



University of Wales Trinity Saint David

School of Engineering

Vehicle Handling Optimisation Through Simulation

Advanced Motorsport Dynamics

ACEA7002

Christian Parry

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Abstract

This report will focus on the optimisation of a vehicle's suspension systems, using multi-body dynamics modelling software, with a view to improving the dynamic handling response of the vehicle. The amount of performance that can be gained by using data analysis is massive and in an industry such as motorsport where every inch of performance counts there is added emphasis on producing the optimum vehicle setups. Two tracks will be analysed, Llandow and Pembrey and then an optimum set-up will be outlined, which may be a compromise, but will offer the best performance across the two tracks.

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1 Introduction

1.1 Aims

The aim of this report is to determine an optimum setup, that offers the most competitive lap time around two tracks, Pembrey and Llandow. Due to the setup being used for both tracks compromises will have to be made, such that a setup offering max performance at one track may not be used due to its unsuitability for the other track, and vice versa. The report will take into account the effects changing the spring rate, damping rate, and anti-roll bar rates has on the lap time of a race car around the two tracks. The simulation will be undertaken using VI Grade which is an industry standard simulation software used by automotive companies and race teams worldwide (VI Grade, 2022).

1.2 Objectives

The main objectives of the report are:

- Complete background research to inform the testing process
- Setup Investigations within VI Grade to analyse the effects of adjusting the following variables:
 - Spring rate
 - Damper rate
 - Anti-Roll Bar rate
- The optimum setup will then be reviewed to analyse the effectiveness of the setup across both tracks.
- The project will then be concluded reviewing the methodology and results achieved to determine whether things could be improved.

2 Background Research

2.1 Spring-Mass-Damper Systems

The spring-mass-damper system is the first principle regarding suspension design/tuning. The single degree of freedom model can be seen in Figure 1.

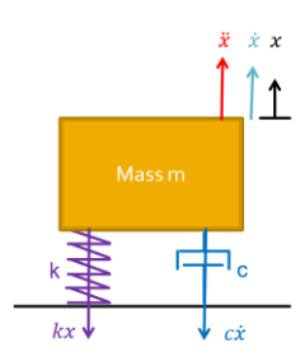


Figure 1 – Single Degree of Freedom SMD model

The derivation for the equation relating to the single degree of freedom spring-mass-damper model can be seen below:

Spring Rate = $K = N/m$

Damping Rate = $C = N/m/s$

Displacement of the Mass = $x = m$

Force = Mass $\times$ Acceleration

So

Spring Force (F_s) is dependent on masses displacement = x

$F_s = Kx$

Damper Force (F_d) is dependent on masses velocity = $\dot{x}$

$F_d = C\dot{x}$

Springs and Dampers create a resistant force:

$F_a = ma$, therefore the equation is $M\ddot{x} = -C\dot{x} - Kx$, or

$C\dot{x} + Kx = -M\ddot{x}$

Analysing this model in relation to vehicle suspension shows that disturbances applied to the mass (vehicle) can be controlled via adjusting the spring rate (k) and damping rate (c). The spring-mass-damper model can be used for every component within a vehicles suspension to dictate its compliance within a system, resulting in basic full vehicle models featuring over 7 degrees of freedom. Such as the 9 degree of freedom model created by Wade Smith, seen in Figure 2. Featuring spring-mass-damper systems for all four corners of the vehicle, taking into account the suspension, tyres, pitch, roll, heave and yaw of the vehicle.

An example of the three different damping characteristics can be seen in Figure 3.

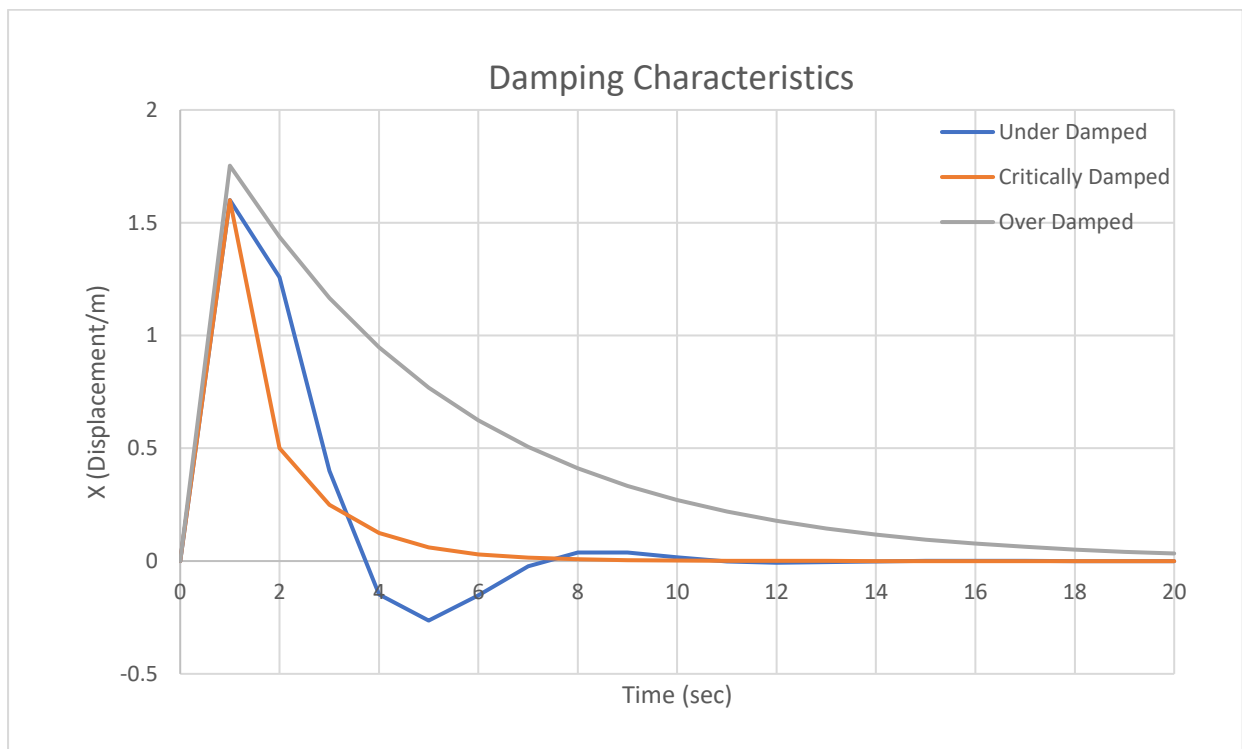


Figure 3 – Damping Characteristics Graph

2.2 Handling Models

2.2.1 Lumped Mass

Advancing from the Spring-Mass-Damper models, lumped mass vehicle models can be produced which outlines the mass of every component within a vehicle to determine its vehicle performance.

An example of a lumped mass model created by the author based on one retrieved from (Mitostile Prototipo, 2022) can be seen Table 2.

Ferrari FF Inertia Calculator

Components	Mass (kg)	Center of gravity (m)			mixi	miyi	mizi	Xi	Yi	Zi	Ixx	Iyy	Izz	Ixz
		xi	yi	zi										
Chassis	500	-0.20	0.00	0.50	-100.0	0	250	-1.85	0.00	0.04	0.849	1708.633	1707.785	-38.076
Chassis	500	3.25	0.00	0.50	1625.0	0	250	1.60	0.00	0.04	0.849	1283.949	1283.000	33.002
Engine Front	160	-0.10	0.00	0.45	-16.0	0	72	-1.75	0.00	-0.01	0.012	488.963	488.951	2.460
Engine Rear	130	0.92	0.00	0.45	120.0	0	58.5	-0.73	0.00	-0.01	0.010	68.365	68.355	0.829
Transaxle	100	3.10	0.00	0.35	310.0	0	35	1.45	0.00	-0.11	1.184	211.978	210.794	-15.796
Bellhousing	20	1.08	0.00	0.35	21.5	0	7	-0.57	0.00	-0.11	0.237	6.754	6.517	1.242
Driver	100	1.78	-0.38	0.49	178.1	-38	49	0.13	-0.38	0.03	14.537	1.858	16.200	0.414
Front Right passenger	100	1.78	0.38	0.49	178.1	38	49	0.13	0.38	0.03	14.537	1.858	16.200	0.414
Rear left passenger	100	2.60	-0.38	0.51	260.0	-38	51	0.95	-0.38	0.05	14.702	90.869	105.046	4.874
Rear right passenger	100	2.60	0.38	0.51	260.0	38	51	0.95	0.38	0.05	14.702	90.869	105.046	4.874
Tank	120	2.70	0.00	0.40	324.5	0	48	1.06	0.00	-0.06	0.415	134.246	133.832	-7.451
Propshaft front	10	1.82	0.00	0.35	18.2	0	3.5	0.18	0.00	-0.11	0.118	0.430	0.312	-0.192
Propshaft Rear	10	2.24	0.00	0.35	22.4	0	3.5	0.59	0.00	-0.11	0.118	3.651	3.533	-0.647
Driver seat	30	1.78	-0.38	0.49	53.4	-11.4	14.7	0.13	-0.38	0.03	4.361	0.557	4.860	0.124
Front right passenger seat	30	1.78	0.38	0.49	53.4	11.4	14.7	0.13	0.38	0.03	4.361	0.557	4.860	0.124
Rear seats	35	2.55	0.00	0.52	89.3	0	18.2	0.90	0.00	0.06	0.131	28.618	28.486	1.933
TOTAL SUSPENDED MASS	2045													
FL Wheel	45	0.00	-0.78	0.25	0	-34.95375	11.43	-1.65	-0.78	-0.20			149.385	
FR Wheel	45	0.00	0.78	0.25	0	34.95375	11.43	-1.65	0.78	-0.20			149.385	
RL Wheel	45	2.99	-0.76	0.25	134.55	-34.03125	11.43	1.34	-0.76	-0.20			106.764	
RR Wheel	45	2.99	0.76	0.25	134.55	34.03125	11.43	1.34	0.76	-0.20			106.764	
TOTAL NON SUSPENDED MASS	180													
TOTAL	2225				3667	0	1021				71	4122	4696	-12

Center of gravity coordinates			v1	v2	m	M	Ix (kg.m²)	Iy (kg.m²)	Iz (kg.m²)	Ixz (kg.m²)	L (m)	a (m)	b (m)	h (m)
xg (m)	yg (m)	zg (m)	0.838	0.83	2045	2225	71.125	4122.056	4696.077	-11.870	2.99	1.648	1.342	0.46
1.65	0.00	0.46	Half-track (m)		Susp Mass. (kg)	Total Mass (kg)	Inertia				Wheelbase		CG height	

Table 2 – Lumped Mass Car Model/Inertia Calculator

With all the masses and inertias calculated, the dynamic index of the vehicle can be calculated which determines what the characteristic of the vehicle is in terms of understeer/oversteer. This is written about in one form or another by all of the key vehicle dynamics authors, featuring in,

- Carrol Smith: Tune to win (Smith C. , 1978)
- Race Car Vehicle Dynamics (William F. Milliken, 1995)
- Fundamentals of Vehicle Dynamics (Gillespie, 1992)

The dynamic index equation can be seen in Equation 1.

$$\text{Dynamic Index} = \frac{I_{zz}}{m \cdot a \cdot b}$$

Equation 1 – Dynamic Index Equation

If $DI < 1$ then $c < b$. This means the inertial conjugate is ahead of the rear axle, which causes the rear of the car to move outwards; inertial effects add to rear tyre slip angle, causing the car to rotate more readily, giving agile turn in. If DI is significantly less than 1 then it can result in a very snappy oversteer prone car that requires lots of driver input.

If $DI > 1$ then $c > b$. This means the inertial conjugate is behind the rear axle, which causes the rear of the car to move inwards; inertial effects reduce rear tyre slip angle. This causes the car to have sluggish response, making it reluctant to rotate, alternatively it creates a stable platform with a more understeer prone characteristic.

2.2.2 Multi-Body

The multi-body vehicle modelling utilised by VI grade is based on the software ADAMS Car produced by MSC Software (MSC Software, 2022) (VI Grade, 2022). This allows every component to be modelled and placed within the suspension system whereby the flex and compliance of the component will be taken into account in the model. This gives the most realistic simulations possible when analysing a vehicles performance, with companies such as Bugatti using it to cut down prototyping times,

“Adams Car was instrumental to tune all the subsystems at their best before any real prototype was available... Testing several configurations on the virtual prototype required a matter of hours; doing the same on the real prototype would have been impossible” – Dr. Peter Tutzer, Bugatti

An example of how in-depth the analysis of the simulation can be is seen in Figure 4, which shows the stresses applied to the A-arm under suspension compression. This amount of in-depth data can help guide a motorsport/automotive company in the direction they need to be heading in, regarding optimisation of the components and of the vehicle as a whole.

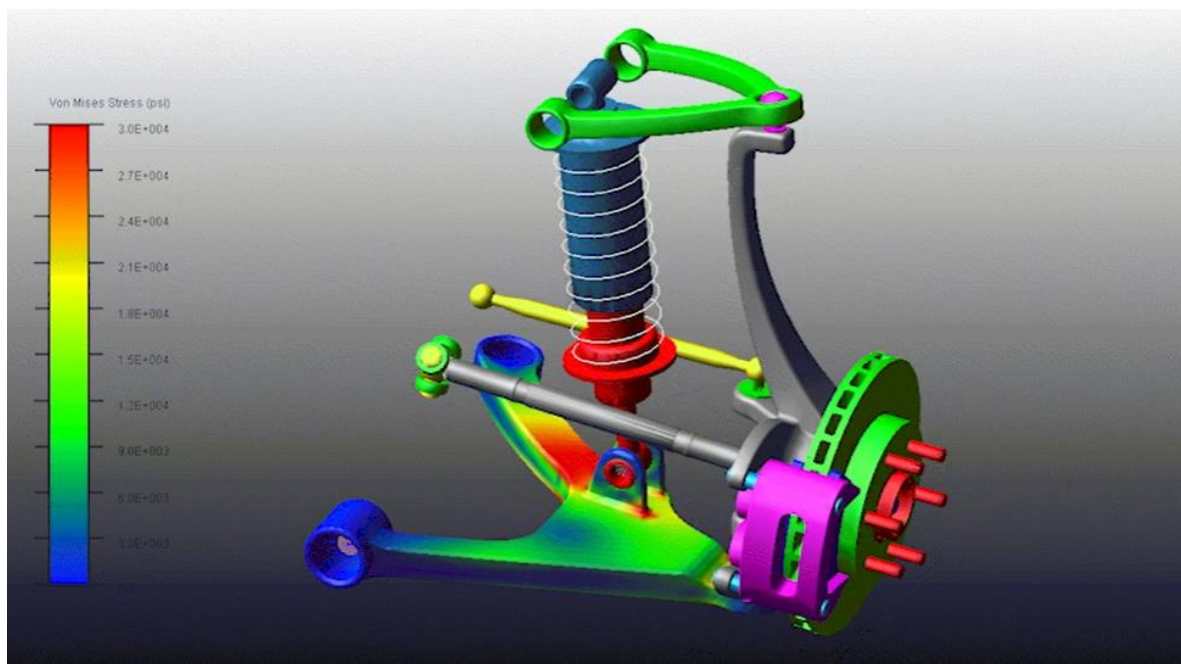


Figure 4 – ADAMS Car Multi-body Simulation (MSC Software, 2022)

2.3 Design of Experiments

When looking at all the parameters to change when undertaking this report, it was apparent that there would be 1000s of potential combinations, therefore design of experiments becomes important to cut down on simulation time. Examples of different design of experiments that could be utilised can be seen in Figure 5.

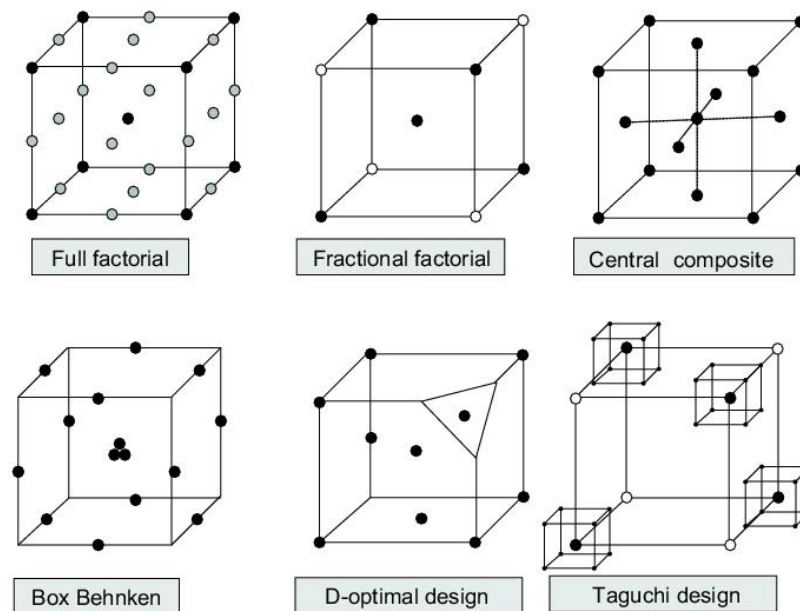


Figure 5 – Different Design of Experiment Methodologies (Veldhuis, 2016)

As can be seen the full factorial design of experiment method analyses every single variable possible, whilst the other methods reduce the amounts of variables tested to try to cut-down simulation times. The design of experiment methodology utilised in this project will be central composite due to its more structured approach to testing. This is supported by the findings of (Rakic, 2014) who found it offered them the best results compared to the other design of experiment methods.

The other testing methodologies are:

- Box Behnken – Independent quadratic design for three factors (Engineering Statistics Handbook, 2022)
- D-Optimal – Generated using an iterative search algorithm (MathWorks, 2022)
- Taguchi Design – Identifies the minimum number of variables that need to be tested (Investopedia, 2021)

These have not been used due to their complexity in comparison to the central composite design.

2.4 Pembrey

Pembrey circuit is a one-and-a-half-mile circuit built in 1989 located near Llanelli, South Wales, officially titled the Welsh Motorsports Centre. During its history it has featured many famous drivers from numerous race categories, with Ayrton senna setting the unofficial lap record of 44.43 in a test session with McLaren Formula 1 team (Evans, 2020). The track, which can be seen in Figure 6 features eight corners with the track run in the clockwise direction featuring six right turns and two left turns. It consists of two low speed corners, one and six, and two high speed corners seven and eight. Turns three and four merge into one to create a long-left hander where the car becomes loaded up and almost steady state mid corner.

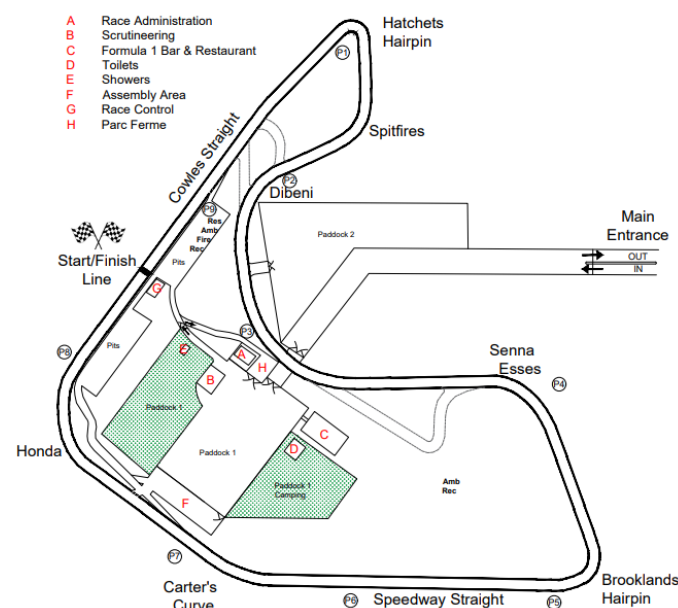


Figure 6 – Pembrey Circuit Track Map (Pembrey Circuit, 2022)

2.5 Llandow

Llandow is a short one-mile circuit which was built in the 1960's located near Cardiff, South Wales. The track is mainly used as a testing venue and for track days/commercial events. The track which can be seen in Figure 7 features twelve corners with the track run in the clockwise direction featuring nine right corners and three left corners. The track is made up of three very fast right handers and two tight chicanes so the car must be agile whilst going through the bus stop chicane and Jack's curve but also stable around the high-speed corners like Nook bend and Glue-pot.

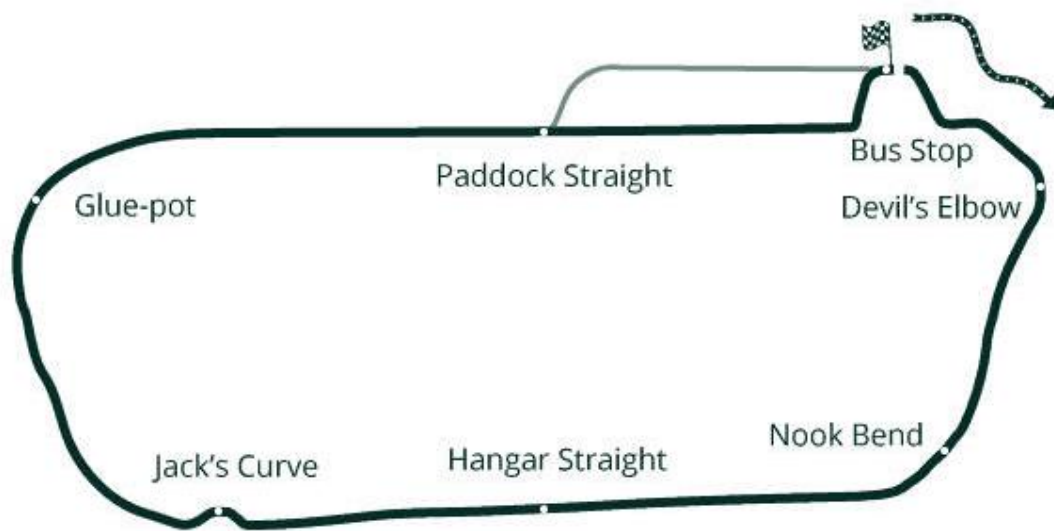


Figure 7 – Llandow Track Map (Lotus on Track, 2022)

3 Methodology

When undertaking these simulations, the laps were completed on the max performance setting, from a standing start, with the following functions selected:

- Use road data in predictor
- Tire limits in predictor
- Use suspension data

The max allowable path distance was kept at 1500, as well as the longitudinal/braking/lateral performance factors being left at 1.

3.1 Spring Rate

The first thing that was changed before testing the car on the track was to set the front and rear suspension so they were the same, that would then make it very clear whether the back or the front had to be stiffer/softer in relation to each other. The spring graph settings can be seen in Figure 8, it was changed from what was originally on the car to be a perfect linear spring rate.

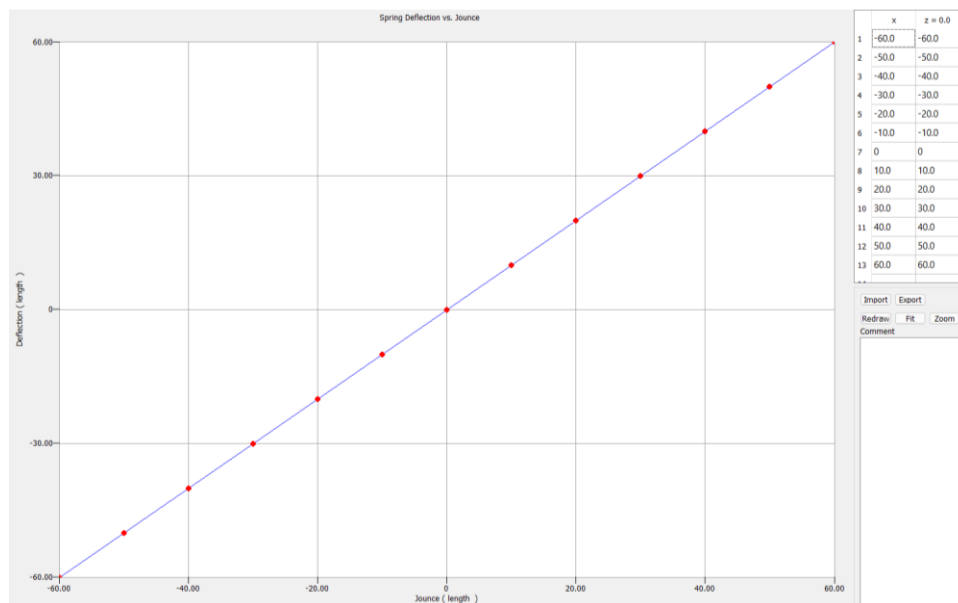


Figure 8 – Base Spring Graph Settings for Both Front and Rear for Both Tracks

To reduce the number of simulations that were required to be run, the plan was to test the springs in four variables, like the central composition design experiment:

- Front kept at base setup and test Rear scale function from 0.5-1.5
- Rear kept at base setup and test Front scale function from 0.5-1.5
- Scale both Front and Rear together 0.5-1.5

- Alternate setup, opposite Front and Back values, starting with Front 0.5, Rear 1.5

The scale function was to be utilised with 0.5 being softer and 1.5 stiffer, due to the speed at which the variable could be changed. This means the base setup occurs at 1, with the ability to soften or stiffen the suspension by 50%.

This meant that the following setups had been tested, as seen in Table 3

		Pembrey										
		Rear										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front	0.5	57.091					56.941					57.331
	0.6		57.071				56.861				57.241	
	0.7			57.051			56.811			57.181		
	0.8				56.871		57.051		56.831			
	0.9					56.871	57.061	57.041				
	1	57.201	57.111	57.061	56.881	56.991	56.831	57.031	56.831	56.801	57.011	57.011
	1.1					56.871	56.871	56.831				
	1.2				56.941		56.851		56.831			
	1.3			57.121			57.011			56.821		
	1.4		57.191				57.001				57.031	
	1.5	57.331					57.001					56.941

Table 3 – First Test results (spring stiffness scale)

As can be seen in Table 3 **Error! Reference source not found.**, the best lap times seem to occur with a slightly stiffer setup. The benchmark time of 56.831 seconds could be improved to 56.801 by adjusting the spring settings.

However due to using the design of experiment approach it wasn't clear which setup would be optimal and if there were any potentially faster setups that had not been tested. Therefore, the author thought that for the purpose of this report it would be beneficial to test every variable, to give a complete overview of the vehicle's setup.

That resulted in the following two completed tables outlining the optimum setups for both Pembrey and Llandow.

		Pembrey										
		Rear Spring										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Spring	0.5	57.091	57.061	56.901	56.911	57.041	56.941	57.181	57.171	57.161	57.261	57.331
	0.6	56.981	57.071	56.901	56.901	57.111	56.861	56.851	56.871	57.201	57.241	56.951
	0.7	57.011	56.961	57.051	57.001	57.081	56.811	57.051	57.051	57.181	57.081	57.071
	0.8	57.161	56.951	57.001	56.871	56.861	57.051	56.831	56.831	57.021	57.041	57.171
	0.9	57.071	57.101	56.911	56.871	56.871	57.061	57.041	56.821	56.931	57.021	56.821
	1	57.201	57.111	57.061	56.881	56.991	56.831	57.031	56.831	56.801	57.011	57.011
	1.1	57.231	57.121	56.941	57.021	56.871	56.871	56.831	56.841	56.821	56.771	57.001
	1.2	57.251	57.151	57.111	56.941	56.861	56.851	56.861	56.831	56.811	56.921	56.891
	1.3	57.271	57.171	57.121	57.041	56.991	57.011	56.851	56.981	56.821	56.791	56.921
	1.4	57.281	57.191	57.141	57.071	57.061	57.001	56.871	56.861	57.041	57.031	57.001
	1.5	57.331	57.211	57.151	57.101	56.991	57.001	57.011	56.851	56.861	56.801	56.941

Table 4 – Pembrey Spring Rate Setup

		Llandow										
		Rear Spring										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Spring	0.5	38.941	38.971	39.241	39.281	39.361	39.411	39.451	39.551	39.651	39.721	39.781
	0.6	38.931	39.061	39.041	39.091	39.191	39.291	39.331	39.441	39.451	39.541	39.651
	0.7	38.901	38.941	38.961	38.981	39.121	39.211	39.161	39.331	39.351	39.461	39.461
	0.8	38.911	38.911	38.971	38.941	39.021	39.181	39.101	39.271	39.301	39.351	39.361
	0.9	39.031	38.901	38.971	38.941	38.951	38.981	39.181	39.161	39.231	39.271	39.321
	1	39.041	39.051	38.911	38.911	38.941	38.961	39.061	39.191	39.231	39.211	39.251
	1.1	39.051	39.031	38.961	38.921	38.961	38.931	39.041	39.091	39.081	39.221	39.161
	1.2	39.061	39.041	38.961	38.901	38.961	38.941	38.951	39.051	39.171	39.111	39.221
	1.3	39.081	39.051	39.101	38.901	38.961	39.011	38.941	38.991	39.041	39.191	39.071
	1.4	39.081	39.061	39.091	38.901	38.951	38.941	38.931	38.981	38.961	39.131	39.091
	1.5	39.091	39.061	39.101	38.931	38.951	38.911	38.921	38.971	38.951	39.081	38.971

Table 5 – Llandow Spring Rate Setup

The fastest lap time achieved at Pembrey is 56.771 seconds, which would have been missed by not testing every variable, an improvement of 0.06 seconds over the base setup seen in blue. This was achieved by the setup with the Front = 1.3, Rear = 1.4 showing that Pembrey requires a stiffer car to deal with the braking zones into the tight hairpins.

The fastest lap time achieved at Llandow is 38.901, an improvement of 0.06 seconds over the base setup. However, unlike the Pembrey setup which required a stiffer front and rear, for Llandow a softer front and rear is optimal.

Due to this difference in optimal setups between the two tracks another table was produced, as seen in Table 6 , adding the two lap times together and dividing by two to provide the average lap time between the two tracks, and therefore identifying which setup gave the best performance across both tracks.

		Average Times for Both Tracks										
		Rear Spring										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Spring	0.5	48.016	48.016	48.071	48.096	48.201	48.176	48.316	48.361	48.406	48.491	48.556
	0.6	47.956	48.066	47.971	47.996	48.151	48.076	48.091	48.156	48.326	48.391	48.301
	0.7	47.956	47.951	48.006	47.991	48.101	48.011	48.106	48.191	48.266	48.271	48.266
	0.8	48.036	47.931	47.986	47.906	47.941	48.116	47.966	48.051	48.161	48.196	48.266
	0.9	48.051	48.001	47.941	47.906	47.911	48.021	48.111	47.991	48.081	48.146	48.071
	1	48.121	48.081	47.986	47.896	47.966	47.896	48.046	48.011	48.016	48.111	48.131
	1.1	48.141	48.076	47.951	47.971	47.916	47.901	47.936	47.966	47.951	47.996	48.081
	1.2	48.156	48.096	48.036	47.921	47.911	47.896	47.906	47.941	47.991	48.016	48.056
	1.3	48.176	48.111	48.111	47.971	47.976	48.011	47.896	47.986	47.931	47.991	47.996
	1.4	48.181	48.126	48.116	47.986	48.006	47.971	47.901	47.921	48.001	48.081	48.046
	1.5	48.211	48.136	48.126	48.016	47.971	47.956	47.966	47.911	47.906	47.941	47.956

Table 6 – Average Lap Time Across Both Tracks (Spring Setup)

Having worked out the average across the two tracks there are three setups which offer the fastest time of 47.896 seconds across both tracks:

- Front 1 Rear 1 (Base Setup)

- Front 1.2 Rear 1
- Front 1.3 Rear 1.1

Due to these findings, it was decided that going forward the Front 1.3, Rear 1.1 spring setup would be used due to the setups around it having faster times than the times surrounding the other two setups. Therefore, the spring rates are 10% stiffer on the rear and 30% stiffer on the front, this setup change will increase the response of the vehicle making it more agile, resulting in quicker direction change (Smith C. , Drive to Win, 1996), perfect for the chicanes on Llandow.

3.2 Damper Rate

The same methodology as the spring setup investigation was used with the damper rate scale being tested from 0.5 to 1.5 for front and rear damper rate. The damper rates were left unchanged so there was a slightly different damper rate between front and rear to begin with, with the damper velocities for front and rear seen in Figure 9 and Figure 10 respectively.

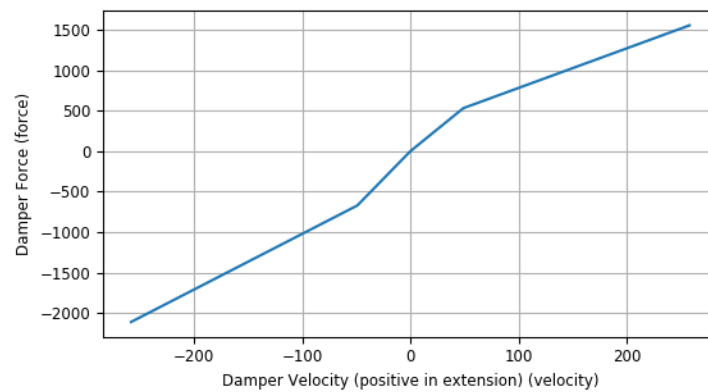


Figure 9 – Front Damper Velocity Graph

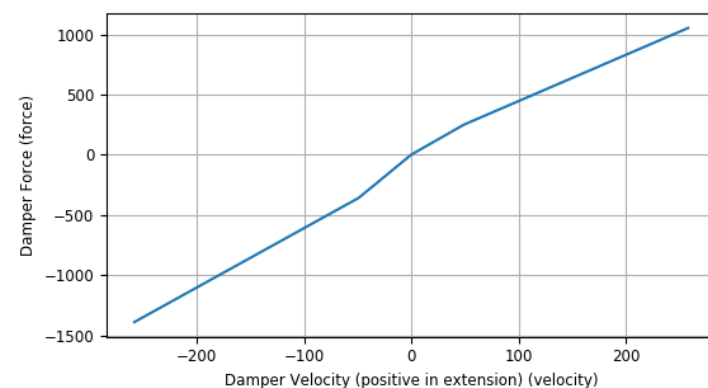


Figure 10 – Rear Damper Velocity Graph

The lap times for Pembrey can be seen in Table 7, the fastest time was 56.801, offering a 0.03 second performance increase over the base damper setup, this was achieved with a much softer setup than the base setup.

		Pembrey										
		Rear Damper										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Damper	0.5	56.801	56.821	56.821	56.841	56.841	56.841	56.841	56.841	56.841	56.841	56.841
	0.6	56.801	56.821	56.821	56.841	56.841	56.841	56.841	56.841	56.841	56.841	56.851
	0.7	56.801	56.801	56.821	56.821	56.841	56.841	56.841	56.841	56.841	56.841	56.841
	0.8	56.801	56.801	56.821	56.821	56.841	56.841	56.841	56.841	56.841	56.841	56.841
	0.9	56.801	56.801	56.821	56.841	56.841	56.831	56.841	56.841	56.841	56.841	56.841
	1	56.821	56.801	56.821	56.821	56.841	56.831	56.841	56.841	56.841	56.841	56.841
	1.1	56.821	56.801	56.821	56.851	56.831	56.831	56.841	56.841	56.841	56.841	56.841
	1.2	56.821	56.801	56.821	56.841	56.841	56.841	56.841	56.841	56.841	56.841	56.841
	1.3	56.801	56.821	56.821	56.841	56.851	56.831	56.831	56.841	56.841	56.841	56.841
	1.4	56.821	56.821	56.821	56.841	56.851	56.831	56.831	56.841	56.841	56.841	56.841
	1.5	56.801	56.821	56.821	56.841	56.851	56.831	56.831	56.841	56.841	56.841	56.841

Table 7 – Pembrey Damper Rate Setup

The lap times for Llandow can be seen in Table 8, the fastest time was 38.941, offering a 0.02 second increase over the base setup, this was achieved by a 50% softer front damper and a 20% stiffer rear damper. This setup suggests that the car was suffering slightly with front end grip issues as by reducing low speed damping you can target understeer (Zuijdijk, 2011).

		Llandow										
		Rear Damper										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Damper	0.5	38.981	38.971	38.961	38.961	38.961	38.961	38.951	38.941	38.951	38.951	38.951
	0.6	38.991	38.961	38.961	38.961	38.961	38.961	38.951	38.951	38.951	38.961	38.951
	0.7	38.981	38.971	38.961	38.961	38.961	38.961	38.951	38.951	38.961	38.951	38.951
	0.8	38.981	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.961	38.951	38.961
	0.9	38.981	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.951	38.961	38.951
	1	38.981	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.951	38.961	38.951
	1.1	38.981	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.951	38.961	38.951
	1.2	38.971	38.971	38.971	38.961	38.961	38.961	38.951	38.961	38.951	38.961	38.951
	1.3	38.981	38.971	38.971	38.961	38.961	38.961	38.961	38.951	38.951	38.961	38.951
	1.4	38.981	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.961	38.961	38.951
	1.5	38.971	38.971	38.971	38.961	38.961	38.961	38.951	38.951	38.961	38.961	38.961

Table 8 – Llandow Damper Rate Setup

The average lap times can be seen in Table 9, showing that the optimum damper setup for both tracks is 30% softer on the front and 40% softer on the rear, this setup is a compromise as it increases the lap time at Llandow slightly to get the bigger performance difference at Pembrey. By ending up with a setup reducing damper force front and rear it is likely the model was suffering with grip issues at the front when cornering, and potentially power down issues when exiting corners, by making front and rear damping softer it has improved grip and improved lap time (Racecar Engineering, 2022).

		Average Times for Both Tracks											
		Rear Damper											
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	
Front Damper	0.5	47.891	47.896	47.891	47.901	47.901	47.901	47.896	47.891	47.896	47.896	47.896	
	0.6	47.896	47.891	47.891	47.901	47.901	47.901	47.896	47.896	47.896	47.901	47.901	
	0.7	47.891	47.886	47.891	47.891	47.901	47.901	47.896	47.896	47.901	47.896	47.896	
	0.8	47.891	47.886	47.896	47.891	47.901	47.901	47.896	47.896	47.901	47.896	47.901	
	0.9	47.891	47.886	47.896	47.901	47.901	47.896	47.896	47.896	47.896	47.901	47.896	
	1	47.901	47.886	47.896	47.891	47.901	47.896	47.896	47.896	47.896	47.901	47.896	
	1.1	47.901	47.886	47.896	47.906	47.896	47.896	47.896	47.896	47.896	47.901	47.896	
	1.2	47.896	47.886	47.896	47.901	47.901	47.901	47.896	47.901	47.896	47.901	47.896	
	1.3	47.891	47.896	47.896	47.901	47.906	47.896	47.896	47.896	47.896	47.901	47.896	
	1.4	47.901	47.896	47.896	47.901	47.906	47.896	47.891	47.896	47.901	47.901	47.896	
	1.5	47.886	47.896	47.896	47.901	47.906	47.896	47.891	47.896	47.901	47.901	47.901	

Table 9 – Average Lap Time Across Both Tracks (Damper Setup)

3.3 Anti-Roll Bar Rate

The Anti-Roll Bar (ARB) Rates were next to be investigated, with the base setup left alone and just the scale factors adjusted. The base ARB values are 42.6 for the front and 33.3 for the rear.

The lap times for Pembrey can be seen in Table 10, with the best lap time being 56.761 a 0.04 second improvement over the base setup, achieved by a 10% increase in stiffness on the front and a 50% increase on the rear, this setup is aiming at improving the agility of the vehicle as a whole, aiming to make the car want to rotate more in corners. The area of the track this is targeting is turn one and six, Hatchets hairpin and Brooklands hairpin, where the rotation of the car is vital in affecting the corner exits, and consequently the straight-line speeds after (Smith C. , Engineer in Your Pocket: A Practical Guide to Tuning the Race Car Chassis and Suspension, 1998).

		Pembrey											
		Rear Anti-Roll Bar											
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	
Front Anti-Roll Bar	0.5	56.941	56.821	56.841	56.831	56.801	56.811	56.981	56.811	57.021	57.021	56.951	
	0.6	56.921	56.871	56.971	56.941	57.031	56.921	56.771	56.991	56.811	57.161	56.841	
	0.7	56.871	56.911	56.831	56.821	56.821	56.801	57.141	56.791	57.011	57.021	57.011	
	0.8	56.951	56.971	56.811	56.831	56.801	56.831	56.771	57.031	57.001	56.801	57.031	
	0.9	56.941	56.851	56.881	56.841	56.941	56.801	57.031	56.921	56.791	57.001	56.811	
	1	56.881	56.871	56.911	56.831	56.841	56.801	56.791	56.801	57.011	56.791	57.011	
	1.1	56.981	56.991	56.971	56.951	56.831	56.961	57.141	56.831	56.771	57.021	56.761	
	1.2	57.061	56.931	56.871	56.911	56.801	56.851	56.781	56.811	57.031	56.791	56.981	
	1.3	57.021	56.951	56.991	56.971	56.971	56.821	56.841	56.791	56.811	56.771	56.801	
	1.4	57.051	57.031	56.961	56.861	56.901	56.801	56.831	56.801	56.801	57.041	56.791	
	1.5	57.071	57.051	57.001	57.011	56.921	56.981	56.951	56.961	56.801	56.811	57.021	

Table 10 – Pembrey Anti-Roll Bar Rate Setup

The lap times for Llandow can be seen in Table 11, with the best lap time being 38.931 a 0.04 second improvement over the base setup. This was achieved by a 40% increase in front stiffness and a 20% decrease in rear stiffness. This setup is targeting two areas of the track, the massive increase in front ARB stiffness is targeting the sloppiness/slow response of the vehicle through the

chicanes on Llandow, and the decrease in rear ARB stiffness is targeting oversteer on corner exits (Racecar Engineering, 2022).

		Llandow										
		Rear										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Anti-Roll Bar	0.5	38.971	38.971	38.961	38.991	39.201	39.201	39.241	39.191	39.201	39.211	39.281
	0.6	38.941	38.951	38.961	39.061	38.981	39.191	39.061	39.121	39.191	39.211	39.231
	0.7	38.961	38.971	38.951	38.961	38.991	39.191	39.181	39.211	39.231	39.181	39.201
	0.8	39.051	38.941	38.971	38.971	39.041	38.991	39.181	39.171	39.201	39.171	39.181
	0.9	38.951	38.941	38.961	38.941	38.971	39.051	39.181	39.181	39.171	39.211	39.081
	1	38.941	39.051	38.941	38.981	38.961	38.971	39.041	39.181	39.071	39.141	39.061
	1.1	38.941	38.951	38.941	38.961	38.951	38.951	39.051	39.071	39.061	39.081	39.191
	1.2	38.961	38.961	38.941	38.941	38.961	38.951	38.961	38.981	39.041	39.091	39.181
	1.3	38.951	38.951	38.941	38.941	38.961	38.961	38.951	39.041	38.981	39.071	39.171
	1.4	38.971	38.941	39.071	38.931	38.941	38.971	38.951	38.961	39.041	38.981	39.071
	1.5	39.071	38.951	38.941	38.961	38.941	38.961	38.941	38.971	39.031	38.971	39.061

Table 11 – Llandow Anti-Roll Bar Rate Setup

The average lap times can be seen in Table 12, showing that the optimum ARB setup for both tracks being a 20% increase in front ARB stiffness and a 10% increase in rear ARB stiffness, creating a more agile car.

		Average Times for Both Tracks										
		Rear Anti-Roll Bar										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Anti-Roll Bar	0.5	47.956	47.896	47.901	47.911	48.001	48.006	48.111	48.001	48.111	48.116	48.116
	0.6	47.931	47.911	47.966	48.001	48.006	48.056	47.916	48.056	48.001	48.186	48.036
	0.7	47.916	47.941	47.891	47.891	47.906	47.996	48.161	48.001	48.121	48.101	48.106
	0.8	48.001	47.956	47.891	47.901	47.921	47.911	47.976	48.101	48.101	47.986	48.106
	0.9	47.946	47.896	47.921	47.891	47.956	47.926	48.106	48.051	47.981	48.106	47.946
	1	47.911	47.961	47.926	47.906	47.901	47.886	47.916	47.991	48.041	47.966	48.036
	1.1	47.961	47.971	47.956	47.956	47.891	47.956	48.096	47.951	47.916	48.051	47.976
	1.2	48.011	47.946	47.906	47.926	47.881	47.901	47.871	47.896	48.036	47.941	48.081
	1.3	47.986	47.951	47.966	47.956	47.966	47.891	47.896	47.916	47.896	47.921	47.986
	1.4	48.011	47.986	48.016	47.896	47.921	47.886	47.891	47.881	47.921	48.011	47.931
	1.5	48.071	48.001	47.971	47.986	47.931	47.971	47.946	47.966	47.916	47.891	48.041

Table 12 – Average Lap Time Across Both Tracks (Anti-Roll Bar Setup)

3.4 Aerodynamics

The next parameter that was investigated was the effect changing the aerodynamics had on the vehicle, this unsurprisingly resulted in a setup where 50% increase front and rear downforce improved lap time with the average lap time across both tracks seen in Table 13. This resulted in a 0.38 second decrease in lap time around Pembrey and a 0.28 second decrease in lap time at Llandow.

		Average Times for Both Tracks										
		Rear Wing										
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Front Wing	0.5	48.556	48.436	48.406	48.201	48.261	48.196	48.136	48.061	48.016	48.081	48.181
	0.6	48.466	48.376	48.321	48.151	48.226	48.151	48.016	48.021	48.086	48.151	48.116
	0.7	48.411	48.371	48.256	48.111	48.156	48.096	47.981	48.066	48.086	48.086	47.941
	0.8	48.461	48.386	48.316	48.171	48.121	48.056	48.036	48.011	47.941	47.916	47.886
	0.9	48.451	48.326	48.261	48.181	48.076	48.001	47.996	47.961	47.891	47.811	47.796
	1	48.416	48.326	48.221	48.311	48.031	47.846	47.951	47.971	47.916	47.826	47.801
	1.1	48.471	48.331	48.271	48.166	48.041	48.031	47.946	47.926	47.781	47.776	47.821
	1.2	48.421	48.341	48.191	48.141	47.981	47.811	47.956	47.921	47.781	47.856	47.721
	1.3	48.521	48.301	48.131	48.251	48.056	47.901	47.881	47.761	47.636	47.781	47.726
	1.4	48.436	48.261	48.156	48.066	47.971	47.911	47.811	47.746	47.781	47.751	47.731
	1.5	48.386	48.291	48.131	48.011	47.936	47.996	47.771	47.701	47.666	47.651	47.541

Table 13 – Average Lap Time Across Both Tracks (Aerodynamic Setup)

4 Results

Overall, the time saved across both tracks was minute, with the savings from each setup change seen in Table 14, the total saving was 0.05 Seconds from the base setup. This is a rather underwhelming result considering the number of iterations undertaken.

			Pembrey	Difference (From Base Setup)	Llandow	Difference (From Base Setup)
Base Setup	Front	Rear	56.831		38.961	
Spring Setup	1.3	1.1	56.851	0.02	38.941	-0.02
Damper Setup	0.7	0.6	56.801	-0.03	38.971	0.01
ARB Setup	1.1	1.2	56.781	-0.05	38.961	0
Total Lap Time Reduction (s)			0.05		0	
Percentage Difference			0.088		0	

Table 14 – Overall Results of Car Setup Optimisation

This shows the importance of having adjustable suspension components on your race car, as opting for a compromised setup between two tracks that have different characteristics has resulted in minimal performance gain over the base vehicle setup. The only parameter that did make a drastic effect to the lap time was increasing aerodynamic forces however this should not be included in the final results as it was an unrealistic parameter to test as you would be unable to achieve a 50% downforce increase without a whole new aerodynamic package.

By increasing the spring stiffness, the ride harshness will have increased however the car should be nimbler and more direct. By softening the damping rate, the cars tyres will contact the ground better, improving traction, to get power down on the exits of corners. By stiffening the anti-roll bars the turn in will have been improved as well as an improvement in the agility/rotation of the vehicle mid-corner benefitting the tight corners on both tracks. One thing of note from completing this report is the difference between the two tracks and the effect that has on vehicle setup, generally what might work for one track did the opposite for the other track. This highlights how a clubman racer who is competing on a budget with a compromised set-up, will be at a massive disadvantage compared to teams with adjustable components for each round of a championship.

5 Conclusions

To conclude, the performance gained across both tracks was 0.05 seconds which equates to about the time of one gearshift in a race car (One Stop Racing, 2022). Therefore, if this project were to be undertaken again further parameters would have to be investigated:

- Camber
- Toe
- Ride Heights
- Weight bias
- Brakes

The parameters investigated in this project would have to be analysed more in depth as well, with the actual spring rates and damper rates being adjusted to match the weight of the vehicle for the baseline setup and then adjusted physically from there, not through the use of scale factors. By investigating the weight bias, the dynamic index of the vehicle could be adjusted to manipulate how the vehicle would behave dictating the vehicles overall handling characteristic.

It is important to remember that in a real situation the vehicle would be tested at a track before entering competition to verify that setup changes made on VI Grade correlate with the results in the real world. For example, all the tests were conducted using a grip scale factor of 1 meaning the model never generates a slip angle, whereas in real life tyres perform at their best at a slip angle of around eight degrees (Seward, 2014). Therefore, the lateral and longitudinal performance factors could also be increased if this project were completed again. Following on from the slip angle evaluation, the sim model itself also brakes unnecessarily on the penultimate corner of Pembrey, if the model could be driven in a Driver in the Loop (DIL) simulator, then this could be solved, and the performance could increase further. It would also be beneficial to have a DIL simulator to either feel for yourself what the car is doing in certain sections of the track or have a driver relay that information to you. Analysing the post-processing is not enough information to give the fine details needed to inform setup changes, as driver feel has a massive effect of the vehicles performance and their feedback has a massive influence on the setup. Such that one driver may prefer a car setup to understeer whilst another prefers an oversteer prone car setup.

Ultimately, it still generated an improvement of 0.05 seconds and in motorsport every bit of performance counts, 0.05 seconds could be the difference between pole position or not (F1, 2020).

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