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**An investigation into how simulation can be used
to evaluate setup ahead of a race weekend.**

**BSc Motorsport Engineering
2017/2018**

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Abstract.

This project has two main aims. The first aim of the project is to use motec in conjunction with the BPS simulator to statically test various setups. The second aim of the project is to analyze the tested setups using motec and conclude which setup is the most viable for a race.

Vigorous research has been conducted into testing methods such as design of experiment to better understand the most effective way of testing. Using design of experiment four setup changes were chosen to be tested, these being anti-roll bars, spring stiffness, front toe and finally rear toe. These setups have been critically analyzed using motec and other various software packages to deduce which setup was the most effective.

The conclusion was made that the high anti-roll bar setting, softer spring stiffness, front toe out and rear toe out were the most effective setups for a race. The setups were chosen based on race day rather than qualifying because in many categories of racing points are awarded on race day rather than qualifying.

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1. Introduction.

Data acquisition is a proven way for athletes to be successful. A common sporting discipline, and form of data acquisition, is for them to record their performance, analyze what has happened and draw conclusions from factors that influence their performance.

Sophisticated recording devices are used to collect, store and correlate data. These devices are fed by numerous sensors placed statically within a race car to give race times all the data they need. These sensors could range from G sensors which record lateral/ longitudinal G force, tire temperature sensors to gearbox oil temperature sensors. All the sensors in the car are used to assist engineers and drivers into getting the absolute maximum out of a race over a race weekend or test session. (Segers, 2008)

Motor racing has always been known for its use of high end technology. Simulators have become extremely sophisticated in the past 20 years of racing. Gerhard Berger explained that on his Formula one debut that he did not know the track so he went out and looked at the braking points of the “*quick drivers*”. (Sky Sports, 2013). In modern racing however, simulators are king. All formula one teams have simulation packages to help develop new parts, engine packages and even pit stops. Drivers use simulators for different reasons however. A racing driver’s main aim is to win. With the advancement in driving simulations being quick in a racing car is more about skill than bravery.

This project has two main aims. The first aim of the project is to use motec in conjunction with the BPS simulator to statically test various setups. The second aim of the project is to analyze the tested setups using motec and conclude which setup is the most viable for a race.

2. Literature Review.

2.1. Simulation.

2.1.1. Design of Experiment.

A popular testing system used for simulation is called design of experiment, DOE for short, it is a systematic method to determine the relationship between factors affecting a process and the output of that process. It is mainly used to find cause and effect relationships.

- Common terms of DOE are ‘controllable and uncontrollable input factors’, ‘hypothesis testing’ and ‘replication and interaction’.
- Controllable input factors are input parameters that can be changed. In the case of the project this can be many things such as the car setup.
- Uncontrollable input factors are input parameters that cannot be changed. In the case of the project this will be the car, driver and track for consistency.
- Responses (output measures) are elements of the process outcome that gage the desired effect. In the case of the project this would be the driver being more comfortable driving the car, more consistent driving the car and being able to generate a better lap time with the car. (*Isixsigma.com*)

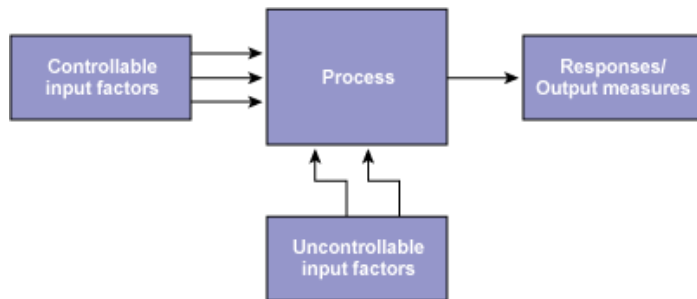


Figure 1; Image illustrating the DOE process taken from *Isixsigma.com*.

Hypothesis testing helps to determine significant factors using statistical methods. Hypothesis statements have two possibilities; these are the null and the alternative. The null hypothesis is only valid if the status quo is true whereas the alternative is only true if the status quo is not valid. Testing is done at a level of significance, which is typically based on probability.

Blocking and replication are both testing techniques. Blocking is a technique used to avoid unwanted variations in the input or experimental process. For example, the testing that is being conducted for this project uses the same simulator, track, driver and car to avoid any performance variations. Practitioners also tend to replicate experiments, performing the same combination run more than once, in order to obtain a variation of error. (*Isixsigma.com*, 2018)

2.1.2. Simulators.

Base performance simulators (BPS) provide simulators for all kinds of racing drivers from professionals to amateurs. The most important thing to remember about simulators is that they will never replace track time. Base performance simulators uses it extensive knowledge of simulation to try and break this old saying. (Race Tech Magazine, 2017)

Driving simulators are often referred to as ‘glorified video games’. *“It would be too easy and in fact, lazy to compare using a professional sim to playing a video game, because the physicality of driving a racing car really comes across. The environment you sit in, with a fully kitted out cockpit, and the driving model gives you a sense of immersion which has to be experienced to be believed.”* Simulators are used to allow drivers to pump in lap after in order to learn a track, the best racing lines and the latest possible point to break without damaging himself, the car or the track. The main problem with driving in a simulator is that there is no danger, drivers will push as hard a possible because it doesn’t matter whether they crash or not because realistically it will only effect the lap time. (*Kilbey*, 2016).

2.2. Data Acquisition.

Data acquisition in race cars is an electronic memory unit that stores user defined parameters while the car is on track. The stored data can then be downloaded and analysed using software packages such as motec. Data acquisition can be broken down into six categories. These are 1. Vehicle performance analysis. 2. Driver performance analysis. 3. Vehicle development. 4. Reliability and safety. 5. Determining vehicle parameters. 6. Running logs.

Data acquisition systems have many sensors to record various aspects of the cars performance. Some race cars, such as formula one cars, have over 100 sensors but not all race cars have this many sensors. Some race cars are raced on a budget and can therefore only afford a limited amount of sensors outputting certain signals. Top of the list would be the following sensors. Engine rpm, wheel speed, throttle position, steering angle, lateral and longitudinal acceleration. These six signals are the most important for engineers because they can express so much. Steering angle could be measured against lateral acceleration to determine cornering speed for example. (Segers, 2008)

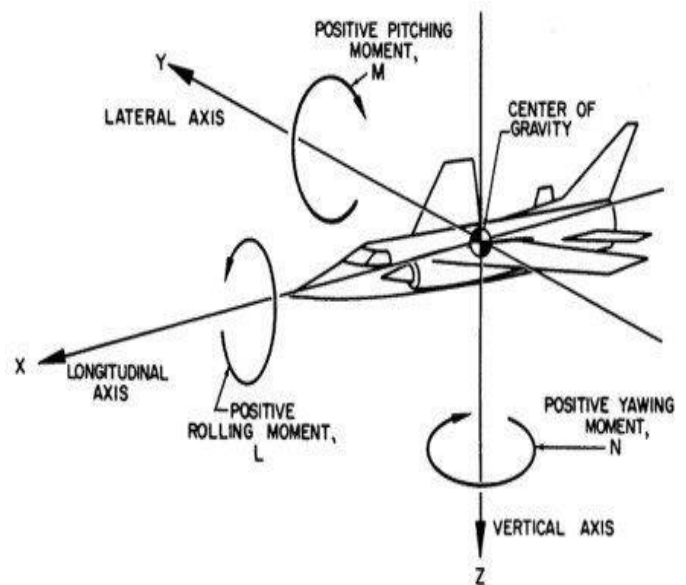


Figure 2; Image from goflightmedicine illustrating axis motion.
- (goflightmedicine.com, 2018)

2.3. MoTeC.

MoTeC has been one of the world leaders when it comes to data acquisition with its distinctive gold ECUs and a philosophy of engineering excellence. MoTeC has grown from a modest home workshop producing a screwdriver-adjusted ECU in the late 1980s to world leaders. MoTeC now has over two hundred dealers worldwide. MoTeC has become synonymous with motor racing success in almost every category across the globe.

MoTeC was initially adopted by sport sedans and road-registered vehicles but has since been picked up by the majority of motorsport categories worldwide such series as Le Mans, ALMS, NASCAR, FIA GT, Australian V8 Supercars, Indy Car, Dakar Rally, World Superbikes, Professional Drag Racing including Top Fuel and Sport Compact, Porsche Carrera Cup, Star Mazda USA, TC2000 Argentina, World Rally, Group N Rally, GP Masters, Formula 4000 and Formula Ford. MoTeC systems have also been put to use in military vehicles and commercial automotive test facilities. - (*Motec.com, 2017*)

2.4. Weight Transfer.

Vehicle weight transfer is an unavoidable side effect of cornering. It occurs as a result of the chassis twisting around the car's roll center, which is determined by the setup of the suspension. When accelerating, braking or steering the body of the car rotates in the opposite direction, when the car is accelerating the car will rotate rearwards because the car is moving forwards for example. - (*Drivingfast.net*)

2.5. Suspension.

2.5.1. Anti-Roll Bars.

“The function of the anti-roll bar in preventing roll and, more importantly, transferring part of the cars weight from side to side and one end to another during cornering is taken over to the remarkable extent that it becomes not simply adjustable but also infinitely variable all the way through any particular corner in any manner the driver or road might demand.” (Staniforth, 1994)

Anti-roll bars, sometimes referred to as sway bars, are part of vehicle suspension systems. Their purpose on the system is to attempt to keep the cars body from rolling. The fundamentals of anti-roll can be summed up by the way our human bodies react to hard cornering. In a hard corner our bodies get pulled to the outside of the turn, the exact same thing is happening to all parts of the car. The parts of the car on the outside of the turn get pushed into the road and the parts on the outside lift up. If a turn is taken fast enough then the tires on the inside can actually lift off the road, this is usually where the car flips over.

To better imagine how an anti-roll bar works, imagine a metal rod that is that is an inch or two in diameter. If the front tires are 5 feet apart then the rod will need to be 4 foot long. Attach the rod to the frame of the car and in front of the front tires, but attach it with bushes to allow it to rotate and attach arms from the rod to the front suspension member on both sides. When the car turns now the front suspension member of the outside of the turn will get pushed up. The arm of the sway bar will also get pushed upward which in turn applies torsion to the rod. The torsional force then moves the arm at the other end of the rod and causes the suspension on the other end of the car to compress. (Garden, Hood and Suspension, 2018)

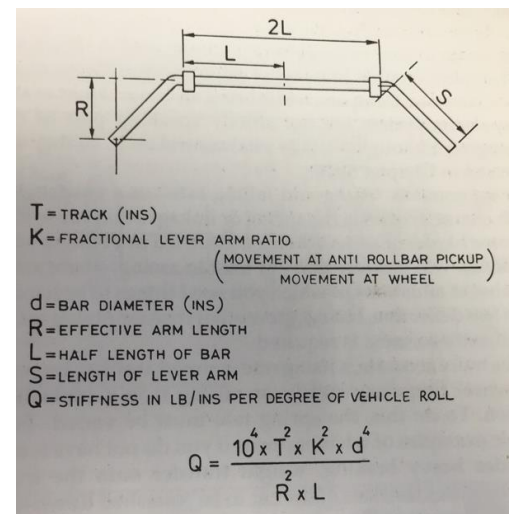


Figure 3; Image illustrating the parts and calculations of an anti-roll bar. (Staniforth, 1994)

2.5.2. Toe.

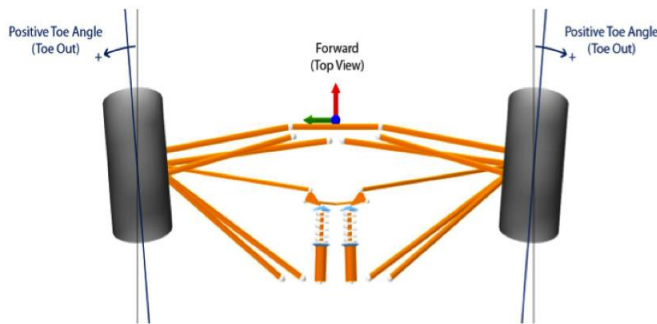


Figure 4; Image illustrating toe in and toe out.
(Carengineer.com, 2013)

Toe angle categorizes the exact direction the tires are pointed compared to the centerline of a vehicle when viewed from above. Toe can be expressed in degrees or fractions of an inch. An axle is said to have positive toe in when the imaginary lines running through the centerlines of the tires intersect. They have negative toe out when they diverge. Vehicles can also have zero toe when the imaginary lines are parallel. Toe settings are typically

used to help compensate for suspension bushes compliance to enhance tire wear. Toe is also commonly adjusted to alter a vehicles handling characteristics.

Rear wheel drive vehicles push the front axle tires as they roll along the road. Tire rolling resistance tends to cause a little bit of drag, which is undesirable, resulting in rearward movement of the suspension arms in relation to their bushes. On the contrary, front wheel drive vehicles pull the vehicle through the front axle resulting in forward movement of the suspension.

Increased toe out will typically result in a reduction in understeer, helping to free up the car especially during the initial turn in while entering corners. Extreme toe settings often bring drivability problems, especially during heavy rain. This is because excessive toe has each tire pointed in a direction other than straight so when the vehicle encounters a wet patch it causes one tire to lose grip. The other tires toe setting will then push (excessive toe in) or pull (excessive toe out) the vehicle to the side. This tends to make the vehicle feel unsettled and nervous.

Furthermore the vehicles toe is one the most critical alignment settings in relation to tire wear. Toe settings that have been incorrectly adjusted can make a vast difference in tire wear. For example, if the toe setting is just $1/16^{\text{th}}$ of an inch off its appropriate setting then each tire on that axle will scrub almost seven feet sideways every mile. (Tirerack.com)

2.6. Driver Specimen.

There is a common misconception outside of the engineering world that racing drivers are not athletes. This is not true. When the word 'athlete' is uttered we immediately think of fit men and women who can run, hit hard, go for longer and are generally at the peak of physical fitness such as Usain Bolt and Dame Jessica Ennis-Hill and Cristiano Ronaldo.

Formula one drivers are constantly exposed to high G forces. During the Spanish GP 2008 Heikki Kovalainen crashed out at 160mph (257kph), a collision at this speed causes the body to decelerate at 26G or 26 times your body weight. While cornering a driver can expect to experience around 5G, even more in the 2017 breed of car (see figure). The most vital part of the human body, the head, is supported by the neck. A common injury is whiplash, It occurs when the soft tissues in the neck become stretched and damaged. (nhs.uk, 2017).



Figure 5; Image from Formula 1 illustrating the increase of G force from 2016 to 2017. - (Formula One, 2017)

Racing drivers also have to the distance. In most sports athletes are allowed time to have a break, half time, in motor racing this isn't very common. Endurance racers have breaks but this is because they tend to race for extremely long periods of time. Average human beings have a resting heartbeat of 70bpm, this will usually raise to around 130-150bpm which exercising. Racing drivers tend to have a lower resting heartbeat of around 45-50bpm. On the grid awaiting a race start racing drivers can reach 185-200bpm. Dehydration also plays it part, especially at high demanding races such as Monaco, Singapore or Malaysia where the heat and concentration levels are extreme. Temperatures in a racing cockpit can reach up to 50 degrees C. Drivers can sweat off anything up to 3kg of their body weight during the course of a race. (Revolution, 2014).

The arms and legs are put to the test also. Some race cars have power assisted steering, this doesn't make the steering incredibly light like some road cars however. Since weight in racing is important drivers need to have strong but not bulky muscle. The legs of a racing driver come under similar scrutiny. Many open wheel, single seater race cars tend to have a slim line cockpit. If the driver were to have big bulky legs then the aerodynamics of the car would suffer due to the increase in cockpit size. The paradox however is that racing drivers need to have strong legs. To stop from approximately 200mph the driver needs to generate 80KG of downward pressure on the brake pedal, usually with just his left leg!

Finally the brain of a racing driver. The brain will be fully engaged, concentrating, from the out lap to the grid to warm down lap after the chequered flag. Many drivers will enter a sort of meditation state before a race, focusing in their mind the track, the apexes and possible overtaking opportunities. The racing drivers mind is constantly focused during a race. Focused on everything from the racing line, braking points, other drivers, strategy and trying to focus on only the important parts of information relayed to him via the radio. (Auty, 2008).

3. Methodology.

3.1. Test Plan.

Test plans are crucial for any form of testing. A test plan can help reduce the amount of time used for testing, time is money after all and most companies do not want to expend money when it could be used in more valuable areas. Therefore most tests have a test plan. Test plans are used to ensure all aspects are tested during each phase of the process. Since the development process is constantly evolving, developers need to be aware of what was tested. (Bissonnette and →, 2017)

The test plan used for the project is relatively simple. It has been designed to ensure that both the driver and engineer can easily keep track of what has been done and what still needs to be done. The test track selected is Brands Hatch GP circuit, the car that is being tested is a GP2 formula car. The brands hatch GP was selected because of its variation of long high speed corners. This allows for different lines to be taken which could be determined by the changes in setup.

1.	Driver gets in car and has a few laps to find his feet, no data is being collected at this point.
2.	A setup change will be made, front anti roll bar will be put to its lowest setting for example, the driver will then do 5 laps trying to be as quick and consistent as he can be.
3.	Once the driver has completed his 5th lap he will be instructed to enter the pits to end the run.
4.	The driver will then answer a questionnaire to determine how the setup change effected the cars performance, handling and his performance.
5.	Another setup change will then be made and the process will be repeated.
6.	After all changes required have been made the driver will comment to the engineer on which setup he felt most comfortable with and which setup he would recommend.
7.	The data will then be collected from software by the engineer. The engineer will then analyze the data and show the driver where he is losing time in each setup.

Figure 6; the test plan.

3.2. Load split calculations.

The load split calculations were calculated using a math channel on motec. The math channels on motec are essentially equations the program uses to calculate things, in this case load split. The equation to calculate load split is Front weight transfer divided by the front weight transfer minus the rear load split (add equation in format).

The load split math channel requires a front and rear weight transfer calculation. The weight transfer equations are the same for front and rear but substituting the front for rear in their respective calculations. The calculations are as follows; Tire load (Left) – Tire load (Right) divided by 2 (add equation in format). The graphs for the load split have been created in excel. They have been created by using two points on the circuit. A slow point and a fast point. The points on the circuit are corners on the circuit. Brands Hatch has many fast corners so the corner that the driver could consistently take quickest has been selected, this being turn 5. Brands hatch only has one corner that would be considered slow. Turn 2 is a slow right hand hairpin so this is the logical choice for the slow corner.

The point at which the data is collected has to be accurate and conclusive. Therefore the same point on the track will be selected for every setup. These points will be selected based on the theoretical potential of showing variable load split. The selection point for both corners is about 1/3 of the way through the corner.

Turn 2.	Anti-Roll Bar	Spring Stiffness	Toe
Entry	9.221s.	8.862s.	8.785s.
Apex	10.656s.	10.597s.	10.559s.
Exit	13.723s.	12.826s.	13.089s.

Figure 7; Table with setup corner times for turn 2.

Turn 5.	Anti-Roll Bar	Spring Stiffness	Toe
Entry	37.184s.	35.885s.	36.378s.
Apex	38s.	36.678s.	37s.
Exit	38.687s.	37.487s.	38.088s.

Figure 8; Table with setup corner times for turn 5.

3.3. Motec math channels.

3.3.1. Understeer channel.

The understeer channel requires other channels to be created in order to be produced. The first channel is an altered speed channel, this channel changes the speed into metres per second. The next channel is a corner radius channel. This channel is created using this equation; $(\text{'Speed M/s' [m/s]}^2)/\text{'G Force Lat' [G]*'G' [m/s]}$. The channel is measured and displayed in metres. The next channel to be created is the ackerman steer angle channel. This is created using this equation; $(\text{'Wheelbase' [m]}/\text{'Corner Radius' [m]}) * 57.3$. The channel is usually measured in radians but shown in degrees but there was trouble with the channel so the result was multiplied by 57.3 in the equation to compensate.

The next channel to be created was the required steering. This math channel required a third test to be conducted. This test would consist of the car being driven in a circle at an extremely low speed. The low speed was to ensure that the car was not understeering or oversteering at all. This data was then added into a blank motec worksheet with the corner radius and steering wheel percentage channels showing. A selection of data was then taken when the car was moving around a corner. This data was then implanted into the equation. The equation for required steering is; $\text{'Ackerman steer' [deg]}*(-18.87/0.038)$. This channel is displayed as a percentage.

The final math channel to be added was the understeer channel, the understeer acts as the oversteer channel also. The equation for the understeer channel is; $\text{abs('Steering Wheel Pct' [\%])}-\text{abs('Required Steer Calibrated' [\%])}$.

3.3.2. Weight transfer & Load split.

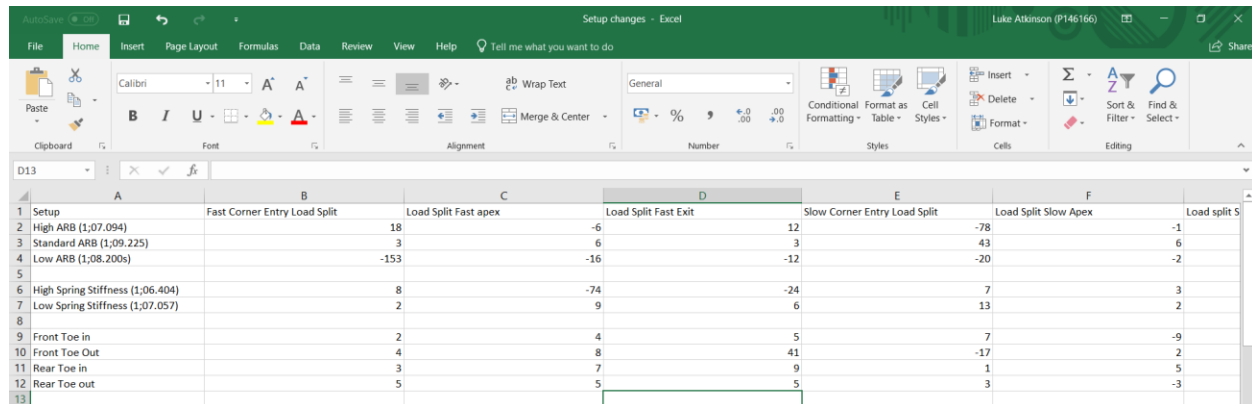
The weight transfer channels were created using the same equation for the front and rear. The front was created by subtracting the front left tire load from the front right tire load then dividing by 2. The equation in motec looks like this; $(\text{'Tire Load - FL' [N]}-\text{'Tire Load - FR' [N]})/2$. The rear weight transfer channel was created using the same equation but using the rear tire loads instead of the front tire loads.

The load split channel was created using the two weight transfer channels. It is created by dividing the front weight transfer by the front weight transfer minus the rear. The equation in motec looks like this; $(\text{'Front Weight Transfer' [N]})/(\text{'Front Weight Transfer' [N]}-\text{'Rear Weight Transfer' [N]})$.

Screenshots of all of the motec channels used can be find in the [Appendices](#).

3.4. Excel spreadsheet.

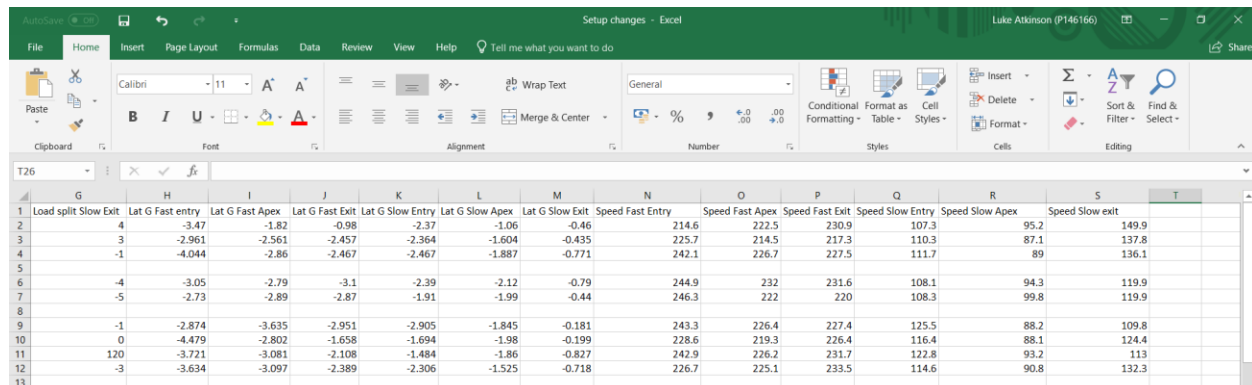
The excel spreadsheet was created to create graphs to analyze the setups with. The spreadsheet consists of all the setups and three main vehicle characteristics, these being lateral G, corner speed and load split. The excel spreadsheet consists of the readings taken from the time in the lap discussed in **Load split calculations**.



The screenshot shows the first half of an Excel spreadsheet. The worksheet is titled 'Setup changes - Excel'. The data is organized into columns A through F. The rows contain various vehicle setup parameters and their corresponding values.

	A	B	C	D	E	F
1	Setup	Fast Corner Entry Load Split	Load Split Fast apex	Load Split Fast Exit	Slow Corner Entry Load Split	Load Split Slow Apex
2	High ARB (1:07.094)	18	-6	12	-78	-1
3	Standard ARB (1:09.225)	3	6	3	43	6
4	Low ARB (1:08.200s)	-153	-16	-12	-20	-2
5						
6	High Spring Stiffness (1:06.404)	8	-74	-24	7	3
7	Low Spring Stiffness (1:07.057)	2	9	6	13	2
8						
9	Front Toe in	2	4	5	7	-9
10	Front Toe Out	4	8	41	-17	2
11	Rear Toe in	3	7	9	1	5
12	Rear Toe out	5	5	5	3	-3
13						

Figure 9; First half of the excel spreadsheet.



The screenshot shows the second half of an Excel spreadsheet. The worksheet is titled 'Setup changes - Excel'. The data is organized into columns G through T. The rows contain various vehicle setup parameters and their corresponding values.

	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Load split Slow Exit	Lat G Fast entry	Lat G Fast Apex	Lat G Fast Exit	Lat G Slow Entry	Lat G Slow Apex	Lat G Slow Exit	Speed Fast Entry	Speed Fast Apex	Speed Fast Exit	Speed Slow Entry	Speed Slow Apex	Speed Slow exit	
2	4	-3.47	-1.82	-0.98	-2.37	-1.06	-0.46	214.6	222.5	230.9	107.3	95.2	149.9	
3	3	-2.961	-2.561	-2.457	-2.364	-1.604	-0.435	225.7	214.5	217.3	110.3	87.1	137.8	
4	-1	-4.044	-2.86	-2.467	-2.467	-1.887	-0.771	242.1	226.7	227.5	111.7	89	136.1	
5														
6	-4	-3.05	-2.79	-3.1	-2.39	-2.12	-0.79	244.9	232	231.6	108.1	94.3	119.9	
7	-5	-2.73	-2.89	-2.87	-1.91	-1.99	-0.44	246.3	222	220	108.3	99.8	119.9	
8														
9	-1	-2.874	-3.635	-2.951	-2.905	-1.945	-0.181	243.3	226.4	227.4	125.5	88.2	109.8	
10	0	-4.479	-2.802	-1.658	-1.694	-1.98	-0.199	228.6	219.3	226.4	116.4	88.1	124.4	
11	120	-3.721	-3.081	-2.108	-1.484	-1.86	-0.827	242.9	226.2	231.7	122.8	93.2	113	
12	-3	-3.634	-3.097	-2.389	-2.306	-1.525	-0.718	226.7	225.1	233.5	114.6	90.8	132.3	
13														

Figure 10; Second half of the excel spreadsheet.

The graphs used in the **Discussion & Analysis** Section of the report were created using these data figures. They were created by adding the setup on X axis and the setup characteristic on the Y axis. Axis titles were then added to assist in reading the graphs. Finally, each portion of the corner was given a specific color. Blue for entry, orange for apex and grey for exit.

4. Discussion & Analysis.

4.1. Anti-Roll bar setups.

4.1.1. Lateral G.

Figure 11 is a graph created using the excel spreadsheet. The graph has been created using the lateral G figures taken from motec. The graph has three data points.

The data points from this graph have been taken from turn 5 which is a right hand turn. This is why the lateral G is in minus figures. If the turn was a left hand turn then the figures would be positive.

The blue line is how the car is reacting on entry. The graph shows that the car is pulling the most G on entry, this is because the driver is entering the corner at a lower speed. But the driver is gaining speed throughout the corner. This can be seen in **Figure 12** via the green line.

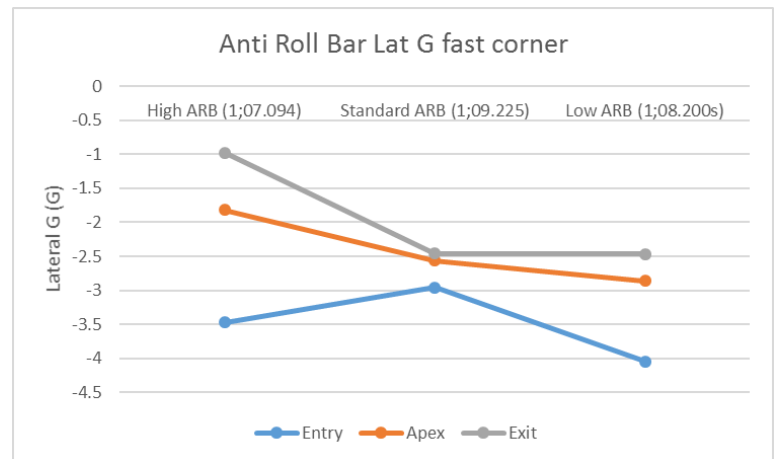


Figure 11; Graph comparing the Lateral G of each of the anti-roll bar setups through turn 5.

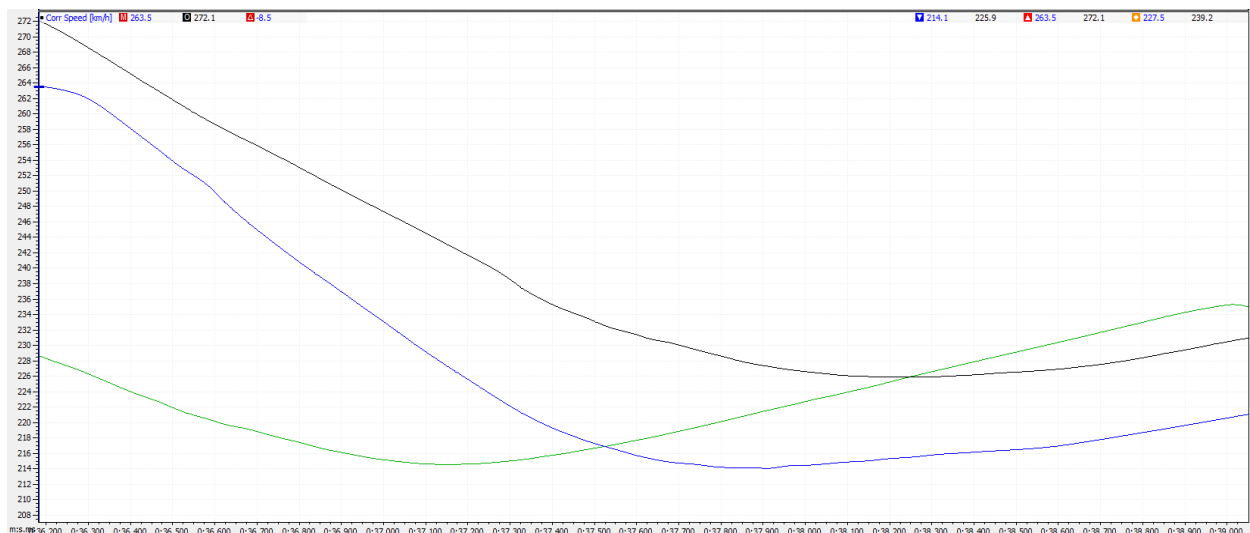


Figure 12; Outing report from motec illustrating corner speeds in turn 5.

The lat G seen in **Figure 11** shows the driver attaining the least amount of lat G on the exit of the corner. This is due to the driver having confidence in the setup. The driver is able to get the car in a straight line with no oversteer, seen in **Figure 13**.

This outing report also proves the early entry on the high setting. The green trace understeers a lot sooner than the blue and black traces. This shows that the car began to understeer sooner on the green trace due to the early entry.

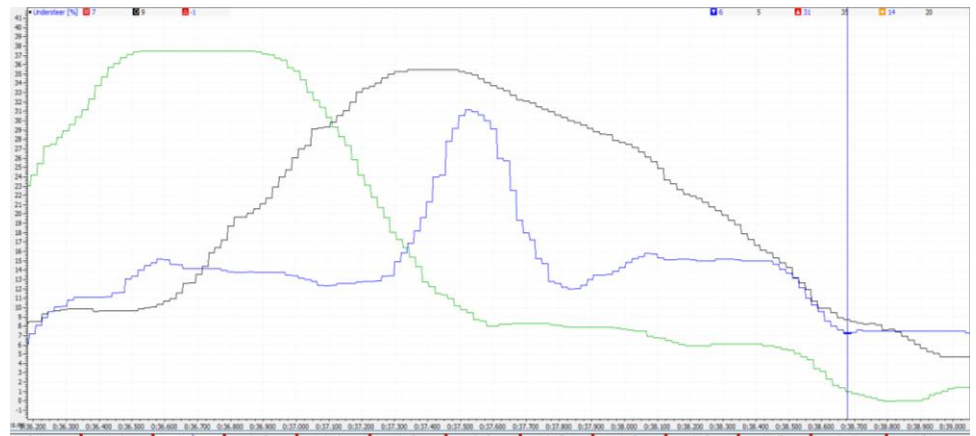


Figure 13; Outing report from motec illustrating the understeer and oversteer through turn 5.

The blue trace on the understeer outing report is the standard setting. This trace shows that there is a spike in understeer mid corner, this is undesirable. The standard setup does seem to be the most balanced however in terms of lateral G. The data points seen in **Figure 11** show that the standard setting pulls consistent lat G throughout the corner showing its balanced nature.

Figure 14 is another graph taken from the excel spreadsheet. This graph shows the lat G attained through turn 2. As before turn 2 is a right hand corner, this corner is a slower corner however.

The graph shows that the lat G is consistent on entry for each setup. This shows that the driver is comfortable which each setup on the entry to slow corners. **Figure 15** is an outing graph showing the braking points for each of the setups. The graph shows that the driver is braking early for the high setup (Green), this can be related to the lack of lateral G force at the apex and exit of the corner. The driver is braking late for the low setting (Black) which forces him to be on the brakes for longer which shows the increase in G at the apex and exit of the corner.

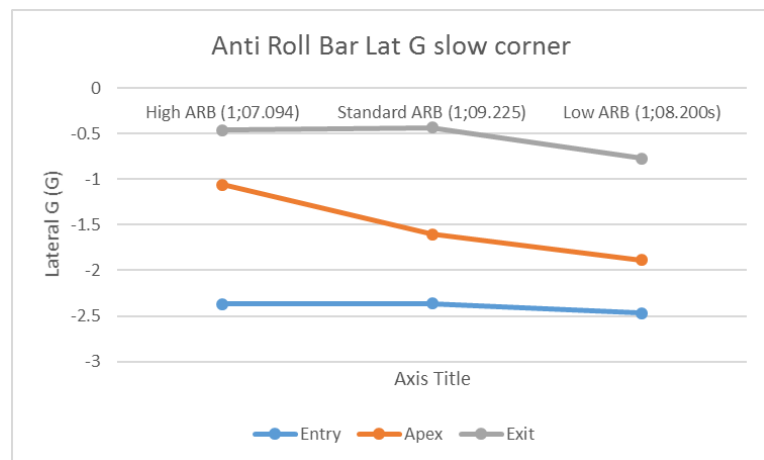


Figure 14; Graph comparing the lateral G of the anti-roll bar setups through turn 2.

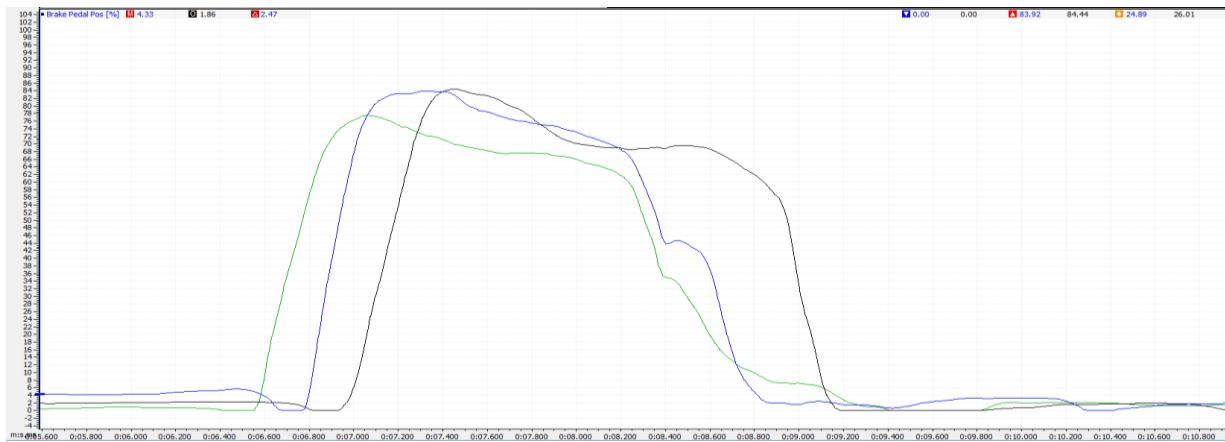


Figure 15; Outing graph from motec showing the braking points for the anti-roll bar setups through turn 2.

4.1.2. Corner Speed.

Figure 16 is a graph created using the excel spreadsheet. The graph compares the cornering speed through turn 5.

The graph shows an increased speed for the low setting. The driver experiences around 35% of understeer through this corner, as seen in Figure 13, the understeer is consistent throughout the corner however. This shows that although the car is understeering it is balanced. An example of an unbalanced car can be seen via the blue trace. There is a spike in the trace which shows that the car is unsettled at that point. This could be due to the driver hitting the curb however.

The speed is much higher at the apex and exit for the low setting. This is yet another indication that the driver is comfortable with this setup, at least through the fast corners.

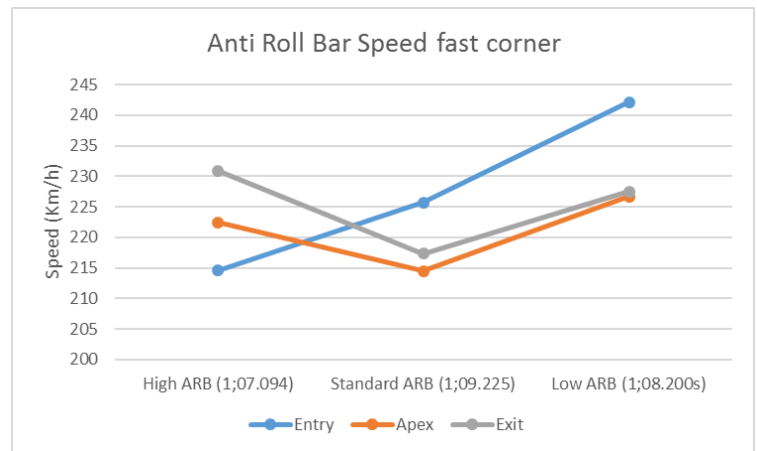


Figure 16; Graph comparing the cornering speed of the anti-roll bar setups through turn 5.

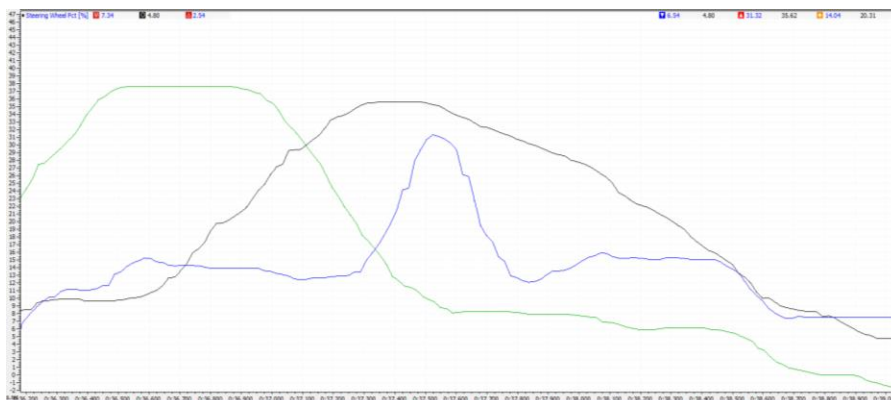


Figure 17; Outing graph showing the steering wheel percentage through turn 5.

Figure 18 is a graph created using the excel spreadsheet. It shows the cornering speeds through turn 2. The speeds are very consistent through the corner. The only real variation is during the high setup. The driver brakes early during this corner, as seen in Figure 15. This shows why the speed on entry is lower. This is however a good thing because the driver gains speed through the corner and is able to get onto the power earlier resulting in a higher exit speed.

4.1.3. Load Split.

Figure 19 is a graph comparing the load split of the anti-roll bar setups through turn 5. The graph shows a large amount of variation on entry for the low setup. This is due to the car being unbalanced in this corner. This could be due to the late turn in shown in Figure 17.

The standard setup shows the most consistent data traces suggesting that this setup is the most balanced through fast corners. This is odd because a stiffer anti-roll bar should allow the body of the car to resist the weight transfer more.

Figure 20 is a graph comparing the load split of the anti-roll bar setups through turn 2. The graph also shows a large variation on corner entry. This could be due to the different braking points seen in Figure 15. The standard setup is shown to be the most balanced during this corner.

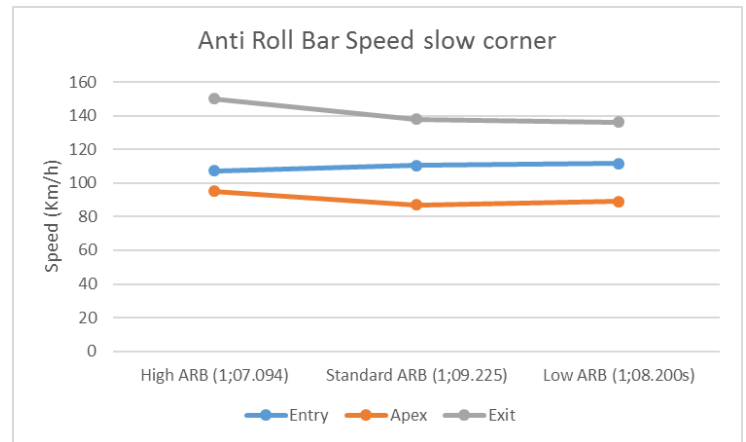


Figure 19; Graph comparing the corner speeds of the anti-roll bar setups through turn 2.

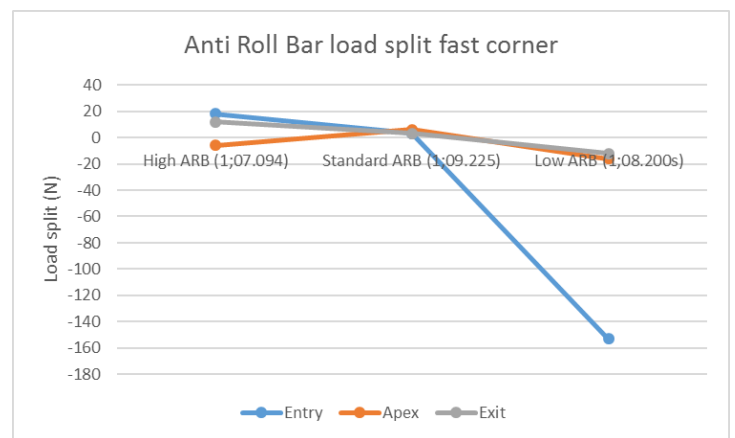


Figure 18; Graph comparing the load split of the anti-roll bar setups through turn 5.

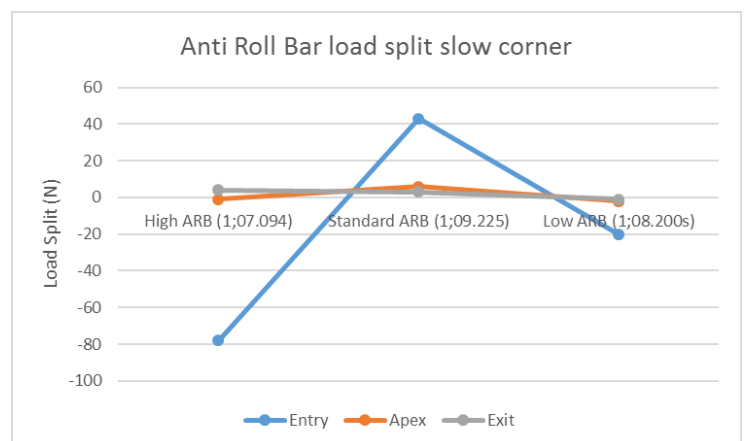


Figure 20; Graph comparing the load split of the anti-roll bar setups through turn 2.

4.2. Spring Stiffness.

4.2.1. Lateral G.

Figure 21 is a graph showing the change in lateral g for the spring stiffness setup changes through turn 5. The high setup shows more lateral g on entry and exit but a big drop when the car reaches the apex. The car approaches the corner faster with the higher setting. Due to the higher spring stiffness the car does not pitch as much and is able to carry more overall speed throughout the corner as seen in Figure 22.

The car does not experience as much lat g for the softer spring setting. The car experiences 0.3g less on entry with the lower spring stiffness. This is due to the driver taking a narrower line than the high setting. This can be shown in Figure 23 by the blue trace. The driver uses more steering while going into the apex of the corner which could be due to the driver taking a narrower line.

The car experiences more lat G at the apex of the corner for the lower setting, this adds credit to the narrower line theory because the driver is now hugging the inside curb.

Some drivers like to turn in late and kiss the apex. If this were the case, then the driver would experience a variation of lat G through this corner due to the car only moving lateral for a short amount of time. Sometimes this is the better approach, but all racing drivers are different and they all find speed in a variation of ways.

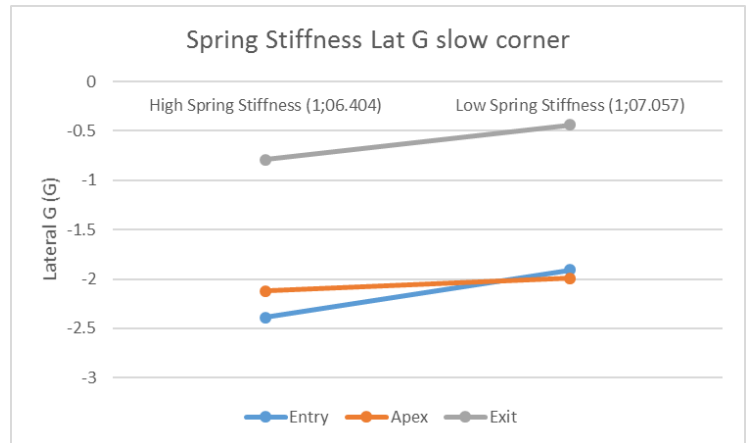


Figure 21; Graph comparing the lat G for the spring stiffness setups through turn 2.

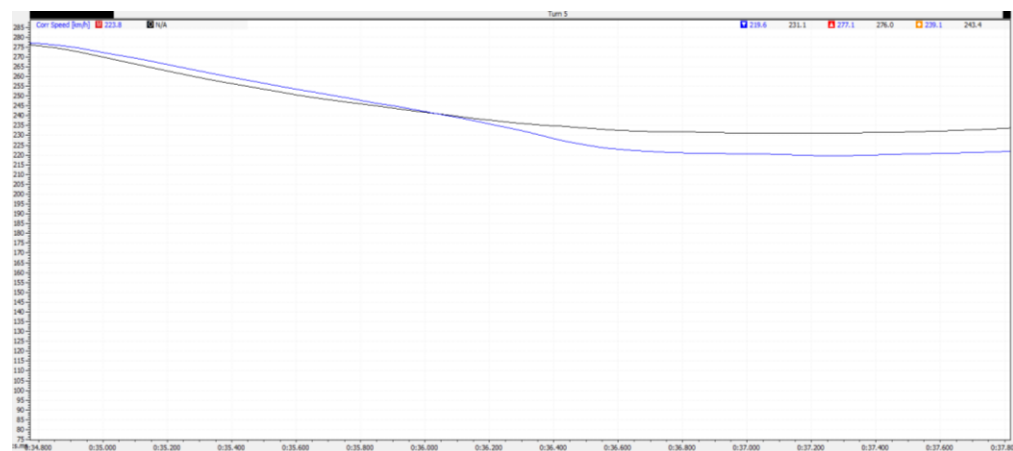


Figure 22; Outing graph from motec comparing speed of the spring stiffness setups through turn 2.

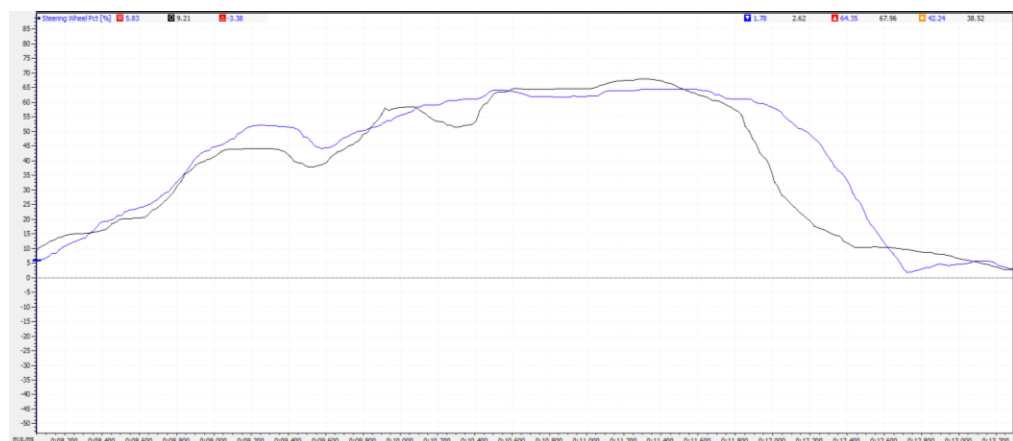


Figure 23; Outing graph from motec comparing the steering percentage of the spring stiffness setups through turn 2.

The car experiences high amounts of lat G on entry due to the high entry speed. This shows the driver is confident enough in the setup to throw the car into the corner.

The lat G then drops off as the car reaches the apex, this is due to the car scrubbing of the speed taken into the corner seen in Figure 25 by the black trace. The driver does manage to pick up a lot of speed through the apex and exit of the corner relative to the lower setting, the blue trace. This further proves that the driver is confident in this setup since he is pushing through this particular corner.

The driver experiences less lat G on entry for the lower setting. Figure 25 shows that the driver takes more speed into the corner but loses a lot more on the apex. This can be seen in Figure 24 also as the lat G increases. This is because the driver has taken more speed into the corner so the car 'slides' more laterally thus resulting in the higher lat G.

Figure 26 is an outing graph from motec, it shows how much the car is understeering. The graph shows that the car oversteers, where the trace goes below 0, on the exit of the corner. It oversteers earlier on the high setting, the black trace, which can also be seen in the graph in Figure 24 where the lat G is higher for the high setting than the low setting where the car oversteers later.

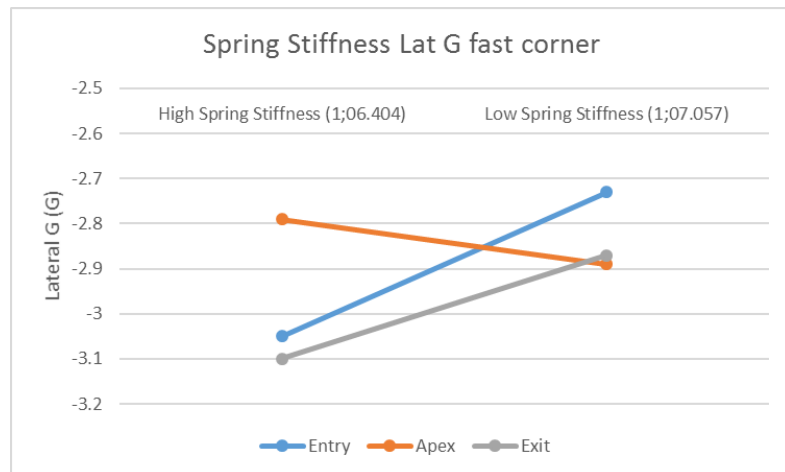


Figure 24; Graph comparing the lat G of the spring stiffness through turn 5.

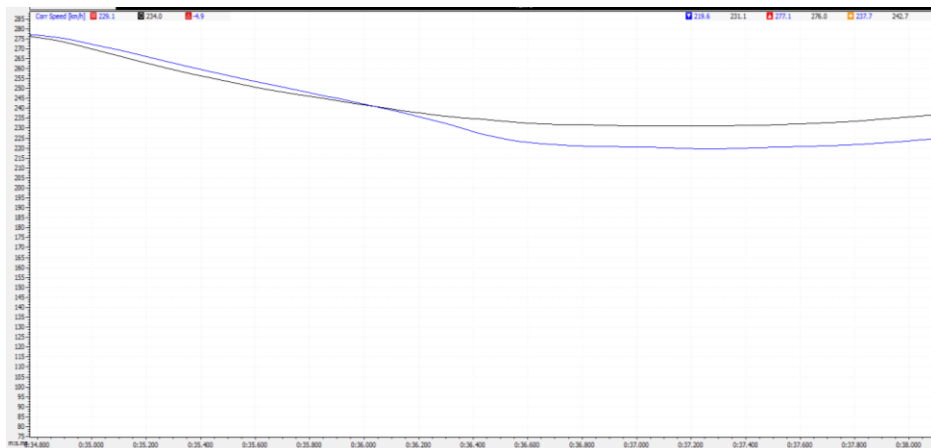


Figure 25; Outing graph from motec showing the corner speeds for the spring stiffness setups through turn 5.

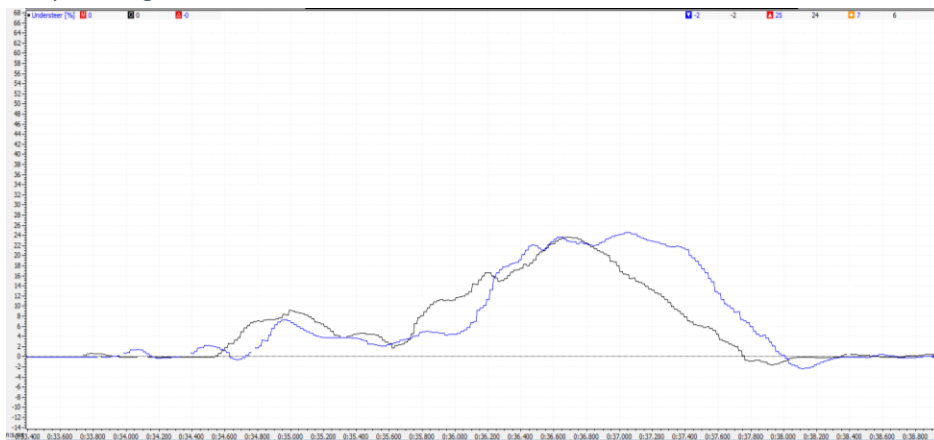


Figure 26; Outing graph from motec showing understeer for the spring stiffness setups through turn 5.

4.2.2. Corner speed.

Figure 27 is a graph comparing the corner speeds for the spring stiffness setups through turn 5. The driver takes more or less the same speed into the corner on both the high and low setting. This shows the driver is confident with both setups on entry for the corner. This adds further credit to the driver's confidence in the setups as discussed previously.

The graph shows that although the entry speed is similar the car or driver cannot carry that much speed through the corner. This can be seen as the speed decreases at the apex and exit of the corner. Figure 25 shows that the driver picks up speed on exit however.

Figure 28 is a graph showing the cornering speeds for the spring stiffness. The graph shows that the speed is almost the same for both setups. The driver is able to gain speed on the exit of the corner as shown in Figure 29. This shows that the driver is able to get on full throttle quicker for the high setting. The driver is able to get on the throttle quicker for the high setting due to the car oversteering less for the high setting as seen in Figure 26.

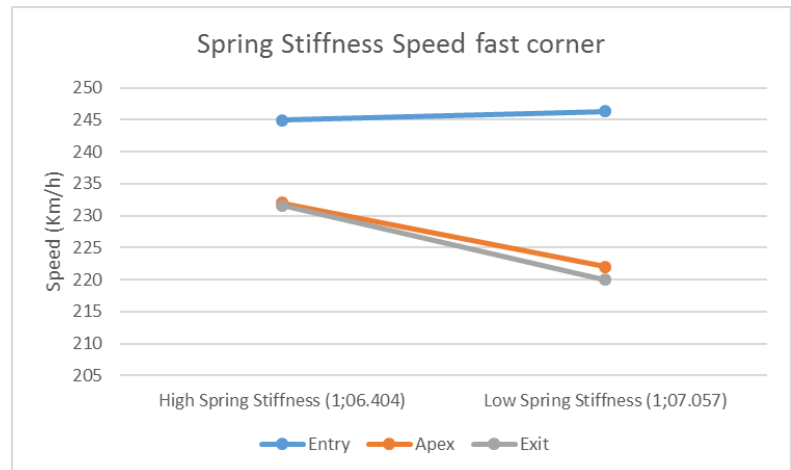


Figure 27; Graph showing the speed for the spring stiffness setups through turn 5.

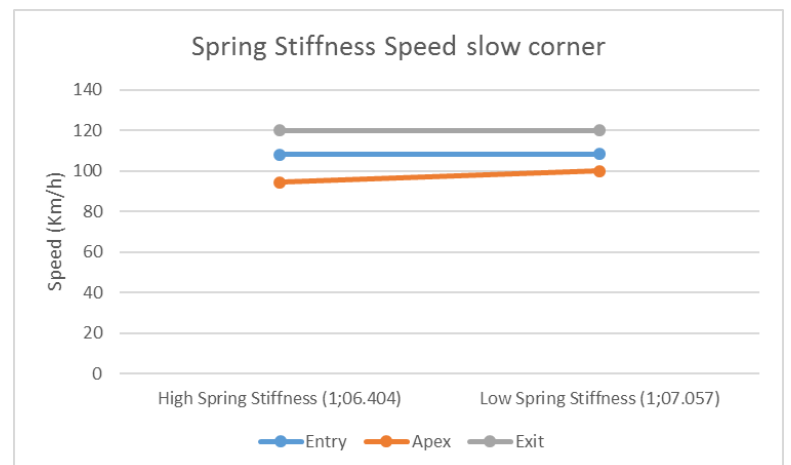


Figure 28; Graph showing the speed for the spring stiffness setups through turn 2.

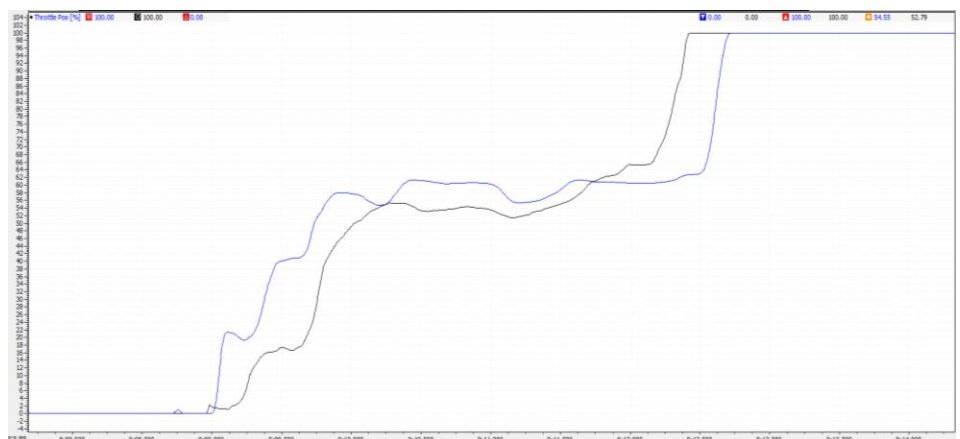


Figure 29; Outing graph from motec showing the throttle position throughout turn 2.

4.2.3. Load Split.

Figure 30 is a graph showing the load split of the spring stiffness setups through turn 5. The graph shows a large amount of variation throughout the corner for the high setting. This is due to the stiffness of the springs. The stiffer the springs are the more of the weight transfer is transmitted to the cars body rather than being absorbed by the spring and shock absorber.

The lower setting has the springs at their softest and most forgiving. This is why the load split doesn't change much for this setting. When the springs are soft they are very forgiving. A good way to visualize this is to imagine squeezing a sponge, very easy, no imagine squeezing a brick, not very easy. This is the same for spring stiffness and this is why the body of the car does not experience as much weight transfer on the lower setting.

Figure 31 shows the load split for the spring stiffness setups throughout turn 2. The high variation in load split for the lower setting contradicts the pervious theory. But, if the figures are taken into account it does not. In Figure 30 the lower setting has a variation in load split of around 10N whereas in Figure 31 the lower setting has a variation of 18N which is not too much difference.

The contradiction in this theory actually comes from the higher setting since this setting now has less variation than before. This could however be due to the lower speeds through turn 2.

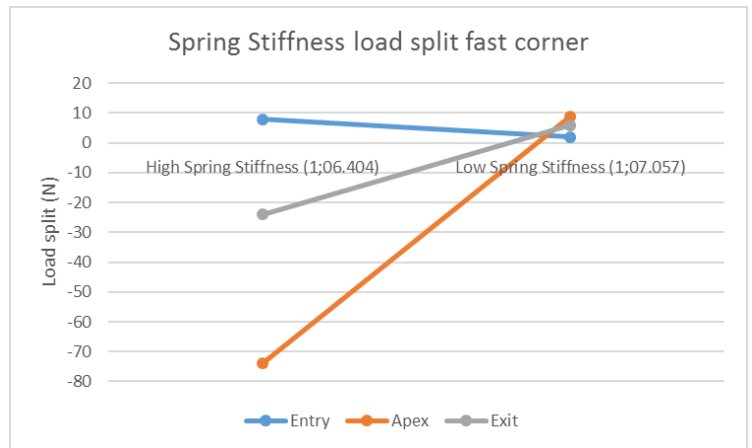


Figure 30; Graph comparing the load split for the spring stiffness setups through turn 5.

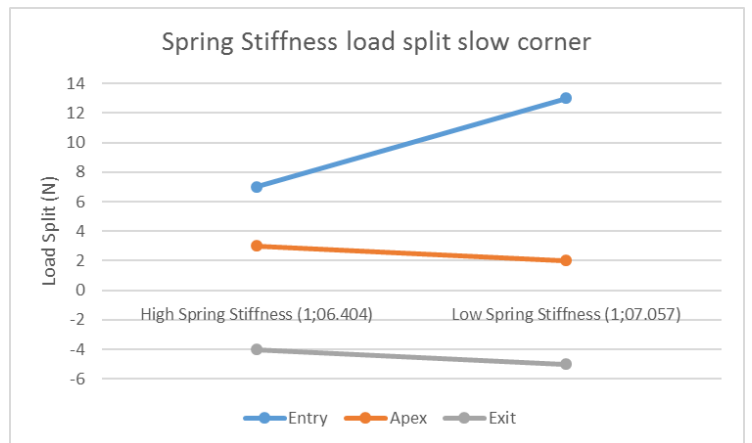


Figure 31; Graph comparing the load split for the spring stiffness setups through turn 2.

4.3. Front Toe.

4.3.1. Lateral G.

Figure 32 is graph comparing the lat G experienced for the front toe setup changes. The graph shows that the driver experiences the most lat G on entry to the corner when the car is set with the toe out. This is because when a car is toe out it tends to aid in the reduction of understeer, therefore the driver is able to turn in more sharply due to the reduction in natural understeer.

Figure 33 is an outing graph comparing the difference in steering wheel input percentage for both setups. The blue trace seen in shows the toe out setting. It is clear to see that the driver is having to apply a lot more steering for the toe out setting. This could be due to the driver having more confidence in the setup and feeling that he can push the car more going into this particular corner.

Figure 34 is an outing graph from motec and it compares the understeer of the car for both setups. The blue trace is the toe out setting and it shows that the car is understeering considerably more with the toe out setting. The car will naturally understeer no matter the setup. The car should understeer less due to the toe out setting, this seems to contradict the previous statement of reduced understeer for toe out. The driver does however apply more steering therefore the understeer factor will be increased.

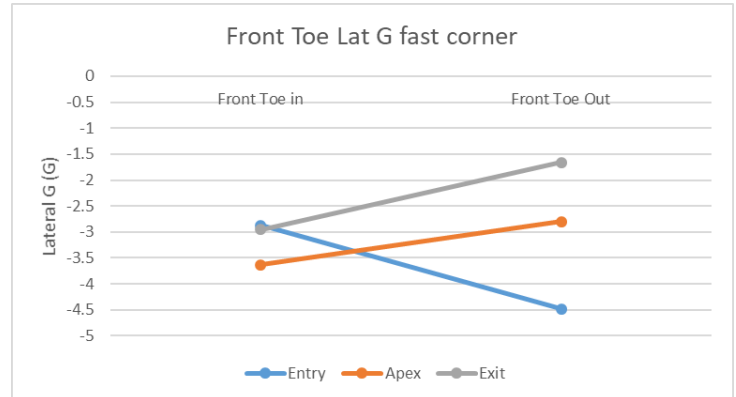


Figure 32; Graph comparing the lat G for the front toe setup changes through turn 5.

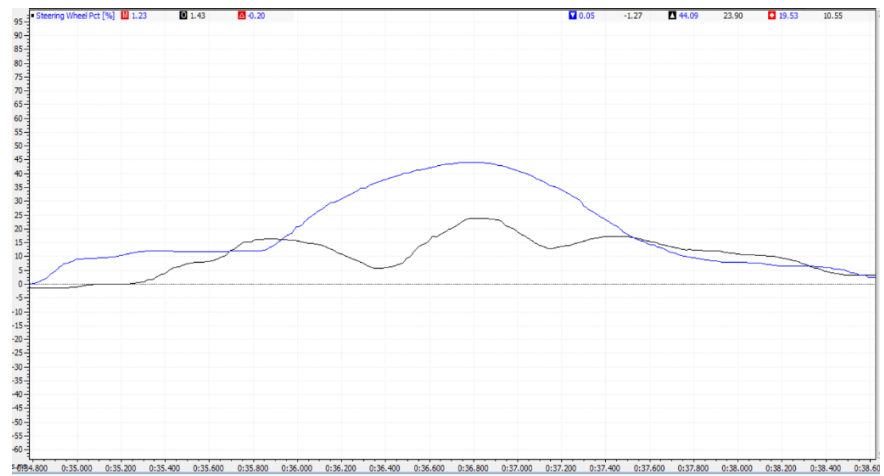


Figure 33; Outing graph from motec showing the difference in steering wheel percentage for both front toe setups through turn 5.

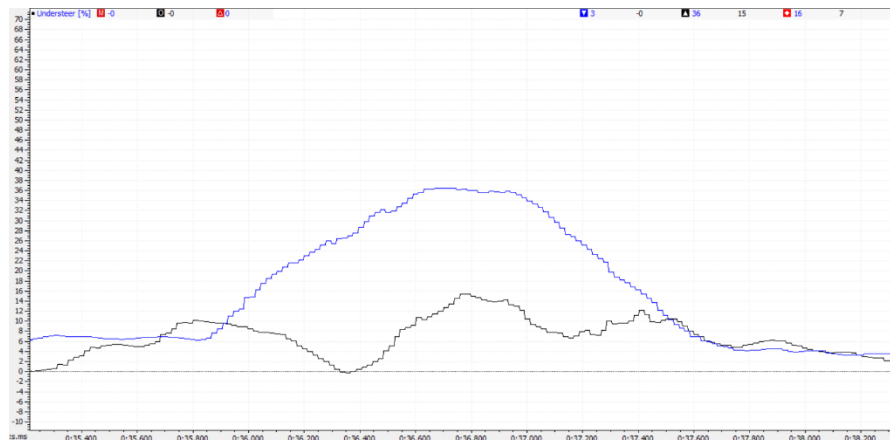


Figure 34; Outing graph from motec comparing the understeer for both settings through turn 5.

Figure 35 is graph comparing the lat G of the front toe setups through turn 2. The car experiences little to no change in lateral G on the exit of the corner. This shows that the driver can get the car in a straight line quicker and onto full power.

The car experiences the most lat G on entry while the car is toe in. This is because toe in generates understeer compared to toe out that generates oversteer. *“For every action, there is an equal and opposite re-action.”* (Newton, I. 1666.) Therefore, the driver needs to turn in more aggressively to counteract the increased understeer as seen in Figure 36.

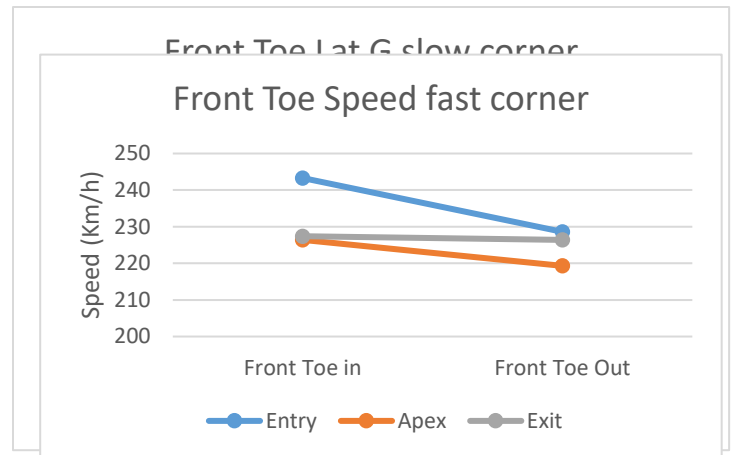


Figure 35; Graph comparing the lat G of front toe setup changes through turn 2.

The black trace in figure 34 shows the toe in setting. It is clear to see that the driver needs to put in more steering while the car is toe in. This is due to the increased understeer created by toe in as seen in Figure 37

Figure 37 shows how the car is understeering through turn 2. This backs up the previous statement since the black trace, which is toe in, understeers more than the blue trace. This is to be expected of course.

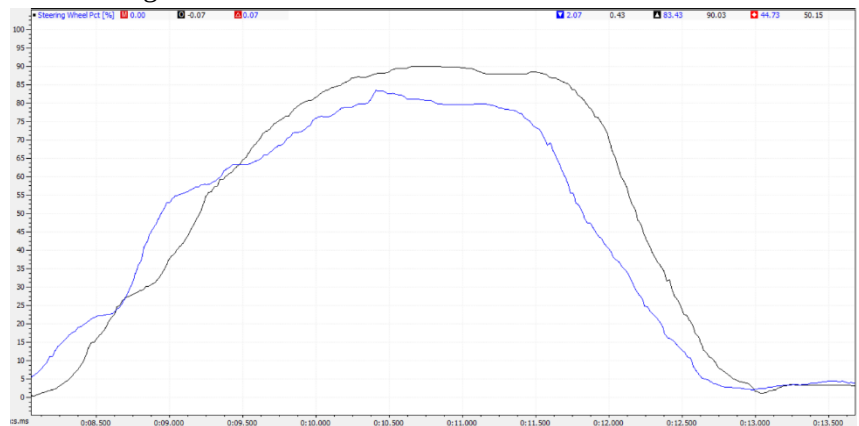


Figure 36; Outing graph from motec showing the difference in steering input for both front toe setups.

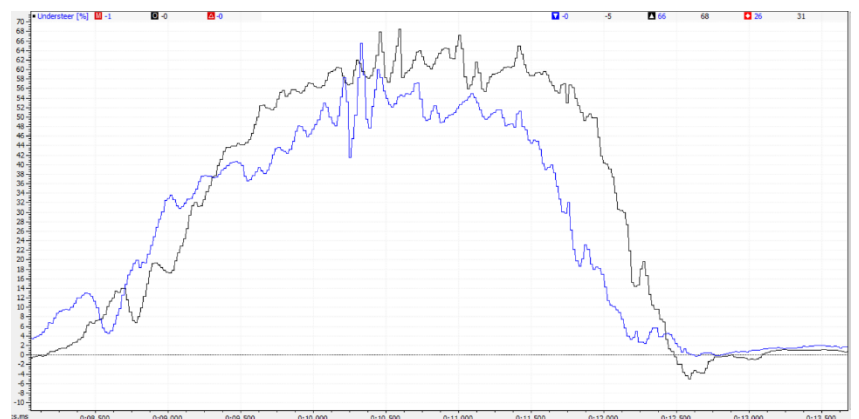


Figure 37; Outing graph from motec comparing the understeer of the car for both front toe setups through turn 2.

Figure 38; Graph comparing the speed of the front toe setups through turn 5.

4.3.2. Corner Speed.

Figure 38 is a graph comparing the corner speed through turn 5 for the front toe setups. The graph shows that the car enters to corner much slower while the car is toe out. Toe out helps to counteract the effects of understeer, but this

comes at a cost. The cost comes in straight line stability. Hence drag racers tend to toe in because they only need to go in a straight line. It is because of this lost stability in a straight line that the car enters the corner at a slower speed. Speed is scrubbing during the straight when the driver is forced to make small, untraceable corrections and this shows in the speed gained down the back straight.

The car also loses more speed at the apex of the corner for the toe out setting, this could be due to the reduction in entry speed being carried through to the apex. **Figure 33** shows that the driver turns in earlier whilst the car is toe in, this explains the lost in speed on entry and through the apex of the corner. It does not disprove the scrubbed speed statement however because this is a natural part of racing.

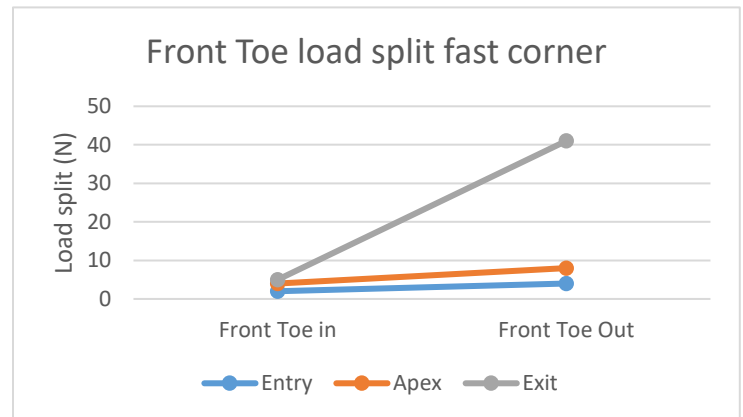


Figure 39 is a graph comparing the corner speed through turn 2 for both setups. The car can get into a straight line and onto the power sooner whilst it is toe out. This is because toe out generates oversteer to counter the understeer. **Figure 40** is an outing graph which compares the throttle position of the car through turn 2. The blue trace shows the throttle position for toe out. The driver can get onto full power much sooner than when the car is toe in. That fraction of a second might not seem like much but it could be a crucial tenth or two of a second that can put a driver on pole during qualifying.

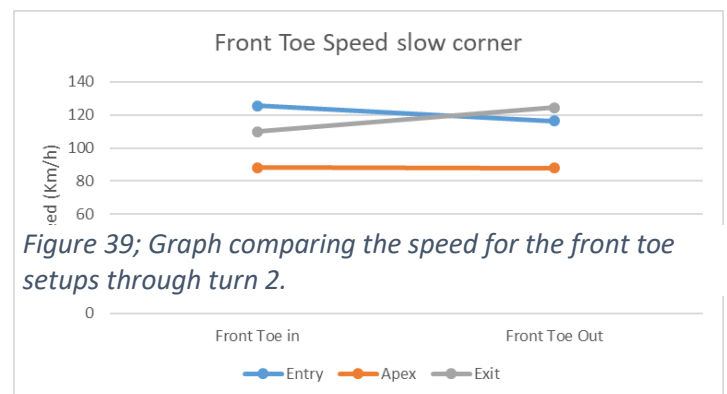


Figure 39; Graph comparing the speed for the front toe setups through turn 2.

4.3.3. Load Split.

Figure 41 is a graph comparing the load split for the front toe setups through turn 5. The graph shows the most change on the exit of the corner for the toe out setup.

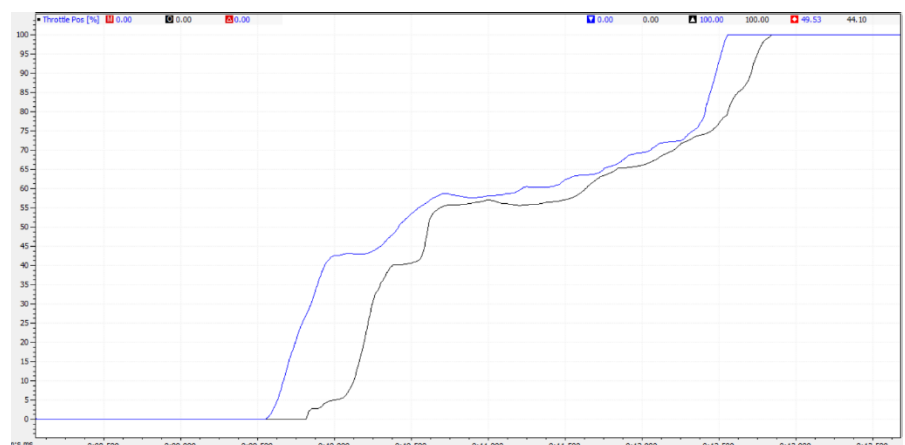


Figure 40; CFigure 41; Graph comparing the load split of the front toe setups through turn 5.

Figure 42 is an outing graph from motec showing the understeer of the vehicle through turn 5. This outing graph also includes the exit of turn 5. The graph shows the black trace, which is toe out, dip below zero indication that car is over steering. It is possible that this is where the reading for load split was taken. This makes it seem like the car is unbalanced but it could be possible that the driver was a bit too eager to get on the power which has resulted in the oversteer.

This theory can be proven with the outing graph seen in Figure 43, which is an outing graph comparing the steering trace of both setups. The driver does not apply opposite lock therefore the oversteer is produced by a heavy right foot.

The data traces for the toe in setup are very consistent. This shows that this setup is very balanced through turn 5. The driver does not have to apply as much steering for the corner but it much more pro active with the steering wheel. This is because when the front wheels toe in the initial turn in is affected. This can be seen on the blue trace also where the car is toe out. The driver applies more steering angle but is much more confident in his decision.

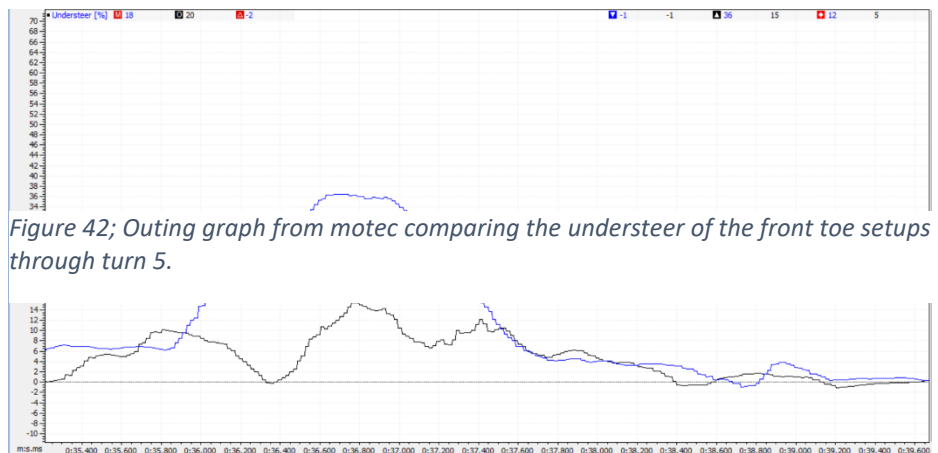
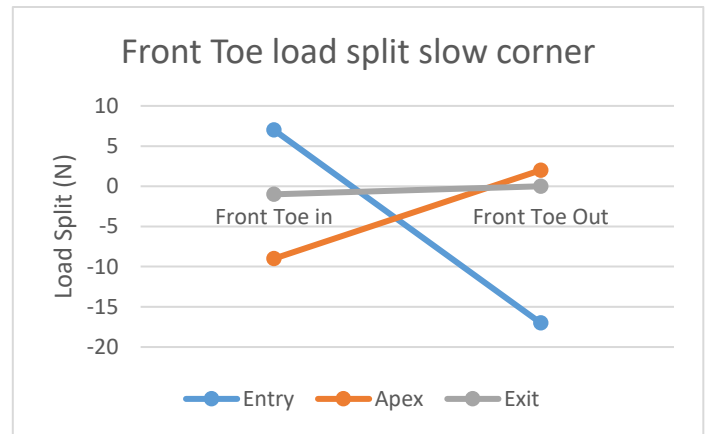


Figure 42; Outing graph from motec comparing the understeer of the front toe setups through turn 5.

Figure 44 is a graph comparing the load split for the front toe setups through turn 2. The graph shows a large difference on entry. This could be due to the small use of the brakes seen on the blue trace after to main use. It is possible that the data for the graph was taken at this point which has resulted in the data being off.

The graph also shows that the car experiences a variation in load split during the apex of the corner. This could be because the driver is taking different lines through the corner.

Figure 36 shows the steering trace for this corner for both front toe setup changes. This outing graph shows that the driver takes difference lines through the corner, which is why the load split varies depending on the setup.

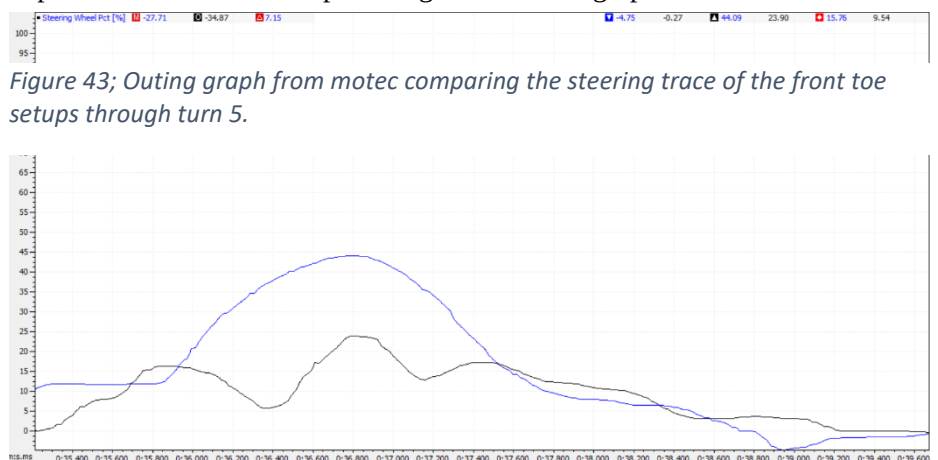


Figure 43; Outing graph from motec comparing the steering trace of the front toe setups through turn 5.

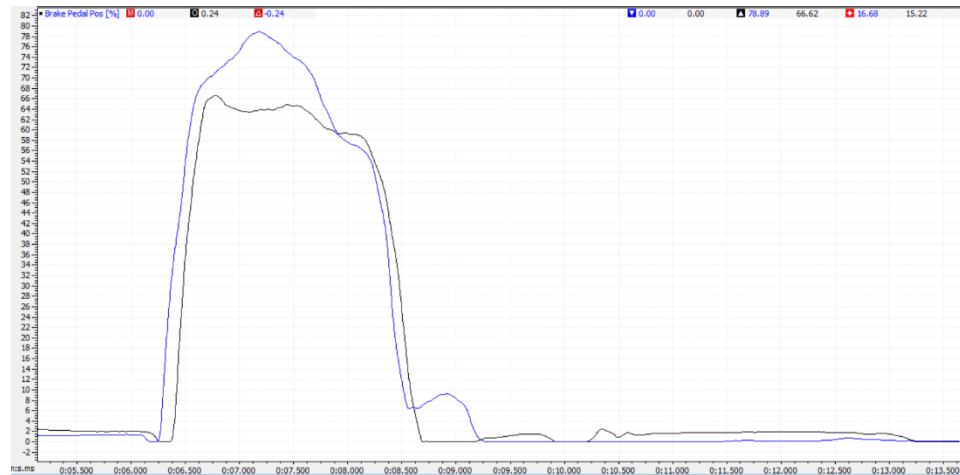
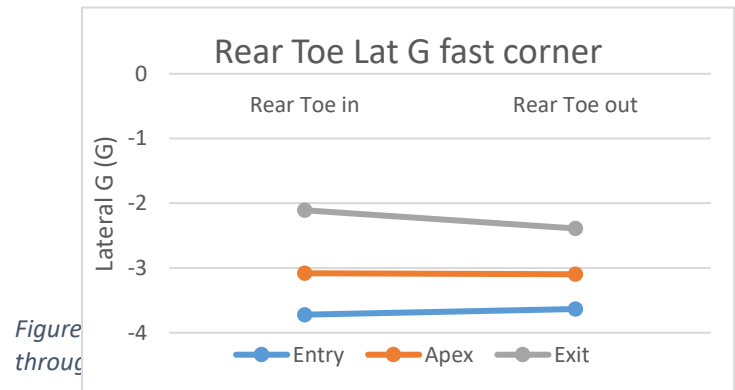


Figure 45; Outing graph from motec comparing the brake pedal position of the front toe setups going into turn 2.

4.4. Rear Toe.

4.4.1. Lateral G.

Figure 46 is a graph comparing the lat G the car experiences for both rear toe settings through turn 5. The car experiences the most lat G on the entry to the corner. The rear toe setting is used to assist the driver in getting on the throttle. Theoretically the driver should be able to get on full throttle sooner when the rear toe is out. The graph shows the car experience more lat G when on exit when the car is setup with rear toe out.

Figure 47 is an outing graph from motec showing the understeer of the car for both rear toe setups through turn 5 and on exit. The blue trace in this graph is the rear toe out setting and the car experiences a small amount of oversteer on the exit of the corner. It is possible that the data was collected when this oversteer occurred resulting in the data seeming off.

Figure 48 is an outing graph from motec comparing the throttle position. The blue trace on this graph is the toe out setting. The driver clearly gets on the throttle sooner than

Figure 46; Graph comparing the lat G for the rear toe setup changes through turn 5.

when the car is toe in. This is to be expected and proves the previous theory.

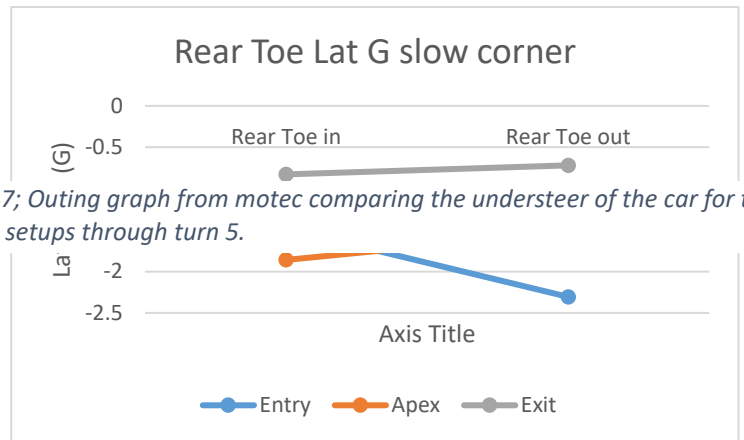


Figure 47; Outing graph from motec comparing the understeer of the car for the rear toe setups through turn 5.

Figure 49; Graph comparing the lat G for the rear toe setups through turn 2.

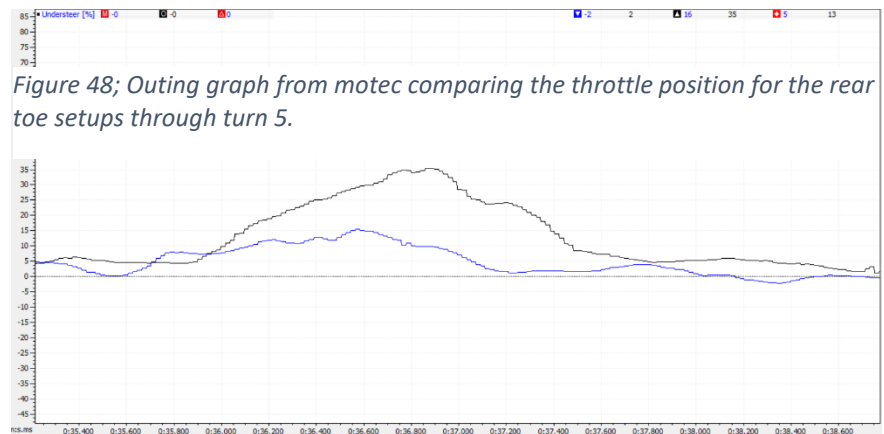
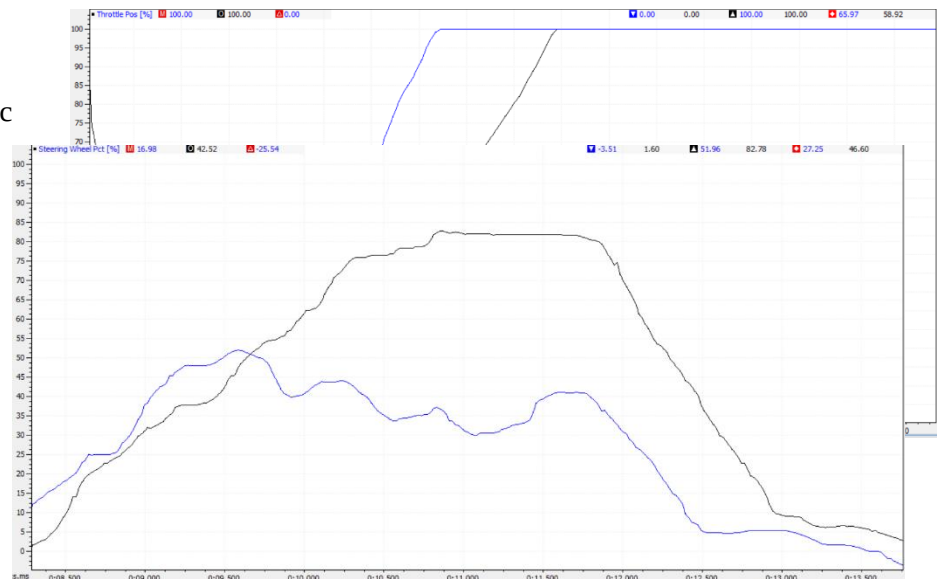


Figure 48; Outing graph from motec comparing the throttle position for the rear toe setups through turn 5.

Figure 49 is a graph comparing the lat G the car experiences through turn 2. The car experiences a large variation on entry but drops at the apex. This is due to the driver taking a different line through this corner on these two setups. The driver experiences the least amount of lat G on the exit of the corner. This is to be expected due to setups. Rear toe is used to control the cars ability to steer through a corner through the rear, or slide. When the car is toe in it will experience more oversteer, much the same how the front controls understeer. This can be seen in the graph by the small variation in lat G on exit.

Figure 50 is an outing graph from motec comparing the steering trace of the rear toe setups trough turn 2. The blue trace shows the trace for the toe out setup. The driver is having to make many corrections mid corner to counteract the 'twitchy' nature of this setup. This is also why the lat G varies more throughout the corner in the graph seen in figure 49.



4.4.2. Corner Speed.

Figure 51 is a graph comparing the corner speed of the rear toe setups through turn 5. The driver takes a lot more speed into the corner for the toe in setting. The driver then loses a lot of speed at the apex of the corner. This is due to the driver applying more steering angle and scrubbing of the speed mid corner.

Figure 52 is an outing graph from motec comparing the steering trace of the rear toe setups. This graph confirms the theory of the driver applying more steering angle as shown by the black trace. It also shows where the driver gains the speed as shown in figure 49. The driver applies steering much sooner for the toe out setting, as seen by the blue trace.

Figure 49 also shows that the driver gains speed on the exit for the toe out setting. This is to be expected because rear toe out reduces oversteer. Therefore, the driver can get onto full power sooner as seen in Figure 47

Figure 53 is a graph comparing the speed for both rear toe setups through turn 2. The graph shows that the driver takes less speed into the corner for the toe out setting but gains more on exit relative to the toe in setting.

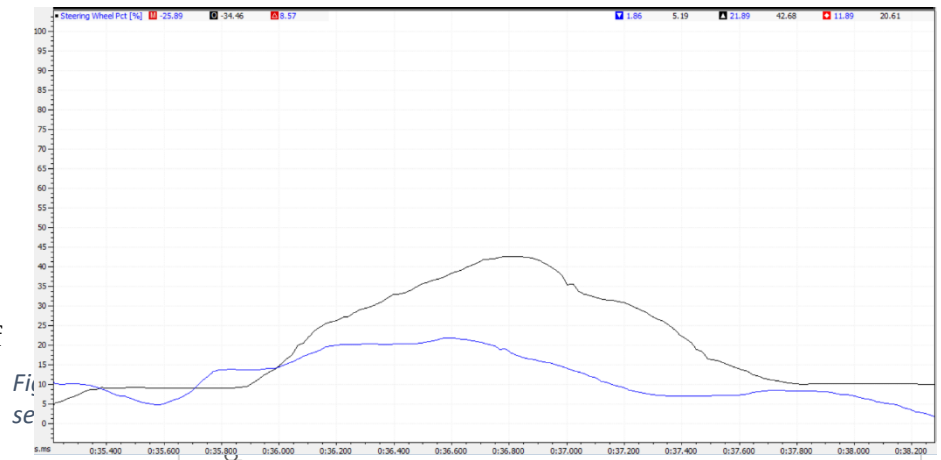


Figure 52; Outing graph from motec comparing the steering trace of the rear toe setups through turn 5.

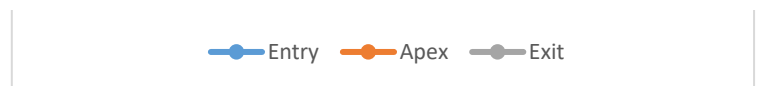


Figure 51; Graph comparing the corner speed of the rear toe setups through turn 5.

This is important to note because sometimes the highest speed is not always the fastest. It is usually better to take less speed into a corner but carry that speed through the corner and not push the car too hard through the corner. Doing this will not only affect lap times but also tire wear because the tires are not moving as much laterally which is what shreds tires during race day.

4.4.3. Load Split.

Figure 54 is a graph comparing the load split values taken for the rear toe setups through turn 5. The graph shows that almost no change in load split occurs when the car is set to toe out. This is an early indication that the toe out setting is an extremely balanced setup.

The toe in setup shows a variation in values through the corner. This is due to the struggle of the steering input seen in **Figure 52** via the blue trace. This outing graph shows the driver struggle to find the correct input for the corner. This results in the weight constantly being transferred from one side of the car to the other thus making the setup feel unbalanced. This could however be due to a lack of confidence in the setup from the driver.

Figure 55 is a graph comparing the load split values of the rear toe setups through turn 2. The toe out setting again seems to be extremely balanced with little to no change through all 3 stages of the corner.

The driver seems to struggle on the exit of the corner for the toe in setting however. **Figure 56** is an outing graph from motec comparing the understeer of the car through turn 2. The black trace, toe in, shows no sign of oversteer on the exit of the corner. This suggests that the extreme fluctuation in load split on the exit of the corner for toe in could be an error in the data.

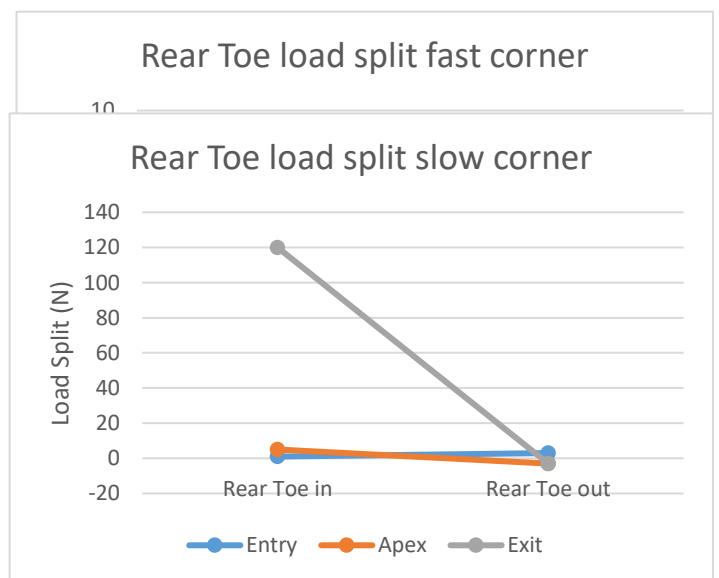


Figure 55; Graph comparing the load split for the rear toe setups through turn 2.

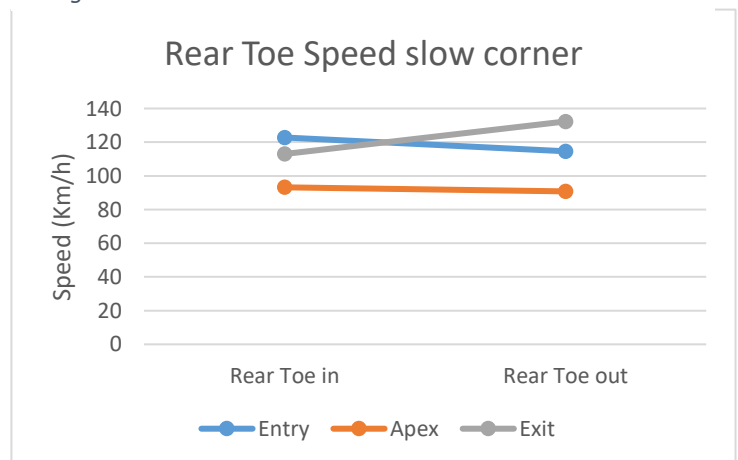


Figure 53; Graph comparing the speed of the rear toe setups through turn 2.

5. Conclusion.

Based on all the findings from the project it is possible to come to three recommendations for setups. The first setup to be recommended is the high anti-roll bar setup. On the face of it the standard setting for anti-roll bars is the most balanced through the corners. The standard setting was however the slowest setup with a time of 1;09.225, over 2 seconds slower than the higher setting with a time of 1;07.094. With more testing however, a happy medium could be found between these two setups.

The next setup to recommend is the softer spring stiffness setup. This setup is the slower setup, but it seems to be the more balanced and more forgiving setup of the two setups tested. The higher setting would be a good qualifying setup, but in many categories of racing cars enter parc ferme where no setup changes are allowed. Therefore, it is logical to choose a setup that is more forgiving and better for tire wear relative to lap time. This is the softer setting.

The front toe out setup is the next to be recommended. This is because it is the most balanced of the two setups tested. This setup also allows the driver to turn in earlier and carry more speed through corners due to there being less mechanical understeer in the car. This is especially important at Brands hatch due to the large number of fast corners this track possess.

The final setup to be recommended is the rear toe out setup. This setup has been selected for many of the same reasons as the front toe setup. It is a balanced setup and allows the driver to push the car more on the exit of corners. It is important for racing drivers to feel comfortable in the car and many racing drivers will suffer over the course of a race if the rear of the vehicle feels unstable.

The 4 setups recommended will all have to be applied to the car at the same time in the simulator to truly discover whether it can be considered as a race setup. Even if the results in the simulator are positive this does not guarantee that the car and driver will gather the same results in on track. Simulators are beautiful tools that allow us to test endless possibilities in setup throughout the course of a day. If these setups were all to be tested on

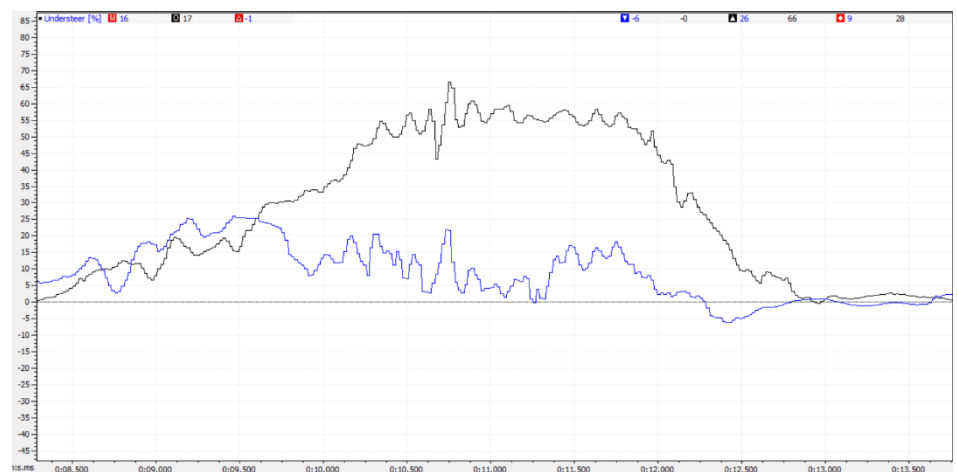


Figure 56; Outing graph from motec comparing the understeer of the car for the rear toe setups through turn 2.

track it would take days rather than hours, so it is important to condemn possible weak setups now rather than waste precious track time testing these setups.

Of course, more setup changes could have been tested. This project focused solely on suspension but GP2 cars are known for downforce. It is possible that if the front and rear wing angles were to change then the car would behave differently with these setups that have been tested. In future projects it will be the goal to test as many variations in setup as possible to gather the clearest picture of how the car is behaving.

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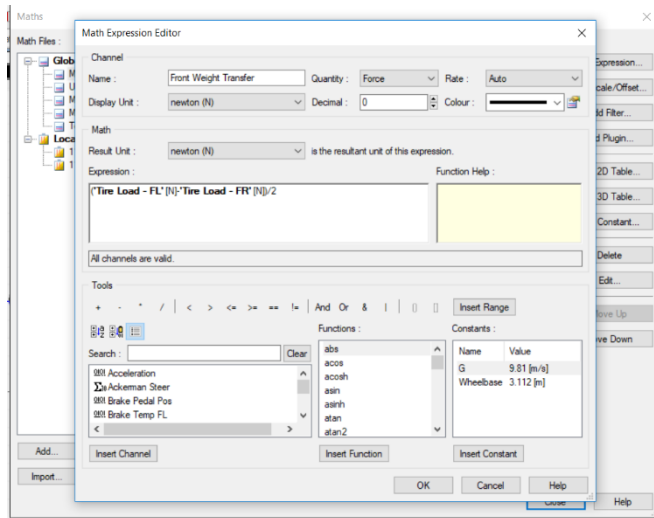


Figure 60; Front weight transfer channel

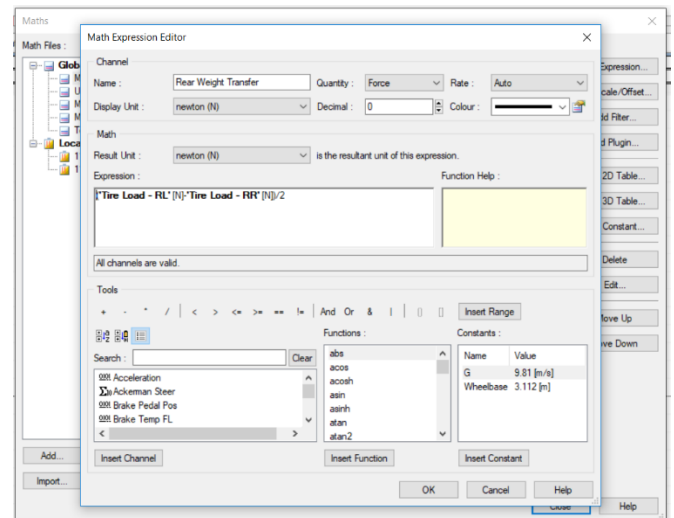


Figure 59; Rear weight transfer channel

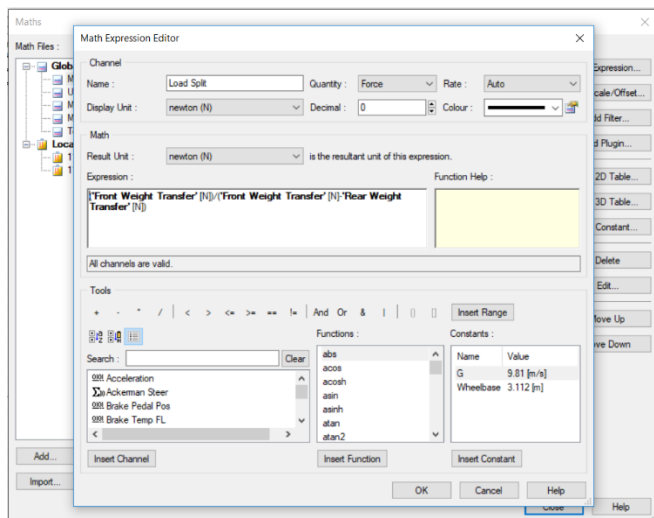


Figure 58; Load split channel

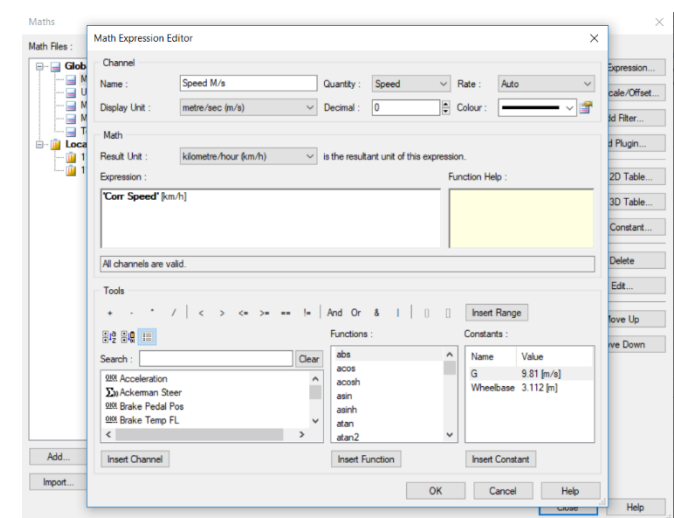


Figure 57; Speed M/s channel

7. Appendices.

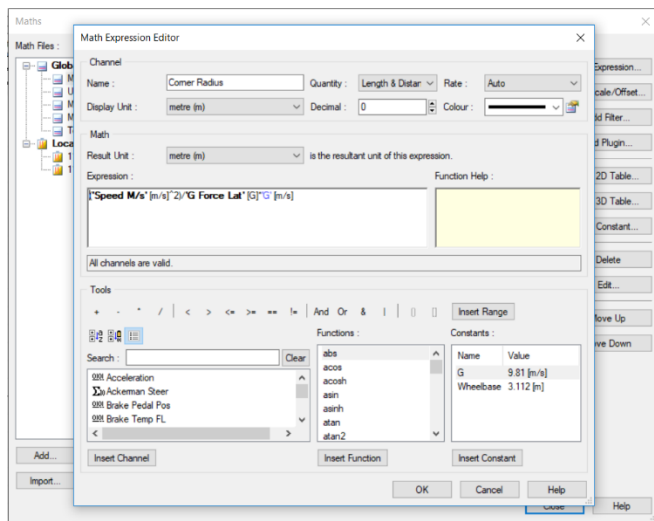


Figure 64; Corner radius channel

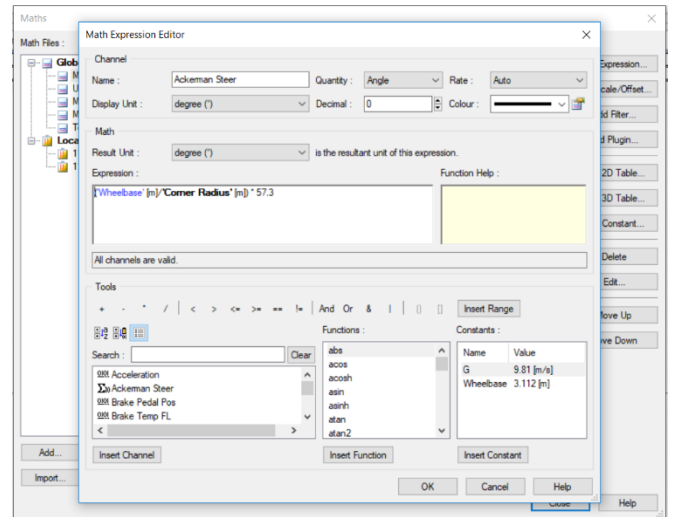


Figure 63; Ackerman steer channel

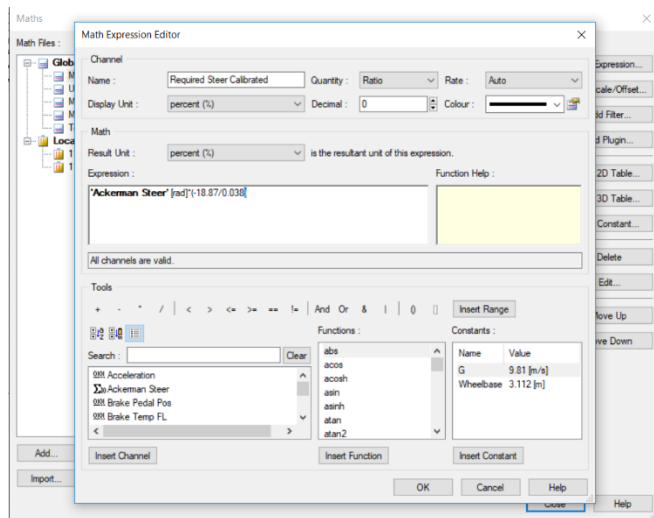


Figure 62; Required steering calibrated channel

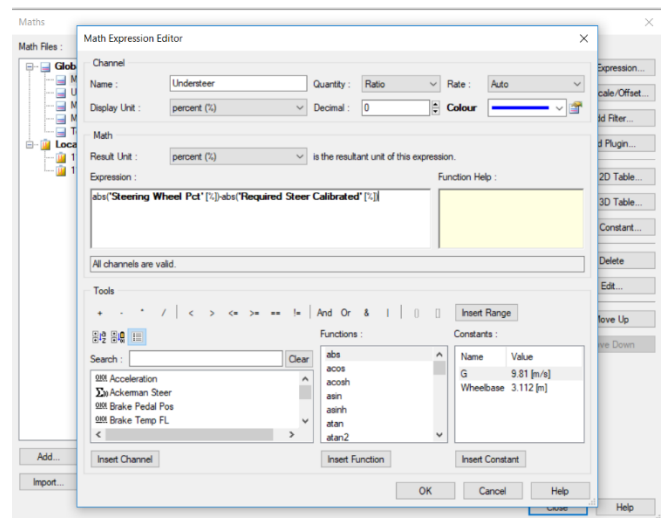


Figure 61; Understeer channel

