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Aerodynamic Vehicle Testing and Analysis (F3 Car)

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1.0 Introduction

The given task for this assignment was to utilise the performance simulator in university to design and run a set of aerodynamic vehicle tests to characterise the handling performance of the chosen vehicle around a chosen track. The chosen vehicle used in this test was a F3 race car and the track chosen was Pembrey due to the layout of the track; there are a few high speed corners and a few tight, sharp corners where the driver will have to dramatically reduce the speed of the vehicle. A detailed test plan was devised to collect the intended data to complete the assignment. Each test will be justified, backed up by research. Each group were given two, hour and a half sessions to complete all tests and gather all relevant information. One driver would be used across all tests to keep the driving as consistent as possible and instructions provided to the driver prior to each session. As seen in the image blow, this is the track that was used to perform the second testing session on. It's a small track featuring a high speed straight, sharp corners and a few long, quicker corners.

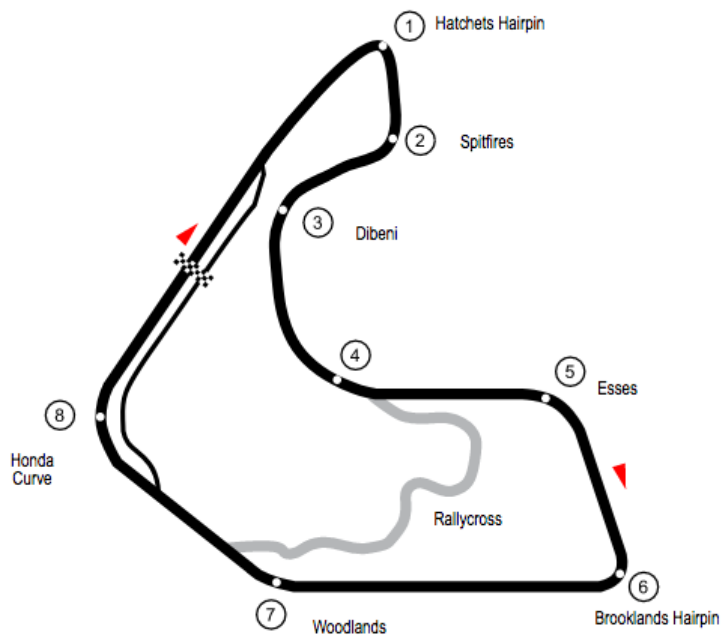


Figure 3: Pembrey Track (Anon, n.d.)

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3.0 Methodology

3.1 Test plan 1

During the first test the aerodynamic wing and splitter angles were changed on the front and the rear of the vehicle. A test plan had to be devised prior to testing as seen in the table below to keep track of each test that was being completed. The testing was done in groups of approximately six; one person would transfer data, two people were changing the aerodynamic set up, two people were keeping an eye on the live data and the last person would be receiving feedback from the driver on how the car handled and felt to drive. The test was completed using the university's simulator due to practicality as well as ruling out any variables such as wind speed or direction, any water on the track, tyre wear or any inconsistencies in the track surface, therefore all variables were constant. The maximum speed was reached in fifth gear and held for a couple of seconds before the vehicle was put in neutral and coasted down to zero.

Front Aero	Rear Aero
1	1
1	9
1	18
9	1
9	9
9	18
18	1
18	9
18	18

The table above shows each set up completed on the first day of testing. The group decided to try and keep some logic and pattern with the testing. Each test was conducted with the front splitter as the base test and the rear wing changed around the front splitter setting. Towards the end of the first set of testing, ride height was altered to discover whether this would have an effect on the aerodynamic properties of the vehicle. It didn't have a noticeable effect therefore the group decided to remain with just using changes in the front and rear aero in the second session of testing.

3.2 Test Plan 2

The second set of testing was still based on the aerodynamics of a Formula three car, whereas the vehicle was used around a track this time rather than a straight line test. The choice of track was up to the group; Pembrey was chosen due to the nature of the track. Pembrey features a variety of conditions for the vehicle to undergo such as high speed corners, tight corners and a long straight where considerable speed can be produced. Similarly to the first test different wing and splitter angles were devised as seen in the table below. Each of the set ups were conducted in five minute stints, providing the driver to complete three to four laps. Each set up had a different number of laps due to the vehicle being almost impossible to drive whereas some had brilliant amount of downforce and the driver was able to produce very competitive lap times.

Front Aero	Rear Aero
1	1
9	9
18	18
18	1
1	18
18	9
1	9
9	1
9	18
18 + Min Ride Height	18 + Min Ride Height
18 + Max Ride Height	18 + Max Ride Height

During the second session, the time wasn't quite up for the testing session therefore we discovered which the most stable and quickest aero set up was and changed the ride height for two of the tests; first test was with the ride height setting at minimum and the second was with the ride height setting at its highest.

4.0 Results

4.1 Test Session 1

Set Up		Static Loads (N)						Ride Height (mm)				Max Vel (kph)	Constant Velocity Loads (N)						Ride Height (mm)			
		FL	FR	RL	RR	Mass (N)	Mass (kg)	FL	FR	RL	RR		FL	FR	RL	RR	Mass (N)	Mass (kg)	FL	FR	RL	RR
1	1-1	1161	1165	1582	1578	5486	559.225	31.35	31.34	51.15	51.14	220.0	2745	2797	3297	3359	12198	1243.425	10.07	10.02	27.10	27.03
2	1-9	1164	1161	1579	1583	5487	559.327	31.37	31.39	51.26	51.28	219.2	2719	2706	3680	3667	12772	1301.937	9.70	9.73	21.17	21.21
3	1-18	1164	1161	1579	1582	5486	559.225	31.34	31.35	51.11	51.12	218.4	2647	2646	4057	4056	13406	1366.565	9.41	9.41	14.83	14.83
4	9-1	1160	1165	1583	1578	5486	559.225	31.37	31.36	51.17	51.15	219.9	3104	2977	3330	3210	12621	1286.544	6.66	7.02	27.89	28.31
5	9-9	1164	1161	1579	1582	5486	559.225	31.36	31.37	51.17	51.18	219.1	2996	2964	3631	3600	13191	1344.648	6.32	6.41	22.15	22.26
6	9-18	1160	1165	1583	1578	5486	559.225	31.37	31.35	51.15	51.14	218.3	2917	2910	4002	3995	13824	1409.174	5.99	6.00	15.66	15.68
7	18-1	1162	1163	1581	1580	5486	559.225	31.37	31.37	51.25	51.24	219.8	3354	3331	3214	3195	13094	1334.760	4.21	4.25	29.23	29.28
8	18-9	1163	1163	1580	1580	5486	559.225	31.37	31.37	51.25	51.24	219.0	3324	3316	3520	3580	13740	1400.612	4.20	4.25	29.22	29.28
9	18_18	1164	1161	1579	1582	5486	559.225	31.35	31.36	51.10	51.11	218.2	3222	3202	3942	3925	14291	1456.779	3.04	3.09	16.78	16.84

Figure 1: Vehicle Loads (Thomas, 2019)

Figure 1 demonstrates the static and constant velocity loads acting upon the vehicle during the testing at different aerodynamic settings. There isn't much variation in the static corner loads due to the wings not having an effect at this point. At maximum velocity there's a significant difference in the loads on the vehicle. At minimum front and rear aero, the vehicle is producing over twice its own weight in downforce. As the wing angles become more prevalent to downforce, the maximum speed of the vehicle decreases by 1.2kph. Figure 1 also shows the ride height change from static to constant velocity. As expected, the ride height hasn't changed much during all the static measurements but has changed considerably at maximum velocity. From minimum front and rear to maximum front and rear aero, the front ride height has dropped by approximately 7mm in the front and 10mm in the rear.

Set Up		Aero Loads & Balance				Max Vel (m/s)	Aero Lift Coefficient		
		Aero F	Aero R	Aero T	CoP		CLF	CLR	CLT
1	1-1	-3216	-3496	-6712	0.521	61.111	-1.408	-1.531	-2.939
2	1-9	-3100	-4185	-7285	0.574	60.889	-1.367	-1.846	-3.213
3	1-18	-2968	-4952	-7920	0.625	60.667	-1.319	-2.200	-3.519
4	9-1	-3756	-3379	-7135	0.474	61.083	-1.646	-1.481	-3.127
5	9-9	-3635	-4070	-7705	0.528	60.861	-1.605	-1.797	-3.402
6	9-18	-3502	-4836	-8338	0.580	60.639	-1.557	-2.151	-3.708
7	18-1	-4360	-3248	-7608	0.427	61.056	-1.913	-1.425	-3.338
8	18-9	-4314	-3940	-8254	0.477	60.833	-1.906	-1.741	-3.647
9	18_18	-4099	-4706	-8805	0.534	60.611	-1.825	-2.095	-3.919

Figure 2: Aerodynamic Loads (Thomas, 2019)

Figure 2 demonstrates aero loads acting upon the vehicle at maximum velocity. The first column demonstrates the aero loads at the front of the vehicle and the second column demonstrates the aero loads at the rear of the vehicle. The two circled areas are with the front splitter on max and the rear wing on max. This demonstrates that the rear wing has more of an effect on the vehicles overall downforce than the front splitter does. This result is what most would expect. Roberts explains that higher the area of the front splitter, the more downforce will be generated but only up to a certain point. "The effectiveness of adding splitter area falls rapidly as it extends away from the body". This is due to the reduction in air speed above and below the splitter decreases the further away from the body it is (Roberts, 2013). Aero F is calculated by adding the front loads at a static state and subtracting that from the front loads at constant velocity.

The same is done in the rear to calculate the rear aero. Both Aero F and Aero R are added to discover the total aero acting upon the vehicle. Centre of Pressure (CoP) is calculated by dividing the total aero by the rear aero. The frontal coefficient of lift is calculated by multiplying the frontal aero by two and dividing the total by the density of air multiplied by velocity squared. The same calculation is used to discover the coefficient of lift in the rear.

Set Up		Coastdown Data										Drag Forces		
		Vel 1	Time 1	Vel 2	Time 2	Vel 3	Time 3	Vel 4	Time 4	Accel 1	Accel 2	Rolling Res	Aero Drag	Cd
1	1-1	47.47	60.031	45.83	61.071	4.94	130.084	4.36	132.069	-1.577	-0.292	-163.401	-718.454	0.450
2	1-9	47.39	22.012	45.67	23.038	4.64	90.694	4.22	92.036	-1.678	-0.311	-174.217	-764.537	0.481
3	1-18	47.44	21.929	43.75	24.069	4.28	89.376	3.47	92.071	-1.724	-0.299	-167.041	-797.230	0.523
4	9-1	48.72	21.275	45.75	23.038					-1.685		-168.530	-773.557	0.472
5	9-9	48.06	21.038	44.56	23.041	4.78	88.024	4.17	90.028	-1.747	-0.304	-170.223	-806.955	0.513
6	9-18	47.94	20.882	45.81	22.016					-1.878		-168.530	-881.867	0.547
7	18-1	48.25	21.079	44.86	23.020					-1.747		-168.530	-808.169	0.508
8	18-9	47.89	20.686	45.42	22.003					-1.875		-168.530	-880.283	0.551
9	18-18	48.53	20.549	44.67	22.512					-1.966		-168.530	-931.118	0.584
10		47.22	23.042	44.89	24.560	4.36	85.269	3.83	87.013	-1.535	-0.304	-169.948	-688.415	0.442
11		48.00	21.016	44.50	23.033	4.06	96.064	3.33	98.476	-1.735	-0.303	-169.282	-801.290	0.510
12		47.78	21.026	46.03	22.005	5.19	86.648	4.78	88.043	-1.788	-0.294	-164.390	-835.429	0.517
13		48.94	20.698	46.56	21.992					-1.839		-168.530	-860.217	0.514
14		47.25	21.344	46.08	22.002					-1.778		-168.530	-825.837	0.517
15		48.00	21.027	46.25	22.008					-1.784		-168.530	-829.069	0.509
16		48.06	21.062	46.33	22.003	4.28	89.646	3.86	91.030	-1.838	-0.303	-169.738	-858.568	0.525
17		47.94	21.112	45.36	22.525					-1.826		-168.530	-852.561	0.534
18		47.67	21.598	45.25	23.006					-1.719		-168.530	-792.638	0.500
19		48.17	21.326	46.08	22.501					-1.779		-168.530	-826.177	0.507
											Average	-168.530		

Figure 3: Drag Forces (Thomas, 2019)

Figure 3 demonstrates the drag forces that are being applied on the vehicle during the coast down. Acceleration 1 is discovered by time 1 minus velocity 1 divided by time 2 minus time 1. Acceleration 2 is calculated by using velocity three and four. Rolling resistance is calculated by multiplying the vehicles mass by the second acceleration. There isn't much of a difference in rolling resistance between runs due to the speed doesn't change very much and the weight change is very minimal. Aero drag is calculated by using the vehicles mass, acceleration 1 and rolling resistance. The calculation for Cd is as seen below:

$$= -((\text{Mass} * \text{Accel 1}) - (\text{Rolling Resistance})) / (0.5 * 1.223 * (((\text{Velocity 1} + \text{Velocity 2})/2)^2))/1.2$$

The formula above is a negative formula to ensure the answer is a positive number. Due to a few of the tests not coast down all the way, velocity 3 and 4 couldn't be calculated therefore acceleration 2 couldn't be calculated either. On the tests where the velocity didn't get run down to zero, the average rolling resistance was used for these blank spaces.

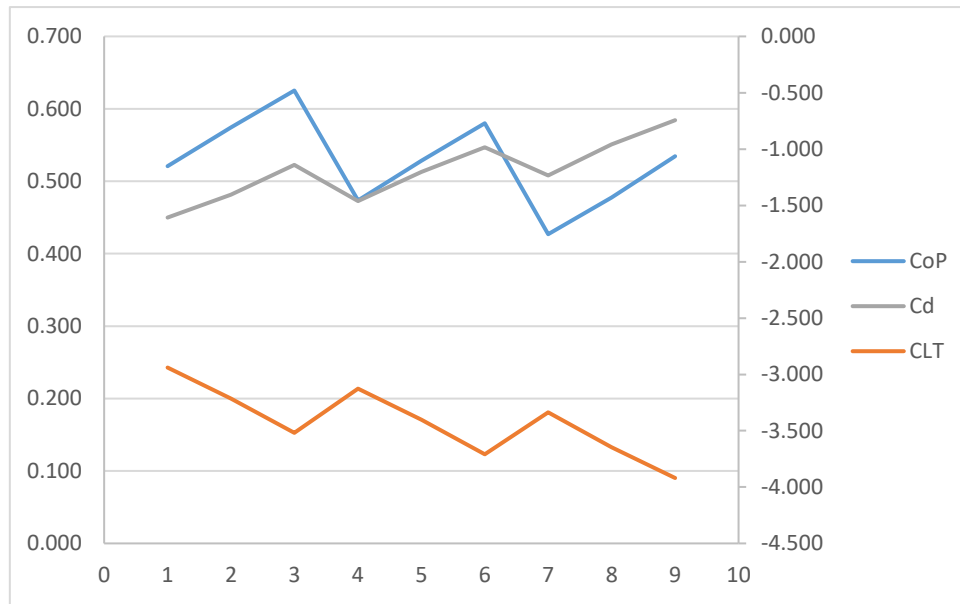


Figure 4: CoP, Cd and CLT Graph (Thomas, 2019)

Above is a graph demonstrates the correlation between the vehicles Centre of Pressure, Coefficient of Drag and the total Coefficient of Lift for the different aerodynamic set ups during first session. It demonstrates as the Centre of Pressure and Coefficient of Drag increase, the lift decreases. Each set up line follows a trend as the tests were completed in a logical order.

		Front		
	CoP	1	9	18
Rear	1	0.521	0.574	0.625
	9	0.474	0.528	0.580
	18	0.427	0.477	0.534
		Front		
	CL	1	9	18
Rear	1	-2.939	-3.213	-3.519
	9	-3.127	-3.402	-3.708
	18	-3.338	-3.647	-3.919
		Front		
	Cd	1	9	18
Rear	1	0.450	0.481	0.523
	9	0.472	0.513	0.547
	18	0.508	0.551	0.584

Figure 4: CoP, Cd and CLT colour chart (Thomas, 2019)

In figure 4, a colour scale has been created to demonstrate the change in Centre of Pressure, Coefficient of Lift and Coefficient of Drag from the front to the rear between each session. Centre of Pressure is demonstrated by green as a pressure closer to the front and red when it's closer to the rear. Coefficient of Lift is demonstrated by green being a higher downforce (smaller lift) and red being a low downforce (larger lift). Coefficient of drag is demonstrated by having green as a smaller amount of drag and red being a higher drag.

4.2 Test Session 2

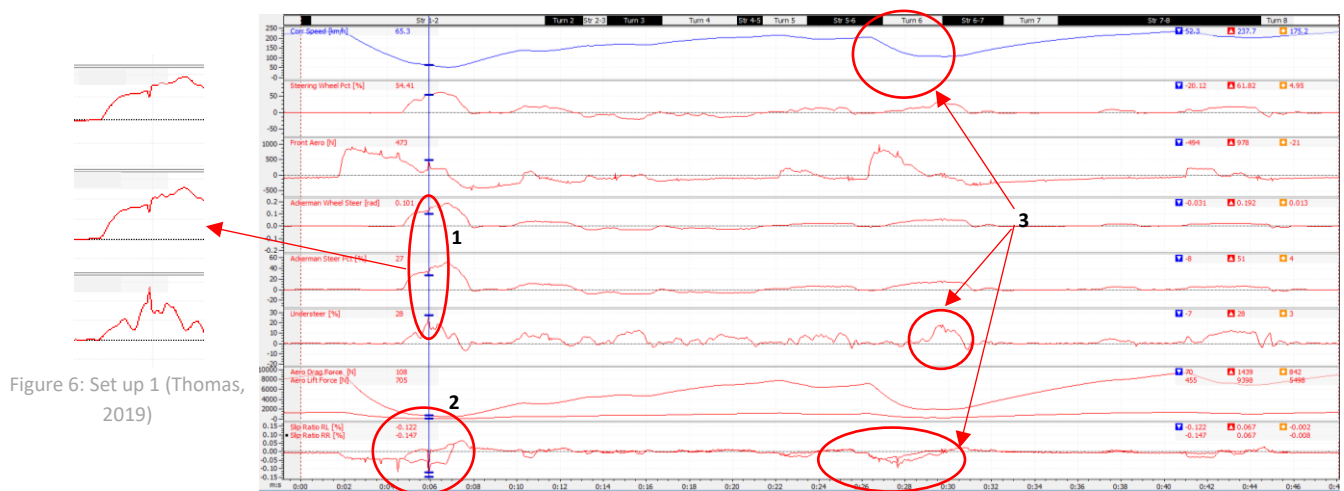


Figure 6: Set up 1 (Thomas, 2019)

Figure 6 displays the fastest lap of the first set up; minimum aero on the front and minimum on the rear. The blue marker is currently on the area of highest understeer, whilst understandably it's the lowest area of drag and lift force across the whole lap. As seen in the zoomed in section at the point of highest understeer, the driver attempts to correct this by counteracting the slide with an adjustment in the steering. As seen in the circled section 2, there's a negative slip ratio, meaning the brakes have been applied very suddenly; "When F_x and σ are positive, the car is being forced forward by the ground's reacting to the tyres. When they're negative, the car is being forced backwards" (Beckman, 2001). By reviewing the whole of the understeer graph, there's understeer throughout the whole lap; this is due to the wing angle providing a lack of downforce applied to the vehicle. Throughout the lap there are also a few incidences of over steer; understeer are negative numbers. This statement from Beckman can be backed up by section 3. The vehicles speed is slowing for a corner, the car understeers considerably and the brakes applied forcing the vehicle backwards.



Figure 7: Set up 1a (Thomas, 2019)

To support my point above, figure 7 demonstrates the brakes were applied suddenly as seen in the weight transfer graph; there's a sudden increase in frontal weight transfer as well as a sudden directional change in the steering wheel. This could be due to a loss in traction such as a spin or a loss of control in the rear end of the vehicle. During this set up, the driver noticed that the set up was balanced but didn't have any grip around the corners at all. The driver rated this set up as a six out of a possible ten.

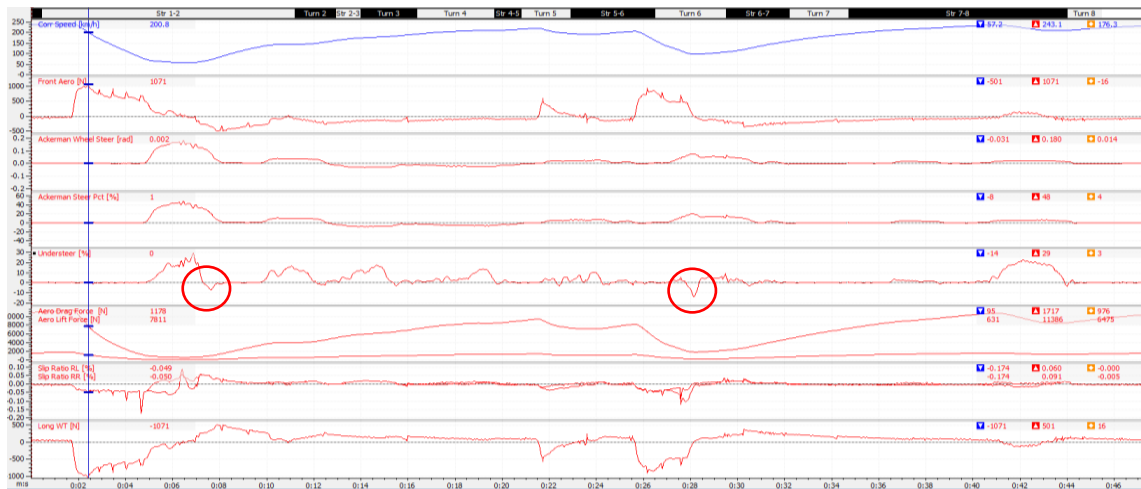


Figure 8: Set up 2 (Thomas, 2019)

Down the straight at the start of the lap, the longitudinal weight transfer is very central until the point of the blue marker where the weight transfer suddenly shifts to the front due to the sharpness of the first corner. There is almost zero wheel angle therefore it's understood that the vehicle is traveling along a straight. As seen in figure 8 above, the understeer is rather prominent but there are also a couple of points of oversteer as seen in the circled sections above. The rate of understeer is a lot less in this set up compared to the previous set up, this is due to the additional downforce. The second set up, the driver felt that the vehicle was again balanced, but had more grip than the first set up. The driver rated this set up at seven out of ten

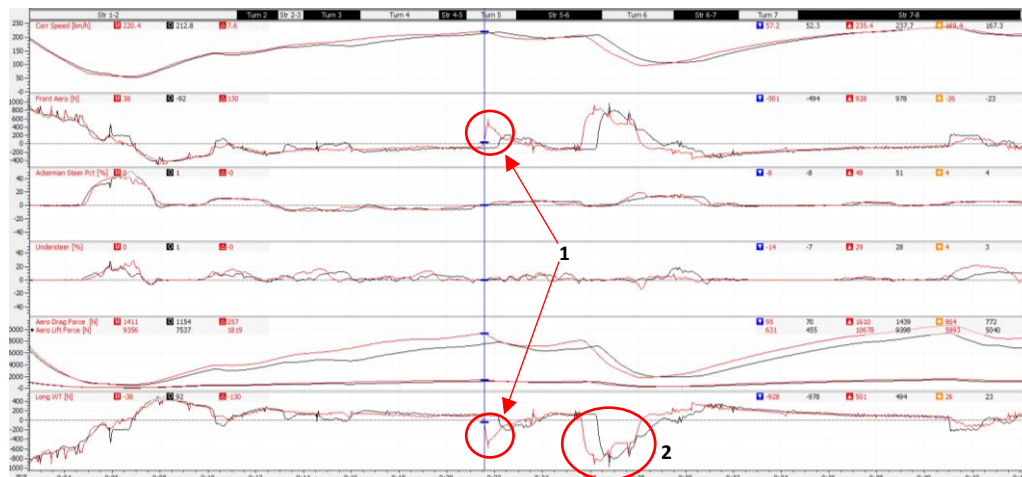


Figure 9: Set up 2 Comparison (Thomas, 2019)

As seen in figure 9, the comparison between set up 1 and set up 2 are rather different. The drag forces acting upon the vehicle are considerably more in the second set up; this is due to the increased wing angle. During the second set up, the understeer occurs a lot later in the corner; it occurs about half way through the corner whereas the understeer occurred at the start of the corner in the first set up. This is probably due to the vehicle not getting sufficient downforce for the angle of the corner. As seen in point 1, there's a sudden shift in the weight

transfer towards the front of the vehicle and a sudden spike in the front aero at the same time. This is due to the sudden braking force that the driver has applied.

Even though the weight transfer, transfers to the front of the vehicle sooner in set up 2 than set up 1, the driver has shed half a second off the time of the first set up. As seen on the corrected speed graph, the speed remains consistent between the two set ups; set up two has a slightly slower top speed by 2 kph, but has a much faster lower speed being 5 kph faster. This is where the driver gained time on the first set up. The driver was able to carry more speed through the corners. To ensure the optimum speed through a corner, the correct driving line must be driven. The image below demonstrates the correct driving line for a racetrack. The driver remains wide on the entry of the corner before bringing the vehicle in to hit the apex of the corner and leaving the corner in the same fashion as it was entered, wide, hitting the outer edge of the track.

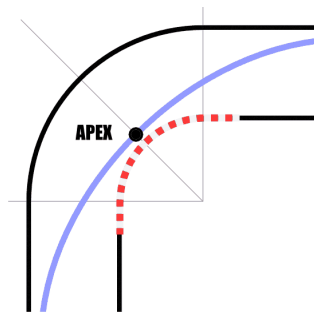


Figure 10: Racing Line (Anon, n.d.)



Figure 11: Set up 3
(Thomas, 2019)

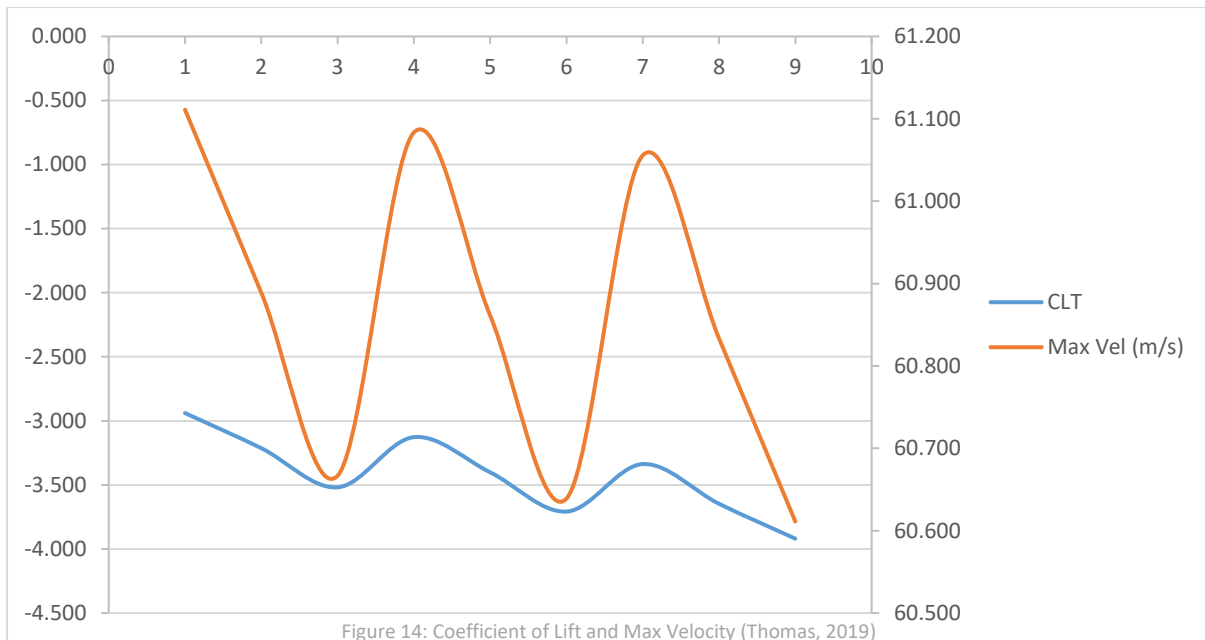
Figure 11 is the third set up of the testing session. This is where maximum downforce was applied to the front and the rear of the vehicle. As seen in point 1, this is where the driver suddenly applied the brakes as the weight transfer has shifted towards the front of the vehicle and the front aero has increased simultaneously. Section 2 demonstrates a sudden spike of oversteer in the vehicle on the straight. This could be a driver error coming out of turn 6 where the front left wheel was on the grass and ended up losing traction. On a whole, this set up is very stable for a track such as Pembrey. The driver felt most comfortable with this set up as it was a lot more balanced than the other two whilst providing the most amount of grip.

The driver rated this set up at a nine out of a possible ten.

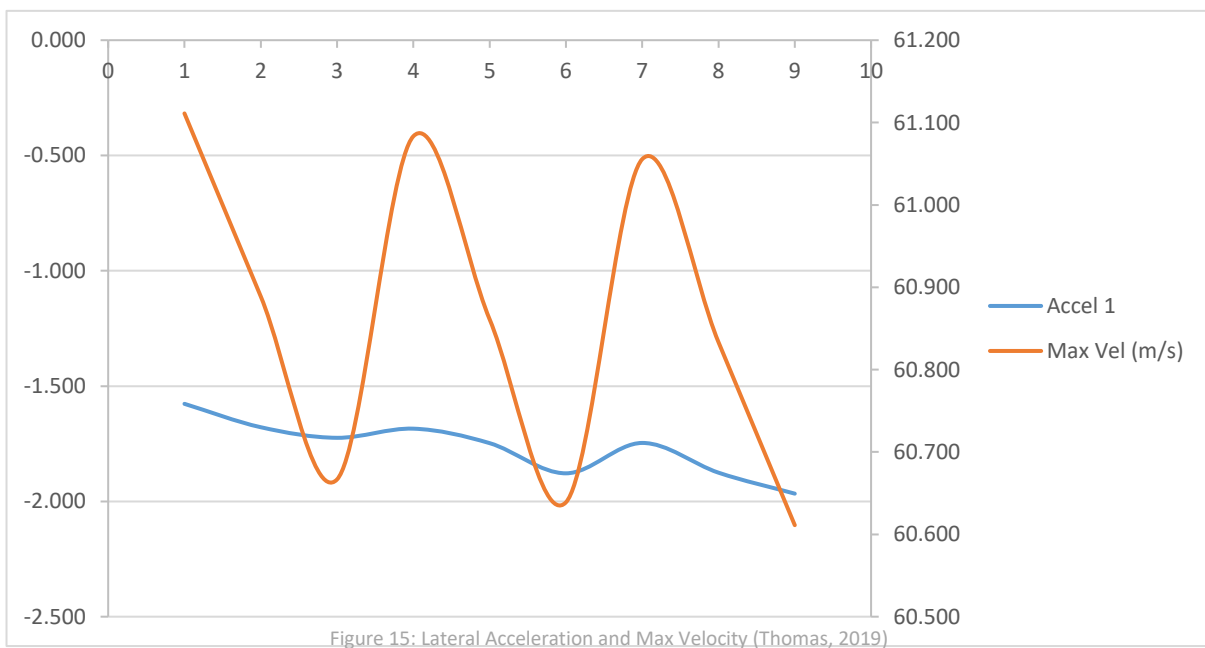


Figure 12: Min and Max Ride Height (Thomas, 2019)

Figure 12 demonstrates the affect minimum and maximum ride height have on the vehicle with maximum aero on the front and rear. On the whole the red line (min ride height) has more understeer around the corners than the green line (max ride height) this is due to the vehicle having less body roll and not being able to absorb the forces of the corners in the suspension due to the reduction in suspension travel. There is one circled section where the green line's understeer exceeds the red line. This is due to the vehicle losing control slightly as there's a sudden change in the steering wheel percentage. The driver was also asked to rate both ride height set ups. The first set up was at minimum ride height and the driver felt like the car was understeering at high speeds, but had very good capabilities at the lower ends. He rated this at a nine out of ten. The second ride height set up was rated at an eight out of ten due to the vehicle understeering slightly more and the vehicle being slightly 'wobbly' whilst not being balanced at all. This statements can be supported by the graphs above. The 'wobbly' drive is represented by the green line which has points of high understeer but on the whole the red line (min ride height) has more understeer.



The graph above demonstrates the correlation between the coefficient of lift and the maximum velocity of the vehicle. This graph displays as the speed of the vehicle decreases, the total lift of the vehicle also decreases. These two figures work in correlation with each other; as one decreases the other will also decrease.



Similarly, the graph above demonstrates the lateral acceleration against the maximum velocity. The same trend is displayed in this graph whereby the vehicles velocity will increase as the lateral acceleration will increase which is what most would expect. This graph can prove this is correct.

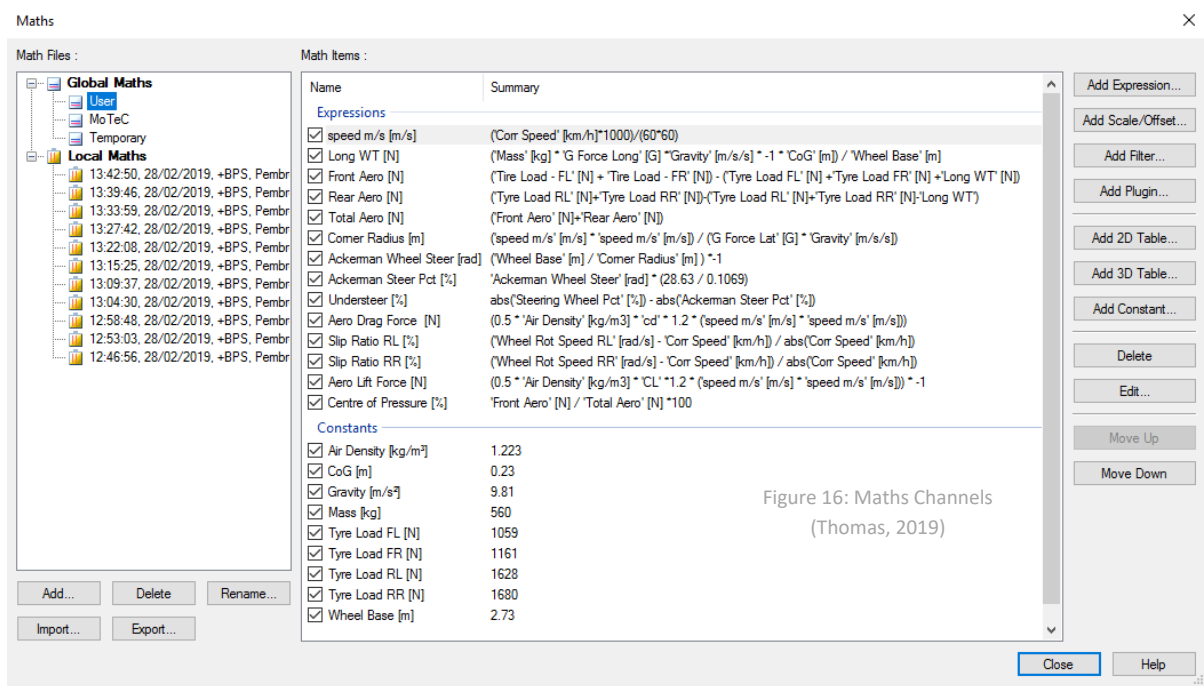


Figure 16: Maths Channels
(Thomas, 2019)

As seen in figure 16, these are the maths channels that have been used in this assignment. The maths channels that have been most useful are the speed m/s, longitudinal weight transfer, Ackerman steer pct and understeer. These channels have shown where the vehicle isn't producing enough downforce for the speed that the corner has been entered at.

5.0 Conclusion

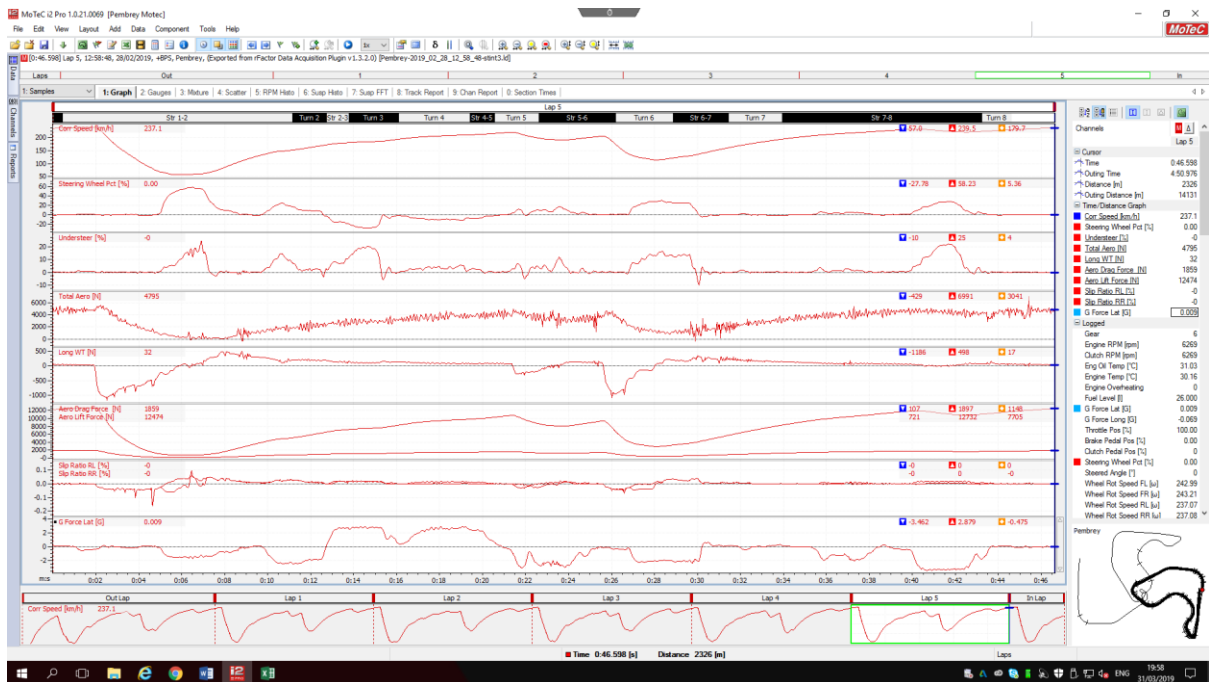
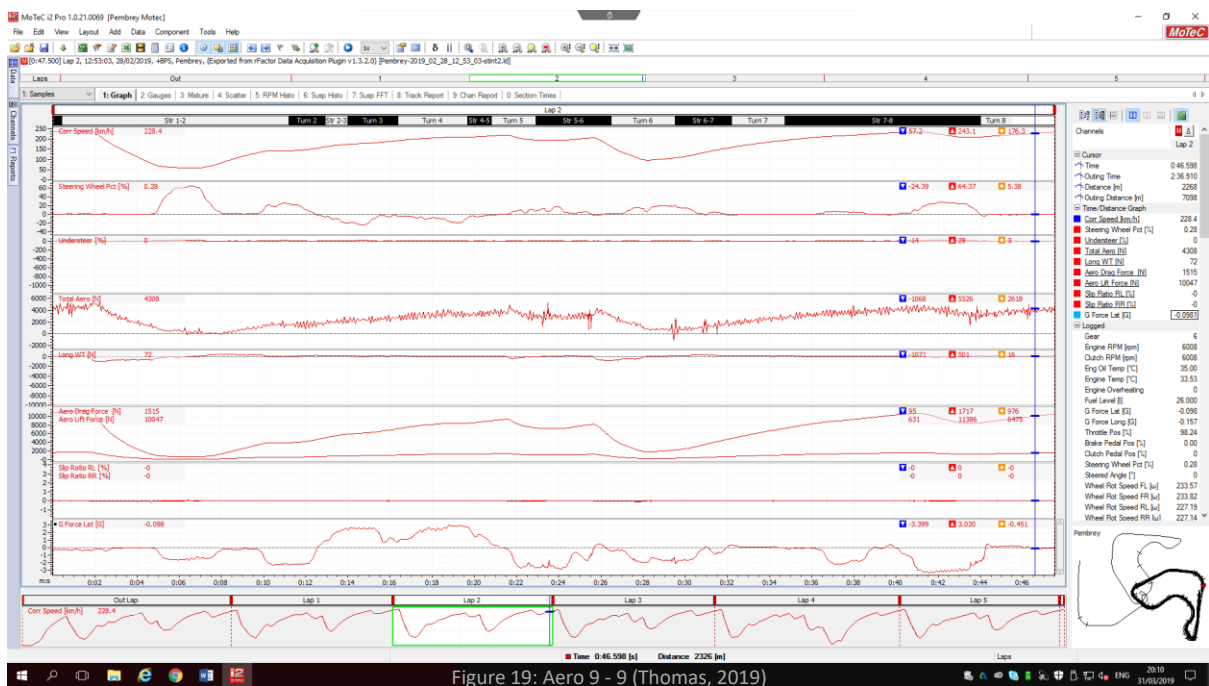
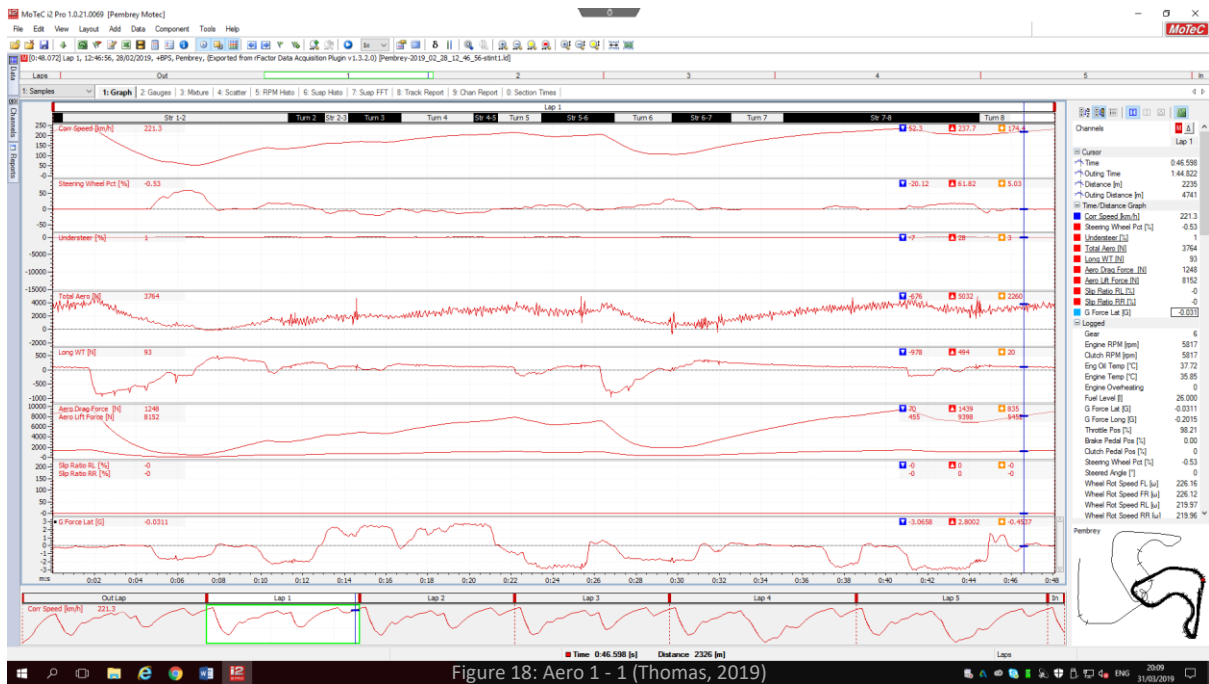
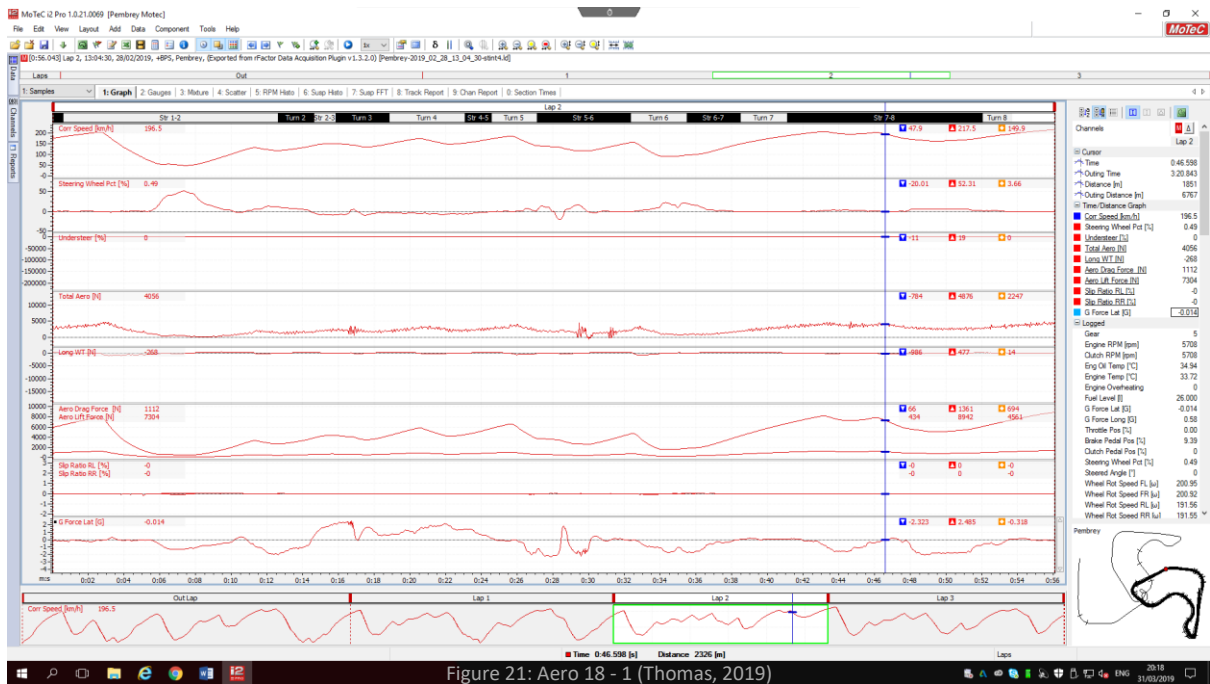
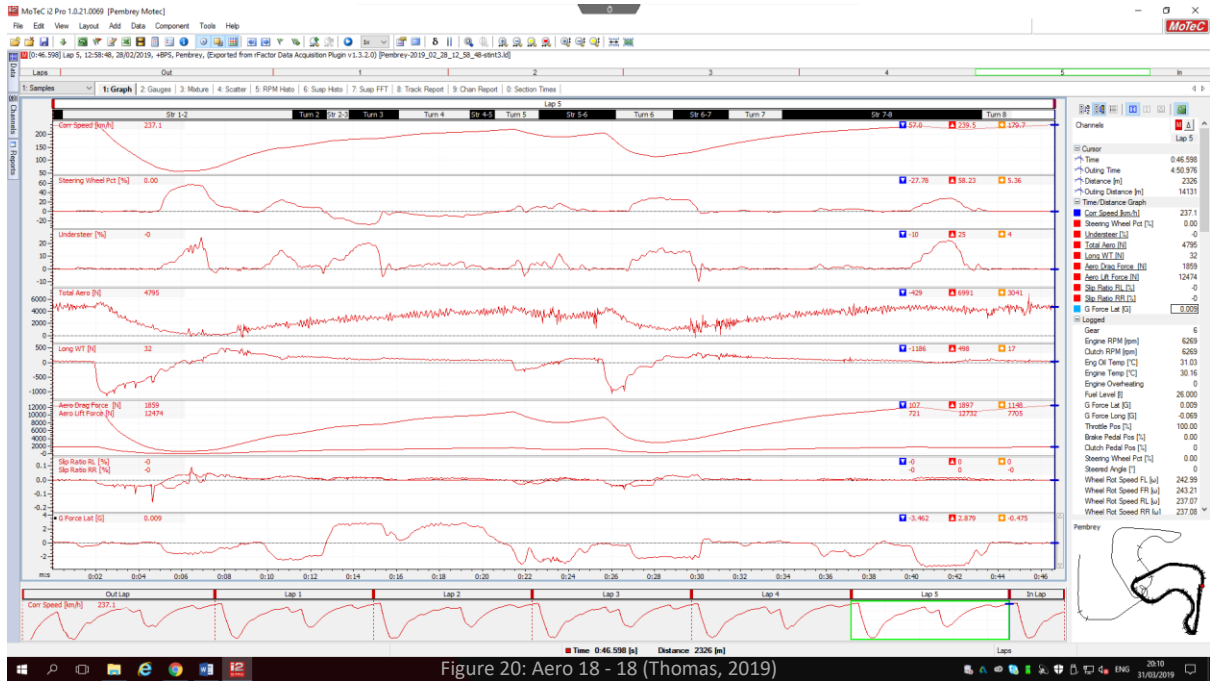


Figure 17: Best Set Up (Thomas, 2019)

As seen in the image above this is what's believed to be the best set up for Pembrey race circuit. Even though this set up causes more drag for the vehicle across the whole lap, the downforce is considerably improved. This set up is perfect due to the sharp tight corners that this track has and the lack of long straights where maximum speed is needed. This set up wouldn't be as effective on a track such as Spa Francorchamps race track or a high speed track that would need max speed out of the vehicle. The 18 aero on the front and 18 aero on the rear would be perfect for Pembrey race track.

6.0 Appendices





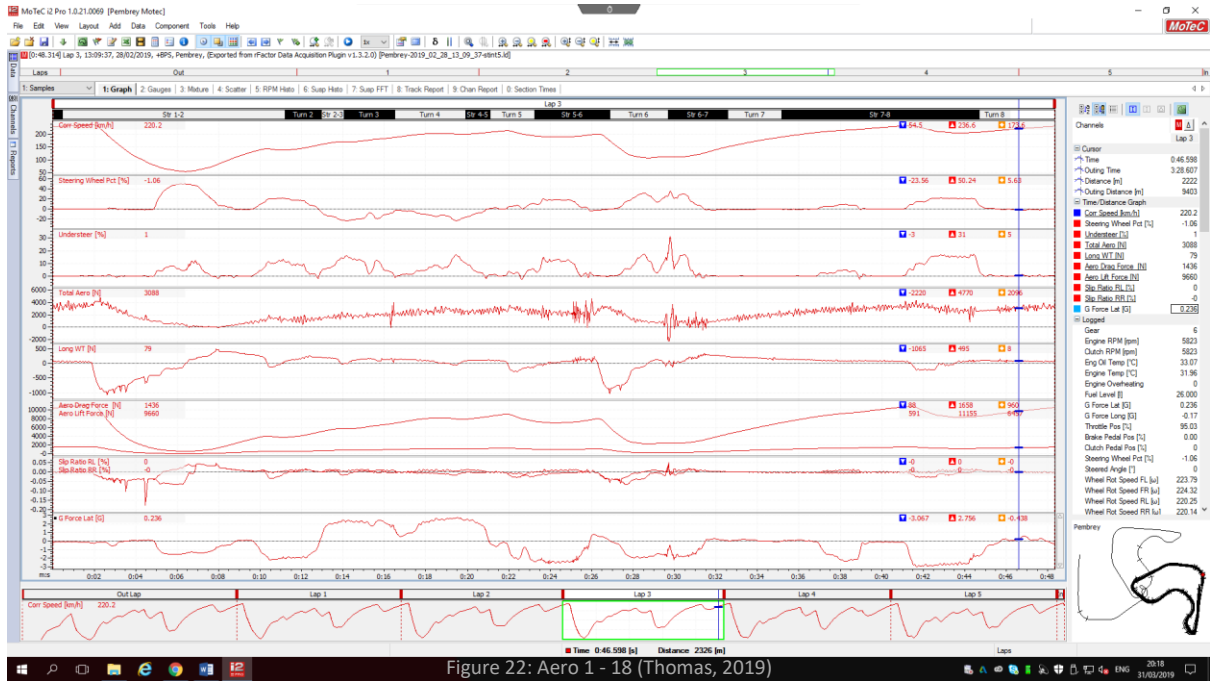


Figure 22: Aero 1 - 18 (Thomas, 2019)

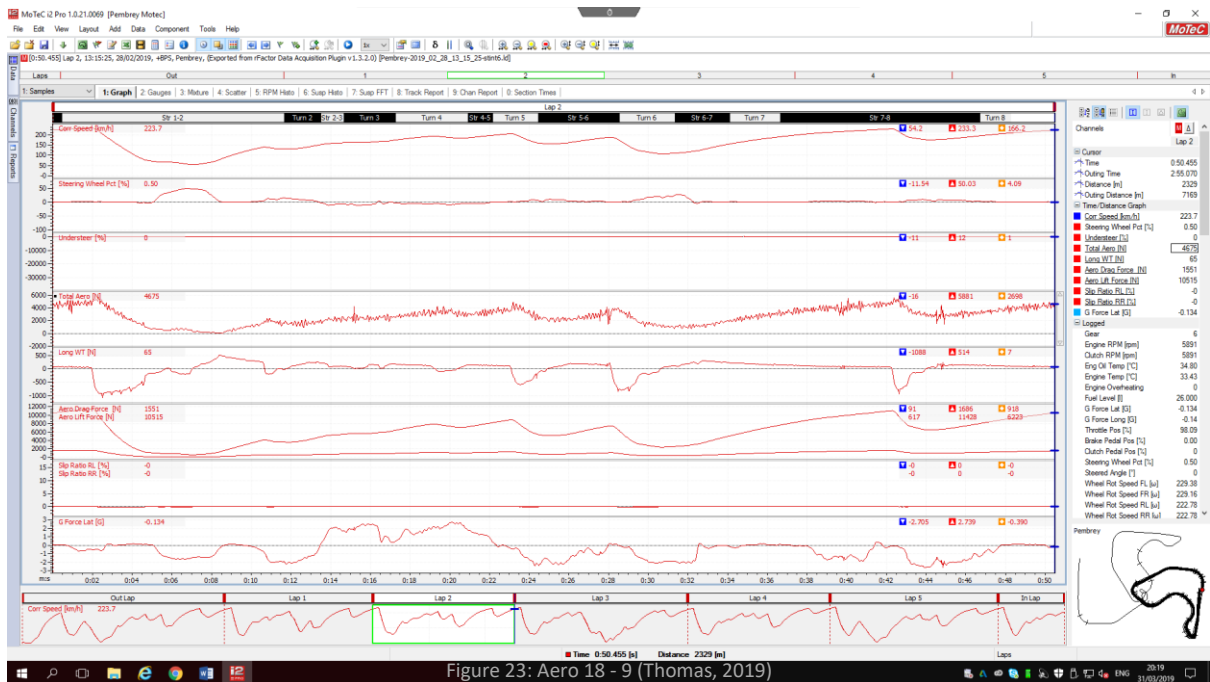
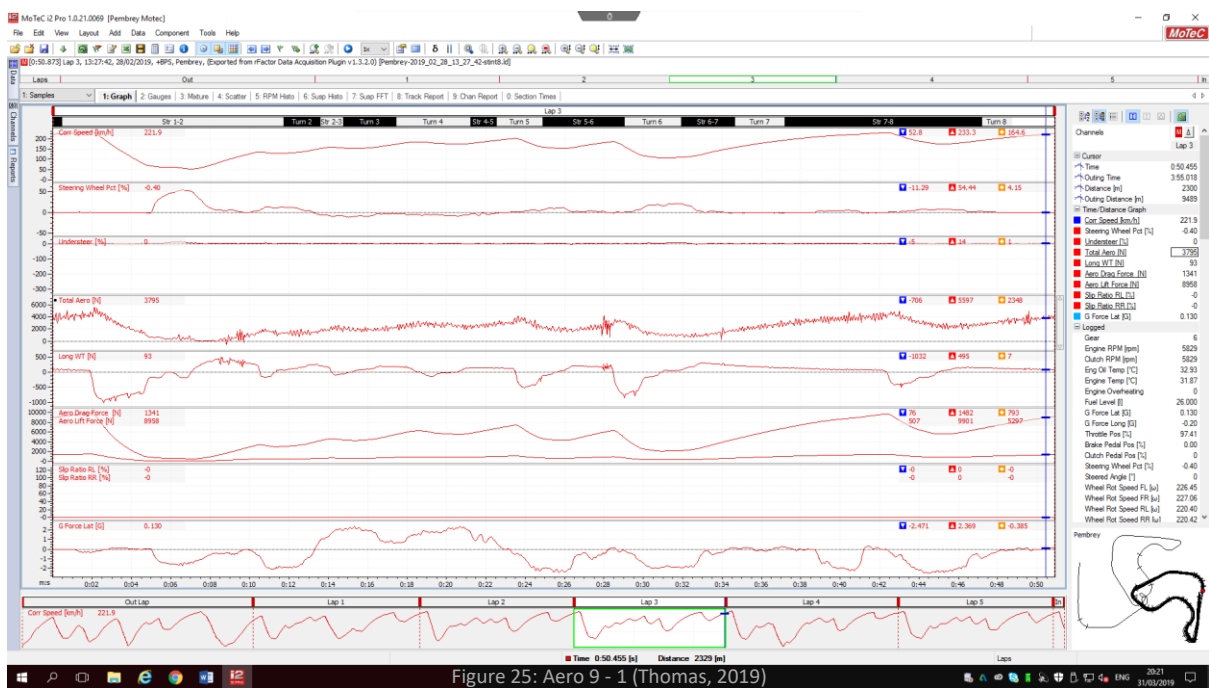
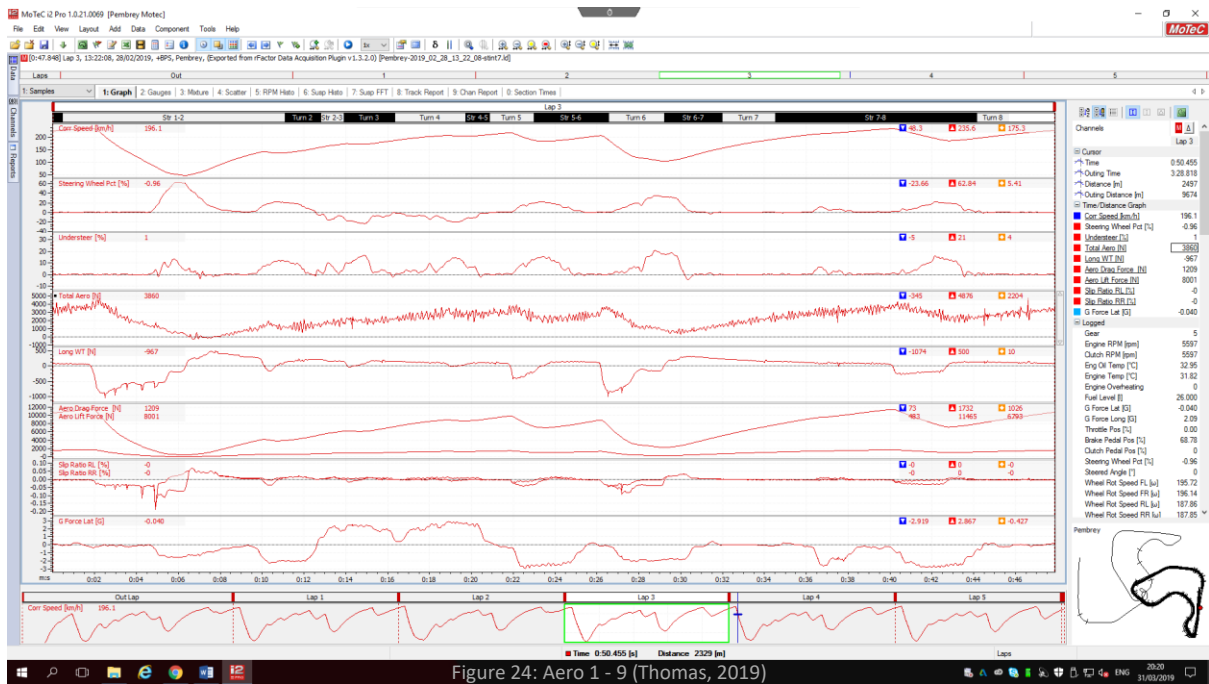
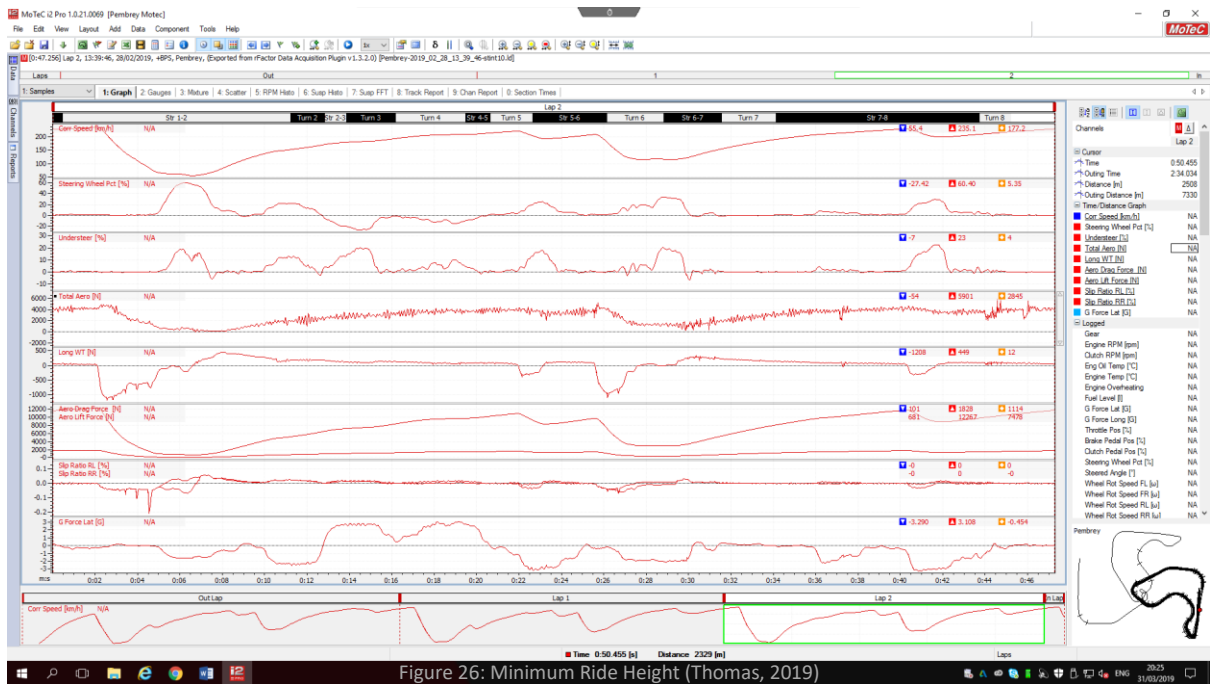
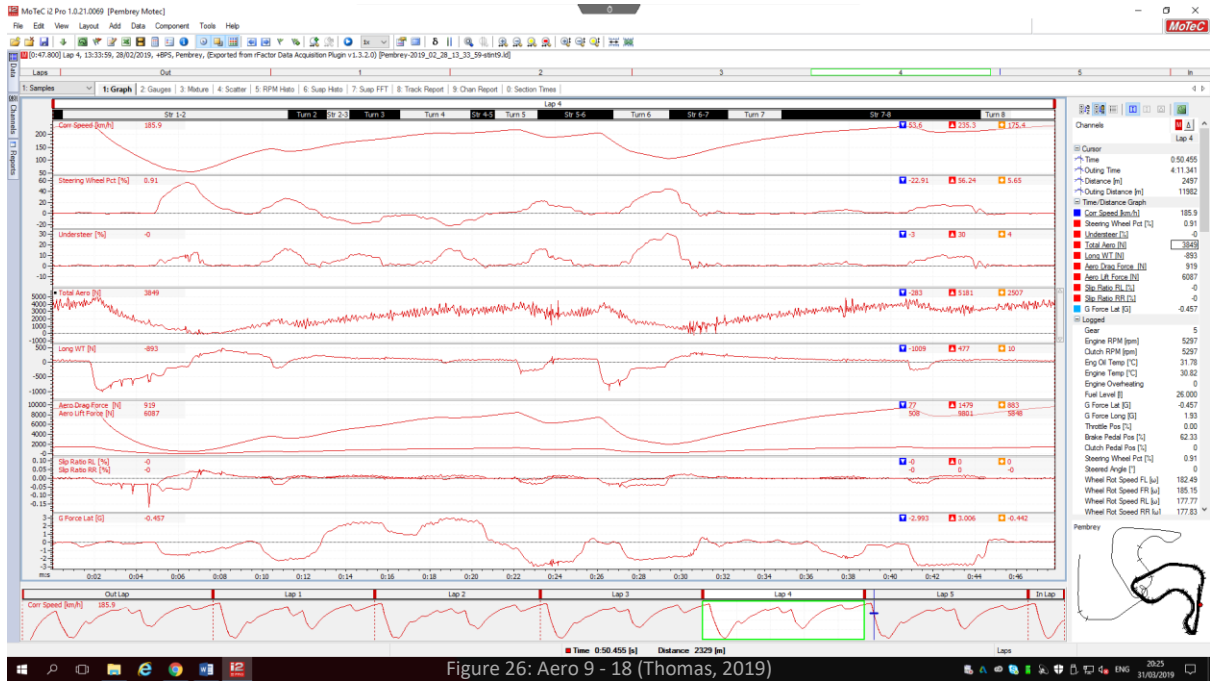


Figure 23: Aero 18 - 9 (Thomas, 2019)





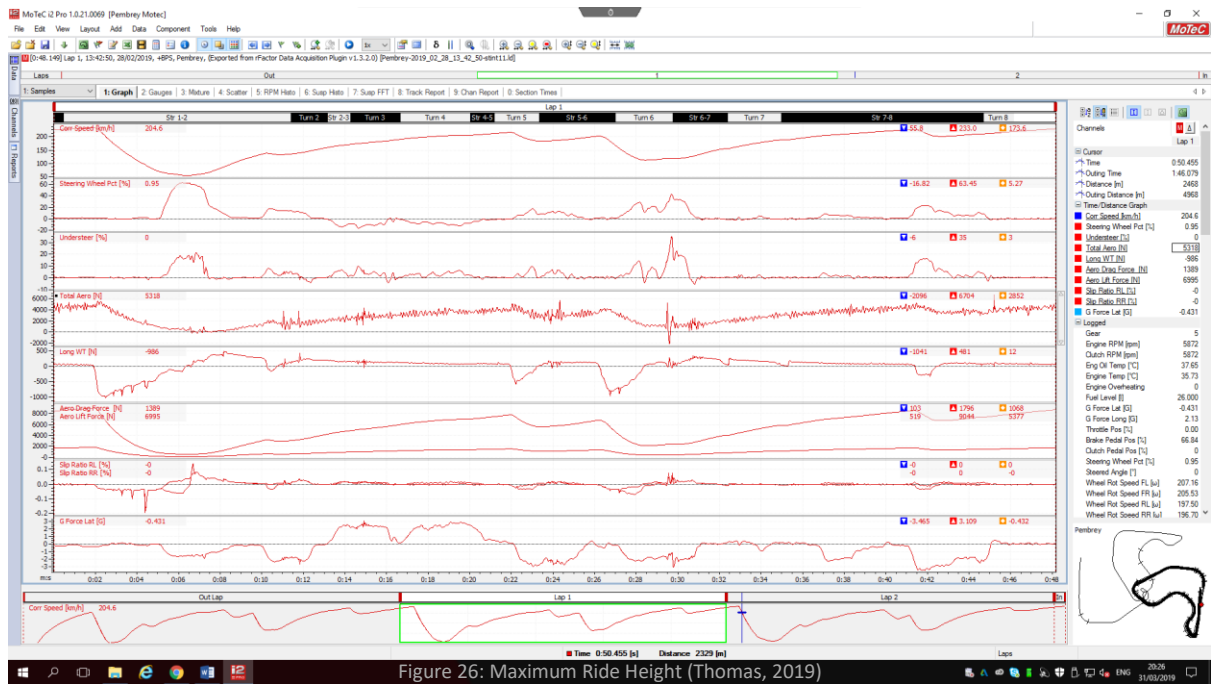


Figure 26: Maximum Ride Height (Thomas, 2019)

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