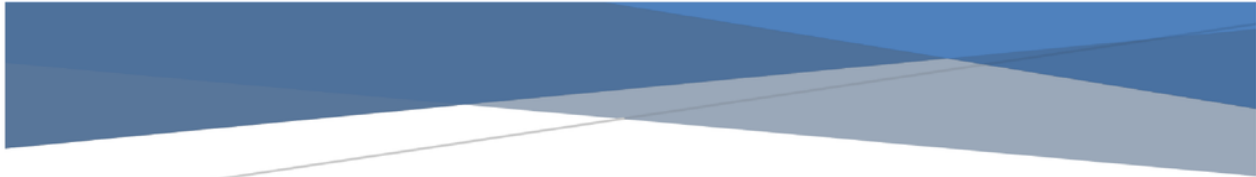


Aerodynamic vehicle testing and analysis

by Stephen Hutchings

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Abstract

A F3 race car model on a base car simulator was employed to critically analyse aerodynamics and handling performance. A coast-down test and a circuit test was used to measure how total lift and drag changes over the course of a racing track and how varying wing parameters affect these principles. Motec maths channels were utilised to analyse data sets. From this analysis, it was found that wing parameters have an effect on grip, balance and handling. It was also discovered that wing setups have a significant influence on downforce and drag which can subsequently affect the overall lap time. Efficient cornering handling and the avoidance of understeering and oversteering were also shaped by vehicle balance, grip and stability, which were all related to the vehicle's aerodynamics.

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Symbols used:

C_d	Lift coefficient	L	Lift
C_l	Drag coefficient	D	Drag
M	Mass	A	Area
g	gravity	F	Front
V	velocity	R	Rear
CoG (m)	Centre of gravity	CoP	Centre of pressure
θ	Theta		

Aerodynamic Vehicle Testing and Analysis (F3 car)

1.0 Introduction

Vehicle aerodynamics relate to the investigation of airflow around and traveling through a vehicle whilst the vehicle is moving (Katz, 2016). Furthermore, this movement of airflow is categorised into three flow fields, these being the vehicle body, vehicle parts such as the wheels and windshield and through the passenger compartment (Regert and Lajos, 2007). This suggests the flow of air interacts with many different vehicle components and this could influence the operational characteristics of a vehicle. This means that aerodynamics could greatly affect the race cars ability. In addition, aerodynamic forces affect cornering ability and vehicle acceleration (McBeath, 2017). This is explained further by Sergers, (2014) who states that vertical and horizontal aerodynamic forces affect handling performance in different ways; vertical or downforce impact on tyres and cornering and horizontal or drag influences engine power which subsequently has an impact on acceleration. From this, it can be seen that aerodynamics has a major influence on handling performance. During this report, secondary research will be collated on aerodynamic principles and testing methods in order to justify testing procedures. A test plan will be created and two simulated tests will be performed in order to characterise aerodynamic and handling performance of the race car with varying front and rear wing parameters, a further explanation of this is provided in the methodology section. The findings of the test will then be analysed and evaluated using a series of maths channels.

1.1 Aims

The main aim of this report is to critically analyse and assess the aerodynamic and handling performance of an F3 race car model.

2.0 Literature review

2.1 Horizontal aerodynamic forces

As mentioned previously, aerodynamic forces experienced by race cars can be separated into two categories; these being vertical and horizontal (Edmundson, 2011). The horizontal force, known as drag is defined by Sergers (2014) as “the resisting force acting on the

vehicle, which is parallel and in the opposite direction of travel". This suggests that drag pushes against the vehicle whilst the vehicle is in motion and therefore could slow the vehicle down. According to Rashaduddin and Waheedullah (2017, pg21) "drag is comprised primarily of three forces; these being frontal pressure, rear vacuum and boundary layer", this indicates that the vehicle body has several different interactions with airflow. In their study, it was found that reductions in coefficient drag improved fuel consumption and vehicle handling. The study simulated a car model and recognised that many different types of turbulence could be present in road conditions; however, these were not present in the study and therefore could be a possible limitation. This could have affected the study's validity. Nevertheless, a wind tunnel study conducted by Larose et al (2016) which analysed turbulent flow established that vehicles with smaller frontal areas experienced less drag than vehicles with larger frontal areas. They also discovered that drag reducing technologies such as active grille shutters, bumper air dams and ride height control reduced drag further, of these active grille shutters was seen to be the most effective in drag reduction. Therefore, this study suggests that components can be added to the vehicle in order to counteract with aerodynamic forces and potentially improve handling performance.

2.2 Vertical aerodynamic forces

Aerodynamic lift is a force that reacts vertically on the vehicles body as is downforce (negative lift). Lift is the term given when the force attempts to lift the car up and downforce if the term given when forces try to push the car down on the ground; downforce is a positive aspect as it enhances vehicle grip (Machin, 2015). Furthermore, this links to Bernoulli's principle, which relates to pressure applied to the vehicle and the velocity (Hucho, 2013). It is apparent that there are several ways that downforce can be increased, these include fitting a spoiler, splitter or using wings (Katz, 2016). In a numerical simulation study conducted by Cai et al (2017) it was discovered that appropriate wing shapes influenced the vehicles stability, they concluded that aerodynamic wings permitted a much higher level of lateral acceleration, they also found that active aerodynamic wings increased traction and improved braking performance. To add to this, research by Yakkundi and Mantha (2017) discovered that downforce was enhanced when vehicles were fitted with spoilers. In their computational fluid dynamics study, they established that rear spoilers enhanced handling characteristics by improving tyre and braking performance and offering stability when the vehicle was travelling at high speeds. However, it was found that these enhancements were only present when the vehicle was travelling at high speeds; also a marginal drag increase was present when a rear spoiler was added. Therefore, this suggests that the addition of

certain components may decrease one aerodynamic force but unwantedly increase another aerodynamic force whilst doing so.

2.3 Aerodynamic testing

It can be seen from literature that there are several different ways to test vehicle aerodynamics, these include wind tunnels, CFD software and ground simulation (Buckley, 1995; Jakirlic et al, 2014 and Ljungskog et al, 2017). However, it has been noted that these testing methods may not be financially viable for all and do not always replicate real-road data. Sergers (2014, pg331) explains that data logging systems which record “dynamic pressure, suspension load and ride height along with speed RPM and longitudinal acceleration” can provide an estimation of drag and downforce. Therefore, suggesting that aerodynamic testing can take place during track testing. Other aerodynamic testing methods include the coast-down test and the constant-velocity test. Altinisik (2017) defines the coast-down test as a procedure where the vehicle is accelerated to a particular speed of interest, moved into neutral and then is permitted to decelerate freely. From this, forces are calculated. This research determined that the coast-down test produced more accurate results than wind tunnel testing. Conversely, Huertas and Coello (2017) suggest that the isolation of resistive force calculations can be difficult. Therefore, it is important that thorough analysis techniques are used to gather the correct data. Another type of aerodynamic testing method is the constant velocity test; this is when the vehicle is travelling at a constant speed in order to conduct downforce measurements (Pascoa et al, 2012). This research showed that the determination of vehicle drag was the key purpose of this test, it was also identified that accurate velocity measurements were extremely important. In addition, it was recognised that the distribution of total downforce between axles and the ride height had to be taken into consideration when using this method. Thus, suggesting that several factors need to be measured accurately in order to obtain reliable results from this type of testing.

3.0 Methodology

3.1 Testing

In order to critically analyse and assess the aerodynamic and handling performance of an F3 race car model two tests were carried out; these being a coast down test and an

aerodynamic circuit test. These tests can be used to measure how total lift and drag changes over testing and main purpose for each test is to establish the aerodynamic coefficient and static rolling coefficient of the F3 race car Chen et al(2018). Therefore, aerodynamic forces can be evaluated using both types of test. It was also important to evaluate two tests which had different driving patterns, this was in order to determine whether aerodynamic setups affected driver handling patterns (Erihim, 2012) and this increased the reliability of the testing methods. So that all team members were aware of what information needed to be gathered, their roles and the requirements of the driver a test plan was created, this can be found in appendix A. Team members were given a specific role during testing and this stayed the same for both tests; this enhanced the reliability of data gathered. Individual roles included data collection, inputting data into spreadsheet, debriefing the driver (see appendix B for driver feedback), starting and stopping of the simulator and providing the driver with instructions for each test (see appendix C for driver instructions). So that team members and the driver fully understood the test objectives, testing requirements and aerodynamic setups for each test a test schedule was created (see appendix D).

A skid pad test was chosen for the first session and the track used for the second session was Silverstone, it was not appropriate to use the same track for both sessions as a race track circuit would not allow a coast-down test to be conducted as the straight stretches on the circuit are limited (Kato et al, 2011). However, Segers (2014) states that coast down tests are designed so that they can take place during track testing, therefore this suggests that Silverstone could have been used for both studies. Nevertheless, it is believed that the use of two different tracks did not affect the reliability or validity of results. The top speed requirement on the coast down test was 220kph and the vehicle was then coasted down in neutral to 0kph; this test was repeated until 10 different aerodynamic setups had been tested. Following this, the same test was conducted on 4 additional setups, this time the vehicle was coasted down to 100kph. The reason for this was that no errors had occurred in the data collection and enough data had been gathered to analyse the aerodynamic setups. For the aerodynamic circuit test, an out lap was completed before data gathering commenced. Following this, data was gathered for 14 tests. However, the lap needed to be completed if an error occurred in driving as this would have a negative impact on results. A test for Ackermann steering was completed using a skidpad; this was to ensure that steady-state conditions were present in the test (Mitchell et al, 2006).

3.2 Analysis of data

Following the coast-down test, an excel spreadsheet was created in order to calculate the drag coefficient (C_D), this equation is shown below in equation 3-1. According to Segers (2014), the coast-down test provides an viable alternative to determine the coefficient of drag when wind tunnel testing is not available.

$$C_D = \frac{M a_{long}}{0.5 \rho V^2 A}$$

Where

M= mass

$A_{long} = G_{long} \times 9.8$

Air density = 1.223 Kg/m³

Vehicle frontal area = 1.2m²

(Equation 3- 1: coefficient drag)

After this, the values of C_D for each setup were entered into Motec Excel for the coastdown test. Several maths channels were added to this software (see appendix E for maths channel equations). Then the data sets from the circuit test were added to the sheet and the C_D values of these were calculated using the above equation. However, only four data sets from the circuit test matched the coastdown data sets, therefore this could be a limitation of the study as data sets were limited (Hauser, 2009). Next, lift coefficient (C_L) was determined (see equation 3-2), this relates to the characteristics of dynamic lift and links with the drag and downforce (Houghton and Carpenter, 2003).

$$C_L = \frac{2L}{\rho \times V^2 \times A}$$

(Equation 3-2: lift coefficient)

Data traces were then created on Motec in order to examine how lift and drag alters around the circuit lap. The data analysis was conducted on the fastest lap and the second fastest lap, the aerodynamic set ups used in this data was: R1-R6 (fastest) and F18-R18 (second fastest). These will be compared in the results section. The equation for lift and the equation for drag

is shown below. Linking with this, a total lift vs speed (x-y) and lateral acceleration (x-y) was plotted for the setups, this will be discussed further in the results section.

$$Drag = C_D \times \frac{1}{2} \rho V^2 \times A$$

(Equation 3-3: Drag force)

$$Lift = C_L \times \frac{1}{2} \rho V^2 \times A$$

(Equation 3-4: Lift force)

Then a series of maths channels were created to analyse the total downforce and downforce (negative lift) on the front and rear axle, this was in order to establish how traction and drag were affected over the course (Alexander, 2001). The equation used to calculate front lift and rear lift are shown in equation 3-5 and 3-6.

$$CL_f = \frac{2 \times a_{aero\_front}}{\rho \times V^2} = \frac{2 \times [(FL+FR)-(FL_0+FR_0)+wt]}{\rho \times V_{air}^2}$$

(Equation 3-5: Front lift)

$$CL_r = \frac{2 \times a_{aero\_rear}}{\rho \times V^2} = \frac{2 \times [(RL+RR)-(RL_0+RR_0)-wt]}{\rho \times V_{air}^2}$$

(Equation 3-6: Rear lift)

Centre of pressure was also analysed as this relates to the balance between the axles on the front and rear of the car (Kenny, 2012). These maths channels will be analysed further in the results section so that the drag, lift and balance of each setup can be investigated; the setup which best enhances aerodynamic performance will be recommended to use on a dry race track day. In addition, driver feedback and vehicle handling balance will be analysed using maths channels such as corner radius, theoretical steering, understeer and oversteer and vehicle rake angle. This is the aim of the analysis in the next section.

4.0 Results

4.1 Lift, balance and drag

To investigate the drag and lift of wing parameters, total lift was compared against lap distance and speed (see figure 1 for lift vs lap distance). The red line on the graph illustrates the setup with the fastest lap time, where the black line on the graph shows the setup with the second fastest lap time. From the graph it can be established that there is a more of a negative lift on the fastest lap and therefore implying that more downforce is present in this setup. As more downforce is present this suggests that more frictional force is exhibited by the car (Seward, 2014). Also, it can be seen from the graph that the red line has a greater downforce during cornering (see red circles on graph). Thus, this suggests that the fastest lap setup caused increased traction whilst cornering and permitted quicker decelerating and acceleration when cornering (Segers, 2014). In addition, the blue circles on the graph illustrate that the second fastest setup has more lift present before the corners, this suggests that there is less traction present before the corner (McBeath, 2017) meaning that corner handling will be more difficult and the car is more likely run out of control. In addition, an aerodynamic lift vs aerodynamics maths channel was created (see figure 2). This shows the total aerodynamic forces vary from the total aerodynamic lift but a similar pattern is followed for both. It can be seen that there are more variations in the aerodynamic trace; these could have been caused by a change in surface such as bumps in the road and steering fluctuations (Seward, 2011).

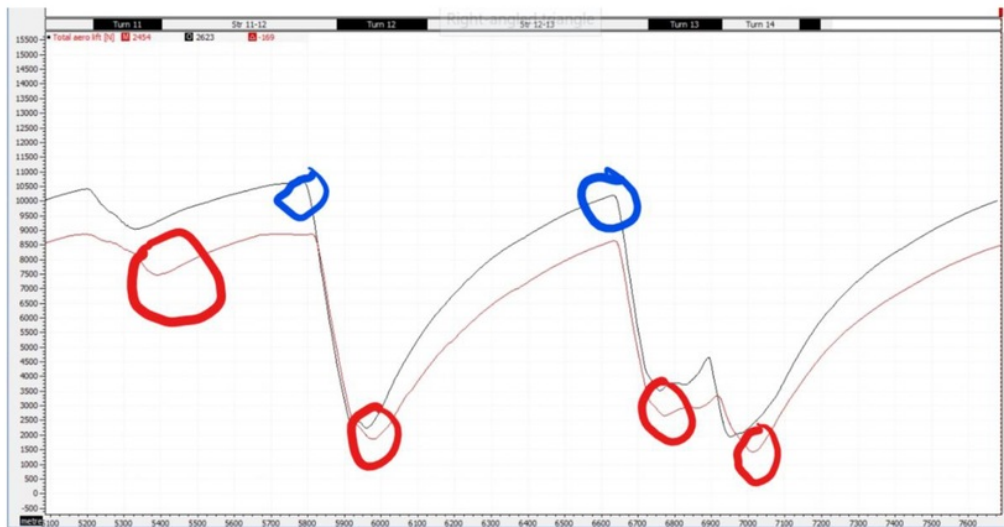


Figure 1: Motec graph of total lift vs lap distance

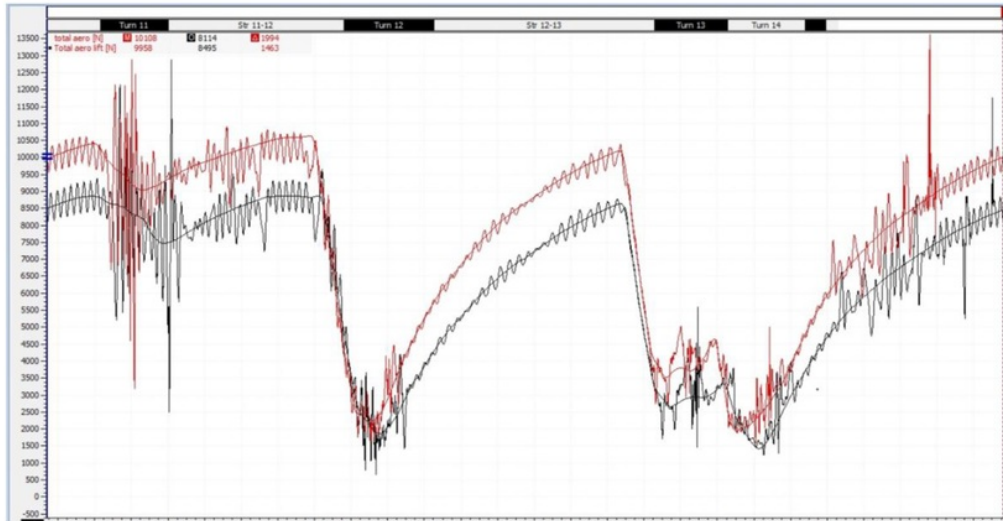


Figure 2: Maths channel, aerodynamics vs aerodynamic lift.

Total lift was then compared with speed to determine whether how downforce had an overall effect on lap time (see figure 3). From the graph it can be seen that the red setup (fastest lap) has more downforce (negative lift of 8541) than the black setup (second fastest) which has a negative lift of 9508 and travels at a faster time of 67 m/s in comparison to 63 m/s. This is supported by Edgar and Benard (2019) who states that downforce permits high speed cornering which increases speeds and reduces the overall lap time. Furthermore, it can be established from the graph that the black set up started the course at a slightly higher speed of approximately 29m/s in comparison to 27m/s (red setup). This also indicates that the gain in speed was a result of better braking and cornering. However, it could also suggest that the black setup was able to reach a higher speed quicker than the red setup. This could relate to drag as the reduction of drag allows for faster speeds on straight sections of the course and downforce increased drag (Katz, 2016).

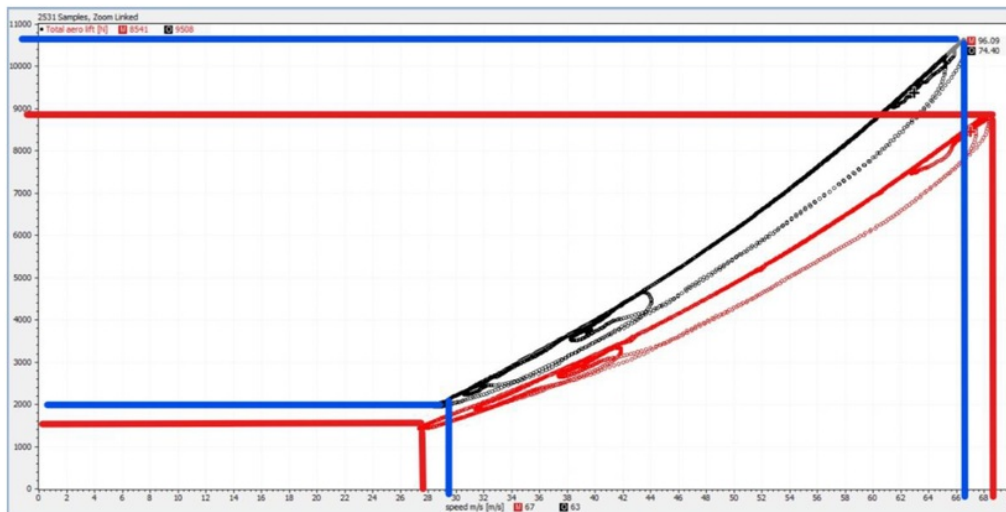


Figure 3: Maths channel, downforce (negative lift) vs speed

To establish whether downforce affected aerodynamic drag force, the total drag was plotted against lap distance (see figure 4). From this graph it can be determined that more drag was present in the black setup (second fastest) in comparison to the red setup (fastest), especially on the straight sections of the track. Therefore, this suggests that the downforce did produce more drag in several sections of the course. However, it can be seen from the graph that the black set up has a significant reduction in drag on one section of the course (see blue cross on graph), this indicates that a long stretch of the course permits drag reduction and possible higher speeds for the black set up (Hucho, 2013).

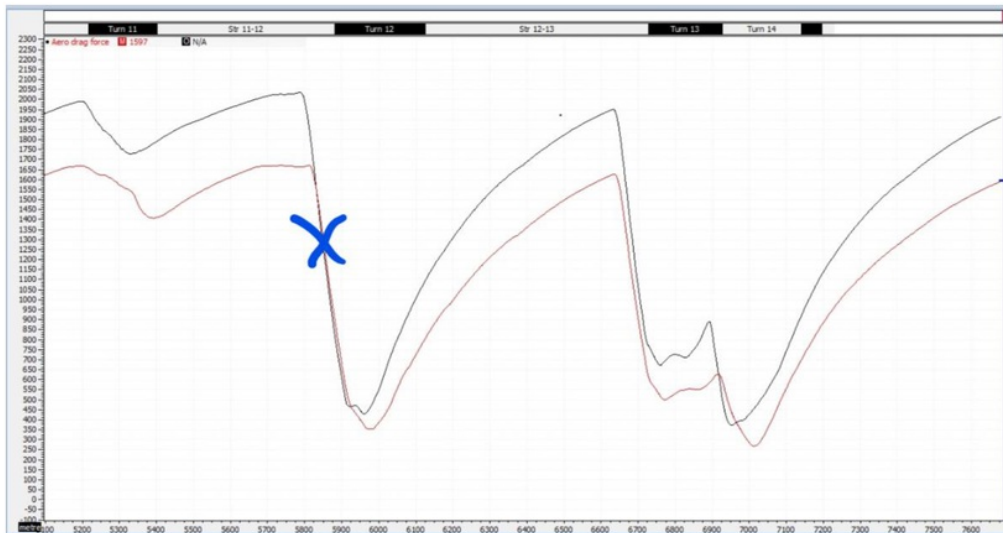


Figure 4: Maths channel, drag vs lap distance

Longitudinal weight transfer was analysed to determine how the braking, acceleration and deceleration whilst travelling around the circuit affected weight transfer and load on the wheels; this affects the available traction for each wheel. From figure 5 it can be seen that there that both setups have a similar weight transfer. During cornering braking both setups demonstrate large rates of negative acceleration. However, in comparison the positive longitudinal acceleration appears at a much lower rate. Seward (2014) suggests that this deceleration occurs at a higher rate than acceleration because aerodynamic drag and grip from all wheels are involved in braking. As a slightly higher rate of negative acceleration is apparent for the red setup this suggests that this car has more grip during cornering.

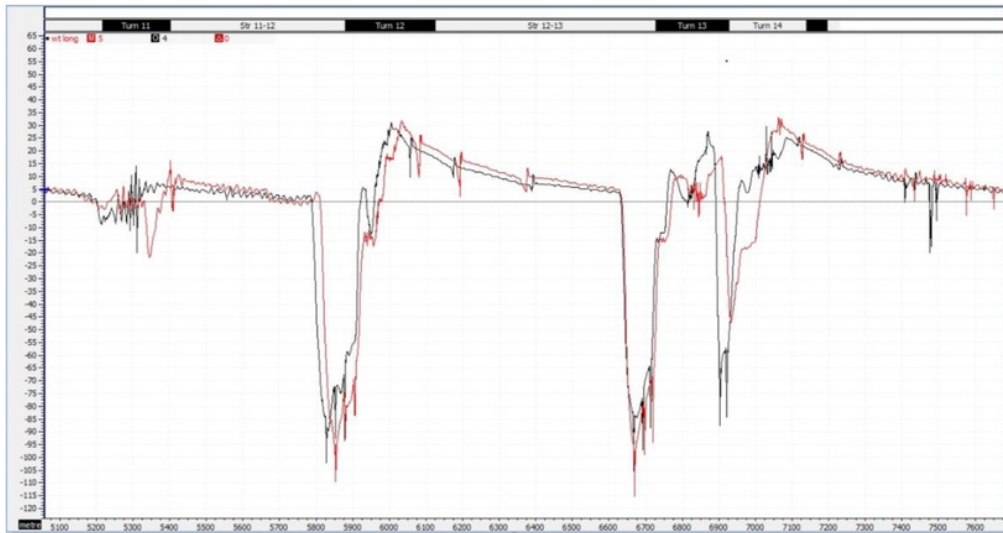


Figure 5: Longitudinal weight transfer vs lap distance

The downforce of the front and rear axle was analysed as Sergers (2014) states that it is important that the downforce is balanced between the front and rear of the vehicle can cause the vehicle to understeer or oversteer. From figure 6 it can be seen that there is a major imbalance on the black set up during the start of the course, this could indicate that the black set up is more likely to oversteer at this part of the track. However, as this is the only major spike in the graph this could have been caused by a factor such as driver error (Kumar, 2014) Nevertheless, this does indicate that grip has been lost for a fraction during this section. It is important to add that TotalSim (no date) states that approximately “45% of downforce acts through the front tyres, where 55% of downforce acts through the rear tyres”. Therefore, this could suggest that there will be less frontal grip and therefore less downforce is present in the front axle. However, this is not the case in the graphs below as more downforce is present in the rear axle for both setups. When looking at the front and rear downforce of both setups it is apparent that the red setup has less fluctuations in the rear axle than the black setup. In addition, there is less downforce present for the red setup on both front and rear axle, this suggest that this set up is more balanced and more successful in reducing lift than the black setup.

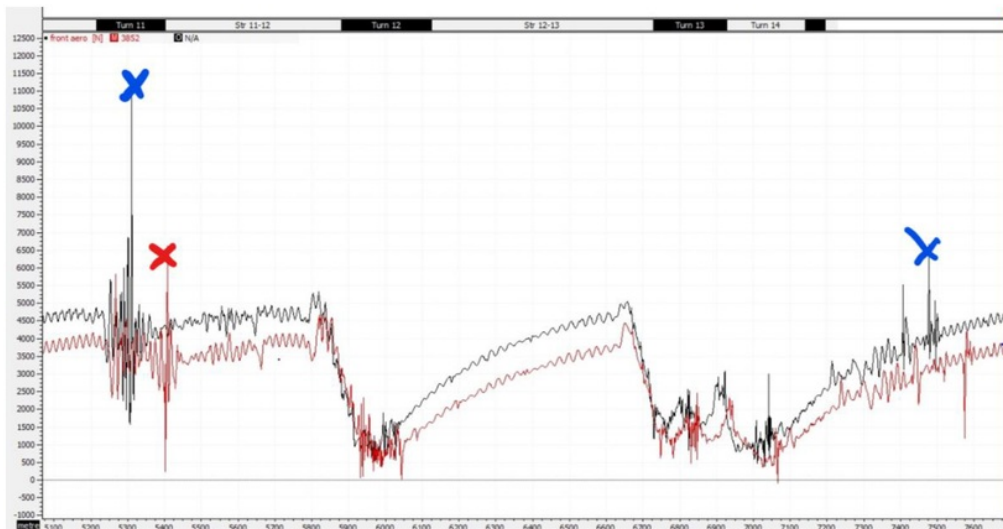


Figure 6: Maths channel: downforce on front axle vs lap distance

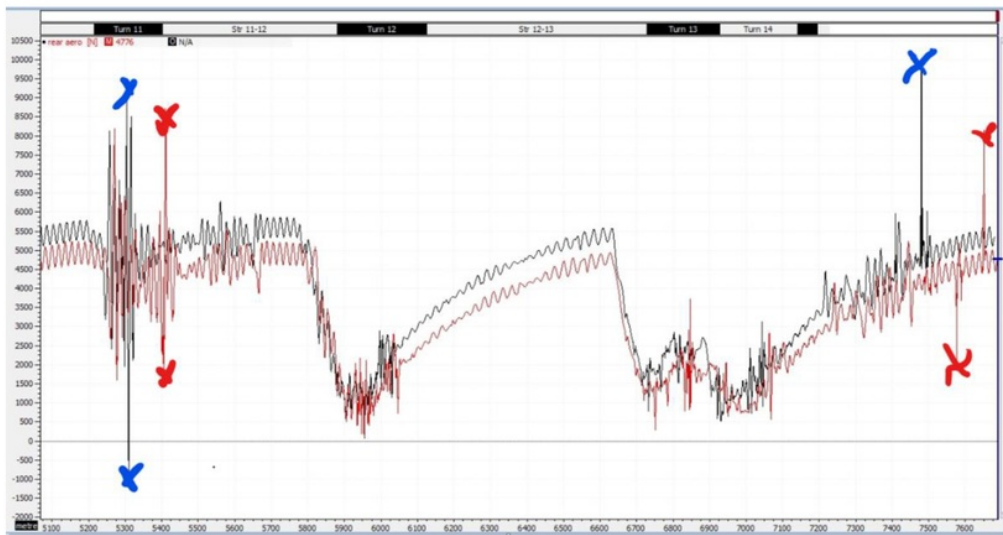


Figure 7: Maths channel, Downforce on rear axle vs distance

To analyse the balance of the downforce between the front and rear axle further the centre of pressure was measured against lap distance. From figure 8 it can be determined that the centre of pressure is imbalanced during cornering for both the red and black set up. However, Hucho (2013) states that during cornering a slightly higher rear downforce will be present as this prevents oversteering whilst entering cornering. Therefore, this suggests that the

imbalances on certain parts of the circuit are normal. Also, as more downforce was present in the red setup this explains why greater fluctuations are shown in the red setup during cornering. A histogram was created to analyse the centre of pressure further (see figure 9), From the histogram it can be seen that the centre of pressure is close to the middle and is not largely spread out, this illustrates that the centre of pressure is adequately balanced in both setups (Kenny, 2016). Also, the histogram demonstrates that more pressure forces are at the rear of the car. This will have a positive effect on handling characteristics as a larger amount of downforce is more desirable at the rear of the vehicle and behind the CoG (Campbell, 2012). As the is more prominent in the red setup this indicates that this car will handle better than the black setup.

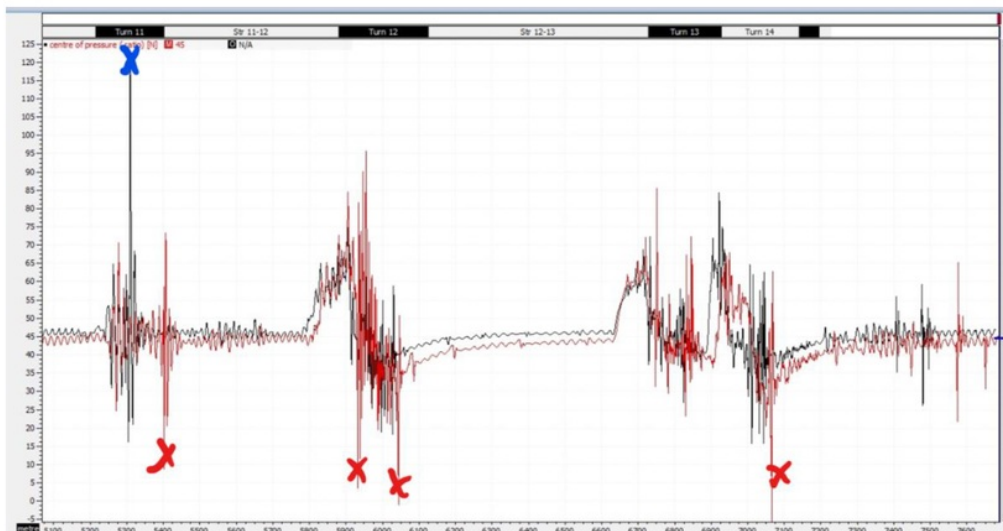


Figure 8: Maths channel: Centre of pressure vs lap distance

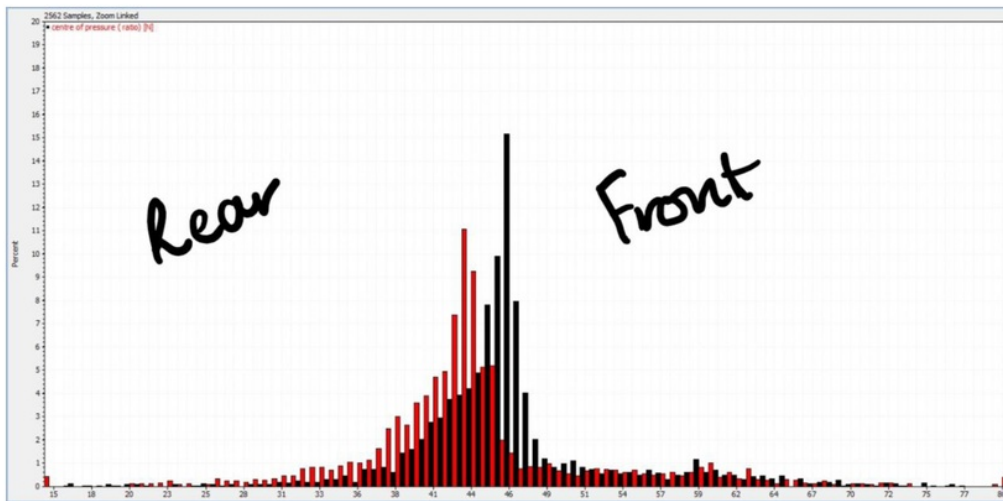


Figure 9: Centre of pressure histogram for both setups

4.2 Cornering, handling and steering

Lateral acceleration is linked to cornering; Segers (2014, pg230) states that “the higher speed in which a corner with a given radius is negotiated, the higher the lateral acceleration is”. This was analysed using a maths channel to compare lateral acceleration vs speed (see figure 10). From the graph it can be seen that there is little difference in the maximum lateral acceleration achieved in both setups. It is apparent that roughly the same amount of lateral acceleration is present for both right and left turns on the track for both setups; right turns are displayed as positive values on the chart and left are displayed as negative values (Karnopp, 2016). However, it can be seen that the red setup is faster to manoeuvre around the track than the black setup.

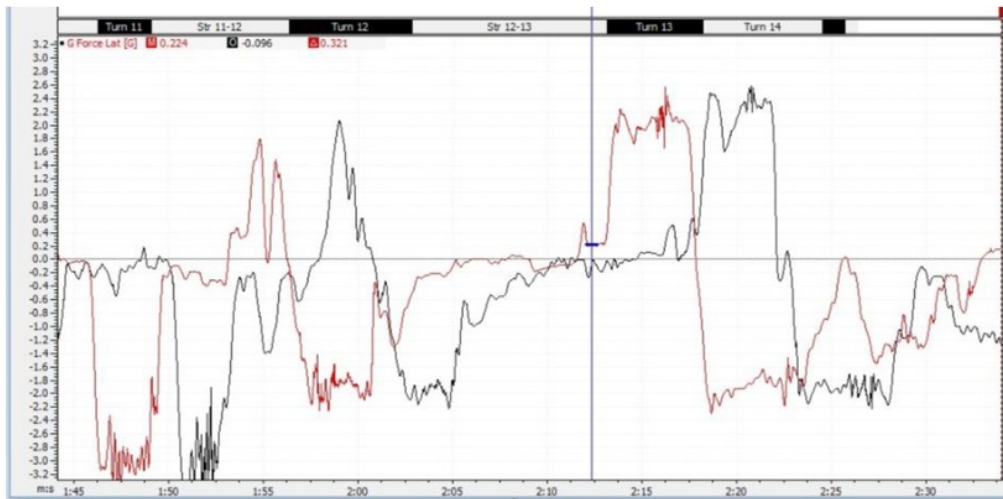


Figure 10: Maths channel, lateral acceleration vs speed

Longitudinal acceleration was then plotted against lateral acceleration to determine the amount of grip produced by both cars whilst travelling around the track. From figure 11 it can be seen that more lateral G's are present especially for the red setup. Therefore, this suggest that the red setup has more grip when cornering (Kenny,2016).

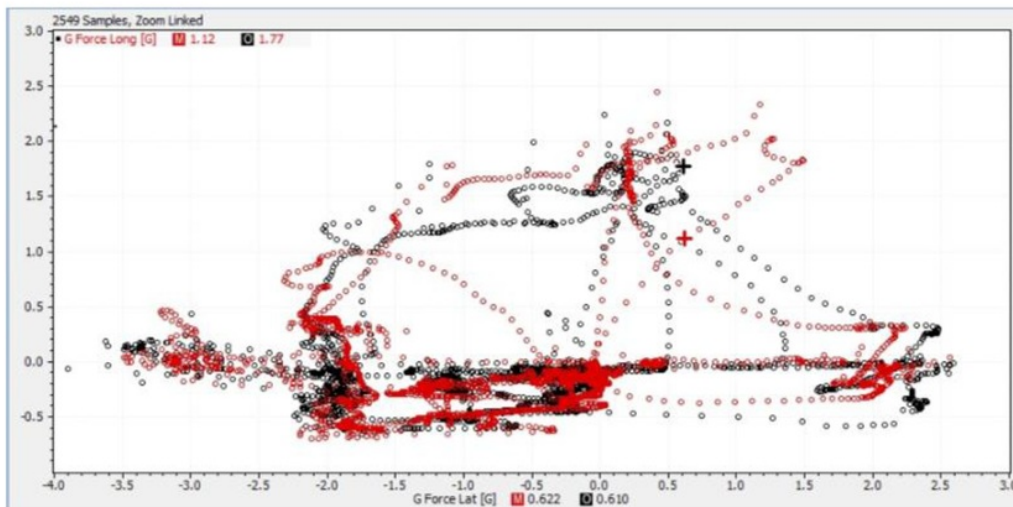


Figure 11: C-G diagram for both setups

To evaluate corner handling further, the corner radius was analysed (see figure 12), this relates to the line that the driver took across different corners of the track (Segers, 2014). Therefore, this will allow the corners of the circuit to be compared. The graph shows that the trace drops sharply for both lines suggesting that a sharp turn it is required (Templeman, 2008). However, on the red line it can be seen that there is a step up in the trace whilst during the corner (see red circle on the graph) and this could be an indication that understeering has occurred (Bentley, 2011).

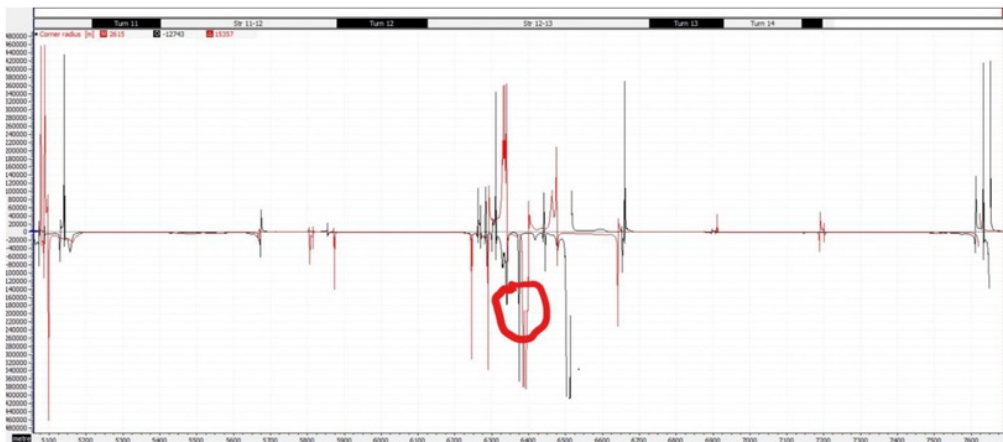


Figure 12: Corner radius

In order to analyse understeering further, a maths channel was created which compared understeering against distance. From figure 13 it can be seen that understeering is present during cornering on several occasions, this also matches driver feedback which states that slight understeer was present (see appendix B for driver feedback). Also, a slight increase in steering angle on the graph demonstrates that slight understeering has occurred on corner entry (Segers, 2014). In addition, there is a peak in the downforce and downforce decreases during this part of the course suggesting that understeering has occurred. It is apparent from the graph that understeer has not occurred for the black setup, this is consistent with the driver feedback which states that the setup was good at the front end and had lots of grip.

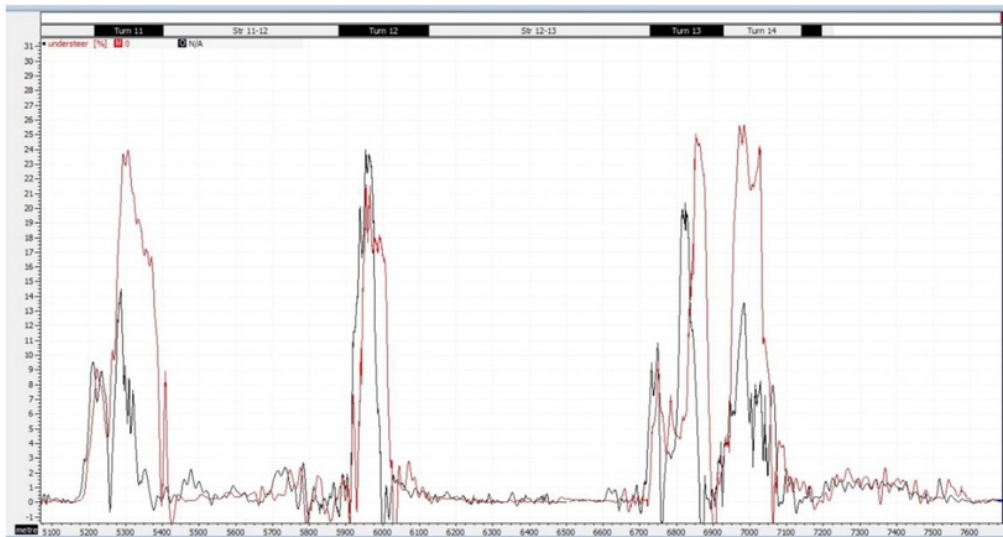


Figure 13: Maths channel understeer vs lap distance

Correct steering can be affected by using Ackerman steering geometry (Hucho, 2013). Maths channels were used to demonstrate how Ackerman steering angle can be determined (see figure 14). Before this, the required steering angle for both setups needed to be found (see equation 4-1), for the purpose of this example steady state low speed data was used (see red circles on figure 14). Theta could also be calculated using the theta maths channel (see blue circles on figure 14).

$$\text{Black} = \theta = \frac{\text{wheelbase}}{\text{corner radius}} = \frac{2.73}{-5148.04} = -0.001$$

$$\text{Red} = \theta = \frac{\text{wheelbase}}{\text{corner radius}} = \frac{2.73}{-5148.04} = -0.002$$

(Equation 4-1 required steering angle)

The Ackerman steering angle percentage was found using equation 4-2.

$$\text{Ackerman steering \%} = \theta \times X$$

$$\text{Black} = X = \frac{\text{Ack Wheel steer (rad)}}{\text{Wheel steer \%}} = \frac{0.24}{0.0005} = 480$$

$$\text{Ackerman steer \%} = -0.001 \times 480 = -0.48\%$$

$$\text{Red} = X = \frac{\text{Ack Wheel steer (rad)}}{\text{Wheel steer \%}} = \frac{0.93}{0.0024} = 387.5$$

$$\text{Ackerman steer \%} = -0.002 \times 387.5 = -0.075\%$$

(Equation 4-2 Ackerman steering angle)

From the equations above it can be established that the Ackerman steering angles for this part of the track are displayed in negative figures. According to Majerus (2007) negative values of X indicate negative steering angles for example left turns. Therefore, this could suggest that the car is bearing slightly to the left on this part of the track.

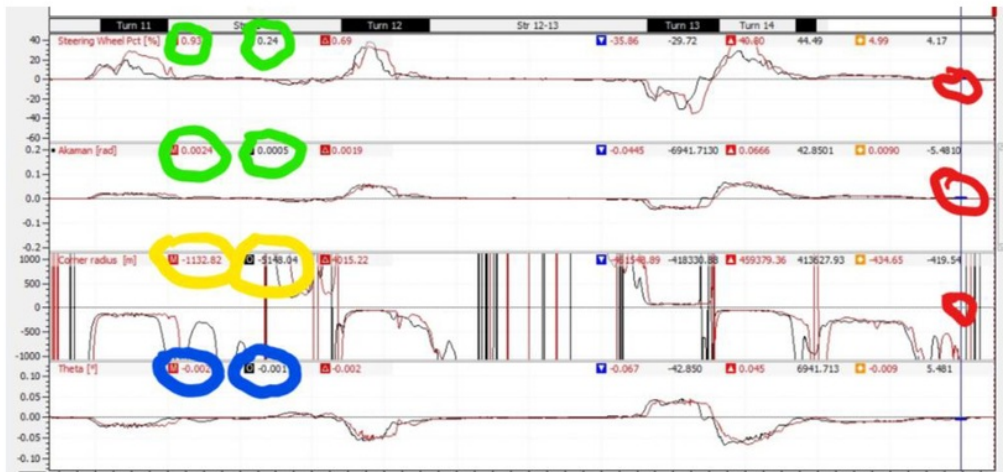


Figure 14: Maths channels used to work out Ackermann steering angle

To determine whether the setups affected vehicle-handling balance and permitted efficient corner handling, a theoretical steer maths channel was created (see figure 15). The top graph is related to the steering wheel position and is the actual steering trace that has taken place on the track. From this figure, it can be seen that understeering and oversteering has occurred on several occasions, this is highlighted in red and there are clear differences between the Ackerman maths channel and steering wheel position maths channel.

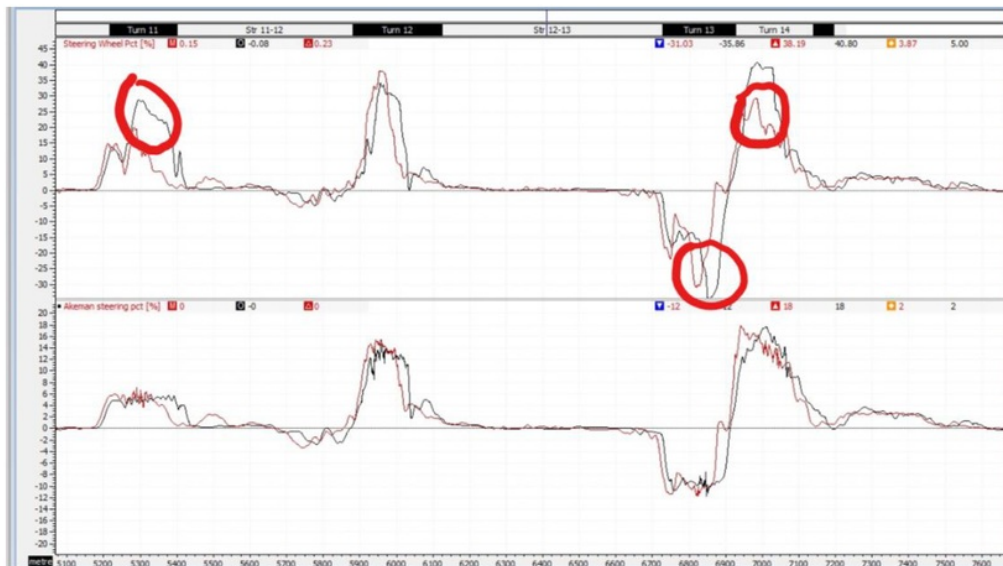


Figure 15 : Maths channel, theoretical steer vs steering wheel position

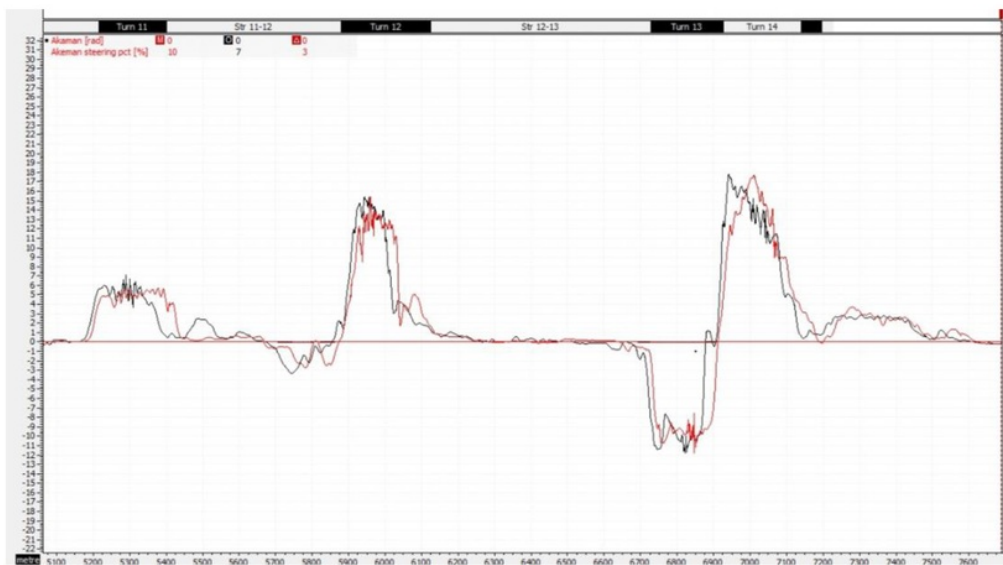


Figure 16: Rake angle

Next, the rake angle of the setups were compared (see figure 16). The rake angle is connected with the front and rear ride height and is linked to the front wing (Bentley, 2011). Furthermore, when the wing at the front is closer to the ground the generated downforce is increased (Kenny, 2012). Both setups have similar trace patterns suggesting that the rake angle is similar. According to Segers (2014) right height can also affect the rake angle;

however, as the ride height for both setups were the same this was not a factor that needed to be considered in this analysis.

4.3 Preferred set up for dry track racing

When deciding on the preferred track set up it is important that a number of aspects are taken into consideration; these being driver preference and time taken to complete the course. As the set up F1-F6 completed the lap the fastest and was the setup most favoured by the driver it would be logical to choose this setup. However, as there was a slight understeer present further correction work is needed on either driver technique or car setup, for example reduction of front tyre pressure (Glimmerveen, 2004). Furthermore, it is also important to consider the aerodynamic efficiency of both setups (see figure 17). From this figure it can be seen that the F1-R6 (red) setup is slightly more efficient than the second R18-F18 setup (black). Nevertheless, it is important to note that the driver believed that this set up was stable and had lots of grip; also, there have been many similarities in the maths channels for the both setups. Therefore, this setup is a close contender.

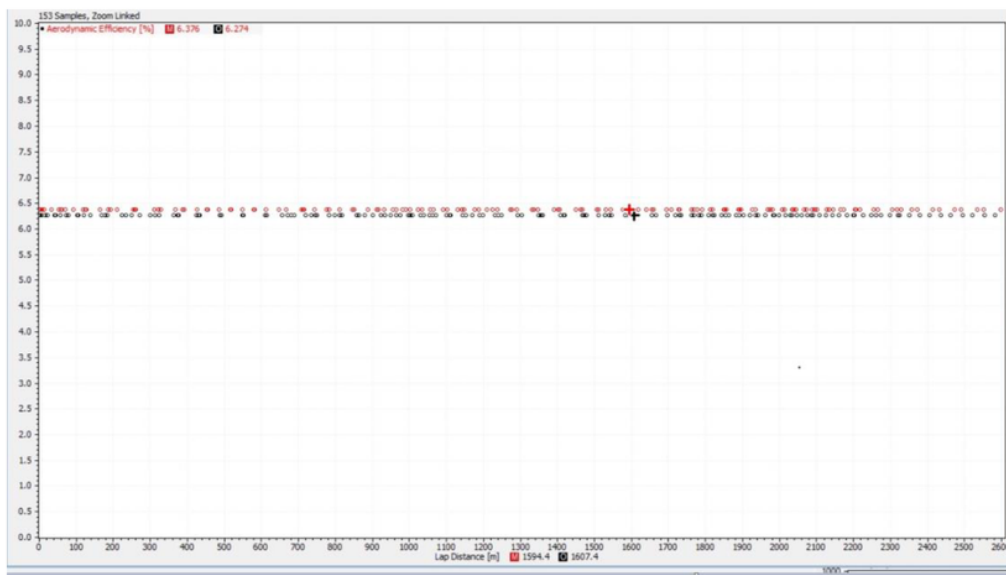


Figure 17: Maths channel, aerodynamic efficiency for F1-R6 and F18-R18

5.0 Conclusion

It was discovered in this study that different front and rear wing set-ups enormously affect factors such as handling, balance and grip. It was also found that setups influence the amount of downforce exhibited by a car and this impacts on cornering performance which subsequently affects the overall lap time. It was also established that downforce can have a negative effect on drag and top speeds on the straight. Balanced downforce was also discovered to be an important characteristic of effective handling performance as was longitudinal weight transfer. It was also learned that pressure forces affected downforce and that a greater percentage of rear pressure force had a positive effect on performance. Grip and stability, which were influenced by downforce and lift, promoted efficient corner handling and reduced the likelihood of understeering and oversteering. Overall it can be seen that horizontal and vertical aerodynamic forces have a significant influence on a car's handling performance and different setups can majorly manipulate these forces.

5.1 Further work and recommendations

It was recognised from early that only four of the circuit testing data sets matched the coast-down data sets and this was acknowledged to be a limitation of the study. Therefore, it is recommended that more data sets are matched and analysed in future. Nevertheless, the time constraints during this study may have made it a little difficult to compare more data. Also, when researching about lift, downforce and the rake angle it was found that ride height has an effect on vehicle aerodynamics, thus in future studies it would be advantageous to include ride height as a variable.

6.0 Reference List

- Altinisik, A. (2017) Aerodynamic coastdown analysis of a passenger car for various configurations. *International journal of automotive technology*. Vol 18(2). PP 245-254
- Bentley, G. (2011) *Ultimate speed secrets: Complete guide to high performance and race driving*. Monopolies: Motor books
- Buckley, F. (1995) ABCD - An improved coast down test and analysis method. *SAE International Journal of Passenger Cars*. PP 1136-1148
- Campbell, C. (2012) *The sports car: its design and performance*. London: Springer
- Chen, X., Duan, Y., and Zhang, Y. (2018) FSAE Race Car Dynamics and Trajectory Optimization Considering Aerodynamic Effects, *SAE Technical Paper 2018-01-0821*,
- Cai, J., Kapoor, S., Sikder, T., and He, Y. (2017) Effects of Active Aerodynamic Wings on Handling Performance of High-Speed Vehicles, *SAE Technical Paper 2017-01-1592*.
- Edgar, J. and Benard, R. (2019) *Modifying the aerodynamics in your car*. Dorset: Veloce Publishing
- Edmundson, C. (2011) *Fast car physics*. Baltimore: John Hopkins University Press.
- Ehirim, O. (2012) Optimal Diffuser Design for Formula SAE Race Car Using an Innovative Geometry Buildup and CFD Simulation Setup with On-Track Testing Correlation, *SAE Technical Paper 2012-01-1169*
- Glimmerveen, J. (2004) *Hands-on race car engineering*. Warrendale: SAE International and TV Motorsports
- Hauser, J. (2009) *Numerical Methods for Nonlinear Engineering Models*. USA: Springer
- Houghton, E. and Carpenter, P. (2003) *Aerodynamics for engineering students*. Oxford: Butterworth Heinemann
- Hucho, W. (2013) *Aerodynamics of road vehicles: from fluid mechanics to vehicle engineering*. Cambridge: University Press
- Huertas, J. and Coello, G. (2017) Accuracy and precision of the drag and rolling resistance coefficients obtained by on road coast down tests. *Proceedings of the International Conference on Industrial Engineering and Operations Management Bogota, Colombia, October 25-26, 2017*
- Jakirlic, S., Kutej, L., Basara, B. and Tropea, C. (2014). Computational study of the aerodynamics of a realistic car model by means of RANS and hybrid RANS/LES approaches. *SAE International Journal of Passenger Cars*. Vol 7 (2). PP559-574
- Katz, J. (2016) *Automotive Aerodynamics*. San Diego: Wiley and Sons
- Kato, D., Hashizume, Y., Kohri, I., and Takagi, M. (2011) Comparison of Impact Due to an Aerodynamic Component in Wind Tunnel and On-Road Tests, *SAE Technical Paper 2011-01-0157*

- Kenny, L. (2016) *The science of race cars: Studying force and motion*. Minnesota: ABDC Publishing
- Kumar, S. (2014) *Aerodynamics of F1 race car*. Oxford: Veloce Publishing
- Larose, G., Belluz, L., Whittal, I and Belzile, M. (2016) Evaluation of the Aerodynamics of Drag Reduction Technologies for Light-duty Vehicles: a Comprehensive Wind Tunnel Study," *SAE International Journal of Passenger Cars*. Vol 9(2). PP 772-784,
- Ljungskog, E., Sebben, S., Broniewicz, A. (2017) A parametric study on the influence of boundary conditions on the longitudinal pressure gradient in CFD simulations of an automotive wind tunnel. *Journal of Mechanical Science and Technology*. Vol 31(6) pp2821-2827
- Machin, R. (2015) *Introduction to race car aerodynamics*. (online) available from: https://www.competition-car-engineering.com/Racecar_Aero_intro.pdf [last accessed 26/02/2019]
- Majerus, J. (2007) *How to build a sports car safely*. London: RVI
- Mitchell, W., Staniforth, A., and Scott, I. (2006) Analysis of Ackermann Steering Geometry, *SAE Technical Paper 2006-01-3638*
- McBeath, S. (2017) *Competition car aerodynamics*. 3rd eds. Dorset: Veloce Publishing
- Pascoa, J., Brojo, F., Santos, F. and Fael, P. (2012) An innovative experimental on-road testing method and its demonstration on a prototype vehicle. *Journal of Mechanical Science and Technology*. Vol 26(6). PP1663-1670
- Rashaduddin, M. and Waheedullah, A. (2017) A study of airflow over a car. *International Journal of Science, Engineering and Technology*. Vol 5 (3). PP21-28
- Regerts, T. and Lajos, T. (2007) Description of flow field in the wheelhouses of cars. *International Journal of Heat and Fluid Flow*. Vol 28 (1). PP 616-629
- Sergers, J. (2014) *Analysis Techniques for Racecar Data Acquisition*. 2nd Eds. Warrendale: SAE International
- Seward, D. (2014) *Race car design*. London: Palgrave Macmillan
- Templeman, G. (2008) *The competition car data logging manual*. Dorset: Veloce Publishing
- TotalSim (No, date) *Importance of aerodynamics* (online) available from: <https://www.totalsimulation.co.uk/secrets-formula-1-part-2-importance-aerodynamics/> [last accessed 29/03/2019]
- Yakunndi, V. and Mantha, S. (2018) Effects of spoilers on Aerodynamic Properties of Car. *International Journal of Scientific Research and Review*. Vol 7 (3) 271-280

7.0 Appendices

Appendix A – test plan

Aerodynamics Test plan	
Testing objectives : To carry out a series of tests on different aerodynamic setups in order to distinguish aerodynamic and handling performance of the F3 Race car model	
Type of test and track used: <i>Coast down test – Skid pad</i>	<i>Aerodynamic circuit – Silverstone/Skidpad for Ackermann</i>
Specific test details: Driver to stop on start line then accelerate to 220(kph) once driver has reached the (kph) required, then put the car in to neutral and coast down until car has stopped. Repeat this for every run until coast down data has been collected. Once data has been collected coast down can be stopped when cars speed has decreased to 100(kph).	Driver to come out of the pit and complete out lap. Then data will be used from completed lap if no driving errors occur. Driver will be de-briefed after every setup.
Equipment needed: Base performance simulator Motec	Base performance simulator Motec
Specific information: Ride height – front 3, rear 5 Air density - 1.223 Kg/m ³ Frontal Vehicle area- 1.2m ² Total vehicle mass – 560kg Dry test conditions	Specific information: Ride height – front 3, rear 5 Air density - 1.223 Kg/m ³ Frontal Vehicle area- 1.2m ² Total vehicle mass – 560kg Dry test conditions
Team roles: Driver – drive car, listen to instruction and provide feedback Team member 1 – data collection Team member 2 – data collection Team member 3- input data into spreadsheet Team member 4- driver debrief Team member 5- start/stop, adjust data Team member 6 – relay instructions to driver	Driver – drive car, listen to instruction and provide feedback Team member 1 – data collection Team member 2 – data collection Team member 3- input data into spreadsheet Team member 4- debrief driver Team member 5- start/stop, adjust data Team member 6 – relay instructions to driver
Aerodynamic setups measures:	Front splitter and rear wing:

Test (T) 1 - Front 1 - Rear 1	Test (T) 1 - Front 11 – Rear 12
T2- Front / Front 1 – Rear/Rear 1 (Re-test)	T2 - Front 1 – Rear 1
T3 - Front 18 - Rear 18	T3- Front 18 – Rear 18
T4 - Front / Front 18 – Rear/Rear 18 (Re-test)	T4 - Front 9 – Rear 9
T5 - Front 3 - Rear 1	T5 -Front 1 – Rear 18
T6 - Front / Front 3 – Rear/Rear 1 (Re-test)	T6 -Front 1 – Rear 9
T7 - Front 6 - Rear 1	T7 -Front 1 – Rear 6
T8 Front / Front 6 – Rear/Rear 1 (Re-test)	T8 -Front 1 – Rear 12
T9 Front 1 - Rear 3	T9 -Front 1 – Rear 10
T10 Front 1 - Rear 6	T10- Front 2 – Rear 12
	T11 -Front 3 – Rear 12
	Setup's for Front splitter and Rear wing + Ride height
Coasted down to 100 (kph) then stopped test:	Ride height –
T11 Front 9 - Rear 9	T12 - Front 2 – Rear 4
T12 Front 12 - Rear 12	T13- Front 2.5 – Rear 4.7
T13 Front 15 - Rear 15	T14- Front 2.7 Rear 4.7
T14 Front 6 - Rear 6	T15- Skid pad test for Ackerman steering.

Appendix B – Driver feedback

Tim's test session 2 feed back

Ratings: Understeer oversteer

1 5 10

F= Front wing

R=Rear wing

FH= Front height (CM)

RH= Rear height (CM)

Adjustments	Ratings	Feed back
Default (F11,R12) (FH 3, RH 5)	N/a	Fairly balanced, limited grip, low speed okay, slight under steer.
F1,R1 (FH 3, RH 5)	N/a	Slightly more grip, oversteer slightly, slightly more stable.
F18,R18 (FH 3, RH 5)	6	Loads of grip, lot more stable, good front end, touch the apex much better.
F9,R9 (FH 3, RH 5)	7	Slight less stable, more to over steer. (no phone record)
F18,R1 (FH 3, RH 5)	8	Very oversteery, brakes okay (worst setup so far)
F9,R1 (FH 3, RH 5)	6.5	Slightly less oversteer
F1,R18 (FH 3, RH 5)	4	Slightly under steer, safe to drive as always find the limit on the grip, low speed understeer.
F1,R9 (FH 3, RH 5)	5	Nice balance good confidence in car high speed, understeer low speed corner.
F1,R6 (FH 3, RH 5)	4.8	Best setup, so far loads of grip, very stable slightest understeer.
F1,R12 (FH 3, RH 5)	4.8	Slight understeer, high speed still stable, top out at a higher speed.
F1,R10 (FH 3, RH 5)	4.5	Balance good, slight understeer, less grip overall, didn't feel good when planted at high speed corner.
F2,R12 (FH 3, RH 5)	5	Perfect balance, slight understeer low speed corner, felt very planted.
F3,R12 (FH 3, RH 5)	4.5	Balance very good, not as much grip as previous, low speed understeer, high speed corner scrubbing across track as not enough grip.
F2,R12 (FH 2CM, RH 4CM)	4	Felt more understeer, general good grip overall, low speed corner responded well to inputs.
F2,R12 (FH 2.5, RH 4.5)	4.8	Tiny bit understeer, flat out very good high speed through corner which couldn't previous low speed felt good.

Appendix C – Driver instructions**Driver instructions – Coast down test**

1. You (the driver) are required to head down in the track in a straight line, avoid any movement in steering.
2. Accelerate to 220kph, travelling up the gears as doing so.
3. Once you have reached the required KPH of 220, shift the car into neutral and continue to coast down until the vehicle has stopped, avoid applying brake at any time. Also attempt to avoid steering fluctuations
4. The same test will be repeated 10 times
5. Follow the same procedure as listed above but instead of coasting down to 0, this time coast down to 100KPH.
6. Repeat this a further 3 times.
7. Provide any feedback necessary to other team members and listen to feedback from team

Driver instructions – Aerodynamic circuit test

1. Exit the pit and complete warm up lap, this will enable you to familiarise yourself with the road surface/patterns and factors which may affect driving conditions.
2. Once you have completed the out lap, continue straight to test laps without stopping in the pit. Take the first corner as fast but as controlled as possible.
3. Travel down the straight, slow down before the next corner, travel straight and slow down before next sharp corner.
4. Continue lap as long as no errors occur, if errors do occur then start the lap from the beginning.
5. Repeat the following steps for each step up.
6. You will be debrief following each set up.
7. For test 15 you will be required to complete test on skid pad, drive around the skid pad at the same speed.

Appendix D – testing schedule

Number of simulation sessions required: 2 - coast down test x1 , aerodynamic circuit x1

First test to complete: **Coastdown test**

Time required: 1 hour

Tests required: see test plan

Date that testing will take place: TBC

Test objectives: Distinguish aerodynamic and handling performance of the F3 Race car model

Test track used: Skid pad

Second test to complete: **Aerodynamic circuit test**

Time required: 1 hour

Tests required: see test plan

Date testing will take place: TBC

Test objectives: Distinguish aerodynamic and handling performance of the F3 Race car model

Test track used: Silverstone
Skidpad

Appendix E – Maths channel equations

Math Items :	
Name	Summary
Expressions	
☒ wt long	$(\text{mass} \text{ [kg]} * (\text{G Force Long} \text{ [G]} - 1) * \text{'Cog'} \text{ [m]}) / \text{'wheelbase'} \text{ [m]}$
☒ front aero [N]	$(\text{Tire Load - FL} \text{ [N]} + \text{Tire Load - FR} \text{ [N]}) - \text{'flo'} \text{ [N]} - \text{'fro'} \text{ [N]} + \text{'wt long'}$
☒ rear aero [N]	$\text{Tire Load - RL} \text{ [N]} + \text{Tire Load - RR} \text{ [N]} - \text{'rlo'} \text{ [N]} - \text{'RRO'} \text{ [N]} - \text{'wt long'}$
☒ speed m/s [m/s]	$(\text{Corr Speed} \text{ [km/h]} * 1000) / (60 * 60)$
☒ centre of pressure (ratio) [N]	$\text{front aero} \text{ [N]} / \text{'total aero'} \text{ [N]} * 100$
☒ total aero [N]	$\text{front aero} \text{ [N]} + \text{'rear aero'} \text{ [N]}$
☒ Aero drag force	$(0.5 * \text{'air density'} \text{ [kg/m3]} * \text{'Cd'} * 1.2 * (\text{speed m/s} \text{ [m/s]} * \text{'speed m/s'} \text{ [m/s]}))$
☒ Corner radius [m]	$(\text{speed m/s} \text{ [m/s]} * \text{'speed m/s'} \text{ [m/s]}) / (\text{G Force Lat} \text{ [G]} * \text{'g'} \text{ [m/s/s]})$
☒ Akaman [rad]	$(\text{'wheelbase'} \text{ [m]} / \text{'Corner radius'} \text{ [m]}) * -1$
☒ Akeman steering pct [%]	$(\text{'Akaman'} \text{ [rad]}) * (28.60 / 0.1075)$
☒ understeer [%]	$\text{abs}(\text{'Steering Wheel Pct'} \text{ [%]}) - \text{abs}(\text{'Akeman steering pct'} \text{ [%]})$
☒ Total aero lift [N]	$0.5 * \text{'air density'} \text{ [kg/m3]} * \text{'cl'} * \text{'speed m/s'} \text{ [m/s]}^2$
☒ Theta [deg]	$(\text{'wheelbase'} \text{ [m]}) / (\text{'Corner radius'} \text{ [m]})$
Constants	
☒ air density [kg/m ³]	1.223
☒ Cog [m]	0.23
☒ flo [N]	1170
☒ fro [N]	1159
☒ g [m/s ²]	9.81
☒ mass [kg]	560
☒ rlo [N]	1580
☒ RRO [N]	1584
☒ wheelbase [m]	2.73

