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Steady State Load Transfer and Aerodynamic
Loading

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Vehicle Dynamics M5X00407

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1) Introduction

1.1 Objectives

This report will help guide the reader into understanding the basic principles behind the 'Steady State Cornering' and the 'Constant Velocity Coast Down' experiments.

The intention is to analyse and gain further knowledge on:

- To what degree, altering the roll stiffness distribution by means of the suspension springs and anti-roll bars rates at the front and rear of a vehicle, modify the handling, directional control and load distribution throughout different speeds and corner radii.
- How changing the impact of the aerodynamic features of a race car (front splitter length and rear wing angle of attack) affect the amount of downforce (negative lift), drag, centre of pressure and other variables that affect the aerodynamic efficiency and performance of the car.

The results of these experiments will then be analysed using the MoTeC data acquisition program, the accuracy of which, will be validated against an Excel spreadsheet using the same formulas, which theoretically, should provide similar results.

1.2 Assumptions Throughout Simulator Session

1.2.1 Global

- Weather inside the simulation stayed constant with no wind
- Entire track was flat with no incline or descent
- Tyre didn't simulate wear and temperatures stayed constant
- Fuel level didn't decrease
- No damage or deformation to vehicle
- Infinitely rigid chassis implying no deformation or distortion
- COG Roll centre doesn't change significant amount and therefore neglected
- Damping coefficient remained constant
- Air temperature, pressure and density stayed constant
- A 50/50 vehicle weight distribution was assumed
- rFactor Pro can't simulate separation of airflow around a vehicle

1.2.1 Steady-State Cornering

- Nothing other than roll stiffness was changed
- Same driver for accurate and consistent results

1.2.2 Constant Velocity Coast Down

- Same driver for accurate and consistent results
- Throttle kept flat short period after knocking into neutral to eliminate mechanical drag
- Rumble strip between lanes would interfere with results, kept vehicle central in lane

2) Equations Used for Calculations

2.1 Steady-State Cornering

2.1.1 Velocity [m/s]

$$= Velocity[Kph] * \left(\frac{1000}{3600}\right)$$

Equation 1 - Velocity

2.1.2 Lateral Acceleration [m/s²]

$$= \frac{Velocity^2[\frac{m}{s}]}{Corner\ Radius[m]}$$

Equation 2 – Lateral Acceleration

2.1.3 Corner Radius [m]

$$= \frac{Velocity^2[\frac{m}{s}]}{Lateral\ Acceleration[\frac{m}{s^2}]}$$

Equation 3 – Corner Radius

2.1.4 Roll Centre (RC) Height at Centre of Gravity (COG) [m]

$$= \frac{(RC\ Height\ Rear[m] - RC\ Height\ Front[m])}{\left(\frac{1}{2} * Wheelbase[m]\right)} * \left(\frac{1}{2} * Wheelbase[m]\right)$$

Equation 4 – Roll Centre Height at Centre of Gravity

2.1.5 Difference Between Roll Centre (RC) Height at Centre of Gravity (COG) [m]

$$= COG\ Height[m] - RC\ Height\ at\ COG[m]$$

Equation 5 – Height Between Roll Centre and Centre of Gravity

2.1.6 Overturning Moment [N/m]

$$= Sprung\ Mass[Kg] * Lateral\ Acceleration[\frac{m}{s^2}] * Height\ Difference\ of\ RC\ \&\ COG[m]$$

Equation 6 – Overturning Moment

2.1.7 Wheel Rate Front [N/m]

$$= \left(Spring\ Rate\ Front\left[\frac{N}{m}\right] * Motion\ Ratio\ Front^2\left[\frac{N}{m}\right] \right) + Anti\ Roll\ Bar\ Rate\ Front\left[\frac{N}{m}\right]$$

Equation 7 – Wheel Rate Front

2.1.8 Wheel Rate Rear [N/m]

$$= \left(\text{Spring Rate Rear} \left[\frac{N}{m} \right] * \text{Motion Ratio Rear}^2 \left[\frac{N}{m} \right] \right) + \text{Anti Roll Bar Rate Rear} \left[\frac{N}{m} \right]$$

Equation 8 – Wheel Rate Rear

2.1.9 Roll Stiffness Front [Nm/rad]

$$= \frac{\left(\text{Track Front}^2 [m] * \text{Wheel Rate Front} \left[\frac{N}{m} \right] \right)}{2}$$

Equation 9 – Roll Stiffness Front

2.1.10 Roll Stiffness Rear [Nm/rad]

$$= \frac{\left(\text{Track Rear}^2 [m] * \text{Wheel Rate Rear} \left[\frac{N}{m} \right] \right)}{2}$$

Equation 10 – Roll Stiffness Rear

2.1.11 Roll Stiffness Total [Nm/rad]

$$= \text{Roll Stiffness Front} \left[\frac{Nm}{rad} \right] + \text{Roll Stiffness Rear} \left[\frac{Nm}{rad} \right]$$

Equation 11 – Roll Stiffness Total

2.1.12 Roll Stiffness Distribution (RSD) [Coefficient]

$$= \frac{\text{Roll Stiffness Front} \left[\frac{Nm}{rad} \right]}{\text{Roll Stiffness Total} \left[\frac{Nm}{rad} \right]}$$

Equation 12 – Roll Stiffness Distribution

2.1.13 Roll Angle [rad]

$$= \frac{\text{Overturning Moment} [Nm]}{\text{Roll Stiffness Total} \left[\frac{Nm}{rad} \right]}$$

Equation 13 – Roll Angle

2.1.14 Wheel Deflection Front [rad]

$$= \frac{(\text{Track Front} [m] * \text{Roll Angle} [rad])}{2}$$

Equation 14 – Wheel Deflection Front

2.1.15 Wheel Deflection Rear [rad]

$$= \frac{(\text{Track Rear} [m] * \text{Roll Angle} [rad])}{2}$$

Equation 15 – Wheel Deflection Rear

2.1.16 Anti Roll Moment Front [Nm]

$$= \text{Wheel Deflection}[\text{rad}] * \text{Wheel Rate Front} \left[\frac{\text{N}}{\text{m}} \right] * \text{Track Front}[\text{m}]$$

Equation 16 – Anti Roll Moment Front

2.1.17 Anti Roll Moment Rear [Nm]

$$= \text{Wheel Deflection}[\text{rad}] * \text{Wheel Rate Rear} \left[\frac{\text{N}}{\text{m}} \right] * \text{Track Rear}[\text{m}]$$

Equation 17 – Anti Roll Moment Rear

2.1.18 Elastic Weight Transfer Front [N]

$$= \text{Wheel Deflection}[\text{rad}] * \text{Wheel Rate Front}[\text{Nm}]$$

Equation 18 – Elastic Weight Transfer Front

2.1.19 Elastic Weight Transfer Rear [N]

$$= \text{Wheel Deflection}[\text{rad}] * \text{Wheel Rate Rear}[\text{Nm}]$$

Equation 19 – Elastic Weight Transfer Rear

2.1.20 Sprung Geometric Weight Transfer Front [N]

$$= \frac{\left(\text{Sprung Mass Front}[\text{Kg}] * \text{Lateral Acceleration} \left[\frac{\text{m}}{\text{s}^2} \right] * \text{RC Height Front}[\text{m}] \right)}{\text{Track Front}[\text{m}]}$$

Equation 20 – Sprung Geometric Weight Transfer Front

2.1.21 Sprung Geometric Weight Transfer Rear [N]

$$= \frac{\left(\text{Sprung Mass Rear}[\text{Kg}] * \text{Lateral Acceleration} \left[\frac{\text{m}}{\text{s}^2} \right] * \text{RC Height Rear}[\text{m}] \right)}{\text{Track Rear}[\text{m}]}$$

Equation 21 – Sprung Geometric Weight Transfer Rear

2.1.22 Unsprung Geometric Weight Transfer Front [N]

$$= \frac{\left(\text{Total Front Unsprung Mass}[\text{kg}] * \text{Lateral Acceleration} \left[\frac{\text{m}}{\text{s}^2} \right] * \text{Front Tyre Rolling Radius}[\text{m}] \right)}{\text{Track Front}[\text{m}]}$$

Equation 22 – Unsprung Geometric Weight Transfer Front

2.1.23 Unsprung Geometric Weight Transfer Rear [N]

$$= \frac{\left(\text{Total Rear Unsprung Mass}[\text{kg}] * \text{Lateral Acceleration} \left[\frac{\text{m}}{\text{s}^2} \right] * \text{Rear Tyre Rolling Radius}[\text{m}] \right)}{\text{Track Rear}[\text{m}]}$$

Equation 23 – Unsprung Geometric Weight Transfer Rear

2.1.24 Weight Transfer Total Front [N]

$$= \text{Elastic Weight Transfer Front} + \text{Sprung Geometric Weight Transfer Front} \\ + \text{Unsprung Geometric Weight Transfer Front}$$

Equation 24 – Weight Transfer Total Front

2.1.25 Weight Transfer Total Rear [N]

$$= \text{Elastic Weight Transfer Rear} + \text{Sprung Geometric Weight Transfer Rear} \\ + \text{Unsprung Geometric Weight Transfer Rear}$$

Equation 25 – Weight Transfer Total Rear

2.1.26 Weight Transfer Total [N]

$$= \text{Total Weight Transfer Total Front} + \text{Total Weight Transfer Total Rear}$$

Equation 26 – Weight Transfer Total

2.1.27 Total Load Transfer [N]

$$= \frac{\text{Total Vehicle Mass}[Kg] * \text{Lateral Acceleration} \left[\frac{m}{s^2} \right] * \text{Height Difference of RC \& COG}[m]}{\text{Average Track}[m]}$$

Equation 27 – Total Load Transfer

2.1.28 Magic Number (Weight Transfer Distribution) [Coefficient]

$$= \frac{\text{Weight Transfer Total Front}}{(\text{Weight Transfer Total Front} + \text{Weight Transfer Total Rear})}$$

Equation 28 – Magic Number

2.1.29 Theoretical Wheel Steer [°]

$$= \frac{\text{Wheelbase}[m]}{\text{Corner Radius}[m]} * 57.3$$

Equation 29 – Theoretical Wheel Steer

2.1.30 Theoretical Steering Wheel Percentage (Ackerman Steer Angle) [%]

$$= \frac{\text{Theoretical Wheel Steer}[^{\circ}] * \text{Steering Wheel Pct}[\%]}{\text{Theoretical Wheel Steer}[^{\circ}]}$$

Equation 30 – Theoretical Steering Wheel Percentage

2.1.31 Understeer [Coefficient]

$$= ABS(Theoretical Steering Wheel Percentage[\%]) - ABS(Theoretical Wheel Steer[^\circ])$$

Equation 31 – Understeer

*ABS is a command function used to attain the 'absolute value', which ignores the sign convention of the data and takes just the magnitude into consideration for calculations.

2.2 Constant Velocity Coast Down

2.2.1 Velocity [m/s]

$$= Velocity[Kph] * \left(\frac{1000}{3600}\right)$$

Equation 32 – Velocity

2.2.2 Aerodynamic Load Front [N]

$$= Tyre Load FL[N] + Tyre Load FR[N] - (Static Tyre Load FL[N] + Static Tyre Load FR[N])$$

Equation 33 – Aerodynamic Load Front

*Each tyre load is recorded from the simulator and given as a MoTeC Maths Channel within the program. Tyre loads were taken when the vehicle was stationary with no force exhibited upon it, these values were inputted into MoTeCs' project setup sheet as a constant variable.

2.2.3 Aerodynamic Load Rear [N]

$$= Tyre Load RL[N] + Tyre Load RR[N] - (Static Tyre Load RL[N] + Static Tyre Load RR[N])$$

Equation 34 – Aerodynamic Load Rear

2.2.4 Aerodynamic Load Total [N]

$$= Aerodynamic Load Front[N] + Aerodynamic Load Rear[N]$$

Equation 35 – Aerodynamic Load Total

2.2.5 Coefficient of Lift Front [Coefficient]

$$= \frac{Aerodynamic Load Front[N]}{\left(\frac{1}{2} * Air Density \left[\frac{Kg}{m^3}\right] * Velocity^2 \left[\frac{m}{s}\right]\right)}$$

Equation 36 – Coefficient of Lift Front

*Air density is taken as a constant at 1.233Kg/m³

2.2.6 Coefficient of Lift Rear [Coefficient]

$$= \frac{\text{Aerodynamic Load Rear}[N]}{\left(\frac{1}{2} * \text{Air Density} \left[\frac{Kg}{m^3}\right] * \text{Velocity}^2 \left[\frac{m}{s}\right]\right)}$$

Equation 37 – Coefficient of Lift Rear

2.2.7 Coefficient of Lift Total [Coefficient]

$$= \frac{\text{Aerodynamic Load Total}[N]}{\left(\frac{1}{2} * \text{Air Density} \left[\frac{Kg}{m^3}\right] * \text{Velocity}^2 \left[\frac{m}{s}\right]\right)}$$

Equation 38 – Coefficient of Lift Total

2.2.8 Centre of Pressure Position Along Wheelbase Relative to the Front Axle [%]

$$= \frac{\text{Aerodynamic Load Rear}[N]}{\text{Aerodynamic Load Total}[N]} * 100$$

Equation 39 – Centre of Pressure

2.2.9 Balance of Aerodynamic Forces Applied to the Front axle [%]

$$= \frac{\text{Aerodynamic Load Front}[N]}{\text{Aerodynamic Load Total}[N]} * 100$$

Equation 40 – Aerodynamic Balance

3) Steady State Investigation

3.1 Aim & Methodology

During the time within the 'Base Performance Simulator 4.8' (BPS) (Base Performance Simulators Ltd, 2019) running rFactor pro software (rFactor, 2019), four individual suspension and anti-roll bar vehicle setups were used to analyse how each specific setting affected the vehicles characteristics while performing a series of experiments as described within ISO 4138:2012 (The British Standards Institution, 2012).

Two separate experiments were conducted using the same driver for accurate results:

1. The first kept the car at a constant speed of 60Kph, while varying the radius of the corner the Aston Martin DBR9 race car (Aston Martin Racing, 2011) was undertaking.
2. The second maintained a corner radius of 50m, and then subjected the car to different velocities, 60-100Kph.

As given within the assignment brief, three initial vehicle setups were supplied to us for the investigation:

Group 3 (Springs and ARB Investigation)		Setup 1	Setup 2	Setup 3
Front Spring Rate (N/mm)	K_{sf}	202	254	307
Rear Spring Rate (N/mm)	K_{sr}	307	254	202
Front Anti Roll Bar Wheel Rate (N/mm)	KW_{arbf}	160	280	400
Rear Anti Roll Bar Wheel Rate (N/mm)	KW_{arbr}	72	48	12

Table 1 - Initial Vehicle Suspension and Anti-Roll Bar Setups

The first experiment was initially performed using the standard vehicle setup that the simulator provided, this created a baseline to compare the results obtained from the altered setups that were stipulated within the assignment brief. Unfortunately, the group accidentally forgot to alter the Aerodynamic settings for the car, leaving both the 'Splitter Length' and 'Wing Angle' at their maximum settings, this was because the 'Constant Velocity' investigation was executed before the 'Steady State'. Sadly this affected our baseline results slight and altered the forces being applied to each tyre throughout the 'Steady State' analysis.

During the second experiment, the group decided to reuse the previous setups supplied to us, which should provide us with data to understand how the forces and load distribution are affected at different speeds. The table below details the variables changed with each setup.

Group 3 (Springs and ARB Investigation)		Setup 4	Setup 5	Setup 6
Front Spring Rate (N/mm)	K_{sf}	254	202	307
Rear Spring Rate (N/mm)	K_{sr}	254	307	202
Front Anti Roll Bar Wheel Rate (N/mm)	KW_{arbf}	280	160	400
Rear Anti Roll Bar Wheel Rate (N/mm)	KW_{arbr}	48	72	12

Table 2 - Additional Vehicle Suspension and Anti-Roll Bar Setups

“Stiffening a corner in compression will result in a load increase at that corner and it’s diagonal corner in addition to a load decrease at the opposite diagonal corners. The opposite is true when the corner is softened.” (Rowley, 2003-04)

Once the ‘Steady State’ data had been obtained from the Simulator, the data was imported into the data analysis software ‘MoTeC’ (MoTeC Pty Ltd, 2019), this gave the individual the ability to analyse and visually represent forces acting on the vehicle at each moment in time in the form of a graph.

MoTeC gave basic information that was recorded through the simulation session as if a real-life data logger had been used. In order to enhance this, formulas that were detailed previously, were inputted into MoTeC in the form of ‘Maths Channels’. These calculated additional data which contributed in understanding the individual characteristics of the vehicle and included the forces applied to it.

To check the validity of the results attained from the MoTeC software, an Excel spreadsheet was created using the same basic information and formulas used to create the ‘Maths Channels’ for MoTeC in order to validate the results.

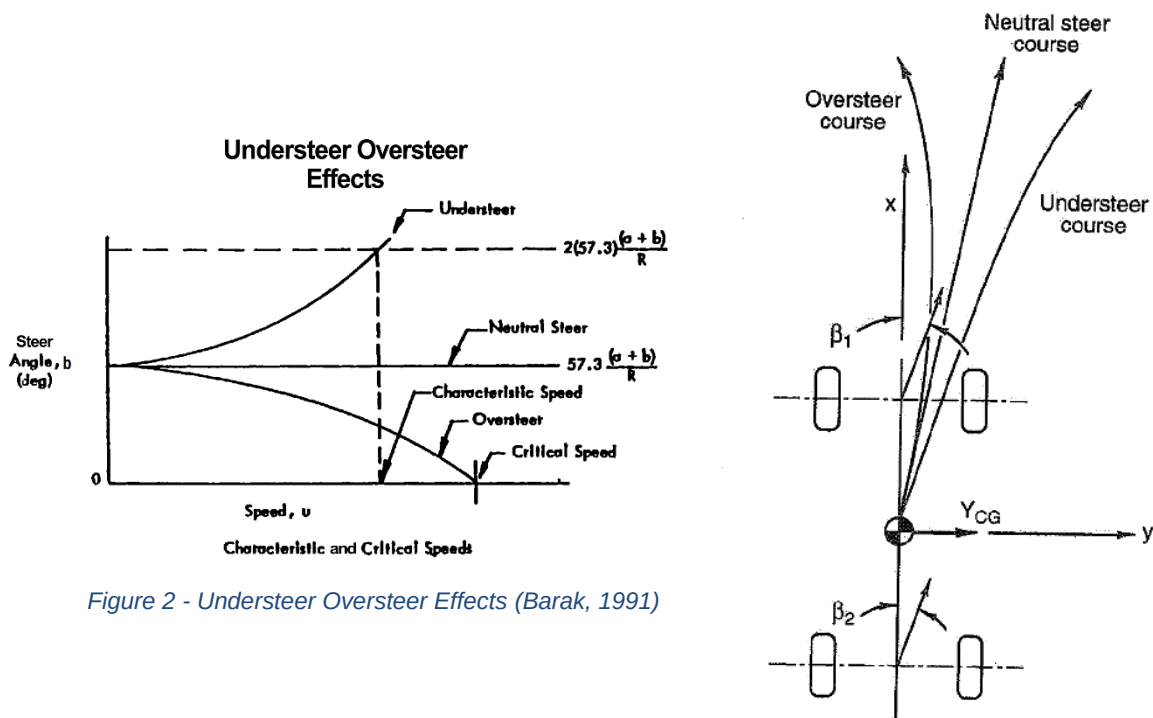


Figure 2 - Understeer Oversteer Effects (Barak, 1991)

Figure 1 - Under/Oversteer Representation of Vehicle Stability (Milliken, W, 1995)

3.2 Results & Analysis

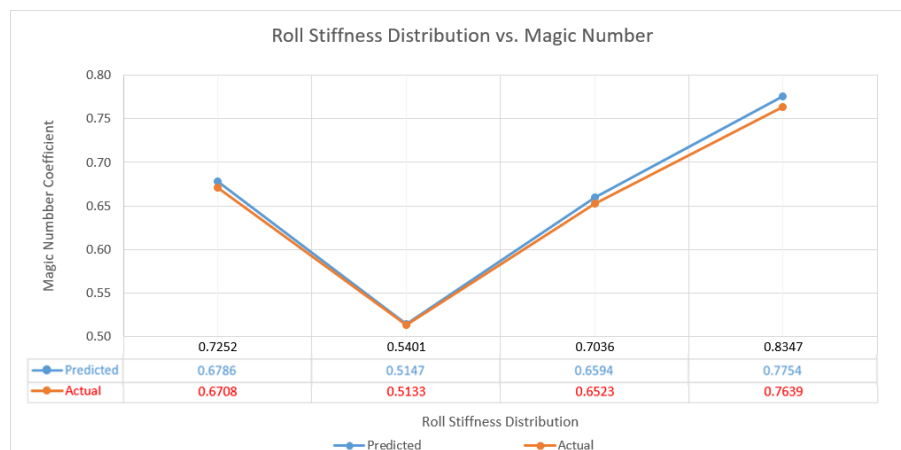


Figure 3 - Roll Stiffness Distribution vs Magic Number

Roll stiffness is the resistance to body roll, thus, affecting the amount of weight transfer that vehicle encounters during a corner at a given speed. The Roll Stiffness Distribution (RSD) of the vehicle is relative to the rear axle, the higher the number, the more percentage of the total roll stiffness is present at the front of the vehicle. (Richard Hathaway, 2017)

The Magic Number (Weight Transfer Distribution) describes the dynamic motions of a vehicle on the road and can be used to determine the vehicles' directional control and stability. This number relates to how much weight transfer the front of the car is experiencing due to its' elastic and geometric suspension setup. (Barak, 1991)

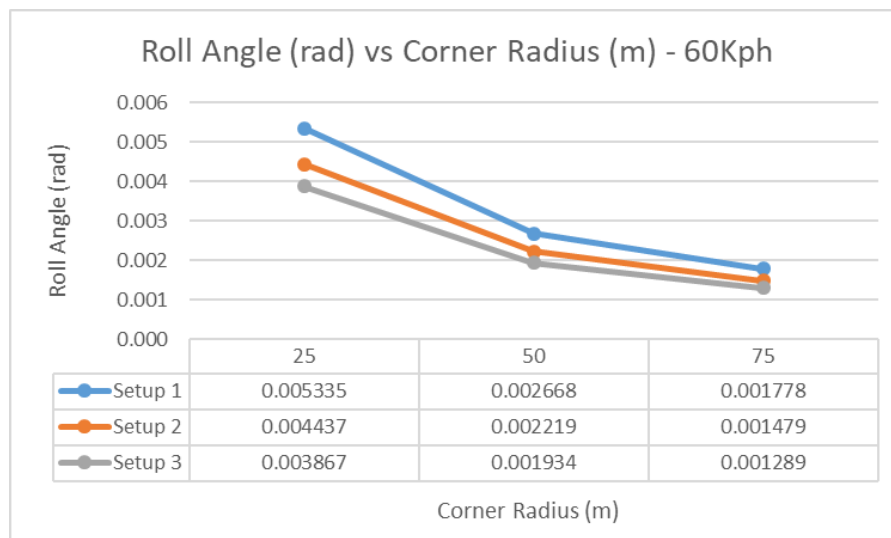


Figure 4 - Roll Angle vs Corner Radius

It is clear that as the vehicle is travelling at a constant speed, while the corner radius increases, the roll angle exhibited by the vehicle decreases in proportion to the lateral acceleration (See Appendix ***). Throughout setup 1-3 the front roll stiffness is increased, while the rear is decreased, this causes the roll angle to decrease through each iteration.

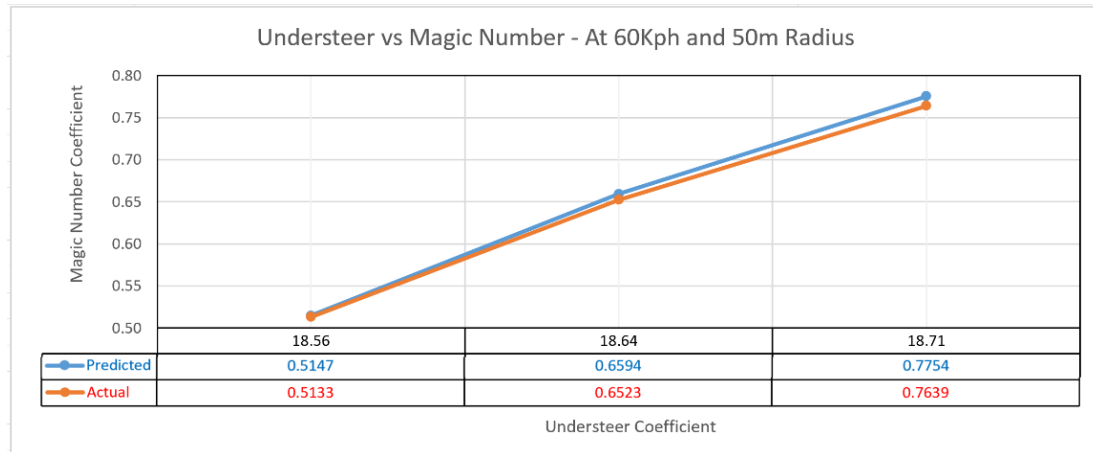


Figure 5 - Understeer vs Magic Number

The figure above shows the relation between the Understeer coefficient and the Magic Number. The expected outcome of this is that as the Magic Number relating to the suspension setup increases, the amount of Understeer the vehicle experiences through a corner, should also increase.

The vehicle has a tendency to understeer throughout the experiment, this is down to the RSD being biased towards the front of the car, this will require the driver to provide more steering input on turning a corner, which is generally a safer alternative than that of an oversteering bias, where the driver will have to quickly correct the vehicles' trajectory, before the rear end loses grip sharply and causes the vehicle to spin out.

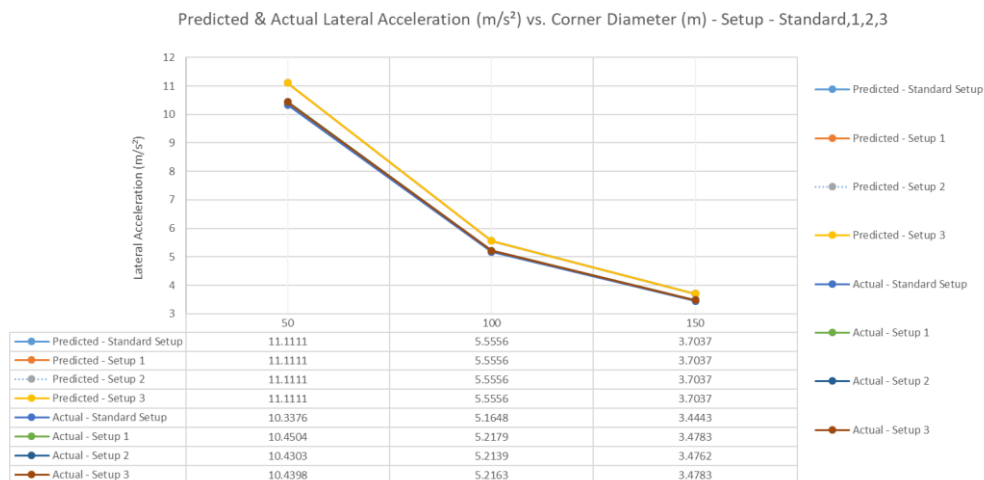


Figure 6 - Lateral Acceleration vs Corner Diameter

The lateral acceleration applied by physics upon the vehicle at a constant velocity of 60Kph around different corner diameters, performed as predicted. Although varying minutely, the actual results recorded from MoTeC followed very closely to those of the predicted Excel calculations. The predicted results expected the lateral acceleration to be exactly the same for each diameter, whereas, with the actual data, the smaller the diameter, the bigger the fluctuation between each value.

“Lateral acceleration acts transversely to the direction of travel of a car. It is noticeable, for instance, when driving through a bend as a centrifugal force towards the outside of the bend.” (Seat, 2019)

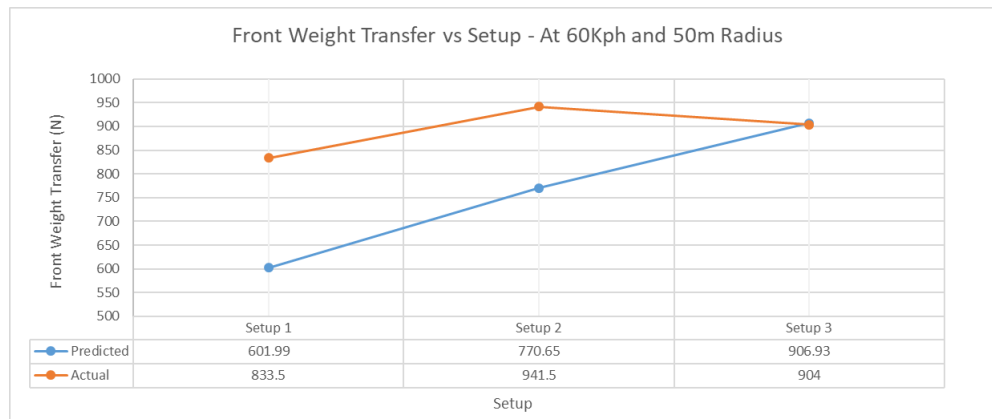


Figure 7 - Front Weight Transfer vs Setup

The load that is distributed onto the outside tyres increases incrementally as the front spring and anti-roll bars are stiffened, while the rears are softened. The predicted values throughout the experiment provide a smooth linear increase throughout each setup, which is what would be expected as the front is stiffened. (William F. Milliken, 1995)

The figure above displays the car throughout each set up while experiencing a 50m corner radius at a constant speed of 60kph, this would prompt the assumption of following the trend of the predicted results by means of a similarly linear escalation in weight transferred, as the front suspension was stiffened incrementally through setups 1-3. It can be determined that setup 3 provided accurate results as both the actual and predicted results were minutely different. The discrepancy between the other two variables could be down to data been inaccurately taken from the MoTeC software.

“When the vehicle rounds a corner the axle with the most roll stiffness attracts the most weight transfer. ...Essentially the strategy is to change roll stiffness, largely by upgrading anti-roll bars to ensure that the tyre loads are distributed to optimise outright grip. ...It is worth remembering though that if you go too far with front or rear roll stiffness you will lift the inside wheel.” (Balance Motorsport, 2019)

4) Constant Velocity and Coast down Investigation

4.1 Aim & Methodology

During the Simulator session, an investigation was launched into the aerodynamic effects that take place while changing both 'Splitter Length' and 'Wing Angle'. Unfortunately, these values were not known as the simulator only displayed them as settings, this meant the 'Splitter Length' was only shown as setting '1', '2' or '3' and the 'Wing Angle' was shown on a scale of '1' to '12' without units. It could be assumed that these settings were in 'mm' and 'degrees' respectively, but without confirmation, it was best to leave them unitless and just analyse the effect that these settings had upon the vehicle.

"The coast down method is often used to estimate the drag forces that act on a full-scale vehicle when operating in its natural environment" (Frank T. Buckley, 1995).

The 'Fischer Racing Aston Martin DBR9 Young Drivers 2010-2011 Race Car' (The Advantage, 2011) was accelerated as quickly as possible in a straight line from a stationary point, once the vehicle had achieved maximum velocity in fourth gear, the velocity was held for approximately 5 seconds to ensure that it was constant, the driver then declutched and selected the neutral position within the transmission, while the throttle was held at 100% for one second after the gear change, reducing the possibility that the drivetrain would sap any power from the vehicle in motion (mechanical drag), which would affect the results upon analysis. The vehicle rolled along the track until the resistive forces acting upon it, reduced the velocity back to zero.

This experiment was conducted ten times, using multiple variations of aerodynamic setups:

	Splitter Length		
	1	2	3
Wing Angle	1	1	1
	6	6	6
	12	12	12

Table 3 - Aerodynamic Setup Variations for The Coast Down Experiment

The run using the maximum aero settings of splitter length '3' and wing angle '12' was repeated in the reverse direction, this was to either confirm or deny the theory that the results should be the same in both directions, due to the general assumptions already stated, which would invalidate the collected data.

Each stint was imported into the MoTeC software for analysis, using the formulas stated within the introduction, to create the necessary 'Maths Channels' calculating all required data. As before, the data was exported into an Excel spreadsheet, generating a table of results which would accurately compare the data collected from each aerodynamic setup, and observe how these values change depending on the aerodynamic setup of the vehicle.

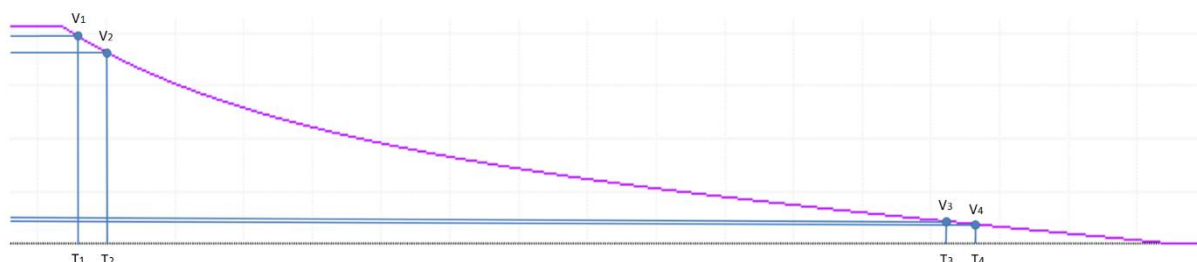


Figure 8 - Points Taken for Velocity and Time to Calculate Drag

4.2 Results & Analysis

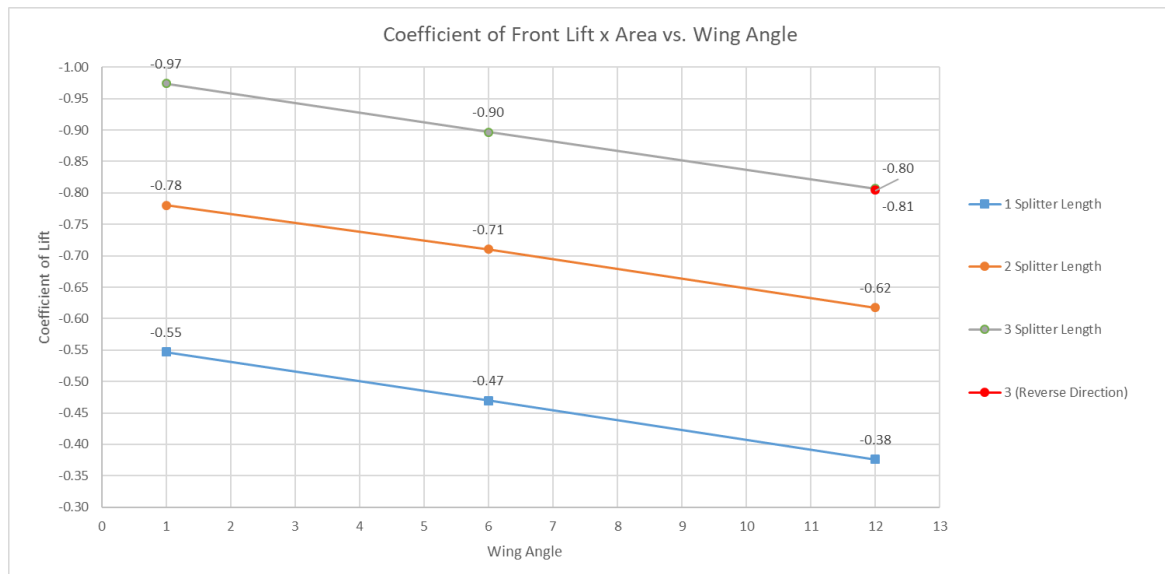


Figure 9 - Coefficient of Lift Front vs Wing Angle

It is visible to see the effect that the change in rear wing angle has upon the front of the car. It is easy to see the effect that the change of splitter length has upon the front Coefficient of Lift x Area (CL_{Af}), the gradients are similar and follow identical trends with a near constant distance between each splitter length at every wing angle setting. This shows a consistent decrease in CL_{Af} as the angle of attack on the rear wing is increased.

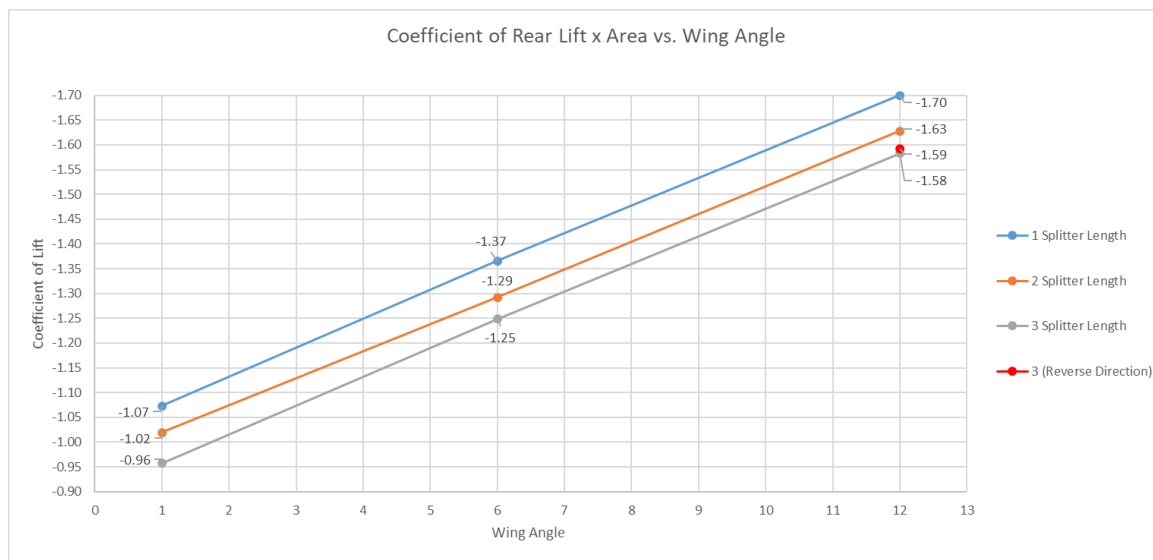


Figure 10 - Coefficient of Lift Rear vs Wing Angle

This graph shows the rear Coefficient of Lift x Area (CL_{Ar}) as the rear wing angle changes. Compared to the front splitter, the rear wing produces a higher negative lift coefficient, with a higher gain in value as the angle is increased and becomes more aggressive. It is clear to see that the shortest splitter length also provides the highest rear negative lift coefficient throughout each wing angle iteration, as the balance of aerodynamic forces acting around the centre of pressure are distributed to each end of the vehicle in motion.

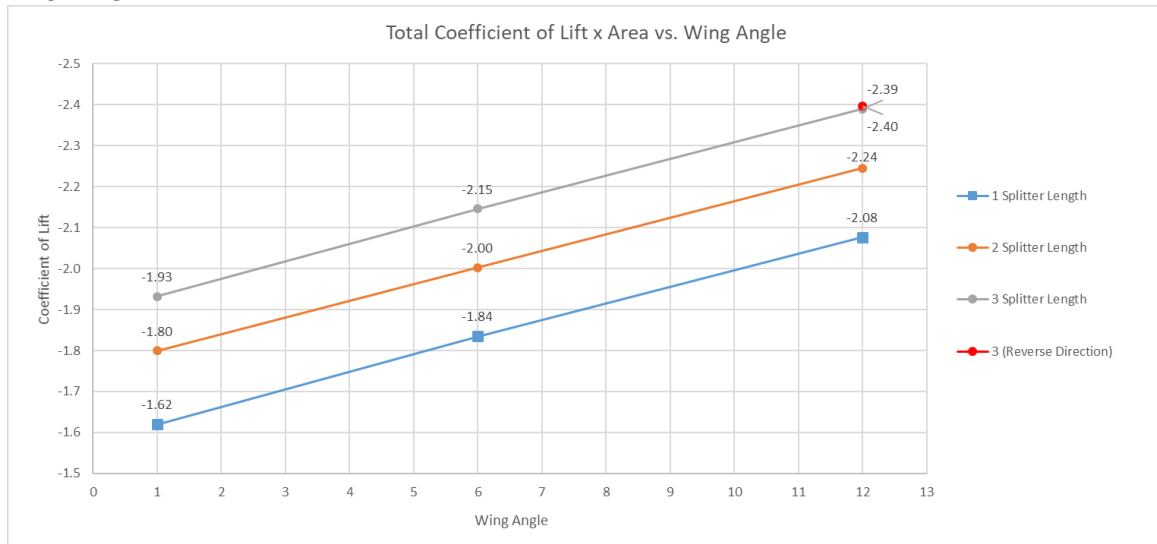


Figure 11 - Total Coefficient of Lift vs Wing Angle

A constant increase in the negative lift coefficient was evident in all three splitter lengths as trialed, however, splitter '1' maintained the lowest coefficient out of all three iterations. The increase in splitter length shows a virtually constant difference between the coefficient values at every wing angle throughout the experiment. Therefore, it is easily viable to use the graph to support the conclusions on which would be the most appropriate aerodynamic setup for the application it would be used for.

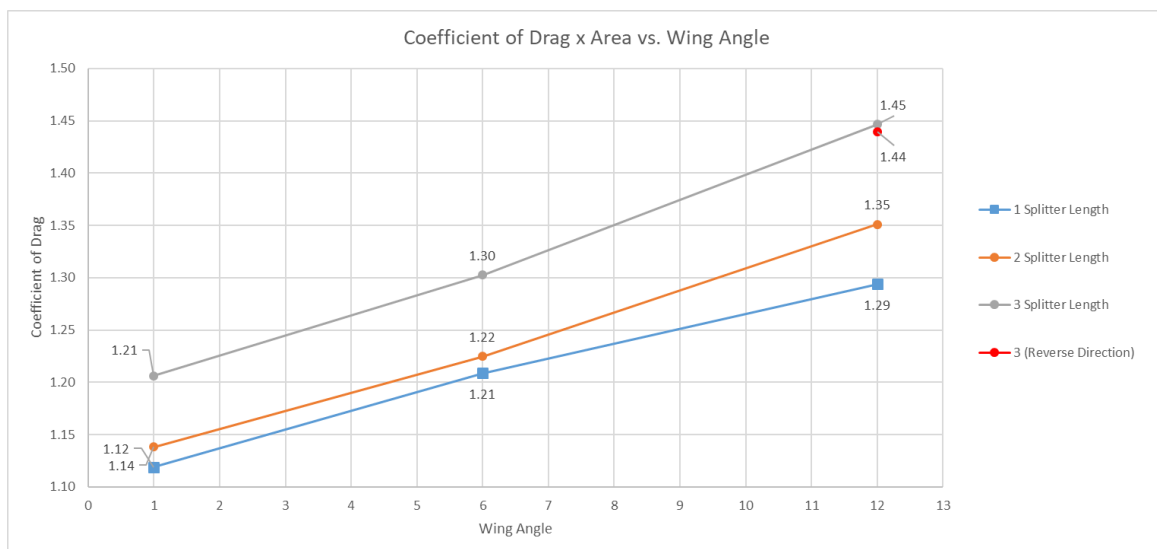


Figure 12 - Coefficient of Drag vs Wing Angle

The Coefficient of Drag x Area (C_{DA}) graph shows comparable trends between each Splitter and wing variable. 'Splitter length 1' has a linear gradient, and therefore, increase in measured drag coefficient throughout each wing angle iteration and consistently providing the least amount of drag relative to its minimal downforce creation. Splitter lengths '2' and '3' keep a slightly similar gradient to '1' between wing angles '1' and '6', but as the angle of attack is steepened to setting '12', they both show a slightly higher increase in drag coefficient. 'Splitter length 2' was expected to be equidistant between splitters '1' and '3' as this experiment was performed in a near perfect simulated environment, with no external unmeasured resistive forces acting upon the vehicle, this may be an error within the data, but after re-taking numbers from MoTeC, the drag coefficient values retained the same trend and consistency. The gradient then steepens at 'wing angle 12', increasing the distance from splitter '1' at the same wing angle but is still significantly lower than splitter '3'.

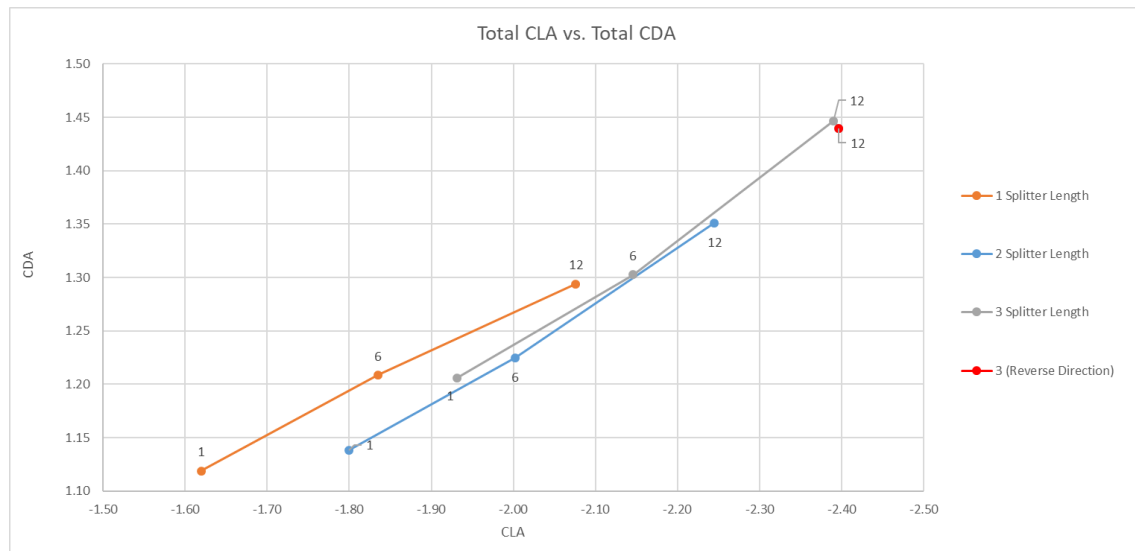


Figure 13 -Total Lift vs Drag Coefficients

This graph shows both lift and drag coefficients (C_L & C_D) plotted against each other to clearly see the effect each aerodynamic setup had upon the forces applied to the vehicle throughout the coast down investigation. Although splitters '2' & '3' have different gradients, they have fairly consistent steps between each value and at 'wing angle 12' quite a big jump in both coefficients is observed, requiring further analysis into whether the gain in downforce outweighs the increased drag the vehicle is subjected to.

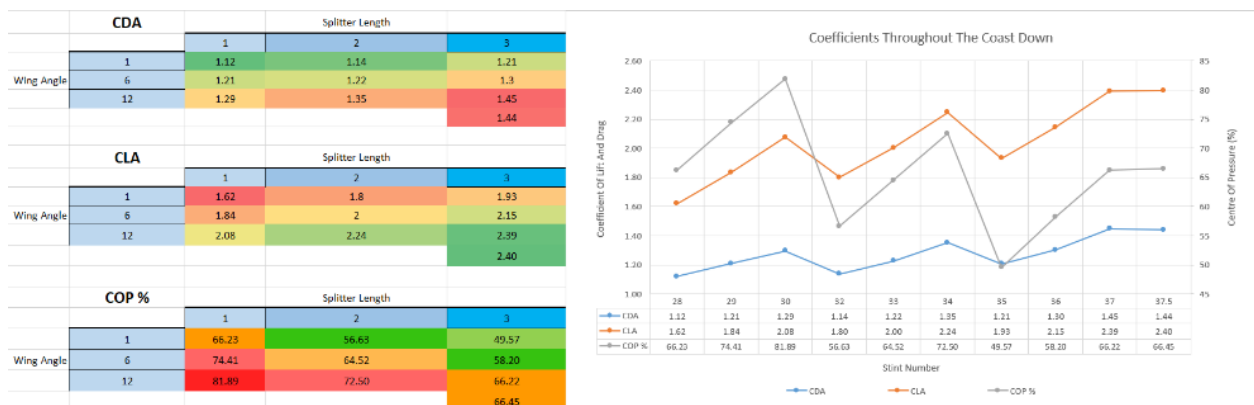


Figure 14 - Centre of Pressure, Drag and Lift Coefficients vs Stint Number

The sign convention of the Lift coefficient was reversed to be a positive number, this made it easier to plot against the Drag coefficient and evaluate. It is clear to see that as the negative lift increases in value, so too does the drag coefficient, but not to the same proportion. It can be noted that as the coefficient of lift increases into a higher value, the centre of pressure relative to the front axle increases; the higher the percentage, the further away from the front axle the centre of all aerodynamic forces are, acting upon the car.

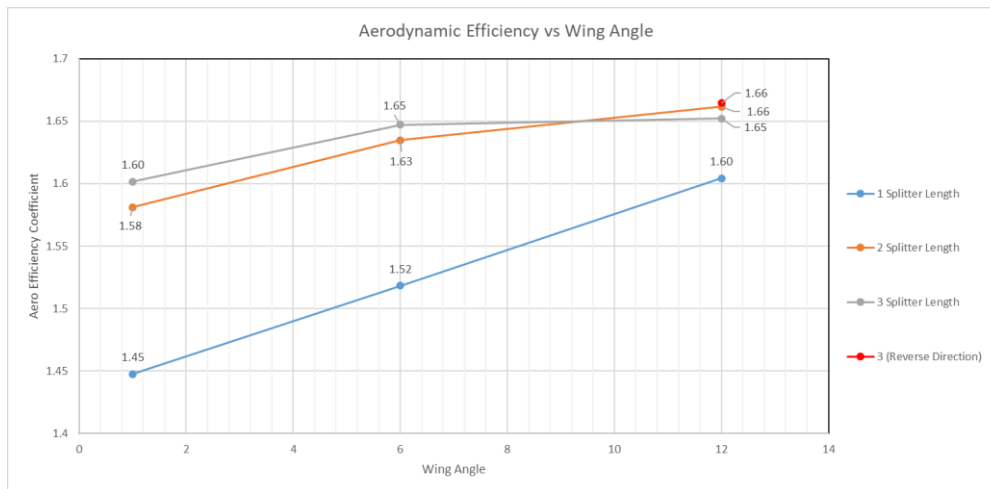


Figure 15 - Aerodynamic Efficiency vs Wing Angle

The aerodynamic efficiency of the vehicle is the result of using the total C_{LA} value and dividing it by the C_{DA} . This determines a relationship between how much downforce the vehicle experiences, versus how much drag is created by the aerodynamic devices used for each setup. As expected, the lowest drag is created by the shortest splitter length and minimal wing angle, what wasn't anticipated, is that splitter '2' at wing angle '12' has a slightly higher efficiency coefficient than both splitter '3' and '3 (Reverse Direction)' at wing angle 12. This is most likely because splitter '2' produces a lower C_{DA} value than '3', even though the negative lift produced by splitter '2' is lower, the efficiency dictates this is a better option for performance. This may be a result of a data error but even after re-taking data points from MoTeC, the trends remained constant.

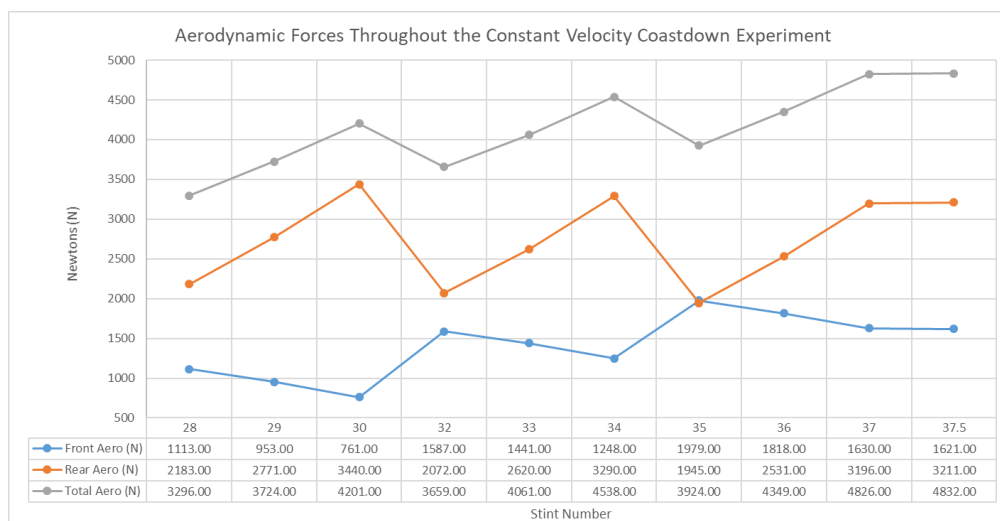
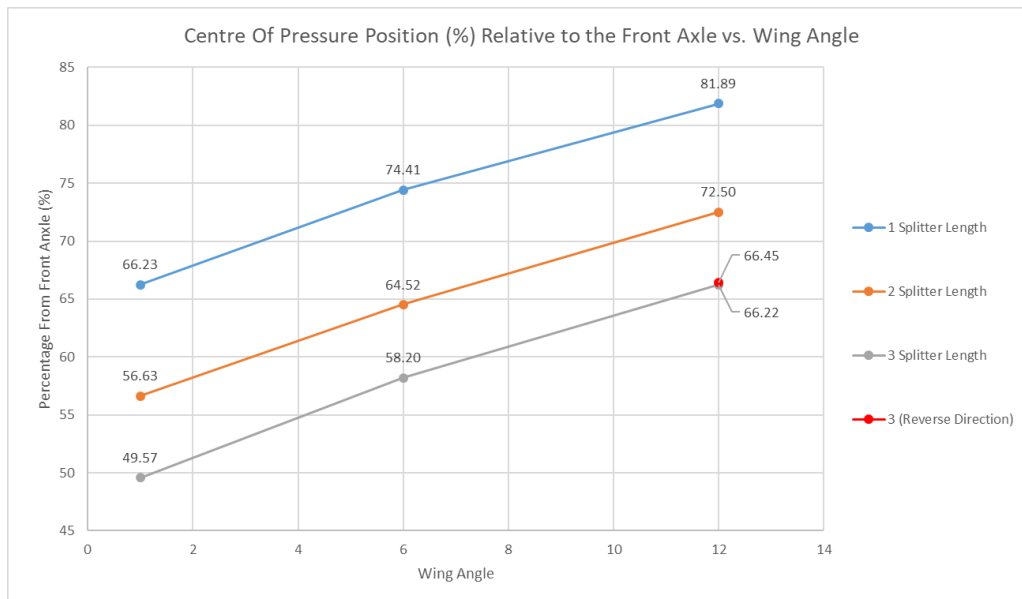


Figure 16 - Front, Rear and Total Aerodynamic Forces

Using formulas, it was possible to calculate the aerodynamic forces being applied to the front and rear axles of the vehicle, throughout each splitter length and wing angle variable. The total of these forces were included for comparison between the aerodynamic setups used throughout the experiment. As shown, the front aerodynamic force increases proportionally to the splitter length, just as the rear force intensifies relative to the rear wing angle. It is clear to see how the front and rear forces are affected through manipulation of the rear wing, and how they are opposed from each other, but the vehicle gains more downforce overall with the highest settings.



“In terms of handling, the most important characteristic of the pressure centre is its position along car’s wheelbase, because it will define how much of the overall downforce will act on the front wheels and how much on the rear ones.” (Quintarelli, 2018)

In addition to this, the centre of pressure can be considered as the position along the vehicle’s wheelbase whereby the resultant aerodynamic forces are applied to the vehicle, acting in the form of a moment. This is proven by values calculated, for example, splitter ‘1’ (minimum) at wing angle ‘12’ (maximum) has a position 81.89% along the wheelbase away from the front axle, as the highest downforce is exhibited on the rear.

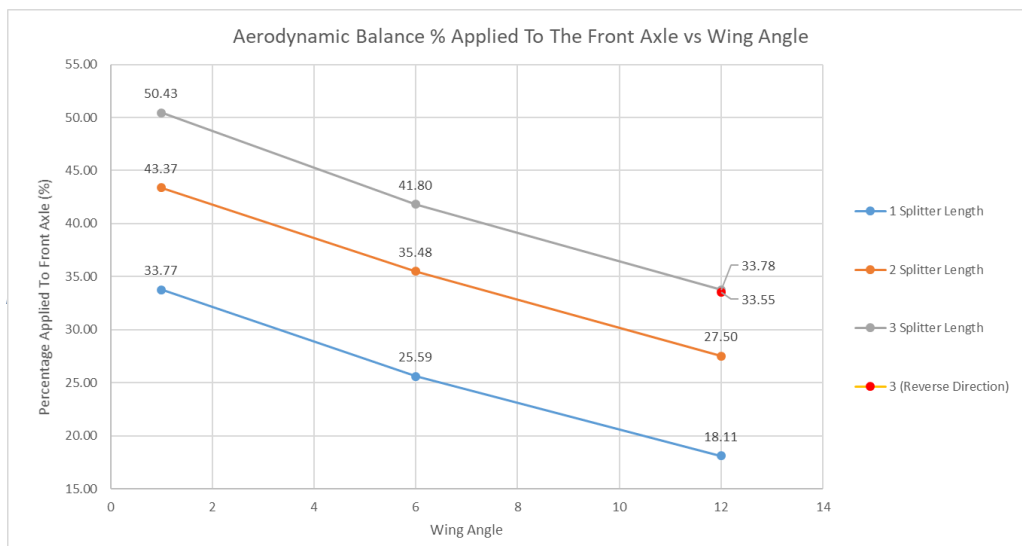


Figure 18 - Centre of Pressure Position Along Wheelbase Away from Front Axle

“The aero balance is the portion of downforce acting on the front wheels, with respect to the overall downforce acting on the car.” (Quintarelli, 2018)

It can be observed that by increasing the splitter length on the front of the car, the downforce applied to the front axle increases proportionally, and as a result, alters the balance of aerodynamic forces that the vehicle encounters. The higher the number, the more percentage of negative lift is acting on the front axle, likewise, the lower the number the higher the percentage on the rear axle is being applied.

5) Conclusion

5.1 Steady-State Cornering

The experiment provided a plethora of results to consider. By changing only the stiffness of the vehicles' suspension, the impact it has on multiple variables will need to be carefully considered before choosing an appropriate suspension composition, as it will vary massively on the required application.

"A proper distribution of front and rear roll stiffness to control the lateral load transfer on the front and rear axles can improve the vehicle's handling and stability obviously." (Yang, et al., 2007)

It has been made clear that as the roll stiffness is increased on the front of the vehicle, so too does the magic number, which means, there will be less body roll from the sprung mass and it will experience more weight transfer around a corner, which in turn, increases the amount of understeer the vehicle will encounter at a given speed. Although this can be combatted by driver skill, on average this will cause the car to not perform as desired, so if possible, it would be best to aim for a compromise of the roll stiffness distribution slightly bias to the rear, this will try and ascertain both a neutral steer position for handling coordination and a balanced weight transfer for maximum grip on all four tyres. Using this knowledge, the best setup can be used as a baseline for testing and modifying

Neutral steer would ensure a concrete base point in which to start with testing and modifications depending on what it will be used for and how the vehicle is required to handle on any given road/track and driver's preference.

5.2 Constant Velocity Coast Down

After analysing the results from the coast down experiment and taking into consideration the assumptions previously mentioned, a conclusion could be drawn on how different aerodynamic devices and their iterations of adjustments affect the overall performance of the vehicle. As before, it will depend entirely on the requirements for the road/track. A fast track, such as; Monza or Le Mans, which has long straights will require downforce, as any other, but this will need to be balanced with the amount of drag the vehicle is producing, as this will directly relate to the top speed that can be achieved throughout the circuit and how quick the vehicle can accelerate at any given point.

Although drag, both mechanical and aerodynamic, will aid with the braking process, which means the driver can brake later into the corners, potentially giving them an edge over their competitors. This will have a negative impact due to ratio of acceleration vs braking throughout a lap of a circuit as a typical driver spends significantly more time, on average, on the throttle as much as physically possible.

Therefore, a balanced aerodynamic setup should be used to approach any given situation and then adapted through experience and knowledge to accomplish a desired performance specification. By analysing the C_L vs C_D graph from this experiment, it can be determined that by using splitter length '3' in conjunction with wing angle '12' you will receive both the highest downforce coefficient, along with the most drag caused by the increases frontal area. By evaluating the aero efficiency graph, Splitter '2' at wing angle '12' provides a slightly higher efficiency rating so this could be used as an improved baseline from which could be adapted into a beneficial aerodynamic setup using different analytical methods, such as; CFD or a wind tunnel for a controlled environment giving as accurate results as possible.

5.3 Summary and Overall Conclusion

Overall, the aerodynamic experiment provided fairly accurate results which could correlate well into real-life practice. Considering the assumptions previously mentioned about discrepancies within the simulator, such as; the inability to simulate the separation of air within BPS, aerodynamic forces are constantly calculated even while stationary, and the air pressure, temperature and density remaining constant throughout the experiment, all of these would affect the calculations and predictions made if this experiment was recreated in real-life and could drastically change an engineer's or drivers' preferred setup.

This applies just as much to the suspension and desired handling preference almost as much as its' application. The correlation between the magic number and roll stiffness distribution was made apparent by performing this experiment. The stiffer the front suspension is, the less elastic weight transfer it will experience, leading to more load on the outside tyres, and therefore, more lateral slip angle the vehicle will encounter on the front axle, hence, the more the car will understeer around a corner. (VBOX Automotive, 2015)

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7) Appendix

7.1 Appendix 1

Name	Summary
Expressions	
☒ Anti Roll Moment Front	'Wheel Deflection'*'Wheel Rate Front' [N.m]*'Track Front' [m]
☒ Anti Roll Moment Rear	'Wheel Deflection'*'Wheel Rate Rear' [N.m]*'Track Rear' [m]
☒ Corner Radius [m]	('Speed' [m/s]^2)/'Lateral Acceleration' [m/s/s]
☒ Gyro Roll Angle [rad]	'Gyro Roll Angle' [rad]
☒ Lateral Acceleration [m/s/s]	'G Force Lat' [G]*9.81
☒ Load Transfer	((Total Tyre Load' [N])*'Lateral Acceleration' [m/s/s]*'Height Difference of RC and COG' [m])/'Track Front' [m]
☒ Magic Number (Front)	'Total Weight Transfer Front'/(('Total Weight Transfer Front'+'Total Weight Transfer Rear')
☒ Magic Number (Rear)	'Total Weight Transfer Rear'/(('Total Weight Transfer Front'+'Total Weight Transfer Rear')
☒ Over/Understeer	'Total Weight Transfer Rear'/'Total Weight Transfer'
☒ Over/Understeer2	'Total Weight Transfer Rear'/(('Load Transfer' * 'Gravity' [m/s/s])
☒ Over/Understeer3	'Static WT Rear'/(('Static WT Front'+'Static WT Rear')
☒ Overtuning Moment [Nm]	'Sprung Mass' [kg]*'Lateral Acceleration' [m/s/s]*'Height Difference of RC and COG' [m]
☒ Roll Angle [rad]	(Overtuning Moment' [N.m]/'Roll Stiffness Total')
☒ Roll Angle 2 [rad]	'Wheel Deflection'/(0.5*'Track Front' [m])
☒ Roll Stiffness Front	((('Track Front' [m]^2)*'Wheel Rate Front' [N.m])/2
☒ Roll Stiffness Rear	((('Track Rear' [m]^2)*'Wheel Rate Rear' [N.m])/2
☒ Roll Stiffness Total	'Roll Stiffness Front' [rad]+ 'Roll Stiffness Rear' [rad]
☒ Speed [m/s]	'Ground Speed' [km/h]/3.6
☒ Static WT Front	('Tire Load - FL' [N] - 'Tire Load - FR' [N])/2
☒ Static WT Rear	('Tire Load - RL' [N]-'Tire Load - RR' [N])/2
☒ Theoretical Wheel Steer Angle [rad]	'Wheelbase' [m]/'Corner Radius' [m]
☒ Theoretical Wheel Steer [rad]	'Wheelbase' [m]/'Corner Radius' [m]
☒ Theoretical Steer % [%]	'Theoretical Wheel Steer Angle' [deg]/('Steering Wheel Pct' [%]/'Theoretical Wheel Steer Angle' [deg])
☒ Total Weight Transfer	'Total Weight Transfer Front'+ 'Total Weight Transfer Rear'
☒ Total Weight Transfer Front	'Weight Transfer Elastic Front'+ 'Weight Transfer Sprung Geometric Front'+ 'Weight Transfer Unsprung Geometric Front'
☒ Total Weight Transfer Rear	'Weight Transfer Elastic Rear'+ 'Weight Transfer Sprung Geometric Rear'+ 'Weight Transfer Unsprung Geometric Rear'
☒ Total Tyre Load [N]	('Tire Load - FL' [N]+ 'Tire Load - FR' [N]+ 'Tire Load - RL' [N]+ 'Tire Load - RR' [N])
☒ Understeer	abs('Theoretical Steer %' [%])-abs('Theoretical Wheel Steer Angle' [deg])
☒ Weight Transfer Elastic Front	'Wheel Deflection'*'Wheel Rate Front' [N.m]
☒ Weight Transfer Elastic Rear	'Wheel Deflection'*'Wheel Rate Rear' [N.m]
☒ Weight Transfer Longitudinal	((('Static Weight FL' [N] + 'Static Weight FR' [N] + 'Static Weight RL' [N] + 'Static Weight RR' [N])*(9.81*'G Force Long' [G])*'Centre of Gravity Height (m)' [m]))/'Wheelbase' [m]
☒ Weight Transfer Sprung Geometric Front	('Total Front Sprung Mass' [kg]*'Lateral Acceleration' [m/s/s]*'Static Roll Centre Height Front' [m])/'Track Front' [m]
☒ Weight Transfer Sprung Geometric Rear	('Total Rear Sprung Mass' [kg]*'Lateral Acceleration' [m/s/s]*'Static Roll Centre Height Rear' [m])/'Track Rear' [m]
☒ Weight Transfer Unsprung Geometric Front	('Total Front Unsprung Mass' [kg]*'Lateral Acceleration' [m/s/s]*'Front Tyre Rolling Radius' [m])/'Track Front' [m]
☒ Weight Transfer Unsprung Geometric Rear	('Total Rear Unsprung Mass' [kg]*'Lateral Acceleration' [m/s/s]*'Rear Tyre Rolling Radius' [m])/'Track Rear' [m]
☒ Wheel Deflection	('Track Front' [m]*'Roll Angle' [rad])/2
☒ Wheel Rate Front [Nm]	('Spring Rate FL' [N/m])*('Motion Ratio FL' [N/m]^2)+ 'Anti Roll Bar Rate Front' [N/m]
☒ Wheel Rate Rear [Nm]	('Spring Rate RL' [N/m])*('Motion Ratio RL'^2)+ 'Anti Roll Bar Rate Rear' [N/m]
☒ WT Totals dyna	- 'Static WT Front'+ 'Static WT Rear'
Constants	
☒ Air density [kg/m³]	1.223
☒ Gravity [m/s²]	9.81

Figure 19 - MoTeC Steady State Cornering Maths Channels and Formulas

7.2 Appendix 2

Name	Summary
Expressions	
☒ Aero Front [N]	'Tire Load - FL' [N]+ 'Tire Load - FR' [N]-('Static Weight FL' [N]+ 'Static Weight FR' [N])
☒ Aero Rear [N]	'Tire Load - RL' [N]+ 'Tire Load - RR' [N]-('Static Weight FL' [N]+ 'Static Weight FR' [N])
☒ Aero Total [N]	'Aero Front' [N]+ 'Aero Rear' [N]
☒ CLf	('Aero Front' [N])/((0.5*'Air density' [kg/m3]*'Speed' [m/s]^2)
☒ CLr	('Aero Rear' [N])/((0.5*'Air density' [kg/m3]*'Speed' [m/s]^2)
☒ CL	('Aero Total' [N])/((0.5*'Air Density' [kg/m3]*'Speed' [m/s]^2)
☒ COP [%]	('Aero Front' [N])/ 'Aero Total' [N])*100
☒ Speed [m/s]	'Corr Speed' [km/h]*(1000/3600)
Constants	
☒ Air Density [kg/m³]	1.233
☒ Gravity [m/s²]	9.81
☒ PI	3.14159265

Figure 20 - MoTeC Aerodynamic Coast Down Math Channels and Formulas

7.3 Appendix 3

Vehicle Sprung Mass (kg)	M_s	1134
Front Corner Unsprung Mass (kg)	M_{usf}	24
Rear Corner Unsprung Mass (kg)	M_{usr}	24
Centre of Gravity Height (m)	$(H+h)$	0.280
Weight Split F:R (%)	-	50:50
Wheelbase (m)	W	2.755
Front Track (m)	T_f	1.636
Rear Track (m)	T_r	1.636
Front Tyre Rolling Radius (m)	r_f	0.325
Rear Tyre Rolling Radius (m)	r_r	0.355
Front Motion Ratio	MR_f	0.69
Rear Motion Ratio	MR_r	0.69
Front Default Spring Rate (N/mm)	K_{sf}	237
Rear Default Spring Rate (N/mm)	K_{sr}	237
Front Default Anti Roll Bar Wheel Rate (N/mm)	K_{warbf}	280
Rear Default Anti Roll Bar Wheel Rate (N/mm)	K_{warbr}	36
Front Roll Centre Height (mm)	h_f	8.21
Rear Roll Centre Height (mm)	h_r	31.12

Figure 21 - Standard Vehicle Data Supplied by Tim Tudor

7.4 Appendix 4

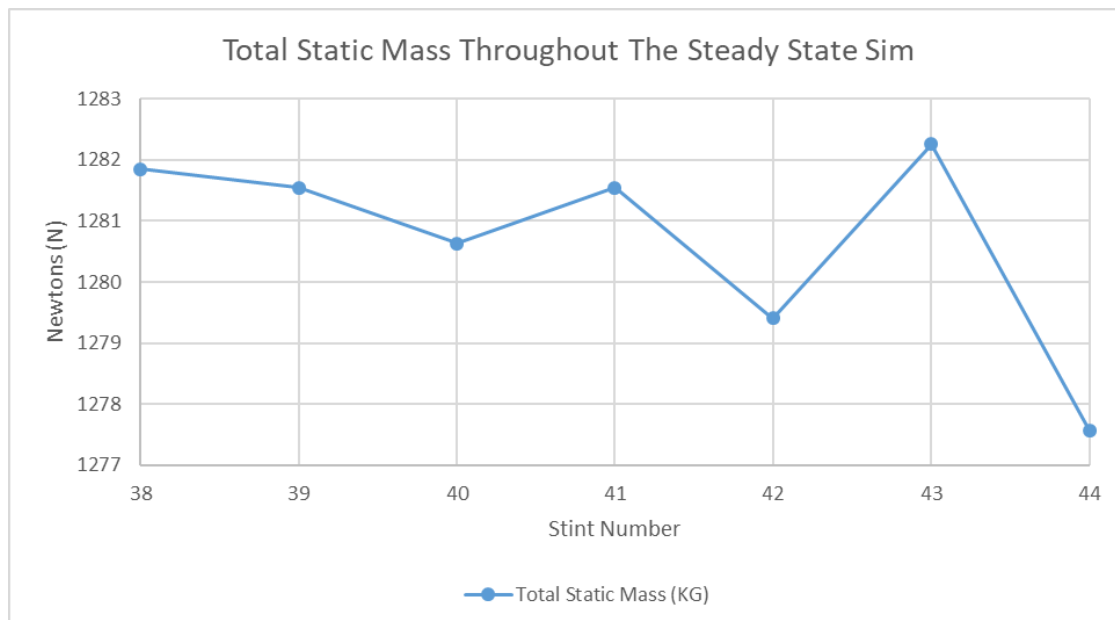


Figure 22 - Static Mass Throughout the Steady State Experiment

7.5 Appendix 5

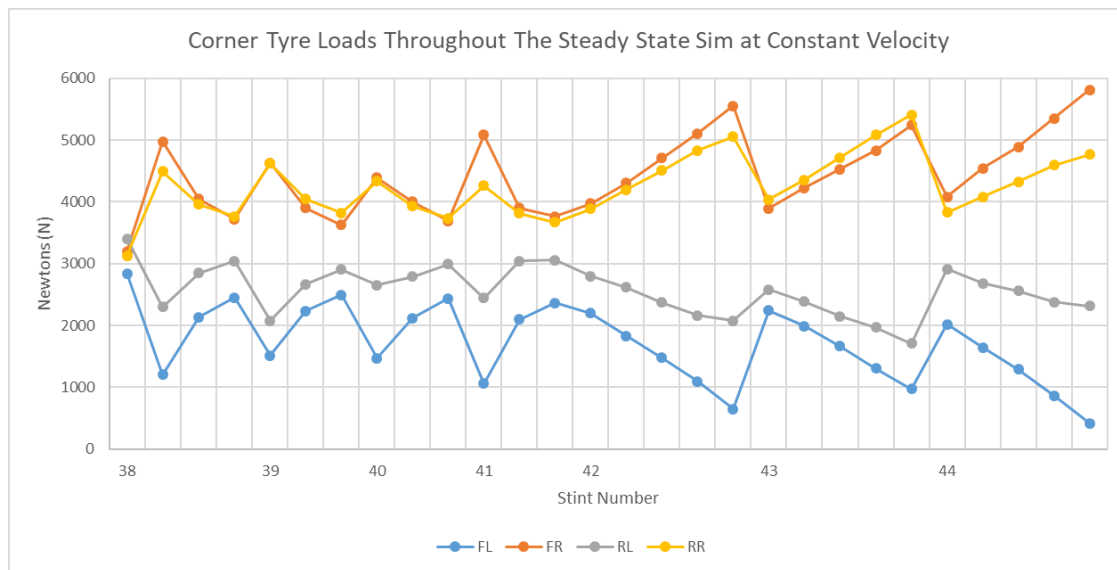


Figure 23 - Tyre Loads Taken During a Corner Throughout the Steady State Experiment

7.6 Appendix 6

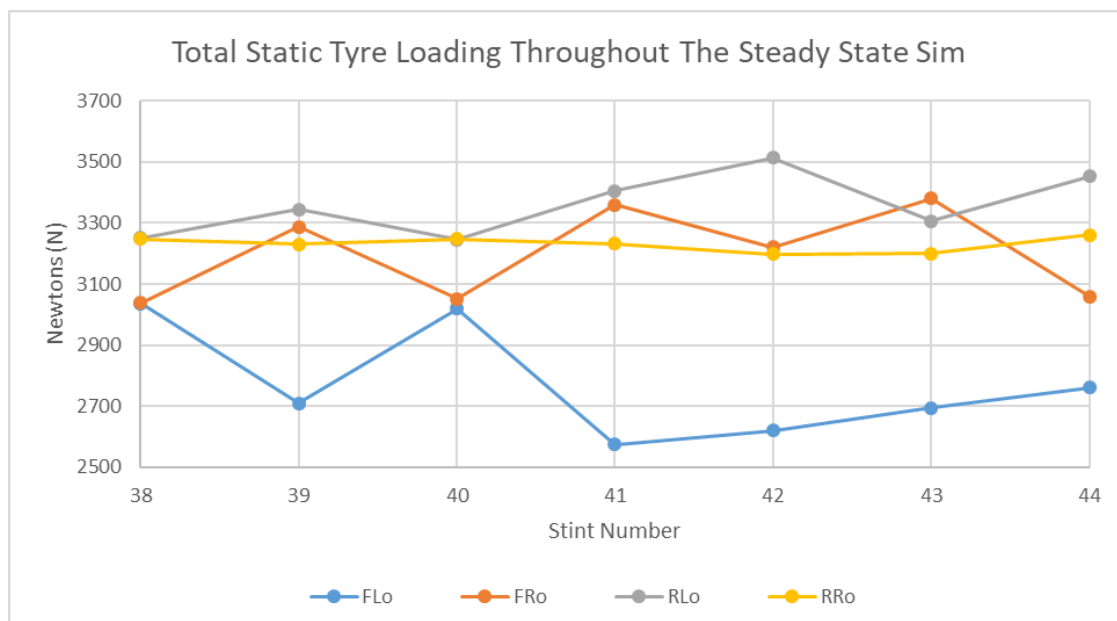


Figure 24 - Total Static Tyre Loading Throughout the Steady State Experiment

7.7 Appendix 7

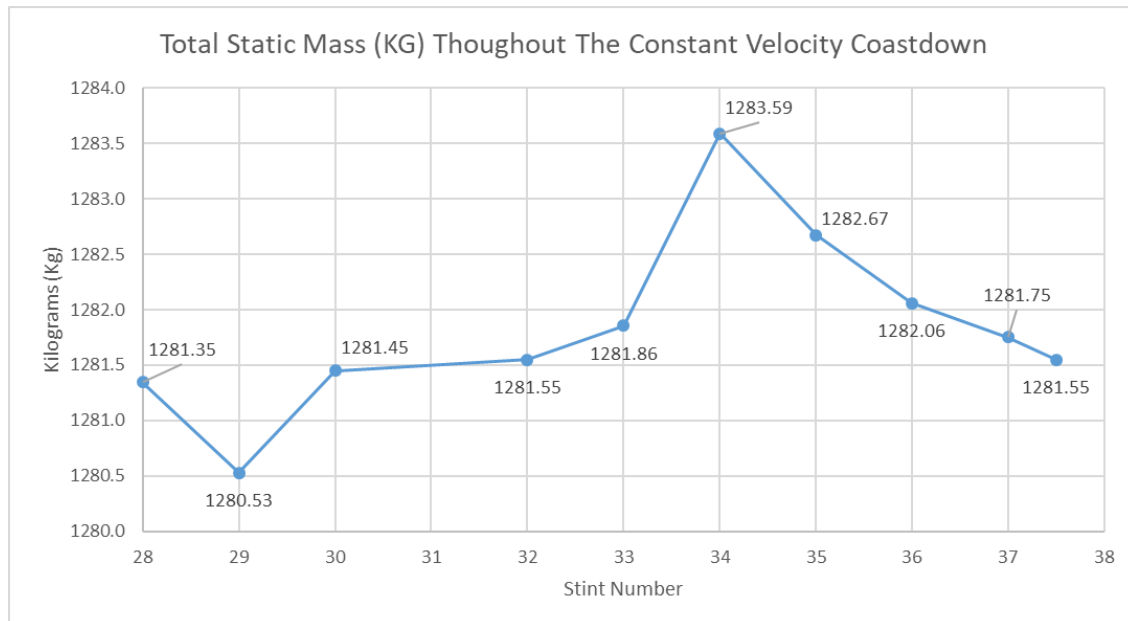


Figure 25 - Total Static Mass Throughout the Coast Down Experiment

7.8 Appendix 8

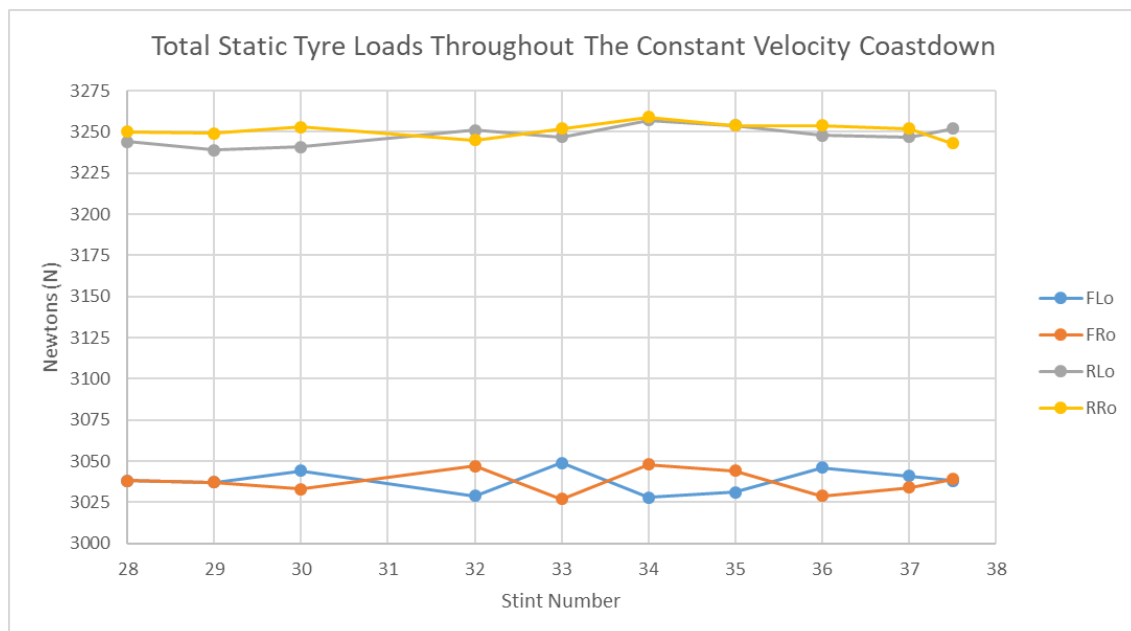


Figure 26 - Total Static Loads Throughout the Coast Down

7.9 Appendix 9

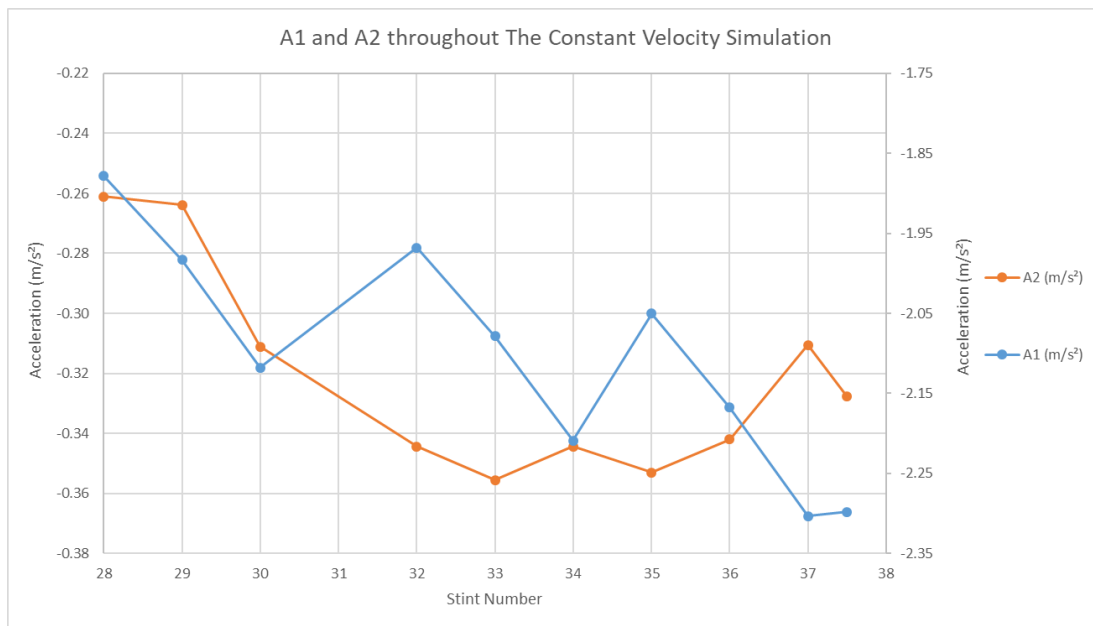


Figure 27 - Both Decelerations Throughout the Coast Down Experiment

7.10 Appendix 10

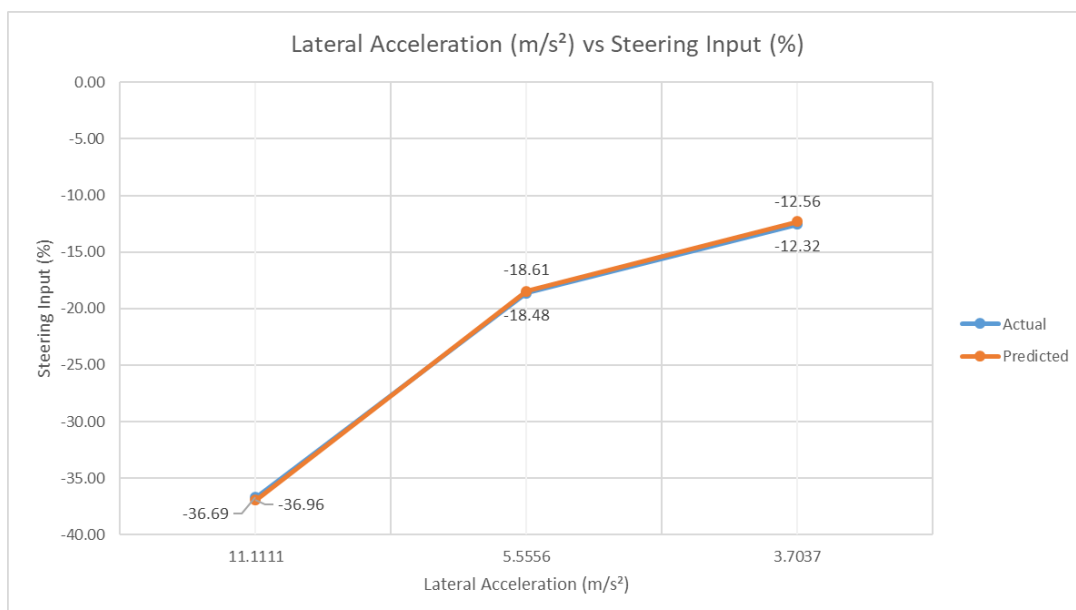


Figure 28 - Lateral Acceleration vs Steering Input