

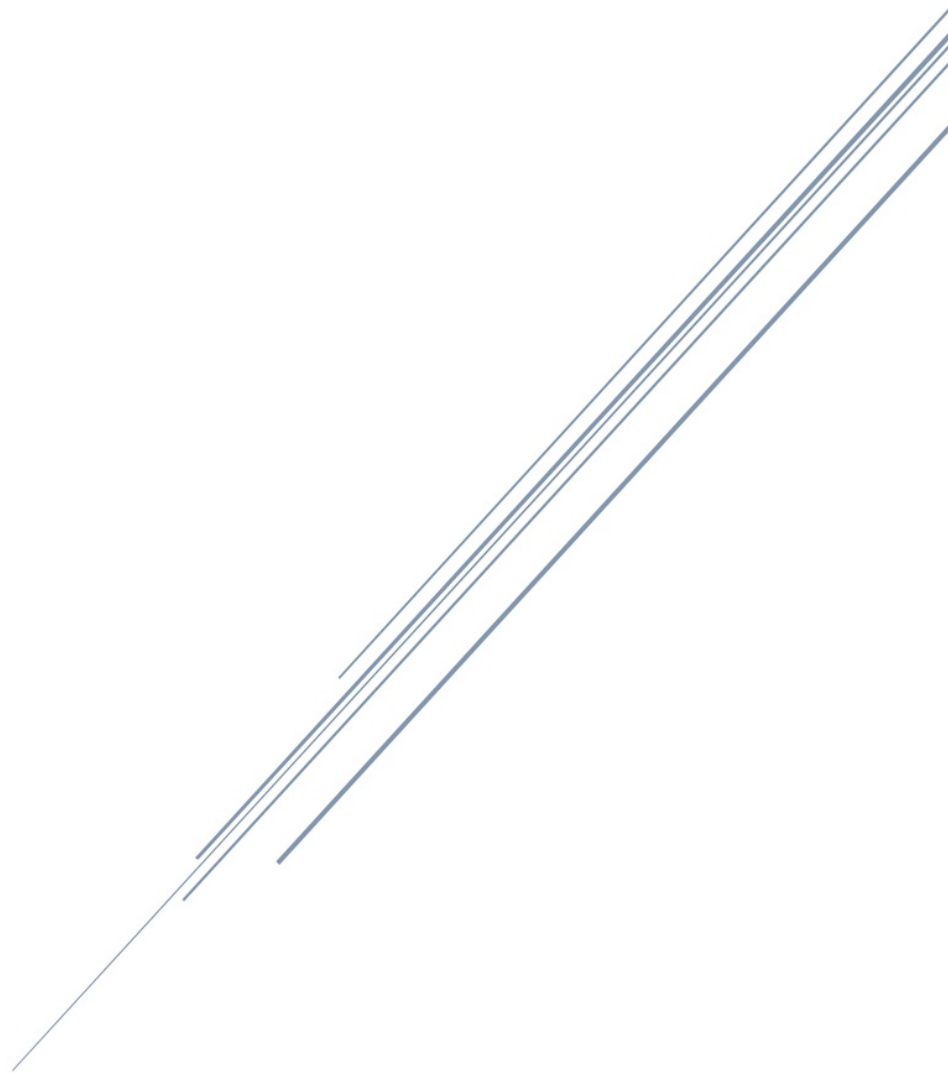
aerodynamic vehicle testing and analysis

by Luke Cripps

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TIME SUBMITTED	31-MAR-2019 09:03PM (UTC+0100)	WORD COUNT	2646
SUBMISSION ID	103726433	CHARACTER COUNT	16222

AERODYNAMIC VEHICLE TESTING AND ANALYSIS

Race Engineering



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Introduction

The aim of this assignment is to analyse the aerodynamic and handling characteristics of a Formula F3 race car, through a combination of straight line and circuit testing, using various different car setups. The analysis would then be used to decide upon the most suitable setup to be used for a dry race. Two planned test sessions using a racing simulator will be used to produce the data needed to perform the analysis. Analysing the data will range from comparing the coefficients of lift and drag for the differing setups using data from the straight line testing, to comparing the amount of understeer that is present, through the use of calculating the Ackerman steering angle.

Research

The aerodynamic drag of a vehicle has a direct effect on the top speed that is achievable. An increased drag force will result in a decreased top speed, as explained by Hucho, 2013. However, the aerodynamic drag of the vehicle has a direct influence of the downforce available for cornering, justified by Bentley, 2011. This means to be able to corner efficiently, a compromise in top speed is needed. The change in downforce can mean that through a slow corner, understeer may be experienced, but through high speed corners, oversteer could be noticed.

The coefficient of lift has a direct effect on the handling characteristics of the vehicle, defined by Hucho, 2013. Decreasing the coefficient at one axle of the vehicle will have a direct impact at both ends of the car, a larger effect being seen at the front of the vehicle.

Centre of pressure or aero balance is the proportion of downforce acting on the front axle with respect to the total downforce acting on the entire vehicle, and is given as a percentage, explained by Quintarelli, 2018. The percentage illustrates its position in between the front and rear wheels. The position of the centre of pressure has an influence on the handling of the vehicle, where if the location is towards the rear, the car is more stable, tending to understeer during fast corners, whereas being located near the front of the vehicle will provide more grip through high speed corners, meaning less understeer.

Methodology

To prepare for the two test sessions, the time spent during the one point five hour time frame needed to be planned to make sure that no time was wasted, as explained by Bagewadi, 2017. Each member of the team has a task to perform, and mistakes cannot occur during the session, as the consequence of that happening would be less time to test the other setups chosen through the planning process. The test plans can be found in the appendix, from appendix 1 through to appendix 2b. The circuit chosen for circuit testing was Silverstone National, as it provided a mixture of left and right hand corners, as well as high and low speed ones.

Using the data from the first test session, the coefficients for lift and drag can be calculated. To achieve this, firstly, the tyre loads of the car need to be found while stationary and while the vehicle is in motion. To do this, a data set from the first session needs to be loaded into the motec software, and the tyre load figures, found on the right hand side of the window, under the channels section,

need to be recorded. The diagrams below illustrate how the values are found, as well as the top speed of the setup:

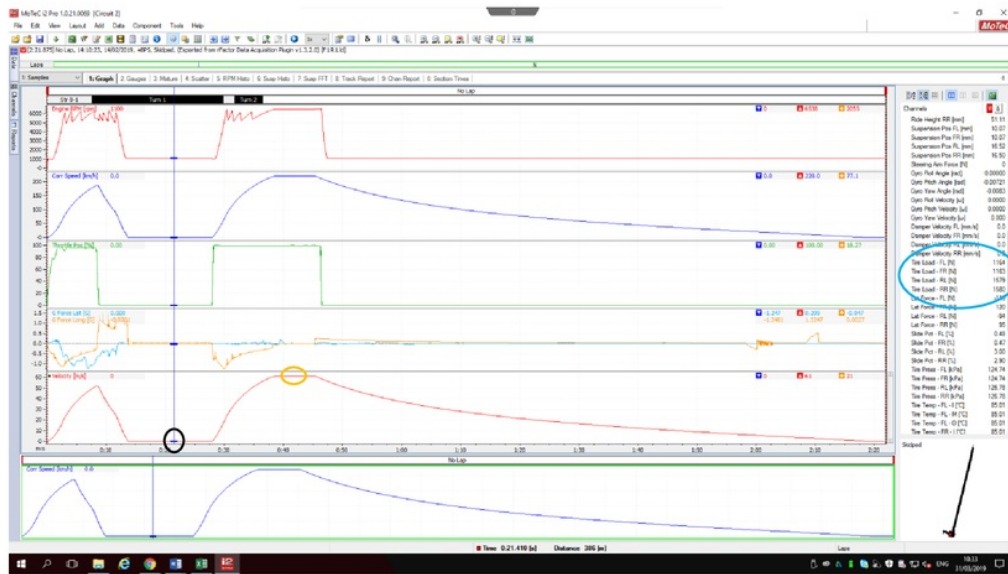


Figure 1 - How to find the tyre loads for at zero velocity and constant velocity

After the values for the tyre loads have been collected, the aero force acting on the front of the vehicle is the next calculation that needs to be carried out, as to be able to calculate the coefficient of lift, the lift force (aero) needs to be known, explained by Maloney, 2018. To calculate the aero force acting on the front axle of the vehicle, the value of the constant velocity loads added together needs to be deducted from the combined value for the static tyre loads. The same calculation needs to be carried out at the rear of the vehicle. The diagram below illustrates this process:

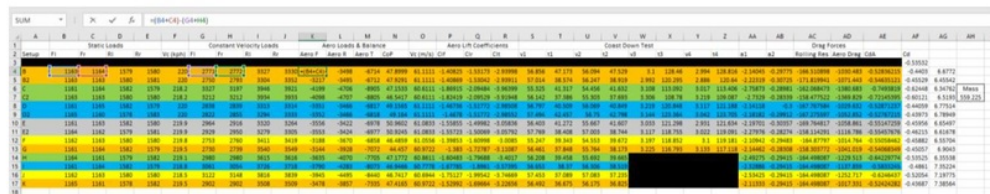


Figure 2 - How aero force is calculated at the front of the vehicle

The coefficient of lift can now be calculated at the front, and the rear of the vehicle. Furthermore, the total lift coefficient can be worked out by adding the front and rear together. The equation below illustrates how coefficient of lift is calculated:

$$C_{lf} = \frac{2 \times \text{Aero F}}{\rho \times v^2}$$

C_{lf} = Coefficient of lift

$Aero F$ = Aero force acting on the front of the vehicle (N)

ρ = Density of air (1.223kg/m³)

v = Velocity (m/s)

The diagram below illustrates this process:

[illegible]

Figure 3 - How to calculate the coefficient of lift at the front of the vehicle

To calculate the coefficient of drag, the rolling resistance, and the aerodynamic drag need to be calculated for each specific setup. The reasoning for calculating both rolling and aerodynamic resistance is because at high speed, the vehicle will be under the effect of both of these concepts, but at low speed, aerodynamic resistance becomes negligible as the volume of air flowing around the car has no effect on the performance of the vehicle, as explained by the work of Mr Aniket Bhawe, 2014.

To work out the rolling and aerodynamic resistances, the rate of deceleration needs to be known. To work this out, velocity and times need to be taken from the motec data and inputted to the spreadsheet. Four sets of times and velocities need to be recorded, two need to be at the beginning of coast down test, as the retardation calculated will include both rolling and aerodynamic resistance, while the other two sets need to be taken at the end of the coast down test, so that only rolling resistance is affecting the retardation. The diagram below illustrates this process:

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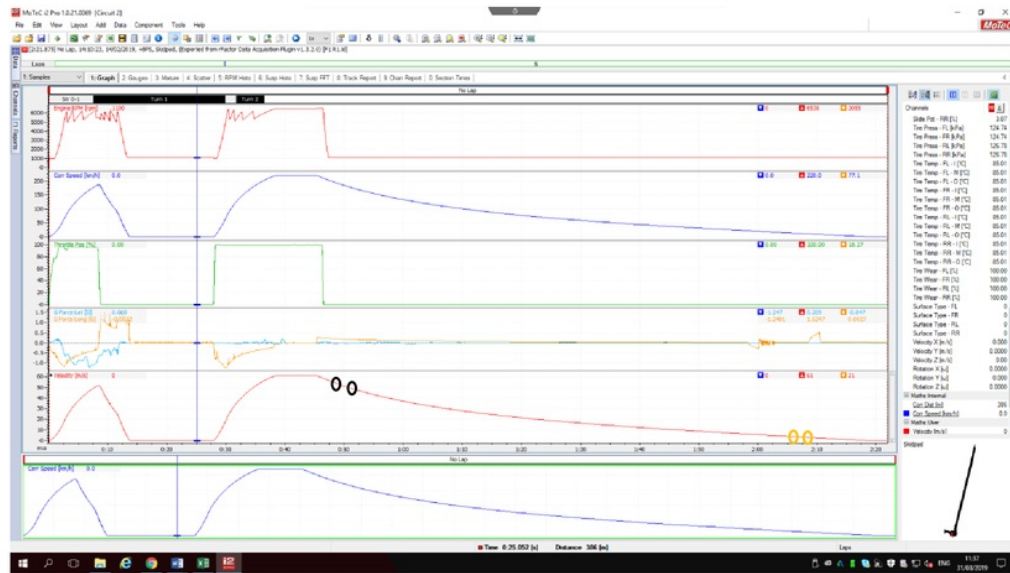


Figure 4 - Where the velocities need to be taken from the motec data

Once those values have been recorded, the rate of deceleration can be calculated using the following equation:

$$a_1 = \frac{v_2 - v_1}{t_2 - t_1}$$

a = Acceleration (m/s/s)

v = Velocity (m/s)

t = Time (s)

Now the decelerations have been worked out, rolling resistance can be worked out by using Newton's second law $F=MA$, as explained by Croce, 2005. The diagram below illustrates this process:

SUM																																				
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	
1	Blank Location																																			
2	Consistent Inventory Levels																																			
3	Aero Launch & Brance																																			
4	Aero Lift Capabilities																																			
5	Clearance Down Time																																			
6	Drug Types																																			
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8	2	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		
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44	38	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000		
45	39	1000	1000	1000	1000	1000	1000	100																												

Figure 5 - How to calculate rolling resistance acting on the vehicle

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Then using the calculated rolling resistance, the aerodynamic drag can be worked out by taking away rolling resistance from mass multiplied by acceleration one, as that will leave just aerodynamic resistance. The diagram below illustrates this process:

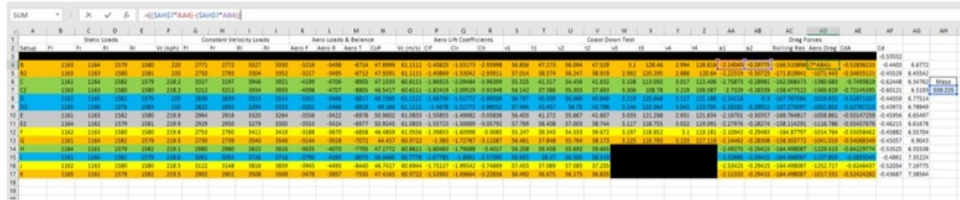


Figure 6 - How to calculate the aerodynamic force acting on the vehicle

Using the calculated aerodynamic drag, the coefficient of drag can now be worked out, using the following equation, provided by Engineering Toolbox, 2004:

$$F_d = C_d \times 0.5 \times \rho \times v^2 \times A$$

$$F_d = \text{Aerodynamic Force (N)}$$

C_d = Coefficient of Drag

ρ = Density of Air (1.223kg/m³)

v^2 = Velocity (m/s)

A = Frontal Area (m²)

The following diagram illustrates this process:

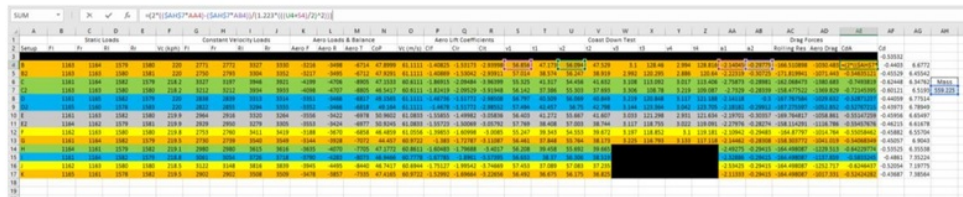


Figure 7 - How to calculate the coefficient of drag for the vehicle

Now all the values for coefficient of drag have been calculated, the analysis of the circuit testing can be started. To be able to do the analysis efficiently, math channels need to be created in the motec software. For these math channels to work, there are some constants that need to be inserted. To add constants, select tools, under the drop-down menu, select maths. Once open, select the add constants option. The process can be seen in the diagram below:

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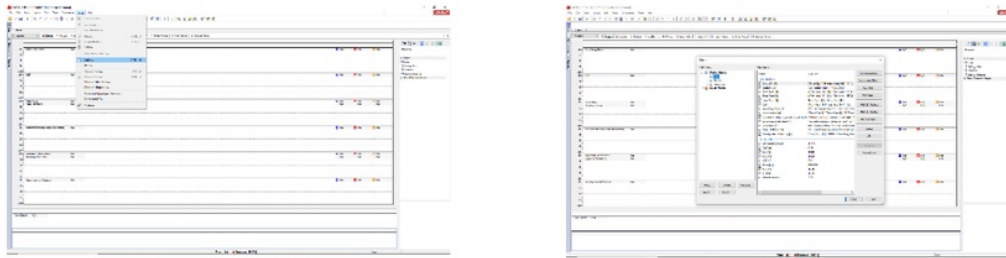


Figure 8 - The process for adding constants into the motec software

Now all required constants are in place, math channels can be made to define some of the aerodynamic and handling characteristics of the specific setup, including understeer and centre of pressure. However, some of these math channels require more information than others. When calculating the aerodynamic drag around the lap for the differing setups, the same coefficient of drag for one setup cannot be used for another, as two different setups will have two different coefficients of drag.

To counter this, an excel spreadsheet within motec can be used where the date and time of the different setups can be inputted with the calculated coefficient of drag from the straight-line testing. A diagram of this can be seen below:

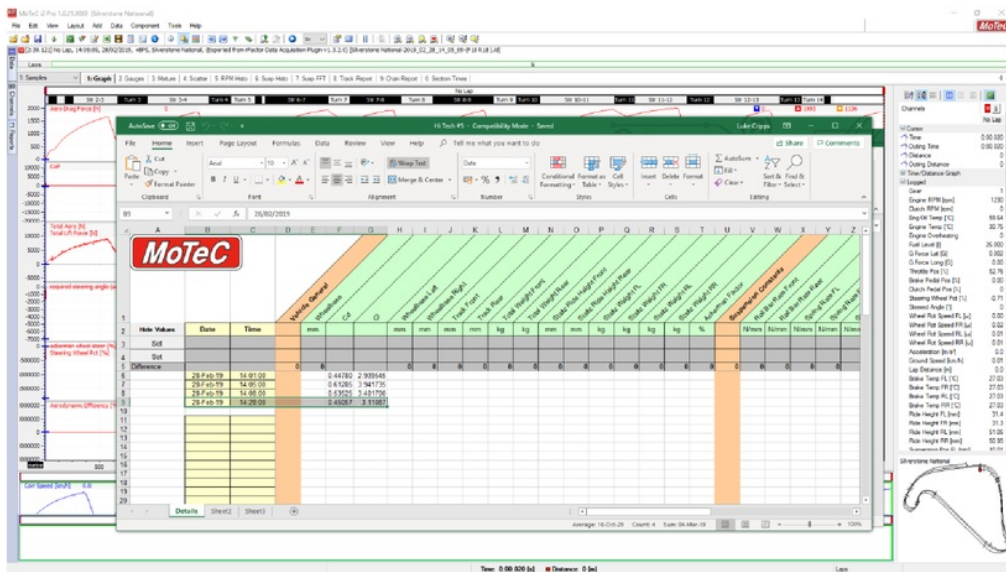


Figure 9 - The excel spreadsheet used in motec for coefficient of drag

All the math channels used can be seen in appendix 3.

There are additional steps that need to be carried out in order to create the math channel for Ackerman steering percentage. The last run of the second test session was used to aid with the calculation, using a skid pad as the track. Firstly, the Ackerman steering angle needs to be calculated first: wheelbase divided by corner radii multiplied by -1, so that the value has the same sign as steering percentage. Once this has been calculated, the data for the skid pad needs to be loaded up and have both the Ackerman steering angle and wheel steer percentage channels open. A point in

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the data needs to be selected, as seen in the diagram below, so that two values, one for Ackerman angle, and one for wheel steer percentage can be recorded. Then using those numbers, the number equation for Ackerman steering percentage can be written.

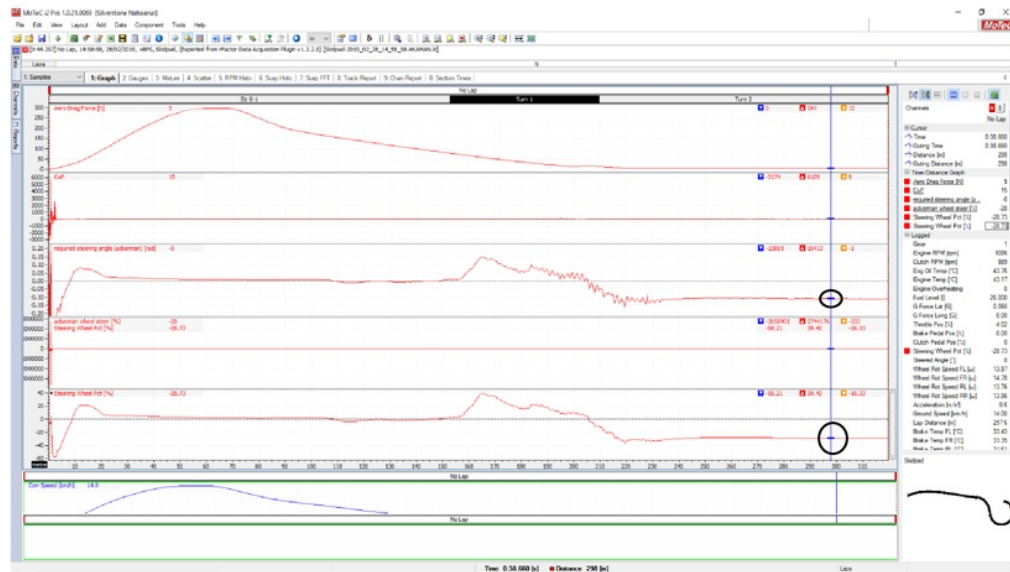


Figure 10 - The points on the skip pad data to get the values to calculate Ackerman steering percentage

Results and Analysis

The spreadsheet showing the results of the straight-line testing can be viewed in the appendix, under appendix 4. For all the graphs shown, unless specified, they follow the same key:

	F18, R18
	F9, R9
	F1, R6

Table 1 - The key used for the following figures

The first math channel to compare is for total lift force against lap distance:

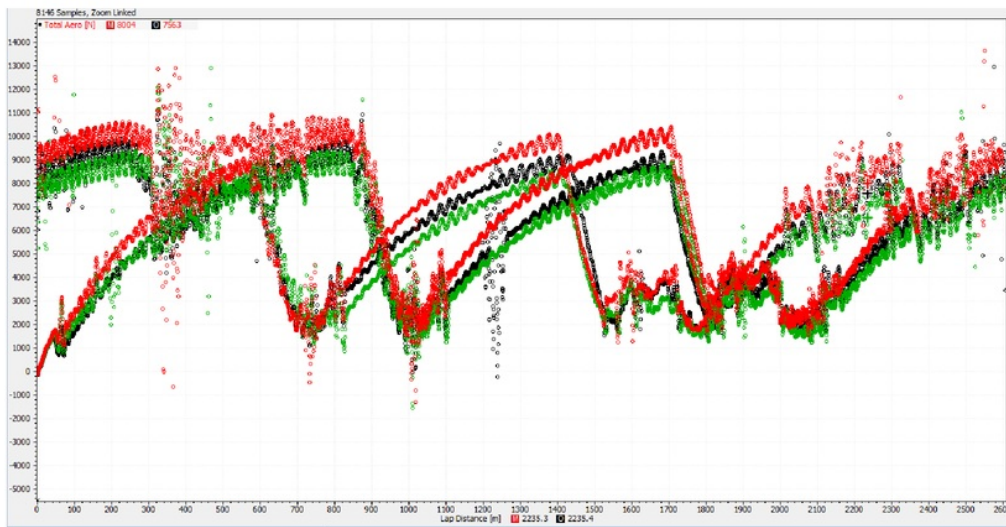


Figure 11 - A graph showing the correlation between total lift force and lap distance for three setups

Looking at the figure above, the trends visible are true to what is expected, as the red setup has the highest degree change to its setup, so would produce more lift when compared to the other two variations.

The next characteristic to check is aerodynamic drag force created by the three different setups, shown in the diagram below:

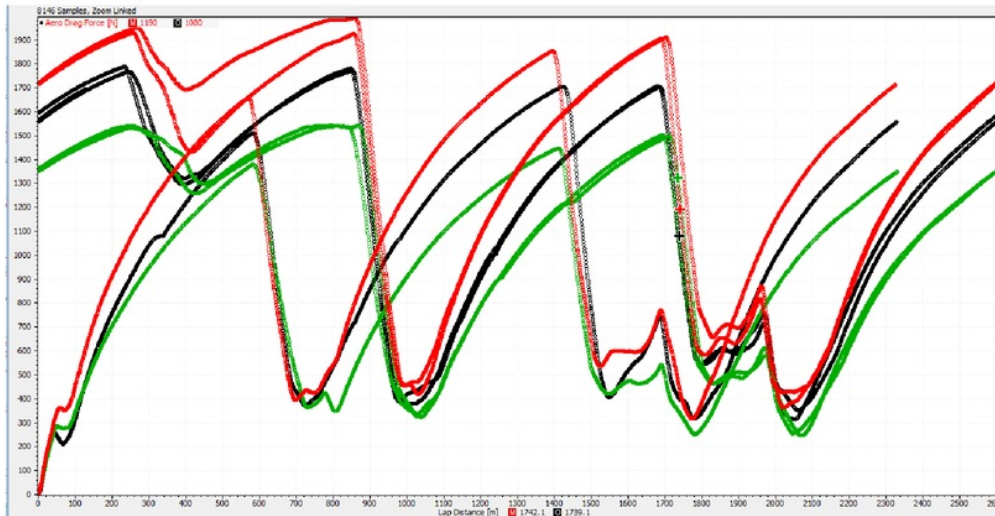


Figure 12 - A graph showing the correlation between aerodynamic drag force and lap distance for three setups

Looking at the figure above, the trend lines the different setups are taking show that the red setup is producing the most drag, as it should, as it also produces the most negative lift (downforce), therefore meaning that the green setup should achieve the greatest top speed.

Total aero against speed is the next characteristic that needs to be compared. Graphs for the individual setups can be seen the appendix, from appendix 5a through to 5c. The diagram below compares all three setups together:

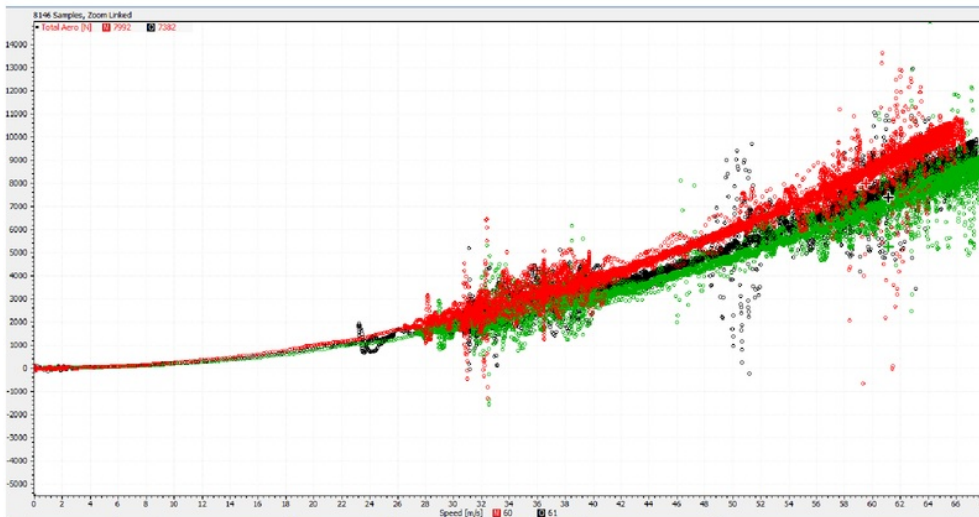


Figure 13 - A graph showing the correlation between total aero and speed for three setups

Looking at the figure above, there is further confirmation that the green setup can provide the greatest top speed out of the three setups, however, it produces the lowest amount of downforce, when compared to the red setup. The black setup can produce more downforce then the green but is not able to reach the top speed of the green.

Lateral acceleration against speed is the next element to compare. Individual graphs for the different setups can be viewed in the appendix, from appendix 6a through to 6c. The following diagram shows the comparison between the three setups:

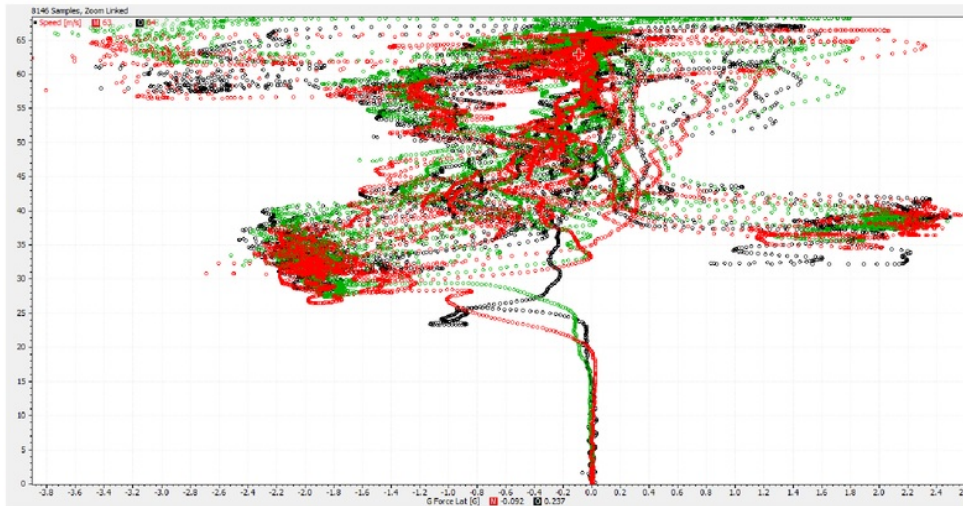


Figure 14 - A graph showing the correlation between speed and lateral acceleration for three setups

The figure above confirms the top speed capability of the green setup. It also shows that the red setup can take left corners at a greater velocity, due to the greater lateral acceleration. All three setups are quite balanced on right hand corner speed, with the green setup able to carry more speed through the first corner.

The aero force acting on the front and rear axles individually needs to be looked at. The diagram below shows the comparison for the front axle:

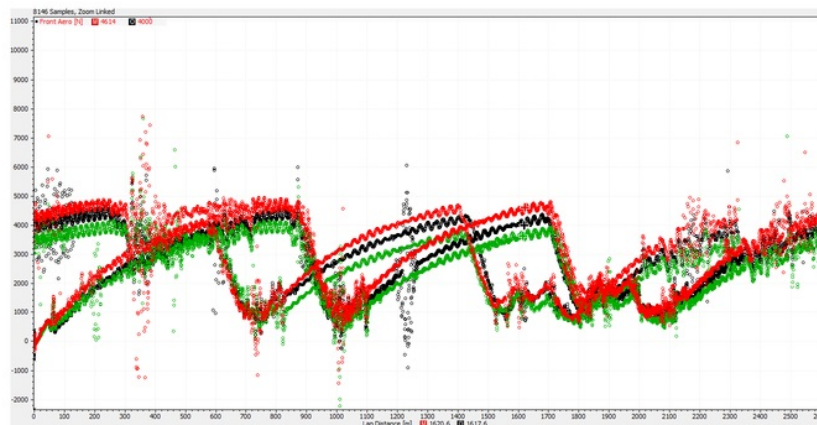


Figure 15 - A graph showing the correlation between front aero and lap distance for three setups

The aero force on the front axle across all three setups is very similar with the red setup having greatest downforce, which is expected, due to having the greatest wing change. The aero force acting on the rear axle can be seen in the diagram below:

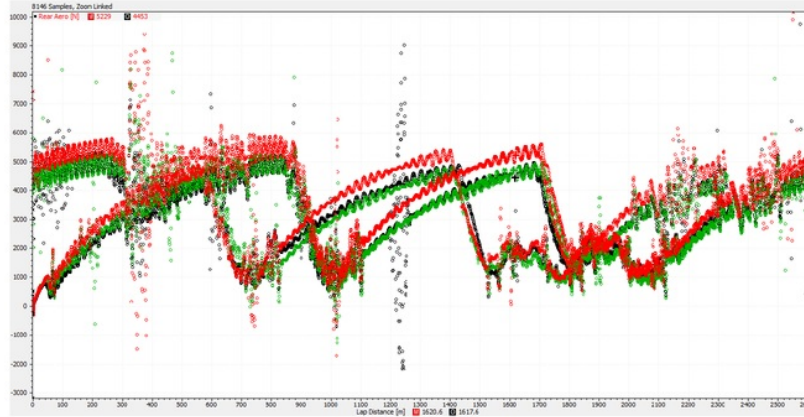


Figure 16 - A graph showing the correlation between rear aero and lap distance for three setups

The aero force for the black and green setup is very similar, due to the rear wing setup being very similar. The red setup is showing greater downforce, due to its greater wing setup.

Centre of pressure (CoP) is the next characteristic to compare. The following diagrams illustrate the comparison between the different setups:

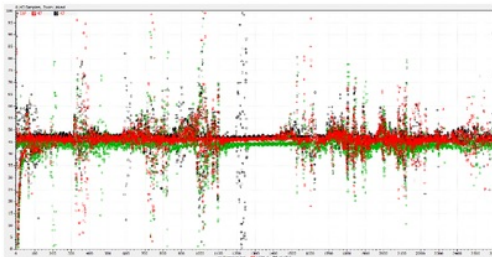


Figure 18 - A graph showing the correlation between centre of pressure and lap distance for three setups

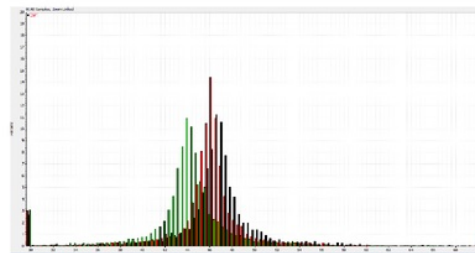


Figure 17 - A graph showing the correlation between centre of pressure and time for three setups

Looking at the figure on the left, the centre of pressure stays stable throughout the lap, with the red and black setups having similar CoPs due to the setups of the front and rear wing being equal. For the green setup, the CoP is further forward compared to the other two. The diagram on the right shows that the CoP of the red setup is the more stable out of the three, and further confirms the similar CoPs of the red and black setups.

Understeer is a very important handling characteristic of the vehicle. The diagram below shows the comparison between the three setups:



Figure 19 - A graph showing the correlation between understeer and lap distance for three setups

The green setup is producing more understeer compared to the red and black, meaning that more steering angle (percentage) is needed to get around the corners, as visible in the following diagram looking at the difference between Ackerman steering percentage and steering percentage for the different setups. Graphs for the individual setups can be viewed in the appendix, from appendix 7a through to 7c. The purple line represents the Ackerman steering percentage:

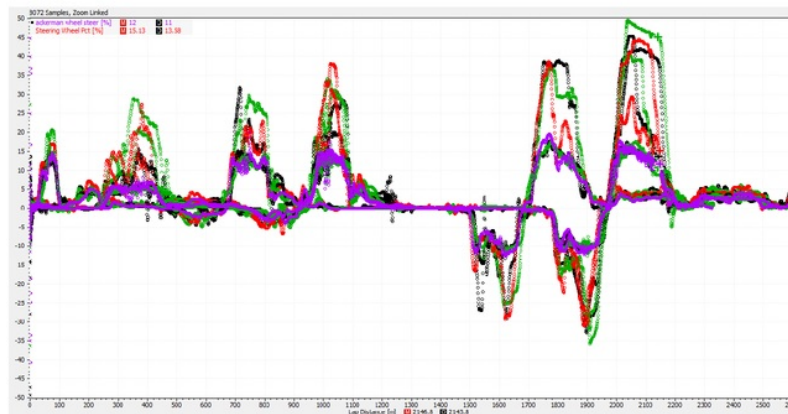


Figure 20 - A graph showing the correlation between Ackerman steer percentage and wheel steer percentage for three setups

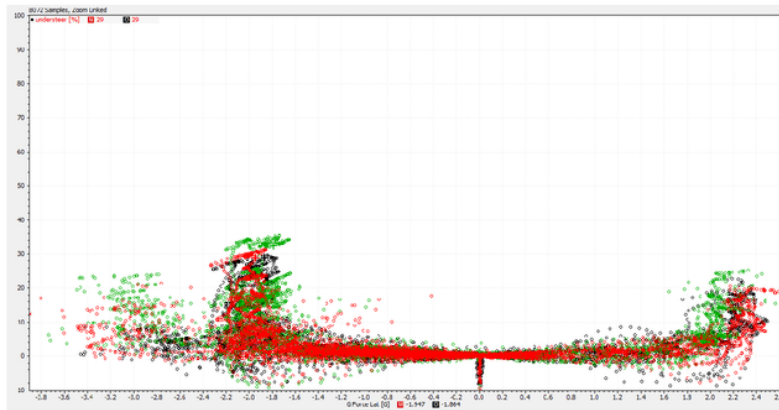


Figure 21 - A graph showing the correlation between understeer and lateral acceleration for three setups

Looking at the figure above, while all three setups are very similar in terms of understeer through left hand corners, the red and black setups are not as badly affected as the green setup through right hand corners.

Conclusion

Through the analysis of the three setups, the green setup, F1R6 should be used for a dry race. Although this setup lacked downforce compared to the other two, a higher top speed was achievable. Furthermore, even if the setup was able to produce the numbers seen throughout, the driver behind the wheel is still important, and through looking at the feedback taken throughout the second test session, out of the three setups, the green one was given the best feedback.

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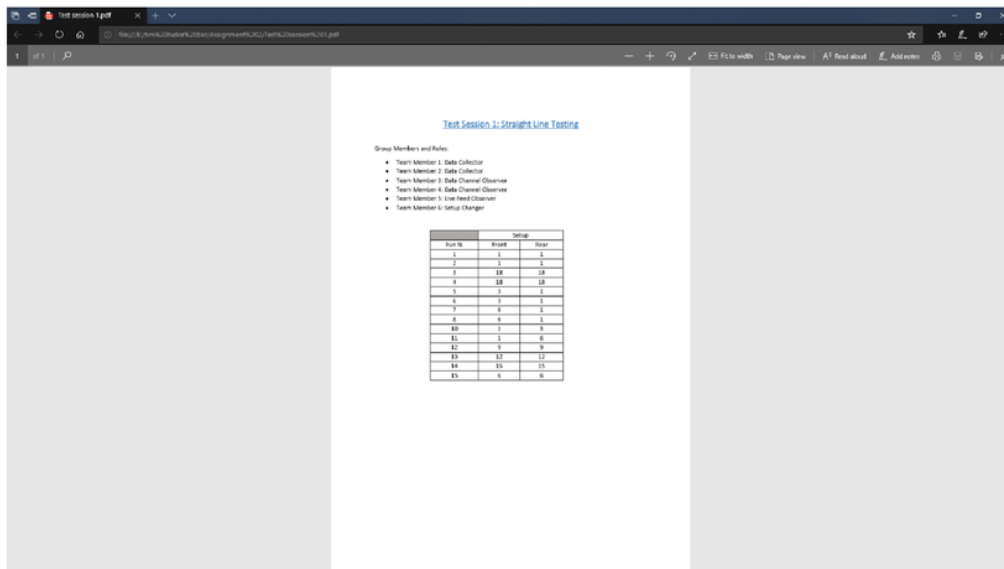
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Appendix



Test Session 1: Straight Line Testing

Group Members and Roles:

- Team Member 1: Data Collector
- Team Member 2: Data Collector
- Team Member 3: Data Channel Observer
- Team Member 4: Data Channel Observer
- Team Member 5: Wind Tunnel Observer
- Team Member 6: Setup Manager

Run No	Speed	Time
1	1	1
2	1	2
3	10	10
4	10	10
5	10	10
6	10	10
7	10	10
8	10	10
9	10	10
10	10	10
11	10	10
12	10	10
13	10	10
14	10	10
15	10	10

Appendix 1 - Test plan for session one: straight-line testing

Test Session 2: Circuit Testing

Group Members and Roles:

- Team Member 1: Data Collector
- Team Member 2: Data Collector
- Team Member 3: Data Channel Clearance
- Team Member 4: Feedback Collector
- Team Member 5: Feedback Recorder
- Team Member 6: Setup Changes/Live Feed Observer

Setup		
Item No.	Brand	Riser
1	ELI	1.2
2	ELI	1
3	L&L	1.8
4	S	9
5	ELI	1
6	S	1
7	S	1.8
8	S	9
ED	S	9
E1	S	1.2
E2	S	1.8
E3	T	1.2
E4	T	1.2
E5	T	1.2
E6	T	1.2
E7	T	1.2

Note: Last three setups used to change the ride height of the vehicle

Appendix 2a - Test plan for second test session: circuit testing

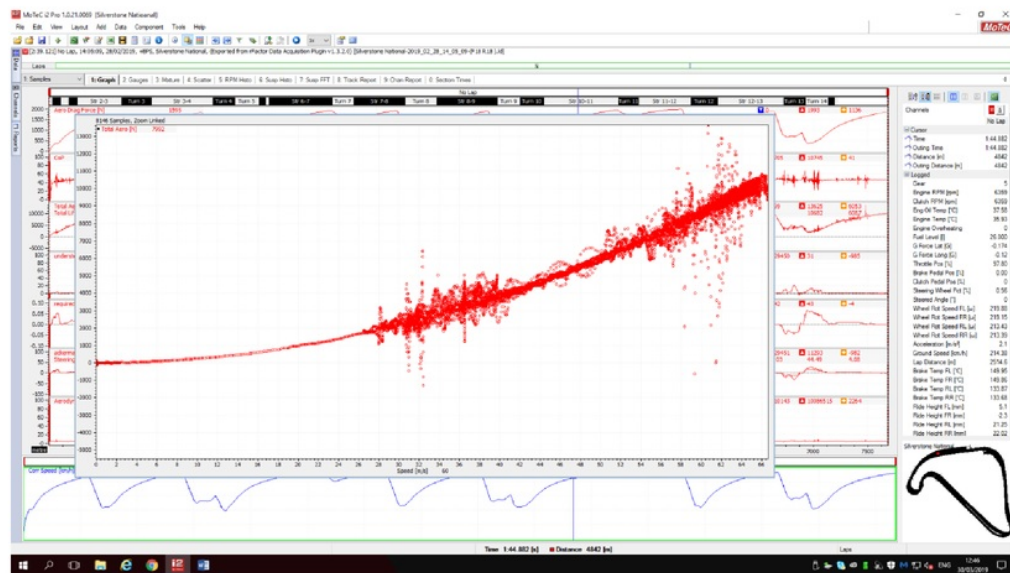
Feedback Section	
Adjustments	Feedback
Default (P LK12) (Ph 1, Rev 1)	4.9a Fairly lateral, limited grip, low speed steer, slight under steer.
FL185 (Ph 1, Rev 1)	4.9a Slightly more grip, oversteer slightly, slightly more stable.
FL183 (Ph 1, Rev 1)	5 Loads of grip, but more stable, good front end, touch the apex much better.
FL189 (Ph 1, Rev 1)	7 Slight less stable, more to over steer, (no phone reward)
FL187 (Ph 1, Rev 1)	8 Very oversteery, brakes okay (reward setup to fail)
FL181 (Ph 1, Rev 1)	6.5 Slightly less oversteer
FL188 (Ph 1, Rev 1)	6 Slightly under steer, safe to drive as always find the limit on the gas, low speed understeer
FL189 (Ph 1, Rev 1)	5 Not a balance good confidence in car high speed, understeer low speed corner
FL186 (Ph 1, Rev 1)	4.8 Best setup, so far loads of grip, very stable slightest understeer
FL182 (Ph 1, Rev 1)	4.8 Slight understeer, high speed still stable, less out at a higher speed
FL180 (Ph 1, Rev 1)	4.5 Balance good, slight understeer, less grip overall, don't feel good when planted at high speed corner.
FL212 (Ph 1, Rev 1)	5 Perfect balance, slight understeer low speed corner, feel very stable
FL182 (Ph 1, Rev 1)	4.5 Balance very good, not as much grip as previous, low speed understeer, high speed corner scrabbling across track as not enough grip.
FL182 (Ph 20M, Rev 40M)	4.8 Feel more understeer, general good grip overall, low speed corner supported well to 100mph
FL182 (Ph 2.1, Rev 4.5)	4.8 Very bit understeer, flat out very good high speed through corner which couldn't tolerate low speed left hand
FL182 (Ph 2.7, Rev 4.5)	4.8 Almost identical to previous, more understeer low and high speed

Appendix 2b - Feedback from driver during second test session

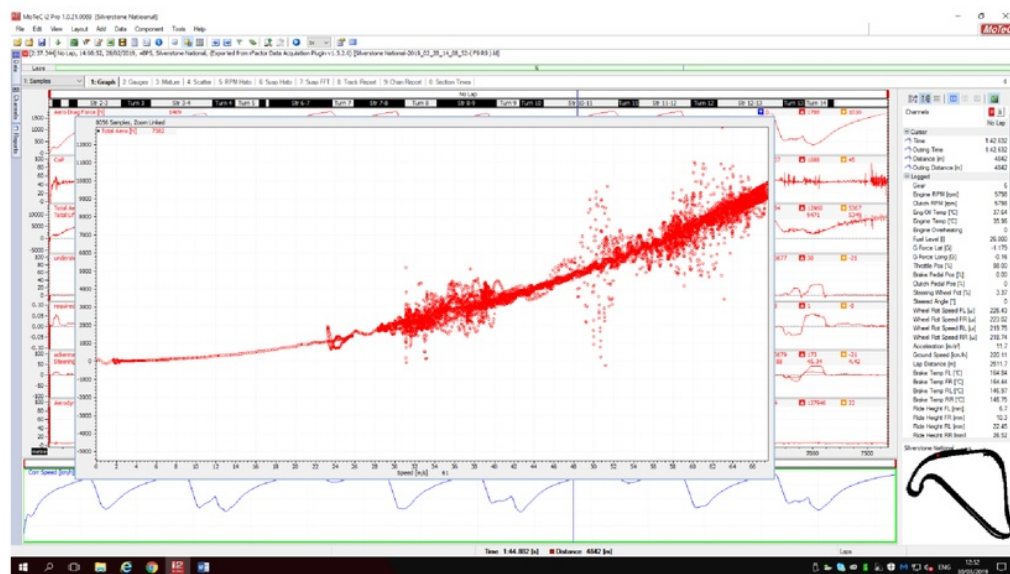
[illegible]

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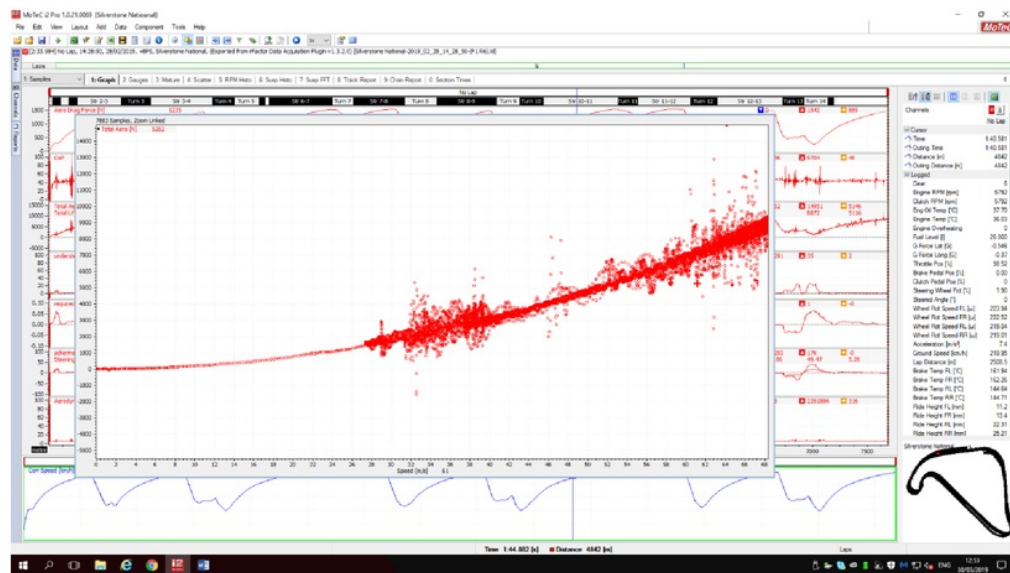
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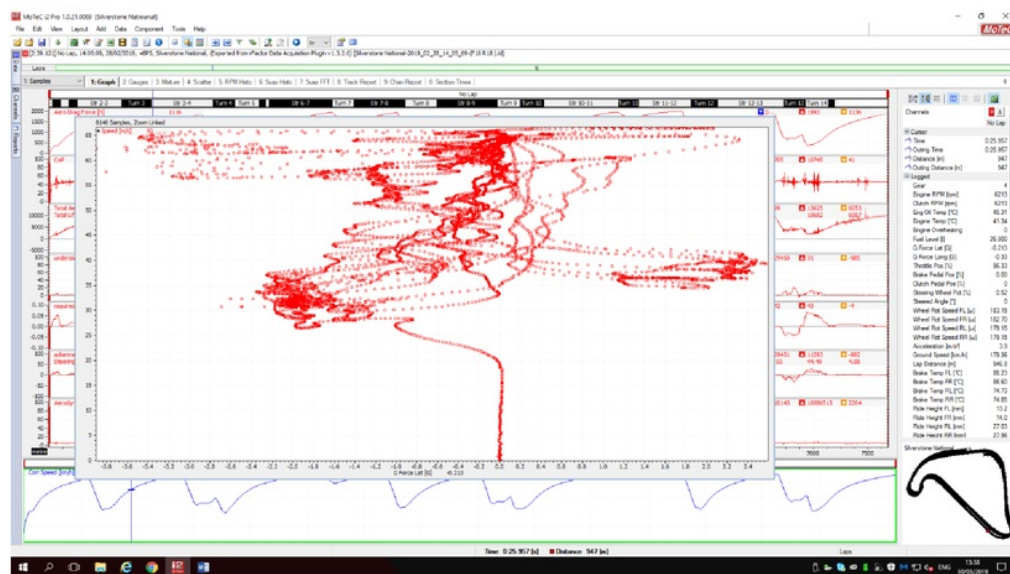
Appendix 5a - A graph showing the correlation between total aero and speed for setup F18,R18



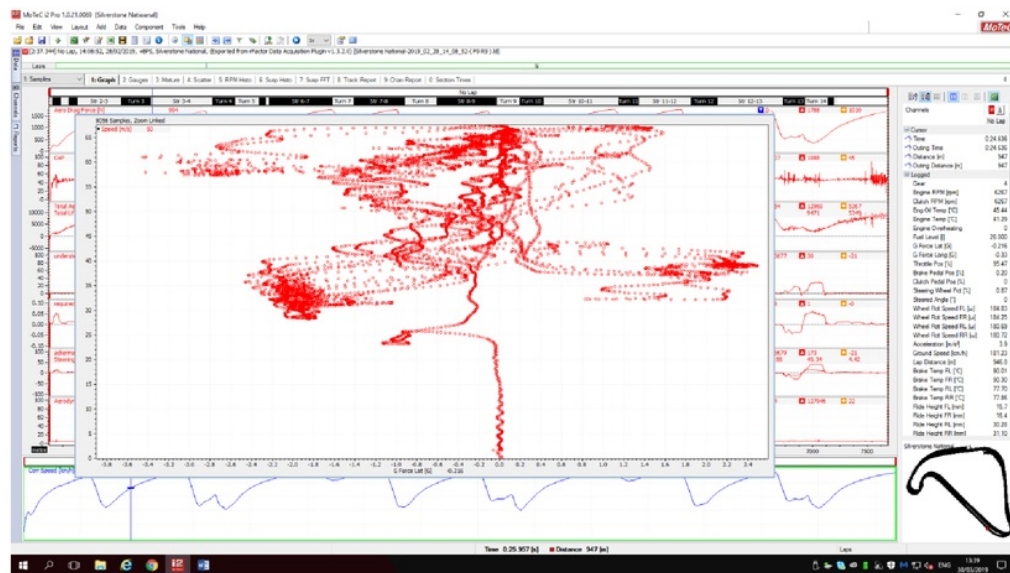
Appendix 5b - A graph showing the correlation between total aero and speed for setup F9,R9



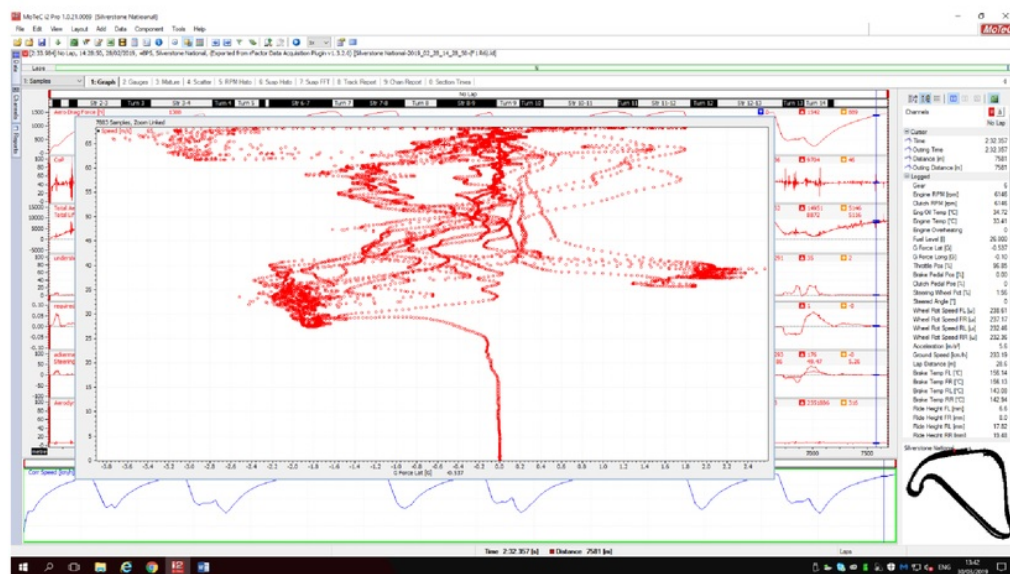
Appendix 5c- A graph showing the correlation between total aero and speed for setup F1,R6



Appendix 6a- A graph showing the correlation between speed and lateral acceleration for setup F18,R18



Appendix 6b - A graph showing the correlation between speed and lateral acceleration for setup F9,R9



Appendix 6c - A graph showing the correlation between speed and lateral acceleration for setup F1,R6

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Appendix 7a - A graph showing the correlation between Ackerman steering percentage, wheel steer percentage and lap distance for setup F18, R18



Appendix 7b - A graph showing the correlation between Ackerman steering percentage, wheel steer percentage and lap distance for setup F9, R9



Appendix 7c - A graph showing the correlation between Ackerman steering percentage, wheel steer percentage and lap distance for setup F1,R6