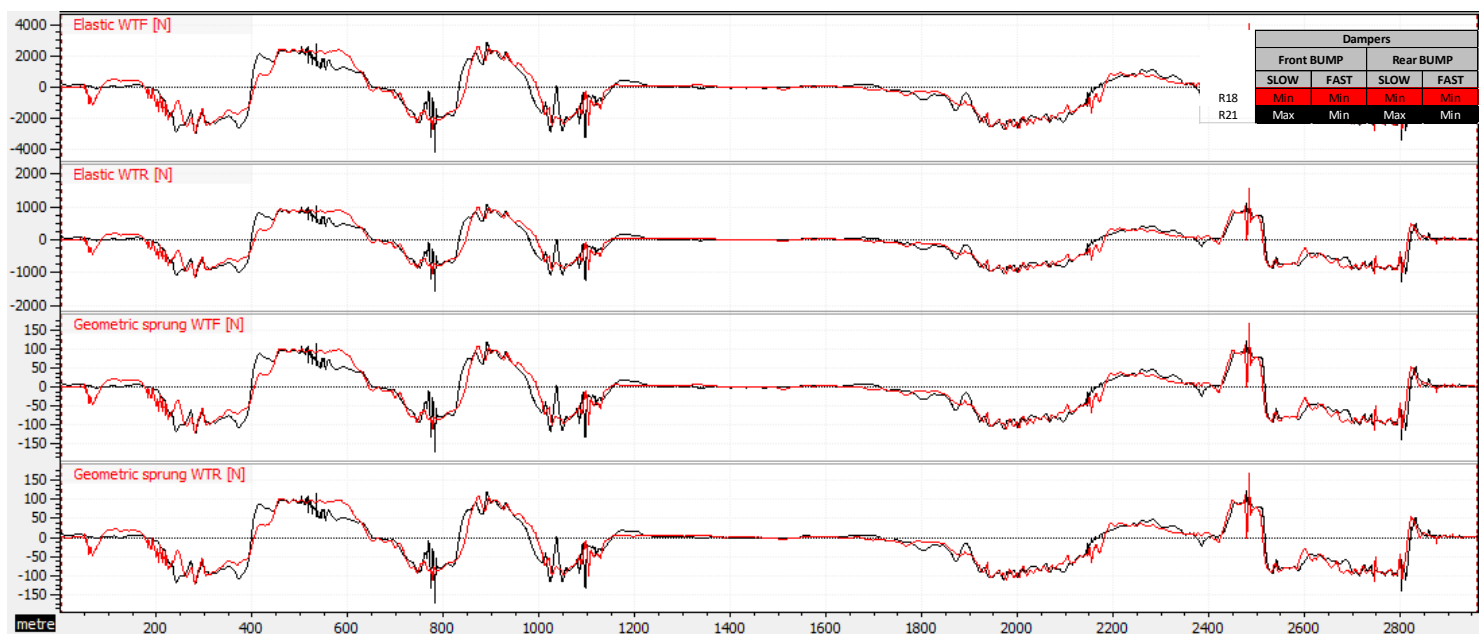


Figure 25-Different Weight transfers, Bump Changes

In theory the higher the bump or compression the more resistance it will have to the car rolling and therefore weight transfer. But as can be seen there is negligible difference on the elastic and geometric sprung weight transfer. What it will have a bigger difference on will be the damper weight transfer.

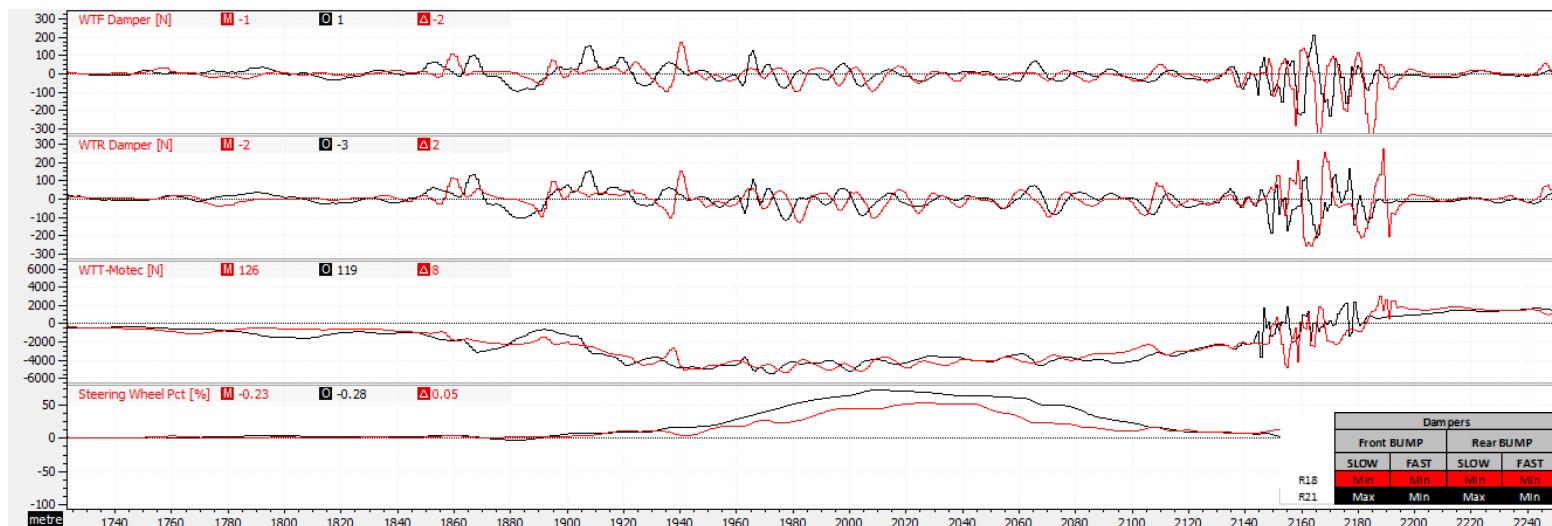


Figure 26-Total Weight Transfer around Stowe, Bump Changes

What can be seen is that there is not much of a difference on corner entry or at the apex but there is a larger effect on corner exit. At the exit when the slow bump is at its maximum there is less damping and elastic weight transfer.

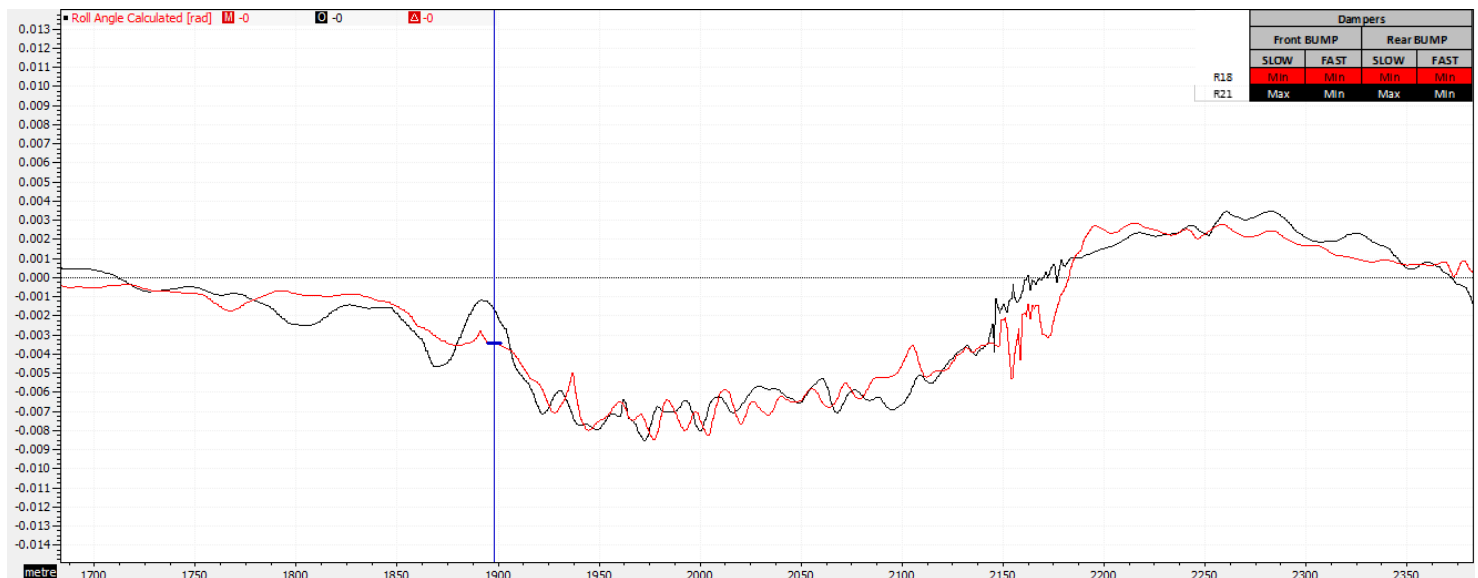


Figure 28-Roll Angle around Stowe, Bump Changes

This shows that again that bump mainly affect the exit of the corner in this case but still has a small effect on entry. Without repeating the test, it is hard to tell if these results are accurate as it may just be driver inconsistency that changes the results. The author would expect that there would be a delay on the roll angle but still have the same roll angle as the damper just slows the roll rather than change it.

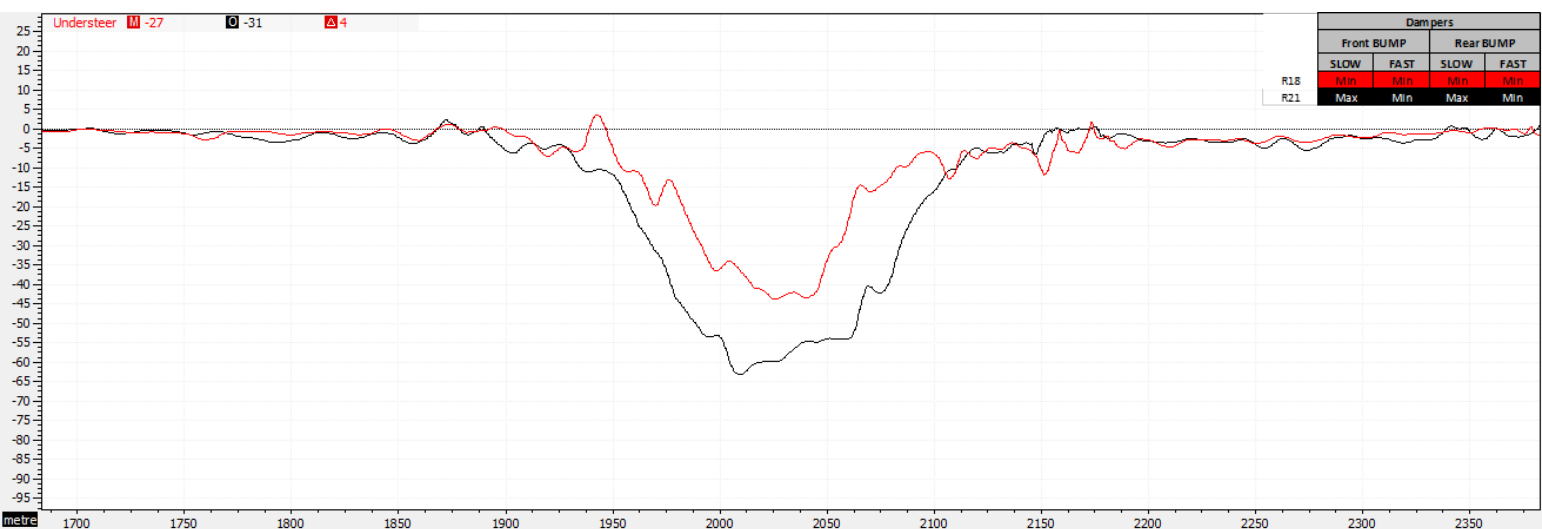


Figure 27-Understeer around Stowe, Bump Changes

This graph shows that there is a large difference in the amount the car is understeering through the corner with the stiffer setup causing more understeer. Particularly on the apex of the corner. This follows up on what the author stated previously in the last section that there is inconsistency with the driver. As Stowe is large corner the author believes that the car would reach steady state therefore the dampers should not be affecting the car when at the apex. However, this graph is suggesting that it is creating a lot more understeer where the author would expect it to be very similar.

4.2.2 Rebound

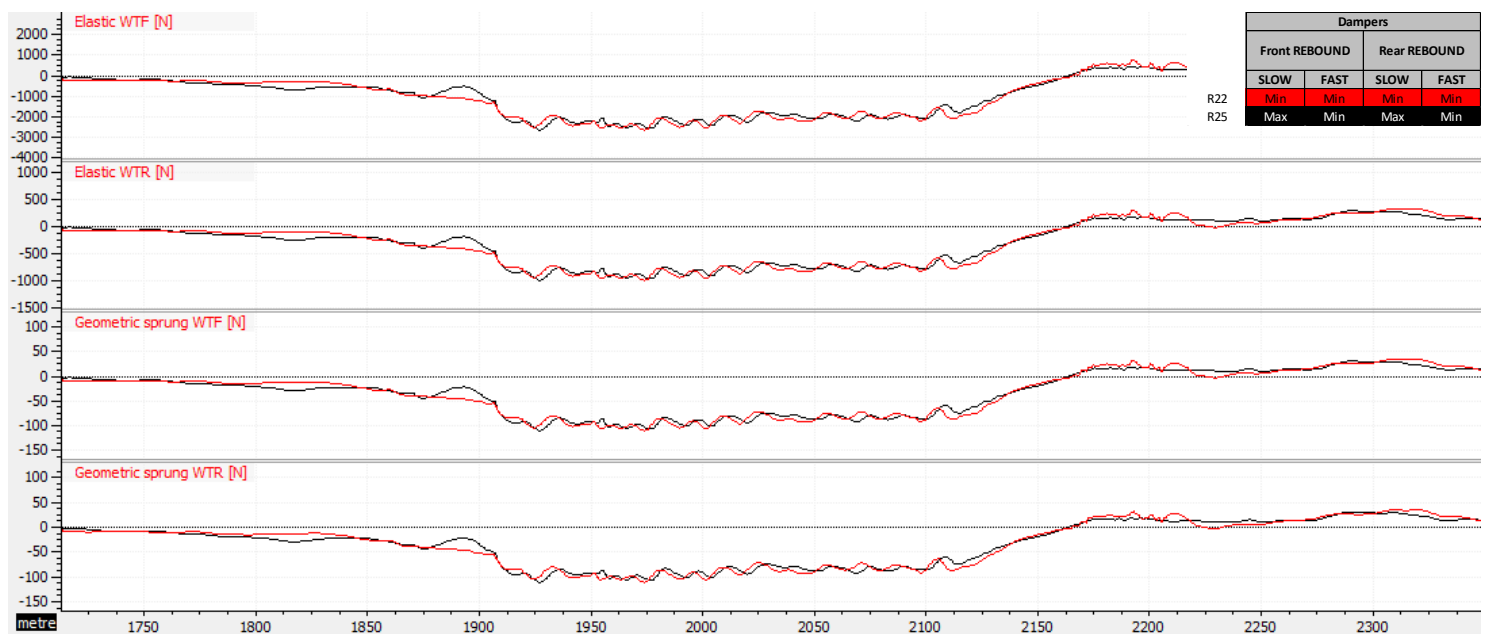


Figure 29-Different Weight Transfers around Stowe, Rebound Changes

This shows that the damper does not have much of an effect on the elastic and geometric weight transfer. Perhaps when the rebound is at its maximum then the weight transfer would settle better on exit but without more data the author cannot assume this is fact or just a coincidence.

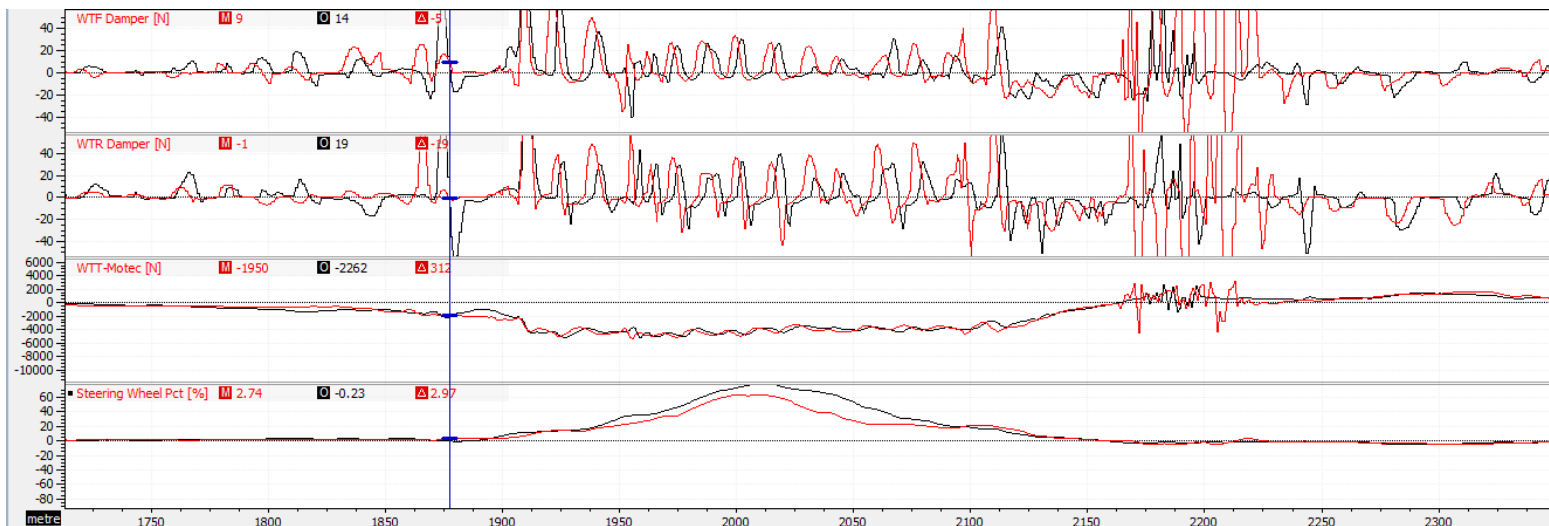


Figure 30- Total Weight Transfer around Stowe, Rebound Changes

Similar to bump there is not much difference in corner entry but on the apex and more so on the exit the maximum rebound is smaller than minimum. To add to that on exit the weight transfer oscillates on maximum damping. This is because the damper is damping more so stops the suspension from oscillating as much.

5 Conclusion

In conclusion the author found that the simulator struggles to model rake angle changes which may stem from it not being able to model near wall aerodynamics. However, the aerodynamic load is still an important tool in changing the handling of the car through adapting the centre of pressure and the efficiency of the vehicle.

I also found the ARB and springs have a very large effect on how much the ratio between elastic and geometric weight transfer is affected. The author is not able to make certain conclusions on how much the dampers effect weight transfer without getting repeats of data but predict that it has only a small effect on elastic weight transfer but a large one on damper weight transfer. But there are signs that it does have effect on corner entry and exit. The author also concludes that the overall weight transfer does not change but just changes between the different types. The author also found that adding dampers to the prediction equations gets the results closer to real life but there is still a big difference as the tyres are not included within the equations.

This investigation is informative, but the limitations of the simulator does have an effect on the results. To add to that more data would need to be gained to make a fully informed judgement on how the dampers effect weight transfer and the rake effects aerodynamics.

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7 Appendices

7.1 Aerodynamics Equations

$$\text{Aero Load} = (\text{Tyre Load} - \text{Static Load}) \pm \text{Longitudinal Weight Transfer}$$

$$CL_z = \frac{\text{Aero Load}}{\frac{1}{2} \times \rho \times V^2 \times A}$$

$$C_{op} = \frac{\text{Aero Load Front}}{\text{Total Aero Load}} \times 100$$

$$\text{Drag Force} = C_d \times 0.5 \rho V^2 \times A$$

$$C_d = \frac{\left(\frac{2(ma_1 - ma_2)}{\rho V_m^2} \right)}{A}$$

- ρ = Air Density (1.223Kg/m³)
- V = Velocity
- A = Frontal Area
- C_d = Coefficient of drag
- C_l = Coefficient of Lift
- Z denotes a variable which can be front, rear, or total

$$\text{Dynamic Ride height} = \text{Static Ride height} - (\text{suspension position} - \text{intial position})$$

$$\text{Calculated Rake} = \tan^{-1} \left(\frac{\text{Mean Dynamic ride height rear} - \text{Mean Dynamic Ride Height Front}}{\text{Wheelbase}} \right)$$

$$\text{Efficiency} = \frac{\text{Aero Load Total}}{\text{Drag Force}}$$

7.2 Weight Transfer Equations

$$\text{Distance from front axle to CoG} = \frac{\frac{\text{Satic Mass Rear}}{\text{Static Mass Total}} \times \text{Wheelbase}}{1000}$$

Roll Axis Height At Cog

$$= \left(\frac{(\text{Static Roll centre height rear} - \text{static roll centre height front}) \times \text{Distance from roll axis to cog}(H)}{\text{Distance from front axle to Cog}} \right)$$

+ Static roll centre hegiht front

$$K_w = (K_s \times MR^2) + K_{warb}$$

- K_w = Wheel Rate (Nm⁻¹)
- K_s = Spring Constant

- MR=Motion Ratio
- K_{warb} =ARB Rate

$$\theta = \frac{M_s \times a_y \times \text{CoG height}}{\left(\frac{T_f^2 K_{wf}}{2} + \frac{T_r^2 K_{wr}}{2}\right)}$$

- Θ =Roll Angle (rad)
- M_s =Sprung Mass (Kg)
- A_y =Lateral Acceleration (ms^{-2})
- T=Track (m)

$$WT_s = \frac{K_w T \theta}{2}$$

- WT_s =Elastic Weight Transfer

$$WT_{sRC} = \frac{M_s \times a_y \times h}{T}$$

- WT_{sRC} =Sprung Geometric Weight Transfer
- h=roll centre height (m)

$$WT_{us} = \frac{M_{us} \times a_y \times r}{T}$$

- WT_{us} =Unsprung Geometric Weight Transfer
- r=Wheel Rolling Radius

$$\text{Damper Force} = \text{Damper Velocity} \times \text{Damper Coefficient}$$

$$WT_d = \frac{Fd_L - Fd_R}{2}$$

$$WT_z = WT_{sz} + WT_{sRCz} + WT_{usz} + WT_{dz}$$

- WT_z =Weight transfer on axle

$$WT_T = WT_f + WT_R$$

$$WT_T = \frac{M_T \times a_y \times \text{CoG Height}}{T_{\text{Average}}}$$

- WT_T =Weight Transfer Total

$$\text{Weight Transfer Distribution} = \frac{WT_f}{WT_T}$$

$$\text{Understeer} = \text{abs(Theoretical Steer \%)} - \text{abs(Actual Steer \%)}$$

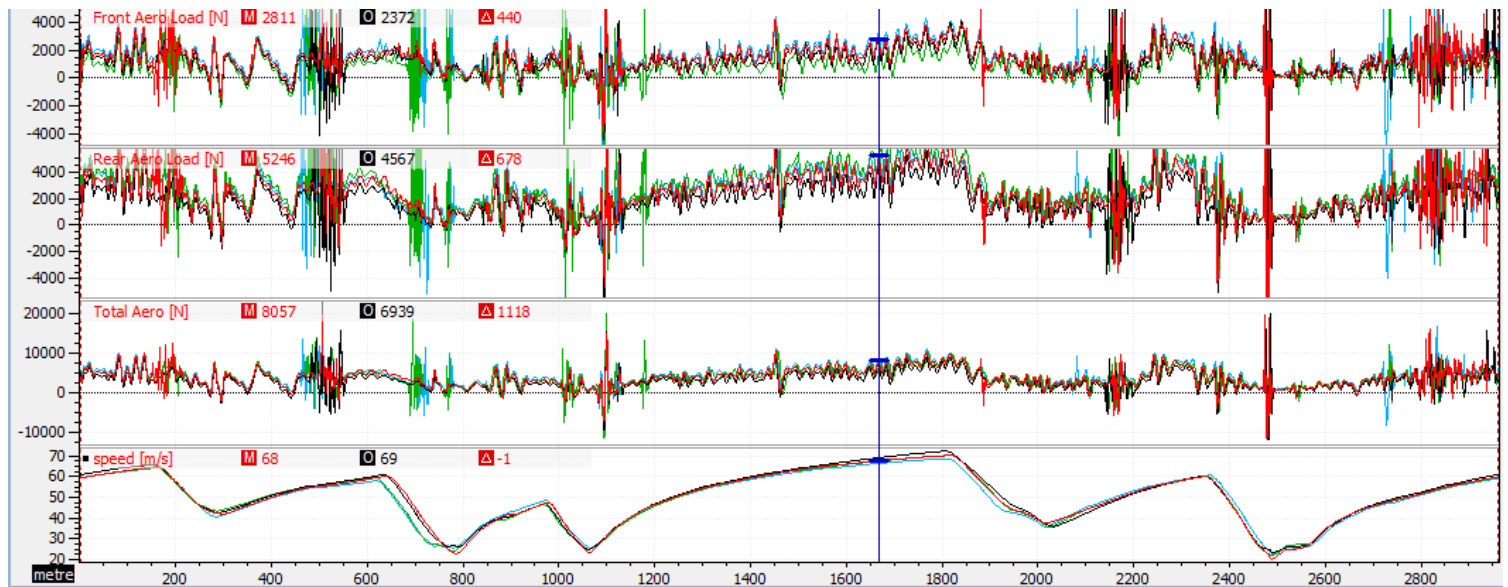


Figure 31-Unfiltered Lift Vs Speed, Wing Changes