

FEASIBILITY OF SIMULATIONS USING

VI-GRADE IN REPLICATING AND

DEVELOPING VEHICLE SETUPS

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DECLARATION OF AUTHENTICITY

This thesis is the sole work of the author and is the result of original research. All the work completed have been done so by the author using resources from University of Wales Trinity Saint David. It has not been previously submitted for examination which has led to the award of a degree.

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ABSTRACT

In this project, a model of the MCR race car is tested using the simulation tool of VI Grade in order to check its feasibility for replicating and developing vehicle setups. This is done by using VI Grade in conjunction with the application of design of experiment (DOE) methods. An existing model of the MCR race car is rectified and validated to an accuracy of 2.428%. Different DOE methods such as one factor at a time (OFAT) and full factorial DOE are applied to a range of factors starting from spring rates, damper rates and anti-roll bar rates to camber and toe angles. This optimization process is done for three different circuits, namely Donington Park National Circuit, Llandow and Pembrey. In the end, when comparing the lap times from the baseline setup to the optimized setups for the different circuits, an improvement of 0.28 seconds, 0.09 seconds and 0.17 seconds is observed for Donington Park National Circuit, Llandow and Pembrey respectively.

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1. INTRODUCTION

Almost all motor racing series depend on the drivers to drive as fast as possible in order to win. But as much as it is important to have the fastest drivers in a team to extract the most out of the race car, that is just one of the factors that are necessary to be the quickest. In order to win any motor race, there are multiple things that have to come together all at once. There has to be a collective effort from all the departments and the individuals in them involved in building and operating the race cars along with the drivers. The drivers can only win a race when the team around them builds a car that is fast enough to be in the front of the field. These departments could range from more technical areas such as engine, chassis, aerodynamics, manufacturing, data and simulation etc. to departments that are less or not technical at all such as mechanics, finance, human resources, media, sponsorship etc.

The top flights of motorsports usually involve very high budgets and have professional drivers driving the race cars. But, there are many other racing series where teams with lower budgets can compete in and these usually involve amateur drivers. University of Wales Trinity Saint David has such a race team. This team competes in a racing series known as the SRCC Sports 2000. It is a student led team and it races the MCR race car. The team enters two cars in every event, the first being driven by one of the professors from the university, Tim Tudor and the other driven by John Iley who worked for various teams IndyCar CART teams like Newman-Haas and Lola along with Formula one teams such as Jordan, Renault, Ferrari, McLaren and Caterham at various capacities starting as an aerodynamicist to performance director. A picture of one of the cars can be seen below in Fig.1.



Fig. 1: UWTSD MCR Team Car 40 Driven by Tim Tudor (UWTSD Motorsport, no date)

Throughout each season, the Sprots 2000 championship consists of numerous rounds, taking place at various circuits across the United Kingdom and occasionally in Europe. In order to be quick and excel in a variety of different circuits, the race cars have to be setup precisely to meet the different demands from each circuit.

A simulator is a device that allows the replication and emulation of real world scenarios. In the context of a driving simulator, it mimics genuine driving conditions that enables the driver to recreate the experience of operating a race car solely through the aid of computers, eliminating the need to go out and drive the race car in real world. This is especially advantageous in cases where there are restrictions on testing that are imposed by the racing championships so that the teams are not able to collect vital real world data that might prove to be beneficial during race weekends. Simulators are also very advantageous when there are financial constraints such as budget caps or when there is a limited budget due to the lack of

proper funding. These simulators are also very helpful when it comes to deciding different possible setup directions for the race cars and to finally choose the most ideal one to go ahead with.

The university has a driver in-loop simulator (Bruck et al., 2021) that is based on the racing platform Automobilista. This simulator has a model of the MCR race car. However, there is uncertainty on the accuracy of the MCR model built in it. As a result, it is not guaranteed that the results obtained by making adjustments to the vehicle setup in the simulator would replicate the same behaviours in the actual car in real world conditions. Hence, this poses a substantial challenge for the UWTSD MCR Team, which operates on a very tight budget anyway and cannot afford to go for multiple test sessions.

Hence, in this project, the application and use of the simulation software VI-CarRealTime will be discussed in detail along with the use of design of experiment (DOE). These two will be integrated together in order to achieve the fastest lap times and hence identify the best setups on a range of circuits. This will also enable us to determine the general vehicle trends and characteristics upon changing the different setup components.

2. THEORY

2.1 VI CarRealTime

During the process of developing a vehicle, having a comprehensive understanding of how even the slightest of change can impact the overall physics of the vehicle is very important. Engineers can only guide a vehicle's development in the correct direction if they possess a thorough understanding of how changing different bits of the car would affect it dynamically. With the advancement of computation and simulation capabilities, engineers now have the ability to achieve this by using different simulation tools that are specifically designed and programmed to simulate the operation of a vehicle in order to understand its vehicle dynamics. One such tool that would be used in this project is VI CarRealTime. VI CarRealTime is a real time vehicle simulation environment that uses a single simplified vehicle model. This tool allows the user to build and make adjustments to every component of the vehicle, starting from major components like spring rates, damper rates, centre of gravity, aerodynamic loads, engine parameters etc to minute things such as positions of every suspension component down to the exact millimetre. With this tool, engineers can effectively evaluate how a vehicle would respond to a range of different manoeuvres at various driving conditions, making it a very useful asset. A picture of the basic VI CarRealTime interface can be seen in Fig. 2 below.

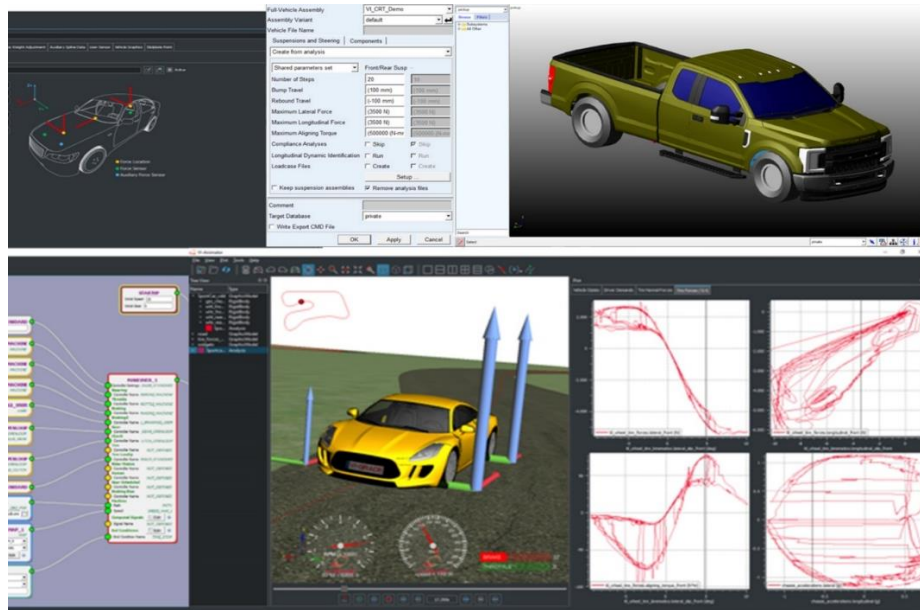


Fig. 2: VI CarRealTime (VI-GRADE, no date)

2.2 VI Road

VI CarRealTime allows to build and modify the models of the vehicles. But in order to complete the assessments of the vehicles, it requires models of the roads and circuits on which the intended assessments are to be conducted. VI Road is a tool that allows us to build the different circuits and roads needed to conduct these assessments. Here, there are two different sections, first being the road file and the other being the path file. The road file contains all the data about the road or track on which the vehicle is operated. This includes things like a map of the road or track, surface of the same, the changes in elevation, position of kerbs etc. On the other hand, the path file contains the details of the exact path that the vehicle needs to follow on the given road or track. When the road and path files are opened together, it gives the complete information on the exact piece of tarmac that the vehicle would traverse through, on a string of different sections of the complete road combined

together. This is a very helpful tool in determining how quickly a race car can travel through a complete lap of any given circuit while following a prespecified path, which in turn allows the engineers to adjust various vehicle parameters to assess if the changes made allows the vehicle to go quicker or not.

After the simulations are completed, the telemetry data generated during the runs can be viewed. Telemetry is the data that is acquired based on multiple sensors that are put into the vehicles (Bugeja et al., 2017). These sensors can be used to assess different parameters of the vehicle. These can be the input parameters from the driver such as throttle percentage, brake pressures, gears, rpm, steering angle etc. or the parameters based on the response from the vehicle such as lateral acceleration, longitudinal acceleration, amount of spring movement etc. If the engineers wish to focus on improving any specific parameters, they could simply look at the telemetry data to identify the areas of deficit in order to improve the performance of the vehicle in a desired way. The term desired way is important here because developing the setup of the vehicle to be the quickest might not always be the best way to go forward. For example, the simulations might show that the quickest setup gives a huge oversteer at a particular corner. If the driver does not feel comfortable with such a huge oversteer, they might end up losing more time compared to a slightly slower setup as per the simulations.

2.3 Design of Experiment (DOE)

The Design of Experiment (DOE) method (Cavazzuti, 2013) is a tool that is used for the collection and analysis of data. It can be defined as a branch within applied statistics which is focused on planning, conducting, analyzing and interpreting controlled tests. These tests are conducted in order to evaluate how different factors influence the value of a parameter or a

group of parameters. Usually, conducting a DOE analysis requires multiple input factors. The values of these input factors can be adjusted in order to observe how changing the factors have an impact on the overall output response. When the input factors are changed, DOE can effectively identify which factors are the most significant and have the greatest influence on the overall output response. There are various different methodologies that can be used to carry out the DOE analysis such as one factor at a time (OFAT) (Wahid and Nadir, 2013), two factorial, three factorial, Box-Behnken design (Ferreira et al., 2007), full factorial etc.

3. LITERATURE REVIEW

To start off, some of the contents of this report, mostly the initial theory and some literature review, will be similar to that of the research proposal report submitted earlier this year, as this is a continuation of the project that was proposed there.

Wu and Pan (2021) used VI CarRealTime to construct a model of the E22 electric formula racing car. They used multi body dynamics as the basic foundational theory with the aim to optimise the suspension system of the vehicle. They used this to analyse the steady state steering traits of the car in order to enhance its handling stability. The process had been carried out by changing the four wheel alignment parameters of the car with the aim of identifying the best combination of front beam angle and wheel camber angle.

In the study by Heilmeyer et al. (2020), the use of strategy based on tyre wear is discussed for a Formula one Car. They introduced a virtual strategy engineer developed using two artificial neural networks. The first network was programmed to decide if the race car was to be called in for a pit stop based on the lap times achieved on the circuit. The other network was used to determine the most ideal tyre to be fit to the race car based on the available allocation of tyres at the time. To develop these, the coding language Python was used. The two neural networks were fed with data points spanning from the 2014 to the 2019 Formula One seasons in order to achieve this.

Law (2017) provides a tutorial on how design of experiment can be used for simulation models. Here, they discuss how altering just one factor at a time is highly statistically inefficient in a simulation environment as all the different factors are usually highly interconnected and just changing one of them might have an adverse effect on the rest of the factors. They delve into other classical design of experiment methodologies as well full

factorial and fraction factorial methods. Lastly, Latin hypercube design is talked about, which are designed for complex, nonlinear responses that are usually associated to simulation models.

Castrounis (2009) employed optimization methods to determine the mean pitch response of a race car. They achieved this by varying various factors to observe their effects and interactions with the mean pitch response. The factors that used in this optimization process were low and high speedbump and rebound damper settings for both the front and rear along with the front and rear tyre stiffnesses. Fraction factorial design of experiment method was used to alter these factors across a range of damper and tyre stiffness settings. At the end of the optimization process, it was determined that the rear damper setting was the most important factor in order to control the pitch response of the vehicle.

The main paper that will be taken as a reference for this project is by Byam et al. (2003). Here, they try to improve the dynamics and the overall performance of a Formula SAE car by applying design of experiment. They do this for a combination of four different events, namely skid pad, acceleration, autocross and endurance. They used seven factors to optimize the vehicle over these events namely, the factors being rear tyre pressure, final drive ratio, ride height, rear spring rate, front and rear compression damping and front and rear rebound damping. Full factorial Design of experiment was employed for the same. At the end, it was revealed that optimal results were achieved when the tyre pressures were in a range between 15 to 20 psi and also gave achieved the best performance when in front and rear toe in conditions for the endurance and autocross events. The highest rates of acceleration were achieved when the ride height was increased and the quickest lap times were achieved when damping coefficients were set to at or around critical damping.

Guiggiani (2014) describes the forces acting on the wheels and tyres as set. They explain the kinematics of the same under steady state conditions in addition to explaining slip and the different forces acting on the wheels and tyres in these conditions. These are supported by the various graphs such as longitudinal and lateral forces with respect to slip angle for a range of camber angles generated from the observed behaviour of the same. They also explain why the tyre can be considered the same as a rigid wheel because of the slip angles achieved are quite small in reality.

Tey and Rahizar (2019) optimized the dynamic handling performance of a race car such as spring stiffness, damper coefficient, anti-roll bar stiffness, and camber and toe angles. It was done using a method based on multi-objective evolutionary algorithm using a software-in-the-loop optimization (SiLO). VI Grade was used for the modelling whereas the optimization process was carried out in MATLAB. In the end, an improvement by 8.9% was seen in the lateral acceleration performance of the vehicle.

4. RESEARCH GAP

As evident from the literature review, it can be seen that there is a huge gap in the research done in this topic area. A major gap can be found in the application of design of experiment (DOE) for the purpose of motor racing. It is well known that design of experiment has got high utility and can be widely used in the realms of motor racing, whether it is for allocation of resources, to steer the direction of vehicle development or for the purpose of developing the setups of the race cars. But a major problem in the field of motorsports is that the race teams do not like to share details on how they use the different tools available to them to improve their cars in order to maintain their competitive advantage. This includes the different applications of design of experiment as well. They do not like to disclose how they use design of experiment and how they apply it to discover what the major areas are for the further development of their race cars and hence their setups. As a result, the details on how the design of experiment approaches can be used for vehicle setup and performance are not available publicly.

5. OBJECTIVES

With the ever increasing computational power of computers and the use of computer aided simulation tools, the objective of this project is to check the feasibility of using one such computer aided simulation tool, VI Grade. This includes the different parts of VI Grade such as VI CarRealTime, VI Road, VI SuspensionGen etc. The primary objective is to use these simulation tools to check if the results attained by using them has any correlation to the actual data available from physical running of the race car. Once the correlation is established, the aim would be to try and improve the lap times of the race car. In order to achieve this, the different suspension component settings would be varied to find the most ideal vehicle suspension setups. But to achieve this primary objective, there are many minor objectives that need to be achieved first. If any of the minor objectives are not met, then there is a huge risk of not achieving the overall major objective of this project.

The main objective of this project:

- Check the feasibility of simulations using VI Grade in replicating and developing vehicle setups.

These are minor objectives that need to be fulfilled in order to achieve the main objective:

- Correctly adjust the available model of the UWTSD MCR race car in VI CarRealTime.
- Validate the model against the data available from actual running of the race car.
- Build the path files for the circuits where it is not available or needs correction in VI Road.
- Apply Design of Experiment (DOE) approaches to the different suspension setups.
- Successfully identify the best suspension setups obtained.

- Compare how the suspension setups vary for the different circuits.
- Examine if the different suspension setups identified by applying design of experiment actually help to improve the lap times and hence test the effectiveness of design of experiment in this scenario.

6. METHODOLOGY

The methodology used here for this project is majorly based around the use and application of computation and simulation applications aided by computers. This means that it revolves around the use of VI Grade and the tools within it. Firstly, it involves making the corrections required to the existing model of the MCR race car in order to make sure that the data attained by running the simulations give the results as expected and similar to the performance that would be expected from the operation of the real race car. Once this was achieved, the next step was to validate the model with the data available from the actual race car. This was done with the use of VI CarRealTime. Alongside this, the circuits that required adding path file were created using VI Road. This concluded the preparatory part of the project. The next bit was to conduct the investigations and the research needed for the project. This started with conducting the simulations for one of the circuits to establish a general baseline for the performance of the race car model. This was done with the model in its original state without altering any of the suspension setups other than the ones necessary for the correction of the model. With the baseline performance established, the design of experiment (DOE) approached were used to conduct the tests by varying different suspension components in different combinations. Once the best results achieved were identified, the same process was repeated for the other circuits as well. A detailed flow chart of the same can be seen below in Fig. 3.

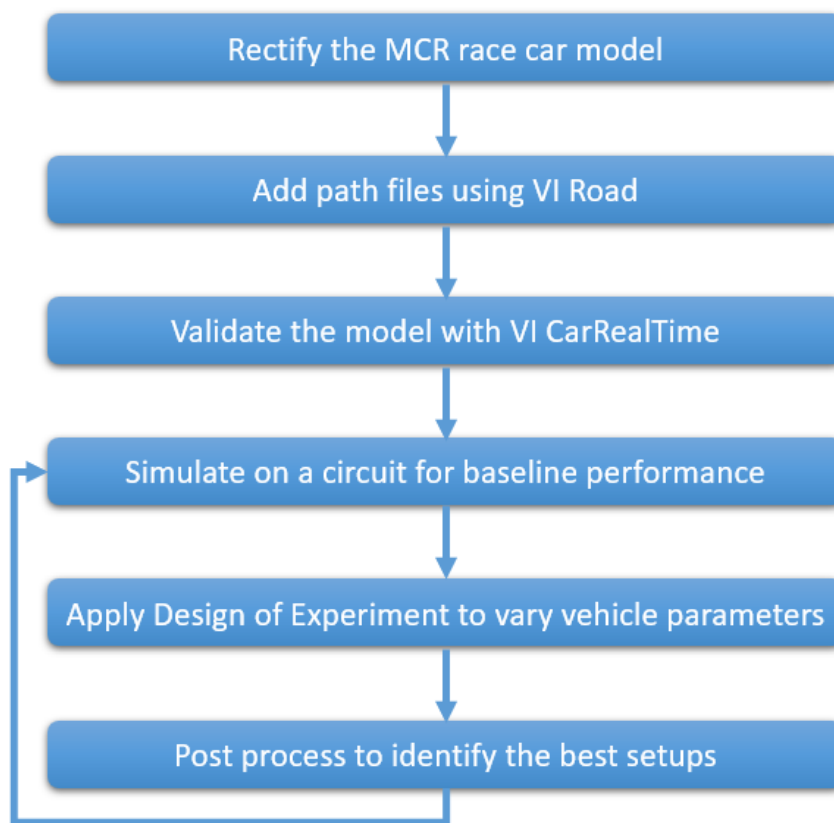


Fig. 3: Methodology Used

6.1 Rectifying the MCR race car model

The first step in this project was to build a model of the MCR race car that could be used in VI CarRealTime. But it was discovered that a model of the same already existed. Hence, there was no point in building the same model again and the already built model was sourced and has been used here. Even though the model was nearly perfect, there were minute changes that were to be made to rectify it in order to be used correctly. This included changing the front and rear ride heights and the gear ratios for the fifth gear. Rectifying these were highly important because the overall ride height of the car has a huge effect on the overall performance of the car. As discussed by Byam et al. (2003), they observed that when they wanted to achieve the highest acceleration possible, changing

the ride height was the most effective way to achieve it. It is also well known that changing the ride height affects the aerodynamic efficiency of the vehicle as discussed by Knight et al. (2019) among other things. Similarly, changing the gear ratio of the final was very important. When the gear ratio of the original model was used, it was discovered that the race car attained a maximum velocity of about 192 km/h. Once 192 km/h was reached, it plateaued as the engine reached its maximum rotational speed. At the SRCC Sport 2000 race in Donington in 2023, the race car achieved a maximum velocity of 206.3 km/h, which is a difference of about 7.4% and it affected the lap time achieved in the simulation severely. Hence, the gear ratio was changed to match a similar top speed and the velocity achieved after the change was 206.4 km/h, a difference of 0.048%.

6.2 Adding path files using VI Road

Within VI Grade, VI CarRealTime is the main software to run the simulations. But in order to run the simulations, the different factors associated with it must be built with it as well. One such factor is building the road and path files. Having the road and path files are of paramount importance because these together define the route that the model of the vehicle is supposed to take during the simulations.

The road file is the one that defines the characteristics of the road the vehicle is supposed to traverse through. This includes the data such as the boundaries of the road or track, the presence of kerbs at the edges of the circuit, elevation changes etc. The road can be built defining different segments of the road individually. Once the segments are defined, these are then stringed together in order to take the form of a complete road or circuit.

The path file is the one that defines the exact trajectory that a vehicle takes over a defined road or circuit. Hence, it is very important that the path file perfectly coincides with the road file. If not, the vehicle would keep following the driving line defined by the path file irrespective of having a defined road underneath it or not. This would be a huge problem because this would mean that the vehicle would simply keep following the path in the fastest possible manner with no defined road surface, leading to incorrect interaction of the vehicle with the road surface and hence giving incorrect responses from the vehicle than expected.

But that being said, having the path file correctly place over the road file is not enough. In order to ensure that a vehicle achieves the quickest lap time possible on a given circuit, it has to follow the path of least resistance. The path of least resistance, more commonly known as the racing line, is the path that a vehicle needs to follow to make sure that it maximizes its speed through every part of the circuit. For any given circuit, there might either be one racing line that is the fastest way around to complete a lap or on some occasions , there might be a range of different racing lines that a vehicle can take to achieve the fastest possible lap time. This heavily depends on the car being used and the setup it is running as well. For example, if a race car has low to no downforce or if it has great acceleration performance compared to cornering performance, the race car would travel through a corner at a lower speed and would try to rotate the car first and then accelerate at the maximum rate possible. In a corner like a hairpin, the car will ideally achieve a faster lap time if it takes a V-shaped racing line for maximum rotation at lower speed. Compared to that, if a car has a lot of downforce, it would typically be faster if the race car travels through the corner at a higher speed in order to utilize the extra grip it is gaining from the aerodynamics of the car. In this situation, the car will theoretically

achieve a faster lap time if it maintains a racing line with a constant radius through the same hairpin corner rather than slowing down to rotate it in a V-shaped racing line. As a result, a circuit might have different racing lines depending on the race car or the setup being used.

Because of the reasons stated above, in order to achieve the correct and desirable data from the simulations, the path file and the road file of a road or a circuit in this situation have to work together harmoniously.

For the completion of this project, the VI CarRealTime model of the MCR race car was simulated for data on three individual circuits. The circuits involved in this project were Donington Park National Circuit, Llandow and Pembrey. All of these circuits had road files readily available for them and did not require the creation of additional road files. On the contrary, the path files were only available for two of these circuits, namely Llandow and Pembrey. The Donington Park National Circuit did not have a complete path file and hence needed the creation of a new path file for the same. But as mentioned above, having the most ideal racing line for a circuit is of utmost importance. So, for the circuits that already had the path files, i.e., Llandow and Pembrey, new path files were created to ensure that the racing lines taken by the race car during the simulation were the quickest in order to achieve the fastest lap times.

6.3 Validation

After the necessary corrections were made to the VI CarRealTime model of the MCR race car and adding the path files, the next step was to validate the model against the data available from the actual race car. The race car collects its data using a device known as

the V-box. A V-box is a device that has the capability to work in conjuncture with multiple sensors around the car. It loads and stores all the data that is received from the different sensors. It can log a variety of different data such as lap times, lateral and longitudinal accelerations, steering angle, speed, throttle and brake maps etc. when used while the car is on the track. A major benefit is using a V-box is that it has the ability to differentiate between different laps using GPS data. Hence, once the position of the start/finish line is denoted, the V-box can differentiate and store the data from different laps separately. This is very useful when to compare data between the different laps and can be used to determine the best techniques to achieve the best lap times.

In the field of motorsports, the race cars always keep evolving and improving in order to maintain their competitive advantage. Hence, the validation process would only be accurate when the most recent data from the actual race car is used to validate it with. As a result, the data with which the corrected model in the simulation software will be compared to is the data from the race at Donington Park in the 2023 SRCC Sport 2000 championship. This event was held on 15th to 16th July, 2023, giving brand new data at the time of the validation.

The validation process is only considered to be successful when the thing that is being validated has a very high resemblance to the object it is being validated against. In this case, the model of the MCR race car in VI CarRealTime needs to have a high resemblance to that of the actual race car. In order to justify this, the simulation model and the actual race car were compared for a range of different parameters. The entire validation process is explained in detail in Section 7.

6.4 Simulation for baseline performance

This section focuses on the process of establishing the baseline performance of the of the MCR race car simulation model in VI CarRealTime. The baseline performance of the car is the performance achieved by it when it is simulated without making any changes to its model, other than the corrections required as mentioned in Section 6.1. This establishes the results the model of the car is capable of achieving and gives the limit to which the car is capable of pushing itself to maximize its performance for the given base setup.

6.5 Applying Design of Experiment approaches

Once the baseline performance of the car was established and the results that could be achieved by the car during simulation were clear, the next step was to apply the design of experiment approaches. As mentioned before, design of experiment is a very useful tool to assess how a range of different factors interact with each other and how each of these factors are affected by one another. Design of experiment also allows the user to set the range by which each of these factors can vary and the number of steps within the range. For this project, design of experiment was used to varying various suspension components of the race car as the factors. These include the different suspension components such as springs, dampers, anti-roll bars, toe and camber. Each of the factors were varied for both the front and rear wheels. Once the analysis was run, it was set to give a range of output responses such as the minimum lap time, maximum acceleration, maximum velocity, maximum yaw and maximum lateral acceleration.

For every circuit, the application of design of experiment started with applying it to just one of the factors first, i.e., one factor at a time (OFAT) method was used. For example, if design of experiment was applied to the springs, every other factor were left in their original settings. Here, each of the front and rear wheels were varied in pairs and were set to be symmetrical.

Initially, to identify the if the springs rates were to be made higher or lower, the range of spring rates were set to vary by 25% on both higher and lower spring rates compared to the original settings. Hence, the spring rates were set to three different levels, -25%, 0% and +25% compared to the original spring rate settings. Once the simulation was completed, the fastest lap time was identified to further narrow down the range. For example, considering the original setup for the spring rates as 1 (0%), at the Donington Park National Circuit, the fastest lap times were achieved for two different setups, firstly 0.75 (-25%) front spring rate and 0.75 (-25%) rear spring rate and secondly, 0.75 (-25%) front spring rate and 1.25 (+25%) rear spring rate, as seen in Fig. 4 below. As a result, the other output responses such as acceleration and velocity were looked at. As shown in Fig. 4, for the same lap time, 0.75 (-25%) front spring rate and 0.75 (-25%) rear spring rate gave higher values for acceleration and velocity compared to 0.75 (-25%) front spring rate and 1.25 (+25%) rear spring rate. Hence, the setup with 0.75 (-25%) front spring rate and 0.75 (-25%) rear spring rate was identified to be the optimum one out of the two.

Identifier	front_suspension.springs.Updated MCR Front 40. front.left.scaleFactor	rear_suspension.springs.Updated MCR Rear 40. rear.left.scaleFactor	Success	Laptime	Acceleration	Velocity	Yaw	Lateral Acceleration
v0001	0.750000	0.750000	▲	72.0410	1.03962	206.458	6.60677	2.08245
v0002	0.750000	1.00000	▲	72.0610	0.993785	206.345	6.57411	2.09298
v0003	0.750000	1.25000	▲	72.0410	0.929762	206.466	5.82690	2.09000
v0004	1.00000	0.750000	▲	72.1210	1.54790	206.331	5.27789	2.10707
v0005	1.00000	1.00000	▲	72.1510	1.48427	206.418	6.78091	2.10512
v0006	1.00000	1.25000	▲	72.1610	1.15917	206.402	6.67656	2.10573
v0007	1.25000	0.750000	▲	72.1810	1.13993	206.319	5.49567	2.10004
v0008	1.25000	1.00000	▲	72.2010	1.27066	206.297	5.49704	2.10131
v0009	1.25000	1.25000	▲	72.1910	1.31228	206.330	5.91368	2.10609

Fig. 4: 25% Spring Rate analysis at Donington Park Nation Circuit

Similarly, the range was then narrowed down to vary by 10% on both higher and lower spring rates compared to the fastest lap from the 25% analysis, i.e., from 0.65 to 0.85 for the front spring rate and from 0.65 to 0.85 for the rear spring rate as well, as both were identified to be the quickest at 0.75.

Again, the fastest lap time from the 10% analysis was identified and the same process was repeated to further narrow the range to complete a 5% analysis. Similarly, the entire process was repeated for the other factors of damper rates, anti-roll bar rates, camber angles and toe angles as well.

All the above simulations were completed using one factor at a time (OFAT) method of design of experiment. As discussed by Law (2017), this is usually an ineffective method when there are multiple factors involved. But in this scenario, OFAT method was used to determine which individual factors influence the performance of the MCR race car the most. Although this is not the best method to extract the maximum performance out of the car, it is highly effective in scenarios where one wants to make quick changes to gain the most performance by just altering one of the factors.

Next, the different factors were split into two different groups. This was done to check how the car would perform if a couple of different factors were altered together at the same time. The first group that the factors were split into included spring rates, damper

rates and anti-roll bar rates. Camber and toe angles of the car were put into the other group. To achieve the best results, full factorial design of experiment method was used here. In this scenario, the optimized results that were achieved from the 5% analysis were used as the base setting and the factors were varied for a further 5%. Taking example of the first group in Donington Park National Circuit, the best setups for the front spring rate, rear spring rate, front damper rate, rear damper rate, front anti-roll bar rate and rear anti-roll bar rate were identified to be 0.6 (-40%), 0.8 (-20%), 1 (0%), 1.25 (+25%), 0.65 (-35%) and 0.65 (-35%) respectfully. Hence, the new 5% range for these to simulate as a group were 0.55 to 0.65, 0.75 to 0.85, 0.95 to 1.05, 1.2 to 1.3, 0.6 to 0.7 and 0.6 to 0.7 for the front spring rate, rear spring rate, front damper rate, rear damper rate, front anti-roll bar rate and rear anti-roll bar rate respectively. The same process was repeated for the other group that had the camber and toe angles as their factors.

Finally, after completing the simulations for both the groups, one more optimization was done additionally. From the results obtained from the two groups, it was quite evident that the factors in the first group, i.e., the one with the spring rates, damper rates and anti-roll bar rates had a much higher influence on the performance of the race car. This group gave a substantially better result in terms of lap time compared to the second group with the camber and toe angles. This meant that the setup from the first group is where the performance window of the car majorly is. Subsequently, it meant that if the fastest setup from the first group is taken as a base setup, it could further be fine-tuned by changing the camber and toe angle results achieved from the second group. For example, the fastest lap time achieved by altering the factors in the first group was by using the setup 0.55 (-45%), 0.85 (-15%), 1.05 (+5%), 1.3 (+30%), 0.6 (-40%) and 0.65 (-35%) for the front spring rate, rear spring rate, front damper rate, rear damper rate, front anti-roll bar

rate and rear anti-roll bar rate respectively. Since this setup influenced the performance of the car the most, it meant that this is the most ideal performance window and hence was kept as constant for the final run. Whereas the fastest lap time achieved by altering the factors in the second group was by using the setup 0.7 (-30%), 1.3 (+30%), 0.7 (-30%) and 1.2 (+20%) for the front camber angle, rear camber angle, front toe angle and rear toe angle respectively. So, for the final run, the factors of the second group were altered again by a margin of 5% on either side, keeping the results from the first group the same. Hence, for the final simulation, the factors of front spring rate, rear spring rate, front damper rate, rear damper rate, front anti-roll bar rate and rear anti-roll bar rate were kept constant at 0.55, 0.85, 1.05, 1.3, 0.6 and 0.65 respectively and the front camber angle, rear camber angle, front toe angle and rear toe angle were varied by 5% on either side again from 0.7, 1.3, 0.7 and 1.2 respectively. The results achieved from this final run was identified to be the most ideal setup of the Donington Park National Circuit.

Similarly, the entire process was repeated for the two other circuits being used in this project, i.e., Llandow and Pembrey. With this, the process of using design of experiment approaches to identify the best setup of the MCR race car with the VI CarRealTime simulation tool came to an end.

6.6 Post processing

The last part of the simulation process is post processing the output data. This involves identifying the most ideal setups for the race car based on the results achieved after each simulation. This means that every time the design of experiment method was used to alter one factor or multiple factors at a time, it is necessary to complete the post processing

immediately in order to identify many things such as how the range of the factors were to be reduced or which factors had the most impact on the overall performance of the race car. This was probably the most important step in the entire optimization process since making one small mistake in identifying the most suitable setup for the race car would mean that the direction of development of the setup would change and as a result, the entire optimization process would be compromised.

After completing the simulations, VI CarRealTime produces a table with data from all the different iterations in it. Fig. 5 below shows the output data from one of the full factorial design of experiment runs from Donington Park National Circuit where the spring rates, damper rates and anti-roll bar rates were altered for both the front and rear. Here, the first column shows the iteration number within the simulation. This is accompanied by the setting that each of the factors were varied to for that particular iteration of the simulation.

Identifier	front_suspension. antiroll.Updated MCR Front 40.front. scaleFactor	front_suspension. springs.Updated MCR Front 40.front. left.scaleFactor	front_suspension. dampers.Updated MCR Front 40.front. left.scaleFactor	rear_suspension. antiroll.Updated MCR Rear 40.rear. scaleFactor	rear_suspension. springs.Updated MCR Rear 40.rear. left.scaleFactor	rear_suspension. dampers.Updated MCR Rear 40.rear. left.scaleFactor	Success	Laptime	Acceleration	Velocity	Yaw	Lateral Acceleration
v0001	0.600000	0.550000	0.950000	0.600000	0.750000	1.20000	Δ	71.9710	1.22184	206.516	6.54418	2.08073
v0002	0.600000	0.550000	0.950000	0.600000	0.750000	1.25000	Δ	71.9410	1.22570	206.506	6.52508	2.08114
v0003	0.600000	0.550000	0.950000	0.600000	0.750000	1.30000	Δ	71.9410	1.22582	206.506	6.52281	2.08271
v0004	0.600000	0.550000	0.950000	0.600000	0.800000	1.20000	Δ	71.9310	1.19251	206.515	6.16865	2.07838
v0005	0.600000	0.550000	0.950000	0.600000	0.800000	1.25000	Δ	71.9210	1.19263	206.509	6.51398	2.05413
v0006	0.600000	0.550000	0.950000	0.600000	0.800000	1.30000	Δ	71.9210	1.19411	206.498	6.52296	2.05543
v0007	0.600000	0.550000	0.950000	0.600000	0.850000	1.20000	Δ	71.9110	1.17166	206.506	6.03561	2.07563
v0008	0.600000	0.550000	0.950000	0.600000	0.850000	1.25000	Δ	71.9210	1.22010	206.497	6.03640	2.07689
v0009	0.600000	0.550000	0.950000	0.600000	0.850000	1.30000	Δ	71.9010	1.21986	206.495	6.09760	2.06762
v0010	0.600000	0.550000	0.950000	0.650000	0.750000	1.20000	Δ	71.9710	1.20123	206.515	6.54933	2.08097
v0011	0.600000	0.550000	0.950000	0.650000	0.750000	1.25000	Δ	71.9510	1.21728	206.494	6.53589	2.08338
v0012	0.600000	0.550000	0.950000	0.650000	0.750000	1.30000	Δ	71.9610	1.22397	206.515	6.56781	2.07617
v0013	0.600000	0.550000	0.950000	0.650000	0.800000	1.20000	Δ	71.9210	1.22476	206.490	6.12534	2.07269
v0014	0.600000	0.550000	0.950000	0.650000	0.800000	1.25000	Δ	71.9010	1.21316	206.502	6.21674	2.05919
v0015	0.600000	0.550000	0.950000	0.650000	0.800000	1.30000	Δ	71.9010	1.20175	206.503	6.14387	2.06020
v0016	0.600000	0.550000	0.950000	0.650000	0.850000	1.20000	Δ	71.9210	1.18495	206.517	5.98721	2.08235
v0017	0.600000	0.550000	0.950000	0.650000	0.850000	1.25000	Δ	71.9210	1.18230	206.517	5.93558	2.07877
v0018	0.600000	0.550000	0.950000	0.650000	0.850000	1.30000	Δ	71.9210	1.20920	206.517	6.15095	2.08844
v0019	0.600000	0.550000	0.950000	0.700000	0.750000	1.20000	Δ	71.9610	1.22278	206.514	6.53609	2.08219
v0020	0.600000	0.550000	0.950000	0.700000	0.750000	1.25000	Δ	71.9510	1.21552	206.514	6.54114	2.08392
v0021	0.600000	0.550000	0.950000	0.700000	0.750000	1.30000	Δ	71.9610	1.22523	206.514	6.53701	2.07285
v0022	0.600000	0.550000	0.950000	0.700000	0.800000	1.20000	Δ	71.9210	1.21448	206.496	6.51324	2.05656
v0023	0.600000	0.550000	0.950000	0.700000	0.800000	1.25000	Δ	71.9410	1.22351	206.496	6.51714	2.06484

Fig 5: Full Factorial Output Table

As seen in iterations v0001 and v0002, all the factors other than the setting of the rear damper was kept the same. The rear damper setting for iterations v0001 and v0002 were 1.2 and 1.25 compared to the original setting (1) respectively. In the latter columns, the different output parameters for which the simulation is being run can be seen. These are lap time, longitudinal acceleration, velocity, yaw and lateral acceleration. The most important parameter out of these is the lap time as the main aim of this project is to identify the quickest setup possible. It can be seen that iterations v0001 and v0002 produced lap times of 71.971 seconds and 71.941 seconds respectively. So, in this case iteration v0002 was identified as the better setup. But this is not the case for every iteration. In the case of iterations v0002 and v0003, both produced the same lap time of 71.941 seconds. In such case, the results from the remaining output parameters were compared. Of the remaining parameters, the maximum longitudinal acceleration and maximum velocity were looked at next. This is because in a situation where the lap times are same, the longitudinal acceleration and velocity of the race car are probably the most important factors for both attacking a driver who is in front or to defend from a driver who is behind. As a result, these factors define the overall pace of the race car in such situations. From Fig. 5 again, it can be seen that the maximum velocity for both iterations v0002 and v0003 was 206.506 km/h. Hence, the maximum longitudinal acceleration was the deciding factor in this case. Iterations v0002 and v0003 achieved maximum longitudinal accelerations of 1.22570 G and 1.22582 G respectively. Although negligible, iteration v0003 achieved a higher rate of longitudinal acceleration and hence was identified as the slightly quicker setup.

In some situations, the maximum longitudinal acceleration and maximum velocity were identical as well along with the lap times. In such a situation, the lateral acceleration of

the race car was looked at next. This was done because when two setups had the same minimum lap time, maximum longitudinal acceleration and maximum velocity, the one with the greater maximum lateral acceleration would logically mean that it is capable of taking a corner slightly quicker. Hence, the hierarchy of the output parameters in identifying the most ideal setup was the minimum lap time, followed by maximum longitudinal acceleration and maximum velocity, maximum lateral acceleration and lastly the maximum rate of yaw.

Similarly, all the iterations of the simulation were compared and quickest setup was chosen as the most ideal one. This process was repeated for all the other simulations as well and the final results were chosen to identify the most ideal setup for the model of the MCR race car.

7. VALIDATION

As mentioned in Section 6.3 above, the process of validation began with the comparison of lap times achieved by the actual MCR race car and by that of the model of the race car in VI CarRealTime. Here, since we are using the flying lap option in VI CarRealTime, it only makes sense to choose the fastest lap completed by the race car in the race. In Race 1 at Donington Park, the fastest lap time achieved by Car #40 was 70.342 seconds. The time needed by the simulation in Vi CarRealTime to complete a lap of the circuit was 72.151 seconds. When compared to the lap time achieved by the actual race car, this time is 1.708 seconds slower. In the field of motorsports where every tenth of a second counts, 1.708 seconds seems like an eternity. But when it is looked at from the perspective of a validation, 1.708 seconds is 2.428 percent of 70.342 seconds. Hence, from the validation point of view, this result of 2.428% is highly acceptable.

For the next part, the telemetry data of the actual MCR race car is compared to that of the telemetry obtained from the simulations. In Fig. 6 below, it can be seen that the trends of the two graphs are very similar. The peaks and troughs for both the graphs are at similar regions as well. It can also be observed where exactly the VI CarRealTime simulation is losing most of its time. It is losing time due to high instability of the car during the corners and for having to make corrections mid corner. This can especially be observed around the distance of 1000 metres, where the instability of the car is highly pronounced. As discussed in Section 6.1, the maximum speed of the actual MCR race car is 206.3 km/h and that of the VI CarRealTime model is 206.4 km/h, which is a difference of 0.1 km/h and 0.048%

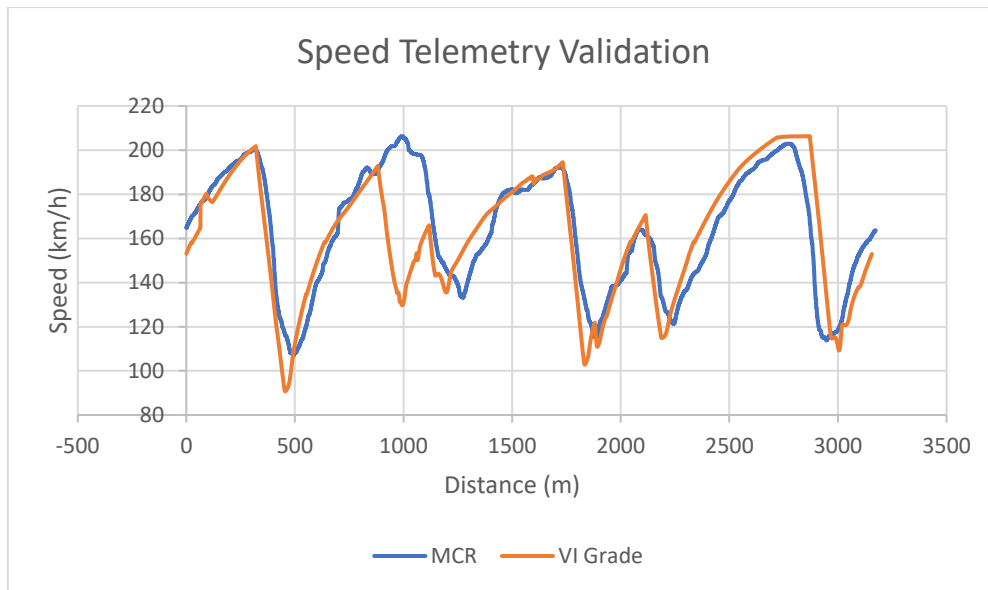


Fig. 6: Speed Telemetry Validation

Next, we have the graph for the lateral accelerations achieved by the actual MCR race car compared against the VI CarRealTime model. Again, it can be observed here that the trends followed by both the graphs are overlapping for most parts throughout the lap. The only major difference that can be observed is that while the graph for the actual MCR race car is pretty smooth, the simulation model in VI Grade gives multiple spikes of peaks and troughs due to instability. The maximum lateral accelerations achieved by the actual MCR race car is 1.86 G, compared to 1.99 G that was achieved by the VI CarRealTime simulation model. This is a difference of 0.13 G which when calculated in percentage is 6.989%. The graphs for the same can be seen below in Fig. 7.

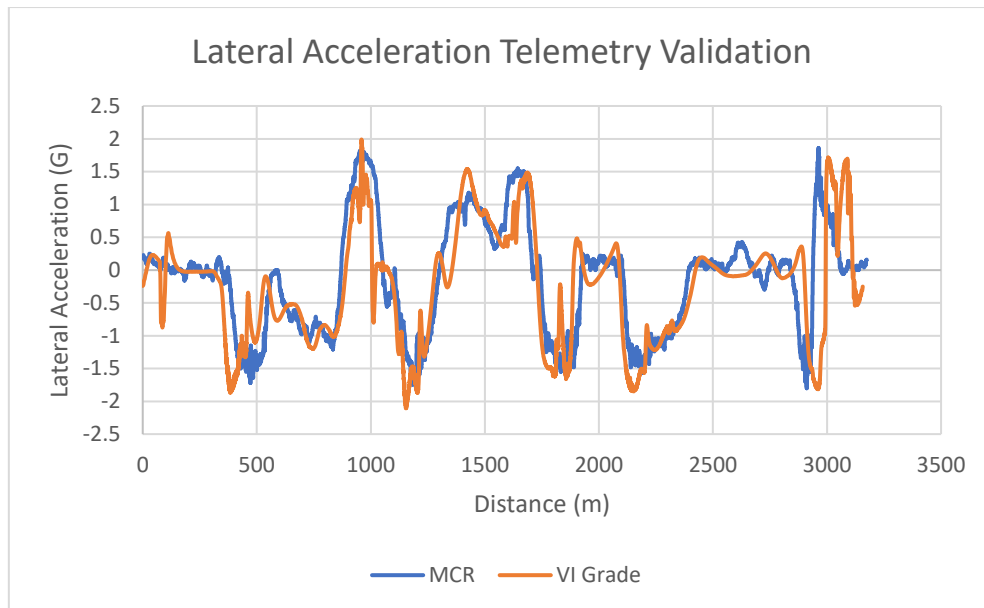


Fig. 7: Lateral Acceleration Telemetry Validation

Lastly, the graph for the longitudinal accelerations achieved by the actual MCR race car compared to that of the VI CarRealTime model are presented below in Fig. 8. As with the graphs for lateral acceleration, it can be observed here that the trends followed by both the graphs are overlapping for most parts throughout the lap. But a major difference observed here is around 1000 metres. This is because of the instability of the car causing it to oversteer at the corner entry. Once the oversteer is caught the car starts to accelerate again before finally braking for the corner again. Here, it can be seen that highest longitudinal accelerations achieved have a negative value. This means that these values are achieved when the car is decelerating. The maximum longitudinal acceleration achieved by the actual MCR race car is -1.49 G, compared to -1.546 G that was achieved by the VI CarRealTime simulation model. This is a difference of 0.056 G, which when calculated in percentage turns out to be a difference of 3.758%.

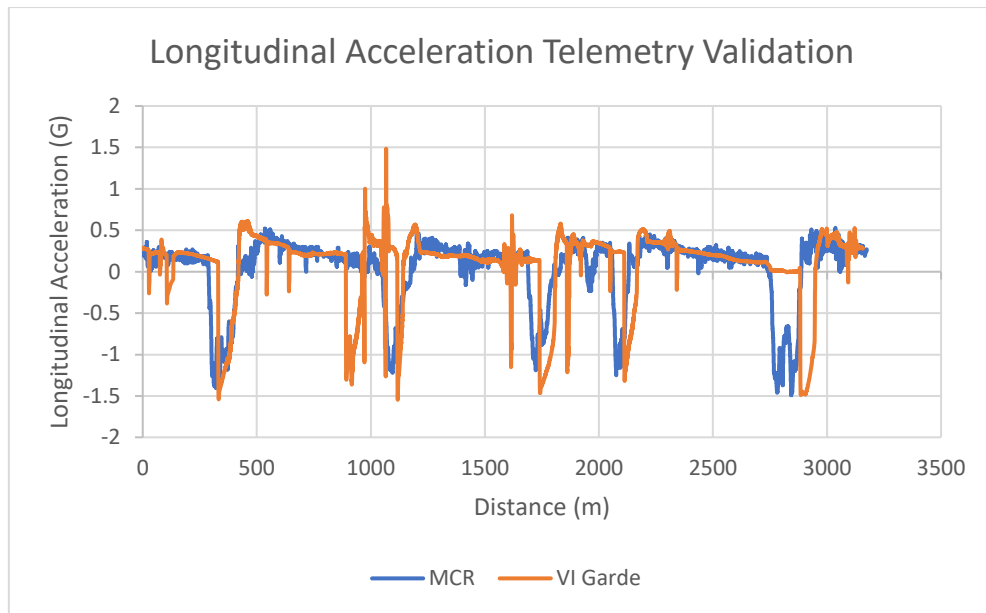


Fig. 8: Longitudinal Acceleration Telemetry Validation

In the three graphs above, the major difference that is consistent is the distance to the final chicane of Donington Park national Circuit. In VI Grade, it seems to be delayed by about 100 metres. This could be because of two reasons. Firstly, and most likely, it could be because of a fault in the road file with respect to the placement of the chicane. The other reason for this might be inaccurate calibration of the V-box leading to slight error in the GPS data.

From the validation of the various different parameters such as the lap time, maximum speed, lateral acceleration and longitudinal acceleration, it can be observed that the results achieved using the VI CarRealTime model are almost identical and within the limit for validation to that of the data retrieved from the V-box of the actual MCR race car. Table 1 below presents the data for the same in a more comprehensive method for comparison.

Table 1: Validation Comparison

	MCR Race Car	VI Grade Model	Difference	Percentage Difference
Lap Time	70.342 s	72.151 s	1.708 s	2.428%
Maximum Speed	206.3 km/h	206.4 km/h	0.1 km/h	0.048%
Lateral Acceleration	1.86 G	1.99 G	0.13 G	6.989%
Longitudinal Acceleration	-1.49 G	-1.546 G	0.056 G	3.758%

8. PROCEDURE

In this section, the procedures of operating the different softwares within the VI Grade family are explained in detail. This section is an integral part of completing this project. But, since it is a step by step instruction of all the procedures in the form of a manual, the detailed procedure can be found in Appendix 1. First, the process of creating a path file in VI Road is explained. This is then followed by the entire process of using VI CarRealTime, starting from loading the different components of the car such as wheels, chassis, suspension etc., followed by the process of altering the different parameters of the car, running the simulation for any particular setup, how to view the output telemetry after the simulation and finally how to apply design of experiment (DOE) to alter the different parameters of the race car.

9. RESULTS

In this section, the results achieved after every simulation is described in detail. This process begins with establishing the results achieved initially when the race car was left at its original state without altering the different factors in order to establish a baseline for the race car's performance. This is done individually for each circuit so that the lap time achieved could be compared to the lap times when design of experiment approaches were applied to each of the factors, both individually during one factor at a time (OFAT) approach and full factorial design of experiment approach.

9.1 BASELINE COMPARISON AND ONE FACTOR AT A TIME (OFAT) METHOD

9.1.1 Donington Park National Circuit

Starting with the Donington Park National Circuit, the lap time that the MCR race car could achieve during the baseline test without altering any of the factors and kept at 1 (0%) was 72.151 seconds.

9.1.1.1 Spring rate optimization

Starting with altering only the spring rates, when the spring rates were altered by 25% on either side, the fastest lap time of 72.041 seconds was achieved for 0.75 (-25%) and 0.75 (-25%) front and rear spring rates respectively compared to the baseline setup. The lap times further improved during the 10% optimization process to 71.981 seconds with 0.65 and 0.85 front and rear spring rates respectively. Again, during the 5% optimization, the lap time improved to 71.971 seconds with 0.6 (-40%) and 0.8 (-20%) front and rear spring rates respectively. The same can be seen below in Table 2.

Similarly, Fig. 9 shows the optimized setup that was identified after the 25%, 10% and 5% analysis. It is seen that better lap times were achieved with lower front and rear spring rates.

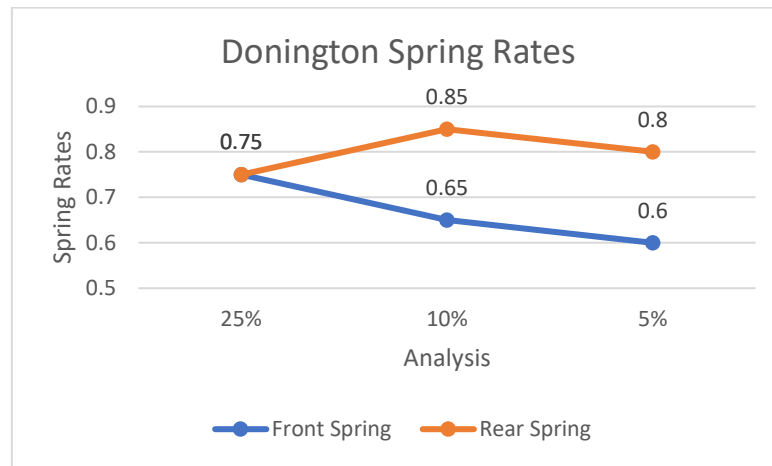


Fig. 9: Donington Spring Rate Optimization Chart

Table 2: Donington Spring Rate Optimization

Donington	Baseline	25%	10%	5%
Front Spring	1	0.75	0.65	0.6
Rear Spring	1	0.75	0.85	0.8
Lap time (s)	72.151	72.041	71.981	71.971
Delta (s)	0	-0.11	-0.17	-0.18

Table 2 shows that lap time worth 0.18 seconds was improved just by optimizing the spring rates of the race car.

9.1.1.2 Damper rate optimization

The most optimum setup for the damper rates were achieved right at the beginning at the 25% analysis, as shown in Fig. 10 below. The setup remained unchanged upon further optimization. It is observed that fastest lap times were achieved with the

default front damper rate but with higher rear damper rate. The most ideal setup was identified to be 1 (0%) at the front and 1.25 (+25%) for the rear damper rates compared to the baseline setup.

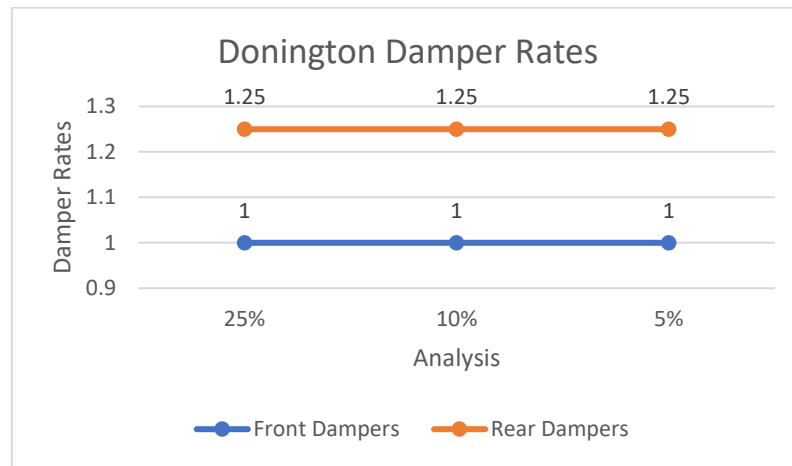


Fig. 10: Donington Damper Rate Optimization Chart

Table 3: Donington Damper Rate Optimization

Donington	Baseline	25%	10%	5%
Front Dampers	1	1	1	1
Rear Dampers	1	1.25	1.25	1.25
Lap time (s)	72.151	72.091	72.091	72.091
Delta (s)	0	-0.06	-0.06	-0.06

Table 3 above shows that lap time worth 0.06 seconds was improved when only the damper rates were optimized.

9.1.1.3 Anti-roll bar rate optimization

From Fig. 11 below, it is seen that the best lap times were achieved when the anti-roll bar rates lowered for both the front and rear. The most ideal setup in this case was identified to be 0.65 (-35%) for both the front and rear anti-roll bar rates compared to the baseline setup.

Table 4 below shows that lap time worth 0.04 seconds was improved when only the anti-roll bar rates were optimized.

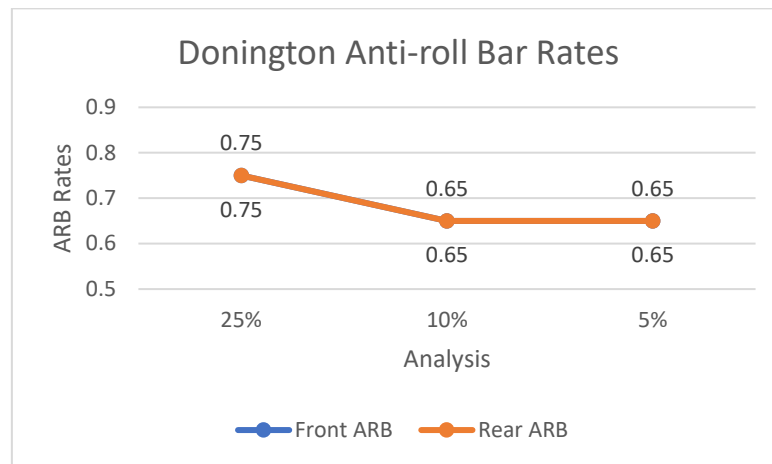


Fig. 11: Donington Anti-roll Bar Rate Optimization Chart

Table 4: Donington Anti-roll Bar Rate Optimization

Donington	Baseline	25%	10%	5%
Front ARB	1	0.75	0.65	0.65
Rear ARB	1	0.75	0.65	0.65
Lap time (s)	72.151	72.131	72.111	72.111
Delta (s)	0	-0.02	-0.04	-0.04

9.1.1.4 Camber angle optimization

Similar to the damper rate optimization, from Fig. 12 below, it can be seen that most optimum setup for the damper rates were achieved right at the beginning at the 25% analysis. The setup remained unchanged upon further optimization. The fastest lap times were achieved with lower front camber angle of 0.75 (-25%) and higher rear camber angle of 1.25 (+25%) compared to the baseline setup.

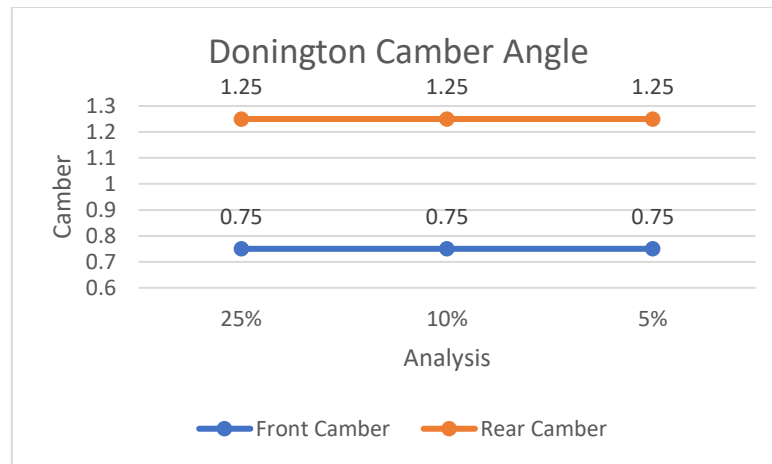


Fig. 12: Donington Camber Angle Optimization Chart

Table 5: Donington Camber Angle Optimization

Donington	Baseline	25%	10%	5%
Front Camber	1	0.75	0.75	0.75
Rear Camber	1	1.25	1.25	1.25
Lap time (s)	72.151	72.081	72.081	72.081
Delta (s)	0	-0.07	-0.07	-0.07

Table 5 above shows that lap time worth 0.07 seconds was improved when only the camber angle was optimized.

9.1.1.5 Toe angle optimization

From Fig. 13 below, it is seen that the best lap times were achieved when the front toe angle was lowered and with higher rear toe angle. The most ideal setup in this case was identified to be 0.75 (-25%) front toe angle and 1.15 (+15%) rear toe angle compared to the baseline setup.

Table 6 below shows that lap time worth 0.05 seconds was improved when only the toe angles were optimized.

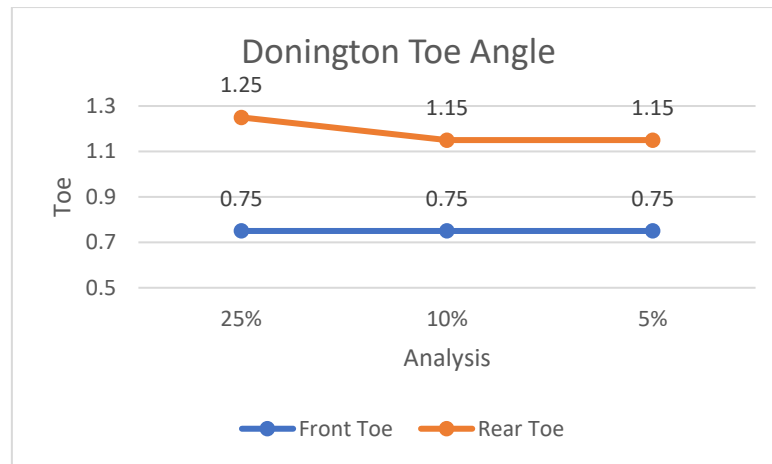


Fig. 13: Donington Toe Angle Optimization Chart

Table 6: Donington Toe Angle Optimization

Donington	Baseline	25%	10%	5%
Front Toe	1	0.75	0.75	0.75
Rear Toe	1	1.25	1.15	1.15
Lap time (s)	72.151	72.101	72.101	72.101
Delta (s)	0	-0.05	-0.05	-0.05

9.1.1.6 Donington one factor at a time comparison

After applying the one factor at a time approach for Donington, it was discovered that optimization of each factor individually gave an improved lap time every time compared to the baseline setup. From Fig. 14 below, it is observed that out of all the factors, just altering the spring rates was the most influential method to gain the most lap time.

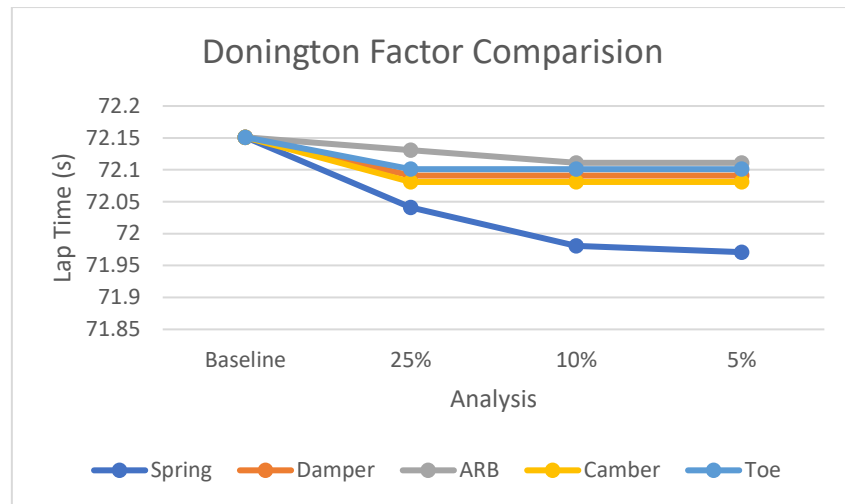


Fig. 14: Donington Factor Comparison Chart

Table 7: Donington Factor Lap Time Comparison in Seconds

Donington	Baseline	25%	10%	5%	Delta
Spring	72.151	72.041	71.981	71.971	-0.18
Damper	72.151	72.091	72.091	72.091	-0.06
ARB	72.151	72.131	72.111	72.111	-0.04
Camber	72.151	72.081	72.081	72.081	-0.07
Toe	72.151	72.101	72.101	72.101	-0.05

As seen in Table 7 above, the improvement in lap time with the spring rate optimization was of about -0.18 seconds, compared to improvements between -0.04 to -0.07 seconds for the rest of the factors. Hence, for the Donington Park national Circuit, the optimization of spring rates are the most influential factor for improvement in lap times.

9.1.2 Llandow

For Llandow, the lap time that the MCR race car could achieve during the baseline test without altering any of the factors and kept at 1 (0%) was 38.791 seconds.

9.1.2.1 Spring rate optimization

From Fig. 15 below, it is seen that the best lap times were achieved with lower front spring rates and higher rear spring rates. The most ideal setup in this case was identified to be 0.6 (-40%) front spring rate and 1.05 (+5%) rear spring rate compared to the baseline setup.

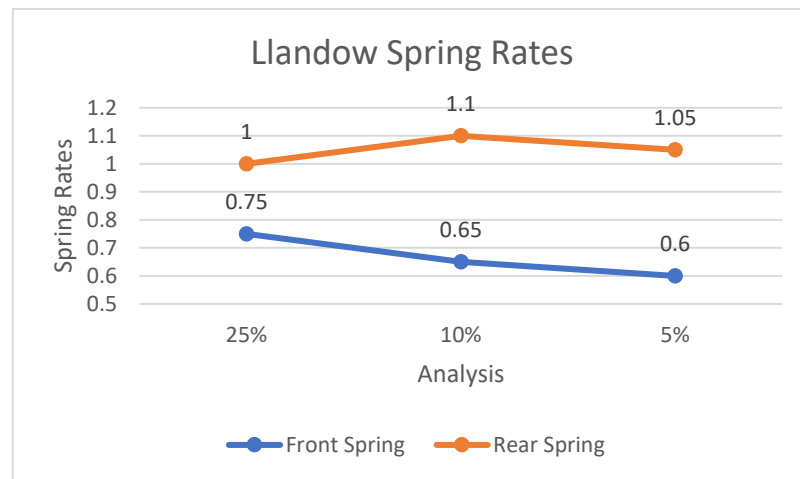


Fig. 15: Llandow Spring Rate Optimization Chart

Table 8 below shows that lap time worth 0.05 seconds was improved when only the spring rates were optimized.

Table 8: Llandow Spring Rate Optimization

Llandow	Baseline	25%	10%	5%
Front Spring	1	0.75	0.65	0.6
Rear Spring	1	1	1.1	1.05
Lap time (s)	38.791	38.761	38.751	38.741
Delta (s)	0	-0.03	-0.04	-0.05

9.1.2.2 Damper rate optimization

From Fig. 16 below, it is seen that the best lap times were achieved with higher damper rates both at the front and rear. The most ideal setup in this case was identified to be 1.3 (+30%) front damper rate and 1.1 (+10%) rear damper rate compared to the baseline setup.

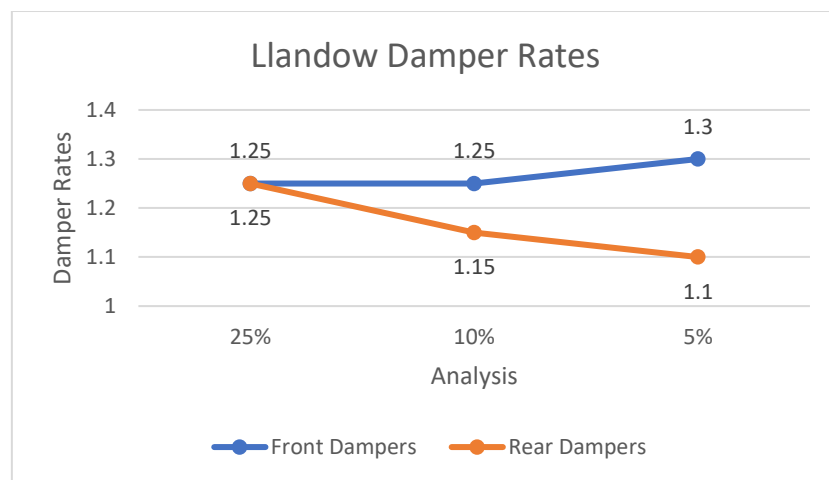


Fig. 16: Llandow Damper Rate Optimization Chart

Table 9 below shows that lap time worth 0.01 seconds was improved when only the damper rates were optimized.

Table 9: Llandow Damper Rate Optimization

Llandow	Baseline	25%	10%	5%
Front Dampers	1	1.25	1.25	1.3
Rear Dampers	1	1.25	1.15	1.1
Lap time (s)	38.791	38.781	38.781	38.781
Delta (s)	0	-0.01	-0.01	-0.01

9.1.2.3 Anti-roll Barr rate optimization

From Fig. 17 below, it is seen that the best lap times were achieved with higher anti-roll bar rates both at the front and rear. The most ideal setup in this case was identified to be 1.25 (+30%) for both the front and rear anti-roll bar rates compared to the baseline setup.

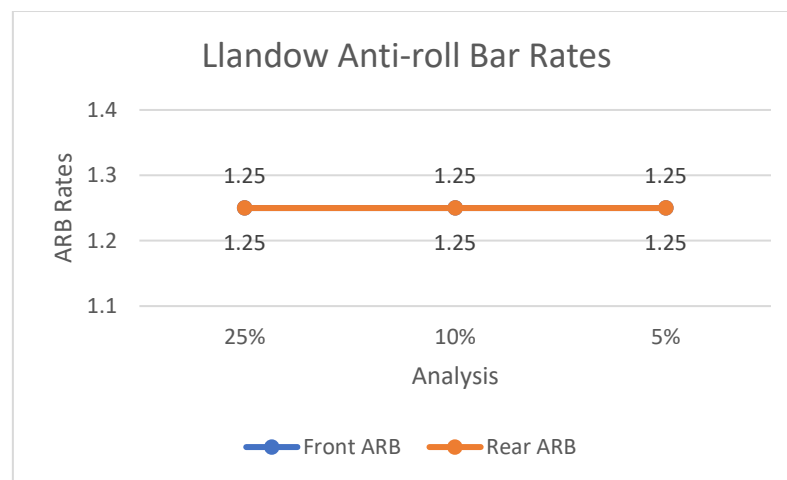


Fig. 17: Llandow Anti-roll Bar Rate Optimization Chart

Table 10 below shows that lap time worth 0.04 seconds was improved when only the anti-roll bar rates were optimized.

Table 10: Llandow Anti-roll Bar Rate Optimization

Llandow	Baseline	25%	10%	5%
Front ARB	1	1.25	1.25	1.25
Rear ARB	1	1.25	1.25	1.25
Lap time (s)	38.791	38.751	38.751	38.751
Delta (s)	0	-0.04	-0.04	-0.04

9.1.2.4 Camber angle optimization

From Fig. 18 below, it is seen that the best lap times were achieved with higher camber angles both at the front and rear. The most ideal setup in this case was identified to be 1.35 (+35%) front camber angle and 1.3 (+30%) rear camber angle compared to the baseline setup.

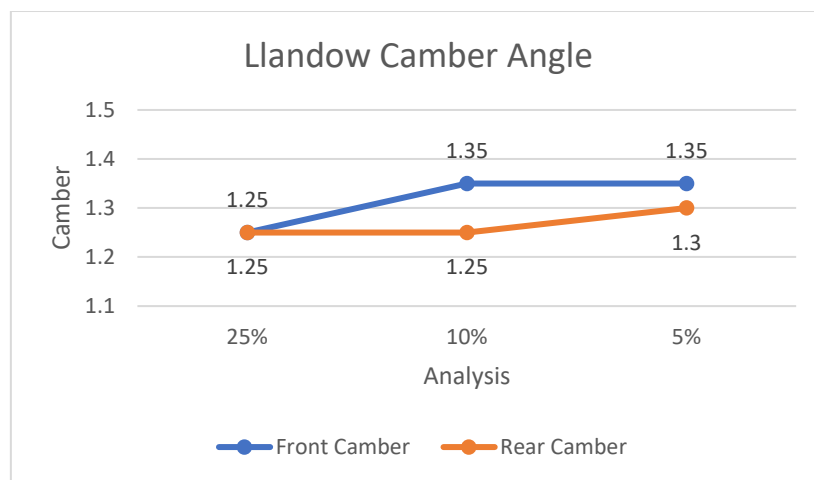


Fig. 18: Llandow Camber Angle Optimization Chart

Table 11 below shows that lap time worth 0.03 seconds was improved when only the camber angles were optimized.

Table 11: Llandow Camber Angle Optimization

Llandow	Baseline	25%	10%	5%
Front Camber	1	1.25	1.35	1.35
Rear Camber	1	1.25	1.25	1.3
Lap time (s)	38.791	38.771	38.761	38.761
Delta (s)	0	-0.02	-0.03	-0.03

9.1.2.5 Toe angle optimization

From Fig. 19 below, it is seen that the best lap times were achieved with lower toe angles both at the front and rear. The most ideal setup in this case was identified to be 0.75 (-25%) front toe angle and 0.9 (-10%) rear toe angle compared to the baseline setup.

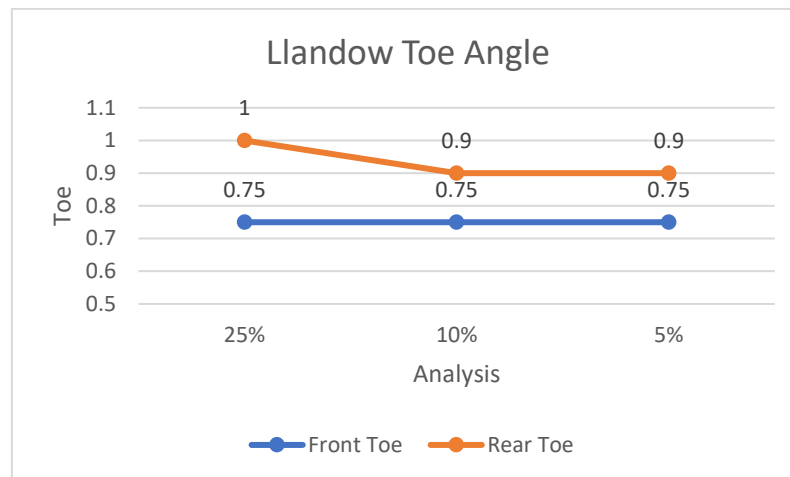


Fig. 19: Llandow Toe Angle Optimization Chart

Table 12: Llandow Toe Angle Optimization

Llandow	Baseline	25%	10%	5%
Front Toe	1	0.75	0.75	0.75
Rear Toe	1	1	0.9	0.9
Lap time (s)	38.791	38.781	38.781	38.781
Delta (s)	0	-0.01	-0.01	-0.01

Table 12 above shows that lap time worth 0.01 seconds was improved when only the toe angles were optimized.

9.1.2.6 Llandow one factor at a time comparison

After applying the one factor at a time approach for Llandow, it was discovered that optimization of each factor individually gave an improved lap time every time compared to the baseline setup. From Fig. 20 below, it is observed that out of all the factors, just altering the spring rates was the most influential method to gain the most lap time.

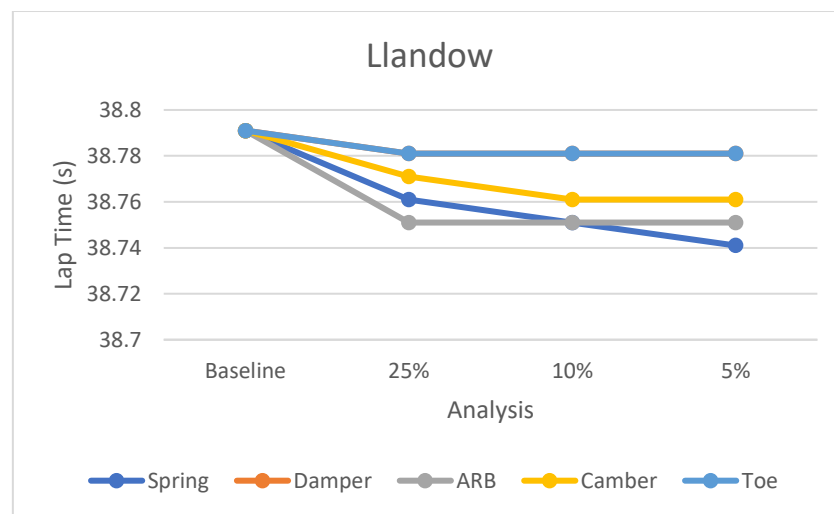


Fig. 20: Llandow Factor Comparison Chart

Table 13: Llandow Factor Lap Time Comparison in Seconds

Llandow	Baseline	25%	10%	5%	Delta
Spring	38.791	38.761	38.751	38.741	-0.05
Damper	38.791	38.781	38.781	38.781	-0.01
ARB	38.791	38.751	38.751	38.751	-0.04
Camber	38.791	38.771	38.761	38.761	-0.03
Toe	38.791	38.781	38.781	38.781	-0.01

As seen in Table 13 above, the improvement in lap time with the spring rate optimization was of about -0.05 seconds followed by anti-roll bar rate and camber angle at -0.04 and -0.03 seconds improvement respectively and lastly the damper rate

and toe angle with improvement of -0.01 seconds. Hence, for the Llandow, the optimization of spring rates are the most influential factor for improvement in lap times.

9.1.3 Pembrey

For Pembrey, the lap time that the MCR race car could achieve during the baseline test without altering any of the factors and kept at 1 (0%) was 56.241 seconds.

9.1.3.1 Spring rate optimization

From Fig. 21 below, it is seen that the best lap times were achieved with lower spring rates both at front and rear. The most ideal setup in this case was identified to be 0.75 (-25%) front spring rate and 0.9 (-10%) rear spring rate compared to the baseline setup.

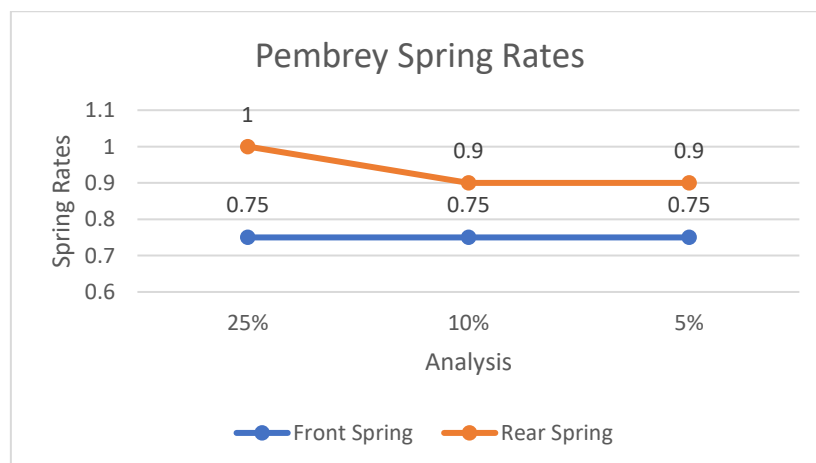


Fig. 21: Pembrey Spring Rate Optimization Chart

Table 14: Pembrey Spring Rate Optimization

Pembrey	Baseline	25%	10%	5%
Front Spring	1	0.75	0.75	0.75
Rear Spring	1	1	0.9	0.9
Lap time (s)	56.241	56.151	56.141	56.141
Delta (s)	0	-0.09	-0.1	-0.1

Table 14 above shows that lap time worth 0.1 seconds was improved when only the spring rates were optimized.

9.1.3.2 Damper rate optimization

From Fig. 22 below, it is seen that the best lap times were achieved with lower front damper rates and higher rear damper rates. The most ideal setup in this case was identified to be 0.95 (-5%) front damper rate and 1.25 (+25%) rear damper rate compared to the baseline setup.

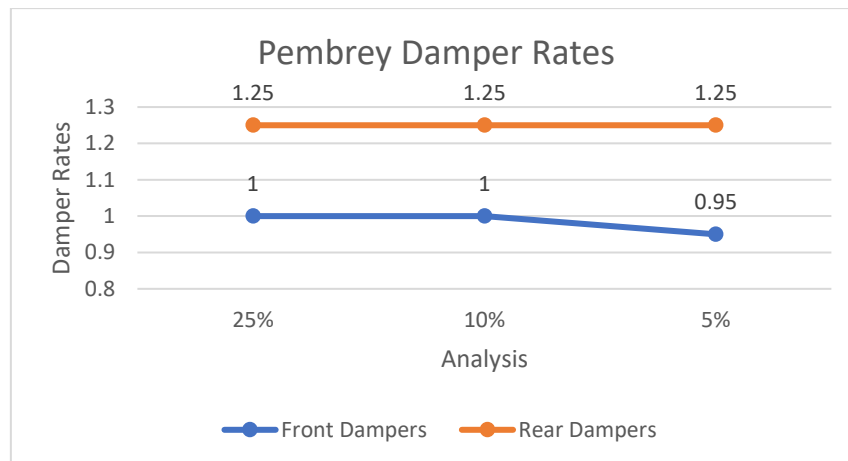


Fig. 22: Pembrey Damper Rate Optimization Chart

Table 15 below shows that lap time worth 0.01 seconds was improved when only the damper rates were optimized.

Table 15: Pembrey Damper Rate Optimization

Pembrey	Baseline	25%	10%	5%
Front Dampers	1	1	1	0.95
Rear Dampers	1	1.25	1.25	1.25
Lap time (s)	56.241	56.231	56.231	56.231
Delta (s)	0	-0.01	-0.01	-0.01

9.1.3.3 Anti-roll bar rate optimization

From Fig. 23 below, it is seen that the best lap times were achieved with higher anti-roll bar rates both at front and rear. The most ideal setup in this case was identified to be 1.05 (+5%) front anti-roll bar rate and 1.4 (+40%) rear anti-roll bar rate compared to the baseline setup.

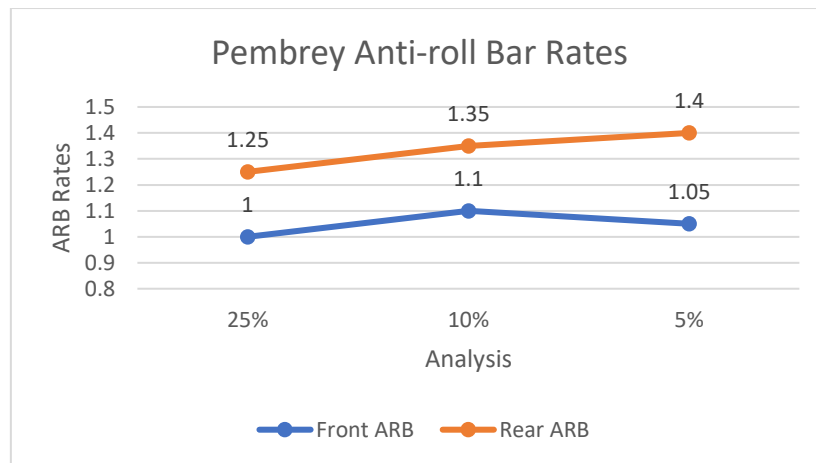


Fig. 23: Pembrey Anti-roll Bar Rate Optimization Chart

Table 16 below shows that lap time worth 0.04 seconds was improved when only the anti-roll bar rates were optimized.

Table 16: Pembrey Anti-roll Bar Rate Optimization

Pembrey	Baseline	25%	10%	5%
Front ARB	1	1	1.1	1.05
Rear ARB	1	1.25	1.35	1.4
Lap time (s)	56.241	56.211	56.201	56.201
Delta (s)	0	-0.03	-0.04	-0.04

9.1.3.4 Camber angle optimization

From Fig. 24 below, it is seen that the best lap times were achieved with higher front camber angle and lower rear camber angle. The most ideal setup in this case was identified to be 1.35 (+35%) front camber angle and 0.9 (-10%) rear camber angle compared to the baseline setup.

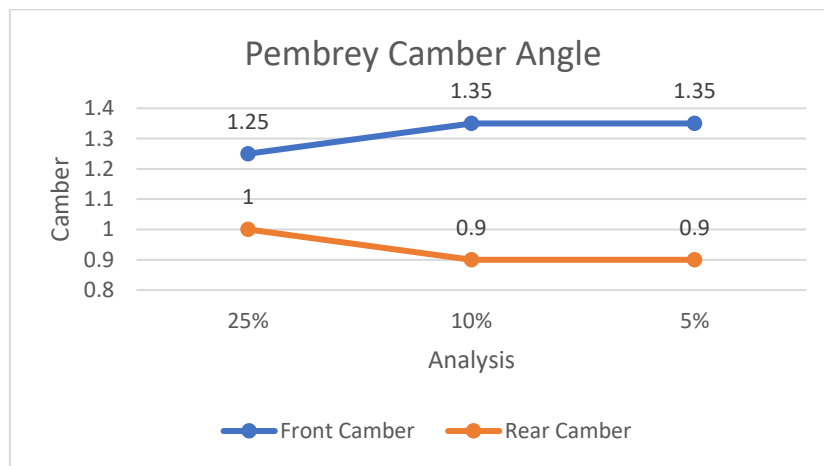


Fig. 24: Pembrey Camber Angle Optimization Chart

Table 17 below shows that lap time worth 0.12 seconds was improved when only the camber angles were optimized.

Table 17: Pembrey Camber Angle Optimization

Pembrey	Baseline	25%	10%	5%
Front Camber	1	1.25	1.35	1.35
Rear Camber	1	1	0.9	0.9
Lap time (s)	56.241	56.171	56.121	56.121
Delta (s)	0	-0.07	-0.12	-0.12

9.1.3.5 Toe angle optimization

From Fig. 25 below, it is seen that the best lap times were achieved with lower front toe angle and higher rear toe angle. The most ideal setup in this case was identified to be 0.6 (-40%) front toe angle and 1.3 (+30%) rear toe angle compared to the baseline setup.

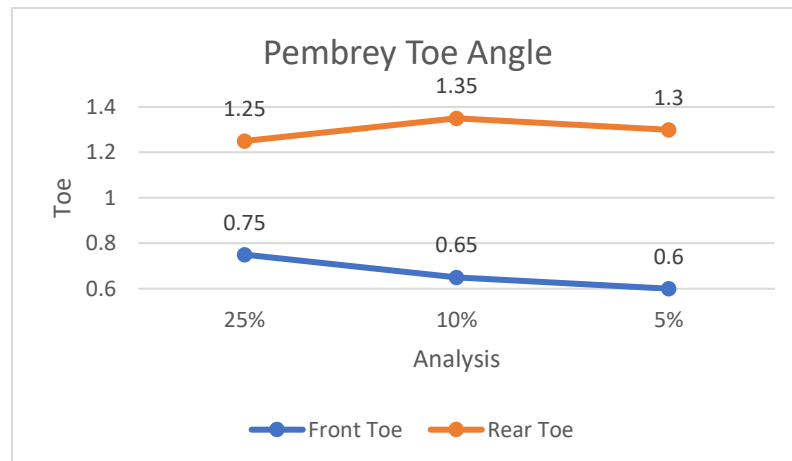


Fig. 25: Pembrey Toe Angle Optimization Chart

Table 18 below shows that lap time worth 0.08 seconds was improved when only the toe angles were optimized.

Table 18: Pembrey Toe Angle Optimization

Pembrey	Baseline	25%	10%	5%
Front Toe	1	0.75	0.65	0.6
Rear Toe	1	1.25	1.35	1.3
Lap time (s)	56.241	56.171	56.171	56.161
Delta (s)	0	-0.07	-0.07	-0.08

9.1.3.6 Pembrey one factor at a time comparison

After applying the one factor at a time approach for Pembrey, it was discovered that optimization of each factor individually gave an improved lap time every time compared to the baseline setup. From Fig. 26 below, it is observed that out of all the factors, just altering the camber angles was the most influential method to gain the most lap time.

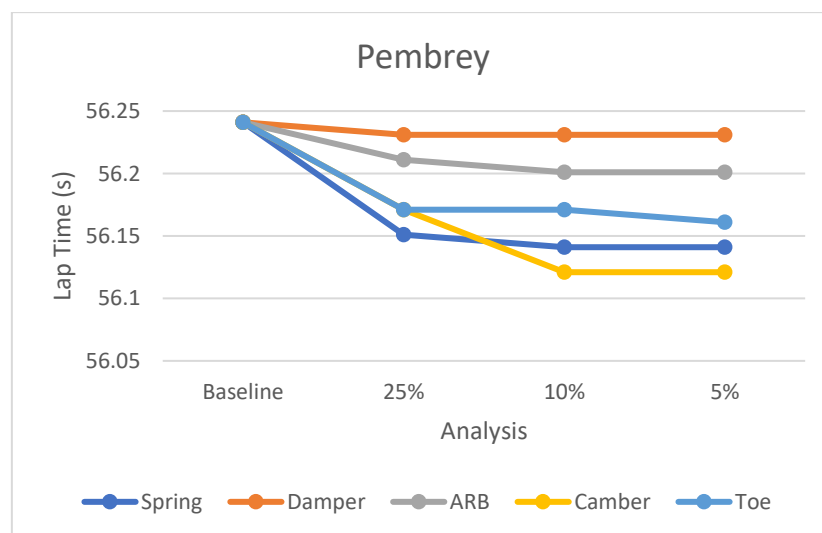


Fig. 26: Llandow Factor Comparison Chart

Table 19: Llandow Factor Lap Time Comparison in Seconds

Pembrey	Baseline	25%	10%	5%	Delta
Spring	56.241	56.151	56.141	56.141	-0.1
Damper	56.241	56.231	56.231	56.231	-0.01
ARB	56.241	56.211	56.201	56.201	-0.04
Camber	56.241	56.171	56.121	56.121	-0.12
Toe	56.241	56.171	56.171	56.161	-0.08

As seen in Table 19 above, the improvement in lap time was the highest with camber angle optimization, with an improvement of about 0.18 seconds, closely followed by spring rate and toe angle optimizations at 0.1 and 0.08 seconds improvement respectively. Lastly, the anti-roll bar rate and damper rate optimizations gave an improvement of 0.04 and -0.01 seconds respectively. Hence, for the Pembrey, the optimization of camber angle is identified to be the most influential factor for improvement in lap times.

9.1.4 Spring Rate Optimization

As seen below in Fig. 27, the spring rate optimization process yielded the best result for Donington Park National Circuit with a lap time improvement of 0.18 seconds. This was followed by Pembrey with a lap time improvement of 0.1 seconds. Lastly, Llandow gave the least lap time improvement of 0.05 seconds.

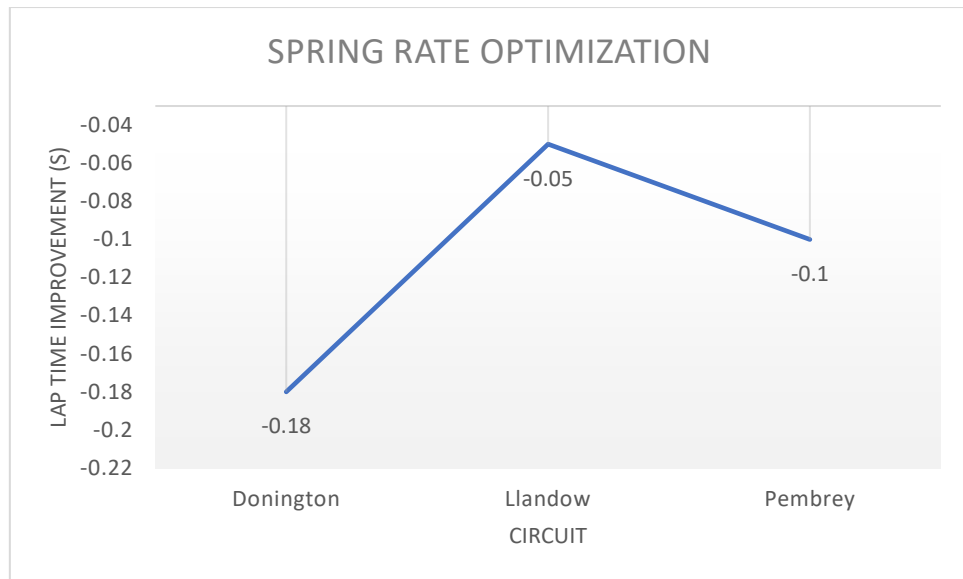


Fig. 27: Spring Rate Optimization

9.1.5 Damper Rate Optimization

As seen below in Fig. 28, the damper rate optimization process yielded the best result for Donington Park National Circuit with a lap time improvement of 0.06 seconds. This was followed by both Llandow and Pembrey with lap time improvements of 0.01 seconds each.

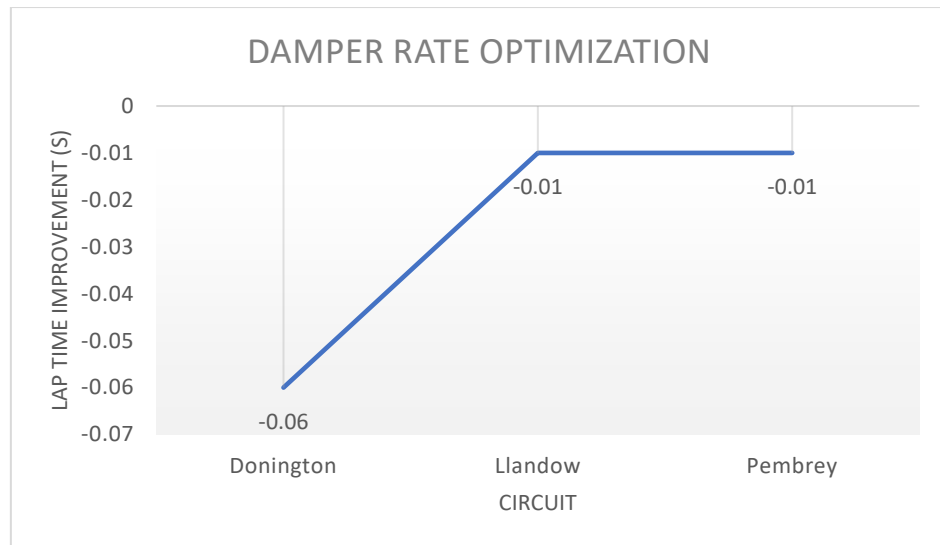


Fig. 28: Damper Rate Optimization

9.1.6 Anti-roll Bar Rate Optimization

During the anti-roll bar rate optimization process, lap time improvement worth 0.04 seconds was observed for all the three circuits of Donington Park National Circuit, Llandow and Pembrey, as seen in Fig. 29 below.

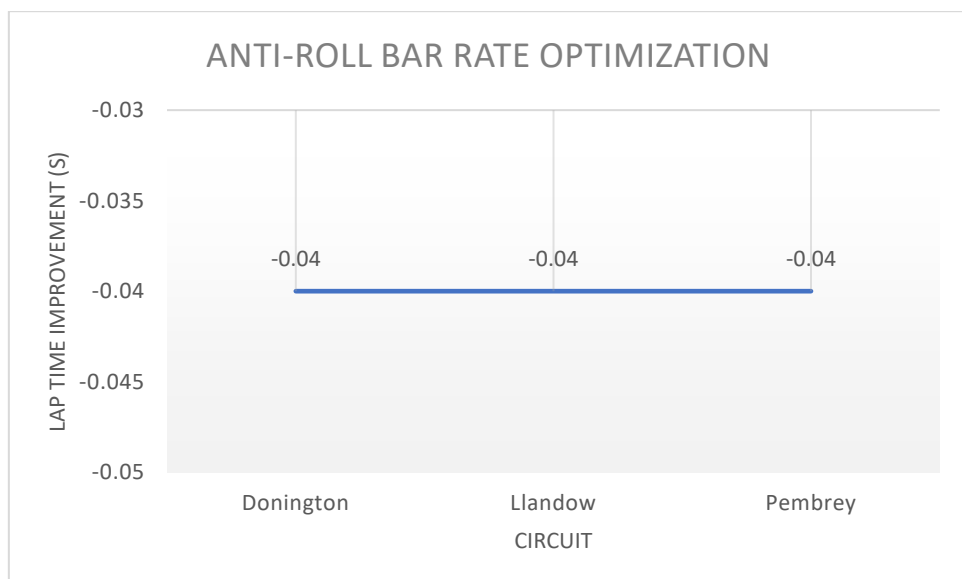


Fig. 29: Anti-roll Bar Rate Optimization

9.1.7 Camber Angle Optimization

As seen below in Fig. 30, the camber angle optimization process yielded the best result for Pembrey with a lap time improvement of 0.12 seconds. This was followed by Donington Park National Circuit with a lap time improvement of 0.07 seconds. Lastly, Llandow gave the least lap time improvement of 0.03 seconds.

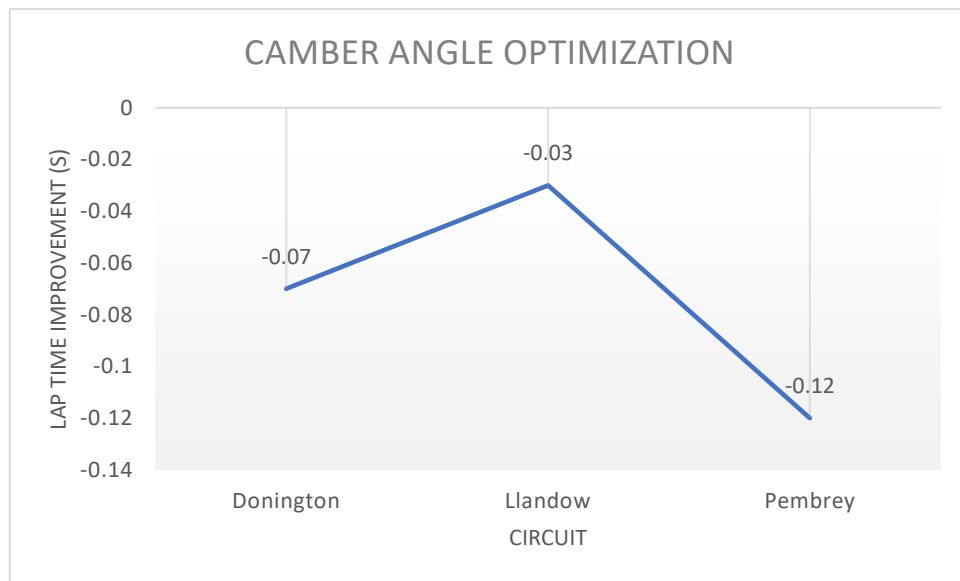


Fig. 30: Camber Angle Optimization

9.1.8 Toe Angle Optimization

As seen below in Fig. 31, the toe angle optimization process yielded the best result for Pembrey with a lap time improvement of 0.08 seconds. This was followed by Donington Park National Circuit with a lap time improvement of 0.05 seconds. Lastly, Llandow gave the least lap time improvement of 0.01 seconds.

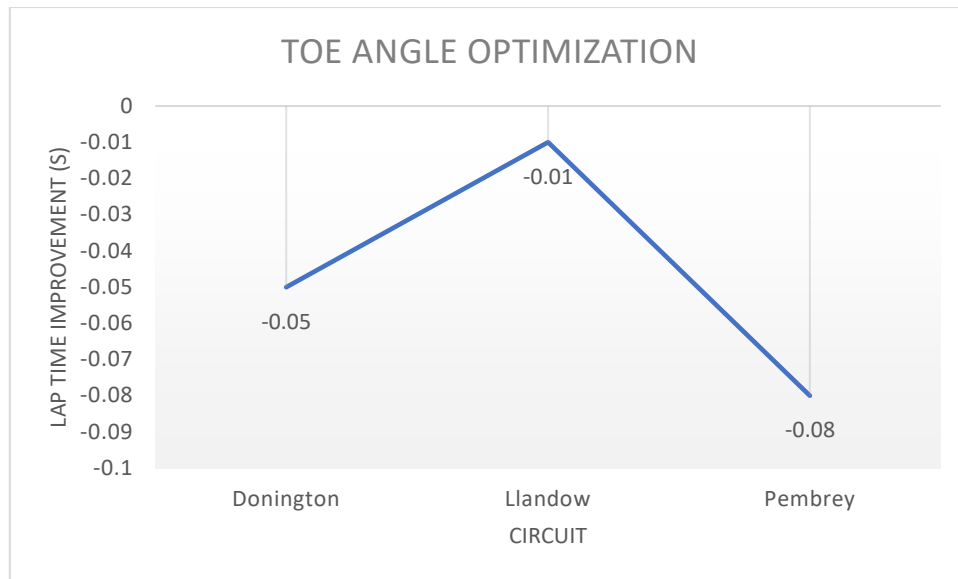


Fig. 31: Toe Angle Optimization

9.2 FULL FACTORIAL DESIGN OF EXPERIMENT

9.2.1 Group 1- Spring, damper and anti-roll bar rates

After the OFAT method was used to identify the optimized setup for each of the factors, these setups were used for further analysis using full factorial DOE method. Once the spring rates, damper rates and anti-roll bar rates were optimized using the full factorial DOE, the final setups obtained varied compared to the ones from the OFAT method.

9.2.1.1 Donington Park National Circuit

Here, after the full factorial optimization, the front and rear spring rate setups were identified to be 0.55 (-45%) and 0.85 (-15%) compared to 0.6 (-40%) and 0.8 (-20%) from OFAT method respectively. Similarly, the front and rear damper rate setups were

identified to be 1.05 (+5%) and 1.3 (+30%) compared to 1 (0%) and 1.25 (+25%) from OFAT method respectively. Lastly, the front and rear anti-roll bar rate setups were identified to be 0.6 (-40%) and 0.65 (-35%) compared to 0.65 (-35%) and 0.65 (-35%) from OFAT method respectively. The same can be seen below in Table 20.

Table 20: Donington Full Factorial DOE for Group 1

Donington	Baseline	OFAT	Full Factorial
Spring Rate Front	1	0.6	0.55
Spring Rate Rear	1	0.8	0.85
Damper Rate Front	1	1	1.05
Damper Rate Rear	1	1.25	1.3
ARB Rate Front	1	0.65	0.6
ARB Rate Rear	1	0.65	0.65

The full factorial design of experiment method for group 1 also helped in improving the lap time achieved by the race car. In Donington, the OFAT method improved the lap time the most when the spring rates were optimized, i.e., by 0.18 seconds compared to the baseline performance. With full factorial DOE, the lap time improved further by 0.27 seconds compared to the baseline performance. The same can be seen below in Fig. 32 where the lap times are compared.

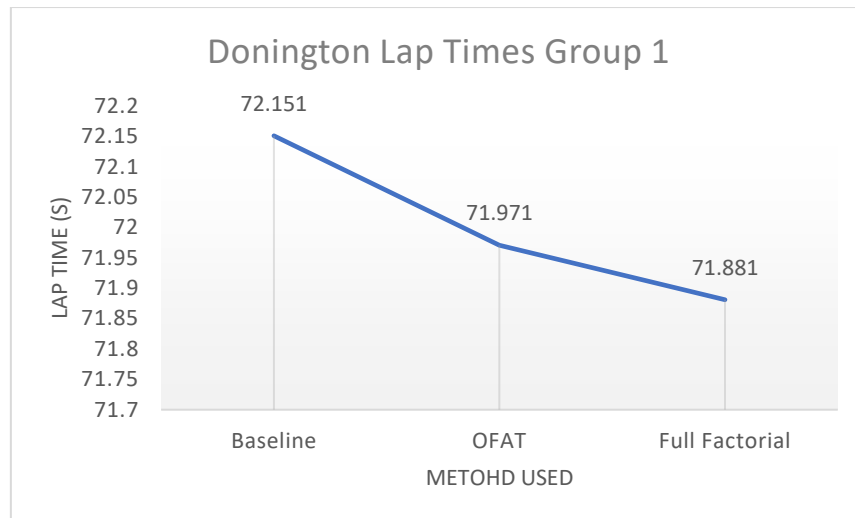


Fig. 32: Donington Full Factorial Optimization for Group 1

9.2.1.2 Llandow

Here, after the full factorial optimization, the front and rear spring rate setups were identified to be 0.55 (-45%) and 1.1 (+10%) compared to 0.6 (-40%) and 1.05 (+5%) from OFAT method respectively. Similarly, the front and rear damper rate setups were identified to be 1.3 (+30%) and 1.15 (+15%) compared to 1.3 (+30%) and 1.1 (+10%) from OFAT method respectively. Lastly, the front and rear anti-roll bar rate setups were identified to be 1.25 (+25%) and 1.25 (+25%) respectively, which was the same as OFAT method. The same can be seen below in Table 21.

Table 21: Llandow Full Factorial DOE for Group 1

Llandow	Baseline	OFAT	Full Factorial
Spring Rate Front	1	0.6	0.55
Spring Rate Rear	1	1.05	1.1
Damper Rate Front	1	1.3	1.3
Damper Rate Rear	1	1.1	1.15
ARB Rate Front	1	1.25	1.25
ARB Rate Rear	1	1.25	1.25

The full factorial design of experiment method for group 1 also helped in improving the lap time achieved by the race car. In Llandow, the OFAT method improved the lap time the most when the spring rates were optimized, i.e., by 0.05 seconds compared to the baseline performance. With full factorial DOE, the lap time improved further by 0.09 seconds compared to the baseline performance. The same can be seen below in Fig. 33 where the lap times are compared.

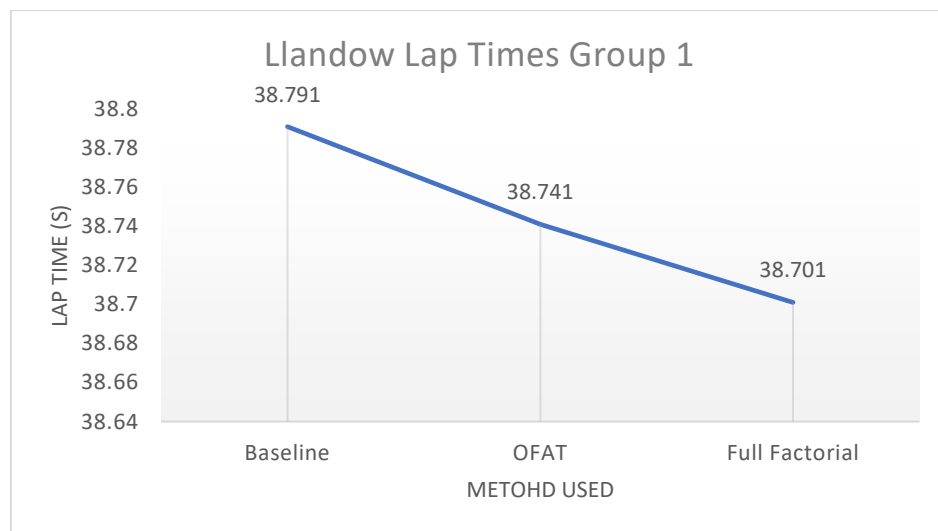


Fig. 33: Llandow Full Factorial Optimization for Group 1

9.2.1.3 Pembrey

Here, after the full factorial optimization, the front and rear spring rate setups were identified to be 0.8 (-20%) and 0.85 (-15%) compared to 0.75 (-25%) and 0.9 (-10%) from OFAT method respectively. Similarly, the front and rear damper rate setups were identified to be 0.9 (-10%) and 1.3 (+30%) compared to 0.95 (-5%) and 1.25 (+25%) from OFAT method respectively. Lastly, the front and rear anti-roll bar rate setups

were identified to be 1.1 (+10%) and 1.45 (+45%) compared to 1.05 (+5%) and 1.4 (+40%) from OFAT method respectively. The same can be seen below in Table 22.

Table 22: Pembrey Full Factorial DOE for Group 1

Pembrey	Baseline	OFAT	Full Factorial
Spring Rate Front	1	0.75	0.8
Spring Rate Rear	1	0.9	0.85
Damper Rate Front	1	0.95	0.9
Damper Rate Rear	1	1.25	1.3
ARB Rate Front	1	1.05	1.1
ARB Rate Rear	1	1.4	1.45

The full factorial design of experiment method for group 1 also helped in improving the lap time achieved by the race car. In Pembrey, the OFAT method improved the lap time the most when the camber angles were optimized, i.e., by 0.12 seconds compared to the baseline performance. With full factorial DOE, the lap time improved further by 0.13 seconds compared to the baseline performance. The same can be seen below in Fig. 34 where the lap times are compared.

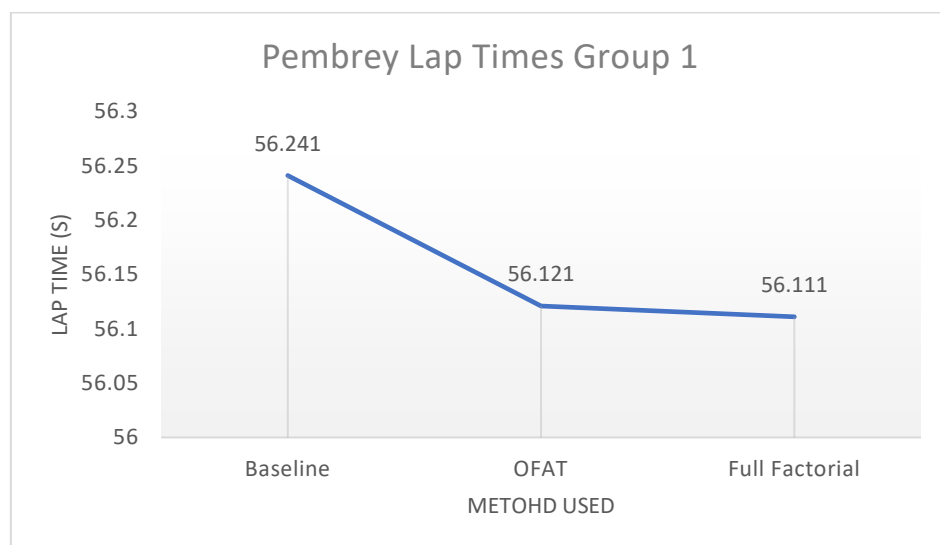


Fig. 34: Pembrey Full Factorial Optimization for Group 1

9.2.2 Group 2- Camber and toe angles

Just like the factors in group 1, full factorial DOE was applied to the camber and toe angles of the car as well.

9.2.2.1 Donington Park Nation Circuit

Here, after the full factorial optimization, the front and rear camber angles setups were identified to be 0.7 (-30%) and 1.3 (+30%) compared to 0.75 (-25%) and 1.25 (+25%) from OFAT method respectively. Similarly, the front and rear toe angle setups were identified to be 0.7 (-30%) and 1.2 (+20%) compared to 0.75 (+25%) and 1.15 (+15%) from OFAT method respectively. The same can be seen below in Table 23.

Table 23: Donington Full Factorial DOE for Group 2

Donington	Baseline	OFAT	Full Factorial
Camber Front	1	0.75	0.7
Camber Rear	1	1.25	1.3
Toe Front	1	0.75	0.7
Toe Rear	1	1.15	1.2

The full factorial design of experiment method for group 2 also helped in improving the lap time achieved by the race car. In Donington, the OFAT method improved the lap time the most when the spring rates were optimized, i.e., by 0.18 seconds compared to the baseline performance. With full factorial DOE for group 2, the lap time only improved further by 0.09 seconds compared to the baseline performance. The same can be seen below in Fig. 35 where the lap times are compared.

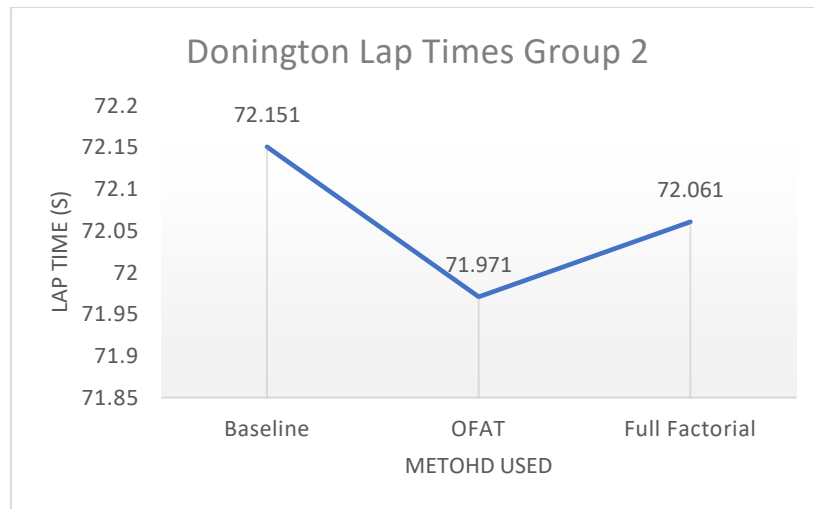


Fig. 35: Donington Full Factorial Optimization for Group 2

9.2.2.2 Llandow

Here, after the full factorial optimization, the front and rear camber angle setups were identified to be 0.7 (-30%) and 1.3 (+30%) compared to 0.75 (-25%) and 1.25 (+25%) from OFAT method respectively. Similarly, the front and rear toe angle setups were identified to be 0.7 (-30%) and 1.2 (+20%) compared to 0.75 (+25%) and 1.15 (+15%) from OFAT method respectively. The same can be seen below in Table 24.

Table 24: Llandow Full Factorial DOE for Group 2

Llandow	Baseline	OFAT	Full Factorial
Camber Front	1	1.35	1.4
Camber Rear	1	1.3	1.35
Toe Front	1	0.75	0.7
Toe Rear	1	0.9	0.95

The full factorial design of experiment method for group 2 also helped in improving the lap time achieved by the race car. In Llandow, the OFAT method improved the lap time the most when the spring rates were optimized, i.e., by 0.05 seconds compared to the baseline performance. With full factorial DOE for group 2, the lap time improved by the same amount of 0.05 seconds compared to the baseline performance. The same can be seen below in Fig. 36 where the lap times are compared.

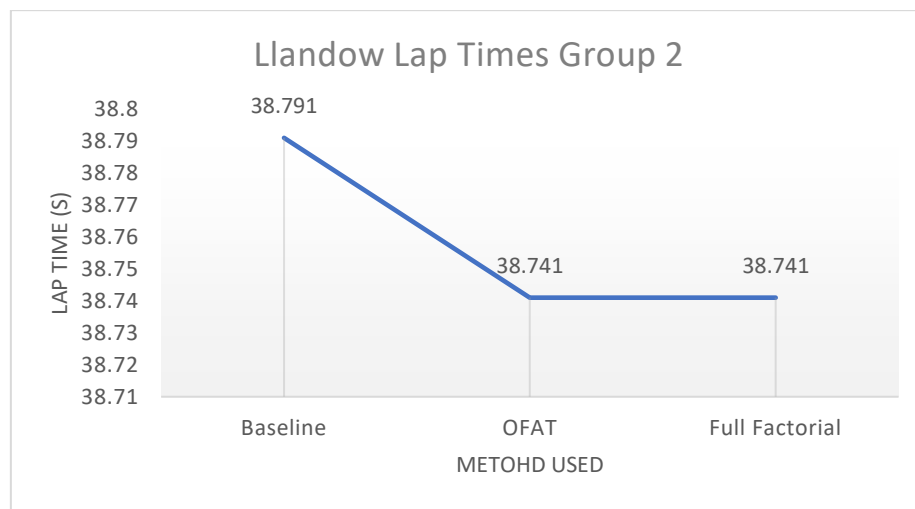


Fig. 36: Llandow Full Factorial Optimization for Group 2

9.2.2.3 Pembrey

Here, after the full factorial optimization, the front and rear camber angle setups were identified to be 1.35 (+35%) and 0.95 (-5%) compared to 1.35 (+35%) and 0.9 (-10%) from OFAT method respectively. Similarly, the front and rear toe angle setups were identified to be 0.65 (-35%) and 1.25 (+25%) compared to 0.65 (-35%) and 1.35 (+35%) from OFAT method respectively. The same can be seen below in Table 25.

Table 25: Pembrey Full Factorial DOE for Group 2

Pembrey	Baseline	OFAT	Full Factorial
Camber Front	1	1.35	1.35
Camber Rear	1	0.9	0.95
Toe Front	1	0.65	0.65
Toe Rear	1	1.35	1.25

The full factorial design of experiment method for group 2 also helped in improving the lap time achieved by the race car. In Pembrey, the OFAT method improved the lap time the most when the camber angles were optimized, i.e., by 0.12 seconds compared to the baseline performance. With full factorial DOE, the lap time improved further by 0.14 seconds compared to the baseline performance. The same can be seen below in Fig. 37 where the lap times are compared.

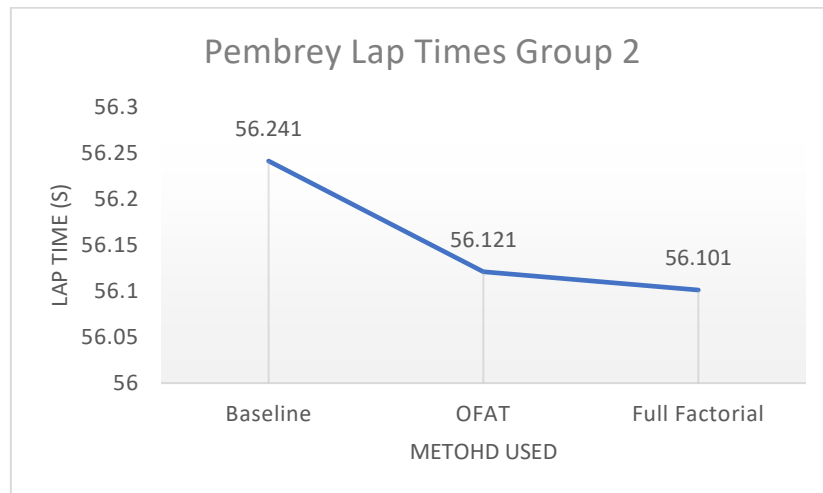


Fig. 37: Pembrey Full Factorial Optimization for Group 2

9.3 COMBINING GROUP 1 AND GROUP 2

Here, design of experiment was applied one last time to check if two independent full factorial DOE can be combined together. For this, the resultant setups identified from group 1 and group 2 were combined together to check if it is possible to achieve even faster lap times. Since the results achieved from group 1 were a lot more influential in improving lap times, they were kept constant and the factors from group 2 were altered again by another 5%, as mentioned above in Section 6.5. the results achieved by this method are mentioned below.

9.3.1 Donington Park National Circuit

The best lap time in Donington was achieved during the full factorial DOE approach for group 1 with a lap time of 71.881 seconds. Upon further optimizing the camber and toe angles, the best setup for the front and rear camber angles were identified to be 0.75 (-25%) and 1.35 (+35%) compared to 0.7 (-30%) and 1.3 (+30%) from group 2 respectively. Similarly, the best setup for the front and rear toe angles were identified to be 0.65 (-35%) and 1.25 (+25%) compared to 0.7 (-30%) and 1.2 (+20%) from group 2 respectively.

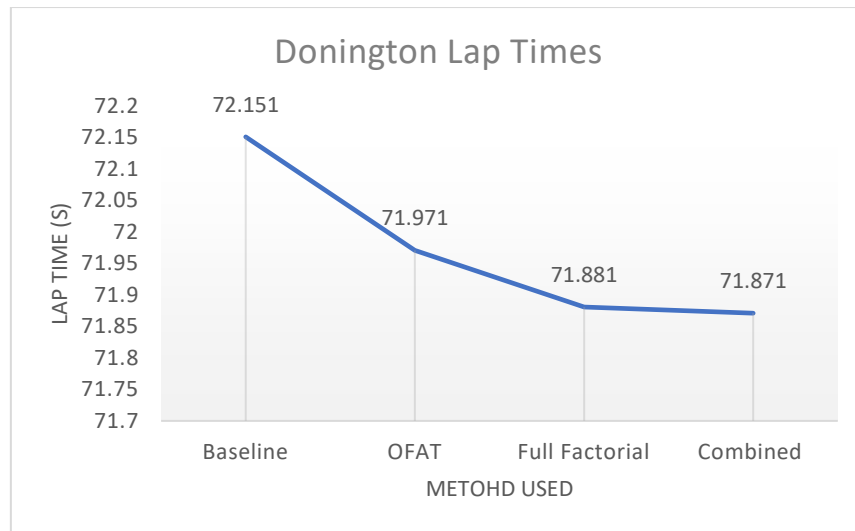


Fig. 38: Donington Lap Times

As seen in Fig. 38 above, the lap time achieved with this setup was 71.871 seconds, which is 0.01 seconds quicker than the lap time from full factorial group 1. Therefore, the combined method is feasible for Donington Park National Circuit.

9.3.2 Llandow

The best lap time in Llandow was achieved during the full factorial DOE approach for group 1 with a lap time of 38.701 seconds. Upon further optimizing the camber and toe angles, the best setup for the front and rear camber angles were identified to be 1.4 (+40%) and 1.3 (+30%) compared to 1.4 (+40%) and 1.35 (+35%) from group 2 respectively. Similarly, the best setup for the front and rear toe angles were identified to be 0.65 (-35%) and 0.9 (-10%) compared to 0.7 (-30%) and 0.95 (-5%) from group 2 respectively.

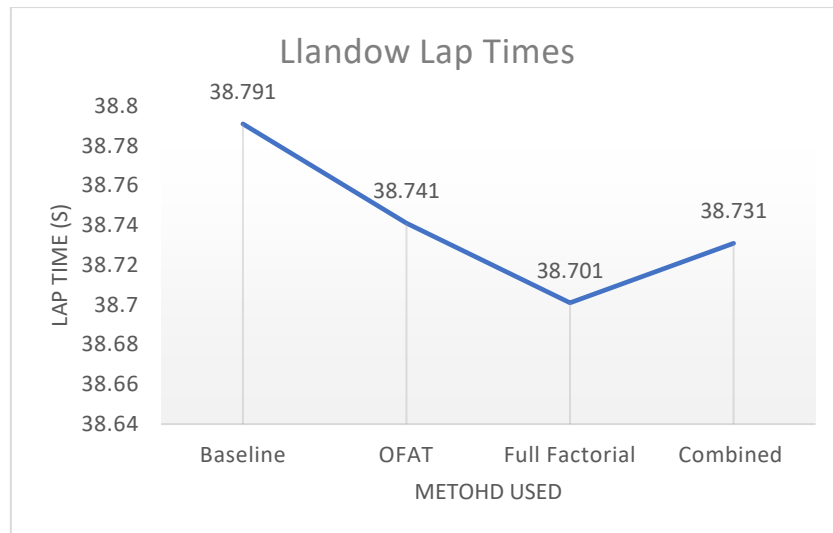


Fig. 39: Llandow Lap Times

As seen in Fig. 39 above, the lap time achieved with this setup was 38.731 seconds, which is 0.03 seconds slower than the lap time from full factorial group 1. Therefore, the combined method is not feasible for Llandow.

9.3.3 Pembrey

The best lap time in Pembrey was achieved during the full factorial DOE approach for group 2 with a lap time of 56.101 seconds. Upon further optimizing the camber and toe angles, the best setup for the front and rear camber angles were identified to be 1.4 (+40%) and 1.3 (+30%) compared to 1.4 (+40%) and 1.35 (+35%) from group 2 respectively. Similarly, the best setup for the front and rear toe angles were identified to be 0.65 (-35%) and 0.9 (-10%) compared to 0.7 (-30%) and 0.95 (-5%) from group 2 respectively.

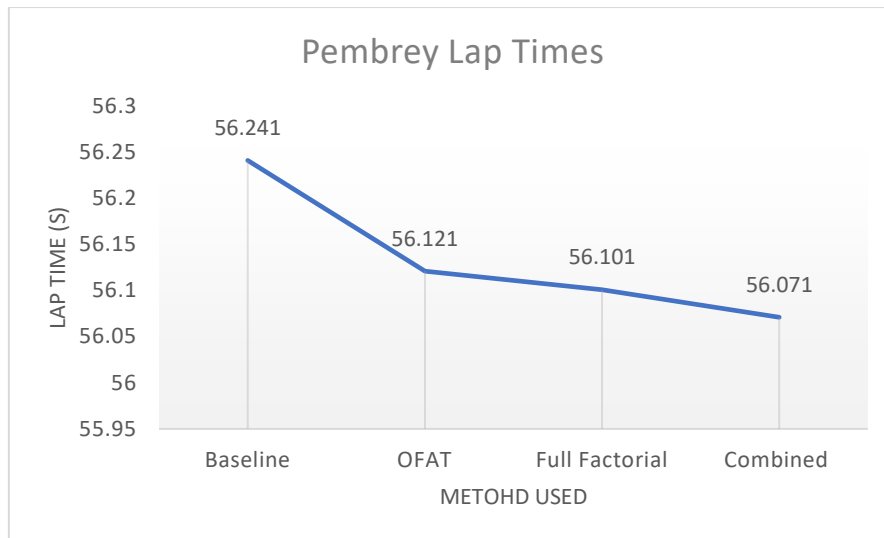


Fig. 40: Pembrey Lap Times

As seen in Fig. 40 above, the lap time achieved with this setup was 56.071 seconds, which is 0.03 seconds faster than the lap time from full factorial group 2. Therefore, the combined method is feasible for Pembrey.

9.4 JOUNCE GRAPHS

Fig. 41 and Fig. 42 below show the camber angle vs jounce and toe angle vs jounce respectively for the front left wheel, for the different setups, starting from the original baseline setup to the optimized setups identified for each track. It can be seen that the trends for each setup for both camber and toe angles are the same. A lower camber angle was better only for Donington while higher camber angle was better for Llandow and Pembrey. For the toe angle, a lower angle was identified to be beneficial for all the circuits.

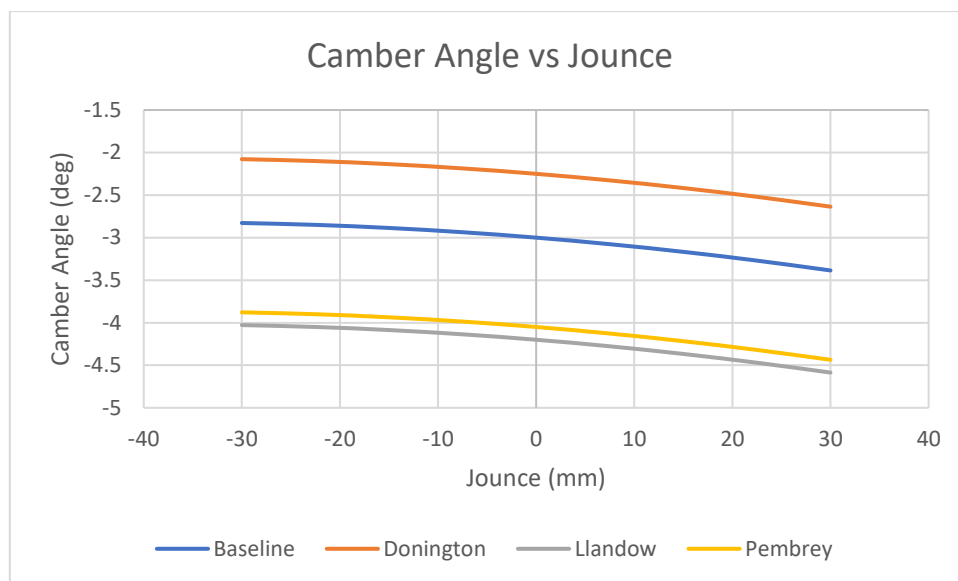


Fig. 41: Camber Angle vs Jounce

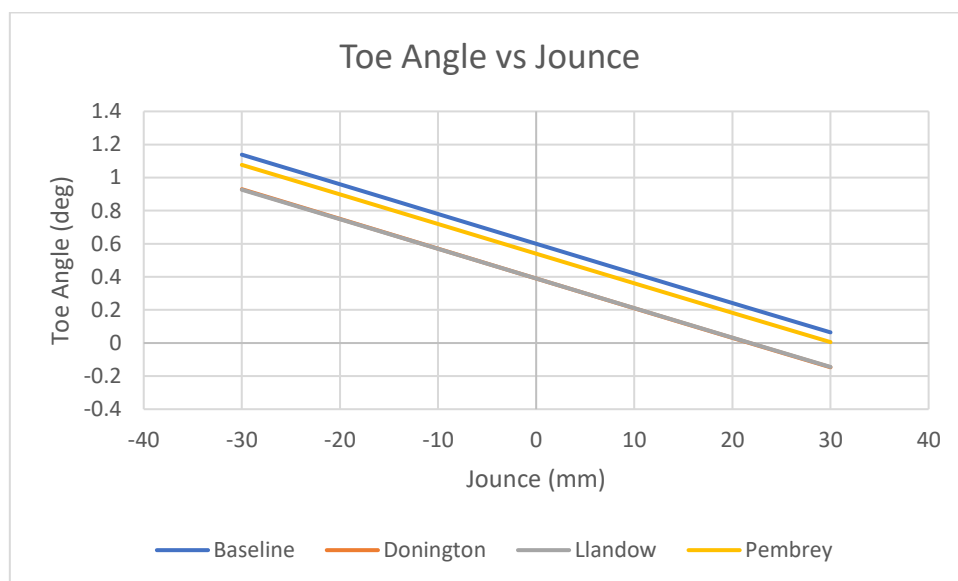


Fig. 42: Toe Angle vs Jounce

9.5 SLIP ANGLE

Fig. 43 below compares the variation in the slip angle for the tyres for different camber angle values. Here, the camber angles tested are -3 degrees, -2.25 degrees, -4.2 degrees and -4.05 degrees which are the camber angles from the baseline model, optimized Donington setup, optimized Llandow setup and optimized Pembrey setup respectively at 2000 N preload. As seen below, the graphs for all the camber angles almost completely coincide with minimal variation in lateral force. Also, the maximum lateral force for all the camber angles are achieved for the same slip angles of around -9 degrees and +7 degrees.

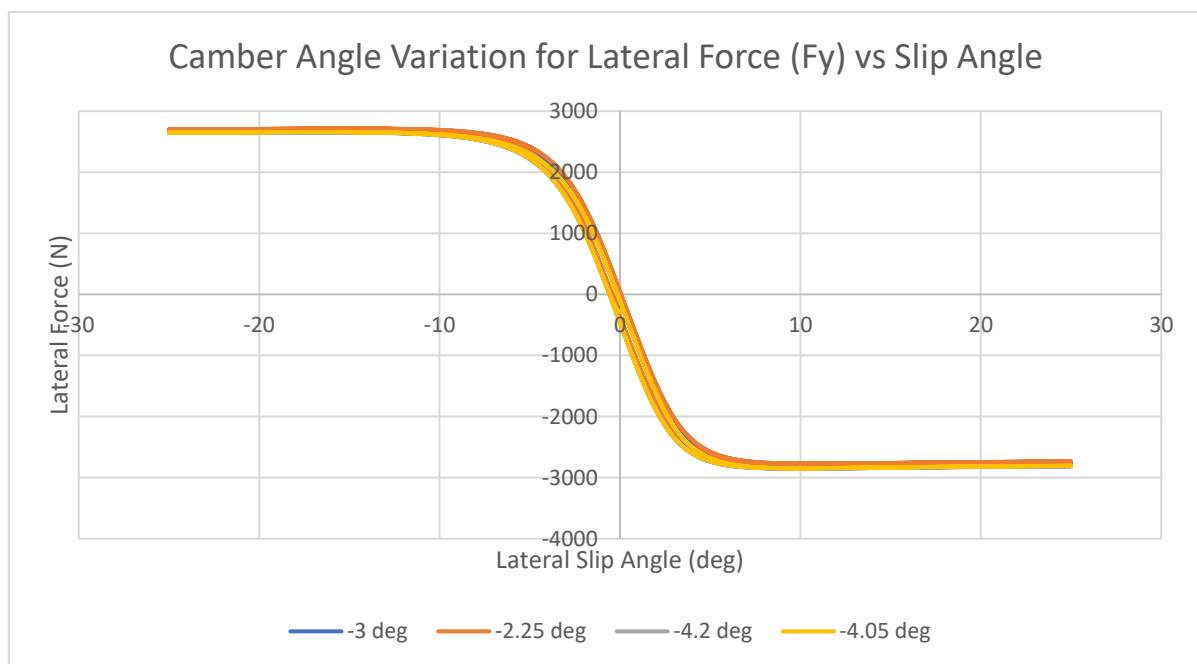


Fig. 43: Camber Angle Variation for Lateral Force vs Slip Angle

The vertical moment, also known as the self-aligning torque, is the moment that tries to realign the wheels in the forward direction when there is a steering angle input. This is a result of the lateral force and pneumatic trail of the tyre (Song et al., 2014). The peak torque here

is achieved at a much smaller slip angle compared to lateral force, as seen around -3 degrees and +2 degrees in Fig. 44 below.

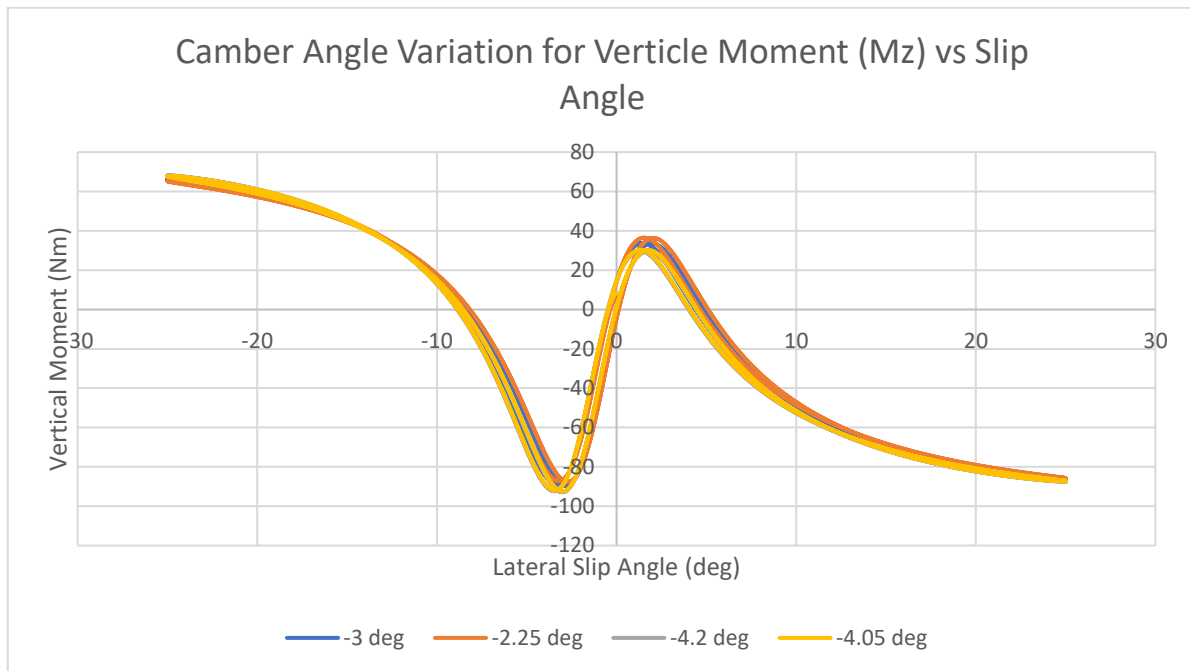


Fig. 44: Camber Angle Variation for Vertical Moment vs Slip Angle

9.6 LATERAL FORCE VARIATION

As it was observed that the camber angle did not have any significant effect on the slip angle. By using the baseline camber angle as an example, the lateral force acting on the tyres was varied to observe its effect on the slip angle. This was done for three different lateral forces of 2000 N, 4000 N and 6000 N which are marked in red, blue and green respectively in Fig. 45 below. For 2000 N load, the maximum slip angle was achieved around -9 degrees and +7 degrees. For 4000 N load, the maximum slip angle was achieved around -14 degrees and +12 degrees. For 6000 N load, the maximum slip angle was achieved around -15 degrees and +13 degrees.

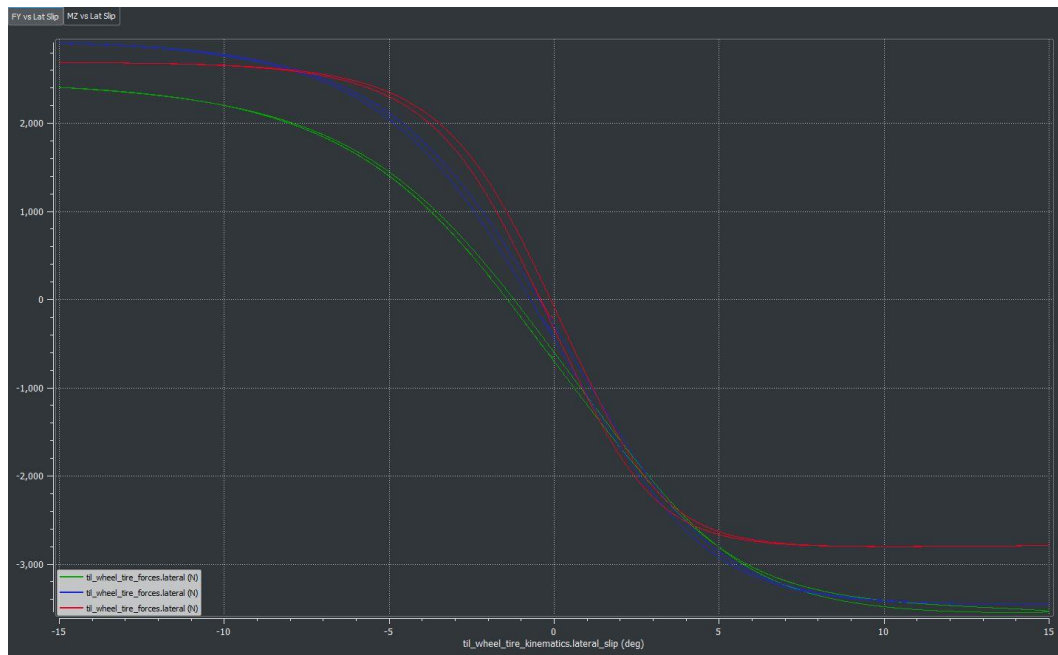


Fig. 45: Varied Lateral Forces vs Slip Angle

Fig. 46 below shows the graph for the vertical moment, also known as the self-aligning torque against slip angle. Here, it can be seen that peak torque values are achieved at different slip angles due to variation in the pre-loads.

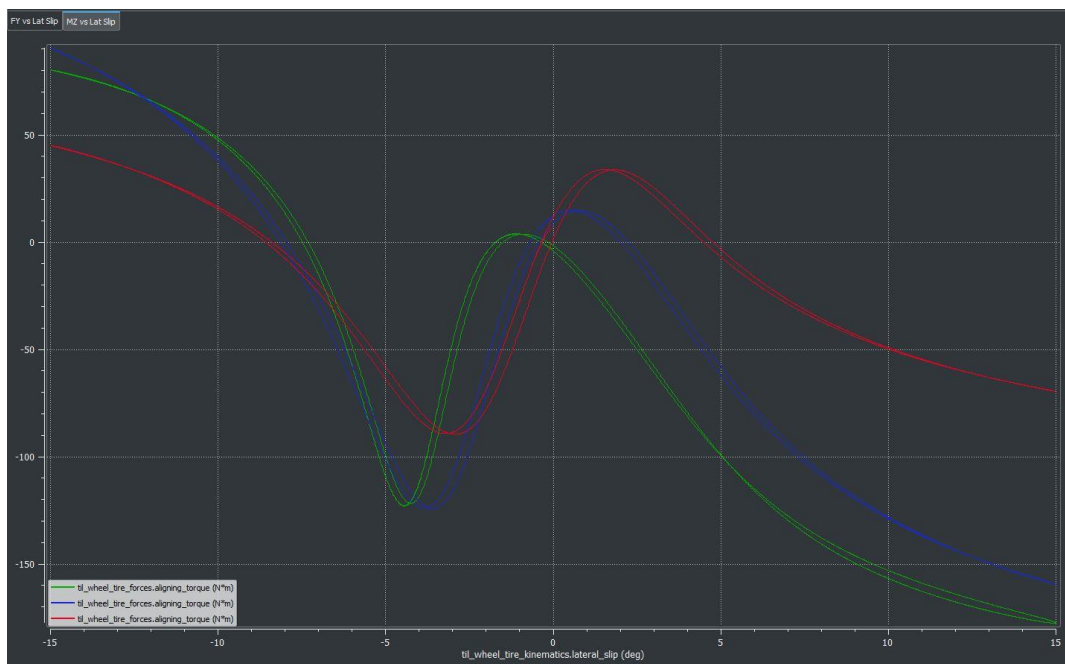


Fig. 46: Varied Lateral Forces for Vertical Moment vs Slip Angle

10. DISCUSSIONS

From the process of using VI Grade, it is observed that the process of simulating the operation of a race car is effective in generating results that replicate that of the operation of an actual race car. In this project, this was observed during the validation process. Here, the lap time achieved by the actual MCR race car was compared to the lap time achieved using the model of the race car in VI Grade. The actual race car had achieved a lap time of 70.342 seconds while the model in VI Grade was able to achieve a lap time of 72.151 seconds, which is a difference of 2.428%. Similarly, the difference in maximum speed, lateral acceleration and longitudinal acceleration were 0.048%, 6.989% and 3.758% respectively.

When applying the design of experiment approaches, each method used here led to improvement in lap time compared to the baseline lap times for each circuit. When one factor at a time method was applied, the fastest lap times for Donington and Llandow were achieved when the spring rates were optimized. In contrast, the fastest lap time for Pembrey was achieved when the camber angle was optimised.

Using full factorial design of experiment method proved to be more beneficial than that of using one factorial at a time. For each case of full factorial DOE, the lap times improved drastically. Here, this method was applied using by dividing the different factors into two groups. For Donington and Llandow the group with the factors of spring rates, damper rates and anti-roll bar rates gave the better results whereas for Pembrey, the group where camber and toe angles were optimized gave the better result. This shows that for each circuit, there are different methods of gaining lap times, depending on the characteristics of the circuit. In the end, when the setups achieved from optimizing both the groups were integrated together, the resultant lap times achieved for Donington and Pembrey were even quicker.

But the same was not the case for Llandow where the combined setup proved to be slower than when only the spring rates, damper rates and anti-roll bar rates were optimized.

In the end, the fastest lap time achieved by optimization of the suspension setup in Donington was 71.871 seconds, which was 0.28 seconds quicker compared to the baseline setup. The fastest lap time achieved by optimization of the suspension setup in Llandow was 38.701 seconds, which was 0.09 seconds quicker compared to the baseline setup. Lastly, the fastest lap time achieved by optimization of the suspension setup in Pembrey was 56.071 seconds, which was 0.14 seconds quicker compared to the baseline setup.

For Donington Park, the ideal setup was achieved with lower front and rear spring rates, front and rear anti-roll bars, front camber angle and front toe angle compared to higher front and rear damper rates, rear camber angle and rear toe angle.

For Llandow, the ideal setup was achieved with lower front spring rate and front and rear toe angles compared to higher rear spring rate, front and rear damper rates, front and rear anti-roll bar rates and front and rear camber angles.

For Pembrey, the ideal setup was achieved with lower front and rear spring rates, front damper rate, rear camber angle and front toe angle compared to higher rear damper rate, front and rear anti-roll bars, front camber angle and rear toe angle.

Next, optimizing only spring rates was most beneficial for Donington with 0.18 seconds improvement, optimizing only damper rates was most beneficial for Donington with 0.06 seconds improvement, optimizing only anti-roll bar rates was equally beneficial for all the circuits with 0.04 seconds improvement, optimizing only camber angle was most beneficial

for Pembrey with 0.12 seconds improvement and optimizing only toe angle was most beneficial for Pembrey with 0.08 seconds improvement.

Lastly, Table 26, Table 27 and Table 28 below show the lap times gained after every step of the various DOE methods were applied.

Table 26: Donington Lap Times

Donington	Baseline	OFAT	Full Factorial	Combined
Lap time (s)	72.151	71.971	71.881	71.871
Delta (s)	0	-0.18	-0.27	-0.28

Table 27: Llandow Lap Times

Llandow	Baseline	OFAT	Full Factorial	Combined
Lap time (s)	38.791	38.741	38.701	38.731
Delta (s)	0	-0.05	-0.09	-0.06

Table 28: Pembrey Lap Times

Pembrey	Baseline	OFAT	Full Factorial	Combined
Lap time (s)	56.241	56.121	56.101	56.071
Delta (s)	0	-0.12	-0.14	-0.17

11. ERROR ESTIMATES AND LIMITATIONS

Even when maximum effort is put into minimizing the amount of error made during the course of any project, there are still certain things that might go unnoticed at the time. As a result, there is always a chance of having some errors. These errors may occur due to multiple reasons, be it in the form of human error, due to faulty equipment or performance of the available tools and machines. First and foremost, there might be errors in the model of the MCR race car available for simulation. This may be in the form of error in measuring the different hard points of the race car, due to faulty measuring equipment or any other negligence during the process of evaluating the real car. Similarly, once all the data from the real car is gathered, there might be some error during building the model and entering all the details into VI CarRealTime. If there was an error in any of this process, there is a huge possibility of making a big difference to the final model built for the simulation and as a result, the resultant output data might be inaccurate.

There might be some errors that may have occurred while using VI Road as well. As the road files being used here were built by someone else, it is impossible to guarantee that every detail of the track was accurately taken care of. As far as the path files are concerned, even though they were specifically built for this project, there still might be small deviations from the most ideal racing line that the actual race car would take in real life. This issue is usually accounted for in the 'Maximum Allowable Path Distance' option in the MaxPerformance section, but there still might be a slightly different line that would give the best results during the simulations. On a similar note, when the flags are placed on the road in order to create the path file, VI Road automatically creates a spline for the racing line. Even though the spline is very smooth, there might be small deviations based on the placement of each flag which

might require small steering inputs which are not really necessary while driving the actual car. These small steering input might affect the maximum acceleration and speed of the simulation model for that section of the road, leading to minute changes in final lap time achieved.

A limitation of VI Grade is its lack of variation in the track conditions. In the simulations, it always considers to the track to be in the most ideal condition for the friction level added to the model of the road. But this is far from how a track behaves in the real world. The different things like the track temperature, track evolution, presence of marbles on the track, effects of the different wind directions on the aerodynamics etc. which are all factors that affect the overall dynamics of the car, are not taken into consideration in VI Grade. When subjected to these factors in real life, these can majorly change how the car behaves and hence changing the end results for the overall performance of the car.

Another major limitation of VI CarRealTime and MaxPerformance specifically is that it considers everything to be constant. It does not take into account things like changes in fuel load and oil levels. This is a highly desirable property when the end goal is to achieve the fastest lap time possible. But because of this, it is not possible to assess how the change in mass would affect the overall performance of the car in a long run over a race distance. As a consequence, it is not possible to identify if the chosen setup is good enough in terms of tyre degradation, which is one of the most important factors while deciding a setup.

The factors that were chosen for the evaluation in this project were spring rates, damper rates, anti-roll bar rates, camber angles and toe angles for both the front and rear suspension setups of the car. While these are the major factors that highly influence the overall performance of a vehicle, its performance is not just limited to these factors. There are other

factors such as tyre pressure, jounce, rebound etc. affect the overall performance of the car as well and hence the setup could theoretically be improved even further if these factors are looked into.

A limitation of using full factorial design of experiment is that it is a very time consuming process. Depending on the number of factors, the number of levels and the time taken to complete one iteration, the simulations could go on for multiple days at a time. This is the reason why the factors were divided into different groups, else the maximum estimated simulation time for one of the circuits was calculated to be around 18 days, which is not time efficient considering only 10 factors were optimized.

Lastly, one of the most major limitation is the tyre model in question. The tyre suppliers are usually very secretive about the integral details of their tyres in order to protect their intellectual property. As a result, it is very hard to find details about the same publicly available. Because of this reason, regenerating a model of the tyre in VI Grade is very hard. In cases where a model of a tyre is generated anyway, the chances that the model is inaccurate is very high.

12. FURTHER WORK

In this project, the factors that were optimized were the spring rates, damper rates, anti-roll bar rates, camber angles and toe angles. Although these are some very influential factors, the ultimate performance of the any vehicle is not limited to these. Hence, further studies can be done by optimizing a range of different factors such as tyre pressures, jounce, rebound etc.

Since using full factorial DOE method for a range of factors at once took multiple days to complete the simulations, the factors were divided into two groups in this project. This was done due to limited availability of time for the completion of the project. But in case multiple weeks to complete the simulations are available, all the factors can be optimized together without having to divide them into different groups as this method should theoretically give better results.

There is a chance to create a better tyre model as well. Olazagoitia et al. (2020) have explained how Artificial Neural Networks can be used to identify the different tyre model parameters. These methods can be used to generate a more accurate tyre model and the setups of the car can be tested using the new model for higher accuracy.

Lastly, the model of the MCR race car used here was fairly accurate to an extent but not perfect. There is a scope of improving the model to increase its accuracy. This would lead to higher performance resemblance when compared to the actual race car. Another fellow student is optimizing the aerodynamics of the car for their project. The car with the optimized aerodynamics could be used in the future to check of the setups identified here for the current model translates to even better performance in comparison to that achieved in this project.

13. TIMELINE

The timeline for the completion of the project is shown below in Fig. 47. This included various stages such as project planning, research, rectifying car model, adding path files, validation, baseline simulations, applying DOE approaches, post processing and writing up the final report.

TASK	MAY	JUNE	JULY	AUGUST	SEPTEMBER
PROJECT PLANNING					
RESEARCH					
RECTIFYING CAR MODEL					
ADDING PATH FILES					
VALIDATION					
BASELINE SIMULATIONS					
APPLYING DOE APPROACHES					
POST PROCESSING					
REPORT WRITE UP					

Fig. 47: Timeline

14. CONCLUSION

In this project, the feasibility of a simulation tool VI Grade was tested for replicating and developing vehicle setups for various race circuits. The vehicle chosen for this was the MCR race car used by the UWTSD race team in the SRCC Sport 2000 racing series. The circuits chosen for the test were Donington Park National Circuit, Llandow and Pembrey. The process began with rectifying an existing model of the race car to the current specifications and creating path files for the circuits in use. Then, the model of the race car was validated against real data from the actual race car in Donington and lap time achieved using simulations was found to be relatively accurate with a variation of 2.428%. Once the model was validated, design of experiment approaches were applied, starting with one factor at a time (OFAT) method at each circuit. The factors that were optimized were spring rates, damper rates, anti-roll bar rates, camber angles and toe angles for both front and rear. Every optimized factor gave better lap times compared to the baseline lap times. For Donington and Llandow, optimizing spring rates gave the best results whereas optimizing camber angle gave the best results for Pembrey. Then, full factorial DOE was applied, first by splitting the factors into groups and then combining them to see its effectiveness. In the end, the optimized lap times for Donington, Llandow and Pembrey were 0.28 seconds, 0.09 seconds and 0.17 seconds quicker compared to the baseline lap times.

To conclude, it is possible to use simulation tools such as VI Grade in order to develop a vehicle and test its setups. It might not always give the exact result due to simulation limitations but it is possible to get fairly accurate results. Hence, it is possible to use it as a tool for developing and optimizing vehicle setups.

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APPENDIX 1

1.1 VI Road

On opening the VI Road application, first and foremost, it opens up the screen where there is the option to load the road and path files. Fig. 48 below shows the interface for the same.

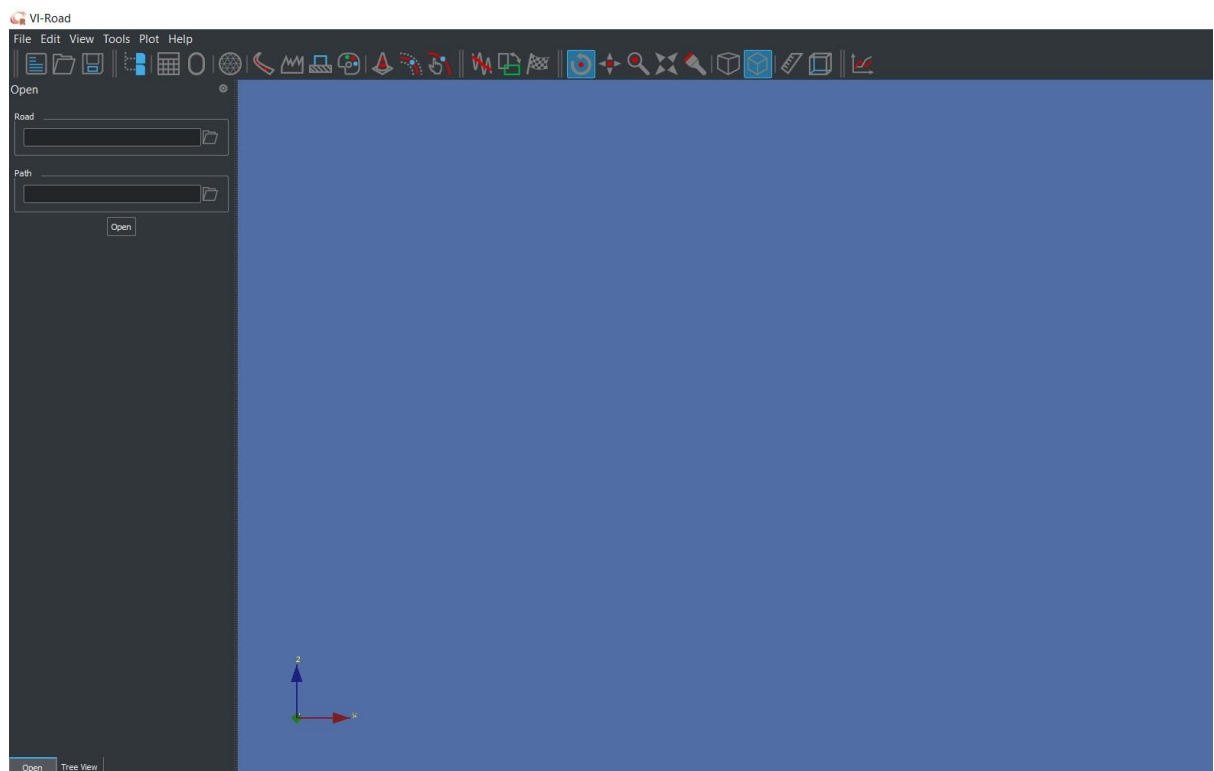


Fig. 48: VI Road

Since we already have all the road files, the first step here is to open one of them. In this case, the road file from the Donington Park National Circuit is used as an example. Upon loading the road file, it gives the complete layout of the road surface along with the kerbs on the edges of the track, as shown in Fig. 49 below. Next, in order to create the path file for creating the path through which the model in the simulation would travel, the path builder option is chosen from the tool bar on the top. This opens up a panel for the control points. Here, the points on the track through which the path is to be created can be

specified. This can be done simply by clicking on the different points of circuit map which was loaded as the road file. All the points on the circuit are shown using flags and the coordinates of each of these points can be seen with respect to the origin.

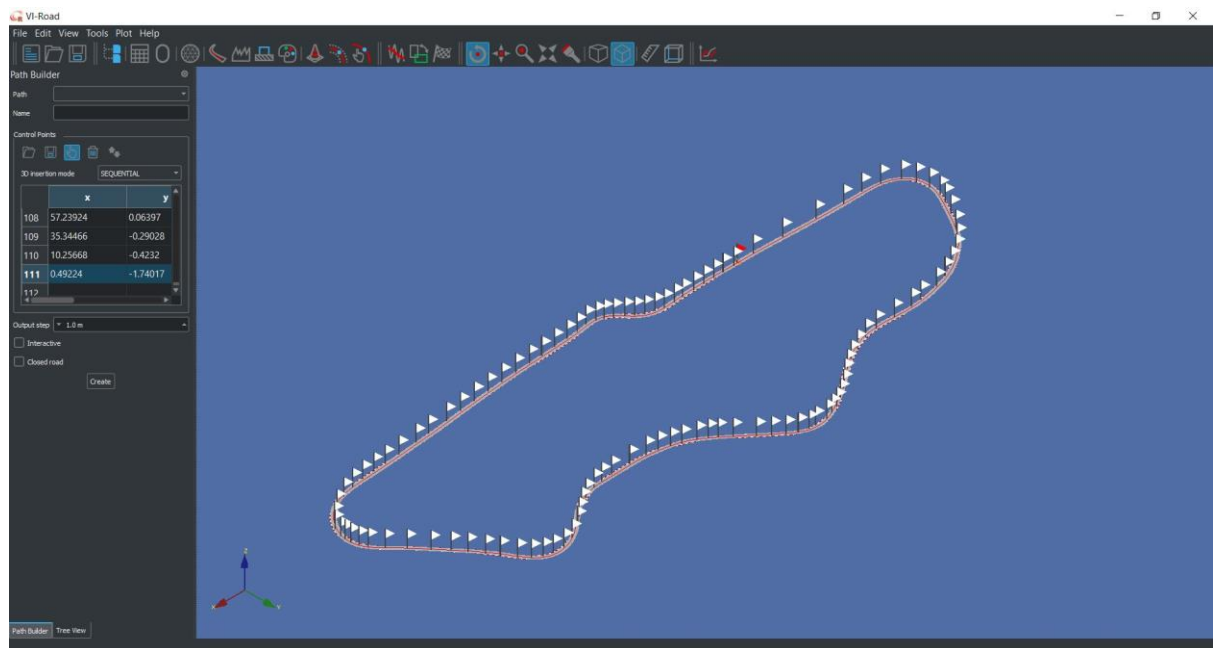


Fig. 49: Setting the Control Points

Once all the points are marks, clicking on the create button gives the racing line through which the car would travel through. The same can be seen in Fig. 50 below where the line in blue is the racing line and the line in red is the centre line of the road file. This can then be saved and exported. Upon exporting, two files are created by the name it was exported, firstly the road file in .rdf format and then the path file in .drd format.

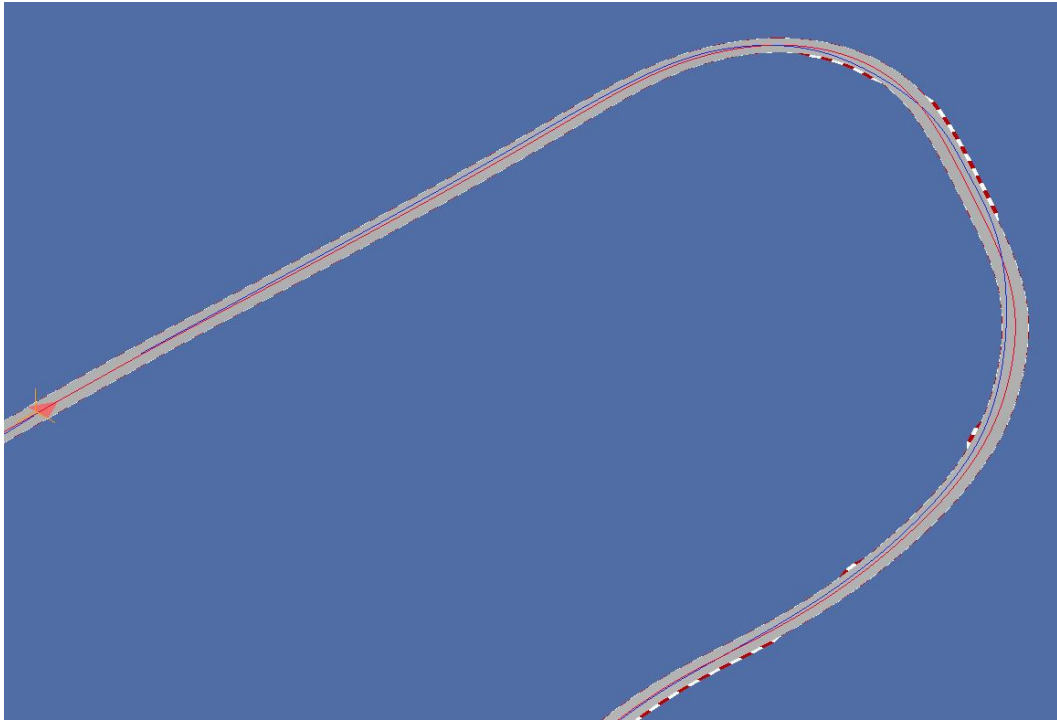


Fig. 50: Racing line

This is how the path file is created using VI Road. Just like the example of Donington Park National Circuit shown here, the path files for the other two circuits, i.e., Llandow and Pembrey were created as well.

1.2 VI CarRealTime

1.2.1 Build Mode

VI CarRealTime is the application where all the simulations take place. Upon starting VI CarRealTime, the desired model can be loaded from the build section in the tool bar on the top. Since we had the entire model built already, the only part thing that needed to be done was to load it. After loading the model, in the Build Mode section, all the different subsystems of the car such as the front and rear suspensions, steering

system, body, front and rear wheel/tires, brakes and powertrain were loaded. Fig. 51 below shows the same.

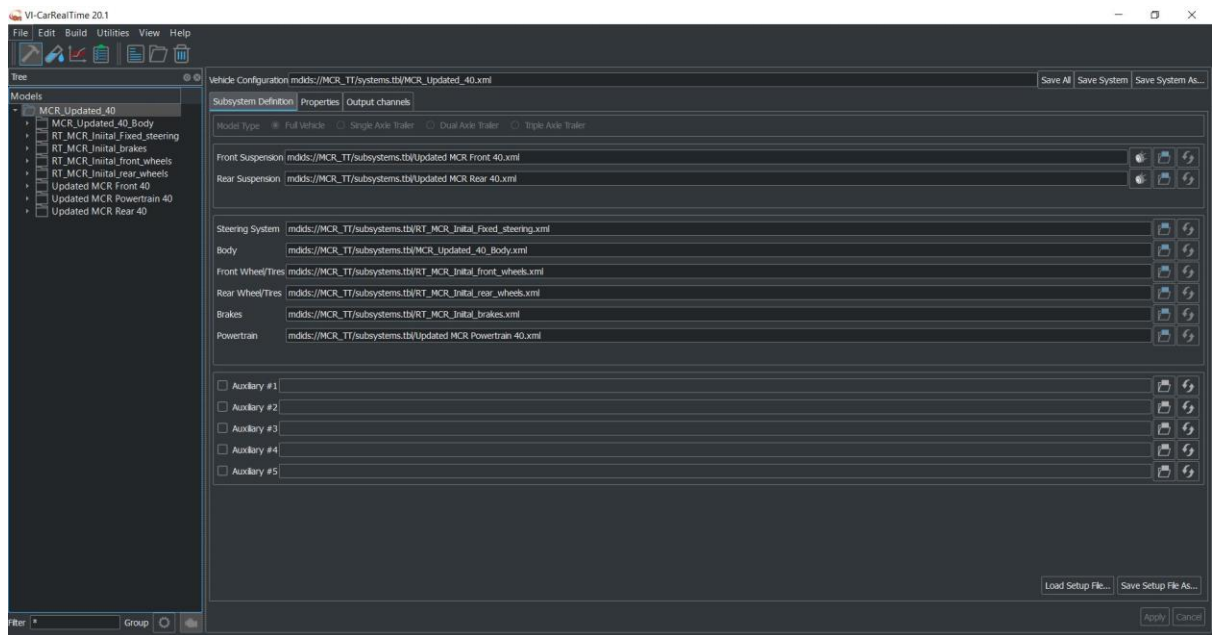


Fig. 51: Loading the Model and its Subsystems

Although the model was built completely, there were minute changes to be made, as mentioned in Section 6.1. Firstly, the ride heights of the car were to be changed. To do this, first the front suspension of the model was chosen from the model tree. There, the Suspension Setup Data section had the subsection for ride height. The correct ride height of 55 mm was entered for both the right and left sides. The same can be seen below in Fig. 52.

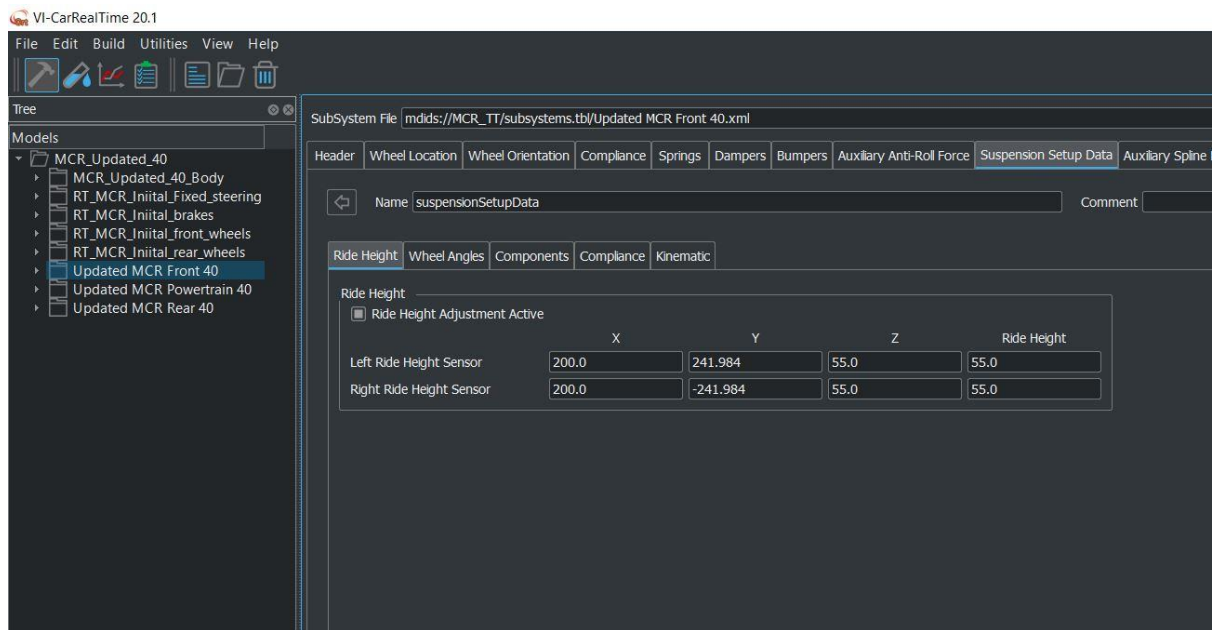


Fig. 52: Ride Height Adjustment

The same process was repeated again in order to adjust the rear ride height as well.

The rear ride height was adjusted to 85 mm.

The other rectification that was needed to be made was the gear ratio for the final gear. This could be accessed from the Powertrain section in model tree, which has a subsection for transmission. Here, the edit data option for the gear ratio was chosen and the gear ratio for the 5th gear was altered to 1.19, as shown in Fig. 53 below. This was done in order to match the top speed of the model in VI CarRealTime to that of the actual MCR race car.

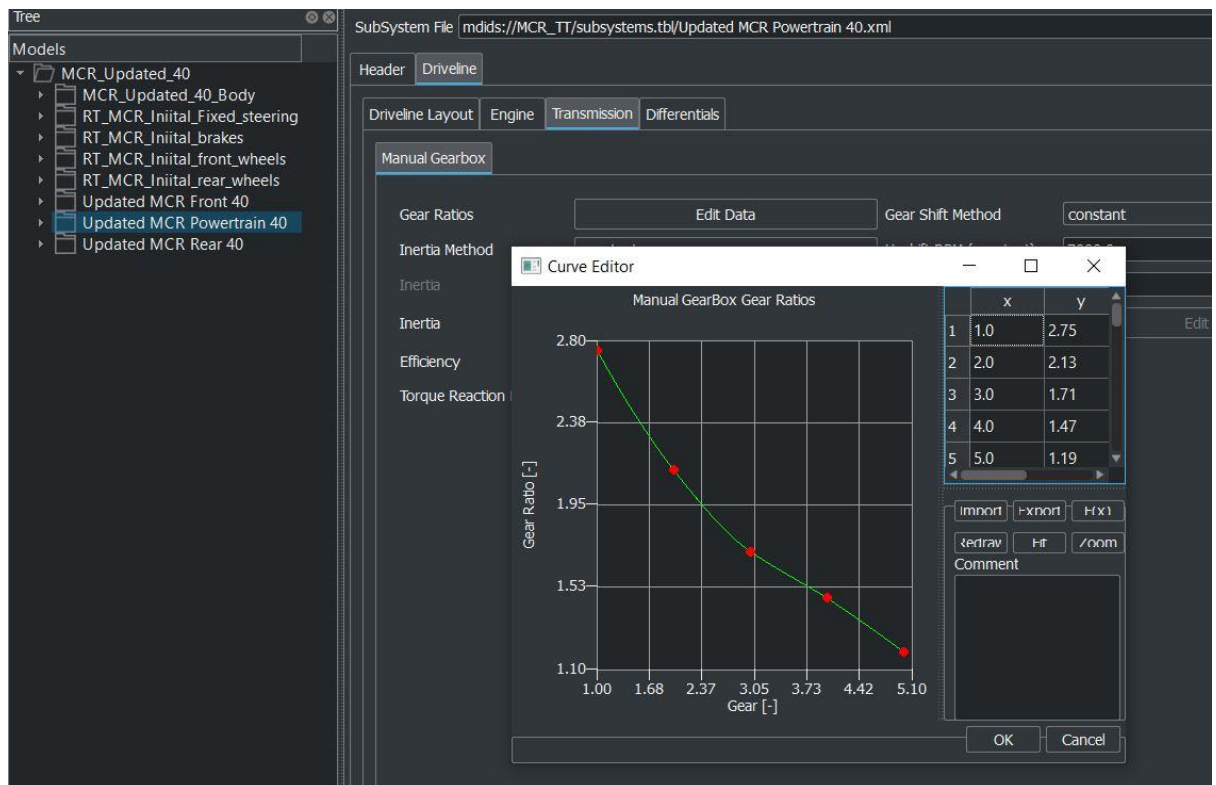


Fig. 53: Gear Ratio Alteration

1.2.2 Test Mode

The Test Mode is the section where all the simulations are run. In this section, there is a tree named Events. This contains a variety of events for which the vehicle could be tested. These range from a magnitude of different tests in order to test things like cornering which has braking in turn, course events such as MaxPerformance and path compensation, open loop steering option such as ImpulseSteer, RampSteer and SineSteer, different stability tests like Fishhook and J-Turn, straight line tests like Acceleration and Braking etc. In this project, since our focus is on finding the best setups for the given circuits, therefore the main focus here would be the CourseEvents and MaxPerformance to be specific. In order to start the event, a new fingerprint has to be created which can be done by right clicking on the desired event,

MaxPerformance in this case. The interface of MaxPerformance is shown below in Fig.

54.

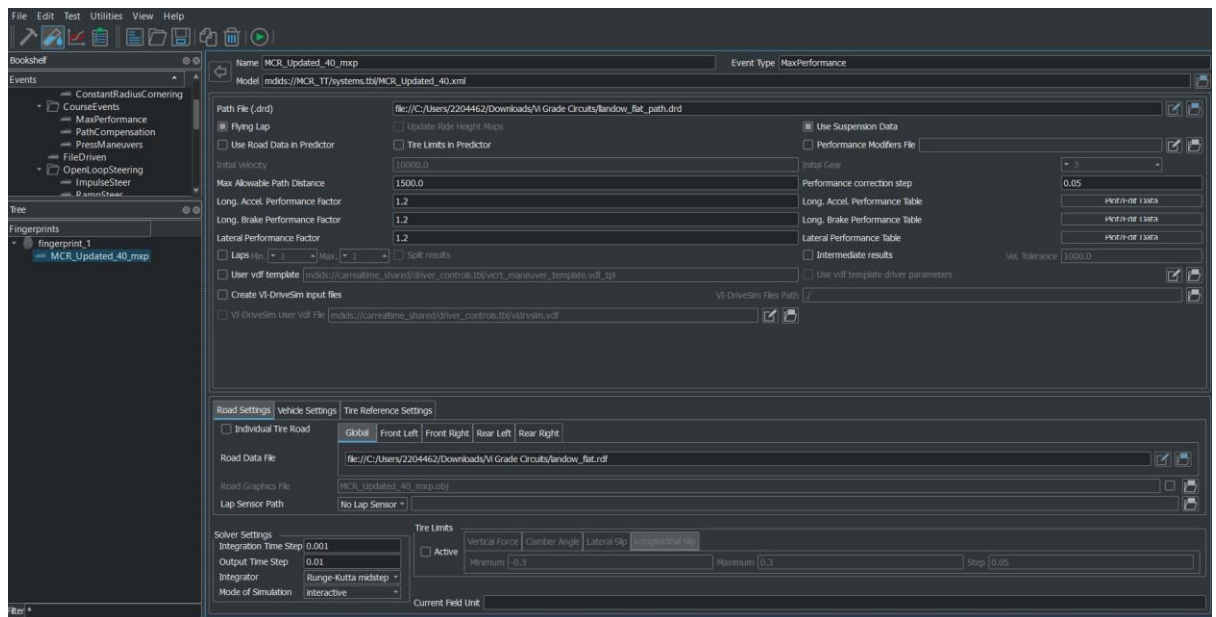


Fig. 54: MaxPerformance Interface

In MaxPerformance, the first option that pops up is to choose the path file. Once the path file is chosen, the radio options of Flying Lap and Use Suspension Data are clicked. The Flying lap option is chosen because in our test, we just need to simulate the fastest lap time that the race car is capable of achieving. Similarly, we are trying to achieve this by altering the setups of the different suspension components only. Hence, the option of Use Suspension Data is chosen as well.

Next, there are the details related to the performance of the race car during the simulation. This starts with the option for Max Allowable Path Distance which specifies how much the race car is allowed to deviate from the racing line defined by the path file. This option exists because regardless of how accurate the racing line defined by the path file is, there might be a slightly different line that the simulation tool is able

to identify that might lead to the car going ever so slightly quicker. In this case, Max Allowable Path Distance is set to 1500 mm.

This leads us to the different performance factors of the car, also known as the driving factors. The performance factors that are available here are Longitudinal Acceleration Performance Factor, Longitudinal Braking Performance Factor and Lateral Performance Factor. The performance factors can be used to alter the performance of the car within its limits of grip. It operates in the form of a scale factor and the default performance factor is set to 1. For example, if the car is capable of better lateral performance of about 1.2 , it can be scaled up to the higher Lateral Performance Factor and this in turn would lead to the car having a better lateral performance and that in turn would lead to faster lap times. Similarly, the other performance factors could be scaled up and down as well.

Next, there is the Performance Correction Step. This is used to scale down the Performance Factors if their values are set higher than the what the car is capable of achieving. For example, if a certain Performance Factor is set to 1.3 but the car is only capable of a Performance Factor of 1.2, the simulation reiterates itself until the Performance Factor is dropped down to 1.2. The Performance Correction Step is the factor by which the Performance Factor is reduced for each iteration.

Lastly, there is the option to choose the road data file which is the road file for the circuit in which the current simulation is being performed. This is followed by the solver settings but they were left at their default values in this project.

After all the settings are entered, the simulation can be run by right clicking on the fingerprint and choosing Run Selected Events

1.2.3 Review Mode

The review mode has a tree titled Fingerprints. This tree contains a list of all the fingerprints that were simulated in Test Mode. Here, when a fingerprint is right clicked, it gives an option to Execute Postprocessing. On choosing that, it brings up a new screen with the title VI Animator. As shown in Fig. 55 below, all the telemetry data that is achieved from the simulation can be viewed in VI Animator. Along with that, it also presents a visual representation of the car being operated on the specified circuit in real time. All the telemetry generated can be exported from the Analysis option on the tree. This is exported in .csv format.

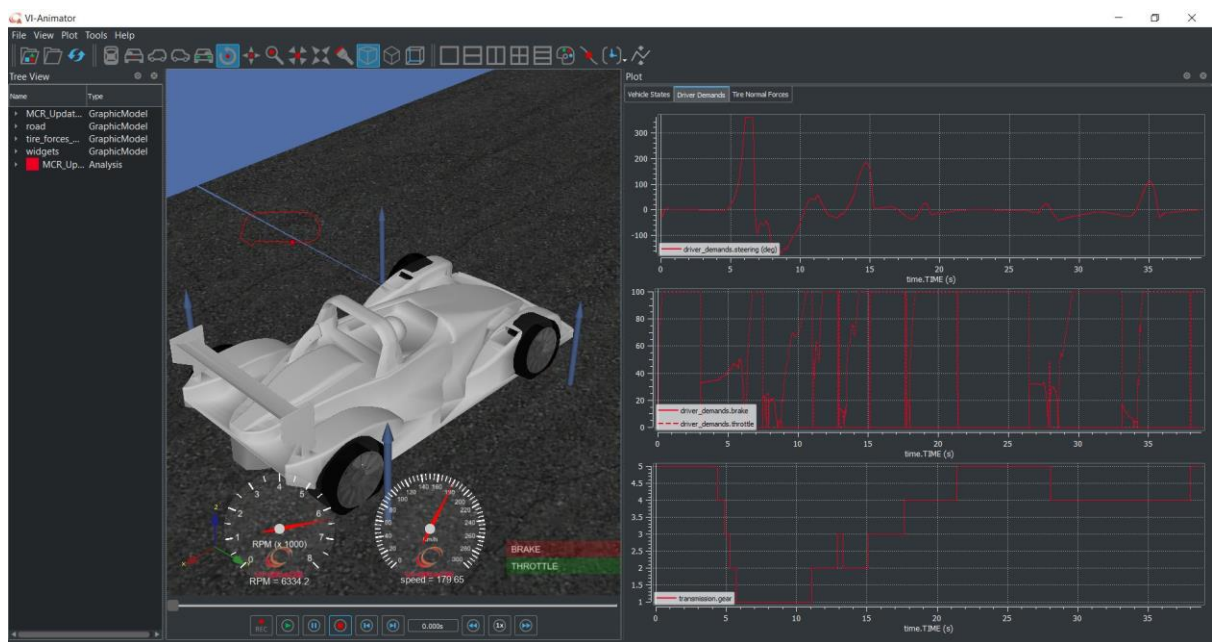


Fig. 55: Review Mode

1.2.4 Investigation Mode

Using the steps as mentioned above, the simulations can be run perfectly. But, all the steps that were explained until now were for completing the simulation for data with

just one particular setup. This means that that was a good method in case the end goal was to look at the telemetry data from the simulation for that particular setup. But VI CarRealTime also has a built in tool to apply design of experiment within it. This can be found in the Investigation Mode.

Here, the fingerprint to which design of experiment methods are to be applied, is added to a new investigation by right clicking on the fingerprint. This generates a new investigation where design of experiment can be applied.

The investigation interface is divided into three colour coded columns, namely candidates in red, factors in green and responses in blue, as seen in Fig. 56 below.

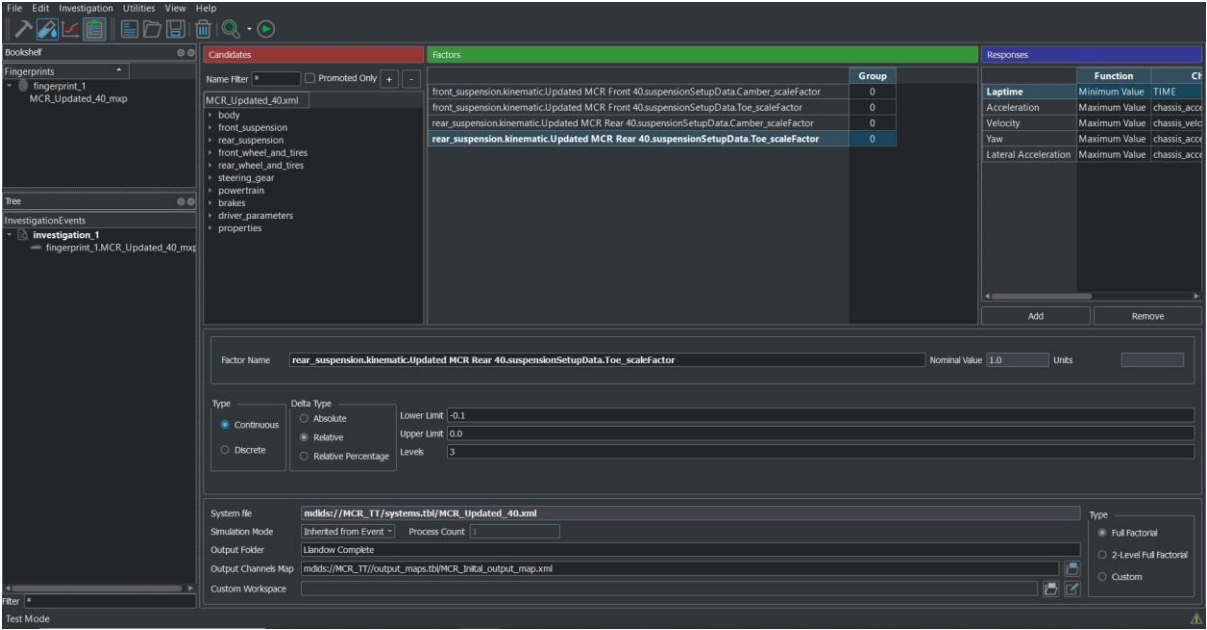


Fig. 56: Investigation Mode

The candidates in red are the different parameters of the car that could be added to the factors. Essentially, these are the thing in the car such as the spring rates, damper rates, anti-roll bar rates etc. that could be set as the factors for the design of experiment analysis. When choosing the candidates for the different design of

experiment analysis, the option of scale factor is chosen as the method to choose the range of each of these.

The factors in green are the list of parameters which were chosen from the candidates for the design of experiment analysis. For example, in Fig. 56, the factor chosen for the analysis were front camber angle, rear camber angle, front toe angle and rear toe angle. When any of the factors are highlighted, the option to set the range for the analysis appears. As shown in Fig. 56, for the range of the rear toe angle, the type of range is set to continuous. The delta type for the range is set to relative so that the values of the limits can be set with respect to the original setting used for the setup. For the particular analysis, the range for the rear toe angle was set to -0.1 for the lower limit and 0 for the upper limit. Along with this, the number of levels was set to 3. What this means is that the analysis will be run for three different settings, -0.1, -0.05 and 0, i.e., -10%, -5% and 0% respectively in comparison to the original setup. Finally, the type of investigation at the bottom is set to full factorial.

Lastly, the responses in blue are the result outputs that are generated after the design of experiment approaches are applied and the simulation is completed. During this project, lap time, longitudinal acceleration, velocity, yaw rate and lateral acceleration were the responses for which all the different analysis were carried out. The different responses can be added to the list by using the add button at the bottom. Every response here is associated to a channel. When a response is first added, it is not defined by any channel. The channels can be added by clicking on Select Output Channel. Upon clicking this, a window with over 100 channels pop up. Of these, the channels of TIME, chassis_accelerations.longitudinal, chassis_velocities.longitudinal, chassis_accelerations.yaw and chassis_accelerations.lateral were chosen for the

output responses of lap time, longitudinal acceleration, velocity, yaw rate and lateral acceleration respectively, as shown in Fig. 57 below. In order to identify the best setup, we need to identify the setup that took the least amount of time to complete a lap. Hence, the function for lap time was set to minimum. On the contrary, since we need to identify the setups with the best longitudinal acceleration, velocity, yaw rate and lateral acceleration, the function for these were set to maximum.

Lastly, the output folder name was given and the simulation with the design of experiment was run by clicking the Run Selected Investigation on the tool bar.

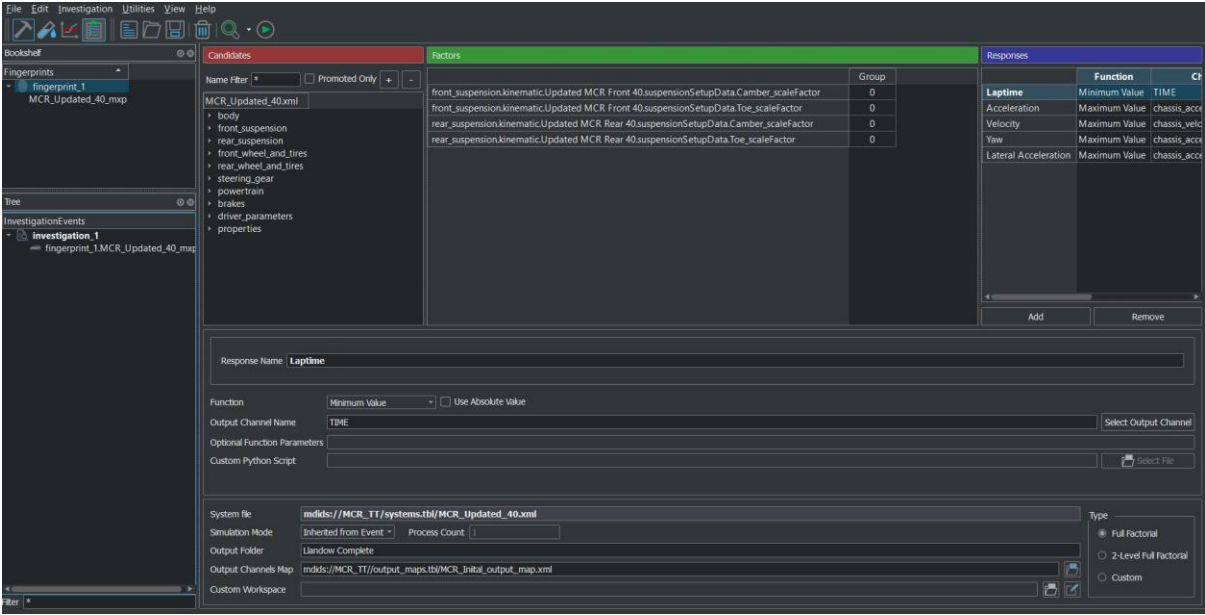


Fig. 57: Investigation Mode Responses