University of Wales Trinity Saint David

School of Engineering

Vehicle Testing and Analysis
Advanced Vehicle Dynamics

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Introduction

The aim of this assignment is to investigate the behaviour of a car around a lap. Changes to the aerodynamics, anti-roll bars, springs and dampers will be made to investigate their impact on the car's performance around a lap. MoTeC will be used to manipulate the data. These investigations will be conducted using the universities simulator running base performance simulator (BPS) software. The car being used for these investigations is the Aston Martin DBR9 GT1 car.

Methodology

Team Roles

For the test there was a team of 6 people all of whom had individual jobs.

- Driver – Drive the car and try to complete consistent laps to make the data as comparable as possible.
- Setup Changer – Load the car in and out of the simulator and alter the setup for each run.
- Setup Caller / Test Organiser – Tell the setup changer what the next setting is to streamline the process and reduce time wasted. The setup caller also lead the creation of the test plan as they would be most familiar with the setups needed.
- Setup Photographer – Take photos of each setup to ensure the correct values were used for each run.
- Data Organiser – Name all of the data files to ensure each run file is the correct settings. Also place each run file on a separate hard drive to be distributed to the group.
- Data Feed Supervisor – Ensure all of the data has recorded correctly.

By assigning roles before the test was started the group was able to enter the simulator room and start the test immediately. As everyone kept the same jobs through the tests it kept consistency in the results and eliminated any confusion with people changing jobs halfway through. A student was chosen to drive the car in case any further runs needed to be completed after the allocated 2 hours, as this could be done when the group is available and there would be no need to work around a lecturer's schedule.

The driver was chosen to decide if a lap was acceptable or needed to be repeated. When the lap was complete and the driver was happy he would pause the simulator so the setup changer to exit, change the setup and the data organiser could check the data was recorded.

Coast down

To conduct the coast down test a track with a long straight was required. On BPS there is a 'test track' which contains a straight long enough to conduct a straight line test and also has no gradient change. This keeps the results consistent.

To conduct this test the splitter and wing settings are selected, and the car is then loaded onto the track. The driver drives to the start line of the straight and stops. When instructed the driver accelerates to 4th gear and hits the limiter for a few seconds before putting the car into neutral and releasing the throttle. The car is then kept in a straight line and allowed to coast, so there are no user inputs apart from steering to keep the car straight until car comes to a complete stop. Once the car is stopped it is left for 10 seconds to make sure everything has returned to its static position. The car is then removed from the track and the test can be repeated with different settings.

This test was conducted in accordance with the ISO standard for coastdown tests. (International Organization for Standardization, 2006).

Steady State

To conduct the steady state test a track with a constant radius corner was needed. Again the 'test track' was used. The greatest radius was used, and the driver tried to keep the speed to a minimum. This data can be used to calculate the Ackerman steering angle.

Dynamic Track Testing

Track

Figure 1 - Map of Silverstone

(Anon., 2017)

For the dynamic testing Silverstone international layout was chosen by the group. It was chosen for a few main reasons. One reason was a lap can be completed in just over a minute, this allowed multiple setups to be tested in the allocated 2 hours. This also allows a second lap to be completed if the first lap was not up to the standard needed to retrieve data from. Another reason is there is a mix of high and low speed corners to see how the cars behaviour changes with different corner types. There is also a chicane so the cars response to a quick change of direction can be observed. Finally, there is a long straight, therefore the change in drag can be seen by altering the wing and splitter settings.

When looking at the data 3 main areas will be looked at. Hanger Straight, Abbey and Vale. Hanger straight is the longest straight on the track so this will be used to see how wing and splitter setting affect the top speed and braking points of the car. It will also be used to see the effects of changing the rake and ride height of the vehicle.

Abbey is a high speed corner and will be used to see the cars behaviour with high speed cornering. Vale is a slow speed chicane so the cars behaviour at low speed cornering and its behaviour when changing direction can be seen.

Equation

Longitudinal Weight Transfer (N)

$$WT = \frac{\frac{Total\ static\ weight}{9.81} * CoG * (Gforce\ Long * 9.81)}{Wheelbase}$$

Equation 1 - Longitudinal Weight Transfer

Coefficient of Lift (Ratio)

$$ClA\ front = Tyre\ Load\ FL + Tyre\ Load\ FR - Static\ Weight\ FL + Static\ Weight\ FR + WT$$

Equation 2 - Coefficient of Lift front/rear

This can be repeated for ClA rear using the rear tyres and subtracting the weight transfer

$$ClA = ClA\ front + ClA\ Rear\ (0.5 * Air\ Density * Velocity2)$$

Equation 3 - Coefficient of Lift

Where Air Density is 1.223, $kg/m3$

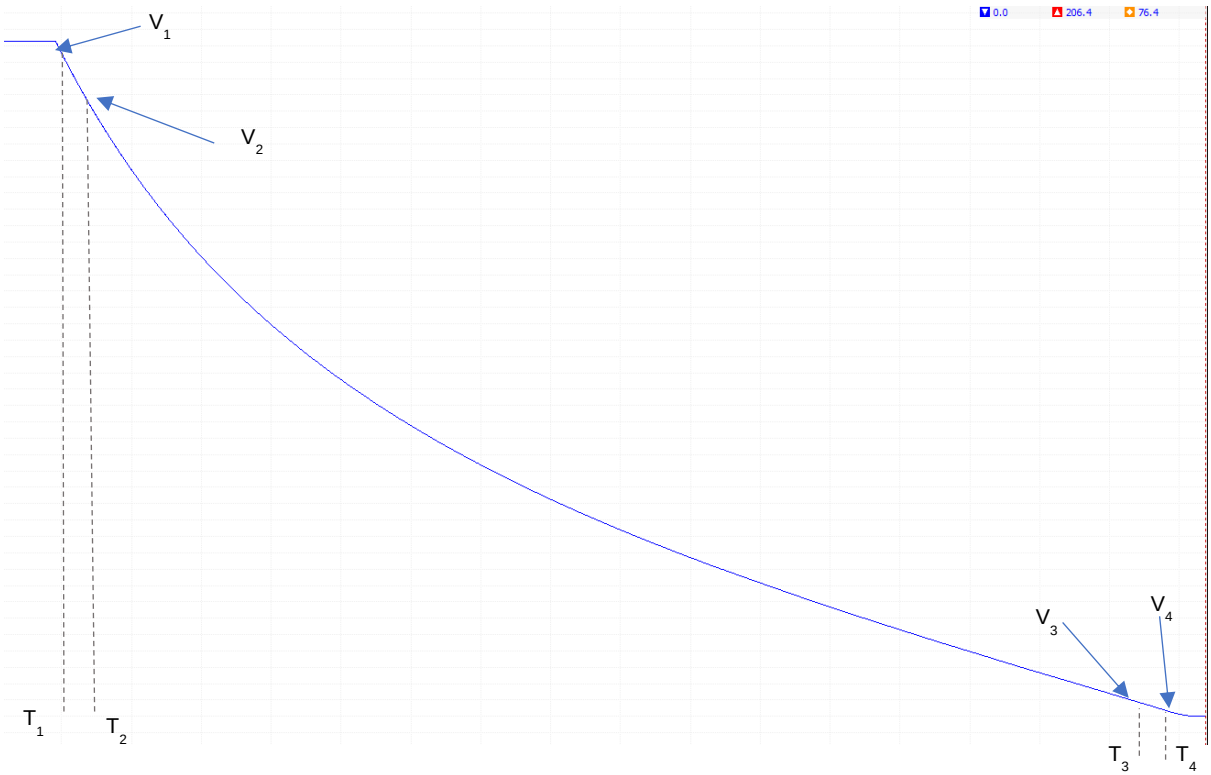


Figure 2 - Graph to show how v and t are obtained for drag equation

Figure 1 Shows how the values for velocity and time were obtained from MoTeC. The time between t1-t2 and t3-t4 were exactly 1 second. V1 was taken 1 second after the car is placed in neutral.

Coefficient of Drag (Ratio)

$$Rolling\ Resistance = \left(\frac{v4 - v3}{t4 - t3}\right) * Total\ mass$$

Equation 4 - Rolling Resistance

$$Aerodynamic\ Resistance = \left(\frac{v2 - v1}{t2 - t1}\right) * Total\ mass$$

Equation 5 - Aerodynamic Resistance

$$CdA = \frac{2(Aero\ Resistance - Rolling\ Resistance)}{Air\ Density * \left(\frac{v1 + v2}{2}\right)^2}$$

Equation 6 - Coefficient of Drag

Efficiency (Ratio)

$$Aerodynamic\ Efficiency = \frac{Lift}{Drag}$$

Equation 7 - Aerodynamic Efficiency

Roll Angle

$$Roll\ Axis\ Height\ (m) = (Static\ Roll\ Centre\ Height * CoG) + \frac{Roll\ Centre\ Height\ Front}{Wheelbase}$$

Equation 8 - Roll Axis Height

$$H = CoG - Roll\ Axis\ Height$$

Equation 9 - Difference Between CoG and Roll axis height

$$Overturning\ Moment\ (Nm) = Total\ Sprung\ Mass * (Gforce\ Lat * 9.81) * H$$

Equation 10 - Overturning Moment

$$Roll\ Angle\ (°) = \frac{Overturning\ Moment}{Roll\ Stiffness}$$

Equation 11 - Roll Angle

Calculated Weight Transfer

$$Elastic\ Weight\ Transfer\ (Front)(N) = \frac{Wheel\ Rate\ Front * Roll\ Angle * Track}{2}$$

Equation 12 - Elastic Weight Transfer (front/rear)

$$Sprung\ Weight\ Transfer\ (Front)\ (N) = \frac{Front\ Sprung\ Mass * (Gforce\ Lat * 9.81) * Roll\ Centre\ Height\ Front}{Track}$$

Equation 13 - Sprung Weight Transfer (Front/Rear)

$$Unsprung\ Weight\ Transfer\ (Front)\ (N) = \frac{Front\ Unsprung\ Mass * (Gforce\ Lat * 9.81) * \frac{Front\ Rolling\ Radius}{2}}{Track}$$

Equation 14 - Unsprung Weight Transfer (Front / Rear)

$$Calculated\ Weight\ Transfer\ Front\ (N) = (Elastic\ Weight\ Transfer\ Front + Sprung\ Weight\ Transfer\ Front + Unsprung\ Weight\ Transfer\ Front)$$

Equation 15 - Calculated Weight Transfer (Front / Rear)

$$Calculated\ Weight\ Transfer\ (N) = Calculated\ Weight\ Transfer\ Front + Calculated\ Weight\ Transfer\ Rear$$

Equation 16 - Calculated Weight Transfer

Actual Weight Transfer

$$Actual\ Weight\ Transfer\ Front\ (N) = \left(\frac{Tyre\ Load\ Front\ Left + Tyre\ Load\ Front\ Right}{2}\right) * -1$$

Equation 17 - Actual Weight Transfer (Front / Rear)

$$Actual\ Weight\ Transfer = Actual\ Weight\ Transfer\ Front + Actual\ Weight\ Transfer\ Rear$$

Equation 18 - Actual Weight Transfer

Basic Weight Transfer

$$Basic\ Weight\ Transfer = \frac{Total\ Mass * (Gforce\ Lat * 9.81) * CoG}{Track}$$

Equation 19 - Basic Weight Transfer

Magic Number

$$Calculated\ Magic\ Number\ (Ratio) = \frac{Calculated\ Weight\ Transfer\ Front}{Calculated\ Weight\ Transfer}$$

Equation 20 - Calculated Magic Number

$$Actual\ Magic\ Number\ (Ratio) = \frac{Actual\ Weight\ Transfer\ Front}{Actual\ Weight\ Transfer}$$

Equation 21 - Actual Magic Number

Roll Stiffness Distribution

$$Roll\ Stiffness\ Distribution\ (Ratio) = \frac{Roll\ Stiffness\ Front}{Total\ Roll\ Stiffness}$$

Equation 22 - Roll Stiffness Distribution

Corner Radius

$$Corner\ Radius\ (m) = \frac{Speed^2}{Gforce\ Lat * 9.81}$$

Equation 23 - Corner Radius

Theoretical Wheel Steer

$$Theoretical\ Wheel\ Steer\ (°) = \left(\frac{Wheelbase}{Corner\ Radius}\right) * 57.3$$

Equation 24 - Theoretical Wheel Steer

Ackerman Steering Angle

$$Ackerman\ Steering\ Angle = \frac{Theoretical\ Steer\ \%}{Theoretical\ Wheel\ Steer}$$

Equation 25 - Ackerman Steering Angle

This is known as the ‘x’ value and is calculated at low speeds where the car is in a state of neutral steer. ‘The steering and side-slip angles which occur when a vehicle is driven slowly around a constant radius turn’ (Ellis, 1994)

Theoretical Steer %

$$Theoretical\ Steer\ \% = Theoretical\ Wheel\ Steer * Ackerman\ Steering\ Angle$$

Equation 26 - Theoretical Steer %

Understeer

$$Understeer = absoulte(Steering\ Wheel\ Pct) - absoulte(Theoretical\ Steer\ \%)$$

Equation 27 – Understeer

Damper Coefficient

```
((('Damper Velocity FL (m/s)' [m/s] > 0) & ('Damper Velocity FL (m/s)' [m/s] <=90)) * 'Front Slow Bump' [N/m/s])+
((('Damper Velocity FL (m/s)' [m/s] > 0) & ('Damper Velocity FL (m/s)' [m/s] >90)) * 'Front Fast Bump' [N/m/s])+
((('Damper Velocity FL (m/s)' [m/s] < 0) & ('Damper Velocity FL (m/s)' [m/s] >=-90)) * 'Front Slow Rebound' [N/m/s])+
((('Damper Velocity FL (m/s)' [m/s] < 0) & ('Damper Velocity FL (m/s)' [m/s] <-90)) * 'Front Fast Rebound' [N/m/s])
```

Equation 28 - Damper Coefficient

Damper Force

$$Damper\ Force = Damper\ Velocity * Damper\ Coefficient$$

Equation 29 - Damper Force

Wing and Splitter Settings

The two adjustable aerodynamic devices on the Aston Martin DBR9 are the splitter and rear wing. It is assumed that the splitter length and rear wing angle are being changed. However, since this isn't confirmed they will be referred to the splitter and wing setting.

CD

Two coastdown tests were conducted, this allowed the coefficient of drag to be found. These tests were used to correlate against data gathered last year. Once it was found they correlated the data was used for the dynamic tests.

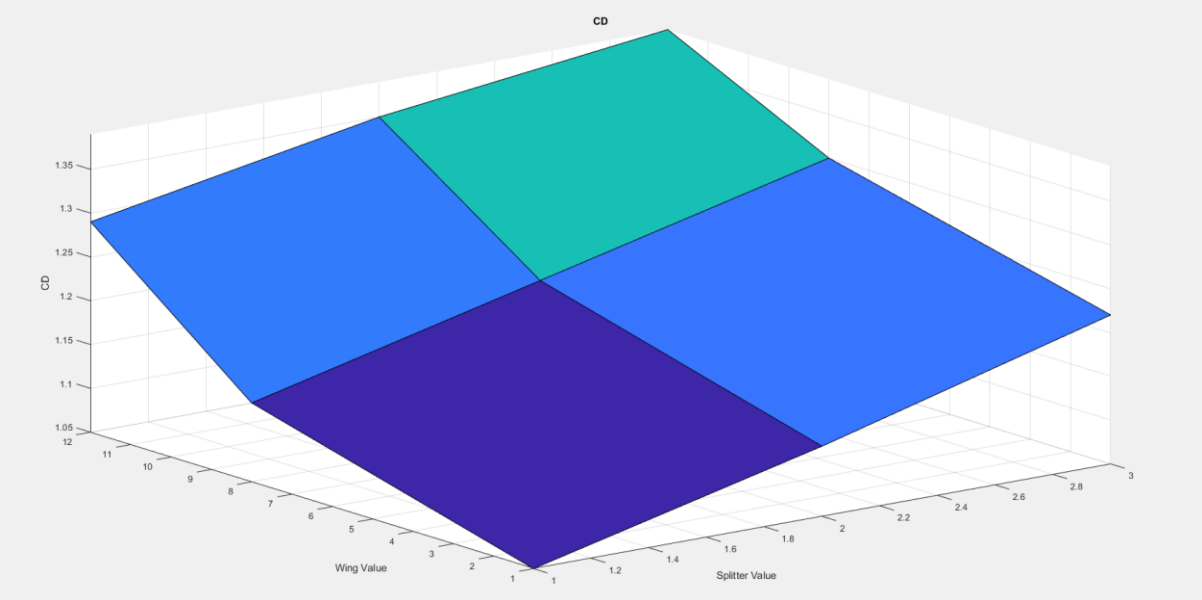


Figure 3 - CD for different aerodynamic settings

Figure 3 shows that as the value of the aerodynamic devices increase the coefficient of drag increases. This would be expected as the increase in wing or splitter value is simulating an increase in angle of attack or length, therefore there would be an increase in frontal area. Due to the drag force equation this increase in frontal area would result in an increase in drag. The graph was created by interpolating the results from last year, using MATLAB to predict the missing values.

Hanger Straight

When comparing the maximum and minimum wing and splitter settings the vmax of the car can be compared.

Table 1 - Vmax and Braking Points

Wing and Splitter Setting	Vmax (m/s)	Braking Point (m)
Min	72	1798
Max	69	1801

From table 1 it can be seen that the minimum settings give the car a greater top speed. This is because the frontal area of the car is reduced due to the angle of the wing and length of the splitter being reduced. When the splitter and wing setting are set to maximum the top speed of the car is reduced as the drag of the car is increased. Drag is proportional to velocity squared. However, this allows the driver to brake slightly later as the car is carrying less speed at the end of the straight.

When comparing the total lift forces acting on the car it wouldn't be guaranteed that the maximum wing and splitter settings would produce the greatest amount of downforce. This is because the flow could start to separate before the trailing edge. (Seetharam & Wentz, 1977). Separation occurs when the air on the underside of the wing doesn't have enough kinetic energy to stay attached due to an adverse pressure gradient. When it separates it causes a local area of low pressure to occur behind the wing, this causes an increase in drag.

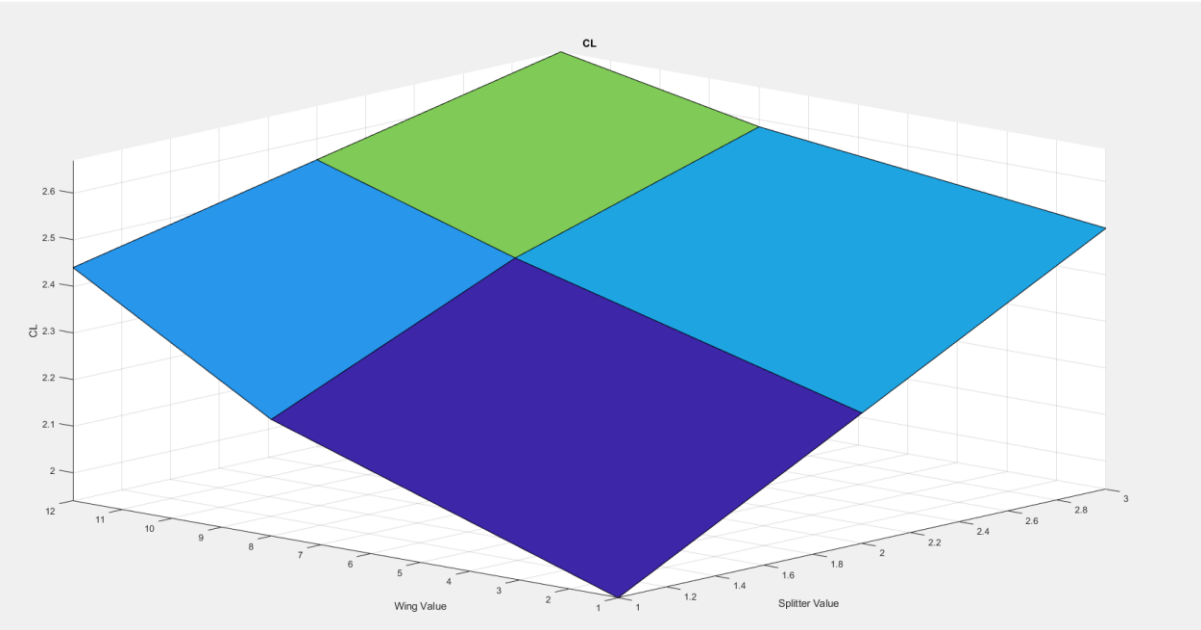


Figure 4 - CL for different aerodynamic settings

Figure 4 has been created by gathering 5 results and interpolating the data to get 9 different results to show a trend. From this graph it can be seen that as the wing and splitter values are increased there is an increase in cl and therefore an increase in downforce.

Abbey

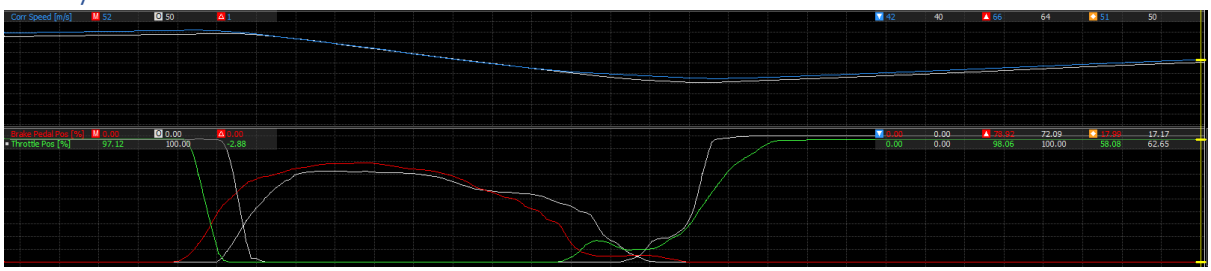


Figure 5 - Speed with throttle and brake position for Abbey

From the graph where minimum aero settings are in colour and maximum in white, it can be seen that when the aero devices are at maximum the driver has slightly less velocity at the braking zone, this means the driver can brake 10m later. At the apex of the corner the car is traveling at the same velocity. However, at the exit of the corner when the aero devices are at maximum the driver is able to reach 100% throttle quicker due to the car producing more downforce.

Table 2 - Lift Force

Wing and Splitter Setting	Lift Force (N)
Min	3323
Max	4451

As can be seen from table 2 with maximum aero settings the car is producing an extra 1128N on average throughout the corner. This should allow the driver to carry more speed through the corner as there is more lateral force acting on the car pushing it into the track. However, when looking at figure 7 the car is understeering more in the corner entry and at the mid corner. This would suggest that a change in the suspension settings would be required to utilise the additional downforce.

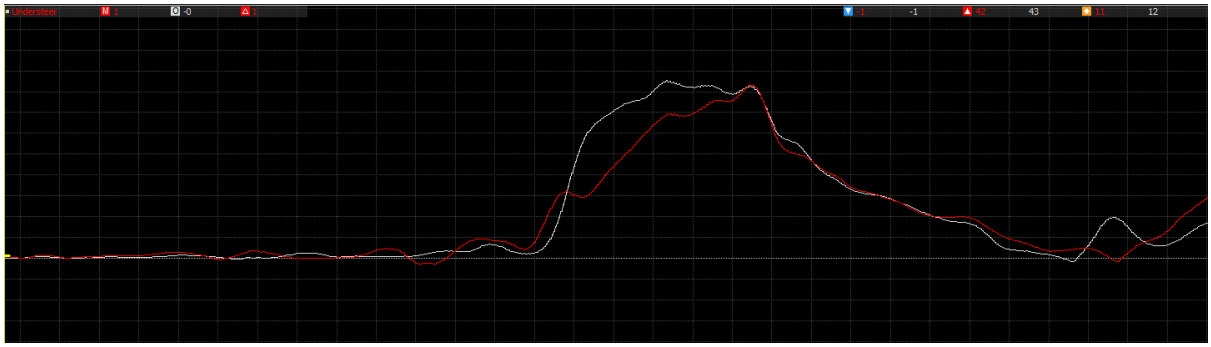


Figure 6 - Understeer through Abbey

Vale

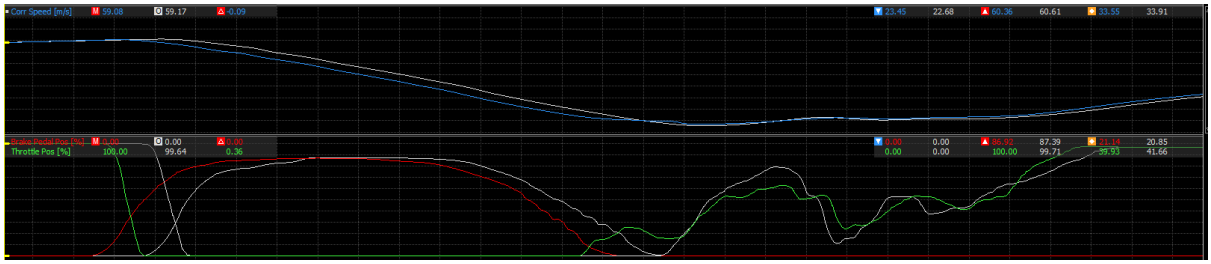


Figure 7 - Speed with throttle and brake position through Vale

From figure 8 it can be seen that approaching the braking zone both setups have the same velocity. With the maximum setting the driver brakes 10m later, this could be due to two reasons. The first being the driver is now more confident with the car and track combination, therefore he could have realised that you can brake later into the corner while still making the apex. Another reason could be due to the increased downforce. As there is more downforce acting on the car into the braking zone there is more lateral force acting on the tyres and thus more grip on the tyres. (Williams, 2016). The maximum setting carries more speed from the braking zone to the apex of the corner, towards the corner exit both setups are travelling at a similar velocity.

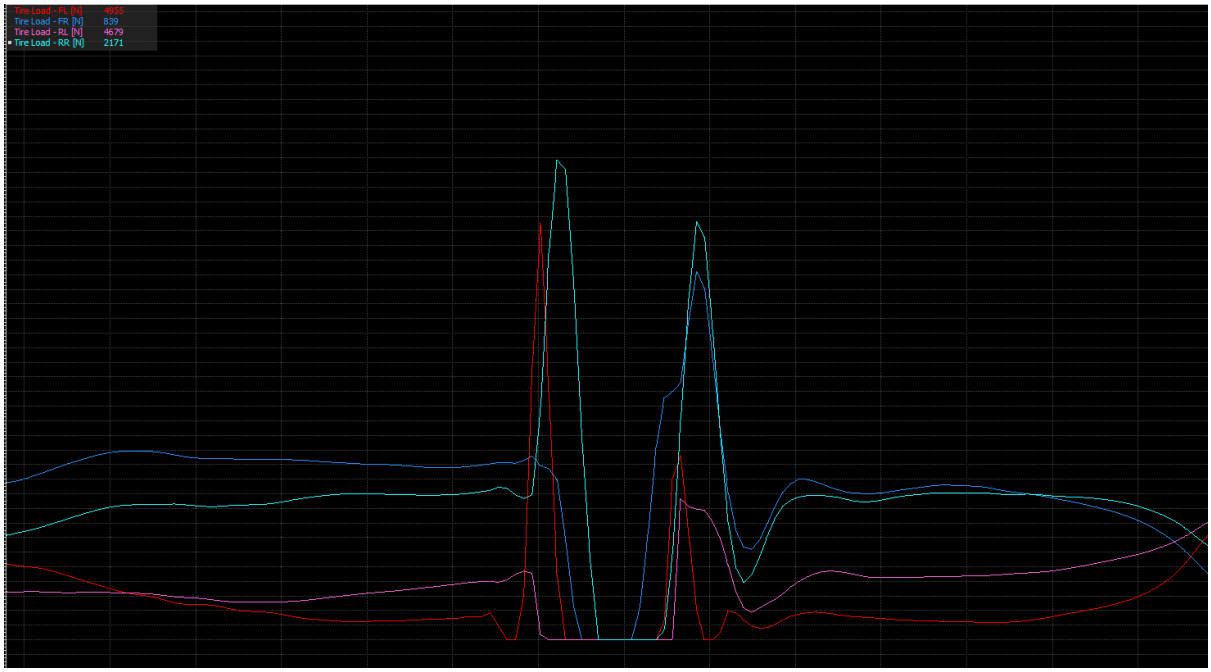


Figure 8 - Tyre loads showing the car lifting off the ground

From the tyre load channel, it can be seen that on the first apex there is a sharp rise in the tyre load, then there is no tyre load, followed by a sharp rise. This is when the driver hits the sausage curb launching the car into the air therefore unsettling the car mid corner. This could have compromised the corner exit speed.

Overall Lap

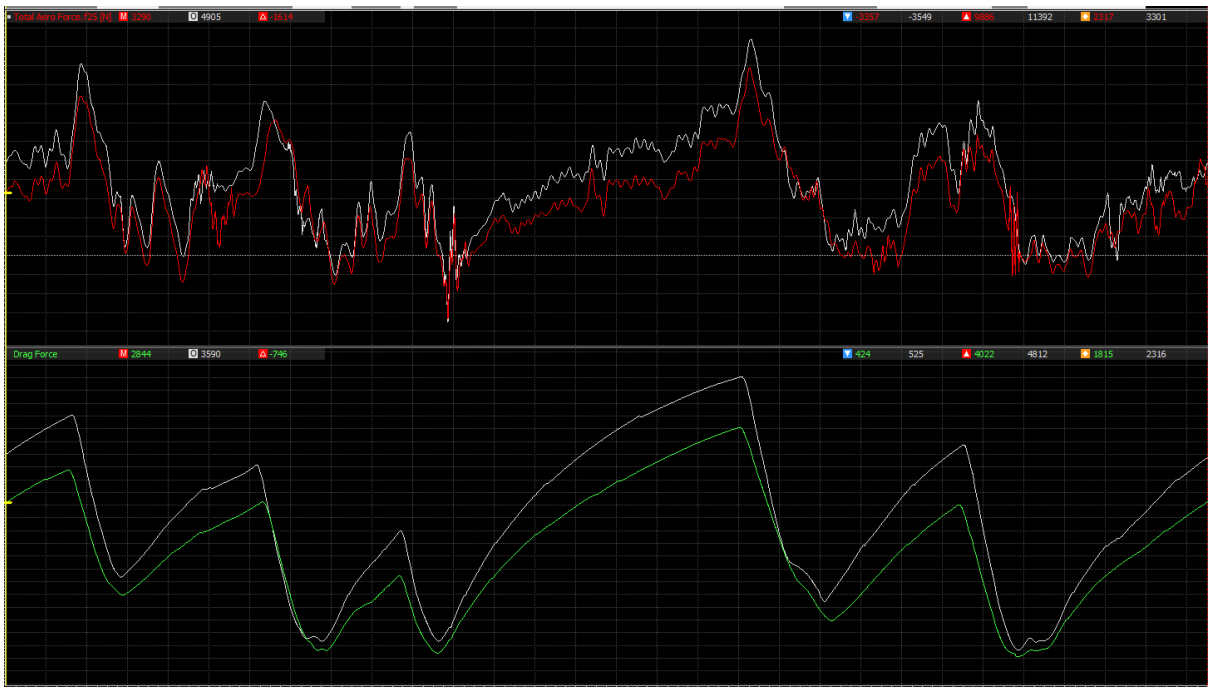


Figure 9 - Lift and Drag force over a lap

Figure 10 is comparing the downforce on the top and drag force on the bottom between the low and high downforce setups. Since the drag force is a predicted value as the velocity of the car increases

the drag force increases. When comparing the drag force at 59m/s there is an 882N difference, this is due to the high downforce setup having a greater CD.

It is clear that the high downforce setup produces a greater downforce and a greater drag force, this is expected. There are a few points where the drag of the low downforce setup is greater than the low downforce, or the downforce of the low setup is greater than the high setup. This is most likely due to the velocity not being great enough to have a major effect. For the downforce it could be due to the line around the corner being different, therefore the car could hit a bump or use a kerb resulting in different tyre loads and therefore different downforce values.

Figure 10 - Lift and Drag force down the straight

When just looking at the hanger straight it can be seen that as the velocity is increasing the drag is increasing at a near linear rate. The downforce does increase as the velocity increases; however, it does not increase at a linear rate and there is some oscillation with the data. This will be due to the lift force being calculated using tyre load values. Since the hanger straight is not flat and has bumps along the whole straight, this means the tyre loads fluctuate, as seen in figure 12 resulting in a downforce value that isn't smooth.

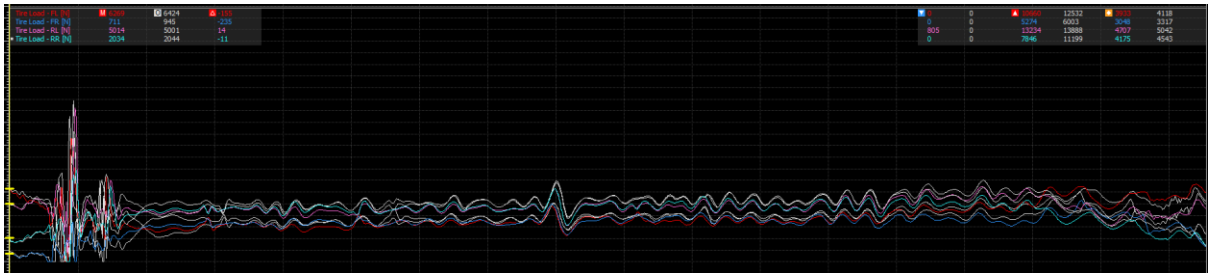
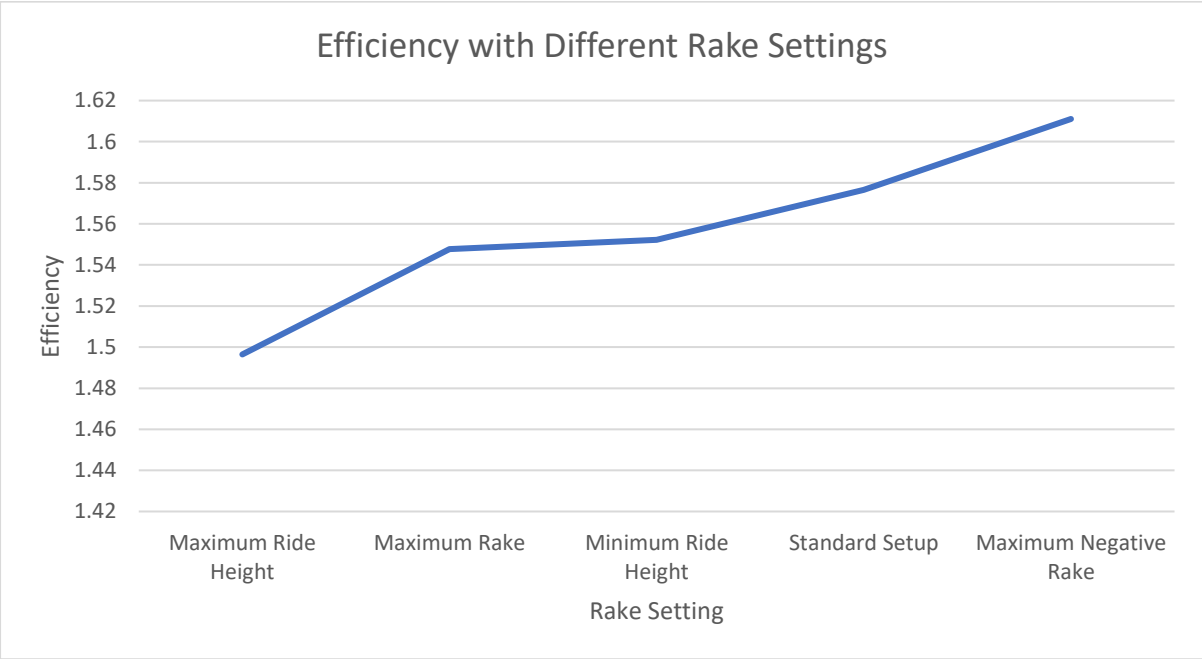


Figure 11 - Tyre loads down the straight

Rake

5 Ride Height studies were tested. The standard setup, maximum and minimum ride height, maximum positive and maximum negative rake.

Hanger Straight



Graph 1 - Aerodynamic efficiency with different rake settings

From graph 1 it can be seen that the least aerodynamic efficiency occurs when the car is at its maximum ride height. It would be expected this would be one least efficient setup as the underbody of the car is one of the most efficient areas of the car where downforce is created. If the car is at its maximum ride height the air flowing under the car will not properly attach to the underside aerodynamic devices such as the floor and the diffuser.

The maximum negative rake, where the car is at maximum height on the front and minimum height on the rear has the best aerodynamic efficiency. This is not what would be expected as nearly all race cars use positive rake. This is because having negative rake is essentially creating a dam under the car. This would increase the drag of the car since the frontal area has increased, it would also dramatically affect the centre of pressure of the car.

Typically, you will have positive rake on a race car. This is to feed the underbody aerodynamics such as the floor and the diffuser. A floor will try to be as flat as possible; this is to try and not interrupt the airflow under the car as this will cause drag and create vortices, thus reducing the clean airflow to the diffuser. A diffuser works by delaying the air returning to ambient pressure as there is a radius on the diffuser it accelerates the air over it, therefore creates a low pressure zone under the diffuser due to Bernoulli's principle. (Schuetz, n.d.) This produces downforce as the pressure on the underside of the diffuser is lower than ambient.

The differences between the results and what is expected is most likely due to the simulator not modelling flow over the car properly and therefore gets confused what the rake should do to the aerodynamics of the car.

Centre of Pressure

Wing and Splitter Settings

The centre of pressure (CoP) should always be monitored when adjusting the aerodynamic setup. The data shows where the centre of pressure acts from the rear axle of the car. Most competition cars are setup to have a baseline centre of pressure at 45%, (TotalSimulation, 2016) therefore, 45% of the vertical aerodynamic force will be acting on the front axle and 55% acting on the rear axle.

Placement of the CoP is very important and is dependent on the car. As the Aston Martin is rear wheel drive a CoP acting slightly towards the rear would be recommended, this would place more vertical load on the drive wheels helping with traction. Since the car is assumed to have a 50/50 weight distribution the weight distribution has no effect on the CoP.

If the CoP is placed slightly towards the rear the stability through high speed corners should be improved (Soliman, et al., 2015) as the chance of the car oversteering is reduced due to the increased force on the rear. However, if the CoP is acting too far towards the rear there wont be enough force acting on the front wheels and they will lose grip, thus causing the car to start understeering. (Barnard, 2001)

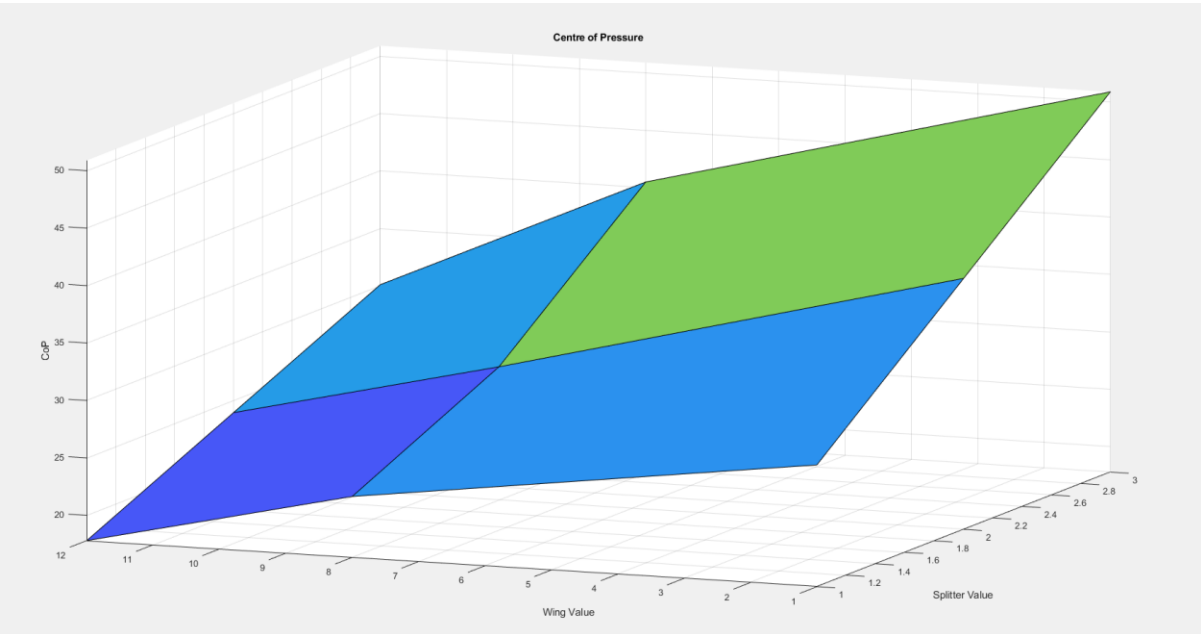


Figure 12 - Average CoP

From figure 13 it can be seen how adjusting the splitter or wing setting effects the CoP. As the splitter value is increased the CoP moves further forward, when the wing setting is increased the CoP moves further towards the rear. If in theory the wing at setting 12 and splitter at setting 1 had the greatest theoretical efficiency its unlikely it will be the best setting as only 17.8% of the vertical load will be acting on the front axle, causing the car to understeer more. When looking at the data this setup was the slowest lap time from all the wing and splitter settings.

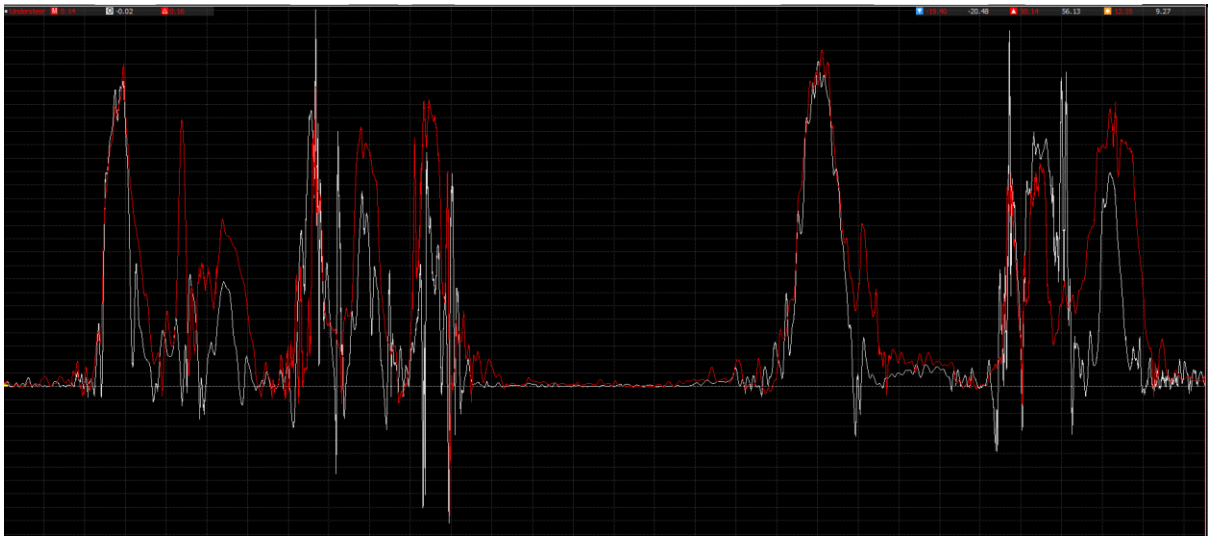


Figure 13 - CoP over a lap

Figure 14 shows the max rear downforce setup in red where the CoP is 17.8% and the max front downforce setup in white where the CoP is 50.9%. This shows that the car understeers 3.08% over the lap. The front setup was also 0.852 seconds quicker around the lap. As expected when more downforce is acting on the front, the car experiences more oversteer. Over one lap this can be quicker as the car wants to rotate more allowing the driver to rotate the car in more aggressively into turns and accelerate out of them. However, over a race this can be more dangerous as oversteer is harder to correct and sometimes the car can experience 'snap oversteer', where the car oversteers with no warning and it can be very difficult to correct.

By looking at this data a compromise be the two setups would be recommended, this should help the car be as responsive as the front setup while experiencing less oversteer, making the setup safer to drive.

Aero Forces Against Velocity

Downforce Against Velocity

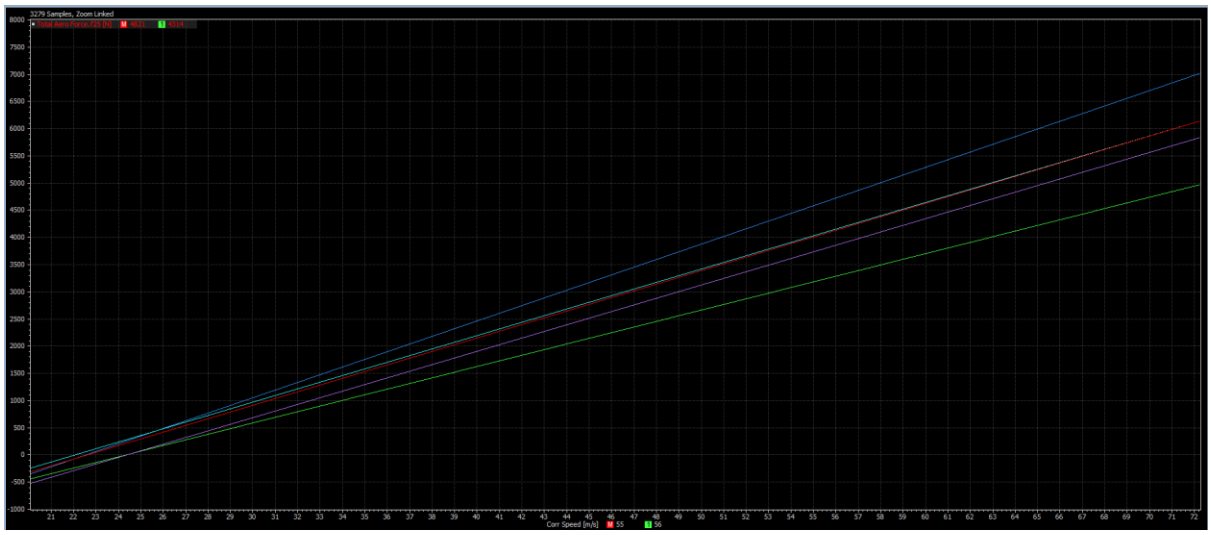


Figure 14 - Downforce against velocity

Figure 15 shows the downforce trendlines for each aero setup. As the velocity increases the downforce increases. When the aero settings are set to a higher value the amount of downforce produced is increased.

Figure 15 - Downforce against velocity

Figure 16 shows the difference in drag force between minimum and maximum aero settings. The greater the aero setting the more drag occurs, the value increases exponentially.

Weight Transfer

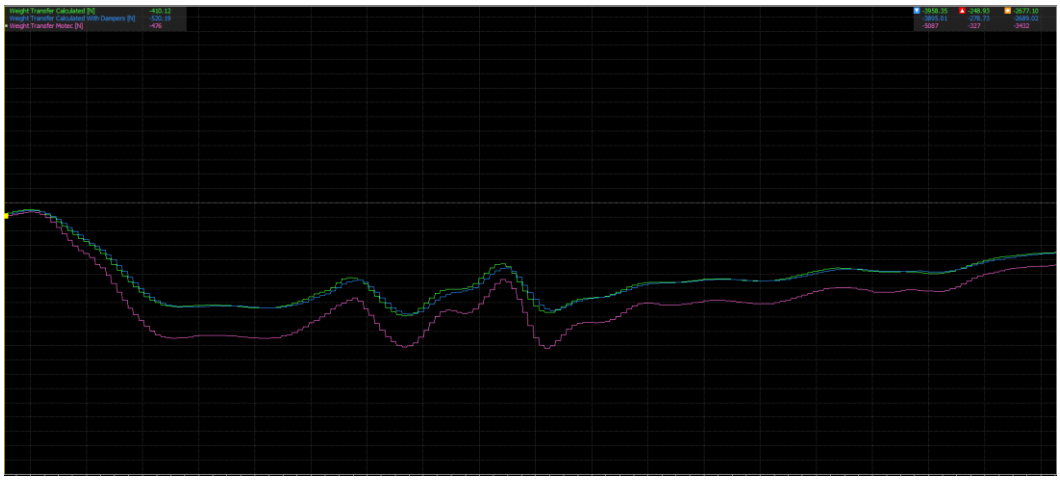


Figure 16 - Weight Transfer Through Abbey

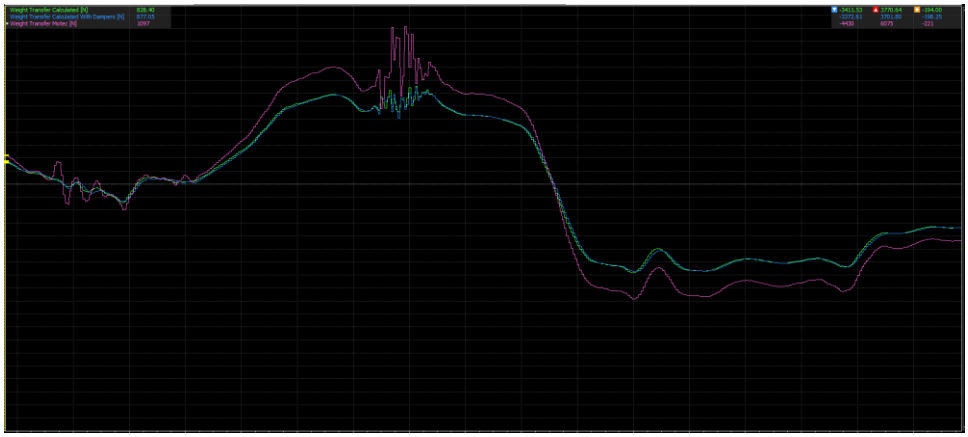
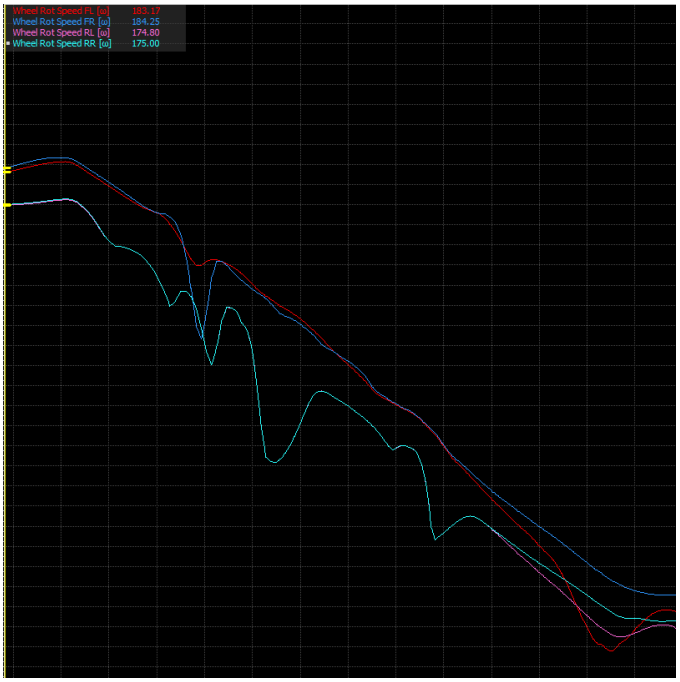


Figure 17 - Weight transfer through vale

Looking at the weight transfer there is a channel created using data from MoTeC, a channel calculated through the setup sheet with out the dampers and a channel created through the setup sheet with damper forces. There are some discrepancies between the MoTeC and calculated values which could be due to the data MoTeC receives from the simulator, they follow the same trends. The damper and non-damper calculated values as the dampers don't produce much force.

When comparing figure 17 and 18 the difference between a low and high speed corner with regard to weight transfer can be seen.

Through Vale the weight transfer goes from positive to negative in the braking zone, there is some slight oscillation, this could be due to the driver pumping the brakes as the front tyres start to lock up as can be seen in figure 19.



In the corner entry there is a gradual increase in weight transfer, this is what would be expected as the car starts to roll more. At the apex there is oscillating weight transfer with sharp spikes. This will be due to the car hitting the sausage curb on the left of the chicane. This causes the car to oscillate.

Through abbey the car slowly reaches the maximum weight transfer as the car turns into the corner, through the middle of the corner there is some fluctuation, this is due to the bumps on the racing line unsettling the car.

Roll Angle

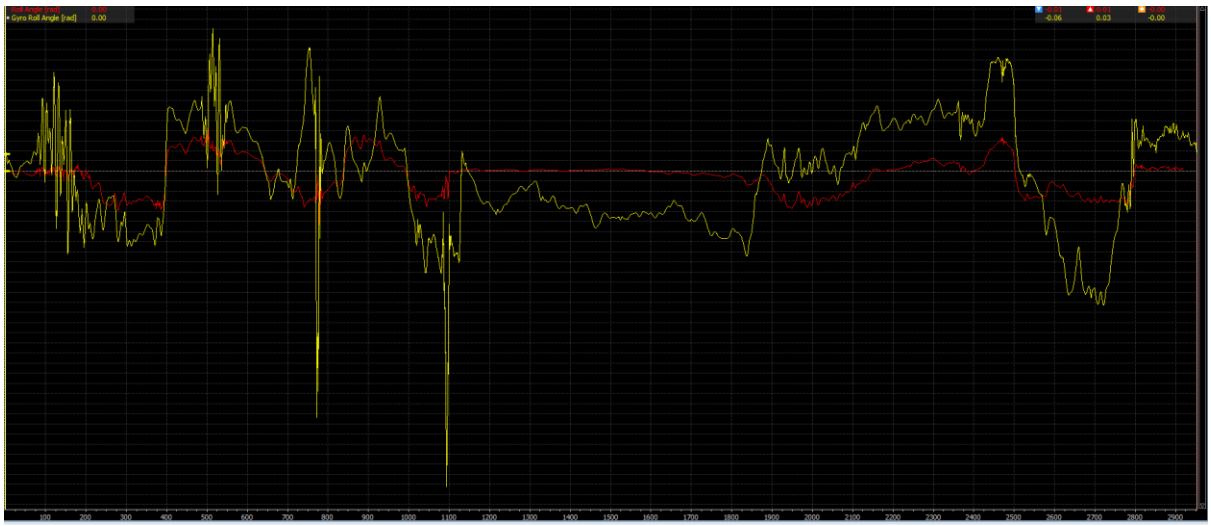


Figure 18 - Roll angle over a whole lap

The roll angle increases as there is an increase in lateral G force. There is a difference between the calculated and actual values of roll angle, however they do show similar trends. One possible reason for this difference is the way the simulator models the tyres. With softer springs the car is able to roll more, since the car is mounted on the springs so they are the only part that rolls. (Staniforth, 1994). Dampers control the rate of roll angle and how much the car is able to roll in and out of corners, they can be used to tune the over/understeer of the car. (Suspension Secrets, 2017)

When there is more roll angle the tyres can sustain a greater contact patch with the tarmac (Parczewski & WNĘK, 2017), due to there being more elastic weight transfer keeping all the tyres in contact with the road.

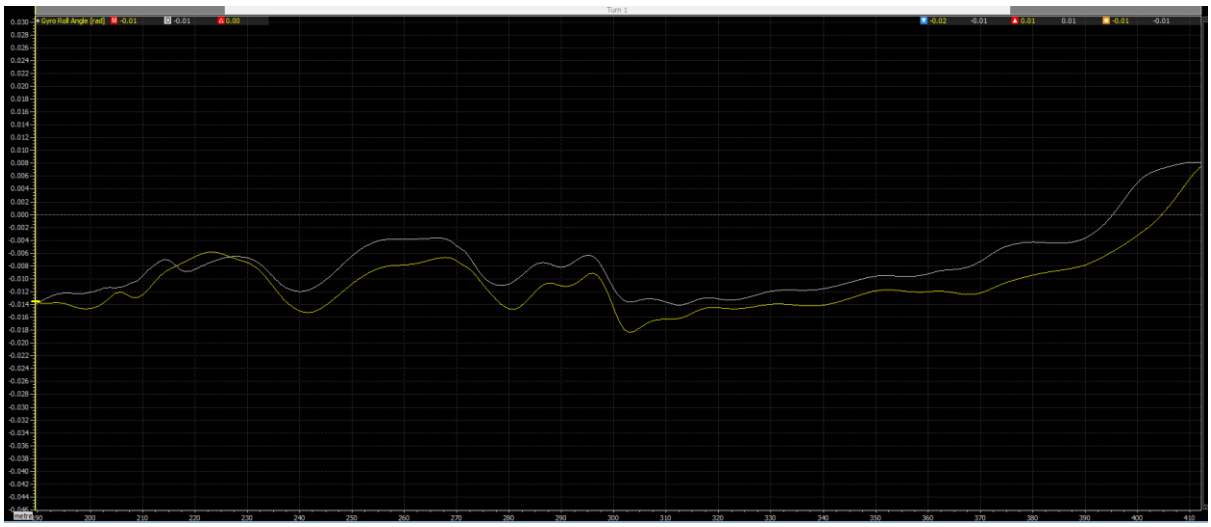


Figure 19 - Roll angle through Abbey

Looking at the roll angle through Abbey with the minimum ARB in yellow and the maximum in white, it can be seen that they both show a similar trend. However, when the ARBs are at minimum there is slightly more roll, which is as expected. This shows that the simulator is modelling anti roll bars.

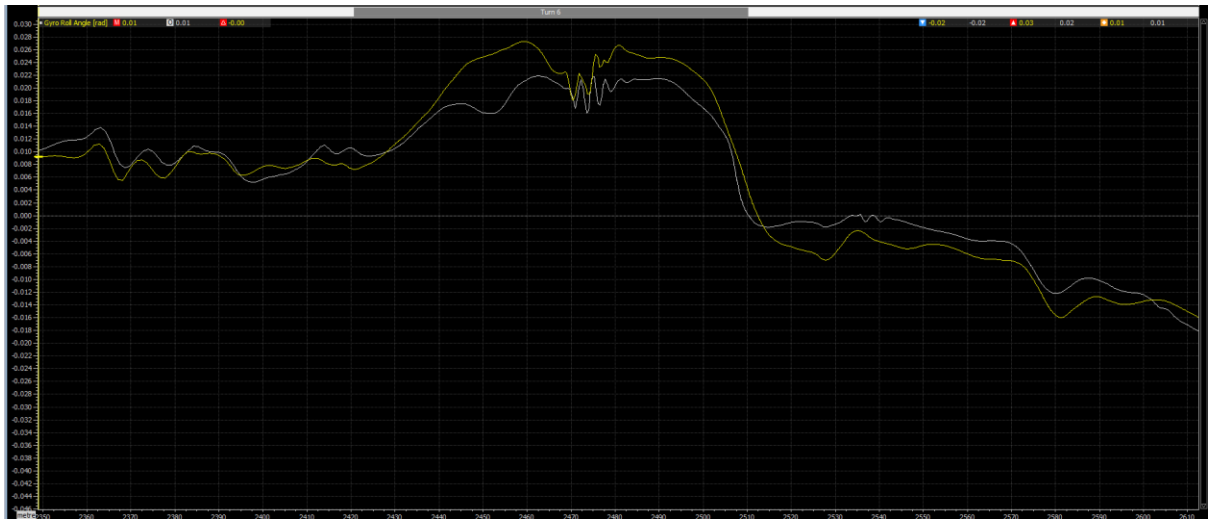


Figure 20 - Roll angle through Vale

Looking at the difference through vale the roll angle is closer, this is because the anti-roll bars work more at high speed

Front and Rear Downforce

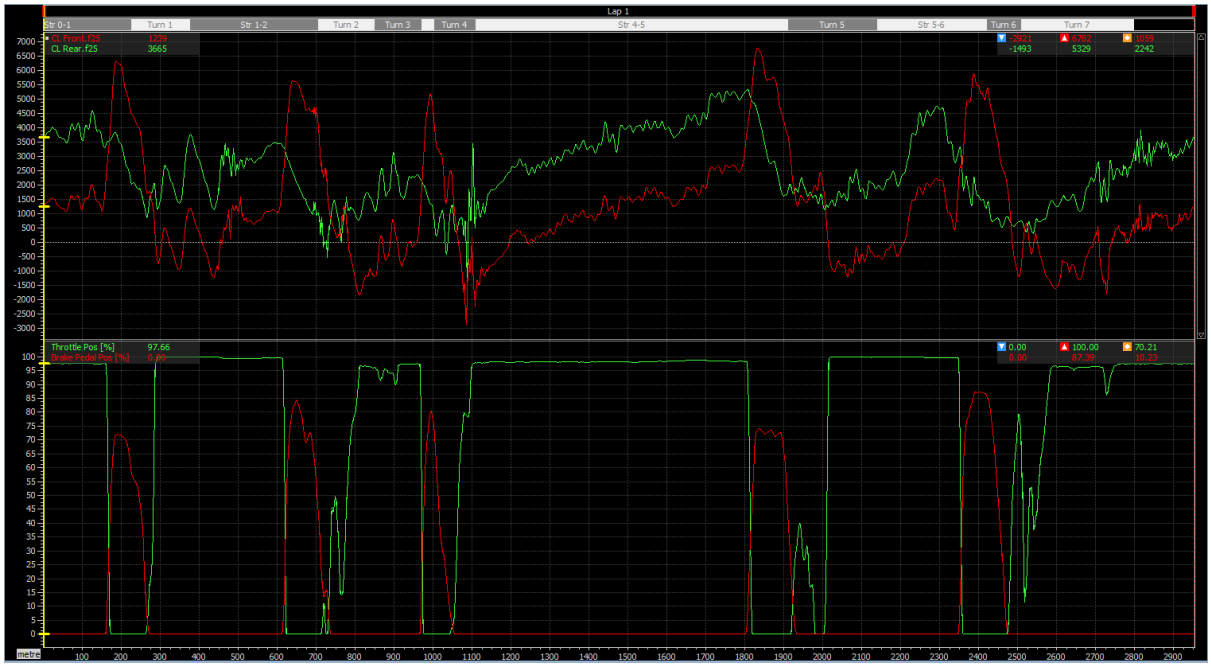


Figure 21 - Front and Rear downforce with throttle and brake position

Figure 22 shows the downforce on the front axle in red and the downforce on the rear axle in green on the top graph, the bottom graph shows throttle and brake position. When the brakes are applied there is a sharp rise in front downforce, this is due to the downforce being calculated using the tyre loads. During braking there is weight transfer happening towards the front of the car, this will increase the load on the front axle and therefore increase the downforce.

During the straights the front and rear downforce increase at the same rate, the rear downforce is 2.9 times greater than the front downforce. This is because of where the CoP is acting. The closer to the middle of the car the CoP is acting the closer the front and rear downforce values will be.

3d Graphs

Magic Number

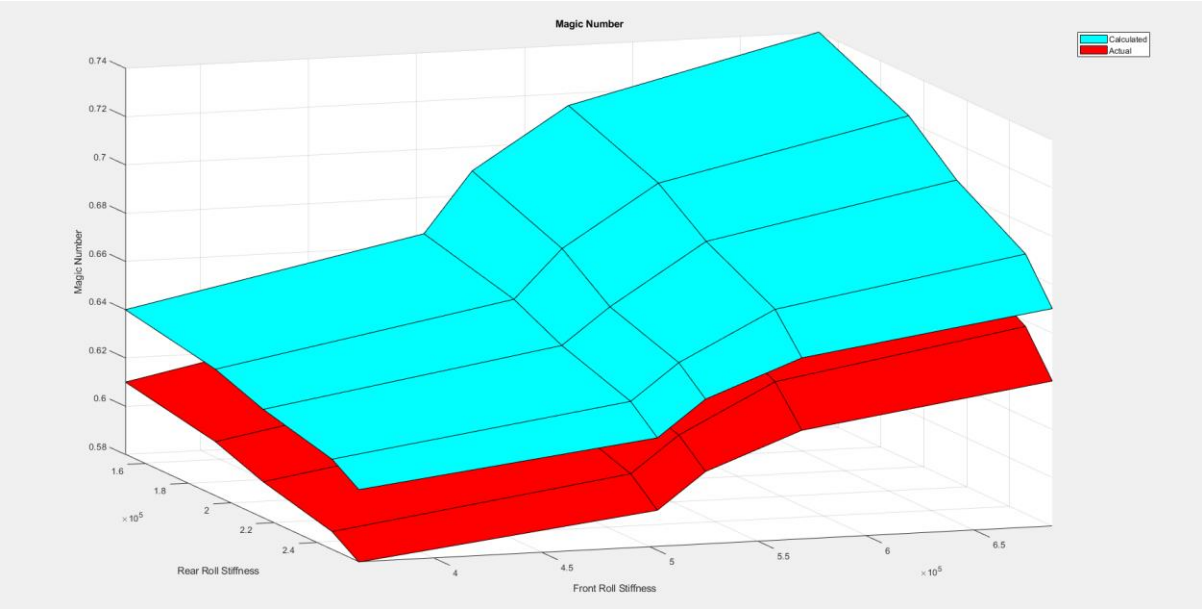


Figure 22 - Magic Number 3D graph

When the roll stiffness moves further rearward the magic number moves further forwards. The magic number is used to predict a cars behaviour in dynamic motion. (Barak, 1991). There is some difference between the calculated and actual values although, they both show the same trends.

Understeer

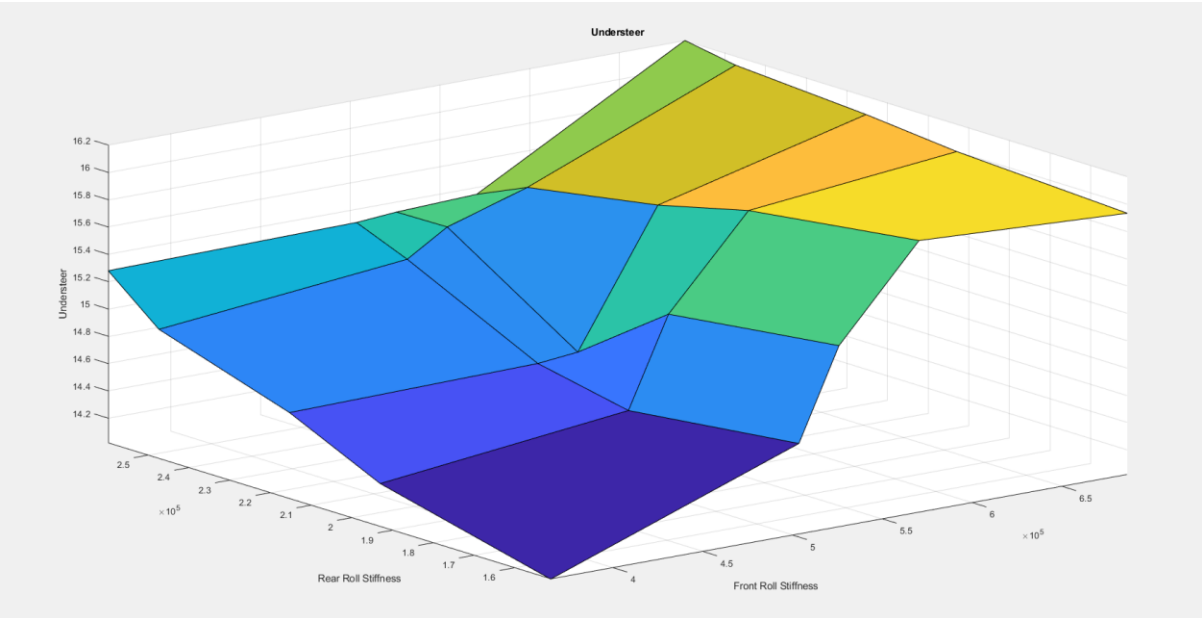


Figure 23 - Oversteer 3D graph

Figure 24 shows the percentage of understeer experienced by the car through vale with different front and rear roll stiffness. If the value is negative the car will be oversteering, if the value was 0 the car would be experiencing neutral steer. Since all the values are positive the car is experiencing understeer.

The minimum understeer occurs with both roll stiffnesses are at their minimum value, thus meaning the suspension is at its softest setting. Since the suspension is at its softest the car is able to roll more, therefore the suspension is able to absorb more of the weight transfer. This means the weight transfer is not transmitted to the wheels, meaning the slip less. As the roll stiffness increases the amount of understeer increases, this is due to the weight transfer becoming more geometric as the chassis and tyres have to absorb more of the weight transfer. Since in the simulator the chassis is assumed to be infinitely stiff, the tyres will have to take all the extra weight transfer which causes them to slip more. If the car becomes too stiff it is possible that the rear wheel can lift off the ground, this will reduce the stability and traction of the car. (Balance Motorsport, n.d.) This is more common in front wheel drive cars as the weight distribution is typically further forward and by lifting a wheel will reduce the rolling resistance.

The maximum understeer is occurring when the roll stiffness is greatest, this is what would be expected. The variation in the data on the graph could be caused by the driver doing something different in one or two of the laps, such as hitting a kerb, entering the corner too early or late, or possibly by accelerating more aggressively causing the car to oversteer. This means that MATLAB can’t interpolate the data correctly, causing the difference.

Dampers

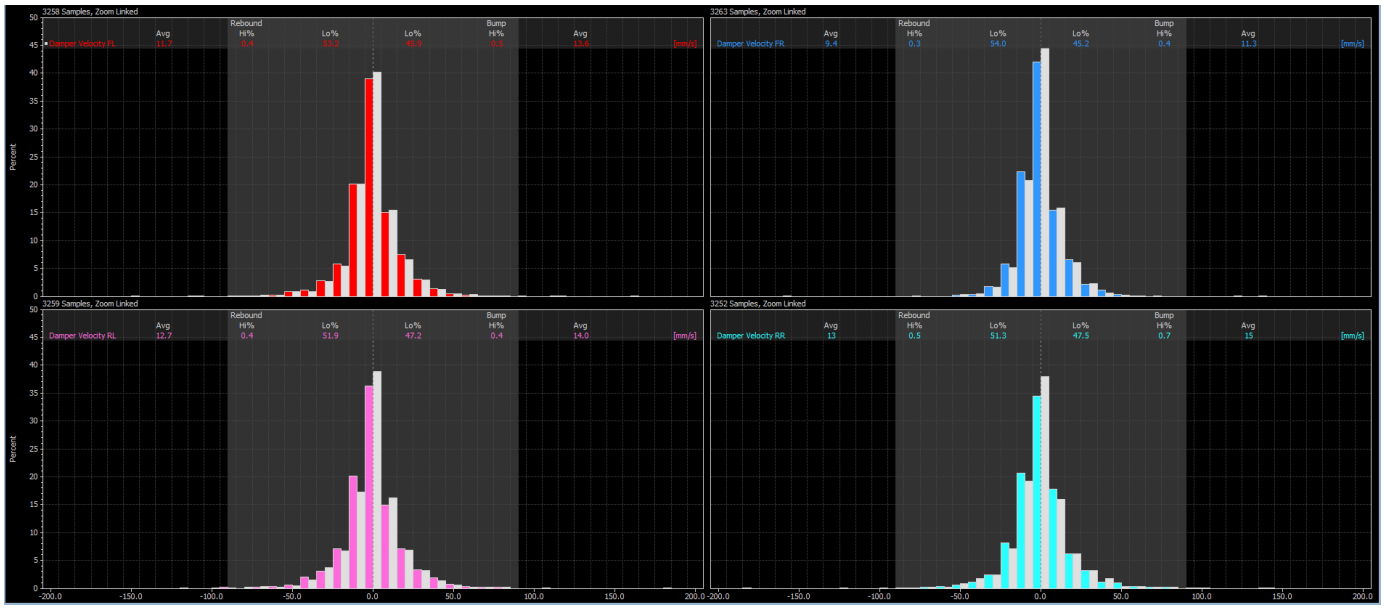


Figure 24 - Damper velocity histogram for max and min bump

Figure 25 shows the damper velocities with high and low speed rebound on the left and high and low speed bump on the right. Minimum bump is in colour and maximum bump is in white. When the bump is set to maximum the dampers spend more time in bump than they do in rebound.

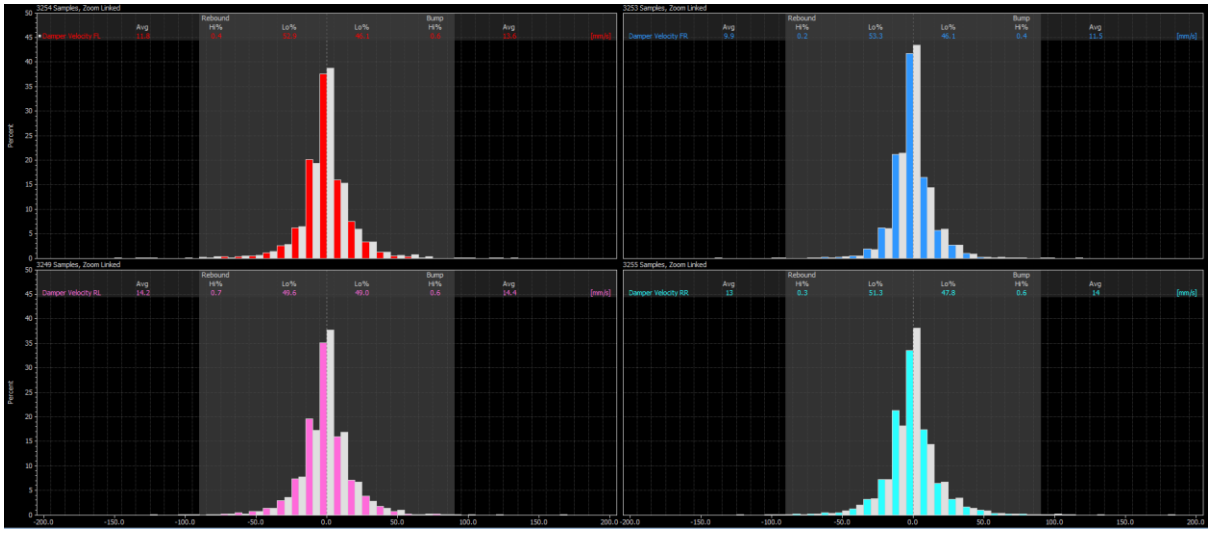


Figure 25 - Damper velocity histogram for max and min rebound

Similarly, when comparing minimum and maximum rebound, when rebound is at maximum the dampers spend more time in rebound.

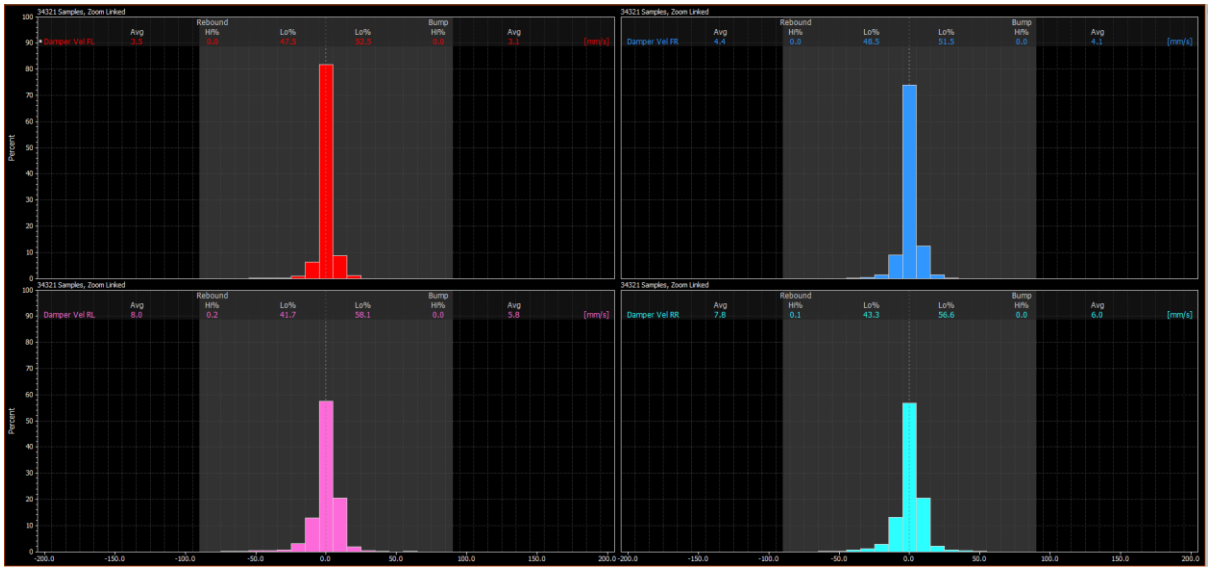


Figure 26 - Damper histogram for MCR

By looking at real data figure 27 from an MCR sports 2000 car, similar trends can be seen. Where most of the time is spent in very low speed damping. Since the data is from a different car with different dampers it would be expected the actual results would be different. However similar trends show some validation between the two dampers

As there is no data to compare the dampers to and since the damper forces are only around 20N, its unknown if the data is reliable as it's possible the simulator doesn't model dampers correctly.

Conclusion

To conclude, it is clear that each setting changed has an impact on the car's performance around a track. The results show that as the aerodynamic devices settings are increased it results in an increase in lift and drag force. Since the angle and length of the splitter are unknown it would be hard to replicate this data in real life.

If someone did want to try and validate the aerodynamic settings there are a few ways it could be done. The first is to run CFD on an accurate CAD model of the car. If the user already has validated CFD settings (McBeath, 2006) this would be a relatively cheap method of obtaining results that should be within 7.7% accurate. (Varga, et al., 2010). Another method would be to place the car in a Windtunnel. The data from this might not directly correlate however it should show similar trends. (Good & Howell, 1995). The physics engine of the simulator could be looked into to see how everything is modelled.

Finally, the car could be taken for real world testing for both a coastdown and dynamic test. The dynamic test could be done by placing pressure taps on the car to measure the pressure differential and obtain the cd values, pushrod sensors could be placed on the car to get the cl values of the car. (Preda, et al., 2010). The coastdown test could be done by placing the car in a shrouded trailer to remove the aerodynamic forces and find the mechanical resistance of the car. (Katz, 1995).

From the tests adjusting the aerodynamic devices can have a bit impact on the performance of the car. Optimising these settings for both driver and track is very important in getting a car that is both quick and comfortable to drive. For a twisty track more downforce will be required or for a track with long straights will require less drag. Maintaining a good CoP also needs to be considered to make sure the car is drivable. This will be personal preference of the driver.

As with the aero settings, the suspension settings need careful consideration to get a well balanced car. These settings will need to be adjusted for each track and driver.

The best way to validate the suspension data would be to take the real car to a track and use a data logger to log the needed data. This would provide a direct comparison between real world data and the simulator. The settings would need to be finely tuned in real life as maximum and minimum settings are rarely used.

To improve the testing less settings could have been tested, especially with regards to dampers as most of the data was not used in the analysis. A better testing method would have been to less settings to test but have more laps to gain more reliable data. 3 laps, all within 0.300 seconds of each other could have be complete to improve the accuracy of the data. This could remove some anomalies in the data.

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Appendix

Expressions	
CL Front	('Tire Load - FL' [N]+'Tire Load - FR' [N])-('Static Weight FL' [N]+'Static Weight FR' [N])+'WT')
CL Rear	('Tire Load - RL' [N]+'Tire Load - RR' [N])-('Static Weight RL' [N]+'Static Weight RR' [N])+'WT')
CL	('CL Front'+'CL Rear')/(0.5*'Air Density' [kg/m3]*('Speed' [m/s]*'Speed' [m/s]))
Lift Using Frontal Area [N]	'CL'*(('Air Density' [kg/m3]*'Speed' [m/s]*'Speed' [m/s])/2)
CoP	('CL Front'/('CL Front'+'CL Rear'))*100
WT	(('Static Weight FL' [N]+'Static Weight FR' [N]+'Static Weight RL' [N]+'Static Weight RR' [N])/9.81)*'CoG' [m]*('G Force Long' [G]*9.81))/'Wheelbase' [m]
Rolling Resistance [N]	-(((2.419-2.797)/(24.115-23.062))*('Total Weight Front' [kg]+'Total Weight Rear' [kg]))
Drag Resistance [N]	-((54.078-56.339)/(10.120-9.067))*('Total Weight Front' [kg]+'Total Weight Rear' [kg])
CD	(2*('Drag Resistance' [N]-'Rolling Resistance' [N]))/('Air Density' [kg/m3]*((56.339+54.078)/2)^2)
Total Aero Force [N]	'CL Front'+'CL Rear'
RRA	('v4' [m/s]-'v3' [m/s])/('t4' [s]-'t3' [s])*('Total Weight Front' [kg]+'Total Weight Rear' [kg])
ARA	(('v2' [m/s]-'v1' [m/s])/('t2' [s]-'t1' [s])*('Total Weight Front' [kg]+'Total Weight Rear' [kg]))
CDA	-(2*('ARA'-'RRA'))/('Air Density' [kg/m3]*(('v1' [m/s]+'v2' [m/s])/2)^2)
Efficiency	'CL'/'CD'
Drag Force	'Cdsheet'*(('Air Density' [kg/m3]*'Corr Speed' [m/s]^2)/2)*1.2

Figure 27 - Aero maths channels

Name	Summary
Expressions	
Damper Coefficient FL [N]	(('Damper Velocity FL (m/s)' [m/s] > 0) & ('Damper Velocity FL (m/s)' [m/s] <=90)) * 'Front Slow Bump' [N/m/s]+ (('Damper Velocity FL (m/s)' [m/s] > 0) & ('Damper Velocity FL (m/s)' [m/s] >90)) * 'Front Fast Bump' [N/m/s]+ (('Damper Velocity FL (m/s)' [m
Damper Coefficient FR	(('Damper Velocity FR' [mm/s] > 0) & ('Damper Velocity FR' [mm/s] <=0.090)) * 'Front Slow Bump' [N/m/s]+ (('Damper Velocity FR' [mm/s] > 0) & ('Damper Velocity FR' [mm/s] >0.090)) * 'Front Fast Bump' [N/m/s]+ (('Damper Velocity FR' [mm/s] < 0) & ('Damper
Damper Coefficient RL	(('Damper Velocity RL' [mm/s] > 0) & ('Damper Velocity RL' [mm/s] <=0.090)) * 'Rear Slow Bump' [N/m/s]+ (('Damper Velocity RL' [mm/s] > 0) & ('Damper Velocity RL' [mm/s] >0.090)) * 'Rear Fast Bump' [N/m/s]+ (('Damper Velocity RL' [mm/s] < 0) & ('Damper V
Damper Coefficient RR	(('Damper Velocity RR' [mm/s] > 0) & ('Damper Velocity RR' [mm/s] <=0.090)) * 'Rear Slow Bump' [N/m/s]+ (('Damper Velocity RR' [mm/s] > 0) & ('Damper Velocity RR' [mm/s] >0.090)) * 'Rear Fast Bump' [N/m/s]+ (('Damper Velocity RR' [mm/s] < 0) & ('Damper V
Damper Force FL [N]	'Damper Velocity FL' [m/s]*'Damper Coefficient FL' [N]
Damper Force FR [N]	'Damper Velocity FR' [m/s]*'Damper Coefficient FR'
Damper Force RL [N]	'Damper Velocity RL' [m/s]*'Damper Coefficient RL'
Damper Force RR [N]	'Damper Velocity RR' [m/s]*'Damper Coefficient RR'
Damper WTF [N]	('Damper Force FL' [N]-'Damper Force FR' [N])/2
Damper WTR [N]	('Damper Force RL' [N]-'Damper Force RR' [N])/2
Weight Transfer Front Calculated With Dampers [N]	('Weight Transfer Elastic Front' [N]+'Weight Transfer Sprung Front' [N]+'Weight Transfer Unsprung Front' [N]+'Damper WTF' [N])
Weight Transfer Rear Calculated With Dampers [N]	('Weight Transfer Elastic Rear' [N]+'Weight Transfer Sprung Rear' [N]+'Weight Transfer Unsprung Rear' [N]+'Damper WTR' [N])
Weight Transfer Calculated With Dampers [N]	'Weight Transfer Front Calculated With Dampers' [N]+'Weight Transfer Rear Calculated With Dampers' [N]
Damper Velocity FL (m/s) [m/s]	'Damper Velocity FL' [m/s]/1000

Figure 28 - Damper Maths Channels

Name	Summary
Expressions	
Corner Radius [m]	('Speed' [m/s]*'Speed' [m/s])/('G Force Lat' [G]*9.81)
Theoretical wheel steer [deg]	('Wheelbase' [m]/'Corner Radius' [m])*57.3
x	-16.444/2.943
Theoretical steer % [deg]	('Theoretical wheel steer' [deg]*'x')
Understeer	abs('Steering Wheel Pct' [%])-abs('Theoretical steer %' [deg])

Figure 29 - Steering maths channels

Name	Summary
Expressions	
☑ Roll axis height [m]	(('Static Roll Centre Height Front' [m]+'Static Roll Centre Height Rear' [m])*'CoG' [m])+('Static Roll Centre Height Front' [m]/'Wheelbase' [m])
☑ Overturning Moment [Nm]	'Total Sprung Mass' [kg]*('G Force Lat' [G]*9.81)*'H' [m]
☑ Roll Angle [rad]	('Overturning Moment' [N.m]/'Roll Stiffness' [Nm/rad])
☑ Weight Transfer Elastic Front [N]	('Wheel Rate Front' [N/m]*'Roll Angle' [rad]*'Track ' [m])/2
☑ Weight Transfer Elastic Rear [N]	('Wheel Rate Rear' [N/m]*'Roll Angle' [rad]*'Track ' [m])/2
☑ Weight Transfer Sprung Front [N]	(('Total Sprung Mass' [kg]/2)*('G Force Lat' [G]*9.81)*('Static Roll Centre Height Front' [m]))/'Track ' [m]
☑ Weight Transfer Sprung Rear [N]	(('Total Sprung Mass' [kg]/2)*('G Force Lat' [G]*9.81)*('Static Roll Centre Height Rear' [m]))/'Track ' [m]
☑ Weight Transfer Unsprung Front [N]	('Front Unsprung Mass' [kg]*('G Force Lat' [G]*9.81)*('Front Rolling Radius' [m]/2))/'Track ' [m]
☑ Weight Transfer Unsprung Rear [N]	('Rear Unsprung Mass' [kg]*('G Force Lat' [G]*9.81)*('Rear Rolling Radius' [m]/2))/'Track ' [m]
☑ Weight Transfer Front Calculated [N]	('Weight Transfer Elastic Front' [N]+'Weight Transfer Sprung Front' [N]+'Weight Transfer Unsprung Front' [N])
☑ Weight Transfer Rear Calculated [N]	('Weight Transfer Elastic Rear' [N]+'Weight Transfer Sprung Rear' [N]+'Weight Transfer Unsprung Rear' [N])
☑ Weight Transfer Calculated [N]	'Weight Transfer Front Calculated' [N]+'Weight Transfer Rear Calculated' [N]
☑ Weight Transfer Motec Front [N]	(('Tire Load - FL' [N]-'Tire Load - FR' [N])/2)*-1
☑ Weight Transfer Motec Rear [N]	(('Tire Load - RL' [N]-'Tire Load - RR' [N])/2)*-1
☑ Weight Transfer Motec [N]	('Weight Transfer Motec Front' [N]+'Weight Transfer Motec Rear' [N])
☑ H [m]	'CoG' [m]-'Roll axis height' [m]
☑ Magic Number Calculated	'Weight Transfer Front Calculated' [N]/('Weight Transfer Front Calculated' [N]+'Weight Transfer Rear Calculated' [N])
☑ Magic Number Motec	'Weight Transfer Motec Front' [N]/('Weight Transfer Motec Front' [N]+'Weight Transfer Motec Rear' [N])
☑ WTbasic [N]	(('Total Weight Front' [kg]+'Total Weight Rear' [kg])*('G Force Lat' [G]*9.81)*'CoG' [m])/'Track ' [m]
☑ Weight Transfer Aero Adjusted [N]	'Weight Transfer Calculated' [N]-'Total Aero Force' [N]
☑ Front/Total Roll Stiffness	'Roll Stiffness Front' [Nm/rad]/'Roll Stiffness' [Nm/rad]
☑ Front Roll Stiffness	'Roll Stiffness Front' [Nm/rad]
☑ Rear Roll Stiffness	'Roll Stiffness Rear' [Nm/rad]

Figure 30 - Weight transfer maths channels

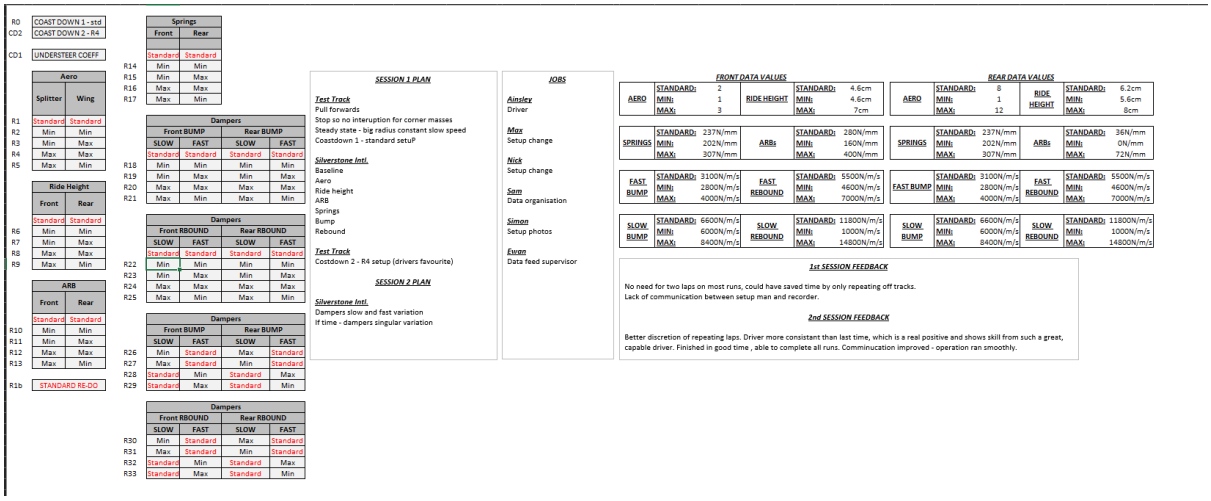

Figure 31 - Test plan including setups

	1	2	3
1	1.94		2.5
8		2.42	
12	2.44		2.67

Table 3 - Table for CL before matlab interpolation

	1	2	3
1	6194		7610
8		7266	
12	7089		7516

Table 4 - Table of lift forces

	1	2	3
1	28.4		50.9
8		29.4	
12	17.8		30.1

Table 5 - Table for CoP

	1	2	3
1	1.05	1.13	1.22
8	1.14	1.22	1.3
12	1.29	1.35	1.39

Table 6 - Table of CD values after matlab interpolation

Magic number calculated					
	151002	192938	215238	247356	259837
365121	0.64				0.61
503411					
525711			0.66		
570311					
686301	0.74				0.67

Table 7 - Magic number calculated

Magic number MoTeC					
	151002	192938	215238	247356	259837
365121	0.61				0.58
503411					
525711			0.63		
570311					
686301	0.71				0.64

Table 8 - Actual Magic Number

Understeer					
	151002	192938	215238	247356	259837
365121	14.02			16.01	
503411		14.54			16
525711			14.71		
570311					
686301	15.28			15.35	16.2

Table 9 – Understeer

WT calculated					
	151002	192938	215238	247356	259837
365121	-201			-215	
503411		-163			-161
525711			-147		
570311					-122
686301	-154			-227	

Table 10 - Calculated Weight Transfer

WT MoTeC					
	151002	192938	215238	247356	259837
365121	-236			-287	
503411		-204			-201
525711			-172		
570311					-157
686301	-202		-234	-295	

Table 11 - MoTeC Weight Transfer