
Steady state load transfer and Aerodynamic loading

Module Code: M5X00407

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Nomenclature

Steady State

Ms	Vehicle Sprung Mass (kg)
Mus	Vehicle Unsprung Mass (kg)
M	Total Mass (kg)
Musf	Front Corner Unsprung Mass (kg)
Musr	Rear Corner Unsprung Mass (kg)
(H+h)	Centre of Gravity Height (m)
-	Weight Split F:R (%)
W	Wheelbase (m)
Tf	Front Track (m)
Tr	Rear Track (m)
rf	Front Tyre Rolling Radius (m)
rr	Rear Tyre Rolling Radius (m)
MRf	Front Motion Ratio
MRr	Rear Motion Ratio
Ksf	Front Spring Rate (N/m)
Ksr	Rear Spring Rate (N/m)
KWarbf	Front Anti Roll Bar Wheel Rate (N/m)
KWarbr	Rear Anti Roll Bar Wheel Rate (N/m)
Hf	Front Roll Centre Height (m)
Hr	Rear Roll Centre Height (m)
KWf	Front Wheel Rate (N/m)
KWr	Rear Wheel Rate (N/m)
Ay	Lateral Acceleration (m/s ²)
H	Height Between RC and CoG (m)
θ	Roll angle (rad)
δ	Wheel Deflection
M_θ	Anti-Roll Moment (Nm)
K_θ	Total Roll Stiffness (Nm/Rad)
K_{θF}	Front Roll Stiffness (Nm/Rad)
K_{θR}	Rear Roll Stiffness (Nm/Rad)
M_{ot}	Overtopping Moment (Nm)
WT_s	Sprung Mass Elastic WT (N)
WT_{sf}	Front Sprung Mass Elastic WT (N)
WT_{sr}	Rear Sprung Mass Elastic WT (N)
WT_{sRCf}	Front Sprung Mass Geometric Weight Transfer (N)
WT_{sRCr}	Rear Sprung Mass Geometric Weight Transfer (N)
WT_{usf}	Front Unsprung Mass Geometric Weight Transfer (N)
WT_{usr}	Rear Unsprung Mass Geometric Weight Transfer (N)
WT	Total Weight Transfer (N)
WT_f	Front Weight Transfer (N)
WT_r	Rear Weight Transfer (N)

Coast Down

Flo	Front Static tyre load (Left) (N)
Fro	Front Static tyre load (Right) (N)
Rlo	Rear Static tyre load (Left) (N)
Rro	Rear Static tyre load (Right) (N)
V	Velocity (m/s)
Fl	Front tyre load (Left) (N)
Fr	Front tyre load (Right) (N)
Rl	Rear tyre load (Left) (N)
Rr	Rear tyre load (Right) (N)
CoP	Centre of Pressure (%)
T	Time (s)
A	Acceleration (m/s^2)
Cda	Coefficient of Drag * Area
RR	Rolling Resistance
Vm	Velocity Maximum (m/s)
Ma	Mass * Acceleration
CoefLf	Coefficient of Lift (Front)
CoefLr	Coefficient of Lift (Rear)
CLa	Total Coefficient of Lift * Area
CD	Coefficient of Drag

Introduction

The aim is to produce two types of data using the Aston Martin DB9 race car model on the Base Performance Simulator; one showing the effects that the aerodynamic setups have on the Aston Martin DB9 in a straight line and the other to show how the roll stiffness distribution effects both the load distribution and the vehicle handling in steady state testing around three different radiuses.

The objective for the coast down test is to evaluate how the front splitter and wing angle can affect the downforce on the Aston Martin DB9. In order to analyse these setups, calculations will be conducted to show which devices are more powerful to use in a straight line. In addition, the objective for the steady state test is to analyse the predicted weight transfer equations and comment on how well they work for load distribution.

Steady State

Background Information

The investigation carried out in group three contains the change in anti-roll bar wheel rates (N/m) and spring rates (N/m) for each setup shown in Figure 1.

	Group 3		Setup 1	Setup 2	Setup 3	Setup 4	Setup 5	Setup 6
Ksf	Front Spring Rate	(N/m)	202000	254000	307000	254000	202000	307000
KWf	Front Wheel Rate		256172.2	400929.4	546162.7	400929.4	256172	546163
Ksr	Rear Spring Rate	(N/m)	307000	254000	202000	254000	307000	202000
KWr	Rear Wheel Rate	Chart Area	218162.7	168929.4	108172.2	168929.4	218163	108172
Kwarbf	Front Anti Roll Bar Wheel Rate	(N/m)	160000	280000	400000	280000	160000	400000
Kwarbr	Rear Anti Roll Bar Wheel Rate	(N/m)	72000	48000	12000	48000	72000	12000

Figure 1: Group 3, Investigation on springs and anti-roll bar

These values were stored in a setup sheet in MoTeC, which counteracts to the associated time where each stint number occurred using each of these setups.

Under the handling characteristics testing methods, the constant radius test is runned on a closed skidpad as the vehicle accelerates slowly left or right around a constant circle until reaching the maximum speed possible and then kept constant. This can be validated by Panke & Ambhore (2014), Mohan & Shankapal (2005), Kraaijeveld, et al., (2019), Blundell (2010), Gupta, et al., (2019) and Naren, et al., (2016).

Determining the understeer level from the vehicle from the steady state test procedure, “At the same time a higher understeer level means a lower maximum cornering speed since the lateral tyre forces on front and rear axles become less balanced” (Kraaijeveld, et al., 2019, p. 3). This can be seen in Figure 8, where it shows ‘the lower the corner radius, the higher the understeer level’, as this results in the front and rear axles being unstable. In addition, to level the amount of understeer and oversteer around a constant radius, the driver needs to pay attention to how much required steering wheel angle is needed for each lateral acceleration, allowing the steering wheel angle to sustain minimal and predictable. This can be validated by Hei3ing & Ersoy (2011).

The roll moment distribution allows the vehicle to roll to the outside corner under a lot of lateral acceleration. The roll moment is different for the front and rear axles which affects oversteer and understeer, as it is relative to the stiffness in roll in the suspension spring rates at either axle. This can be validated by Santos (2015), Hassan, et al., (2016) and (Milliken & Miliken, 1995).

Anti-Roll Bars

Anti-roll bars are the most efficient ways to influence how the vehicle handles. Their purpose is to reduce body roll as the vehicle corners without stiffening the spring rates. “Stiffening the rear axle can reduce understeer or induce oversteer, and stiffening the front axle can reduce oversteer or induce understeer” (Motorsport Essentials, 2017). However, during wet conditions, softening both front and rear anti-roll bars will increase stability.

Figure 2 shows the roll angle characteristics against lateral acceleration with and without anti-roll bars. As shown in the graph, (Fig.2), using anti-roll bars, the vehicle has half body roll while cornering at maximum speed than not using anti-roll bars.

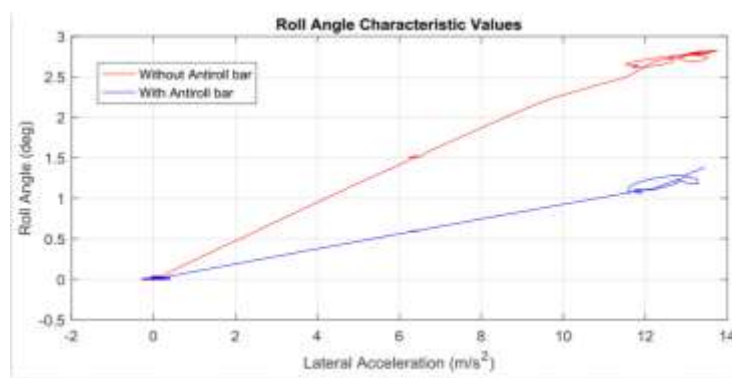


Figure 2: Roll Angle (deg) vs Lateral Acceleration (m/s²) (Gupta, et al., 2019, p. 6)

Methodology

The equations used to calculate the predicted load transfer follows:

Front Wheel Rate

$$(K_{sf} * MR_f^2) + K_{warbf}$$

Equation 1: Front Wheel Rate

Rear Wheel Rate

$$(K_{sr} * MR_r^2) + K_{warbr}$$

Equation 2: Rear Wheel Rate

Ay

$$G \text{ Force Lat} * G$$

Equation 3: Lateral Acceleration

Anti-Roll Moment

$$M_{\theta} = (T^2 * \theta * K_w) / 2$$

Equation 4: Anti-Roll Moment

Roll angle

$$\theta = \xi / (0.5 * T)$$

Equation 5: Roll Angle

Front Roll Stiffness

$$K_{\theta f} = (T_f^2 * K_{w_f}) / 2$$

Equation 6: Front Roll Stiffness

Rear Roll Stiffness

$$K_{\theta r} = (T_r^2 * K_{w_r}) / 2$$

Equation 7: Rear Roll Stiffness

Total Roll Stiffness

$$K_{\theta} = K_{\theta f} + K_{\theta r}$$

Equation 8: Total Roll Stiffness

Overturning Moment

$$M_{ot} = M_s * a_y * H$$

Equation 9: Overturning Moment

Roll Angle 2

$$\theta = M_{ot} / K_{\theta}$$

Equation 10: Roll angle 2

Front Sprung Mass Elastic WT

$$WT_{sf} = (Kw_f * T_f * \Theta) / 2$$

Equation 11: Sprung Mass Elastic WT

Rear Sprung Mass Elastic WT

$$WT_{sr} = (Kw_r * T_r * \Theta) / 2$$

Equation 12: Rear Sprung Mass Elastic WT

Front Sprung Mass Geometric WT

$$WT_{sRCf} = (M_{sf} * ay * h_f) / T_f$$

Equation 13: Front Sprung Mass Geometric WT

Rear Sprung Mass Geometric WT

$$WT_{sRCr} = (M_{sr} * ay * h_r) / T_r$$

Equation 14: Rear Sprung Mass Geometric WT

Front Unsprung Mass Geometric WT

$$WT_{usf} = (M_{usf} * ay * r_f) / T_f$$

Equation 15: Front Unsprung Mass Geometric WT

Rear Unsprung Mass Geometric WT

$$WT_{usr} = (M_{usr} * ay * r_r) / T_r$$

Equation 16: Rear Unsprung Mass Geometric WT

Front Weight Transfer

$$WT_{sf} + WT_{sRCf} + WT_{usf}$$

Equation 17: Front Weight Transfer

Rear Weight Transfer

$$WT_{sr} + WT_{sRCr} + WT_{usr}$$

Equation 18: Rear Weight Transfer

Total Weight Transfer

$$WT = WT_{sf} + WT_{sr}$$

Equation 19: Total Weight Transfer

Magic Number

$$WT_{sf} / WT$$

Equation 20: Magic Number

Figure 3 shows the math channels created in MoTeC using the predicted equations, (Eq.1 –Eq.20

Expressions	
☒ Ay	'G Force Lat' [G] * 'G' [m/s/s]
☒ Speed [m/s]	'Corr Speed' [m/h] / 3.6
☒ Corner Radius [m]	('Speed' [m/s] * 'Speed' [m/s]) / 'Ay'
☒ Theoretical Wheel Steer [deg]	('Wheelbase' [m] / 'Corner Radius' [m]) * 'Rad' [rad]
☒ Theoretical Steer Pct [%]	'Theoretical Wheel Steer' [deg] * (-37.19/6.74)
☒ Understeer Channel	abs('Steering Wheel Pct' [%]) - abs('Theoretical Wheel Steer' [deg])
☒ Overtuning Moment [Nm]	'Sprung Mass' [kg] * 'G Force Lat' [G] * 'G' [m/s/s] * 'Height between RC and CoG' [m]
☒ Roll Stiffness Front	((('Track Front' [m] * 'Track Front' [m]) * 'Front Wheel Rate' [N/m]) / 2)
☒ Roll Stiffness Rear	((('Track Rear' [m] * 'Track Rear' [m]) * 'Rear Wheel Rate' [N/m]) / 2)
☒ Roll Stiffness Total	'Roll Stiffness Front' + 'Roll Stiffness Rear'
☒ Roll Angle [rad]	'Overtuning Moment' [Nm] / 'Roll Stiffness Total'
☒ Roll angle Z [rad]	('Sprung Mass' [kg] * 'Ay' * 'Height between RC and CoG' [m]) / ((('Track Front' [m] * 'Track Front' [m]) * 'Front Wheel Rate' [N/m]) / 2) + ((('Track Rear' [m] * 'Track Rear' [m]) * 'Rear Wheel Rate' [N/m]) / 2)
☒ Small Ang Assumption (Roll Angle)	'Wheel Deflection' / (0.5 * 'Track Front' [m])
☒ Wheel Deflection	('Track Front' [m] * 'Roll Angle' [deg]) / 2
☒ Front Anti Roll Moment [Nm]	'Wheel Deflection' * 'Front Wheel Rate' [N/m] * 'Track Front' [m]
☒ Rear Anti Roll Moment [Nm]	'Wheel Deflection' * 'Rear Wheel Rate' [N/m] * 'Track Rear' [m]
☒ Weight Transfer Front [N]	((('Front Wheel Rate' [N/m] * 'Track Front' [m]) * 'Roll angle Z' [rad]) / 2) + ((('Front Sprung Mass' [kg] * 'Ay' * 'Front Roll Centre Height' [m]) / 'Track Front' [m]) + ((('Front Unsprung Mass' [kg] * 'Ay' * 'Front Tyre Rolling Radius' [m]) / 'Track Front' [m])
☒ Weight Transfer Rear [N]	((('Rear Wheel Rate' [N/m] * 'Track Rear' [m]) * 'Roll angle Z' [rad]) / 2) + ((('Rear Sprung Mass' [kg] * 'Ay' * 'Rear Roll Centre Height' [m]) / 'Track Rear' [m]) + ((('Rear Unsprung Mass' [kg] * 'Ay' * 'Rear Tyre Rolling Radius' [m]) / 'Track Rear' [m])
☒ Total Weight Transfer [N]	'Weight Transfer Front' [N] + 'Weight Transfer Rear' [N]
☒ Sprung Mass Elastic WT Front [N]	('Front Wheel Rate' [N/m] * 'Track Front' [m] * 'Roll angle Z' [rad]) / 2
☒ Sprung Mass Elastic WT Rear [N]	('Rear Wheel Rate' [N/m] * 'Track Rear' [m] * 'Roll angle Z' [rad]) / 2
☒ Sprung Mass Geometric WT Front [N]	('Front Sprung Mass' [kg] * 'Ay' * 'Front Roll Centre Height' [m]) / 'Track Front' [m]
☒ Sprung Mass Geometric WT Rear [N]	('Rear Sprung Mass' [kg] * 'Ay' * 'Rear Roll Centre Height' [m]) / 'Track Rear' [m]
☒ Unsprung Mass Geometric WT Ft [N]	('Front Unsprung Mass' [kg] * 'Ay' * 'Front Tyre Rolling Radius' [m]) / 'Track Front' [m]
☒ Unsprung Mass Geometric WT Rr [N]	('Rear Unsprung Mass' [kg] * 'Ay' * 'Rear Tyre Rolling Radius' [m]) / 'Track Rear' [m]
☒ Front Weight Transfer 2 [N]	'Sprung Mass Elastic WT Front' [N] + 'Sprung Mass Geometric WT Front' [N] + 'Unsprung Mass Geometric WT Ft' [N]
☒ Rear Weight Transfer 2 [N]	'Sprung Mass Elastic WT Rear' [N] + 'Sprung Mass Geometric WT Rear' [N] + 'Unsprung Mass Geometric WT Rr' [N]
☒ Total Weight Transfer 2 [N]	'Front Weight Transfer 2' [N] + 'Rear Weight Transfer 2' [N]
☒ Actual Weight Transfer Front [N]	('Tire Load - FL' [N] - 'Tire Load - FR' [N]) / 2
☒ Actual Weight Transfer Rear [N]	('Tire Load - RL' [N] - 'Tire Load - RR' [N]) / 2
☒ Actual Weight Transfer 3 [N]	'Actual Weight Transfer Front' [N] + 'Actual Weight Transfer Rear' [N]
☒ Weight Transfer 3 [N]	('Total Mass' [kg] * 'Ay' * 'Centre of Gravity Height' [m]) / 'Track Average' [m]
☒ Magic Number (Front)	'Front Weight Transfer 2' [N] / 'Total Weight Transfer 2' [N]
☒ Roll Stiffness Distribution	'Roll Stiffness Front' / 'Roll Stiffness Total'
Constants	
☒ Density of Air [kg/m³]	1.233
☒ G [m/s²]	9.81
☒ Rad [rad]	57.3

Figure 3: MoTeC math channels

Figure 4 shows the setup sheets recorded in MoTeC, by using these values as constants within each time and date of each stint number, they will be implemented into the predicted equations shown in Figure 3.

[illegible]

Figure 4: MoTeC Setup sheet

Results

Figure 5 shows the predicted and actual lateral acceleration (m/s^2) at four different setups over the corner radius (m). The actual lateral acceleration was calculated at one point in time in MoTeC using (Eq.3), compared with the predicted lateral acceleration using the equation (V^2 / R). By comparing the predicted and actual lateral acceleration shows the trends being constant throughout the corner radius, allowing to show a higher G force during the tighter corners with means more steering angle will be applied.

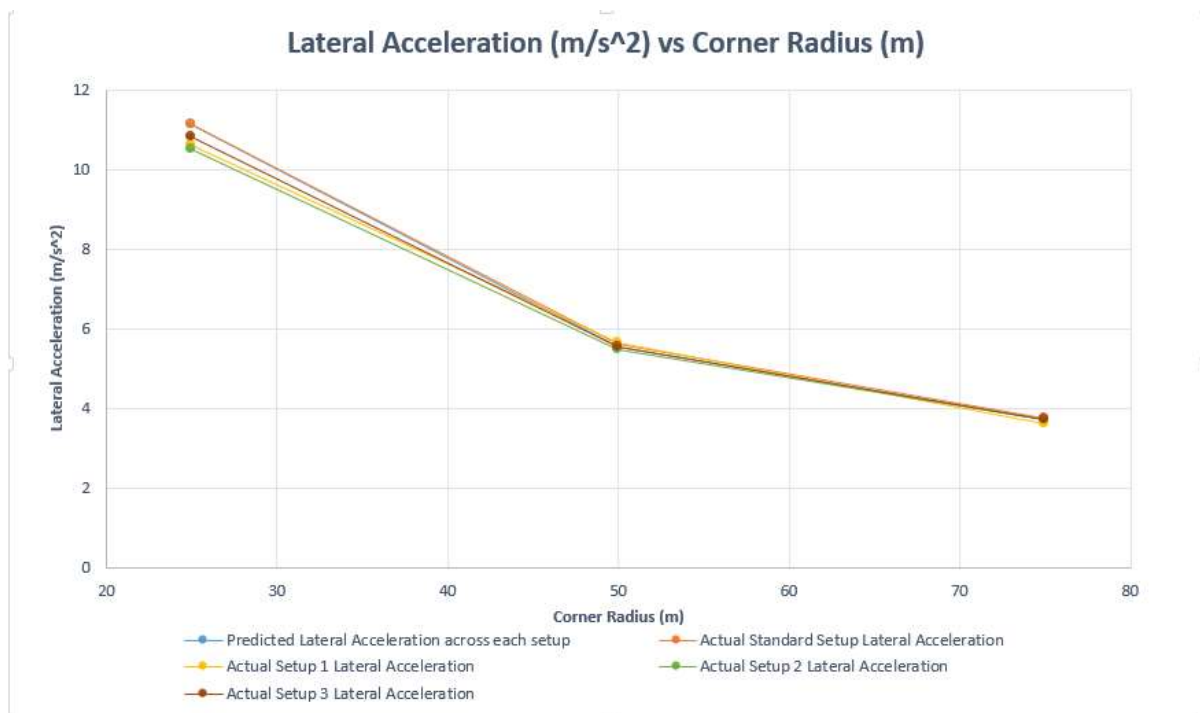


Figure 5: Lateral Acceleration (m/s^2) vs Corner Radius (m)

Figure 6 shows the predicted and actual magic number across each of the setup numbers. As shown from the graph, (Fig.6), the predicted magic number using (Eq.20), gives a low coefficient of weight transfer at setup one and four, where the spring rate at the front is soft and stiff in the rear, resulting in a low proportional load distribution. However, setups three and six shows a high coefficient using a stiff spring rate at the front and a soft suspension at the rear.



Figure 6: Predicted & Actual Magic Number vs Setup Number

Figure 7 shows the same coefficient of load distribution plotted against the roll stiffness distribution (%), showing a linear line throughout each of the setups. This shows when the front roll stiffness is increased, the load distribution on the front axle increases also. Therefore, the front axle turning force decreases as the under-steer ability increases, allowing to keep the handling behaviour and stability at maximum speeds. This is validated from Yang, et al., (2007).

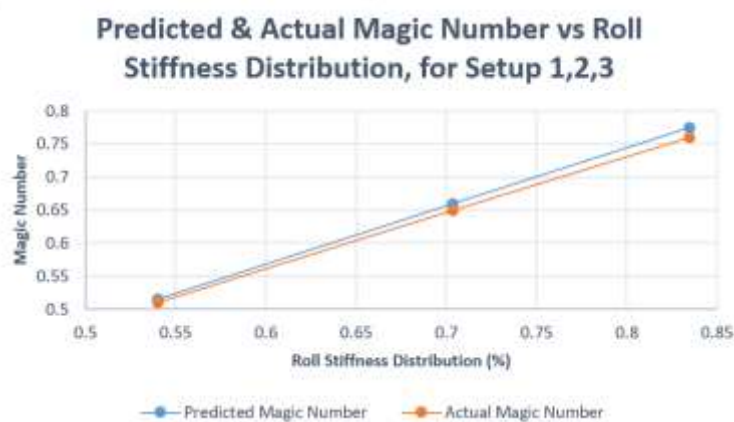


Figure 7: Predicted & Actual Magic Number vs Roll Stiffness Distribution (Setup: 1, 2 and 3)

Figure 8 shows the lower the corner radius the higher the understeer level is, as this results in the front and rear axles being unstable. However, they all result in the same trend over the stiffness distribution at the front. This can be validated from Kraaijeveld, et al., (2019).

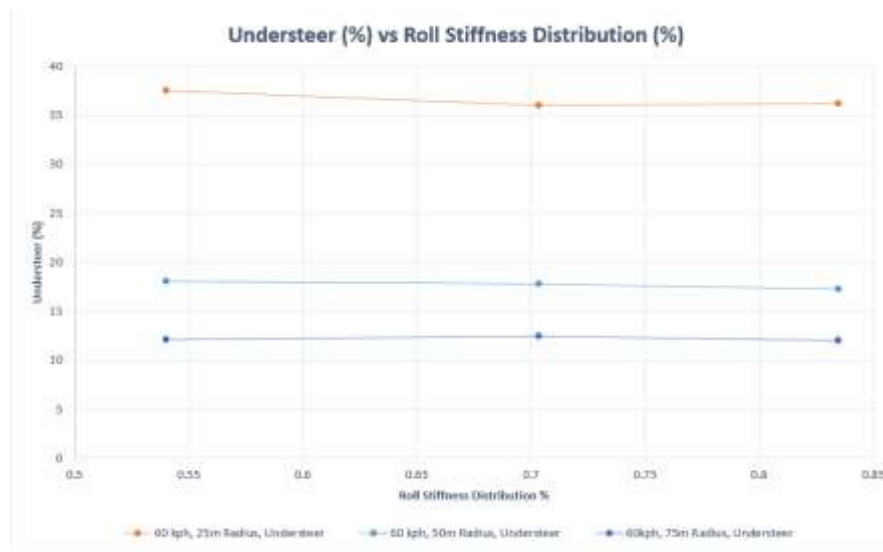


Figure 8: Understeer (%) vs Roll Stiffness Distribution (%)

Figure 9 shows the percentage applied to the steering wheel during each corner radius. As a result, the graph, (Fig.9), shows as the corner radiuses increases, the less steering wheel percentage is applied. However, the actual and predicted wheel steering percentage shows the same trends as the corner radiuses increases.

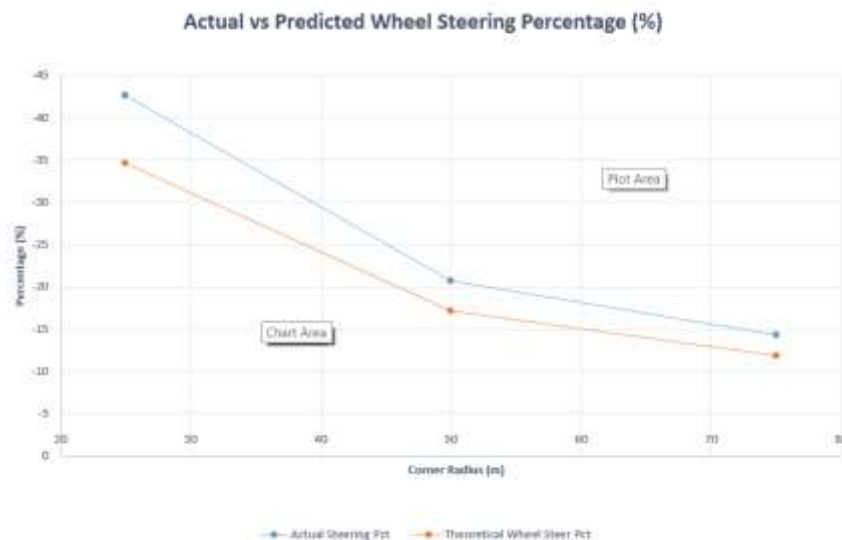


Figure 9: Actual vs Predicted Wheel Steering Percentage (%)

Figure 10 and Figure 11 show an inaccurate representation of understeer vs proportional load distribution. In addition, the data in MoTeC could have been faulty or not calculated correctly, unfortunately resulting to create an inaccurate representation of proportional load distribution over understeer.

Understeer should occur at the most proportion of load distribution, then decrease. However, the graphs, (Fig.10) and (Fig.11), shows an understeering increase, which is not correct. This validates according to Kraaijeveld, et al., (2019).



Figure 10: Understeer (%) vs Magic Number across Setup 1, 2 and 3

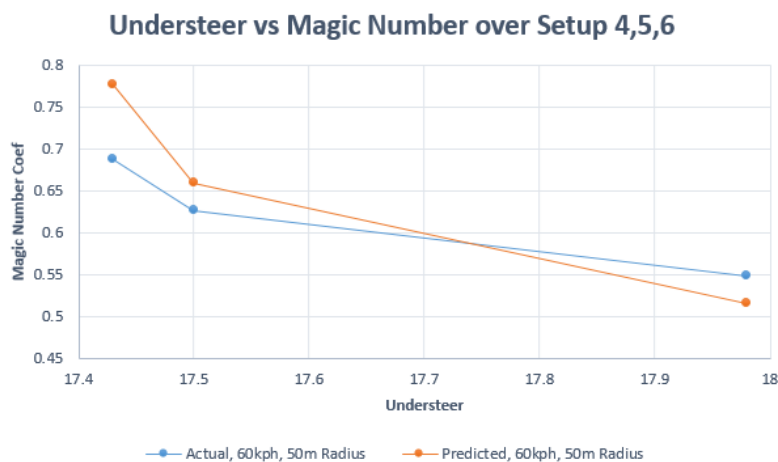


Figure 11: Understeer (%) vs Magic Number across Setup 4, 5 and 6

Coast Down

Background Information

This investigation is involved by testing the aerodynamic performance of the vehicle in a straight line test to determine the most powerful device either front splitter or wing angle.

The coast down test is to determine the characteristics of the aerodynamic drag coefficient by using aerodynamic devices such as spoilers. The principle of the coast down test: the vehicle accelerates on a smooth, aligned straight test track, without any movement of the steering wheel as possible, until the prescribed speed limit for the test. Once the vehicle has attained the speed prescribed, the driver neutralises the drivetrain as this allows the vehicle to freely coast until reaching a stop. This is validated by Emtage (1983), Katz (2006) and Preda, et al., (2010).

The coast down test will involve reducing the amount of lift and drag acting on the vehicle. However, changing the wing angle and front splitter setup to apply downforce to actuate, without producing more drag. This is validated by Machin (2019).

The aerodynamic principle is to “balance the front and rear distribution of downforce” (Technical F1 Dictionary, 2019). This is also known as the centre of pressure (CoP). In addition, this means to balance the amount of pressure acting on the front and rear wheels. This can result in oversteer (at the front) and understeer (at the rear) if too much is applied.

Front Splitters

Front splitters are manufactured to reduce the space from the ground and underneath of the vehicle, which blocks some of the air going beneath the vehicle. The front splitter tries to remain high amounts of air pressure on top of the vehicle instead of underneath as this creates downforce or negative lift. This can be validated by Kshirsagar & Chopade (2018) and Starvos (2014).

Rear wing

The aerodynamic principle of a rear wing is equivalent to the front splitter, both devices create downforce. However, the rear wing will create downforce for the rear to increase its stability and grip. This can be validated by Starvos (2014).

Research analysis

The results to follow are from Le good, et al., (1998) report entitled *A comparison of on-road aerodynamic drag measurements with wind tunnel data from Pininfarina and MIRA*.

Figure 12 shows how the drag coefficient is affected by the height of the rear wing, this graph, (Fig.12), shows by increasing the height of the rear spoiler, it will increase the coefficient of drag.

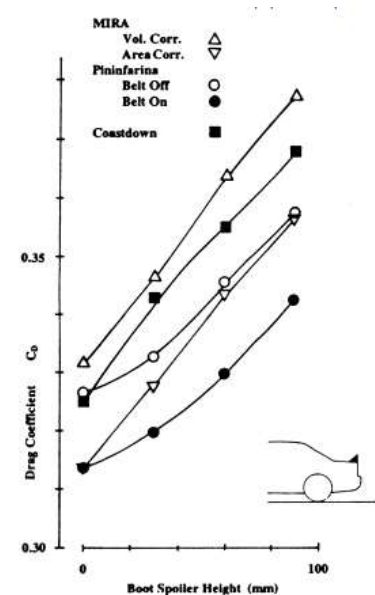


Figure 12: Drag Coefficient vs Rear Spoiler

Figure 13 shows what happens to the drag coefficient when a front spoiler is added to the vehicle. The graph, (Fig.13), shows the coefficient of drag decreasing until the front spoilers length is reached and then rises if the spoiler has too much depth.

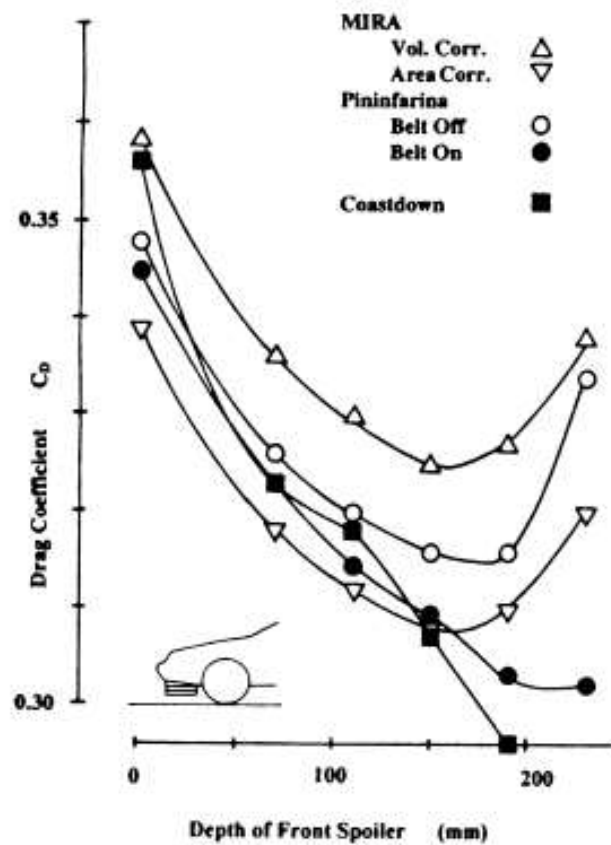


Figure 13: Drag Coefficient vs Front Spoiler

The results to follow are from Katz (1995) book entitled *Race Car Aerodynamics*.

Figure 14 shows the effects of the rear spoiler angle aerodynamics, against the lift and drag of the vehicle. As shown in the graph, (Fig.14), the spoiler angle increases both drag and downforce is greater than before. This is because certain race car wing heights are limited so the wing angle becomes an important factor to change the drag and lift coefficients.

To compare, the graph shown in Appendix 1, (Fig.22), shows a similar trend to Katz (1995), however, the coefficient of lift at the front is decreasing, instead of increasing with the degree of wing angle.

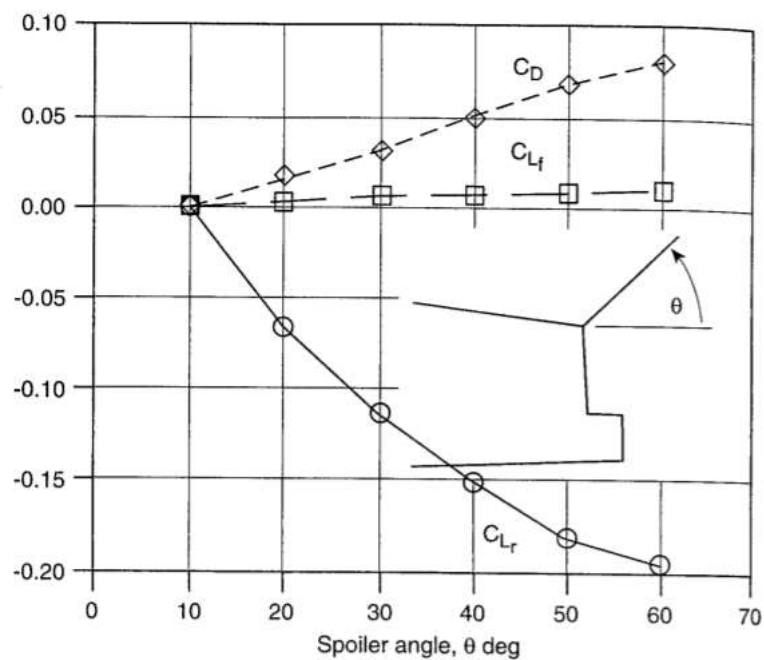


Figure 14: Effects of rear spoiler angle on lift and drag coef

Methodology

The equations used to calculate the performance of aerodynamics for each device.

Static loads and Tyre loads were taken at one point in time from MoTeC, when the vehicle was stationary and when the vehicle was at maximum velocity. In addition, maximum velocity was recorded in m/s, V_1 , V_2 , (Start) V_3 and V_4 (End) were recorded within a second of each other, as can be seen by Figure 15 to calculate A_1 and A_2 shown in (Eq.25 – Eq.26).



Figure 15: MoTeC Coast down test

Front Aero

$$(F_l + F_r) - (F_{lo} + F_{ro})$$

Equation 21: Front Aero

Rear Aero

$$(R_l + R_r) - (R_{lo} + R_{ro})$$

Equation 22: Rear Aero

Total Aero

$$\text{Front Aero} + \text{Rear Aero}$$

Equation 23: Total Aero

Centre of Pressure (CoP)

$$(\text{Front Aero} / \text{Total Aero}) * 100$$

Equation 24: Centre of Pressure

A_1

$$(V_2 - V_1) / (T_2 - T_1)$$

Equation 25: A_1

A₂

$$(V_4 - V_3) / (T_4 - T_3)$$

Equation 26: A₂

C_{da}

$$(2 * (Ma_1 - Ma_2) / (1.223 * Vm^2))$$

Equation 27: C_{da}

Ma₁

$$(Ms * A_1) * -1$$

Equation 28: Ma₁

RR

$$(Ms * A_2) * -1$$

Equation 29: RR

V_m

$$(V_1 + V_2) / 2$$

Equation 30: V_m

C_{ofLf}

$$-((Fl + Fr) - (Flo + Fro) / (0.5 * 1.223 * Vm^2))$$

Equation 31: C_{ofLf}

C_{ofLr}

$$-((Rl + Rr) - (Rlo + Rro) / (0.5 * 1.223 * Vm^2))$$

Equation 32: C_{ofLr}

CL_a

$$- (Total Aero) / (0.5 * 1.223 * Vm^2)$$

Equation 33: CL_a

Drag Force

$$0.5 * CDa * 1.223 * (V^2)$$

Equation 34: Drag Force

Efficiency

$$CLa / CDa$$

Equation 35: Efficiency

Figure 16 shows the aerodynamic calculations, using the equations, (Eq.21 – Eq.35).

Stint			(Static loads)					(Tire loads)										(CoefD) (Ma2)																	
	Splitter Length	Wing Angle	Flo	Fro	Rlo	Rro	Total Static Mass (kg)	V	Fl	Fr	Fl	Rr	Front Aero	Rear Aero	Total Aero	CoP	V ₁	T ₁	V ₂	T ₂	V ₃	T ₃	V ₄	T ₄	A ₁	A ₂	Cda	RR	Vm	Ma1	CoFL	CoLR	CLa	Drag Force	Efficiency
Default	2	8	3024	3045	3265	3230	1281.14	57.36	3761	3681	4710	4648	1369	2863	4232	32.35	55.14	0.00	53.08	0.97	2.44	112.86	2.06	113.92	-2.13	-0.37	1.11	418.80	54.11	2413.04	-0.76	-1.60	-2.36	2244.65	-2.12
28	1	1	3040	3037	3258	3247	1282.57	57.44	3668	3621	4322	4356	1112	2173	3285	33.85	56.47	0.00	54.56	1.00	2.36	118.22	2.08	120.07	-1.91	-0.33	0.95	371.46	55.51	2169.16	-0.59	-1.15	-1.74	1928.06	-1.83
29	1	6	3037	3036	3244	3250	1281.04	57.36	3488	3541	4612	4646	956	2764	3720	25.70	55.36	0.00	53.53	0.93	2.42	116.22	2.06	117.22	-1.98	-0.36	1.01	408.68	54.44	2247.57	-0.53	-1.52	-2.05	2044.52	-2.02
30	1	12	3044	3032	3245	3254	1281.86	57.31	3472	3371	5004	4934	767	3439	4206	18.24	55.03	0.00	52.97	0.98	2.44	153.39	2.11	154.34	-2.11	-0.35	1.12	398.73	54.00	2388.32	-0.43	-1.93	-2.36	2244.29	-2.11
32	2	1	3029	3042	3256	3244	1281.45	57.42	3776	3888	4246	4322	1593	2068	3661	43.51	55.39	0.00	53.47	0.98	2.44	156.73	2.08	157.71	-1.96	-0.37	1.00	419.14	54.43	2224.67	-0.88	-1.14	-2.02	2012.35	-2.03
33	2	6	3035	3039	3254	3245	1281.61	57.36	3724	3792	4537	4581	1442	2619	4061	35.50	55.36	0.00	53.31	0.98	2.47	114.51	2.14	115.49	-2.10	-0.34	1.11	386.90	54.33	2385.88	-0.80	-1.45	-2.25	2231.62	-2.03
34	2	12	3030	3046	3261	3241	1282.16	57.25	3705	3617	4935	4876	1246	3309	4555	27.35	54.97	0.00	52.81	0.96	2.53	111.45	2.17	112.47	-2.22	-0.37	1.18	419.14	53.89	2514.84	-0.70	-1.86	-2.57	2369.14	-2.17
35	3	1	3027	3050	3255	3254	1282.98	57.42	3999	4054	4209	4243	1976	1943	3919	50.42	55.50	0.00	53.50	0.97	2.50	115.09	2.14	116.13	-2.07	-0.35	1.00	394.13	54.50	2347.83	-1.09	-1.07	-2.16	2171.95	-2.01
36	3	6	3041	3035	3241	3254	1281.45	57.33	3963	3926	4534	4507	1810	2546	4359	41.59	54.97	0.00	52.89	0.96	2.44	112.86	2.08	113.90	-2.17	-0.35	1.16	394.13	53.93	2463.50	-1.02	-1.43	-2.45	2342.57	-2.11
37	3	12	3042	3034	3247	3254	1282.06	57.22	3901	3798	4887	4821	1623	3207	4890	33.60	54.67	0.00	52.44	0.96	2.44	110.26	2.08	111.32	-2.32	-0.34	1.28	388.15	53.96	2627.74	-0.93	-1.83	-2.75	2560.93	-2.16
37	3	12	3055	3019	3254	3250	1282.16	57.19	3907	3786	4889	4810	1619	3205	4824	33.56	54.81	0.00	52.47	1.01	2.47	109.64	2.14	110.57	-2.32	-0.36	1.26	409.53	53.64	2627.61	-0.92	-1.82	-2.74	2526.00	-2.17

Figure 16: Excel Aerodynamic Calculations

Results

The values according to front splitter length and wing angle are just a setup number according to its aerodynamic use. For example, front splitter length '1' means it is at its minimum setup and wing angle '12' meaning the maximum degree of wing angle applied.

Figure 17 shows the pressure (downforce) created according to each aerodynamic device, such as 'front splitter length' and 'wing angle'. The graph, (Fig.17a), shows as the splitter length increases in size, the downforce increases dramatically. However, increasing the wing angle will balance the amount of downforce acting on the front of the vehicle. In addition, the graph, (Fig.17b), shows as the wing angle increases the downforce also increases dramatically, however, due to centre of pressure shown in Figure 18, the aim is to balance the amount of pressure on the front and rear wheels. Finally, the graph, (Fig.17c), shows the total downforce reacting on the vehicle; however, during the coast down test, the vehicle should have as little drag for the best aerodynamic performance in a straight line. The graph, (Fig 19), shows the minimum aero setup resulted drag to become as miniature as possible. However, comparing these results to Figure 20, the downforce created from negative lift will increase the vertical load on the tyres and improve the stability and grip of the vehicle. This can be validated from Beeton (2012).

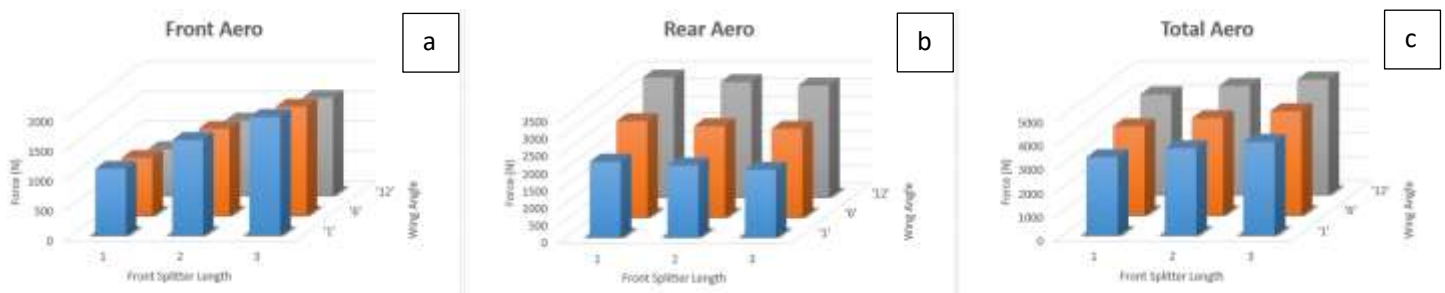


Figure 17: Front, Rear and Total Aero

Figure 18 shows the centre of pressure, this is where the downforce reacts on the vehicle. However, the centre of pressure should be optimised so it sinks in with the centre of mass. This is an important factor because if the vehicle is designed with a lot of downforce, no drag and the centre of pressure is incorrect, it will not make use of its downforce created. If the centre of pressure is less than the centre of mass, this means too much downforce is created on the front and if the centre of pressure is more than the centre of mass, this means too much downforce is created on the rear, or not enough on the front. To make changes to the centre of pressure is relatively easy, simply increase or decrease the rear wing angle. By doing so, it is unlikely to affect the airflow against the rest of the vehicle shown in Appendix 2, (Fig.23). This can be verified by Machin (2019).

As validated by Machin (2019), shown in the graph, (Fig.18), as the wing angle increases the centre of pressure drops. As the front splitter length the frontal downforce increases making the centre of pressure rise, this could appear to have too much downforce or too little.

As can be seen by the graph, (Fig.18), the trends for each splitter length follow the same decline as wing angle increases.

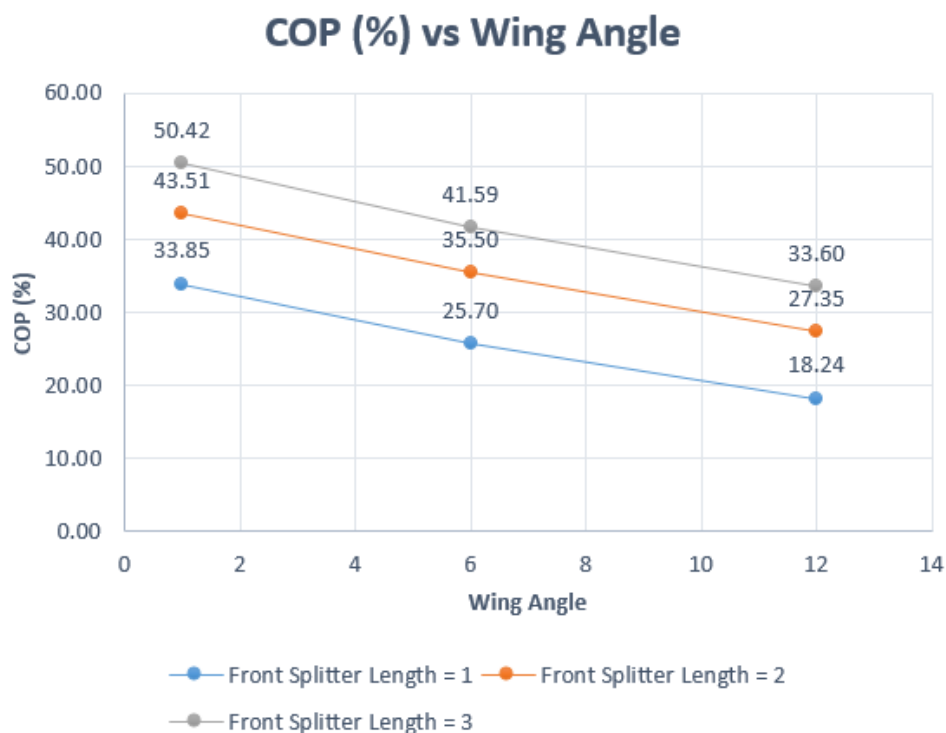


Figure 18: CoP

Figure 19 shows the coefficient of drag created from the front splitter and wing angle. As can be seen from the graph, (Fig.19), using the minimum aerodynamic setup will create the least drag. In comparison, according to the graphs in Research analysis, during the coast down test at setting 2 on the front splitter creates the least drag. However, the difference for the coefficient of drag against the front splitter are not dramatically noticeable.

As can be seen by the graph, (Fig.19), the trends for min and max splitter length show the same increase with wing angle. However, using the second setup for front splitter there is a distinct rise of drag compared to the other setups.

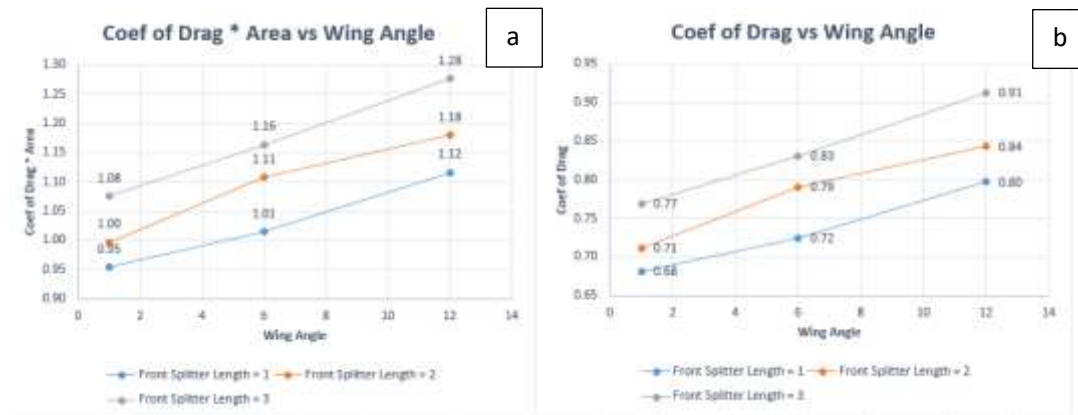


Figure 19: CDa & CD

Figure 20 shows the coefficient of negative lift acting on the vehicle, as can be seen from the graphs, (Fig.20a, Fig.20b), as the front splitter length increases the downforce on the front of the vehicle becomes much larger, resulting in a high amount of pressure acting on the front. However, as the wing angle increases, the downforce on the rear counteracts the amount of downforce on the front, as the rear downforce also increases, balancing of the front and rear distribution.

As can be seen by the graph, (Fig.20), the trends for minimum and maximum splitter length show the same increase of negative lift with wing angle. Whereas, at minimum aero there is a slight increase of negative lift reacting on the vehicle.

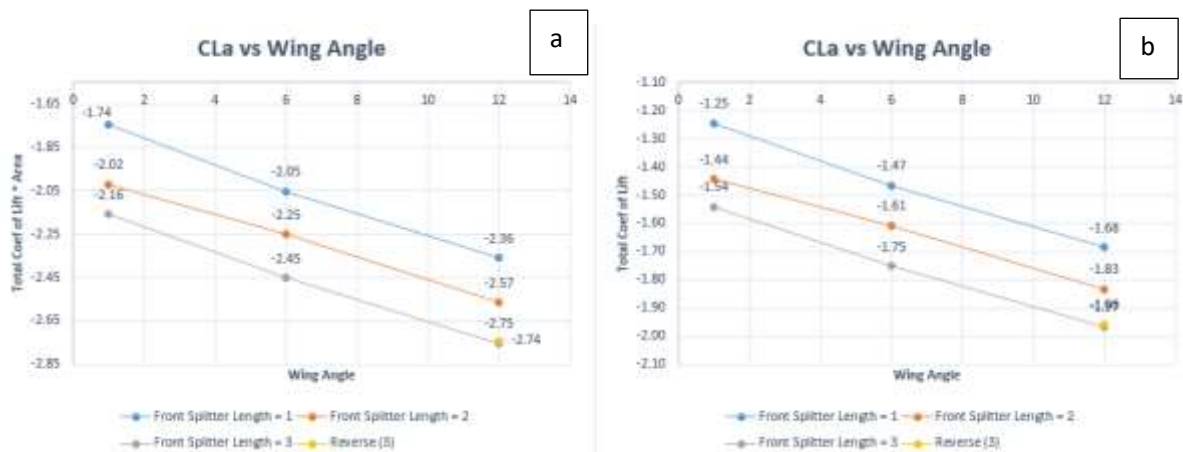


Figure 20: CLa & CL

Figure 21 shows the aerodynamic efficiency of the vehicle in a straight line. This shows CL_a / CD_a , as this compares the balance between downforce and drag acting on the vehicle. As a result, the best aerodynamic setup was setting 2 for front splitter and setting 12 for wing angle.

As can be seen by the graph, (Fig.21), the trends for minimum and maximum splitter length show the same trends as wing angle increases the aero efficiency increases. However, front splitter length setting '2', shows the wrong trend, meaning a fault in the coast down test. As it shows at minimum wing angle is more efficient than standard wing angle. It should follow the same trends for minimum and maximum splitter length.



Figure 21: Aero Efficiency

Conclusion

To conclude, the two main factors used for aerodynamic performance are negative lift and drag. This varies as the aerodynamic devices change, as shown in (Fig.17-Fig.21). From an aerodynamic point of view, having the least amount of drag and most amount of negative lift is described to be the most powerful. However, both devices balance the amount of downforce acting on top of the vehicle, but increasing the rear wing angle will allow the vehicle to be more stable, have more traction and also make the aerodynamics more efficient in which it balances the negative lift and drag acting upon the vehicle.

In the steady state test, the predicted equations showed good results and analysis and showed the trends matching the actual load distribution. However, during the understeer channel there must have been an error, resulting in inaccurate results.

During the coast down and steady state many assumptions were made:

- Only the roll stiffness changed during the steady state test
- The weather stayed constant throughout, no wind interactions. Shown in coast down test, during the reverse maneuver to show a constant result.
- The tyres did not wear, also the tyre temperatures stayed constant
- Fuel did not increase or decrease during the course of the tests
- No damage or deformation to the car.
- Same driver during coast down test for accurate results
- Same driver during steady state test for accurate results
- The simulation could not simulate the separation of airflow around the car, even though it constantly calculates the downforce even at 0kph.
- Throttle remained flat for a consistent amount of time allowing maximum velocity to be reached until putting the drivetrain into neutral to eliminate any driveline drag – Coast down
- Damping coefficient remained constant
- Gravel strip between lane changes so the car was kept in the centre of the lane – Coast down
- Rolling Resistance changed slightly through the simulation, whereas it should not have.
- The air temperature pressure and density remained constant

The limitations during the steady state method is having a set speed during a constant radius. However, the group tested set speeds of 60,70,80,90 and 100kph on a constant radius. The controlled limit was just under 100kph, reaching the end of our testing method.

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Appendices

Appendix 1

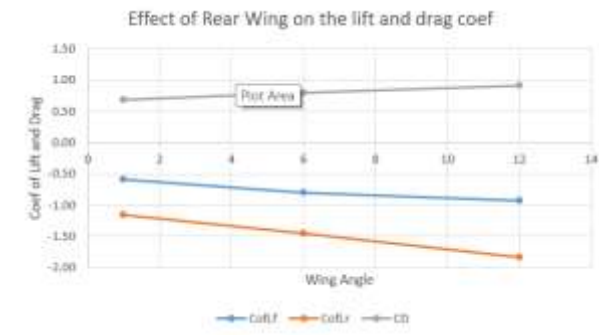


Figure 22: Effect of Rear Wing on lift and drag at minimum front splitter length

Appendix 2

Figure 23 shows how a rear spoiler can obstruct with the airflow around the vehicle, which creates “a controlled segregation of the flow in a desired place.” (Kshirsagar & Chopade, 2018), as this creates positive lift to the vehicle.

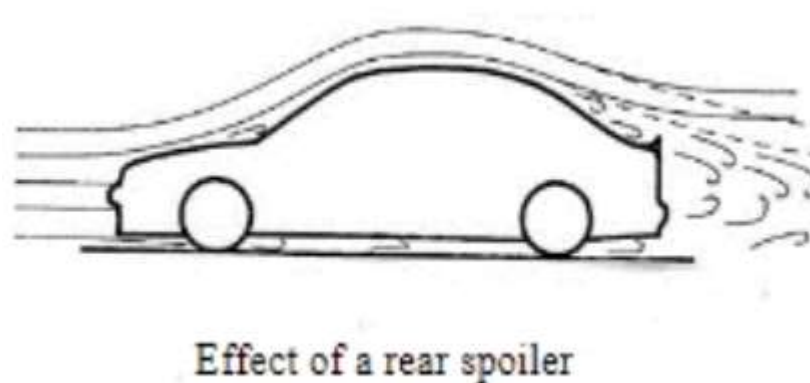


Figure 23: Aerodynamic effect of a rear spoiler (Kshirsagar & Chopade, 2018)