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The development and investigation of Aero Maps on Lap time simulation
for Sports 2000 MCR

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

Signed: 

Date: 10/09/2023

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Abstract

Aero-mapped Sports 2000 MCR VI-CarRealTime model is presented for simulation of lap times and analysis of vehicle dynamics. Data from wind tunnel experiments and computational fluid dynamics (CFD) simulations were utilised to generate and assess various aerodynamic maps. The CFD data proved to be comprehensive, leading to a subsequent investigation of the race car's vehicle dynamics for set-up purposes. The research identifies specific spring and static ride height parameters that are expected to enhance driver confidence. Discrepancies among computational fluid dynamics (CFD) simulations, wind tunnel experiments, and on-track measurements have been identified, indicating the need for additional investigation. The VI-CRT driver model necessitates the inclusion of supplementary parameters in order to replicate human performance more accurately. This study serves as the foundation and verification for a simplified aerodynamic lap simulation tool.

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1. Introduction

Simulation tools have become an essential part of the development process in motorsport, especially since regulations have imposed strict limitations on testing and track time. Simulation allows engineers to design, optimise and evaluate different aspects of a race car, such as suspension kinematics, lap time performance, and race strategy. Simulations also provides data that are difficult or impossible to measure on the actual car, such as tyre loads, dynamic roll centre locations, camber angles, and slip angles and plays a crucial role in various stages of the racing process, spanning from the initial concept generation to the actual on-track racing.

Despite these uses, simulation tools are not flawless and present their own set of limitations and challenges. One of the primary constraints pertains to the precision and reliability of the simulation outcomes, which are contingent upon the calibre of the input parameters, the assumptions and simplifications incorporated within the model. Another constraint that needs to be considered is the computing costs and time needed to execute intricate simulations, which might not be viable or cost-effective for certain teams or projects. Additionally, it should be noted that simulation tools may not accurately replicate the genuine risk perception and behaviour of drivers, potentially impacting the vehicle's overall performance.

The primary research inquiry of this project pertains to the enhancement of simulation tools in order to adequately incorporate the variability in the aerodynamic performance of a race car resulting from alterations in vehicle dynamics. The role of aerodynamics in motorsport is of utmost importance as it significantly impacts the speed, stability, and handling characteristics of the vehicle. When engineers endeavour to enhance the aerodynamic attributes of a vehicle, their objective is to achieve increased downforce and decreased drag. However, it is crucial that these improvements are consistently maintained throughout the entire operating range of the car. This is because excessive variability in the aerodynamic performance can have detrimental effects on both the vehicle's overall performance and the driver's confidence levels. A significant limitation of most simulation tools is their tendency to overlook or oversimplify the impact of vehicle dynamics on aerodynamics. This includes disregarding factors such as ride height variations and yaw angle alterations. Simplifying can potentially result in imprecise forecasts regarding lap duration and overall performance.

The main contribution of this project is to generate and assess aerodynamic maps for the Sports 2000 Car 40 in VI-CarRealTime. This forms part of future work to develop and compare two simulation models incorporating aerodynamic variation due to vehicle dynamics. The first model is a highly detailed multi-body simulation tool called VI-CarRealTime, which models the vehicle dynamics and simulates aerodynamic forces based on front ride height and rear ride height. The second model is a simpler multi-body vehicle model to be created within MATLAB, which accounts for the complex suspension geometry using simplified factors and maintains the aerodynamic changes. Both models require full validation.

The methodology used in this project consists of eight main steps: 1) literature review and analysis; 2) 3D CAD model updating; 3) Dynamic ride height evaluation; 4) CFD Run plan evaluation; 5) Aero mapping and comparing CFD and Wind Tunnel data; 6) Assessing the impact of Aero maps on vehicle dynamics; 7) Tuning set-up to improve vehicle balance; 8) Discussions and conclusion.

The structure of this report is as follows: Chapter 2 provides a literature review on simulation tools in motorsport, focusing on their advantages, disadvantages, and applications, as well as a look into aero mapping and aerodynamic driveability. Chapter 3 presents the development and evaluation of aero maps. Chapter 4 shows the vehicle dynamics testing of various aero maps and the effect of spring and ride height changes on vehicle

performance. Chapter 5 summarises the main results of this project. Chapter 6 provides suggestions for future work, some of which are ongoing. Chapter 7 concludes the report.

For simplicity and ease of use when setting up the race car, FRH and RRH refer to the front ride height of the car 200mm ahead of the front wheel centre line and rear ride height 130mm ahead of the rear wheel centre line, respectively.

2. Literature Review

This section of the report looks at the history and advancements in lap time simulation, developments in the simulation of Sports 2000 racecars and aerodynamic mapping factors and their effects on vehicle dynamics.

2.1. Vehicle and Lap time simulation methods

The utilisation of lap time simulation is employed to estimate the minimum amount of time necessary for a vehicle to complete a designated circuit successfully. The evaluation and optimisation of race car performance is a widely practised activity in the world of motorsport engineering, with its effectiveness being associated with the complexity of the software utilised. Extensive research has been conducted on this topic over numerous decades. Currently, there exist various prevalent computational methodologies employed for solving minimum-lap-time problems. The variations are associated with the selection of the vehicle model, which can be either dynamic or quasi-steady-state (QSS), as well as the choice of the approach for solving the optimal control problem, either indirectly or directly. (Massaro & Limebeer, 2021) discuss the numerous approaches for lap time simulation with unique advantages and limitations. This section will provide an overview and comparative analysis of their respective characteristics and uses of several commonly used methods, including optimum control problem (OCP) approaches, modified quasi-steady-state (QSS) approaches, and point mass vs. multi-body models.

2.1.1. Optimal Control Problem (OCP) Approaches

An optimal control problem is a mathematical problem that involves determining the most effective strategy for controlling a dynamic system as it evolves temporally. To optimise the performance of a system, it is necessary to establish clear definitions for the state variables, control variables, objective function, system dynamics, and constraints. The primary aim is to identify the control strategy that minimises or maximises the objective function while ensuring compliance with the system dynamics and constraints (Singh, 2021).

As discussed by (Massaro & Limebeer, 2021) the problem of minimum-time simulation is a well-established classical optimum control problem (OCP). Therefore, it is unsurprising that OCP techniques play a significant part in simulations focused on minimum-maneuvre-time and minimum-lap-time scenarios. Within the generic OCP model, the driver assumes the role of the “optimal controller,” responsible for overseeing the application of driving power, braking, and steering in the given context. The control method known as “the optimal driver” aims to minimise a performance parameter, such as the lap time, while considering the physical limitations imposed by the road borders and the vehicle’s performance capabilities. The control aim can be broadly defined as the task of operating the vehicle in a manner that allows it to successfully complete a predetermined number of laps in the shortest possible amount of time. In an attempt to make the solution to these computer-intensive problems feasible with the currently available computer resources, various simplifications have been proposed. These simplifications may involve employing tactics such as pre-defining the vehicle’s trajectory, substituting dynamic models with quasi-steady-state (QSS) models, and adopting simplified models for tyre and aerodynamics.

(Limebeer, Perantoni, & Rao, 2014) and (Lui, Fotouhi, & Auger, 2020) made use of a General-Purpose MATLAB Software for Solving Optimal Control Problems to study energy management strategies in Formula One and Formula-E respectively. Both systems showed strategies for optimising energy as well as lap times. A simplification used by (Limebeer, Perantoni, & Rao, 2014) was to use a pre-defined racing line, (Lui, Fotouhi, & Auger, 2020) showed that varying racing lines are necessary with fuel-saving strategies. Both studies utilised a simple aerodynamic force that did not vary with car attitude or closeness to competitors. Ignoring aerodynamic effects was an oversight, considering that racing in a peloton to conserve energy has become crucial in 2023 Formula-E (Mansell, 2023).

2.1.2. Quasi-Steady-State (QSS) Approaches

The lap time simulation necessitates a combination of great robustness and accuracy, together with numerical efficiency. The quasi-steady state solution satisfies these specified requirements. When using the Quasi-Steady-State (QSS) technique, longitudinal and lateral acceleration maxima typically govern the vehicle.

The simple MLT simulator OptimumLap reduces the vehicle to “its most fundamental components”. Despite the point-mass nature of the model, which neglects weight transfer and transitory effects, the simulated results exhibit a strong correlation with the logged data. The conducted validations have demonstrated that the apex speeds, end-of-straight speeds, energy consumption, and overall lap time are all in agreement (OptimumG, 2023). (Halkiopoulos, 2023) provided an open-source, point-mass lap time simulation software, OpenLAP. OpenLAP simulates the best lap time and the speed trace of a given vehicle and circuit. The software is implemented using Python or MATLAB programming languages and encompasses a diverse range of models pertaining to engines, powertrains, tyres, aerodynamics, and steering. The OpenVEHICLE and OpenTRACK programmes enable users to generate their own vehicle and track files. OpenDRAG also enables the execution of linear simulations. OpenLAP finds the apexes of a track, sets the condition to pure lateral acceleration, and utilising a velocity-modified g-g diagram (g-g-v), keeps the vehicle within this plot. The point-mass model is assumed to accelerate away from these points and decelerate towards them. The aforementioned techniques exhibit a satisfactory level of precision, thereby enabling the examination of how changes in macro vehicle characteristics impact lap times. One advantage of employing a QSS model is the ability to reduce computational complexity. However, as the simulation utilises a point-mass, no weight transfer or transient effects are taken into account. These programmes become ineffective in the context of examining springs, dampers, anti-roll bars, and the impacts of rake and yaw on the aerodynamics of vehicles. Another disadvantage is that QSS models generate bang-bang solutions, characterised by abrupt transitions between the lower and upper bounds. This behaviour leads to a control history that is impractical for the driver to reproduce, hence affecting the optimal trajectory and manoeuvre duration. This phenomenon may be illustrated in the OpenLap and Optimum lap scenarios, where unrealistic downshifts are encountered. In such instances, the model is fulfilling the need to deliver peak torque as per the specified parameters, albeit unnatural.

Work from Warsaw University of Technology incorporated experimentally based optimal control constraints to consider some effects of vehicle inertia and human physical limitations. The results achieved with the suggested approach exhibit outputs that are more likely possible to replicate by a professional race driver compared to those obtained in a conventional OCP formulation (Biniewicz & Pyrz, 2023). Due to the simple aerodynamic model and calibration method of utilising a g-g diagram, this method is not likely to be useful for detailed aerodynamic studies for potential parts. It would be useful once a part is manufactured as it would require real-world testing of the bike with the component to create a new g-g plot.

As previously noted, the quasi-steady state (QSS) technique cannot facilitate the assessment of transient or dynamic phenomena. The QSS approach was combined with a transient vehicle model and presented by (Völkl, Muehlmeier, & Winner, 2013) as the extended steady-state lap time simulation. In this extended QSS model, the transient states are regarded as distance-dependent parameters. Figure 2-1 describes the process where the quasi-steady state outcome is subsequently utilised to generate a new dynamic output, which in turn generates another quasi-steady-state solution. The process of looping through the two solutions is carried out until the dynamics reach a state of convergence. The method incorporates the influence of dynamic factors, such as the damping and temperature of tyres. This is achieved by utilising a grip scaling factor that is contingent upon the surface temperature of the tyre, as well as a cornering stiffness factor that is contingent upon the core temperature of the tyre. It is stated that the calculation of aerodynamic downforce and drag is derived from the

analysis of body movement, but further details are not made available. Unlike other QSS techniques, this method does not rely on pre-computed g-g diagrams. Instead, it computes the states of the quasi-steady-state (QSS) model incrementally while solving a nonlinear programming problem.

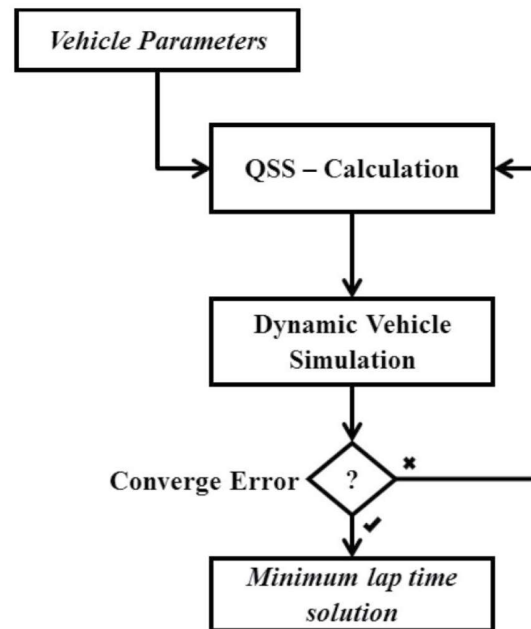


Figure 2-1: Extended QSS Model methodology (Völkl, Muehlmeier, & Winner, 2013)

Increasing the size or nonlinearity of the problem with more detailed vehicle models reduces the numerical efficiency and robustness of numerical optimisation. To analyse a more complex vehicle model, (Kelly, 2008) utilised a finite horizon approach, which did not require all vehicle states for optimisation. The effects of tyre temperature and vertical dynamics were consequently analysed. The method's disadvantage is its lowered efficiency. Stability constraints were added to avoid nonlinear vehicle states and strengthen the solution's robustness.

(Malcher, et al., 2018) built on the extended QSS model by adding a dynamic engine model. The utilisation of the dynamic engine model has been found to significantly enhance the amount of detail in engine-specific investigations. The primary drawback associated with the extended duration of simulation time can be mitigated by a range of approaches, however it cannot be eliminated.

A study by (Masouleh & Limebeer, 2016) focuses on modelling and optimising the interactions between the multilink suspension system of an open-wheeled race car and the aerodynamic performance of the vehicle. The research has demonstrated that the kinematics of a car's suspension may considerably impact the vehicle's aerodynamic characteristics. The utilisation of optimal control computations demonstrates the influence of aero-suspension interactions and changes on the Formula One car's lap-time performance.

2.1.3. Vehicle Models

The VI-CarRealTime programme is designed to simulate the real-time dynamics of a vehicle through the utilisation of a simplified model. The utilisation of this technology enables the examination of various design situations and the enhancement of vehicle performance. Additionally, it enables seamless integration with diverse software and hardware platforms. The software possesses several notable attributes, including the capability to automatically export a real-time vehicle model from ADAMS Car or K&C results, the ability to share component property files with ADAMS Car, the utilisation of pre-existing vehicle models from alternative real-time software solutions, and the capacity to conduct extensive Design of Experiments (DOE) and optimisation studies. Several uses of this technology include real-time vehicle simulation, software-in-the-loop testing, fuel consumption analysis, hardware-in-the-loop testing, competitive car assessment, driving simulator (both static and dynamic), and traffic simulation (VI-Grade, 2023).

One of the main differences between VI-CarRealTime and other vehicle simulation software is that VI-CarRealTime uses a single simplified vehicle model that is faster and easier to use but may not capture some of the finer details and nonlinearities that a more complex model can. Other vehicle simulation software, such as VI-Motorsport, use a faster-than-real-time simulation solver that can predict the virtual car behaviour with more accuracy and detail, but may require more computational resources and time. Another difference is that VI-CarRealTime can also be used on a motion base driving simulator to allow the test drivers to experience the vehicle in a more subjective way, while other vehicle simulation software may not have this feature or may require additional software. The accuracy of VI-CarRealTime depends upon the input data's quality, including tyre models, suspension parameters, and aerodynamic coefficients (VI-Grade, 2023).

Determined through initial quasi-static simulation, performance constraints are determined. VI-grade employs a method of iteration wherein it conducts simulations of track runs by adhering to these constraints (Campbell-Brennan, 2021). In the event that an impractical situation arises during a specific corner, characterised by either significant deviation from a predetermined driver path or excessive wheel slip, the pertinent factors related to traction, braking, or cornering are adjusted to a more feasible level. Upon the completion of this iterative procedure throughout an entire circuit, the simulation attains its final state.

(Fullylove, Lawrence, & Arthur, 2023) investigated the suspension kinematics and engine characteristics of the UWTSD MCR Sports 2000. By conducting physical measurements of various parameters (centre of gravity, spring and tyre stiffnesses, damper curves, and suspension geometry hardpoints), the correlation between the real car and the VI-CarRealTime model was improved but still requires full validation. Areas requiring improvement within the model are the tyre model and simulation of aerodynamic forces.

As the acquisition of all the requisite data to establish and implement a VI-CRT model often proves to be impracticable, the process of simplification becomes imperative. The lumped mass vehicle model is a straightforward approach for doing vehicle analysis (Na, Jang, Yoo, & Kim, 2015). Despite simplifying the actual vehicle architecture, analysing vehicle vibration characteristics and the effects of structural parameters on vehicle performance is possible. Mass, spring, and damper elements comprise the lumped parameter modelling of a vehicle with their possible movement defining the model's degrees of freedom. To analyse the vehicle's vertical, pitch and roll vibrations, the lumped mass vehicle model requires a minimum of 7 DOF and is usually three-dimensional (Kim & Ro, 2002). An advantage of the Lumped Mass models is the simplicity and ability to obtain analytic descriptions and design active or semi-active controls (Yang, Li, & Lu, 2013). This model is widely used to study vehicle handling dynamics undergoing emergency collision avoidance, with MathWorks providing a reference application per the ISO 3888-2 standard (MathWorks, 2022), (ISO, 2011).

2.2. Aerodynamics

This section describes different aerodynamic modelling techniques and the effects of aerodynamic balance on vehicle dynamics.

2.2.1. Aero Balance

Aerodynamic balancing pertains to the distribution of downforce and lift (or negative lift) produced by the aerodynamic elements of a racing vehicle. The elements encompass the front and rear wings, underbody diffuser, and other bodywork elements (Bosko, 2023). The aero balance or COP (centre of pressure) refers to the allocation of the aggregate downforce exerted on the front axle. Akin to weight distribution, an aero balance of 55% indicates that the front axle is loaded with 55% of the total downforce, while the remaining 45% is distributed over the rear axle. The vehicle's aerodynamic balance must fall within an acceptable range for the car to be drivable by most drivers.

Due to the regulations, Sports 2000 MCR Cars have flat undersides. A crucial factor to consider in relation to flat floors is the necessity of ensuring that the floor possesses a negative incidence angle, commonly referred to as rake. In alternative terms, it is necessary for the front section of the undertray to possess a lower elevation compared to its rear counterpart. It is widely acknowledged, that if the situation were reversed, with the front of the vehicle being elevated higher than the rear, the airflow beneath the car at high speeds would result in the accumulation of air pressure, leading to an undesirable and potentially hazardous upward force. Hence, ensuring that an automobile possesses a negative incidence angle is imperative. It is anticipated that a properly raked underbody panel will effectively decrease the (positive) lift coefficient of a vehicle, as indicated by references that propose that even a slight inclination of one or two degrees can yield a substantial impact. Fundamentally, the entirety of the lower part of the vehicle assumes the characteristics of a basic venturi section with a short inlet and throat located beneath the front of the car. A region of low pressure is induced by the airflow undergoes acceleration. The remaining portion of the underbody acts as an elongated diffuser, characterised by its sleek surface. It facilitates the uninterrupted flow of air, promoting a gradual decrease in velocity as it approaches the rear section. Therefore, a smooth, flat, raked floor underneath a car can result in reduced static pressure (McBeath, 2017).

During the period in which Volkswagen briefly operated a Formula Volkswagen race series, the vehicles utilised a 1,600cc single-seater configuration equipped with dual-element wings positioned both at the front and rear. However, similar to Sports 2000 MCRs, these vehicles were designed with a flat underfloor. In the year 2002, VW Motorsport made available a set of aerodynamic set-up data. A portion of the data pertained to the impact of altering the chassis rake. It was observed that modifying the rake angle not only influences the wing angles, but also significantly alters the aerodynamics of the underbody.

Figures 2-2 and 2-3 illustrate the fluctuations in the total downforce and aerodynamic balance (% on Front End), respectively for different front and rear ride heights. The total downforce plot illustrates the variation in the overall lift coefficient, wherein reducing the front or adding rear ride height results in an increase of the total downforce. The aerodynamic balance plot illustrates that modifying the front ride height or rear ride height results in a redistribution of downforce towards the front, thereby altering the overall downforce produced. The flat floor in question exhibited characteristics akin to a conventional venturi. Changing the chassis rake clearly provides a powerful tool for adjusting downforce and balance, even with a flat floor. It is important to consider the interdependence between rake and front ground clearance as low ride heights and high negative rake increases the risk of separation or stalling, which are phenomena where the air flow detaches from the surface of the vehicle and creates turbulence and drag (Toet, 2017). The rake must be adequate to prevent it from becoming positive,

meaning that it should not tilt upwards during regular suspension motion and, if possible, when traversing an incline at high velocity. Certain categories have historically exhibited minimal ground clearances, making it evident that a level floor, despite the presence of a rear diffuser, can be highly susceptible to variations in ground clearance and rake angle.

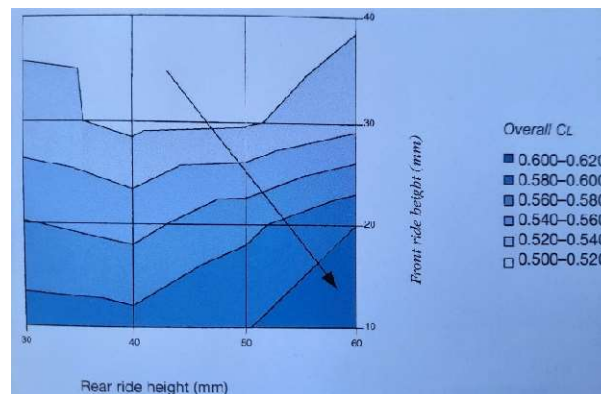


Figure 2-2: Influence of chassis rake on Total Downforce on a flat-bottomed single-seater (McBeath, 2017)

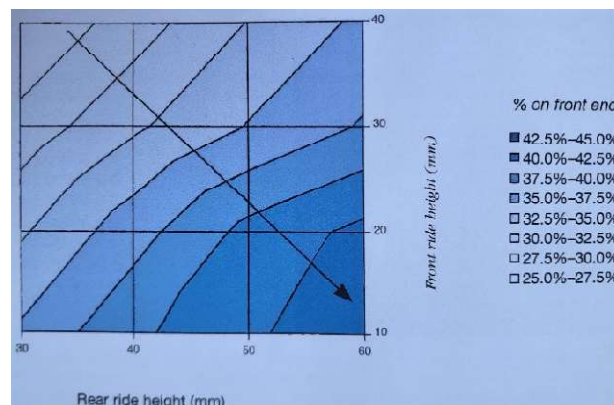


Figure 2-3: Influence of chassis rake on front-to-rear aerodynamic balance on a flat-bottomed single-seater (McBeath, 2017)

Aerodynamic maps play a crucial role in the optimisation of race car set-up. An aerodynamic map illustrates the correlation between a race car's geometric and aerodynamic characteristics. Aero maps are among the various tools employed by engineers in the construction of a racecar model. Subsequently, these models are employed to predict the anticipated response of the vehicle to different adjustments in its set-up. The ability to analyse and comprehend the impact of various set-up modifications is crucial in motorsport engineering, particularly when confronted with alterations in driver, track, and environmental conditions. Consequently, the utilisation of modelling techniques has emerged as a pivotal aspect in this field.

As seen in Figures 2-2 and 2-3 as well as 2-4 the visualisation of downforce levels can be represented by a colour gradient. In Figure 2-4, shades of red indicate higher values and shades of blue indicate lower values across a spectrum of front and rear ride heights. Subsequently, distinct aerodynamic maps can be employed to visually represent the magnitudes of front, rear, and overall downforce, drag and aerodynamic efficiency.

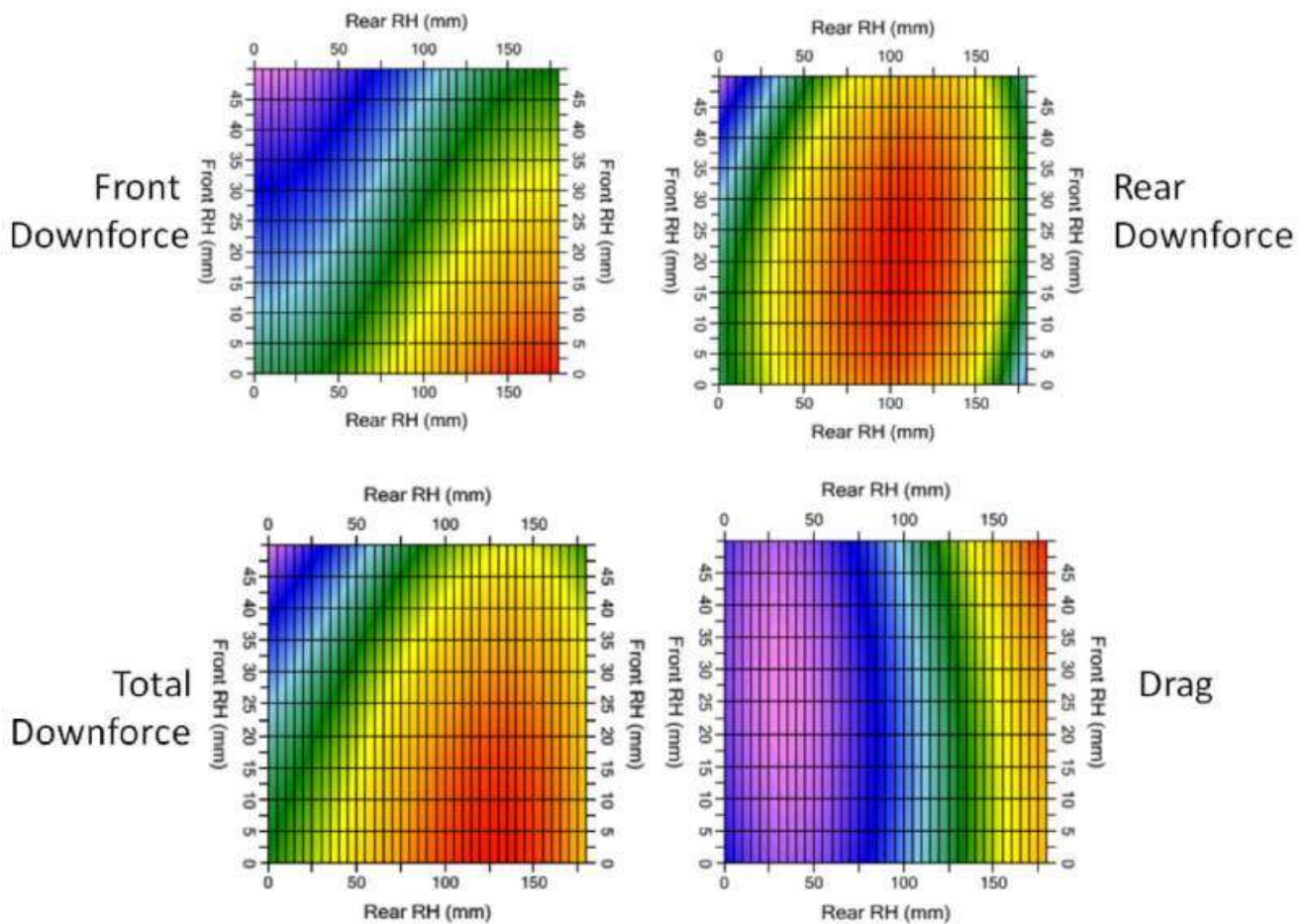


Figure 2-4: An example of some aero maps for a formula racecar (Remmerie, 2023)

Corners can be categorised as low, medium, and high speed, and the vehicle's ride height will exhibit considerable variation over different phases and styles of turns. Consequently, the aerodynamic balance can likewise undergo large fluctuations (Garsed-Brand, Developing a quick racing car from the aerodynamics perspective – aerodynamic driveability part I, 2022). Dividing a corner into distinct phases, including braking, entry/turn-in, apex, departure, and acceleration, is a common practice to identify and improve vehicle behaviour. Figure 2-5 (ride height envelope) shows the ride height fluctuations expected from a high-downforce race car from braking to acceleration. Overlaying ride height envelopes over an aero map produces Figure 2-6. Expanding the range of ride heights (pink region), will result in the vehicle experiencing a modest increase in front-end downforce (as denoted by the yellow region). When positioned at the rear, the redistribution of maximum downforce (indicated by the

red area) towards the centre of the ride height envelope will result in less overall rear downforce but is advantageous in terms of enhancing consistency (Remmerie, 2023).

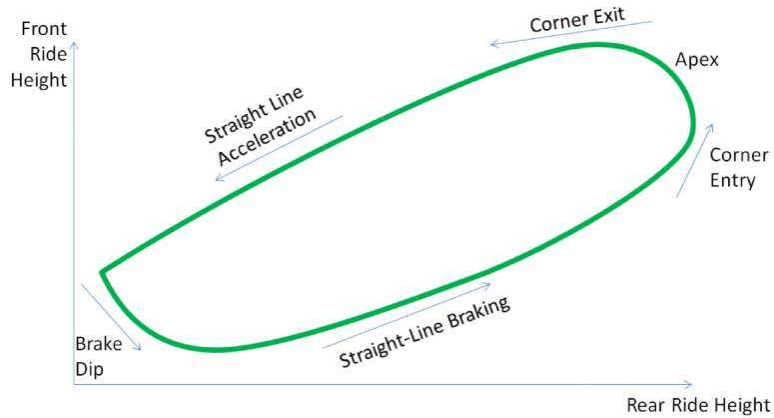


Figure 2-5: Ride height envelope example for a formula car (Remmerie, 2023)

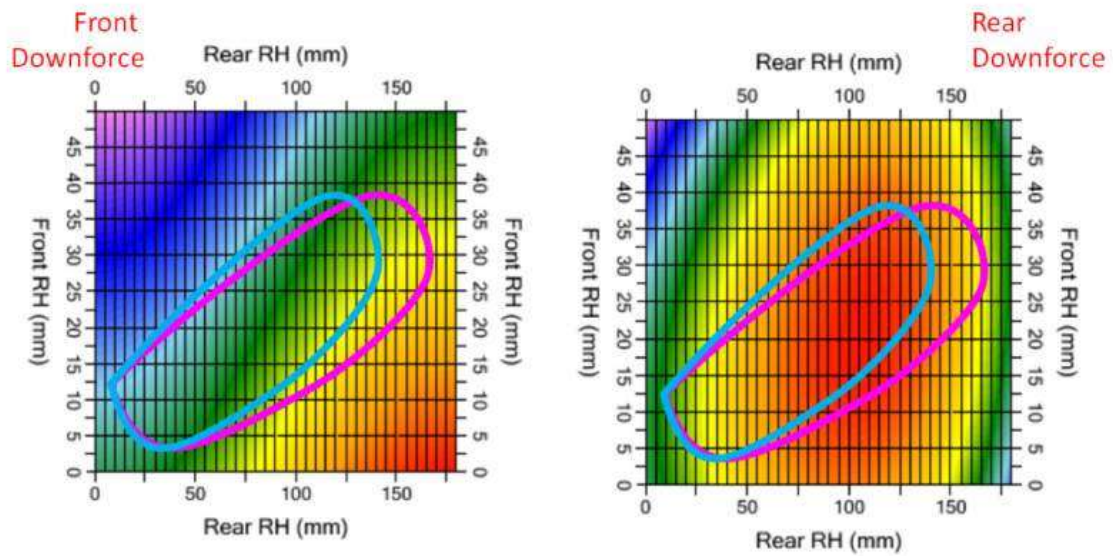


Figure 2-6: Ride Height Envelopes overlaid on Aero Maps (Remmerie, 2023)

2.2.2. Driver Confidence

Drivers encounter difficulties in accurately estimating the level of grip at crucial sections of the track. The level of grip experienced by a vehicle is contingent upon several factors, including the aerodynamic performance of the vehicle, the temperature and wear of the tyres, as well as the dynamic nature of the road conditions, such as the presence of rubber, debris, oil, and precipitation. In the context of competitive racing, it is imperative for drivers to anticipate and forecast the downforce and balance of their vehicles when behind another racer. Consequently, a driver who possesses a high level of confidence will operate the vehicle in closer proximity to its maximum performance capabilities. This entails delaying the application of brakes until a later point, maintaining higher speeds when navigating turns, and initiating acceleration sooner. Such driving techniques have the potential to result in a reduction of lap times. The observed improvement in performance is positively correlated with the presence of rain, wind, or changes in temperature.

One factor that might negatively impact a driver's confidence is significant variations in aerodynamic balance across the operating map, particularly during braking and turning manoeuvres (Garsed-Brand, Developing a quick racing car from the aerodynamics perspective – driver's confidence, 2022). Achieving high downforce coefficient values can often be feasible by maintaining an aero balance of over 50% towards the front. In this scenario, the operation of the vehicle poses challenges in terms of driving. From a vehicle dynamics perspective, the focus is on achieving a suspension configuration that maintains the automobile within a desired range of 42-48%. When creating aerodynamic components, it is crucial to ensure that the car is appropriately rebalanced for practical utilisation. A splitter that produces a large amount of additional front downforce and total downforce without altering the rear downforce lacks practicality and drivability (Iley, 2023).

2.2.3. Creating Aero Maps – Wind Tunnel vs. CFD

Two primary methodologies exist for generating an aero map: wind tunnel testing and computational fluid dynamics (CFD) simulations.

2.2.3.1. Wind Tunnel

Wind tunnels are instruments that generate a regulated airflow within a confined tube or chamber. Wind tunnels are utilised for the purpose of evaluating and enhancing the aerodynamic capabilities of various types of vehicles, including automobiles, motorcycles, and aircraft. The dimensions, configuration, and velocity of wind tunnels may differ, contingent upon the intended application and the specific specimen under examination (Chandler, 2022). Wind tunnels play a crucial role in the development and optimisation of racing car designs within the realm of motorsports. These devices assist engineers in quantifying and mitigating aerodynamic drag, enhancing downforce, and achieving vehicle balance. Wind tunnels provide for the study of many configurations and scenarios, encompassing alterations in the angle of attack, ride height, and wind direction (Autosport, 2022). Typically, wind tunnel models are scaled down to approximately 50 or 60% of the full-scale dimensions of the car. These models are equipped with interchangeable components, facilitating convenient experimentation with various designs during testing. In this manner, engineers possess the ability to identify incremental enhancements and afterwards cultivate substantial developments (Garsed-Brand, Predictive tools - Wind Tunnel, 2022). Certain wind tunnels are equipped with a rolling road mechanism comprising a conveyor belt that operates synchronously with the airflow, facilitating vehicle movement. This simulation provides a more realistic representation of the relative motion between the ground and the car compared to a stationary car. The utilisation of a rolling road can potentially enhance the precision and dependability of the wind tunnel data (Silvestro, 2018). Limitations of wind tunnels are high energy consumption, environmental impact, regulatory restrictions, and cost. Furthermore, the

wind tunnel inherently represents an approximation of real-world conditions. The data obtained undergoes analysis across a range of model sizes, Reynolds numbers, geometrical approximations, variations in part deformation under load, diverse tyre shapes, ground roughness, absence of flow curvature, approximations related to internal obstructions, and several other factors (Garsed-Brand, Predictive Tools – Wind Tunnel and CFD, 2022).

2.2.3.2. Computational Fluid Dynamics

Computational fluid dynamics (CFD) is an interdisciplinary field that employs sophisticated mathematical techniques and computer-based simulations to effectively simulate and forecast the dynamics of fluids and physical systems, including but not limited to air and racing vehicles. CFD has the ability to address intricate aerodynamic challenges that are difficult or impossible to investigate experimentally. CFD is critical in the motorsports industry because it is a fundamental tool for developing and enhancing car designs, allowing the examination of various configurations and scenarios, such as changes in wing shape, diffuser inclination, and tyre inflation (Holm, 2022).

There exist numerous computational fluid dynamics (CFD) modelling methodologies. The more costly methodologies exhibit higher precision in modelling flow and turbulence, whereas the less expensive and time-efficient methodologies employ a less refined discretisation approach and rely on notable approximations. Selecting a position within this modelling spectrum presents a challenging task. The modelling approach should consider the comprehension of the system, the developmental stage, the temporal framework, and the financial resources available. Teams often opt to utilise lower-resolution models for bulk development while reserving higher-resolution models for correlation exercises (Garsed-Brand, Garsed-Brand, 2022). Due to incremental advancements in computer hardware and CFD software, generating an aerodynamic map through computational fluid dynamics simulations presents a more cost-effective alternative to wind tunnel testing (AirShape, 2019).

2.2.3.3. Data Points and Surface Fitting (MATLAB)

An aero map comprises numerous data points that are interpolated and extrapolated in order to generate a comprehensive representation of different vehicle characteristics. It is imperative to establish the specifications for front and rear ride heights, yaw angles, and various vehicle set-ups in order to conduct comprehensive testing. When conducting surface fitting, it is of utmost importance to establish a boundary around the region of interest while simultaneously preserving sufficient level of detail to eliminate non-linearities (Iley, 2023). The precision of the map is contingent upon the accuracy of the model as well as the strategies employed in the simulation/ wind tunnel data.

The process of data fitting involves identifying a mathematical model that most accurately represents the correlation between a given set of data points. MATLAB provides a range of tools and functions designed for data-fitting purposes, including the Curve Fitting app, the fit function, and the Curve Fitting Toolbox. The Curve Fitting application is a user-friendly graphical interface that facilitates fitting curves and surfaces to data. It enables users to compare various models, tailor fit options, and modify the resulting outcomes according to their preferences. Additionally, it is possible to export the fit objects and results to the MATLAB workspace to conduct further analysis (MathWorks, 2023). The Curve Fitting Toolbox supports six interpolation methods that can be utilised for fitting curves and surfaces to given data. The polynomials employed in the various methods exhibit variations in terms of their types and the shape and smoothness of the resulting fit. Additionally, disparities exist in the speed and accuracy of the fit achieved by these methods.

The methods employed include linear interpolation, nearest neighbour interpolation, cubic spline interpolation, shape-preserving interpolation, biharmonic interpolation, and thin-plate spline interpolation. In the context of

curves, linear interpolation involves the utilisation of distinct linear polynomials to approximate the relationship between consecutive data points. Similarly, in the case of surfaces, linear interpolation is employed to establish a linear polynomial between sets of three points. Nearest neighbour interpolation assigns the value of an interpolated point equal to the value of the nearest data point. In the context of curve interpolation, cubic spline interpolation involves the utilisation of distinct cubic polynomials to connect adjacent data points.

Conversely, cubic spline interpolation employs a distinct collection of three points to establish the desired surface when dealing with surface interpolation. The PCHIP (piecewise cubic Hermite interpolation) method is known for maintaining the monotonicity and shape of data, specifically for curves. The MATLAB® 4 `griddata` method, also known as the Biharmonic (v4) method, is capable of fitting surfaces with good extrapolation properties. However, it should be noted that this method is specifically designed for surface fitting and may not be suitable for other data types. Thin-plate spline interpolation is a suitable method for generating smooth surfaces that exhibit good extrapolation capabilities, specifically for surfaces.

The MATLAB function `scatteredInterpolant` is employed for the linear and nearest neighbour methods, while the cubic spline and biharmonic methods utilise the MATLAB function `griddata`. The `tpaps` function is employed within the context of the thin-plate spline method. The selection of the interpolant method is contingent upon various factors, including the inherent properties of the data being fitted, the desired level of smoothness for the resulting curve, considerations pertaining to computational efficiency, and the subsequent analysis requirements following the fitting process. While the linear and nearest neighbour methods demonstrate good model fitting capabilities, the resulting curves exhibit a lack of smoothness. The computational algorithms known as cubic spline, shape-preserving, and biharmonic methods require more time to fit models yet yield exceptionally smooth curves (MathWorks, 2023).

3. Aero Map

This section of the report discusses the methodology, generation and evaluation of aero maps pertaining to the UWTSD Sports 2000 MCR. Wind tunnel experiments and computational fluid dynamics (CFD) simulations are utilised. The wind tunnel data utilised in this analysis is derived from a study conducted in 2022, specifically focusing on the MCR new Bodywork. The study was carried out at the esteemed MIRA facility. The computational fluid dynamics (CFD) technique was employed by Sabe Fluid Dynamics in their study.

3.1. CAD Preparation and CFD Simulation Properties

In order to produce a map utilising CFD, it is imperative to possess a race car 3D model of superior quality. The UWTSD Motorsport team members employed a 3D scanning technique to enhance the visual representation of the car. The necessity to update the car model utilised for CFD arises from the presence of manufacturing tolerances and supplementary alterations implemented to the initial computer-aided design (CAD). One of the discrepancies in the front pontoon is illustrated in Figure 9-1, which can be found in Appendix A. The figure showcases the 3D scan overlaid on the original car model. Additional areas requiring modification encompassed the sidepods, rear pontoon, upper deck, and rear wing. Figure 9-2 illustrates a comprehensive comparison between the car and the scan, while Figure 10-3 showcases the updated car model by the UWTSD MCR team. The labels from 1 to 5 indicate the necessary modifications still required to ensure proper execution of the model. The final model is illustrated in Figure 9-4.

In Figure 9-3, label 1 is utilised to emphasise the front pontoon. The front pontoon exhibited two primary concerns: an erroneous configuration in terms of shape and dimensions and a deficiency of a hollow space within it, thereby impeding the range of motion of the wheel. The aforementioned concerns were addressed through the modification of the primary Solidworks part file associated with the component. The form underwent iterative modifications until it closely resembled the scan. Figure 9-5 illustrates the revised pontoon in relation to the side, front, and top scans. Additionally, the inclusion of fillets was implemented at the pressure release outlet as a proactive measure to address apprehensions regarding the existence of sharp edges that are challenging to mesh correctly. Floor and wishbone cover surface holes were also identified and rectified.

The sidepods designated as “2” in Figure 9-3 exhibit alterations that students from UWTSD have carried out. However, these modifications have not yet been integrated with the vehicle’s main structure. The third label designates the front and rear wheels. An error was encountered in the modified model, leading to the utilisation of the rear wheels in place of the front wheels—another straightforward remedy. The rear pontoon designated as “4” did not undergo the hollowing-out process, resulting in a restriction of vertical movement for the rear wheel. The use of surface tools in Solidworks was employed to rectify this issue. The identification of the splitter designated as 5 presented a challenge. The left side of Figure 9-6 illustrates the presence of sharp edges and imprecise profile steps, which can lead to complications in meshing and produce inaccurate results. Sabe Fluid Dynamics successfully resolved the complex problem, and the outcomes are visually presented in Figure 9-6 (right).

Additionally, the provided model did not include any radiators. The model was enhanced by incorporating a generic race car radiator, as per the contributions of Sabe Fluid Dynamics. The image shared with Sabe for modelling is depicted in Figure 10-7. The objective of the CFD aerodynamic mapping is to precisely simulate the MCR while the vehicle is on the racetrack. The CFD method employed rotating wheels and a moving road in its implementation. The cases were held in a steady state, with the vehicle speed maintained at 35 m/s.

3.2. CFD Run Plan

In order to ensure a feasible number of runs, limited to 15, while maintaining accuracy across the aero map, this study will exclusively focus on investigating the impact of ride height and rake changes while excluding the consideration of yaw angles. The literature review highlights the necessity of determining the perimeter of the potential ride height ranges in order to achieve precise surface fitting of an aero map. The procedure for determining the ride heights involved computing dynamic ride heights based on actual damper position data as well as conducting tests and assessing the original VI-CarRealTime MCR 40 model. The use of VI-CarRealTime will be discussed further in the next section of the report.

The code in Appendix B calculates a vehicle's minimum ride heights. The ride height at each corner of the car is calculated by taking the static ride height (from set-up sheets) and subtracting the damper movement. As seen in Appendix B in Figure 9-8, for the 2022 Race 2 at Donington, damper position sensors had a non-zero static value. This is accounted for in the calculations. The respective motion ratios provided by (Fullylove, Lawrence, & Arthur, 2023) are used to covert damper travel to wheel travel. The process was conducted for numerous tracks, and results are shown in Table 3-1. Apart from Donington and Thruxton, it was observed that the minimum rear ride heights were consistently 10 to 15mm greater than the minimum front ride heights. The concurrent occurrence of these ride heights is not explicitly mentioned; however, the inclusion of these minimum values facilitates the establishment of a perimeter for the aero map construction. The location of Donington's atypically low rear ride height values is illustrated in Figure o99, as presented in Appendix B. Upon the car's arrival at the exit of turn 3, also known as the Craner Curves, a substantial decrease in the rear of the vehicle is observed. This phenomenon can be attributed to the acceleration experienced by the car subsequent to a rather abrupt decline in altitude. Due to the leftward direction of turn 3, the rear right section of the vehicle exhibits the lowest elevation.

Table 3-1: Minimum ride heights 2022 Season

Venue	Session	Min			
		FL	FR	RL	RR
Donington	Race 2	43.2826	40.2777	43.9786	37.4557
Silverstone	Race 2	47.8959	48.1015	56.1429	53.5614
Brands GP	Race 2	23.5002	26.6587	35.4214	37.0543
Brands GP	Qualifying	17.1964	26.4756	35.3486	39.2686
Snetterton	Race 1	24.6166	24.8887	42.7486	43.9443
Thruxton	Race 2	39.7402	45.3746	45.2057	46.1586

When investigating vehicle ride height, laser ride height sensors exhibit superior performance compared to damper position sensors due to their direct measurement of the vertical distance between the vehicle chassis and the road surface. Damper position sensors indirectly assess suspension compression. Consequently, laser ride height sensors exhibit enhanced precision and reduced susceptibility to variables such as tyre pressure, fuel load, aerodynamic downforce, and calculation errors. However, laser ride height sensors exhibit a higher cost and increased vulnerability to the presence of dirt and debris (HP Academy, 2021). Damper position sensors use potentiometers (rotary or linear) to measure the position and rate of change of the suspension components. Laser ride height sensors employ a non-contact optical technique for quantifying the vertical distance between the vehicle chassis and the ground surface (KA Sensors, 2023).

Based on the data in Table 3-1 as well as the previously mentioned surface fitting considerations, a CFD run plan was formulated. Table 3-2 shows runs 1 – 15. The model used for runs 1-13 will have a 25mm rear gurney and have the rear wing in the mid position. Runs 14 and 15 replicate the ride heights used in 12 and 13. For these cases, a car model with no gurney is simulated, and the test intends to show the aerodynamic effects of using a rear gurney.

Table 3-2: CFD Run plan

RUN No.	FRH	RRH
1	10	30
2	30	50
3	35	65
4	20	50
5	25	60
6	20	30
7	30	75
8	15	40
9	25	40
10	30	35
11	35	50
12	45	55
13	55	70
14	45	55
15	55	70

Table 3-3 further shows the map points, and Figure 3-1 shows the occurrence of different levels of rake in testing. The primary objective of the map is to collect data for the car while it is on the track. Therefore, allocating computational resources to acquire valuable data during dynamic rake angles was imperative. After the completion of the run plan, Sabe Fluid Dynamics conducted CFD tests.

Table 3-3: CFD Run plan 25mm gurney set up

25mm gurney		FRH										
		10	15	20	25	30	35	40	45	50	55	60
RRH	30	1		6								
	35					10						
	40		8		9							
	45											
	50			4		2	11					
	55								12			
	60				5							
	65						3					
	70										13	
	75					7						
	80											
	85											
	90											

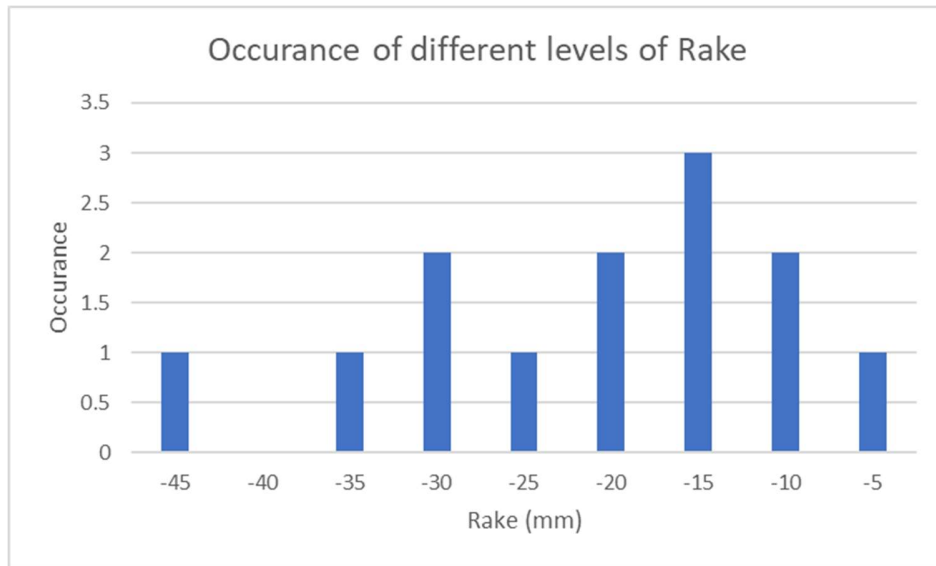


Figure 3-1: Occurrence of different rake levels in CFD tests

3.3. Aerodynamic Data

As mentioned earlier, data from wind tunnel testing is accessible. The present section of the report is dedicated to examining and evaluating wind tunnel and computational fluid dynamics (CFD) data, with particular emphasis on fitting and analysis.

3.3.1. Wind tunnel data

Table 10-1 in Appendix C contains the wind tunnel data. Surface fits were applied to the aero balance, front, rear and total downforce, drag and downforce vs. drag efficiency for the swept ride heights. The thin-plate spline interpolation method was used as it provided a smooth fit-enhancing interpolation. Figures 9-10 to 9-27 in Appendix C plot various aerodynamic properties for front and rear ride height (mm) changes. It is observed that running the most rake at the lowest front ride height produces the most downforce. Decreasing the absolute value of negative rake and increasing the front ride heights results in the car producing less total downforce.

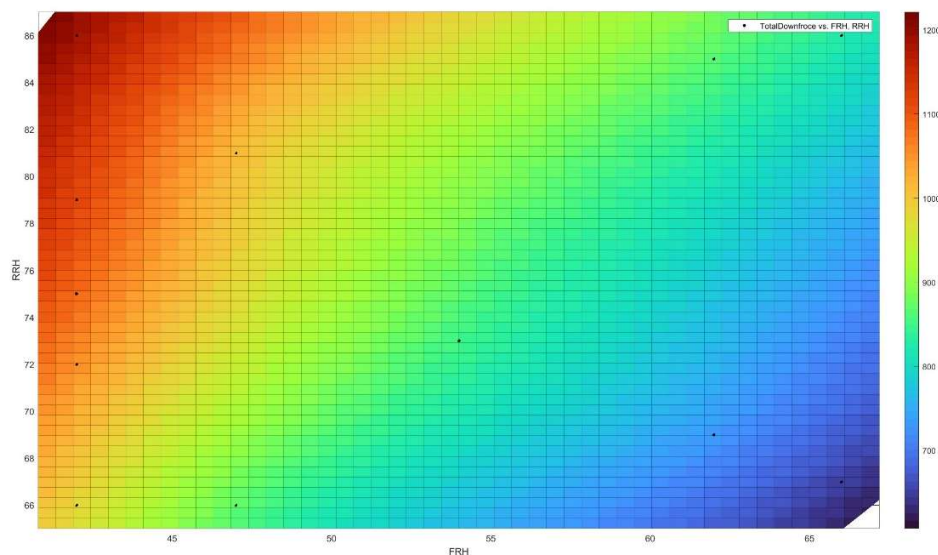


Figure 3-2: WT - Total Downforce

Front aerodynamic balances ranging from 48% to 42% are considered optimal for enhancing the drivability of a vehicle. Figure 3-3 illustrates that the race car is expected to exhibit favourable aerodynamic balance while generating maximum downforce. However, it is important to acknowledge that the depicted map does not encompass the lower range of ride heights at which the car is known to operate. The sensitivity of front and rear downforce to variations in ride heights is depicted in Figures 9-16 to 9-21, which can be found in Appendix C. The analysis of various ride heights reveals that alterations in ride heights or rake have minimal impact on the generation of rear downforce.

Consequently, the magnitude of forces generated at the front of the vehicle determines both the overall downforce and the aerodynamic balance. Similar trends were observed between the total downforce and the generation of front downforce within the parameters of the map. It is probable that the vehicle will exhibit understeer when the front aero balance is below 40%, as indicated by the left side of the diagonal line in Figure 3-3.

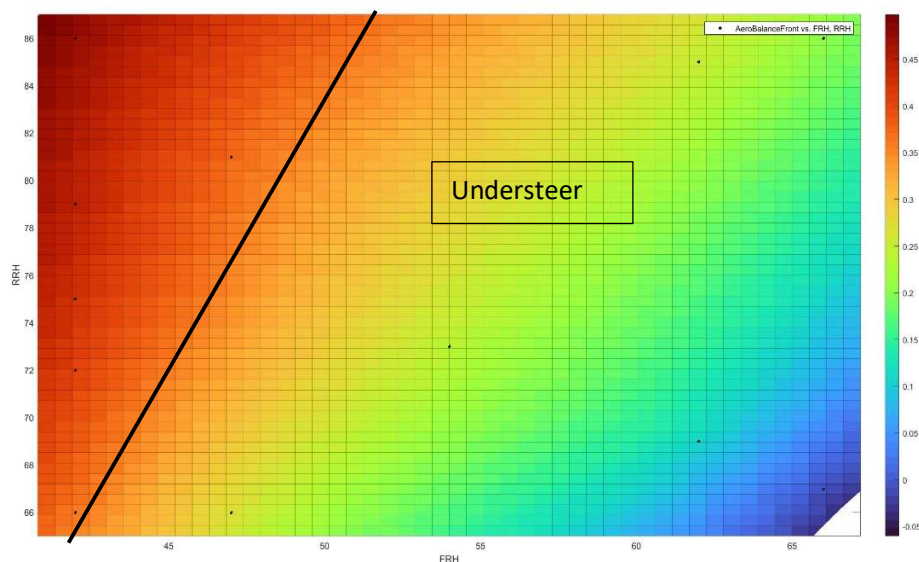


Figure 3-3: WT – Front Aero Balance

3.3.2. CFD Data

Table 10-2 in Appendix D contains the CFD data. Similar to what was done to the wind tunnel data, surface fits were applied to the aero balance, front, rear and total downforce, drag and downforce vs. drag efficiency for the swept ride heights. The thin-plate spline interpolation method was used as it provided a smooth fit-enhancing interpolation. Figures 9-28 to 9-45 in Appendix D plot various aerodynamic properties for front and rear ride height (mm) changes. The selected ride heights for CFD fall below those used during wind tunnel testing.

A higher rake angle at lower ride heights results in increased downforce generation. Between the points 25/60, 30/75, and 35/65, this occurs at the front as the front downforce increases and the rear downforce decreases. The race car exhibits a significant front bias in terms of aerodynamic balance when operating at its maximum total downforce. The driver will experience extreme difficulty in maintaining the car within or in close proximity to the limit of grip.

The reduction in front ride height to exceptionally low levels (approximately 20mm) leads to a decrease in front downforce. This suggests that the splitter could be experiencing a lack of airflow, potentially causing it to stall. However, verifying this hypothesis through further analysis using CFD post-processing is necessary. At significantly reduced ride heights, there is an improvement in the aerodynamic balance and the efficiency of downforce versus drag. This phenomenon can be attributed to the production of reduced front downforce and increased rear downforce. One significant drawback associated with utilising this restricted area pertains to the necessity of traversing an unstable range of 55% to 50% front aerodynamic balance during deceleration. Certain drivers may perceive this alteration in balance during braking as advantageous for inducing rotation in the vehicle. However,

it is probable that this adjustment will be accompanied by a decrease in confidence when navigating high-speed corners.

The depicted grey sketch in Figures 3-4 to 3-8 illustrates a substantial operational region characterised by favourable aerodynamic balance. In order to ensure stability (Figure 3-4, 3-6, 3-7), it becomes imperative to make a requisite trade-off in the overall magnitude of downforce (Figure 3-5). The trade-off between downforce and drag efficiency is somewhat compromised within this particular region (Figure 3-8). However, it should be noted that elevating ride heights leads to a more pronounced decline in efficiency.

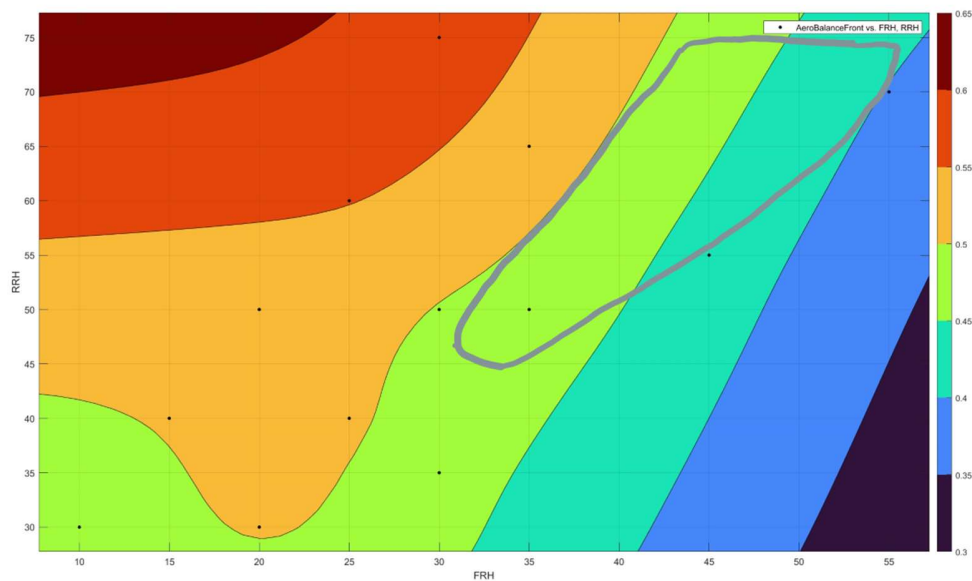


Figure 3-4: CFD - Front Aero Balance contour plot desired ride height range

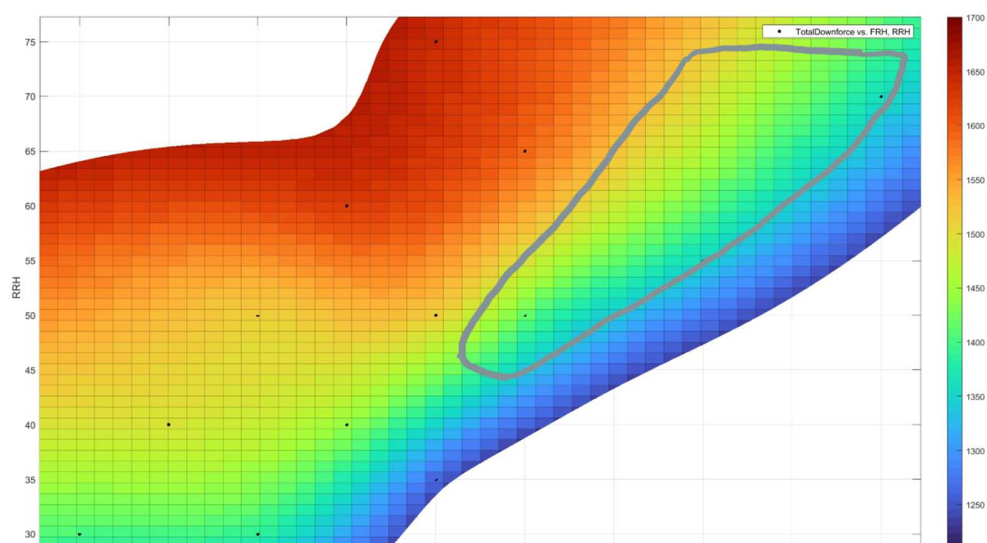


Figure 3-5: CFD - Total Downforce 2D desired range

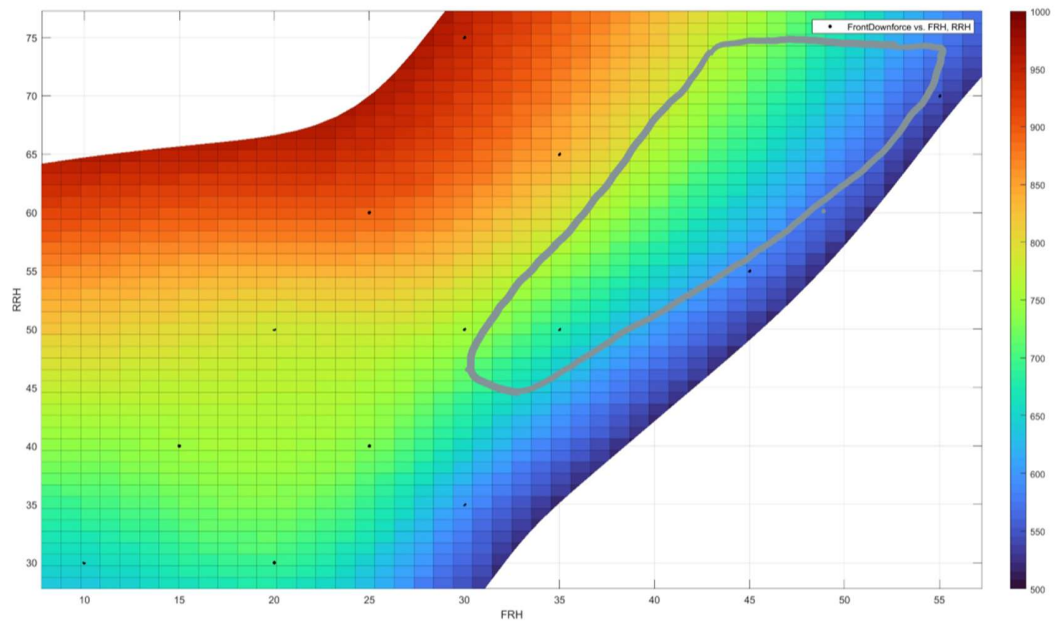


Figure 3-6: CFD - Front Downforce 2D desired range

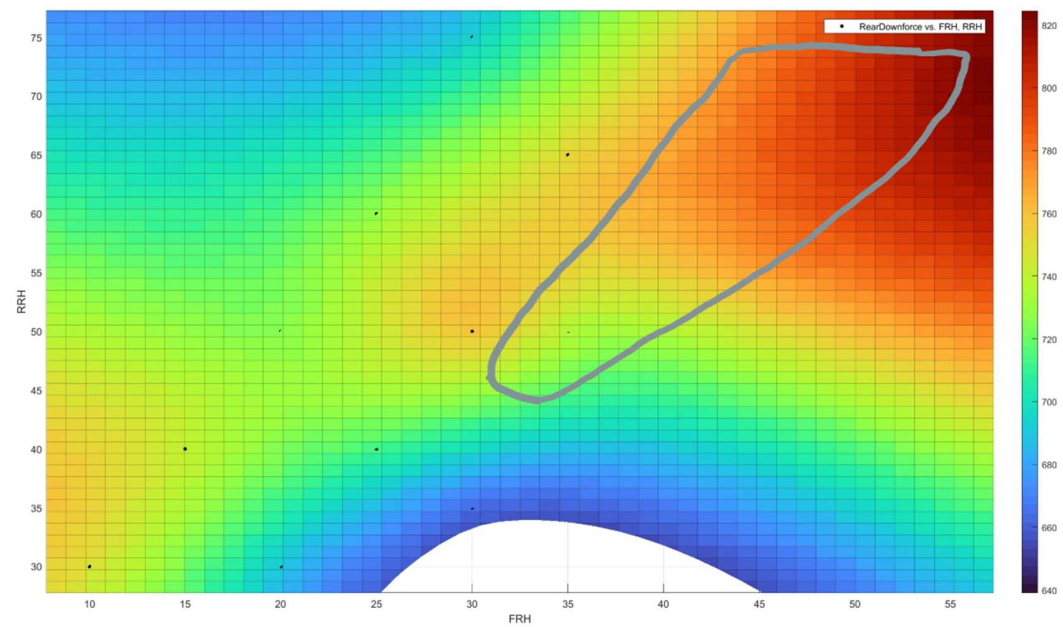


Figure 3-7: CFD - Rear Downforce 2D desired range

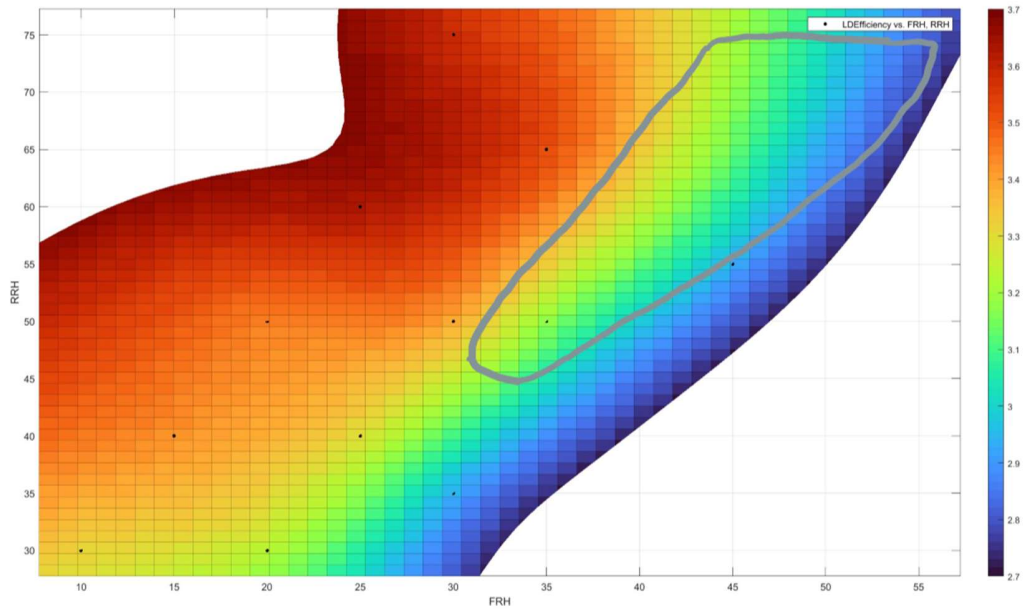


Figure 3-8: CFD - Downforce/Drag Efficiency 2D desired range

3.3.3. Data Comparison

3.3.3.1. CFD vs. Wind Tunnel

The comparative analysis between the Computational Fluid Dynamics (CFD) outcomes and the wind tunnel experimental data is presented in Table 3-4. The CFD data is acquired directly from the CFD results, while the wind tunnel data utilises interpolation look-up tables within the Simulink software. Significant discrepancies between the CFD results and the wind tunnel experimental data are observed. The CFD simulations conducted for runs 14 and 15 utilised the same vehicle configuration as the one employed during the Mira wind tunnel test. However, the objective of the CFD simulations was to capture the on-track performance rather than conducting a validation study of the wind tunnel tests.

In contrast to the wind tunnel, the simulation did incorporate a rolling road and moving tyres. The CFD model also utilised a generic racing radiator, which may not accurately represent reality. The observed error remains higher than anticipated, particularly in relation to front downforce. Therefore, it is necessary to conduct additional research in order to examine the specific factors contributing to the disparities between CFD simulations and wind tunnel measurements.

Table 3-4: CFD vs Wind Tunnel Data

FRH/RRH	CLfA			CLrA			CLtA			CdA		
	CFD	Wind Tunnel	% Error	CFD	Wind Tunnel	% Error	CFD	Wind Tunnel	% Error	CFD	Wind Tunnel	% Error
45/55	0.71	0.37	48%	0.67	0.84	-27%	1.37	1.21	11%	0.55	0.65	-19%
55/70	0.69	0.22	68%	0.82	0.86	-6%	1.50	1.08	28%	0.59	0.67	-14%

3.3.3.2. On-Track Measurements vs. CFD vs. Wind Tunnel

The aerodynamic factors were determined through the analysis of suspension loads using testing data obtained from Silverstone in 2022, where a series of constant speed tests were conducted. The data and processing methods employed are presented in Appendix E. The MoTeC screenshot presented in Figure 9-47 of Appendix E provides a visual representation of the location and data observed during a constant speed test. Front and rear downforce coefficients were determined by utilising suspension loads. The ride heights were determined by analysing the data obtained from the damper potentiometer. These ride heights were then employed in Simulink look-up tables to estimate the forces expected from the CFD simulations and wind tunnel experiments. Tables 9-4 to 9-7 depict the procedural steps. Table 3-5 presents a comprehensive comparison between the results obtained from CFD simulations and the corresponding measurements. Table 3-6 provides a comparison between the data obtained from Wind Tunnel experiments and the corresponding measurements. CFD simulations often exhibit a tendency to overestimate the magnitude of downforce, whereas wind tunnel experiments tend to underestimate it. The most significant disparities are observed in the front downforces, where average absolute errors of approximately 50% are detected. The rear downforce values exhibit a higher degree of similarity, while the discrepancies in total downforce can be attributed to inaccuracies in the measurement of front downforce.

Several potential reasons for the errors observed include sensor malfunctions, inaccuracies in ride height calculations, and variations in car set-ups. Significant levels of noise were observed in the MoTeC data, prompting the adoption of a strategy wherein averages were computed for specific regions where steady-state conditions were assumed. The operational status of the sensors was limited to one front and one rear sensor. Consequently, the available data was duplicated in order to estimate forces. However, there is room for improvement in terms of accuracy. Inaccuracies in ride height calculations may arise due to the aerodynamic elasticity of body

components, which can cause them to move beyond the measurements recorded by damper potentiometers. To enhance accuracy, the utilisation of laser ride height measuring devices is recommended. The tests mentioned above primarily assess performance within a limited range. However, broadening the scope to encompass a wider variety of rake angles and ride heights would likely yield valuable insights. Similar to the comparison between CFD and wind tunnel testing, the discrepancy between the observed error and the expected values persists, particularly regarding front downforce. Hence, it is recommended to undertake further investigation to scrutinise the precise elements that contribute to the disparities observed between CFD simulations and wind tunnel measurements.

Table 3-5: CFD vs Measured Data

FRH/RRH	ClfA			ClrA			CltA		
	CFD	Measured	% Error	CFD	Measured	% Error	CFD	Measured	% Error
51.7/61.0	0.709	0.477	-49%	1.091	1.063	-3%	1.800	1.540	-17%
51.7/61.1	0.709	0.522	-36%	1.091	1.115	2%	1.800	1.637	-10%
52.9/63.9	0.720	0.444	-62%	1.099	1.106	1%	1.819	1.551	-17%
52.0/63.6	0.735	0.463	-59%	1.095	0.917	-19%	1.830	1.380	-33%
52.9/63.5	0.717	0.441	-62%	1.098	0.790	-39%	1.815	1.231	-47%
ABS Average Error			54%			13%			25%

Table 3-6: Wind Tunnel vs Measured Data

FRH/RRH	ClfA			ClrA			CltA		
	WT	Measured	% Error	WT	Measured	% Error	WT	Measured	% Error
51.7/61.0	0.211	0.477	56%	0.876	1.063	18%	1.087	1.540	29%
51.7/61.1	0.212	0.522	59%	0.876	1.115	21%	1.087	1.637	34%
52.9/63.9	0.204	0.444	54%	0.876	1.106	21%	1.081	1.551	30%
52.0/63.6	0.207	0.463	55%	0.876	0.917	4%	1.083	1.380	22%
52.9/63.5	0.193	0.441	56%	0.877	0.790	-11%	1.070	1.231	13%
ABS Average Error			56%			15%			26%

After conducting validation, it was discovered that the force values obtained from CFD were erroneously twice the expected magnitude. However, it was observed that the coefficients were accurately represented. The VI-CarRealTime maps were constructed based on these forces. For the sake of simplicity, the force values in VI-CRT will remain unaltered, while adjustments will be made to the vehicle speed in order to align with the forces. For instance, a speed of 126 km/h will be modified to 178.2 km/h.

4. VI-CRT Tests

This section of the report presents a comprehensive analysis of the set-up, conducted experiments, and obtained outcomes pertaining to the VI-CarRealTime simulation model of car 40. As indicated in the literature review, the aforementioned analyses are based on the model proposed by (Fullylove, Lawrence, & Arthur, 2023), which enhanced the depiction of suspension kinematics and engine performance. The vehicle model consists of eight distinct subsections, namely the vehicle body, brakes, front and rear wheels, front and rear suspension, steering, and powertrain. In order to calibrate the aerodynamic map, it is imperative to modify the VI-CRT sensor placement of the aero map to align with the one employed in wind tunnel or computational fluid dynamics (CFD) testing. Adjustments should also be made to the ride height and ride height sensors to reflect real-world conditions accurately. As previously indicated, it is advantageous to prioritise simplicity and user-friendliness during the race car set-up process. The ride height points on the vehicle and the aero map correspond to the specific locations on the car where measurements are taken for the purpose of configuring the race car.

4.1. Different aero maps – Straight Line Braking

The data representing the different VI-CarRealTime aero maps can be observed in Figures 9-47 to 9-50, which are located in Appendix F. In order to demonstrate the impact of aero maps on car forces and balance, various maps were employed during a straight-line braking event. Four distinct aero maps were utilised. The initial MCR and single-point CFD maps employ a singular average value for drag and downforces, similar to the approach used in simple lap time simulations. In this experimental set-up, the static front ride height was set at a value of 47mm, while the rear ride height was set to 70mm. At an initial velocity of 198 km/h (123.75 mph), a braking force of 0.75 is scheduled to be exerted after a time interval of 2 seconds.

The aerodynamic balance for car 40, along with the initial aero map and a CFD single point average map, can be observed in Figures 9-51 and 9-53 of Appendix F, respectively. It is evident that, in these instances, the aerodynamic balance remains unchanged throughout the braking process. The observed disparity in front and rear downforces depicted in Figures 9-52 and 9-54 indicates that downforce is solely influenced by the velocity at which the vehicle is travelling.

The map results obtained from the Mira wind tunnel experiment are presented in Figures 9-55 and 9-56. Figure 9-55 illustrates a minimal fluctuation in aerodynamic balance resulting from alterations in ride heights. This occurrence can be attributed to the racecar's dynamic ride heights exceeding the limits specified by the wind tunnel-based aerodynamic map. Based on the obtained results, it can be inferred that VI-CarRealTime utilises the nearest neighbour technique for the extrapolation of aerodynamic data.

The outcomes derived from the utilisation of the Sabe CFD full aero map are depicted in Figures 9-57 and 9-58. Modifications in ride heights, the downward inclination of the car's front end during braking, and adjustments to the vehicle's rake all contribute to the anticipated alteration of the aerodynamic balance. It has been observed that when this vehicle configuration is employed, braking results in a front aerodynamic balance exceeding 50%. This will provide guidance for establishing decisions in the subsequent section. The brake dip and straight-line braking on an aero map contour plot are depicted in Figure 4-1. These findings are consistent with the results obtained from VI-CarRealTime.

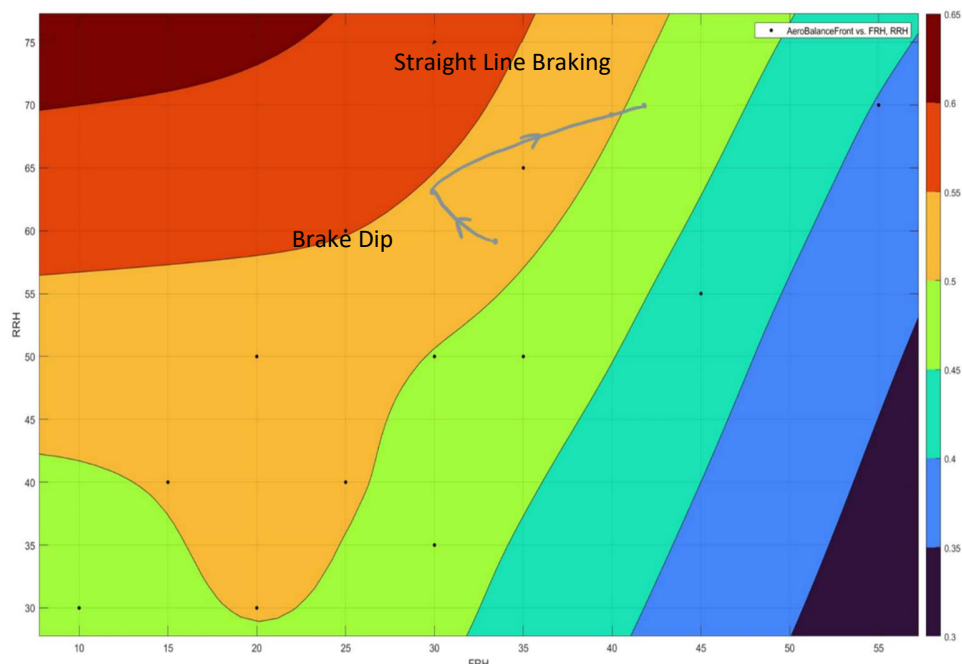


Figure 4-1: Straight Line Braking Sabe CFD Aero Map

4.2. Spring Stiffness and ride height tests

Within this section of the report, modifications are made to the spring stiffness and static ride heights to evaluate their impact on the aerodynamic balance and overall performance of the vehicle. This evaluation is conducted through a maximum performance event at the Pembrey circuit. The performance driver parameters were carefully evaluated, and the specific parameters outlined in Table 4-1 were established. An increased lateral performance factor can facilitate the attainment of reduced lap times; however, it should be noted that the controller's operation of the vehicle may deviate from realistic limits. The configuration of the vehicle will undergo iterative modifications throughout this section. Table 4-2 shows the set up modifications made throughout testing.

Table 4-1: Performance Factors used

Performance Factor	Value
Longitudinal Acceleration	1.25
Longitudinal Brake	1.2
Lateral	1.1

Table 4-2: Set up parameters

Set Up	Static Ride Height		Spring Factor	
	Front	Rear	Front	Rear
1	54	76	1	1
2	46	66	1	0.85
3	46	62	1	0.75
4	46	60	1.25	0.7
5	45	56	1.75	1.25
6	46	56	1.75	1.75

4.2.1. Set up 1 - Base Set Up

The ride heights employed during the 2023 Oulton Park event are designated for VI-CRT set-up 1, with a static front ride height (FRH) of 54mm and a rear ride height (RRH) of 76mm. The spring rates were configured to adhere to the model's default values, specifically 560 lb/in for the front springs and 416 lb/in for the rear springs. The operational range of the vehicle's aerodynamic balance is illustrated in Figure 4-2. Figure 9-59 illustrates the variation in aero balance throughout a lap, while Figure 9-60 portrays the front and rear aerodynamic forces produced throughout the same lap. Figures 9-61 and 9-62 depict a scatter plot illustrating the ride height values. Figure 4-2 was generated using this data. During braking and turning in, an unwanted shift in the aero balance causes it to exceed 50% in the forward direction.

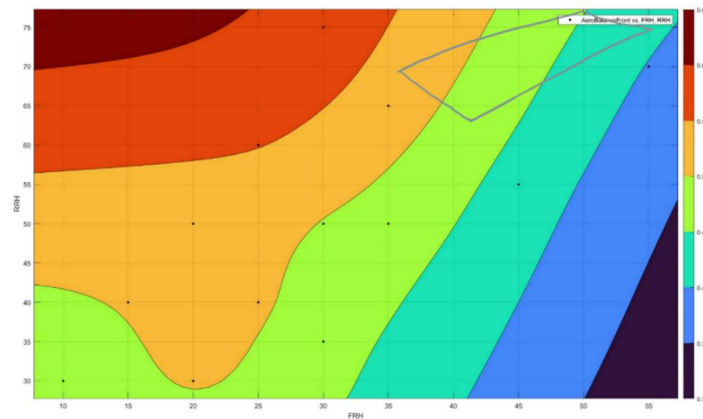


Figure 4-2: Set-up 1 - Aero Balance region where the vehicle operates

4.2.2. Set Up 2

In Set-up 2, the rear spring values are reduced to 0.85 times the original rear springs, which were measured at 353 lb/in. Additionally, the ride heights for the front and rear of the vehicle are set at FRH = 46 and RRH = 66, respectively. Figures 9-63 to 9-66 showcase conformity to the established format as delineated in set one. Figure 4-3 illustrates a notable adjustment wherein the front ride height is reduced to approximately 27mm, leading to a positive outcome. However, it is observed that the elevated rear ride height results in an increase of over 50% in front aero balance during braking and turn-in.

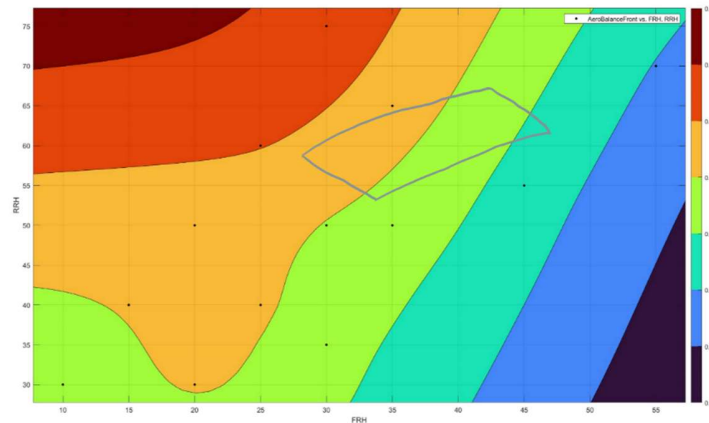


Figure 4-3: Set up 2 - Aero Balance region where the vehicle operates

4.2.3. Set-Up 3

Set-up 3 lowers and softens the rear, thereby reducing the static rake. The rear springs used in the experiment were 0.75 times the stiffness of the original springs, with a spring rate of 312 lb/in. Additionally, the rear ride heights were lowered, with the front ride height (FRH) set at 46 and the rear ride height (RRH) set at 62. Figures 9-67 to 9-70 depict the outcomes of Set-up 3, arranged in a manner akin to that of Set-up 1. Figure 4-4 illustrates a reduction in the utilised area, resulting in a decrease in the duration spent at unfavourable aero balances. However, further advancements are required to address this issue.

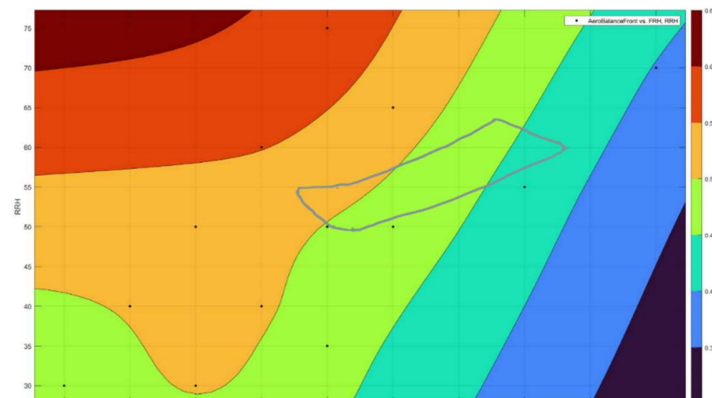


Figure 4-4: Set up 3 - Aero Balance region where the vehicle operates

4.2.4. Set-Up 4

Set-up 4 is characterised by a reduction in the rear height (FRH = 46, RRH = 60) and a decrease in stiffness (0.7 times the original rear spring rate, equivalent to 291.2 lb-in) compared to Set-up 3. To enhance the stability of the vehicle's front end, it is proposed to augment the front springs' stiffness from 560 to 700 pounds per inch. The objective of rear softening is to facilitate the downward compression of the vehicle's rear end during the process of acceleration. According to Figure 4–5, the implementation of front stiffening has resulted in the front remaining above the 30mm FRH (Front Ride Height), which is essential for achieving optimal balance, considering the specific rear ride heights employed. Additional data can be found in Figures 9-71 to 9-74.

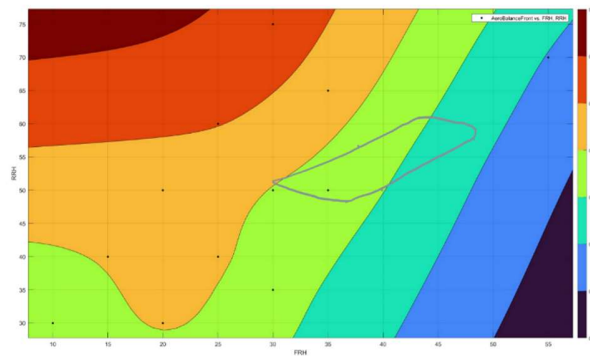


Figure 4-5: Set up 4 - Aero Balance region where the vehicle operates

4.2.5. Set-Up 5

To attain a 27.5mm minimum front ride height (FRH), it is necessary to make minor adjustments to both the front and rear suspensions. Specifically, the front suspension should be slightly lowered, while the rear suspension should also be adjusted accordingly. Additionally, enhancing the stiffness of the front spring is required to meet the desired FRH. The FRH is recorded as 45mm, while the RRH is documented as 56mm. The front springs will undergo a 1.75-fold increase, rising from 560 lb/in to 980 lb/in. The rear springs have been reinforced to 1.25 times their original stiffness, resulting in a spring rate of 624 lb/in, which is indicative of the front end's excellent platform control. The data utilised in the construction of Figure 4-6 can be found in Figures 9-75 to 9-78. Figures 4-6 and 9-78 demonstrate that the vehicle exhibits an excessive forward weight distribution upon application of the brakes.

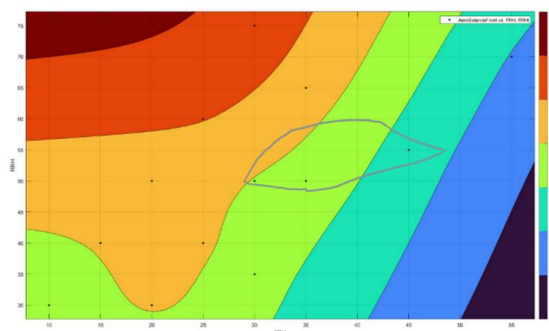


Figure 4-6: Set up 5 - Aero Balance region where the vehicle operates

4.2.6. Set-Up 6

The implementation of set-up 6 restores the front suspension to its previous static ride height while concurrently causing a slight reduction in the rear suspension (FRH = 46, RRH = 56). In order to enhance platform control, the front springs will undergo a 1.75-fold increase from the initial value of 560 lb/in to 980 lb/in. Similarly, the rear springs will experience a 1.75-fold increase, rising from 416 lb/in to 728 lb/in. According to the data presented in Figure 9-79, it can be observed that the front aero balance falls short of attaining the targeted 50% value. The operational range of the vehicle's aerodynamic balance is illustrated in Figure 4-7. Additional information can be found in Figures 9-79 to 9-82, which are located in Appendix F.

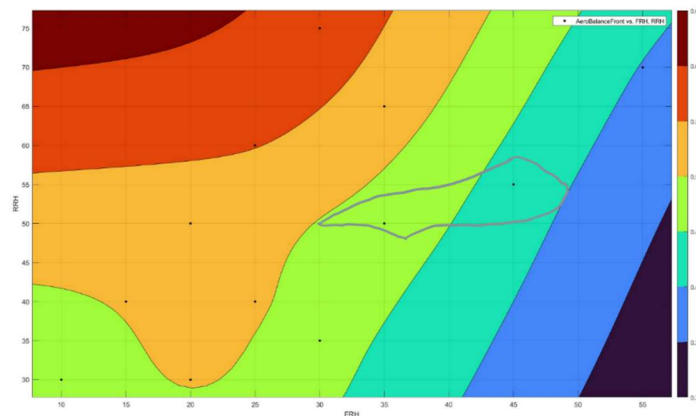


Figure 4-7: Set up 6 - Aero Balance region where the vehicle operates

4.2.7. Comparison

4.2.7.1. Lap times

Table 4-3 shows slight lap time variation. The fastest lap times are from set-ups that use more than 50% front aero balance. This is possible because running the vehicle in this more aggressive region generates more total downforce than when running a more balanced set-up. As the VI-Driver is able to assess the maximum amount of grip numerically and drive accordingly with no consequences if it crashes, it can drive on a level unobtainable to most drivers.

Table 4-3: Lap time comparison

Setup	Lap Time (s)
1	57.021
2	56.991
3	57.021
4	57.041
5	57.061
6	57.061

4.2.7.2. Stability

Figure 4-7 presents a comparison between two distinct aero balance set-ups, namely 2 (located at the top left) and 6 (located at the top right), at Pembrey (located at the bottom). These set-ups represent the most aggressive and stable configurations, respectively. The yellow colouration serves to emphasise the variation in aerodynamic equilibrium during the high-speed turn 4. The slower configuration, denoted as set-up 6, is likely to instil greater confidence in a driver compared to the faster configuration, referred to as set-up 2. Consequently, this enhanced confidence is expected to translate into improved lap times in real-world racing scenarios.

One notable aspect is the anticipated advantage of implementing set up 6, which is visually emphasised through the use of the colour pink. In comparison to set up 2, it can be observed that set up 6 exhibits a more significant rear bias upon exiting the Brooklands Hairpin. It can be inferred that an increase in rear downforce would be expected in this scenario. However, set-up 6 results in a decrease in rear downforce during the exit phase, approximately measuring 20N at a speed of 113km/h upon exiting the corner. The observed phenomenon can be attributed to the manipulation of aerodynamic balance, which is primarily influenced by the generation or absence of front downforce rather than the generation of rear downforce, i.e. set-up 6 produces significantly less front and slightly less rear downforce.

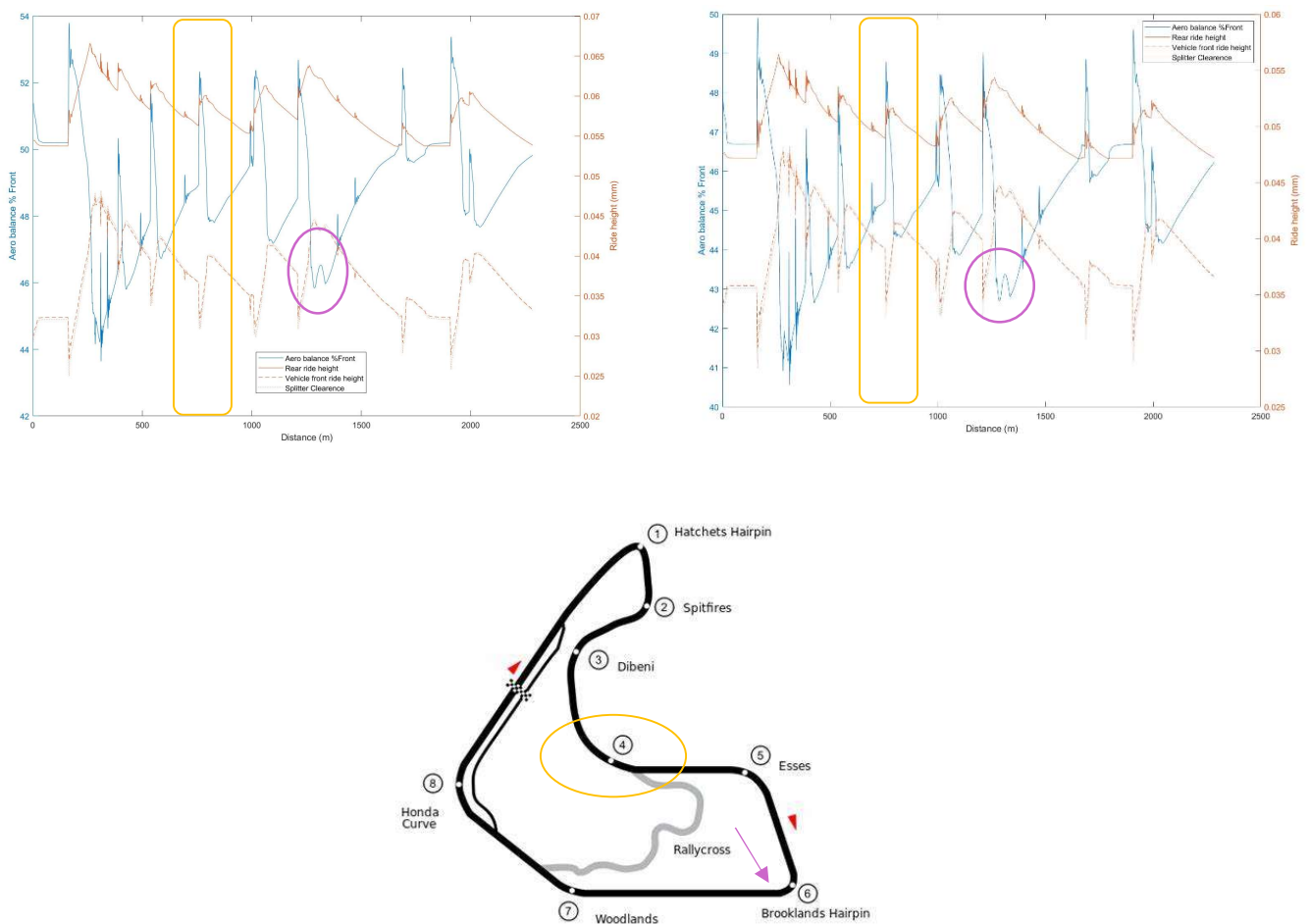


Figure 4-8: Aero balance setups, 2 (top left) and 6 (top right), Pembrey track map (bottom).

5. Discussion

The following section of the report presents an analysis of the aerodynamic mapping and lap time simulation activities, as well as the corresponding outcomes.

5.1. Aero Mapping

Creating and assessing aero maps for the UWTSD Sports 2000 MCR entailed a thorough methodology that integrated wind tunnel experiments and computational fluid dynamics (CFD) simulations. The present discussion will examine the principal discoveries and ramifications of this research.

5.1.1. Aero Map Generation

The acquisition of essential data for the development of aero maps was facilitated through the utilisation of wind tunnel experiments conducted at the MIRA facility and computational fluid dynamics (CFD) simulations performed by Sabe Fluid Dynamics. The importance of ensuring the precision of the underlying 3D model of the race car was explicitly clear. In order to achieve this objective, a rigorous procedure was implemented to revise the computer-aided design (CAD) model, taking into consideration manufacturing tolerances and design modifications. Alterations were made to multiple elements of the vehicle, encompassing the front pontoon, sidepods, wheels, rear pontoon, and splitter. The incorporation of radiators into the model played a crucial role in augmenting its level of realism.

The primary aim of the CFD analysis was to replicate the performance of the MCR on the racetrack. This involved the consideration of dynamic factors, such as the rotation of wheels and the movement of the road. The experiment was conducted under steady-state conditions, where the vehicle speed was deliberately set at a constant value of 35 m/s. The thorough preparations undertaken served as the basis for a comprehensive investigation into the aerodynamic properties. This section emphasised the crucial significance of CAD model preparation in attaining precise CFD outcomes. It is worth mentioning that laser ride height sensors have emerged as a more effective method for measuring ride heights, primarily due to their enhanced precision and reduced vulnerability to external factors. Implementing measures aimed at rectifying inaccuracies in ride height calculations will significantly contribute to the overall improvement of the reliability of our findings. Formulating a structured run plan was essential for ensuring the viability and precision of our aero maps. The research approach involved prioritising ride height and rake adjustments while disregarding yaw angles to enhance the experimental procedure's efficiency without compromising accuracy. The refinement of the approach was facilitated by the utilisation of dynamic measurements and analysis of the VI-CarRealTime MCR 40 model in order to determine ride heights.

5.1.2. Aerodynamic Data

The analysis of aerodynamic data in the study incorporated findings from both wind tunnel experiments and computational fluid dynamics (CFD) simulations. The data was visualised using various plots while acknowledging the limitations of extrapolation associated with this method.

The relationship between ride height, rake, and aerodynamic performance was investigated through the analysis of wind tunnel data. The alteration of the ride heights and rake played a pivotal role in the generation of front downforce and front aerodynamic balance. While the impact of these variations on rear downforce was relatively minimal, maintaining a proper balance between front and rear downforce was of utmost importance. The CFD simulations have provided insights into the impact of ride height and rake on the vehicle's aerodynamics, especially at ride heights lower than the wind tunnel. The findings of this study indicate that the variables of ride height and rake significantly impact the generation of downforce, similar to that shown by wind tunnel results. A

delicate trade-off between downforce and drag efficiency was discovered. According to the data, achieving optimal performance requires the careful balancing of these variables.

The in-depth examination of the results obtained was facilitated by the comparison of data derived from wind tunnel experiments, CFD simulations, and on-track measurements. It is worth noting that there existed substantial disparities between the computational fluid dynamics results and wind tunnel measurements, specifically in relation to the generation of front downforce. The simulation, which included dynamic elements such as a rolling road and moving tyres, resulted in errors that exceeded initial expectations. This highlights the need for a more comprehensive examination of the factors that contribute to these disparities. The examination of on-track measurements in relation to CFD and wind tunnel data has highlighted the difficulties associated with attaining accurate vehicle aerodynamic characteristics. The observed inconsistencies, specifically in the context of front downforce, have raised inquiries regarding the precision of sensors and the potential deviations in the configurations of the vehicles. The findings mentioned above suggest the potential for enhancing the methodology and measurement techniques.

5.2. Lap Simulations

The present section revolves around the VI-CarRealTime (VI-CRT) tests performed on the car model, emphasising various aero maps and their influence on car forces and balance, alongside modifications to spring stiffness and ride heights. These experiments yield significant insights into the vehicle's aerodynamic characteristics and operational efficacy.

The examination of various aero maps during instances of straight-line braking unveils significant discoveries. The impact of selecting an aero map on the aerodynamic balance and force distribution of a car is clearly discernible. The initial MCR and single-point CFD maps, which utilise average values for drag and downforces, demonstrate a lack of substantial alterations in aerodynamic equilibrium throughout the braking process. Nevertheless, the utilisation of data from the Mira wind tunnel experiment and the Sabe CFD full aero map uncovers a greater understanding of the dynamic alterations in aerodynamic equilibrium caused by ride heights and vehicle configuration fluctuations. The findings suggest that VI-CRT employs the nearest neighbour method to extrapolate aerodynamic information. This approach may result in no variations in aerodynamic balance when the vehicle's dynamic ride heights surpass the thresholds established by the wind tunnel-derived aerodynamic map. The results derived from VI-CRT align with those obtained through wind tunnel experiments and CFD simulations, thereby enhancing the reliability and validity of VI-CRT as a valuable instrument for investigating aerodynamic phenomena.

The influence of spring stiffness and ride height modifications on the aerodynamic balance and overall performance of the vehicle during a maximum performance event was examined. Different configurations are examined to assess their impact on the vehicle's performance. These configurations entail modifications in the spring rates and ride heights, and their outcomes are crucial for comprehending the influence of these variables on aerodynamics. The comparison between different set-ups reveals that lap times exhibit minimal variation, but set-ups with more than 50% front aero balance result in faster lap times. This is because such set-ups generate more total downforce, and the VI-Driver can exploit this advantage without the risk of crashing. Moreover, the braking and high-speed corner stability analysis shows that stability-enhancing set-ups instil greater confidence in skilled drivers, leading to improved lap times. The adjustments in aerodynamic balance primarily stem from variations in front downforce rather than rear downforce, emphasising the significance of front-end aerodynamics in determining overall vehicle performance. Further testing is suggested using other vehicle set up parameters (dampers, antiroll bars).

6. Ongoing Work

This section of the report pertains to the future and ongoing efforts in developing the project.

6.1. Aero Lap Sim Model

There is a need for a comprehensive lap time simulator that incorporates vehicle dynamics in order to calculate aerodynamic forces. The tool that has been proposed will utilise an expanded Quasi-Steady State (QSS) model, which will iteratively calculate the vehicle's attitude by taking into account the acceleration forces obtained from lap time simulation. A comprehensive analysis of aerodynamic coefficients will be conducted for every point along the track, enabling the subsequent recalculation of lap times. The present proposal adopts a framework akin to that proposed by (Vökl, Muehlmeier, & Winner, 2013), albeit with a specific emphasis on the domain of vehicle aerodynamics.

6.1.1. Vehicle Modelling - Simulink Models

In order to develop a simple vehicle dynamics model that does not necessitate intricate suspension geometries, one can utilise a spring-mass-damper system. In a study conducted by (Ranjit, 2023), two spring mass damper systems were developed: a half-car system with four degrees of freedom (4DOF) and a full-car system with seven degrees of freedom (7DOF). The model underwent validation and was subsequently compared to the Formula Ford model of a racing simulator. The models utilise pre-defined lateral and longitudinal accelerations as well as a road surface input and have the capability to exhibit variable damping; however, they do not possess the capacity to integrate aerodynamic forces. Figure 6-1 shows a modified 4DOF model that incorporates aerodynamic forces into the dynamic simulation.

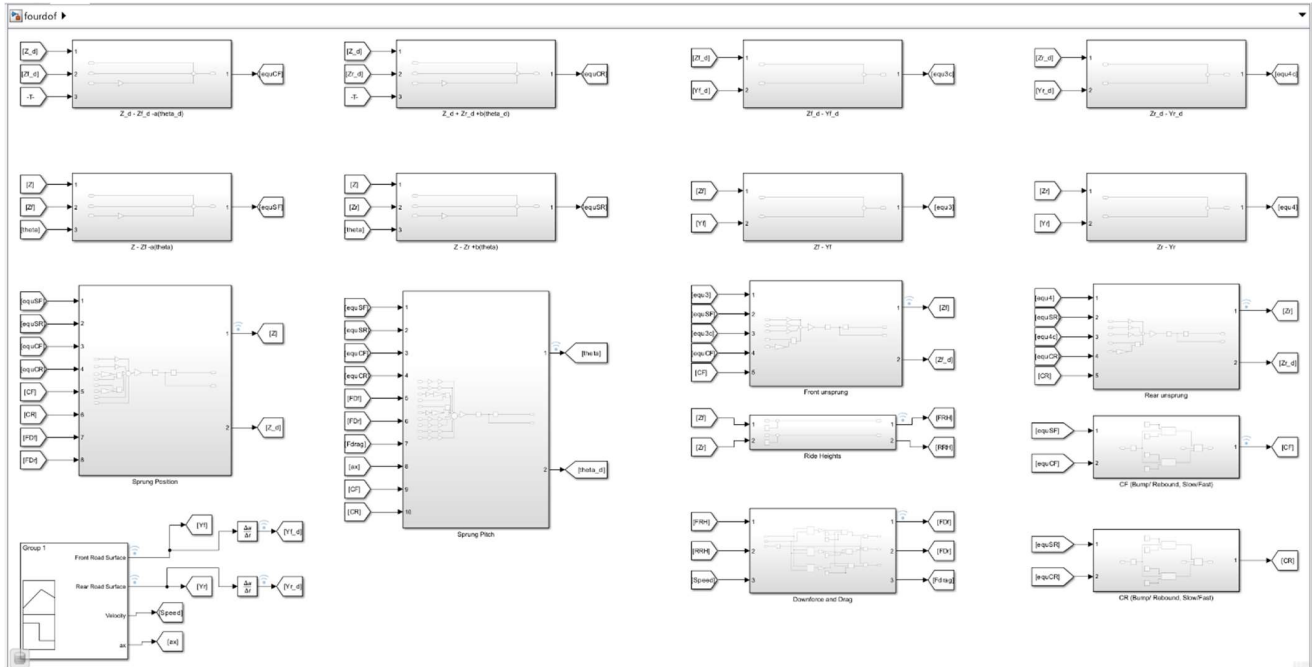


Figure 6-1: Modified 4DOF model that incorporates aerodynamic forces

Figure 6-2 depicts the computational elements accountable for ascertaining the drag and downforce magnitudes. The input parameters for the look-up tables are the ride height values at the front (1) and rear (2) of the vehicle. The purpose of these tables is to calculate the corresponding drag force values corresponding to the specific speed of the vehicle on the map, which is fixed at 35 metres per second. The force is subsequently adjusted in accordance with the input velocity (3). The system is equipped with an integrated switch that facilitates the transition from utilising a comprehensive aerodynamic map to employing a singular, predetermined value. The current model has not yet been subjected to the process of validation. The validation process entails employing the VI-CRT acceleration outputs as input forces in conjunction with an appropriate road surface and subsequently comparing the outputs of the Simulink model to those of VI-CRT. The implementation of this model will constitute one-third of the comprehensive Aero Lap Sim model mentioned earlier.

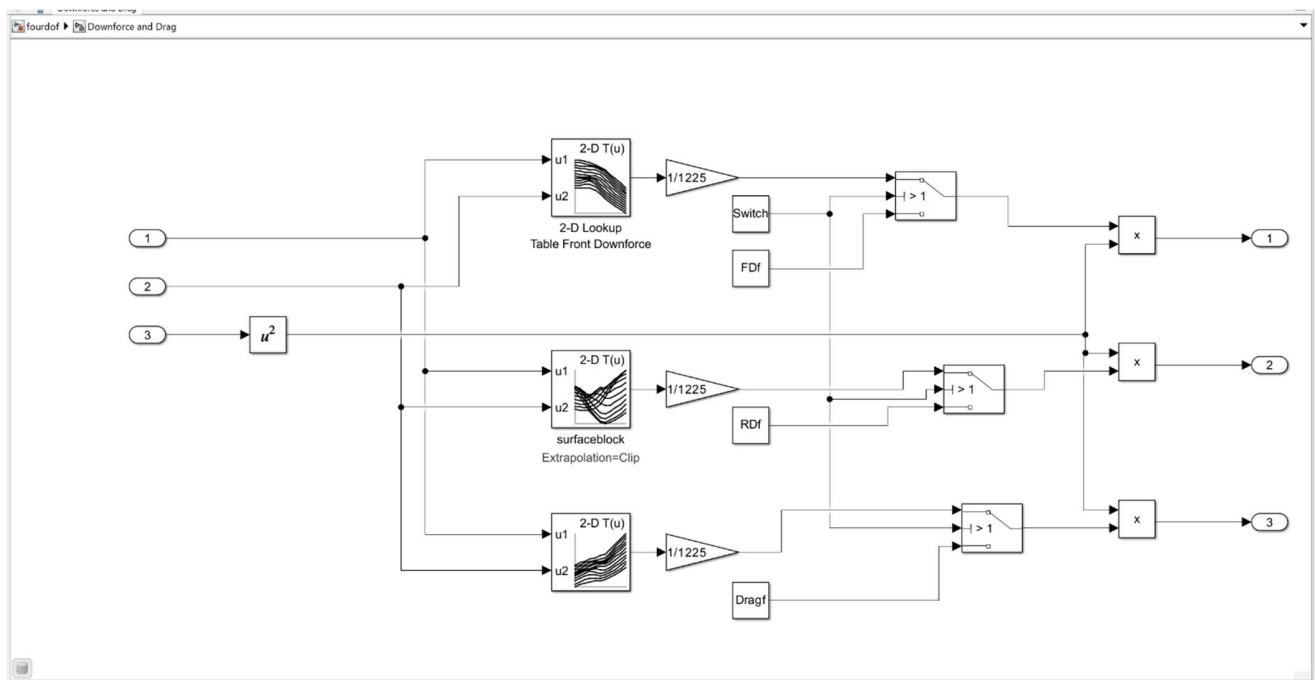


Figure 6-2: Downforce and Drag block

6.2. VI-Grade improvement and use for testing different development routes

The ability to address hypothetical scenarios regarding the influence of downforce and drag levels on vehicle performance and establish performance objectives for forthcoming aerodynamic initiatives will be enabled. A Microsoft Excel file has been created to modify an existing aerodynamic map, allowing for the simulation of increased front or rear downforce and varying levels of drag. The resulting outputs can be utilised as an aerodynamic map in VI-CRT and compared to alternative maps.

The VI-CRT car 40 model necessitates additional enhancements in the precision of its tyre model. A tyre testing apparatus is presently under development and is available for utilisation. An alternative approach involves the development of a model through an iterative process of parameter adjustment, wherein the simulation is gradually refined to achieve alignment with empirical observations.

7. Conclusion

In conclusion, applying a comprehensive methodology in producing and assessing aero maps has resulted in noteworthy findings regarding the aerodynamic characteristics of the UWTSD Sports 2000 MCR. However, the study has underscored the significance of continual improvement and a greater understanding of the factors contributing to the disparities between empirical and simulated data. To enhance our understanding of race car aerodynamics, forthcoming research should emphasise enhancing measurement precision, expanding the scope of testing, and exploring the exact sources of disparities.

The importance of precise CAD models, computational fluid dynamics (CFD) simulations, and wind tunnel experiments in the development of accurate aerodynamic maps is underscored. Variations were observed among CFD, wind tunnel, and on-track measurements; the results obtained from this study indicate the need for additional investigation into measurement methodologies and model enhancements. Potential future research could involve the replication of Sabe CFD findings in order to generate a more comprehensive aerodynamic map encompassing a wider range of race car set-up variations.

The VI-CRT tests offer valuable insights into the dynamic attributes of the vehicle across different configurations, enabling enhancements in aerodynamic balance and overall efficiency. The results presented in this study contribute to the field of race car set-up, facilitating the enhancement of set-ups to correspond with particular driving conditions and driver inclinations more effectively. Further investigation and empirical examination can generate more intricate arrangements and enhance the performance of race cars. Future research could involve fully validating the MCR VI-CRT model and developing an SMD model for a more straightforward lap simulator.

The study examined different set-up configurations to investigate the relationship between spring stiffness and ride height tests. Although there was minimal variation in lap times across different set-ups, it was observed that set-ups with a front aero balance exceeding 50% exhibited faster lap times. This finding underscores the significance of front downforce with overall downforce. Examining braking and high-speed corner stability has demonstrated that configurations that enhance stability can enhance driver confidence, thereby leading to real-world improved lap times. This highlights the necessity for further advancements focused on improving rear downforce. In order to enhance the accuracy of predicting the performance boundaries of professional race car drivers, it is imperative to advance lap time simulation methodologies in terms of driver parameters and tyre modelling.

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9. Appendix

9.1. Appendix A – CAD Modifications

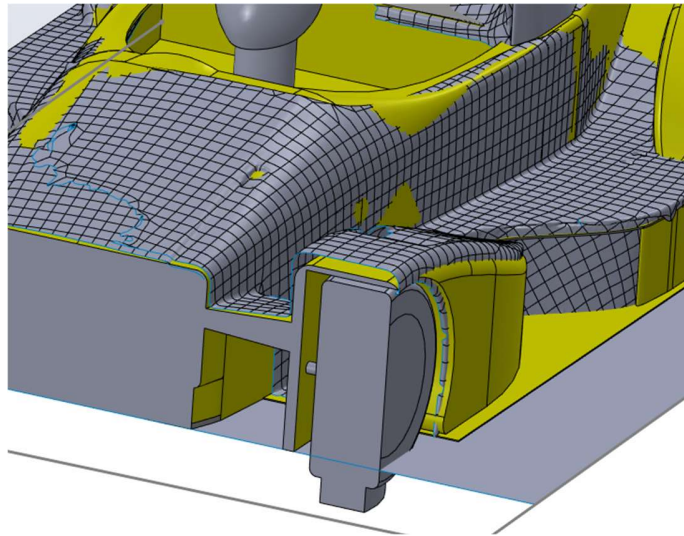


Figure 9-1: 3D scan vs original CAD, front pontoon

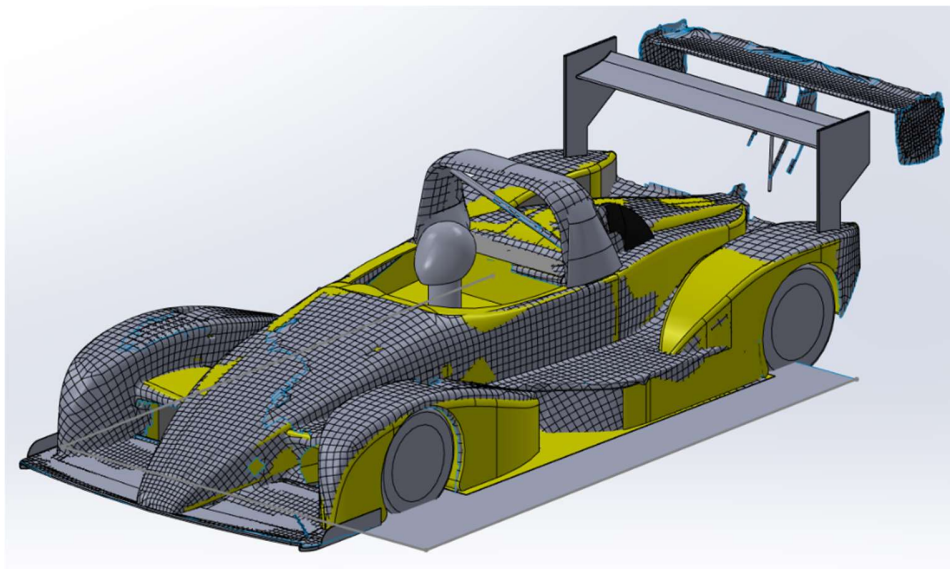


Figure 9-2: 3D scan vs original CAD Car #40

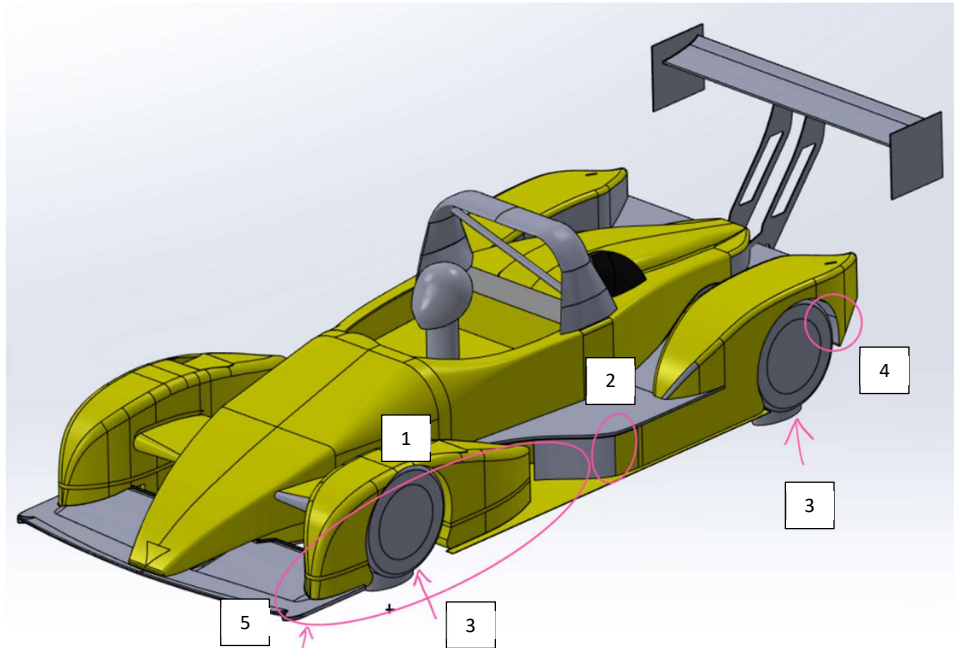


Figure 9-3: UWTSD Student modified CAD Model #40

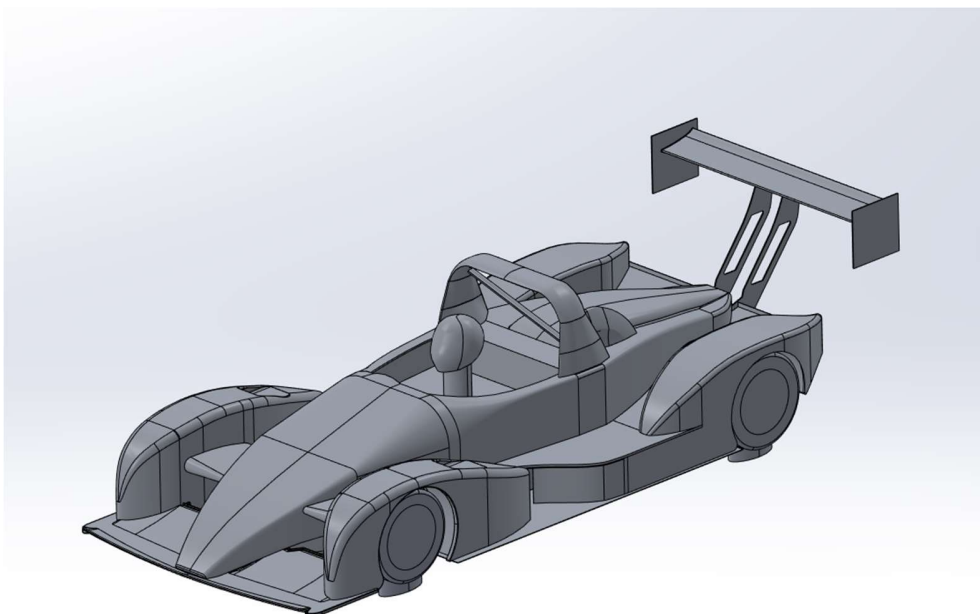


Figure 9-4: Final Car #40 CAD, without radiators

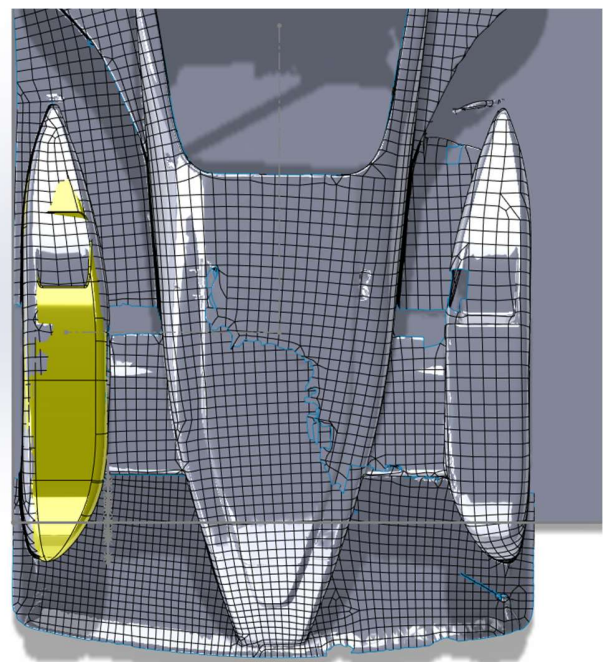
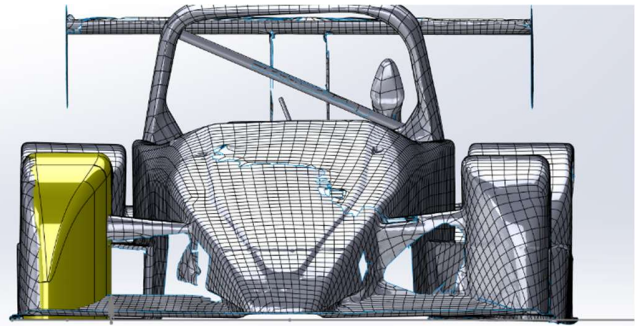
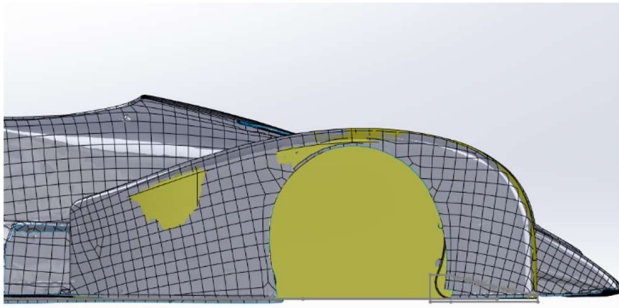


Figure 9-5: Side View, Front View and Top View of modified front pontoon vs 3D scan

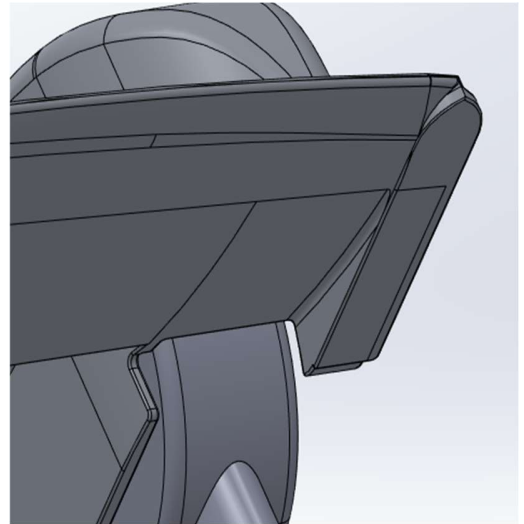
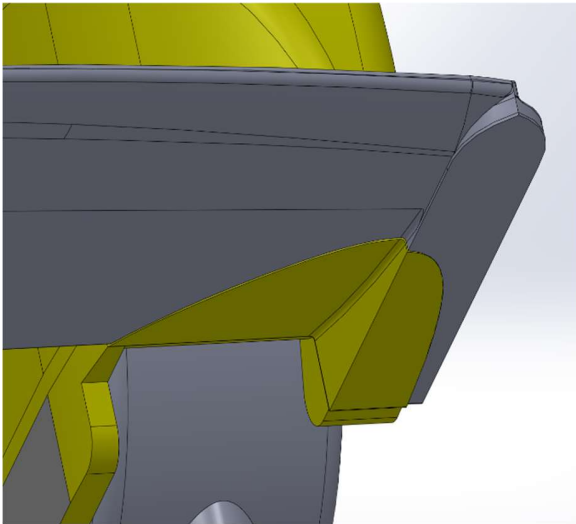


Figure 9-6: UWTSD Student modified splitter (left), Improved splitter (right)

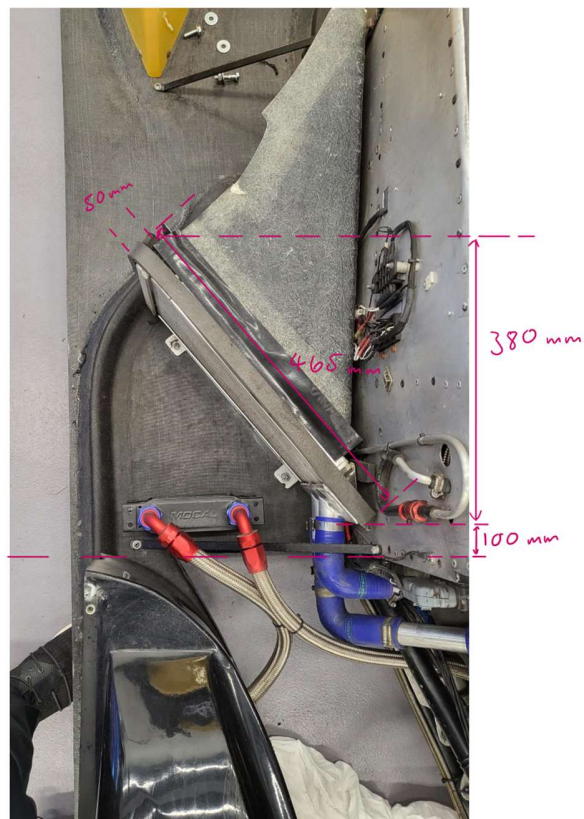


Figure 9-7: Radiator dimensions

9.2. Appendix B - Ride Heights



Figure 9-8: Offsets used for ride height calculations



Figure 9-9: Minimum rear ride heights at Donington

Code for Min ride heights:

```
%Car Motion Ratios
MRfront = 0.61;
MRrear = 0.7;

%Static Ride Heights
FLStaticRH = 61.6;
FRStaticRH = 60.5;
RLStaticRH = 91;
RRStaticRH = 88;

% Damper position offsets
FLOff = -18.24;
FROff = -20.04;
RLOff = -1.65;
RROff = -10.37;

%Calculations
FLRideHeight = FLStaticRH - (FLOff - Damper_Pos_FL.Value./MRfront);
FRRideHeight = FRStaticRH - (FROff - Damper_Pos_FR.Value./MRfront);
RLRideHeight = RLStaticRH - (RLOff - Damper_Pos_RL.Value./MRrear);
RRRideHeight = RRStaticRH - (RROff - Damper_Pos_RR.Value./MRrear);

%Mins and Max

MinFLRH = min (FLRideHeight (:));
MinFRRH = min (FRRideHeight (:));
MinRLRH = min (RLRideHeight (:));
MinRRRH = min (RRRideHeight (:));

MaxFLRH = max (FLRideHeight (:));
MaxFRRH = max (FRRideHeight (:));
MaxRLRH = max (RLRideHeight (:));
MaxRRRH = max (RRRideHeight (:));

% Display min ride heights
disp(['Min ride heights: ' num2str([MinFLRH MinFRRH MinRLRH MinRRRH])])
```

Output:

Min ride heights: 43.2826 40.2777 43.9786 37.4557,

9.3. Appendix C – Wind Tunnel Data

Table 9-1: Mira Wind Tunnel Data

FRH	RRH	Front Downforce	Rear Downforce	Drag	Total Downforce	Aero Balance % Front	L/D Efficiency
42	75	452.45	625.49	487.7	1077.94	42%	2.210
42	66	352.07	625.49	482.4	977.56	36%	2.026
42	72	421.74	626.24	486.9	1047.98	40%	2.152
42	75	457.69	623.99	485.4	1081.68	42%	2.228
42	79	488.41	623.99	486.9	1112.4	44%	2.285
42	86	559.57	623.99	493.6	1183.56	47%	2.398
47	66	229.22	637.47	491.4	866.69	26%	1.764
47	81	375.29	635.23	497.4	1010.52	37%	2.032
54	73	202.25	645.71	501.9	847.96	24%	1.689
62	69	80.15	650.21	501.9	730.36	11%	1.455
62	85	212.74	649.46	508.6	862.2	25%	1.695
66	67	-5.24	654.7	502.6	649.46	-1%	1.292
66	86	167.8	656.2	514.6	824	20%	1.601

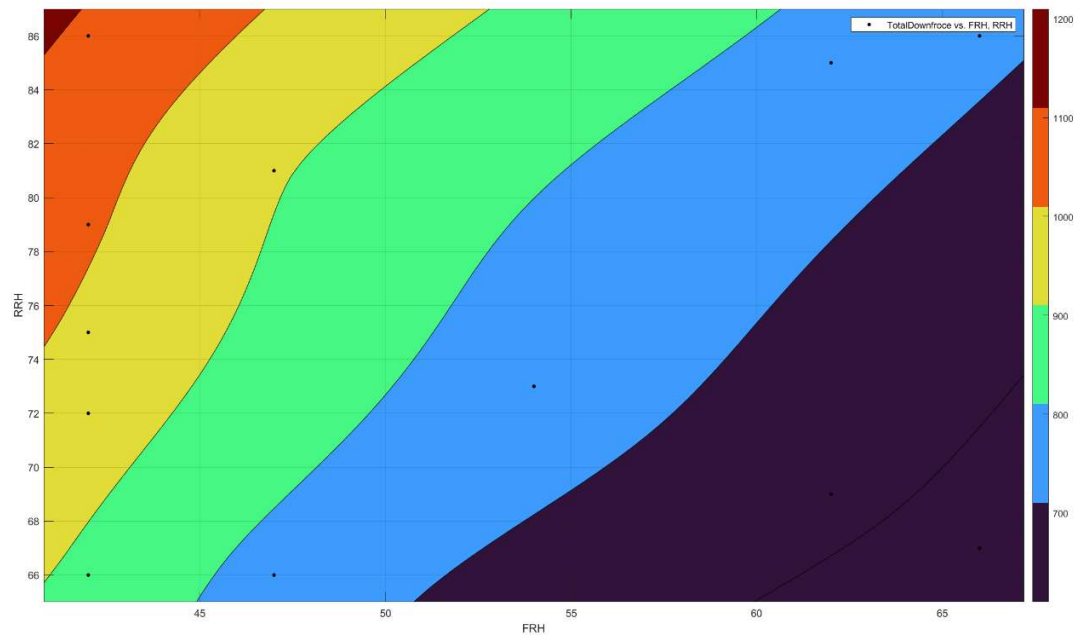


Figure 9-10: WT - Total Downforce contour plot

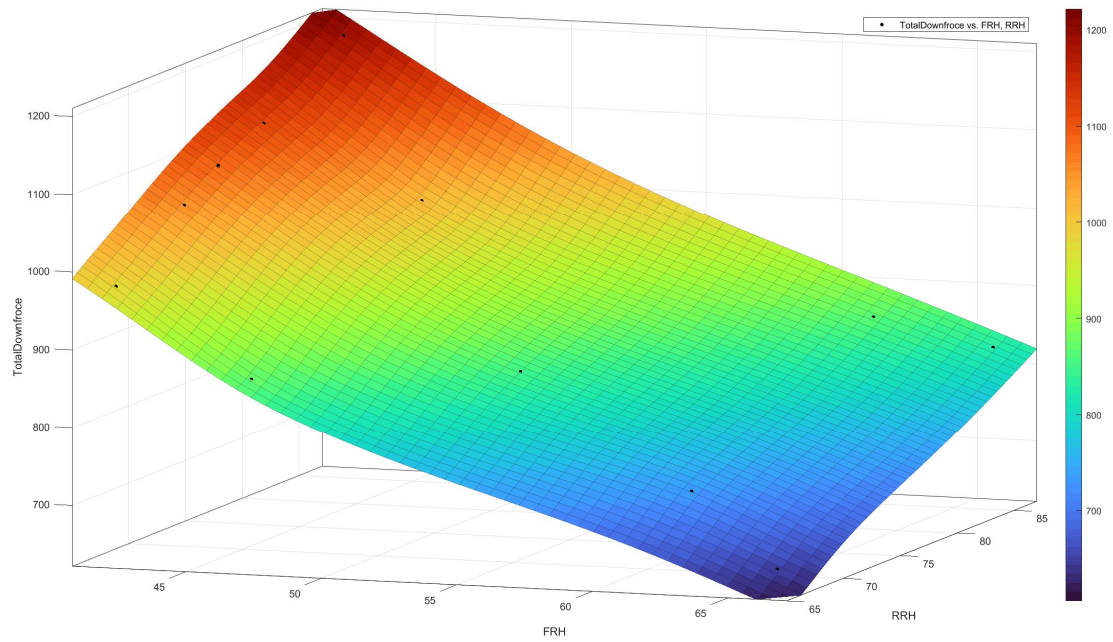


Figure 9-11: WT - Total Downforce 3D Surface

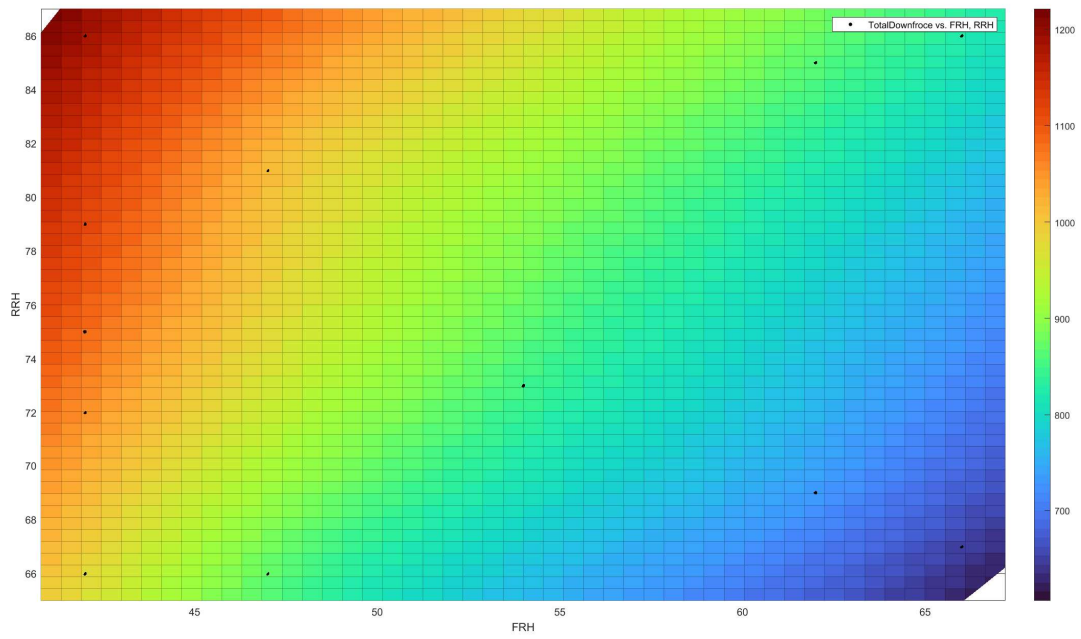


Figure 9-12: WT - Total Downforce 2D

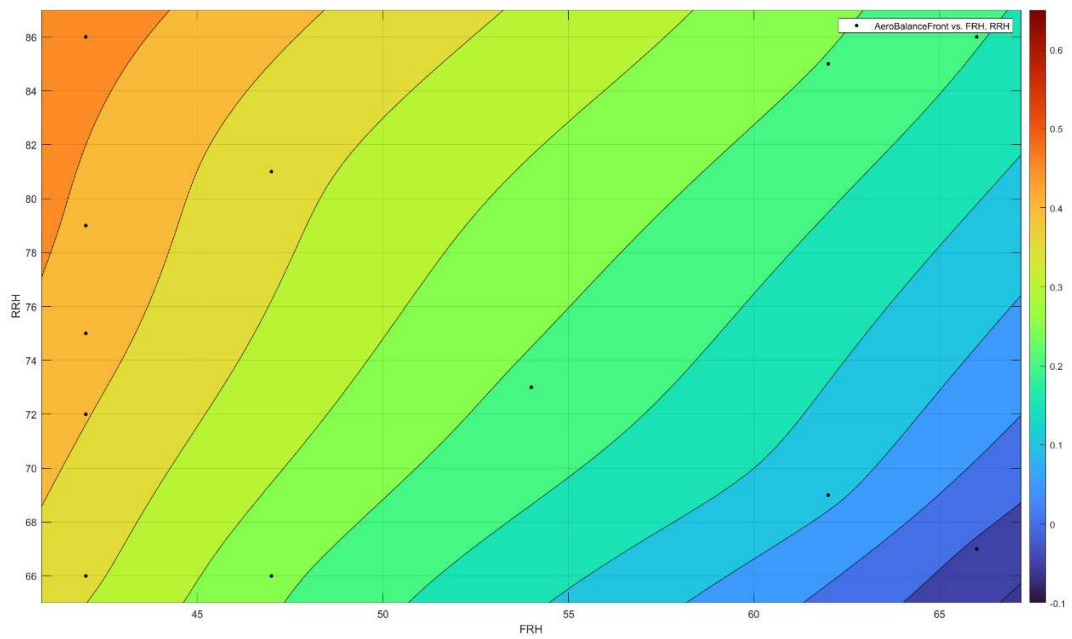


Figure 9-13: WT - Aero Balance Front Contour Plot

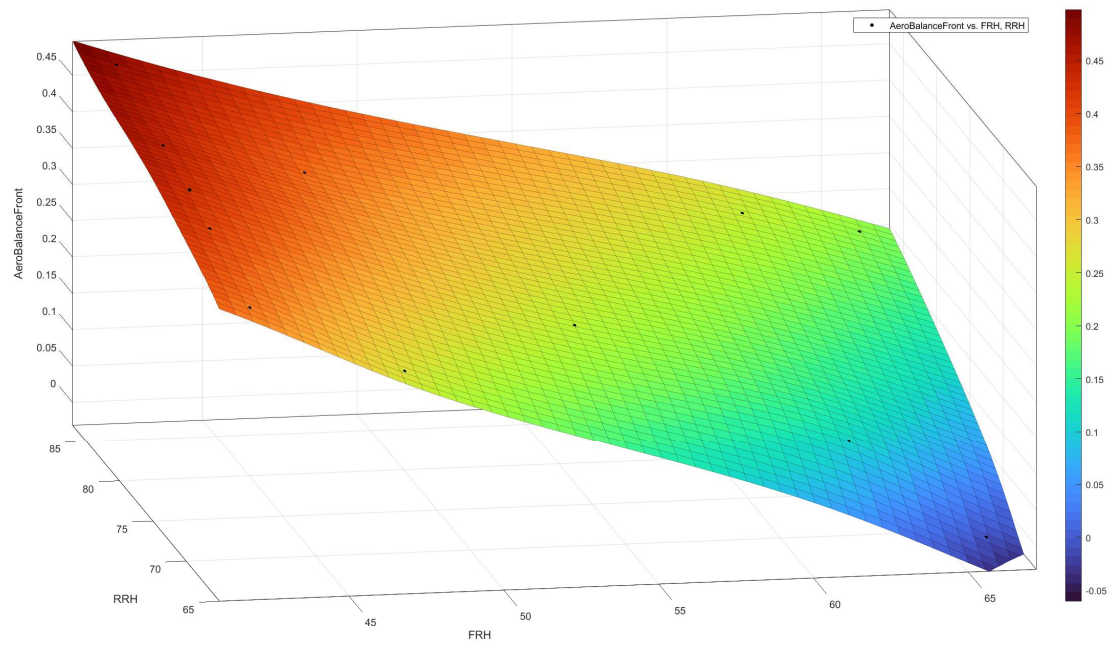


Figure 9-14: WT - Aero Balance Front 3D Surface

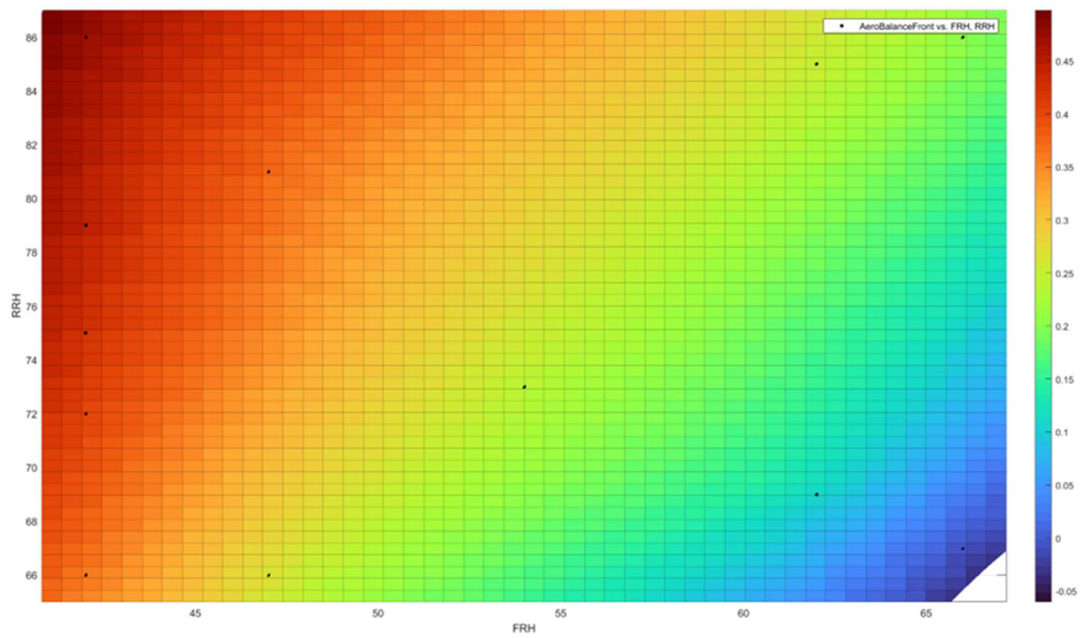


Figure 9-15: WT - Aero Balance Front 2D

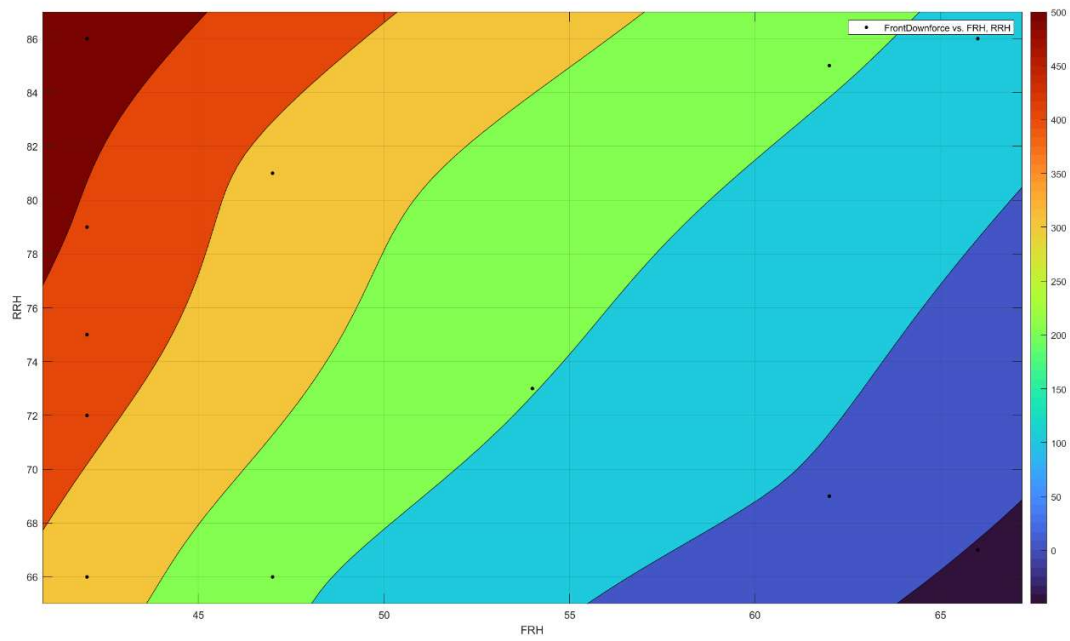


Figure 9-16: WT - Front Downforce contour plot

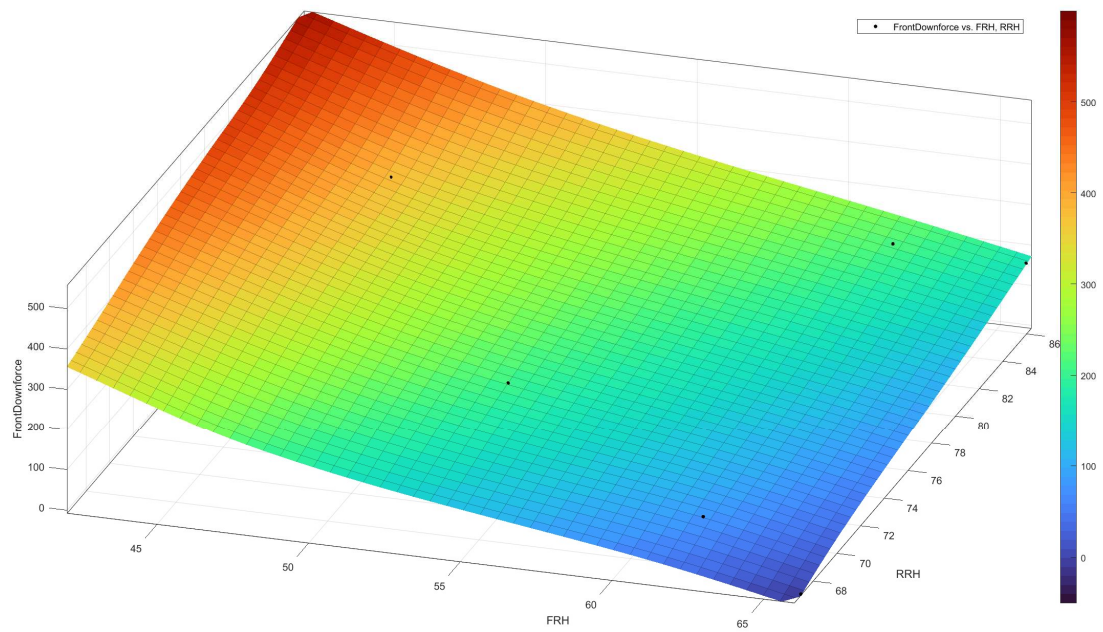


Figure 9-17: WT - Front Downforce 3D Surface

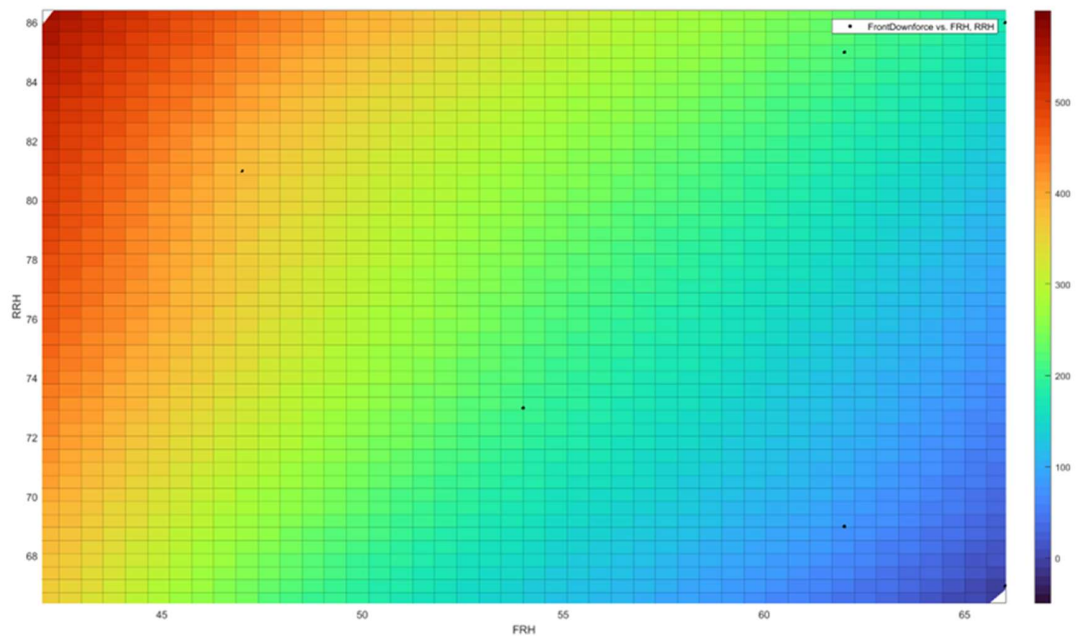


Figure 9-19: WT - Front Downforce 2D

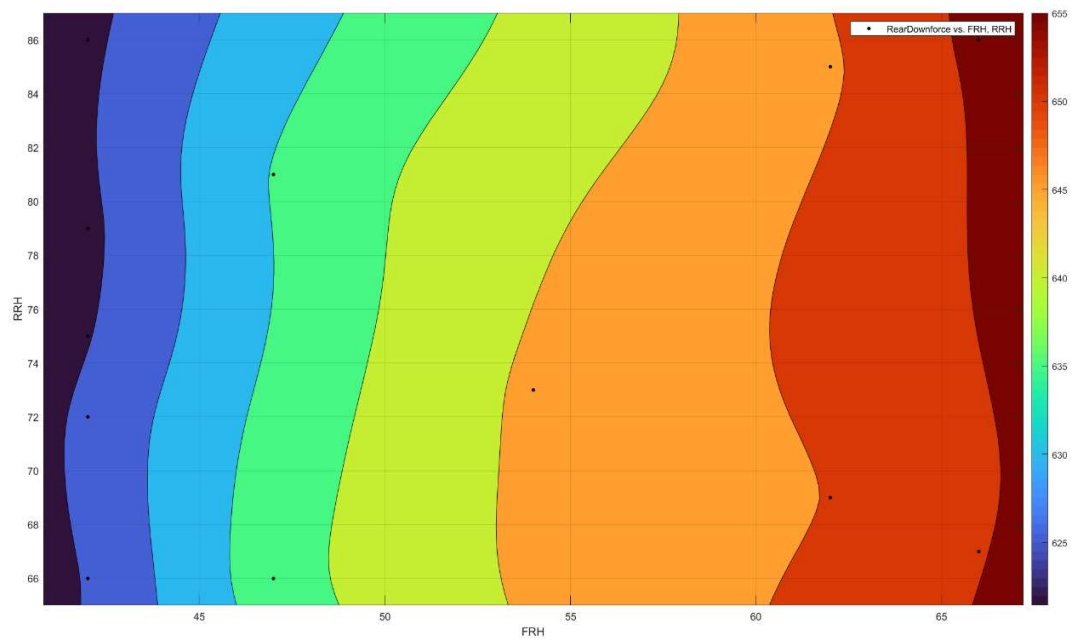


Figure 9-18: WT - Rear Downforce contour plot

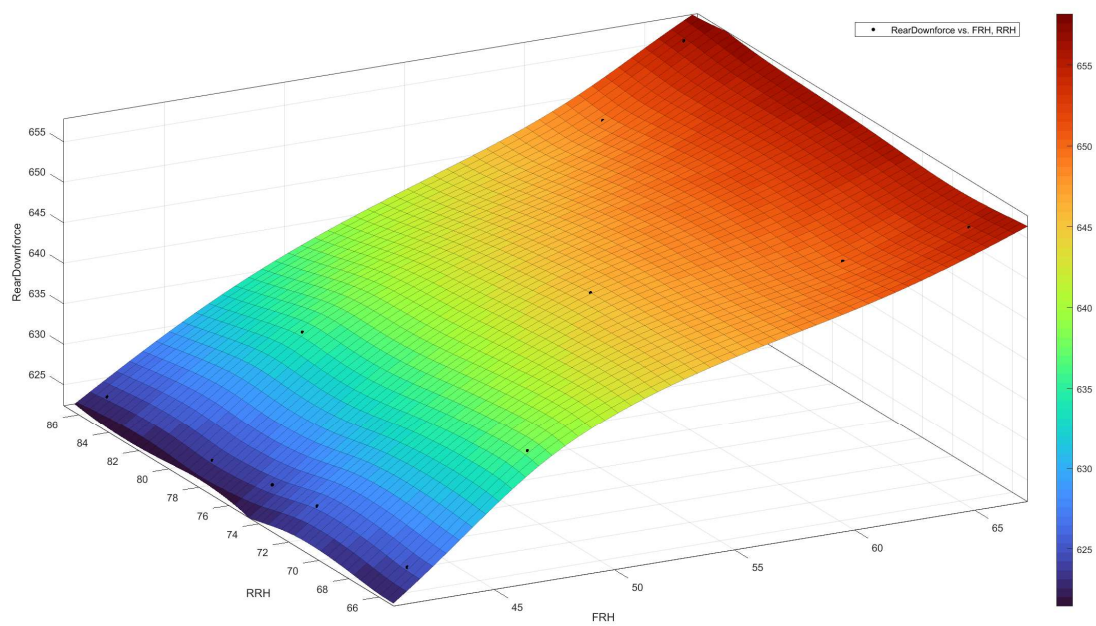


Figure 9-20: WT - Rear Downforce 3D Surface

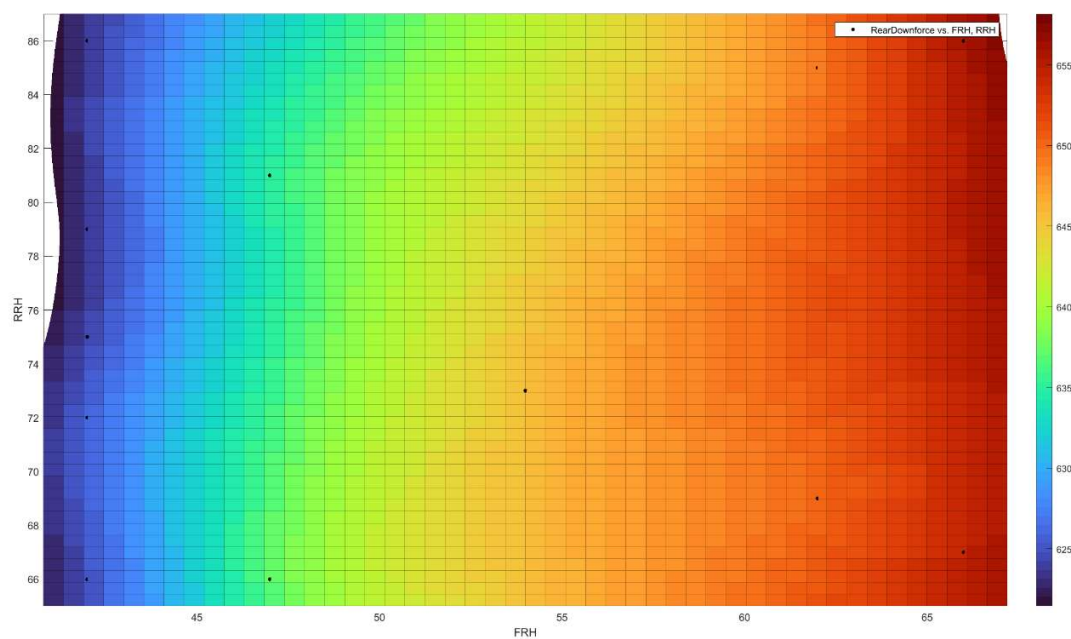


Figure 9-21: WT - Rear Downforce 2D

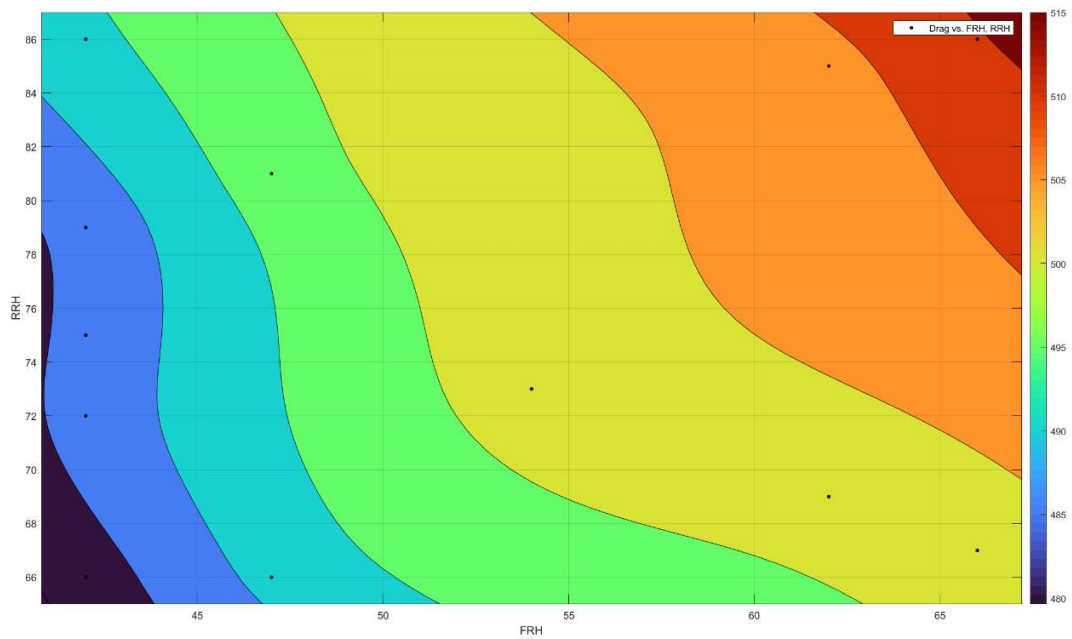


Figure 9-22: WT - Drag contour plot

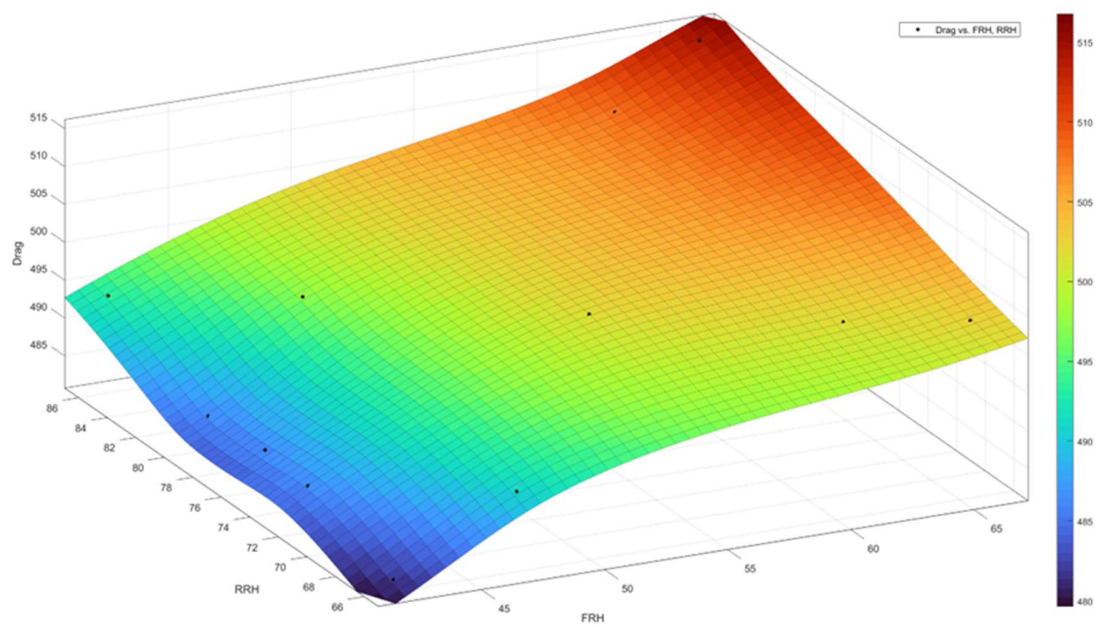


Figure 9-23: WT - Drag 3D Surface

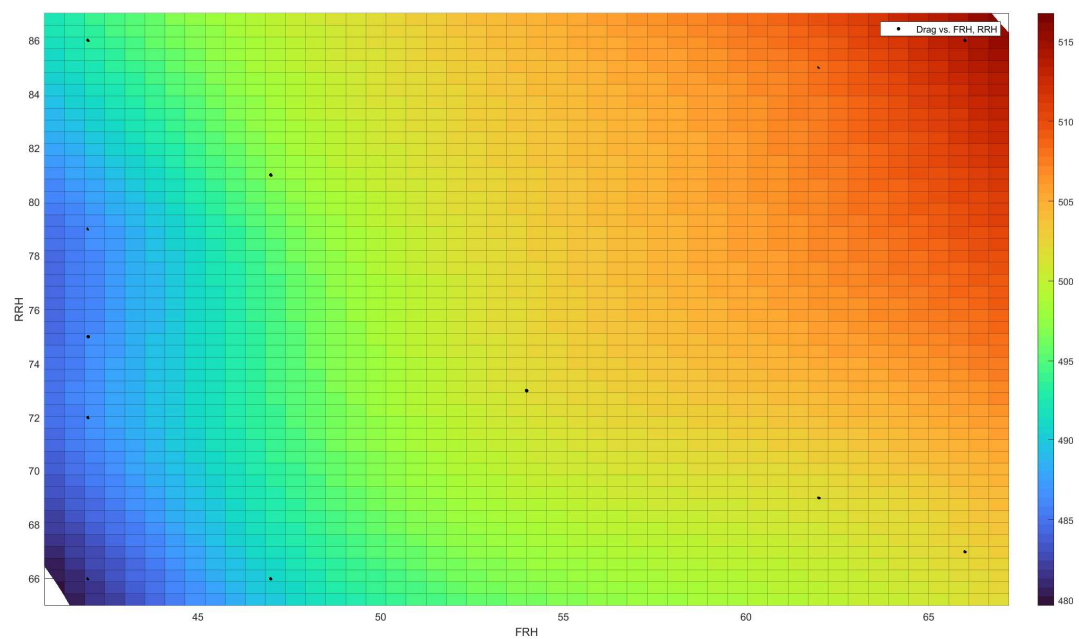


Figure 9-24: WT - Drag 2D

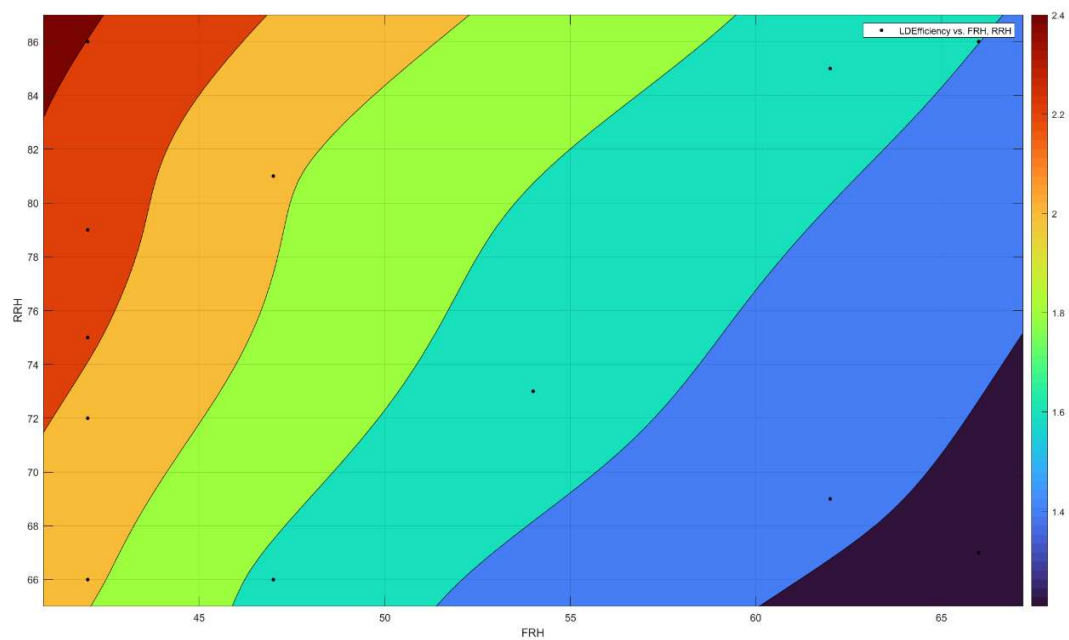


Figure 9-25: WT - L/D Efficiency contour plot

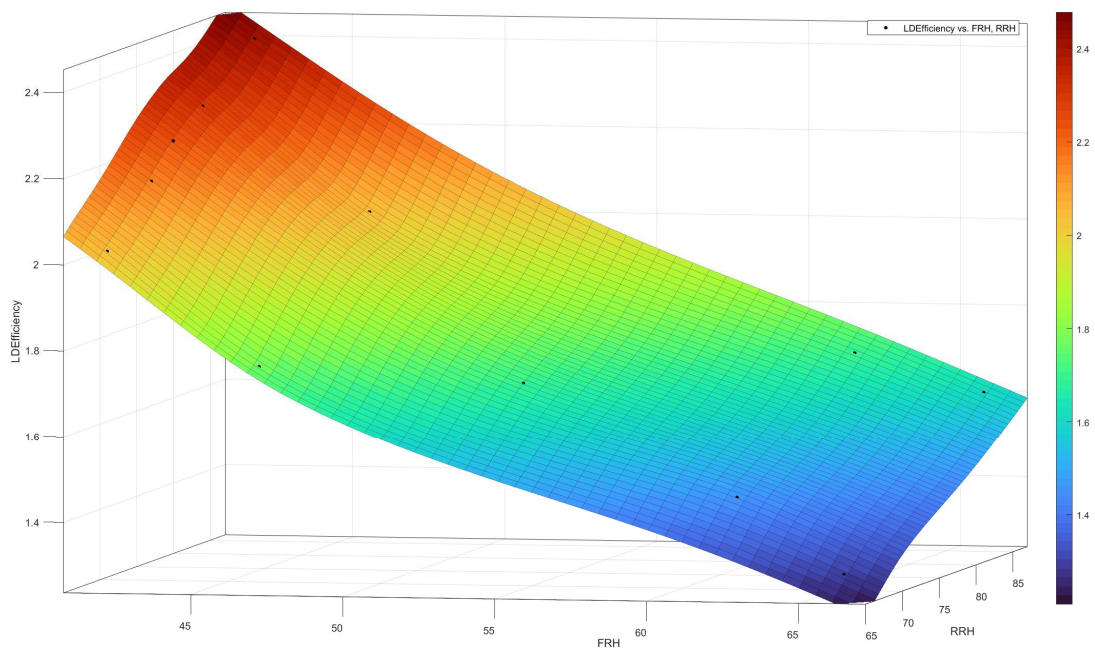


Figure 9-26: WT - L/D Efficiency 3D Surface

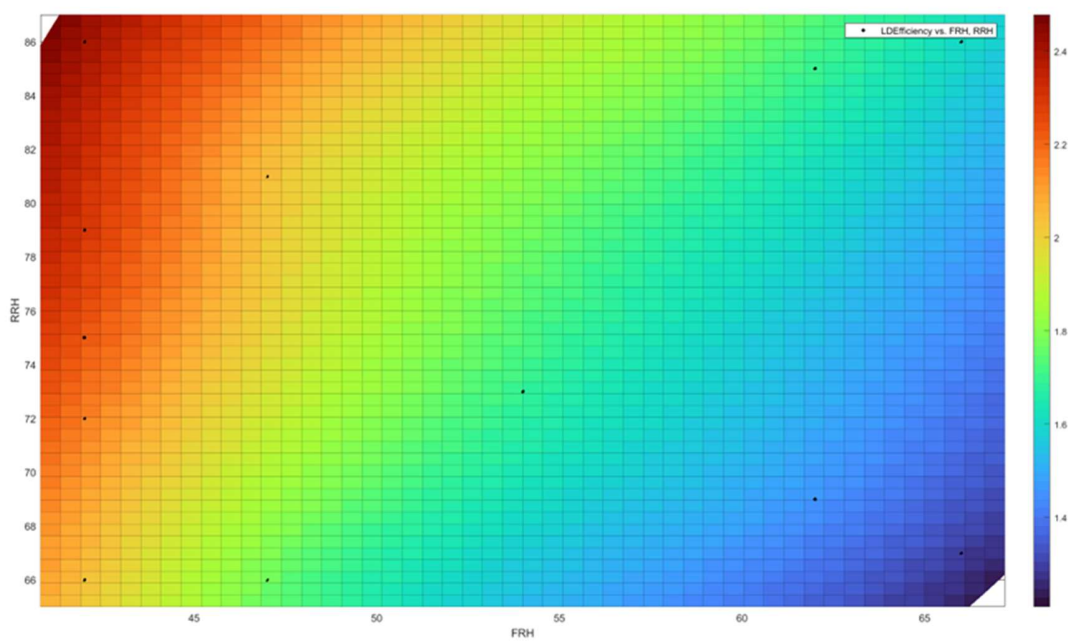


Figure 9-27: WT - L/D Efficiency 2D

9.4. Appendix D – CFD Data

Table 9-2: Sabe CFD Data

FRH	RRH	Front Downforce	Rear Downforce	Drag	Total Downfroce	Aero Balance % Front	L/D Efficiency
10	30	1318.39	1493.68	846.21	2812.07	47%	3.323
30	50	1506.13	1517.42	892.44	3023.55	50%	3.388
35	65	1668.34	1504.24	904.02	3172.58	53%	3.509
20	50	1578.22	1452.46	878.05	3030.68	52%	3.452
25	60	1794.03	1458.43	895.66	3252.46	55%	3.631
20	30	1394.78	1378.45	858.74	2773.22	50%	3.229
30	75	1884.34	1389.96	917.77	3274.30	58%	3.568
15	40	1500.71	1479.73	870.91	2980.44	50%	3.422
25	40	1457.79	1426.97	877.19	2884.76	51%	3.289
30	35	1188.38	1331.64	861.71	2520.02	47%	2.924
35	50	1355.45	1472.48	891.16	2827.93	48%	3.173
45	55	1161.07	1541.86	923.42	2702.94	43%	2.927
55	70	1081.56	1638.21	981.81	2719.76	40%	2.770

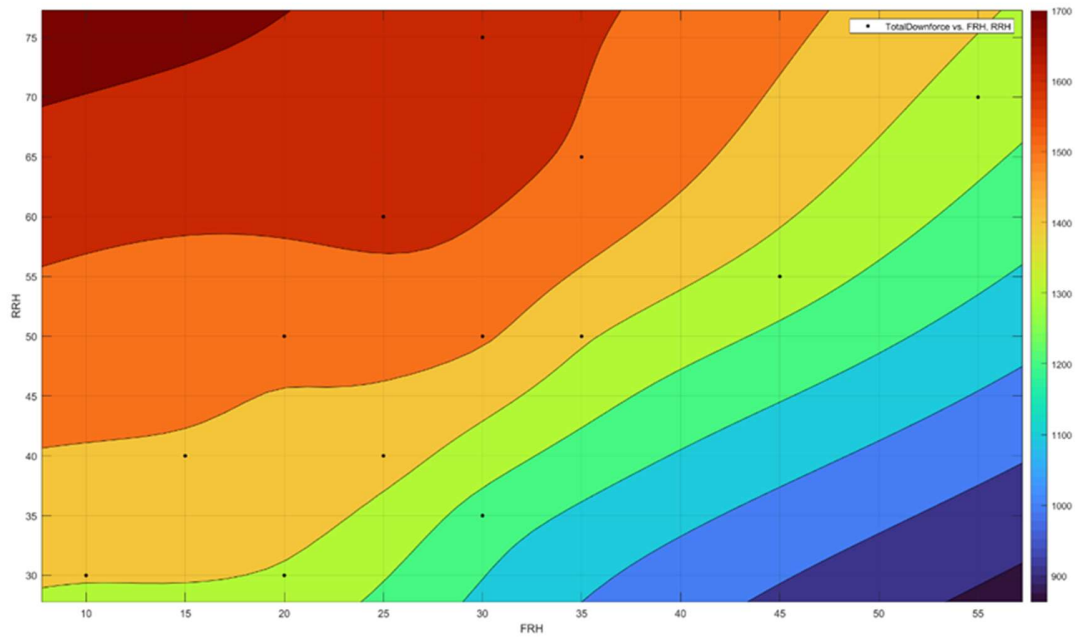


Figure 9-28: CFD - Total Downforce contour plot

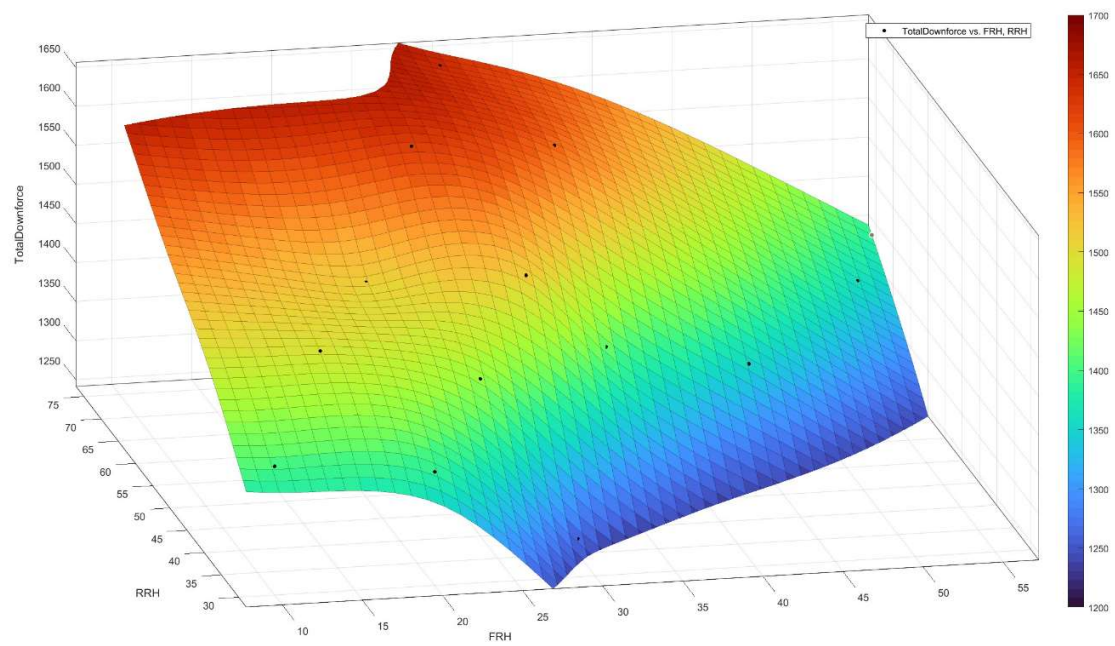


Figure 9-29: CFD - Total Downforce 3D surface

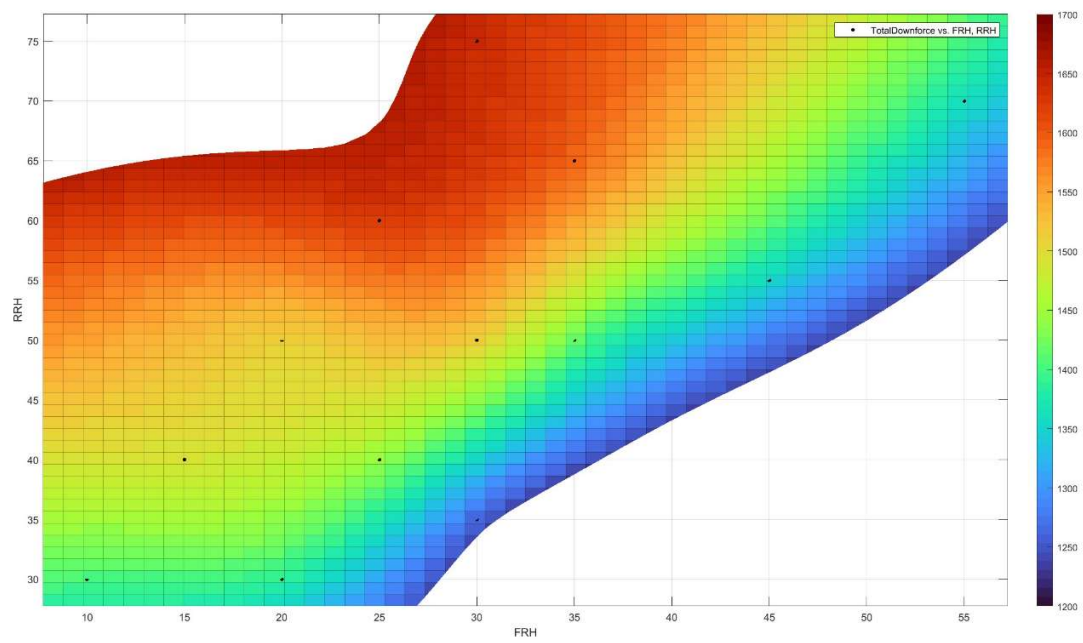


Figure 9-30: CFD - Total Downforce 2D

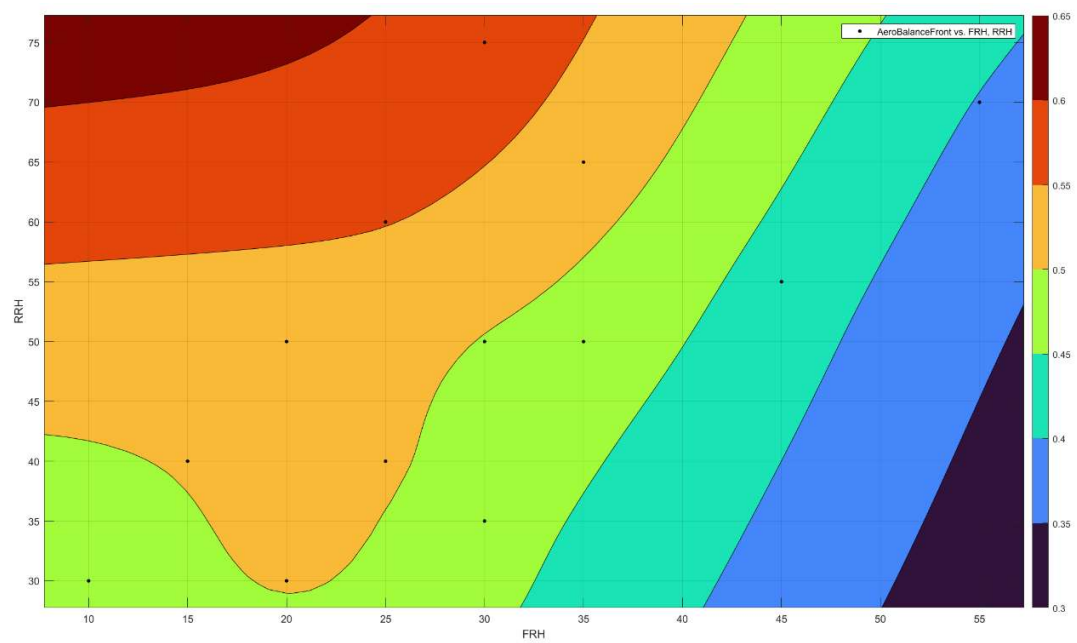


Figure 9-31: CFD – Aero Balance Front contour plot

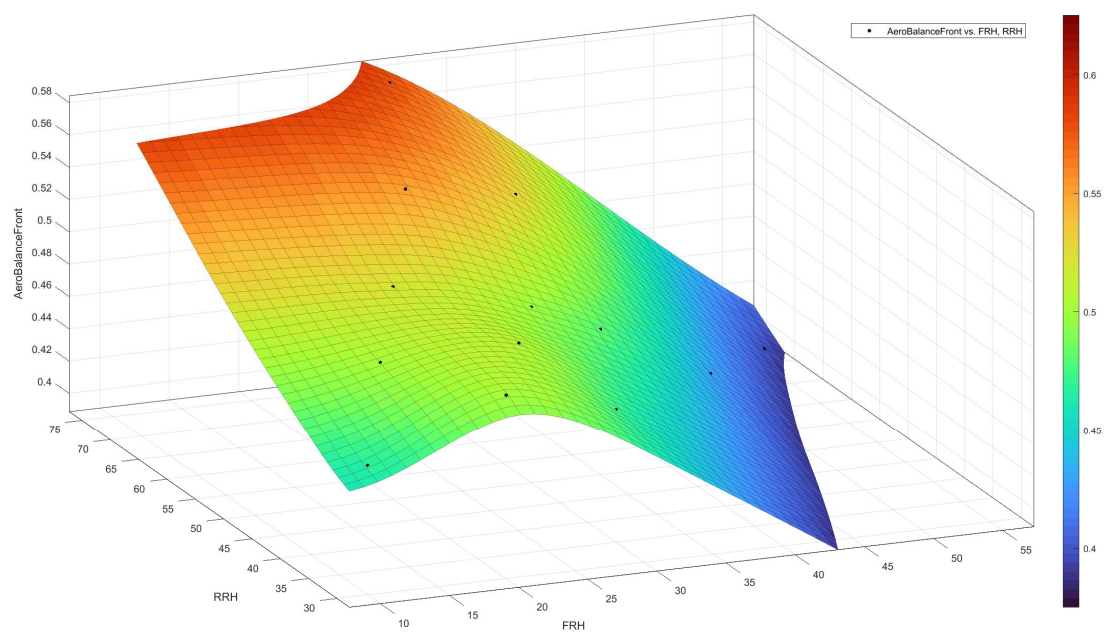


Figure 9-32: CFD – Aero Balance Front 3D Surface

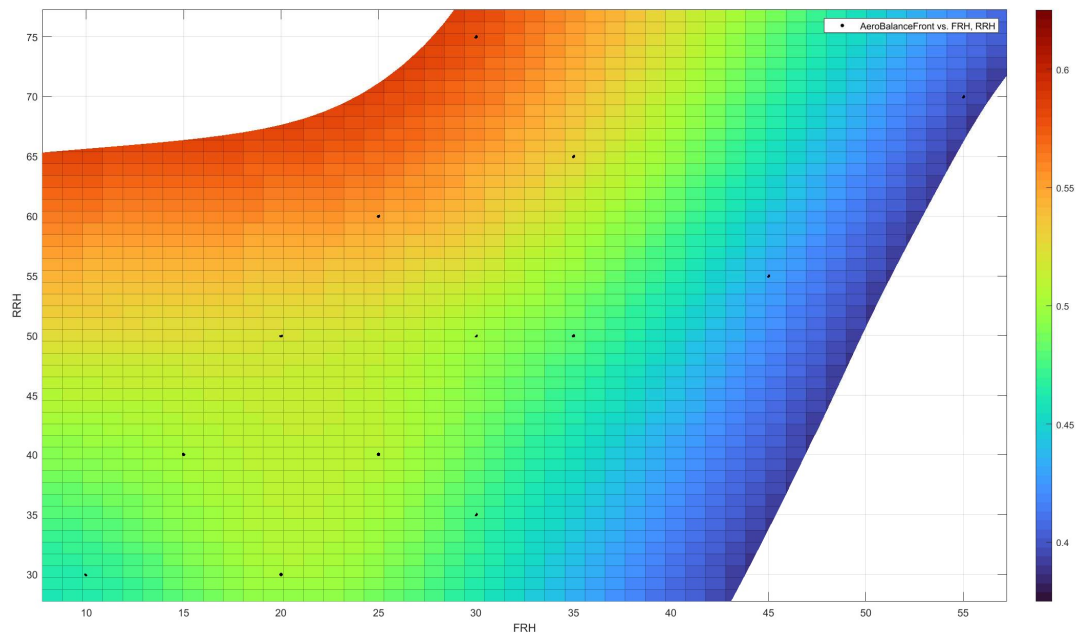


Figure 9-33: CFD – Aero Balance Front 2D

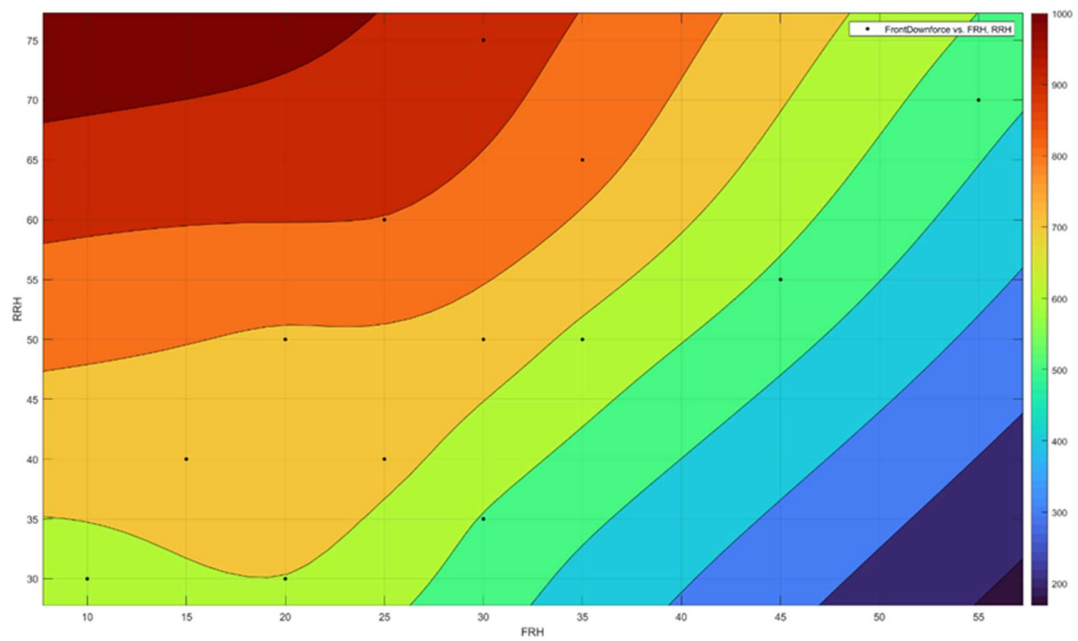


Figure 9-34: CFD - Front Downforce contour plot

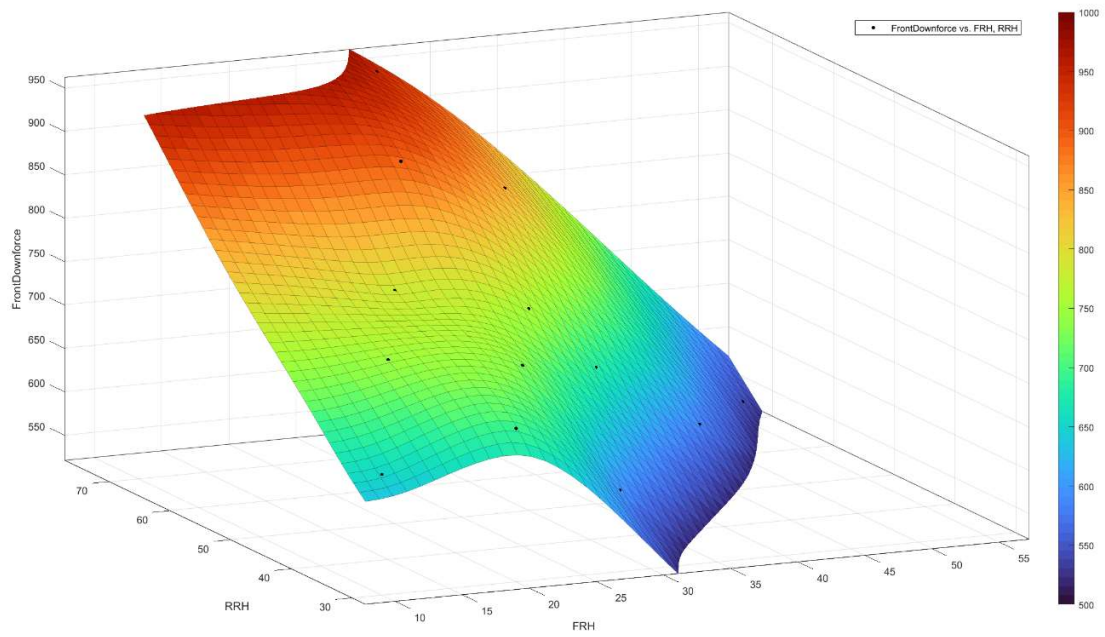


Figure 9-35: CFD - Front Downforce 3D surface

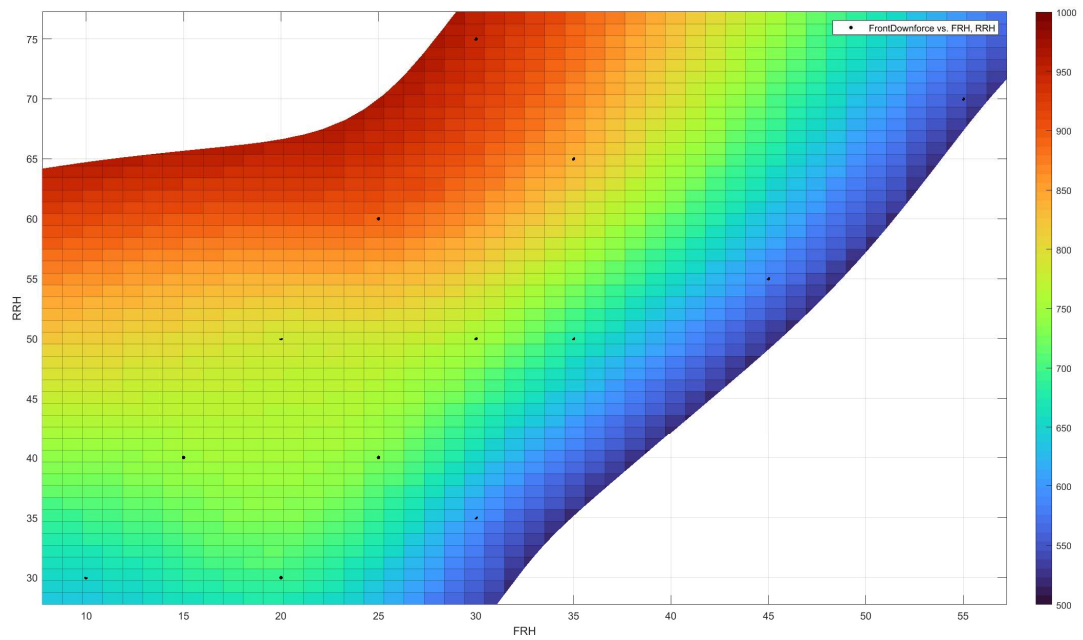


Figure 9-36: CFD - Front Downforce 2D

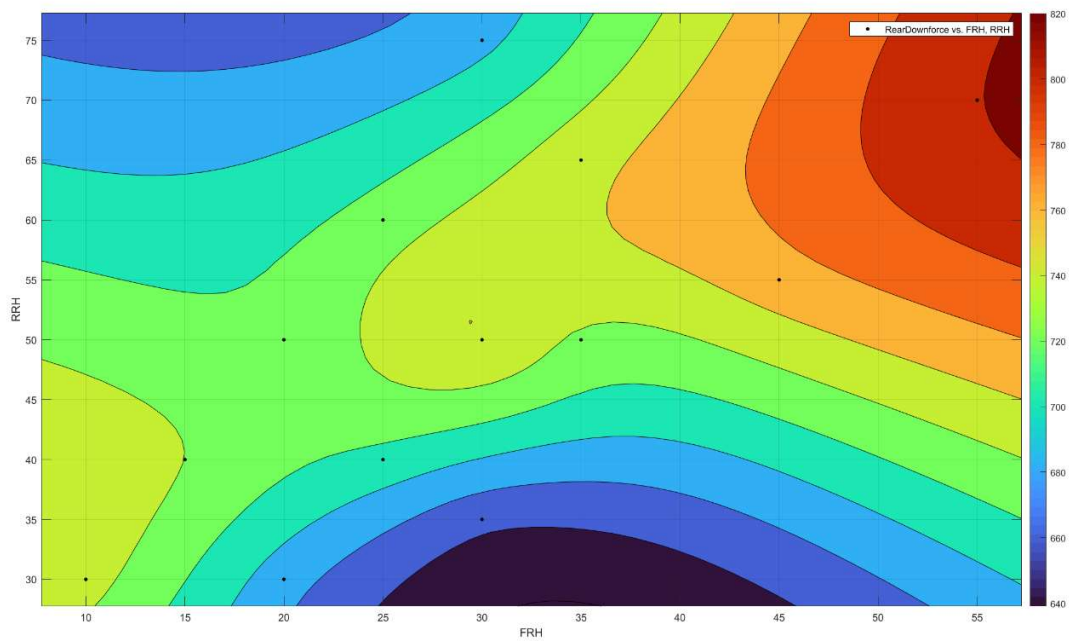


Figure 9-37: CFD - Rear Downforce contour plot

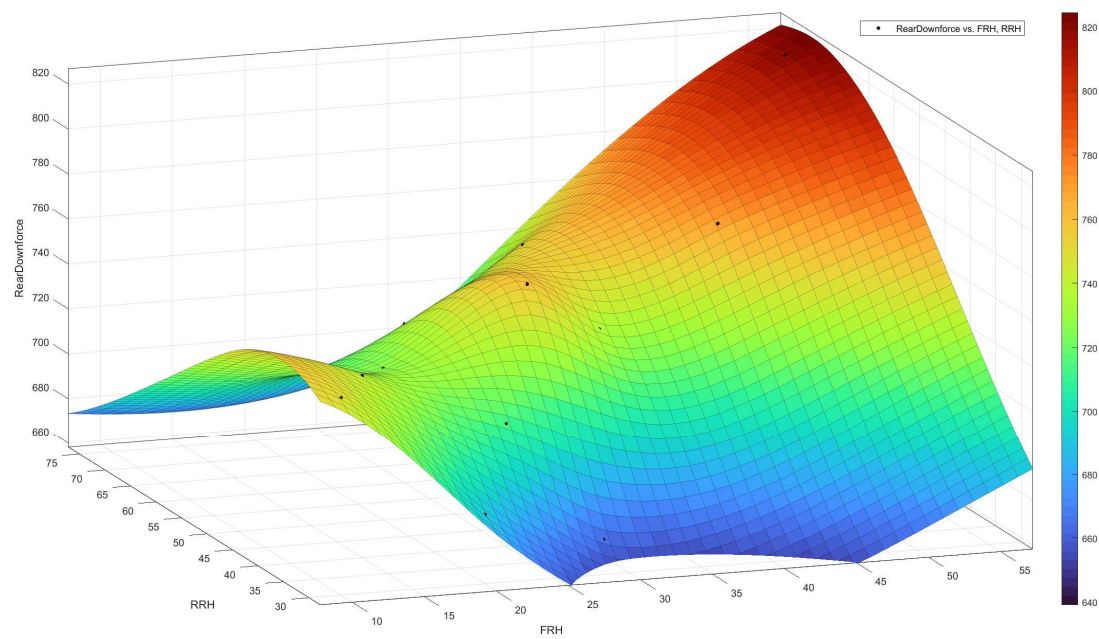


Figure 9-38: CFD - Rear Downforce 3D surface

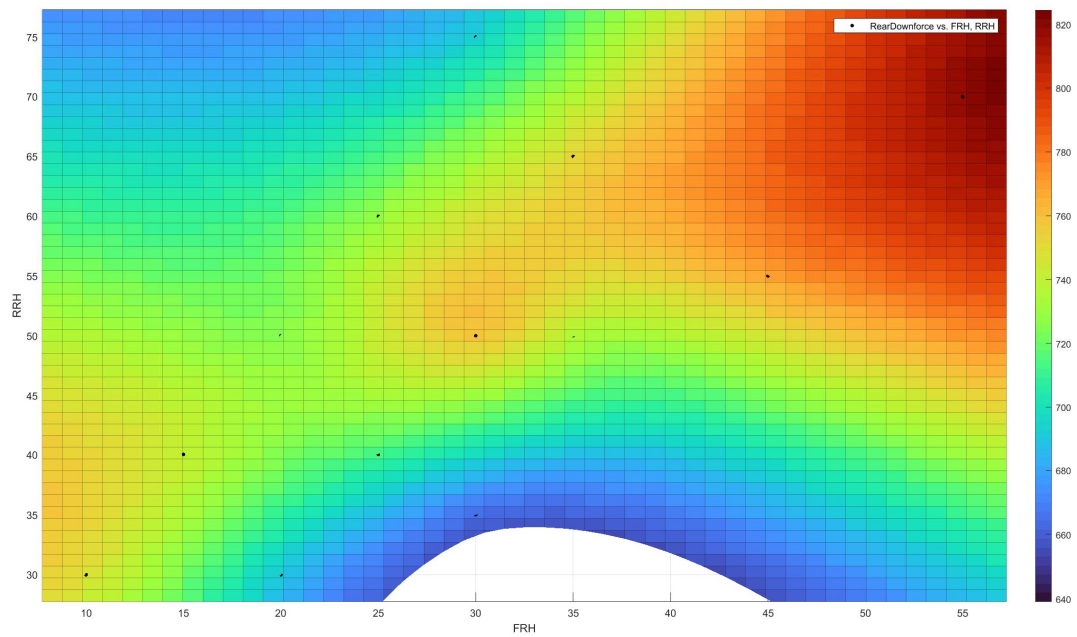


Figure 9-39: CFD - Rear Downforce 2D

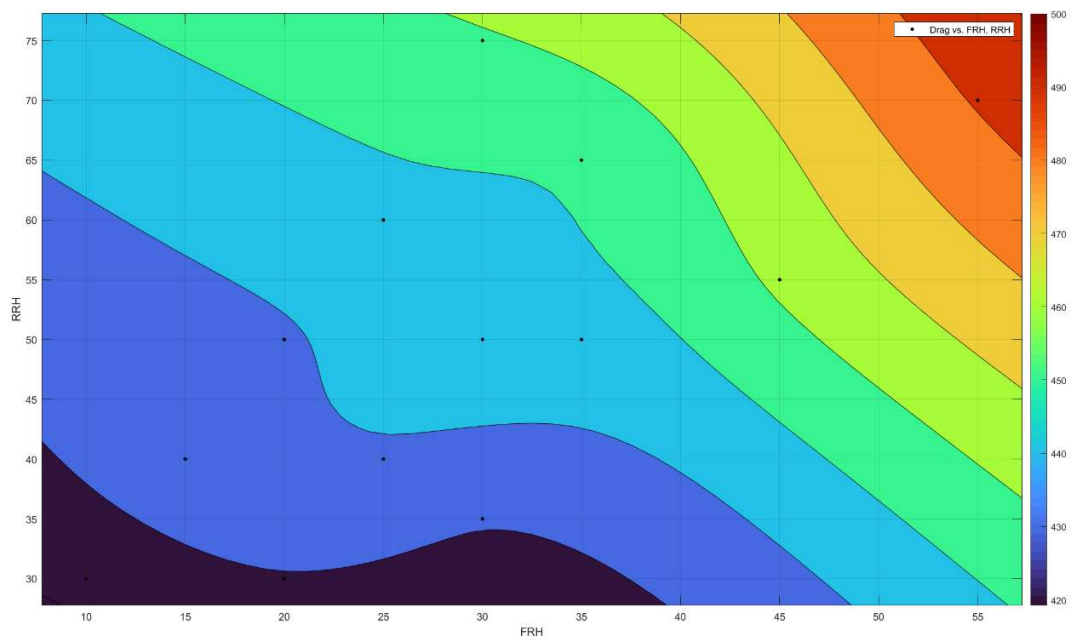


Figure 9-40: CFD - Drag contour plot

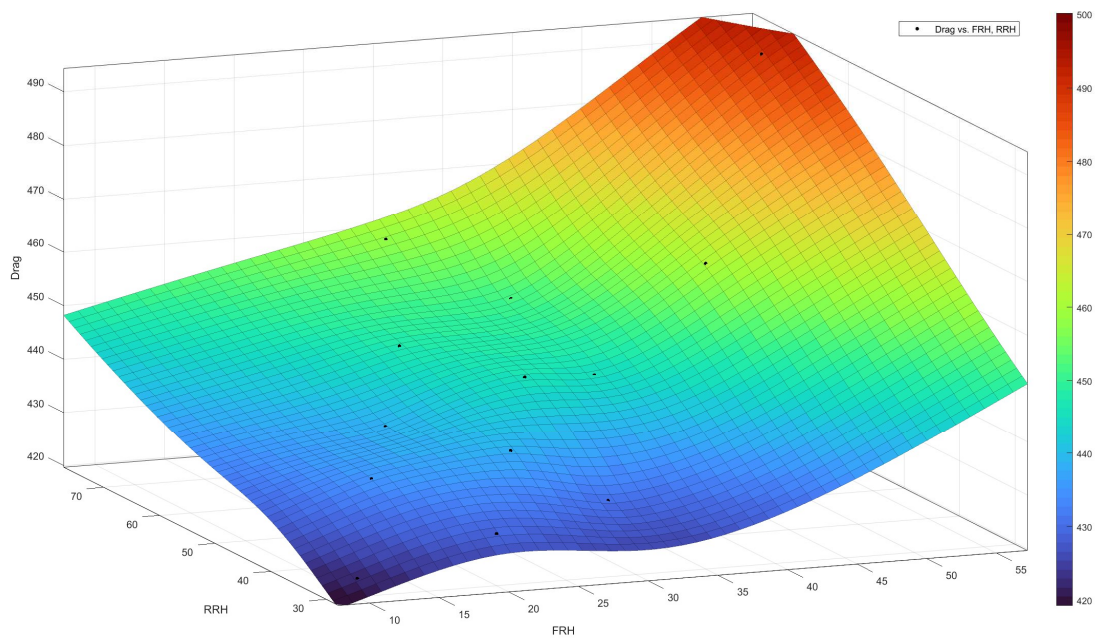


Figure 9-41: CFD – Drag 3D surface

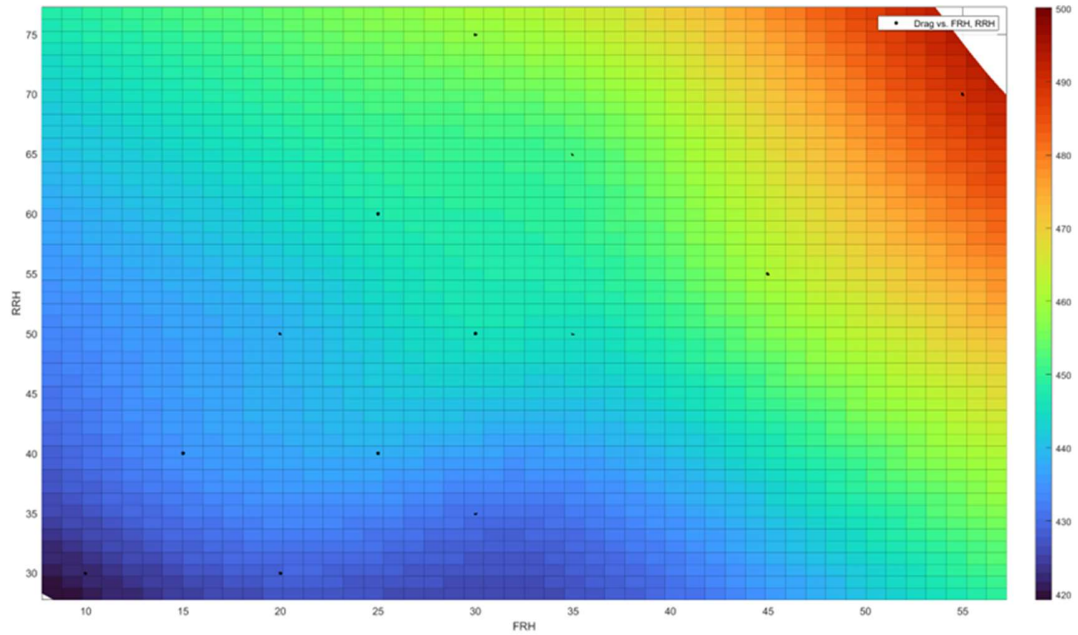


Figure 9-42: CFD - Drag 2D

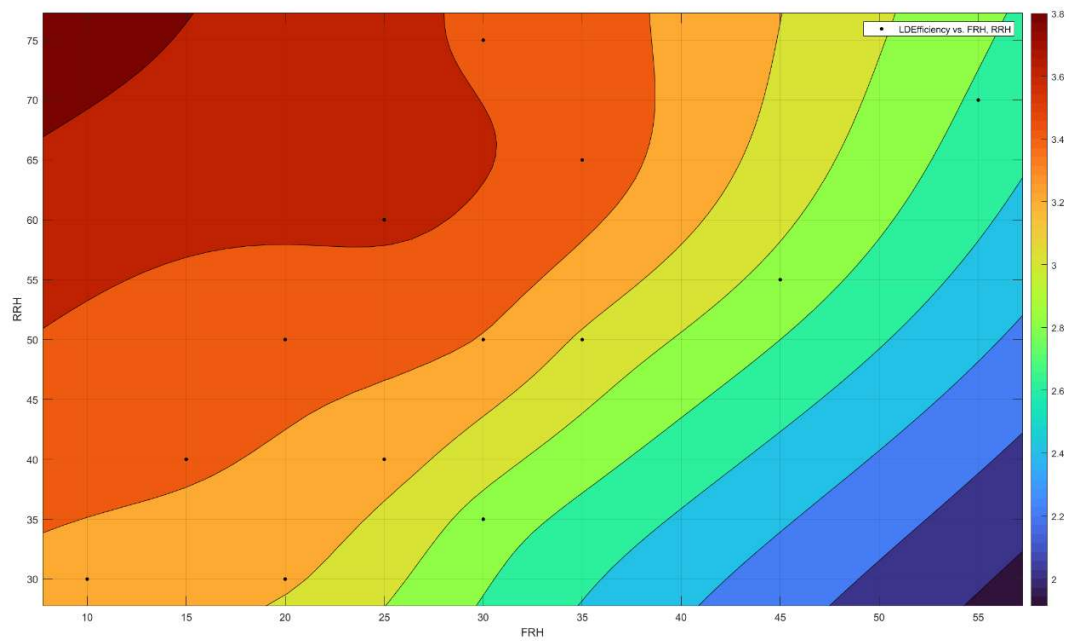


Figure 9-43: CFD - L/D Efficiency contour plot

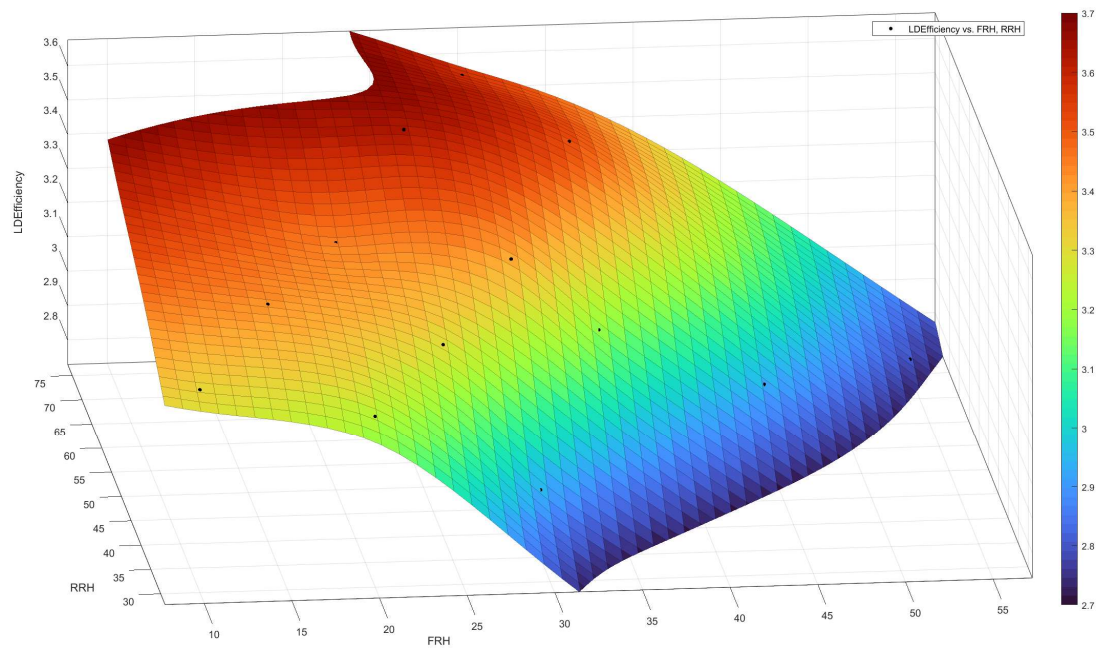


Figure 9-44: CFD - L/D Efficiency 3D surface

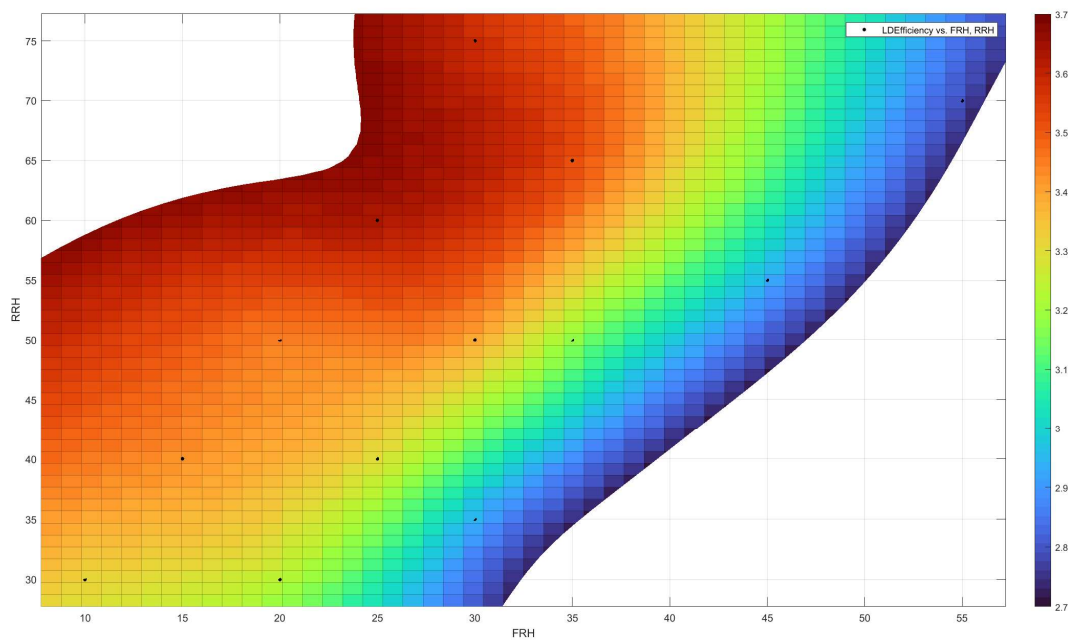


Figure 9-45: L/D Efficiency 2D

9.5. Appendix E – Data Comparison

Table 9-3: Downforce calculation and comparison table part 1

Session	Lap	Location	Speed (km/h)	Measured		Delta			Downforce		
				Front	Rear	Front	Rear	Total	Front	Rear	Total
Testing 1	Lap 8	Wellington Straight	192	363	565	83	185	268	814.23	1814.85	2629.08
Testing 2	Lap 9	Wellington Straight	189	368	568	88	188	276	863.28	1844.28	2707.56
Testing 1	Lap 20	Short Straight	159	308	492	53	132	185	519.93	1294.92	1814.85
Testing 1	Lap 26	AVG Wellington Straight	163	344	478	58	115	173	568.98	1128.15	1697.13
Testing 3	Lap 23	Small AVG Wellington Straight	191	348	510	76	136	212	745.56	1334.16	2079.72

Table 9-4: Downforce calculation and comparison table part 2

Offset (kg)		Offset (mm)				Measured				Ride Heights			
Front	Rear	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR
280	380	-1.92	-0.37	-0.88	-1.45	-5.16	-2.66	-14.64	-17.18	50.46	53.01	68.97	63.91
280	380	-1.92	-0.37	-0.88	-1.45	-5.28	-2.6	-14.53	-16.04	50.26	53.11	69.12	65.54
255	360	-2.69	0.28		1	-4.85	-1.68	-9.96	-9.09	51.74	53.97	73.77	75.49
286	363	-2.65	0.28		1	-1.48	-5.19	-2.31	-9.63	-10.28	51.14	52.93	74.24
272	374	-3.46	-0.65	0.17	-0.68	-5.17	-2.39	-10.84	-11.6	51.98	53.73	73.34	71.11

Table 9-5: Downforce calculation and comparison table part 3

AVG		Downforce (MATLAB) @ 35m/s			Downforce (Mira) @ 35m/s		
Front	Rear	Front	Rear	Total	Front	Rear	Total
51.74	60.99	521	802	1323	155	643.8	798.8
51.69	61.12	521	802	1323	155.5	643.7	799.2
52.85	63.87	529	808	1337	150	644.2	794.2
52.04	63.59	540	805	1345	152	644	796
52.86	63.54	527	807	1334	141.6	644.7	786.3



Figure 9-46: Constant speed zone, Silverstone 2022

9.6. Appendix F – VI-CRT Aero Map Data

9.6.1. Initial Aero Map

```
$-----MDI_HEADER
[MDI_HEADER]
FILE_TYPE = 'aer'
FILE_VERSION = 5.00
FILE_FORMAT = 'ASCII'
(COMMENTS)
{comment_string}
'Sample Aero Data'
$-----UNITS
[UNITS]
(BASE)
{length force angle mass time}
'mm' 'N' 'degree' 'kg' 'sec'
(USER)
{unit_type length force angle mass time conversion}
'kmh' 1 0 0 0 -1 277.77778
'ride_height' 1 0 0 0 0 1.0
$-----TEST_CONDITIONS
[TEST_CONDITIONS]
reference_velocity <kmh> = 100.0
reference_density = 1.0
front_ride_height_min <ride_height> = 0.0
front_ride_height_max <ride_height> = 400.0
rear_ride_height_min <ride_height> = 0.0
rear_ride_height_max <ride_height> = 400.0
$-----FRONT_DOWNFORCE
[FRONT_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
0.0 84.8765323457 84.8765323457 84.8765323457 84.8765323457 84.8765323457
200.0 84.8765323457 84.8765323457 84.8765323457 84.8765323457 84.8765323457
400.0 84.8765323457 84.8765323457 84.8765323457 84.8765323457 84.8765323457
600.0 84.8765323457 84.8765323457 84.8765323457 84.8765323457 84.8765323457
800.0 84.8765323457 84.8765323457 84.8765323457 84.8765323457 84.8765323457
$-----REAR_DOWNFORCE
[REAR_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
0.0 110.339492049 110.339492049 110.339492049 110.339492049 110.339492049
200.0 110.339492049 110.339492049 110.339492049 110.339492049 110.339492049
400.0 110.339492049 110.339492049 110.339492049 110.339492049 110.339492049
600.0 110.339492049 110.339492049 110.339492049 110.339492049 110.339492049
800.0 110.339492049 110.339492049 110.339492049 110.339492049 110.339492049
$-----DRAG
[DRAG]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> drag <force>}
0.0 235.339476049 235.339476049 235.339476049 235.339476049 235.339476049
200.0 235.339476049 235.339476049 235.339476049 235.339476049 235.339476049
400.0 235.339476049 235.339476049 235.339476049 235.339476049 235.339476049
600.0 235.339476049 235.339476049 235.339476049 235.339476049 235.339476049
800.0 235.339476049 235.339476049 235.339476049 235.339476049 235.339476049
```

Figure 9-47: Initial Aero Map

9.6.2. Mira WT Aero Map

```

$-----MDI_HEADER
[MDI_HEADER]
FILE_TYPE = 'aer'
FILE_VERSION = 5.00
FILE_FORMAT = 'ASCII'
(COMMENTS)
{comment_string}
'Sample Aero Data'
$-----UNITS
[UNITS]
(BASE)
{length force angle mass time}
'mm' 'N' 'degree' 'kg' 'sec'
(USER)
{unit_type length force angle mass time conversion}
'kmh' 1 0 0 0 -1 277.77778
'ride_height' 1 0 0 0 0 1.0
$-----TEST_CONDITIONS
[TEST_CONDITIONS]
reference_velocity <kmh> = 126.0
reference_density = 1.0
front_ride_height_min <ride_height> = 42.0
front_ride_height_max <ride_height> = 66.0
rear_ride_height_min <ride_height> = 66.0
rear_ride_height_max <ride_height> = 86.0
$-----FRONT_DOWNFORCE
[FRONT_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
66
69
72
75
79
81
86
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
42 352 388 422 458 488 511 559
47 229 258 288 317 356 375 423
54 159 189 202 240 277 296 344
62 045 080 099 124 156 173 213
66 -05 014 044 070 106 123 168
$-----REAR_DOWNFORCE
[REAR_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
66
69
72
75
79
81
86
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
42 625 626 626 624 624 624 624
47 637 636 634 632 631 635 630
54 642 644 646 644 642 641 639
62 651 655 659 657 654 653 649
66 655 660 665 663 660 658 656
$-----DRAG
[DRAG]
(Z_DATA)
{rear_ride_height <ride_height>}
66
69
72
75
79
81
86
(XY_DATA)
{front_ride_height <ride_height> drag <force>}
42 482 484 487 485 488 490 494
47 491 493 494 495 496 497 498
54 499 501 502 502 503 503 504
62 501 502 503 505 506 507 509
66 503 506 507 508 511 512 515

```

Figure 9-48: Mira WT Aero Map

9.6.3. Sabe CFD Full Aero Map

```

$-----TEST_CONDITIONS
[TEST_CONDITIONS]
reference_velocity <kmh> = 178.2
reference_density = 1.2
front_ride_height_min <ride_height> = 5.0
front_ride_height_max <ride_height> = 55.0
rear_ride_height_min <ride_height> = 20.0
rear_ride_height_max <ride_height> = 75.0
$-----FRONT_DOWNFORCE
[FRONT_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
5.0 1171.879516 1242.525625 1315.534968 1398.507957 1485.247289 1571.814562 1661.334797 1756.658193 1856.258731 1955.728590 2051.210160 2140.990564
10.0 1169.815661 1247.151754 1318.388389 1404.573360 1483.439939 1555.919490 1634.607656 1727.493178 1829.476802 1930.155595 2033.302539 2107.950755
15.0 1176.347024 1279.959987 1372.642543 1445.637050 1500.712077 1546.325941 1606.852163 1701.493511 1810.961437 1912.268261 1999.110909 2074.517020
20.0 1152.737652 1278.103218 1394.776570 1460.581715 1507.080544 1536.363972 1578.218665 1686.905223 1804.922895 1899.253639 1971.790395 2033.273891
25.0 1068.263633 1181.712091 1282.804485 1370.403057 1457.792500 1509.982204 1576.777628 1680.089311 1794.030924 1869.515756 1924.661038 1972.553164
30.0 939.2190967 1030.927103 1110.480277 1188.308953 1300.718420 1403.868326 1506.127493 1609.575612 1711.760877 1789.858169 1842.479128 1884.343039
35.0 797.7990025 878.8809006 955.2297108 1039.142757 1141.607543 1249.265225 1355.445838 1472.389610 1580.695172 1668.342730 1726.625933 1773.635663
40.0 659.7173652 738.8211101 818.0284711 903.5499023 998.7924012 1100.742327 1207.409767 1318.039246 1422.245198 1510.014302 1578.750627 1636.335964
45.0 526.9471949 606.1112004 686.6378610 771.6219568 862.7494402 959.4797641 1060.110034 1161.073622 1255.425412 1339.642302 1413.571179 1480.797586
50.0 397.9954013 477.0814594 557.5372594 641.0063669 728.3369320 819.1287937 911.6746508 1002.860501 1089.094647 1168.962890 1244.418038 1318.826039
55.0 271.6534978 350.2366544 429.8220631 511.2730248 594.9123385 680.2491945 765.9150996 849.8981494 930.3261983 1006.698918 1081.558039 1161.611688
$-----REAR_DOWNFORCE
[REAR_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
5.0 1479.741976 1501.661686 1517.824290 1522.674596 1516.120873 1500.196645 1478.092441 1453.322127 1428.097719 1403.499845 1380.338880 1359.480679
10.0 1444.521271 1469.988661 1493.677580 1503.796729 1502.619841 1488.630895 1466.893882 1443.361253 1419.741111 1396.049115 1373.066722 1352.268073
15.0 1394.784683 1416.570800 1441.004339 1464.380643 1479.728811 1472.003250 1454.149462 1436.385650 1417.045037 1394.464130 1370.784426 1349.172070
20.0 1340.537900 1355.936543 1378.447555 1415.544752 1448.389640 1460.045814 1452.457471 1445.743055 1428.089315 1404.118882 1376.855425 1352.448105
25.0 1295.011214 1307.141934 1330.056087 1371.679570 1426.969144 1468.969922 1489.832239 1483.012394 1458.427407 1438.927550 1393.967673 1364.256742
30.0 1265.616370 1276.189589 1295.597093 1331.642151 1398.078443 1465.764226 1517.419722 1513.102895 1492.772423 1463.776092 1426.088547 1389.956704
35.0 1255.100220 1267.892888 1289.882498 1327.142637 1380.797310 1434.727652 1472.480015 1505.339437 1514.785586 1504.236168 1474.164396 1443.188892
40.0 1261.255843 1278.462036 1304.345409 1340.863634 1385.944492 1432.419032 1475.753442 1514.168353 1536.092299 1537.274651 1521.656847 1499.654646
45.0 1278.935210 1300.305147 1329.091766 1365.744645 1408.795290 1455.159498 1501.478997 1541.862218 1564.474814 1571.460585 1565.463855 1551.311679
50.0 1303.344714 1327.935691 1358.762055 1395.786639 1437.893651 1482.841021 1527.103575 1565.049488 1590.948004 1604.038018 1605.330076 1596.742919
55.0 1330.953073 1357.692734 1389.574622 1426.282153 1466.713749 1508.847232 1549.664733 1585.422763 1612.925699 1630.767131 1638.206780 1633.382559
$-----DRAG
[DRAG]
(Z_DATA)
{rear_ride_height <ride_height>}
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
5.0 819.9845438 829.0895108 837.9379492 846.2957963 853.3272960 858.7029622 863.1128320 867.5040033 872.3755864 877.7942283 883.6929780 890.0289930
10.0 827.2100922 836.8411262 846.2135169 855.4699306 862.5029499 866.5641112 869.5025366 873.2067422 878.0248840 883.5663119 889.5818789 896.0509290
15.0 833.3965130 843.8768796 854.3411880 863.9197650 870.9052050 872.8609697 874.1213249 877.8935648 883.3491133 889.1786102 895.2601589 901.8556014
20.0 837.3860028 847.9028702 858.7393639 868.1689741 875.1529146 877.4873298 878.0456252 883.3327543 889.4064831 894.8635985 900.6166577 907.3712206
25.0 839.0276310 847.8642316 856.9098198 866.7568880 877.1884239 882.9174729 886.9231265 891.0614683 895.6565470 899.4028485 904.9362954 912.4903476
30.0 840.4112392 847.2993351 853.9798612 861.7054817 873.8357959 884.4046471 892.4350983 895.2392873 897.4419052 900.9536735 908.0570440 917.7740847
35.0 843.9984729 850.2758981 856.7832976 864.7553300 874.8075953 884.3175745 891.1580231 897.0881361 900.4472683 904.0245917 913.5838561 925.0871811
40.0 850.5811118 857.2925655 864.5495132 872.8542586 882.1175908 891.3267370 899.7359622 907.0221726 912.4225992 918.1303801 926.8373148 937.5896458
45.0 859.6402688 867.0943006 875.1666710 884.0735897 893.7611843 903.8933645 914.0625555 923.4167980 930.0041057 936.0003897 944.3234303 954.2720570
50.0 870.3771543 878.5722819 887.3870500 896.9356923 907.1884197 917.9365230 928.7429605 938.7773450 947.4505023 955.6258339 963.9744729 972.4182353
55.0 882.1130521 890.9299482 900.3234822 910.3437226 920.9348397 931.8900551 942.8726327 953.4142035 963.3108114 972.7621419 981.8134073 989.7618410

```

Figure 9-49: Sabe Full CFD Aero Map

9.6.4. Sabe CFD Single Point Aero Map

```

$-----UNITS
[UNITS]
(BASE)
{length force angle mass time}
{'mm' 'N' 'degree' 'kg' 'sec'}
(USER)
{unit_type length force angle mass time conversion}
{'kmh' 1 0 0 0 -1 277.77778}
{'ride_height' 1 0 0 0 0 1.0}
$-----TEST_CONDITIONS
[TEST_CONDITIONS]
reference_velocity <kmh> = 126.0
reference_density = 1.0
front_ride_height_min <ride_height> = 0.0
front_ride_height_max <ride_height> = 400.0
rear_ride_height_min <ride_height> = 0.0
rear_ride_height_max <ride_height> = 400.0
$-----FRONT_DOWNFORCE
[FRONT_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
0.0 726.5 726.5 726.5 726.5 726.5
200.0 726.5 726.5 726.5 726.5 726.5
400.0 726.5 726.5 726.5 726.5 726.5
600.0 726.5 726.5 726.5 726.5 726.5
800.0 726.5 726.5 726.5 726.5 726.5
$-----REAR_DOWNFORCE
[REAR_DOWNFORCE]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> downforce <force>}
0.0 734.1 734.1 734.1 734.1 734.1
200.0 734.1 734.1 734.1 734.1 734.1
400.0 734.1 734.1 734.1 734.1 734.1
600.0 734.1 734.1 734.1 734.1 734.1
800.0 734.1 734.1 734.1 734.1 734.1
$-----DRAG
[DRAG]
(Z_DATA)
{rear_ride_height <ride_height>}
0.0
200.0
400.0
600.0
800.0
(XY_DATA)
{front_ride_height <ride_height> drag <force>}
0.0 446.12 446.12 446.12 446.12 446.12
200.0 446.12 446.12 446.12 446.12 446.12
400.0 446.12 446.12 446.12 446.12 446.12
600.0 446.12 446.12 446.12 446.12 446.12
800.0 446.12 446.12 446.12 446.12 446.12

```

Figure 9-50: Sabe single point average Aero Map

9.6.5. VI-CRT Results

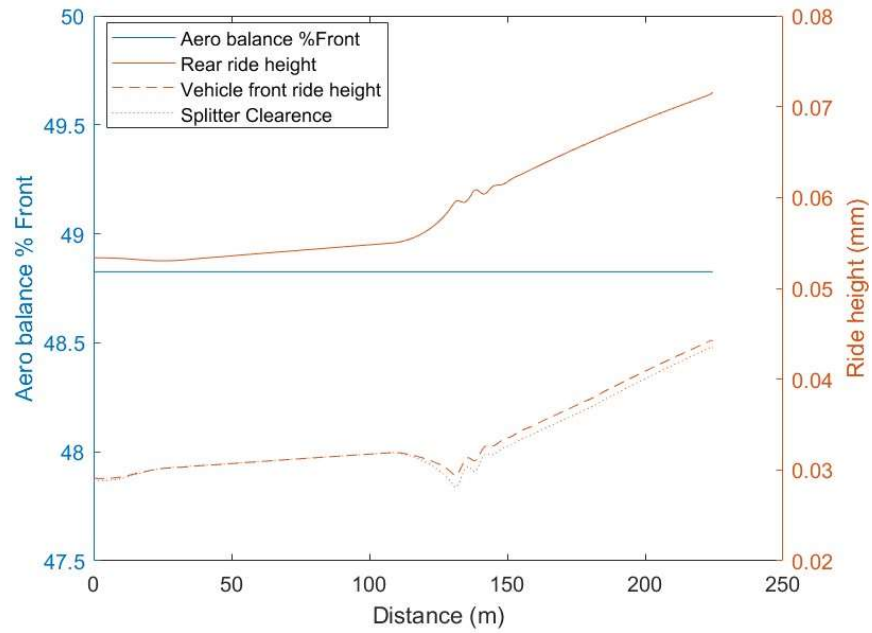


Figure 9-51: Initial New Aero (Single Point) - Aero Balance % Front and Ride Heights vs distance

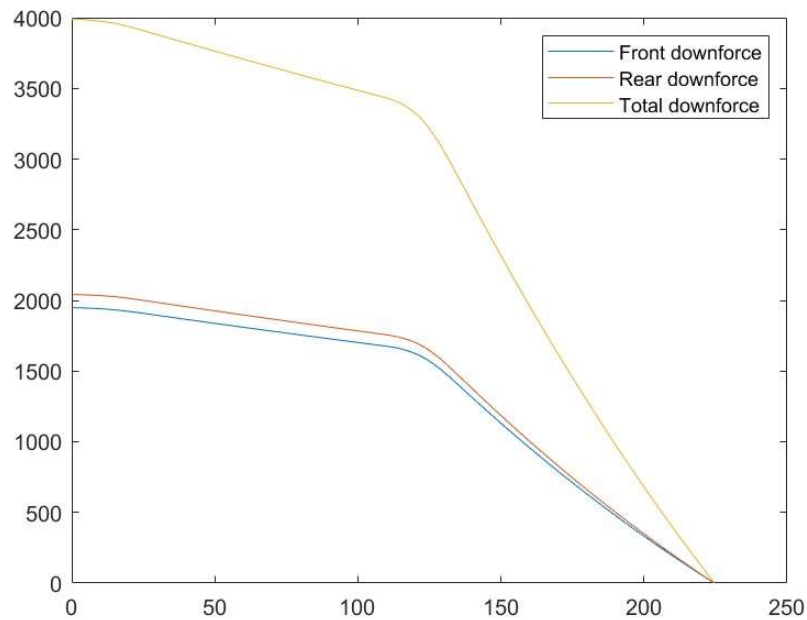


Figure 9-52: Initial New Aero (Single Point) Front, Rear and Total Downforces vs distance

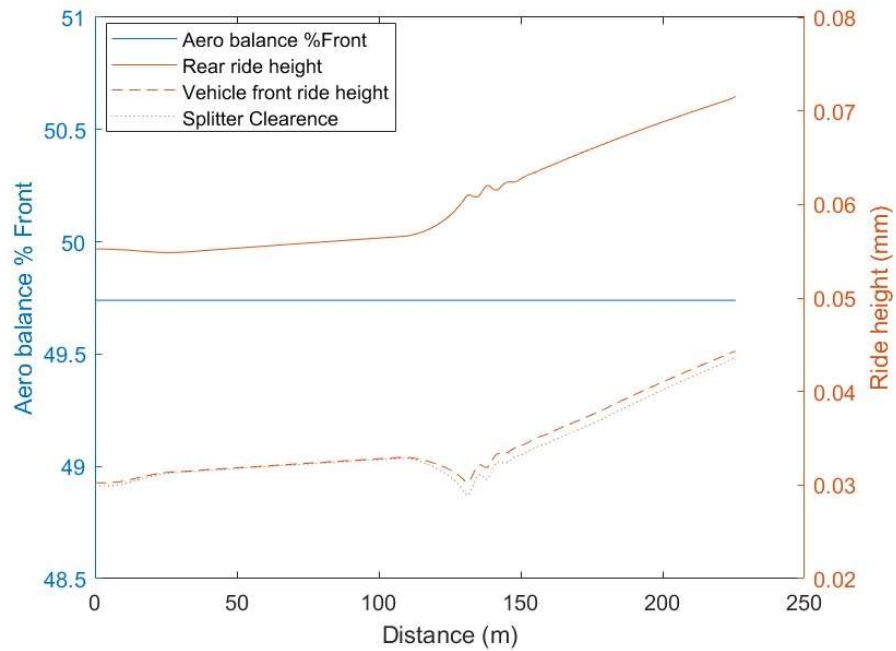


Figure 9-53: CFD (Single Point) - Aero Balance % Front and Ride Heights vs distance

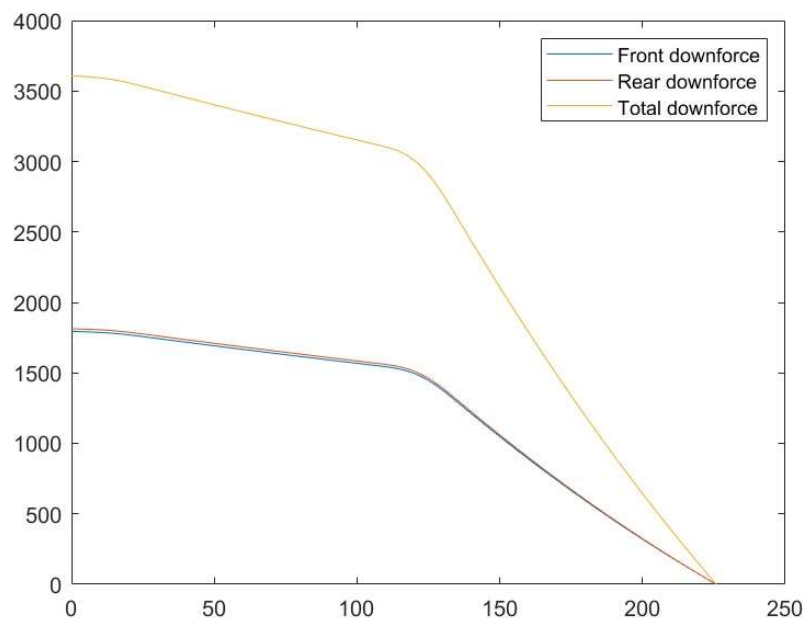


Figure 9-54: CFD (Single Point) Front, Rear and Total Downforces vs distance

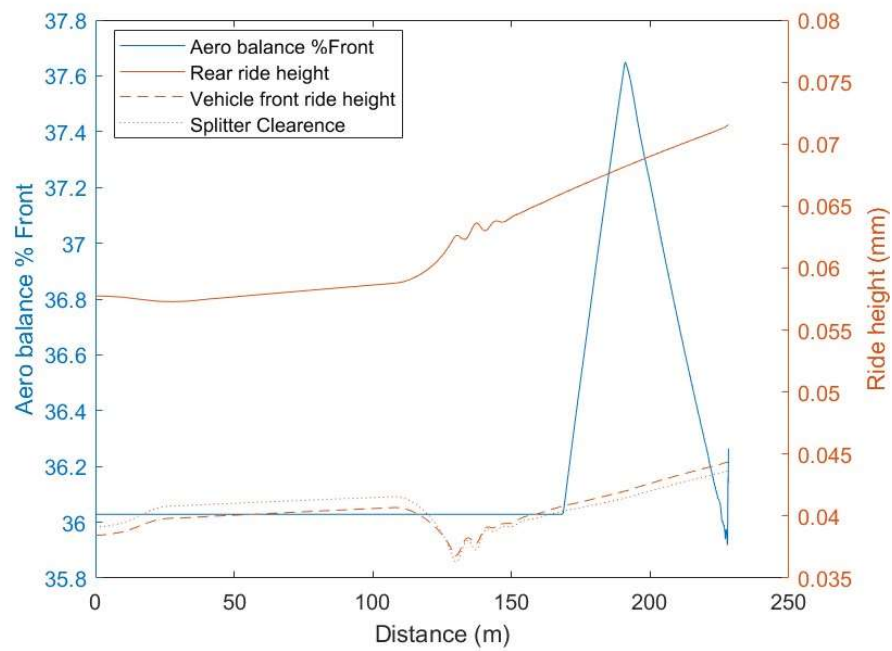


Figure 9-55: Mira WT Map - Aero Balance % Front and Ride Heights vs distance

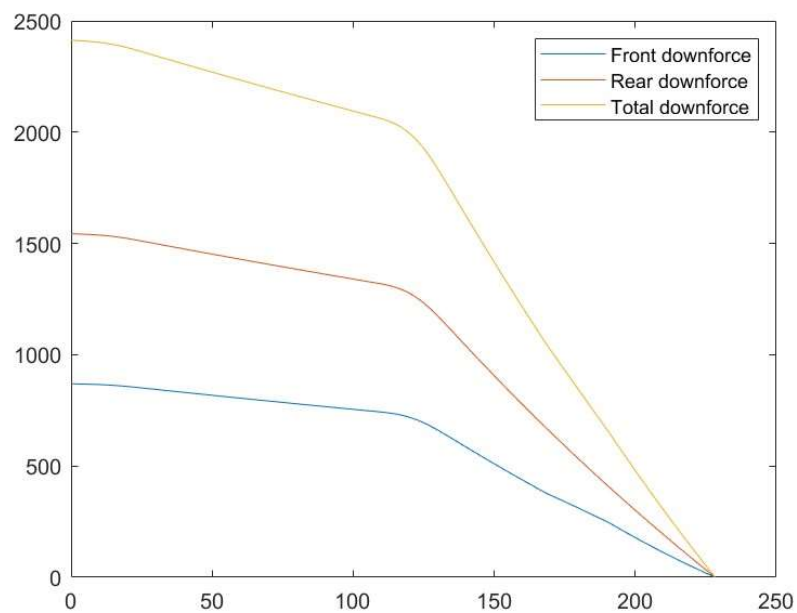


Figure 9-56: Mira WT Map - Front, Rear and Total Downforces vs distance

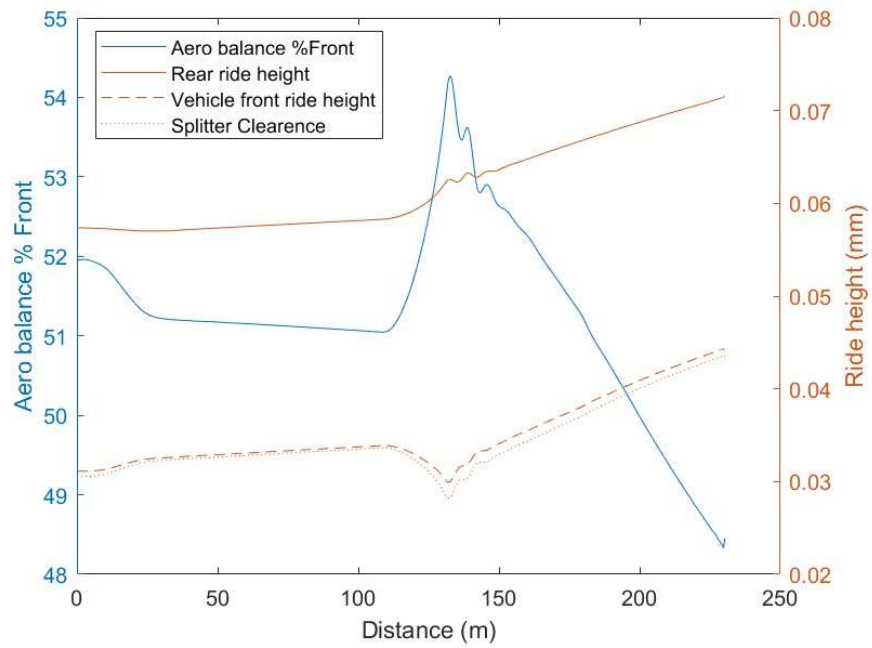


Figure 9-57: Sabe CFD Map - Aero Balance % Front and Ride Heights vs distance

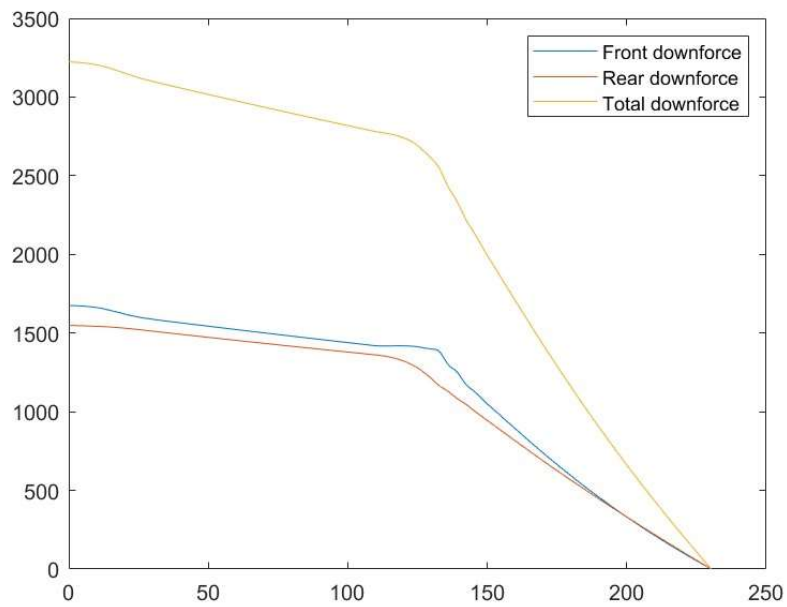


Figure 9-58: Sabe CFD Map - Front, Rear and Total Downforces vs distance

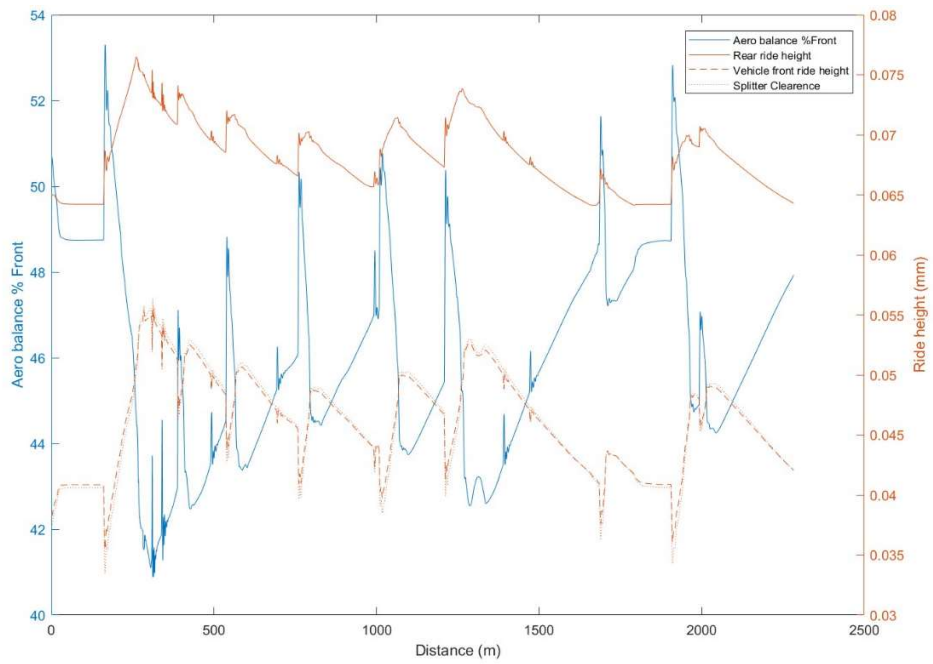


Figure 9-59: Base Set Up %Front Aero Balance for Max Performance

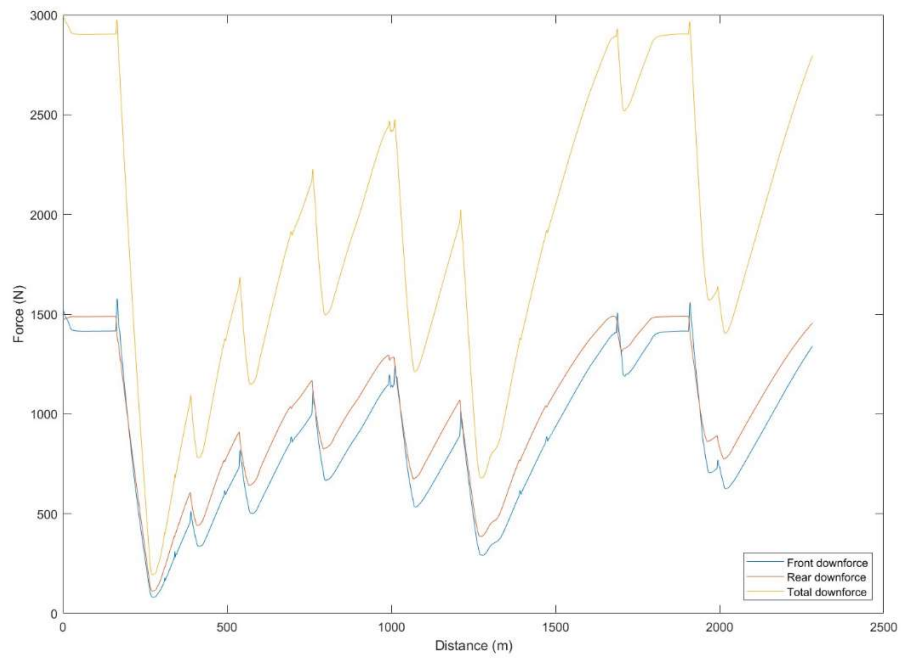


Figure 9-60: Base Set Up Aerodynamic Forces for Max Performance

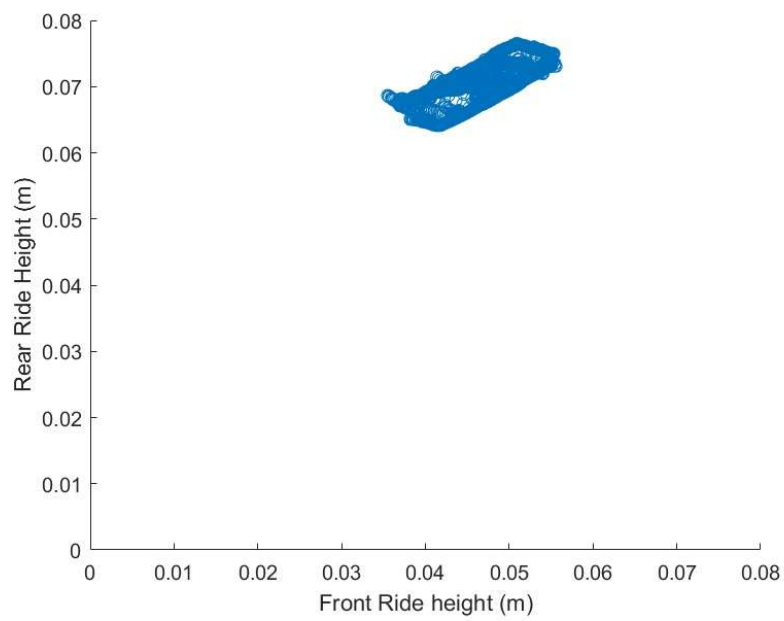


Figure 9-61: Set Up 1 - Scatter plot

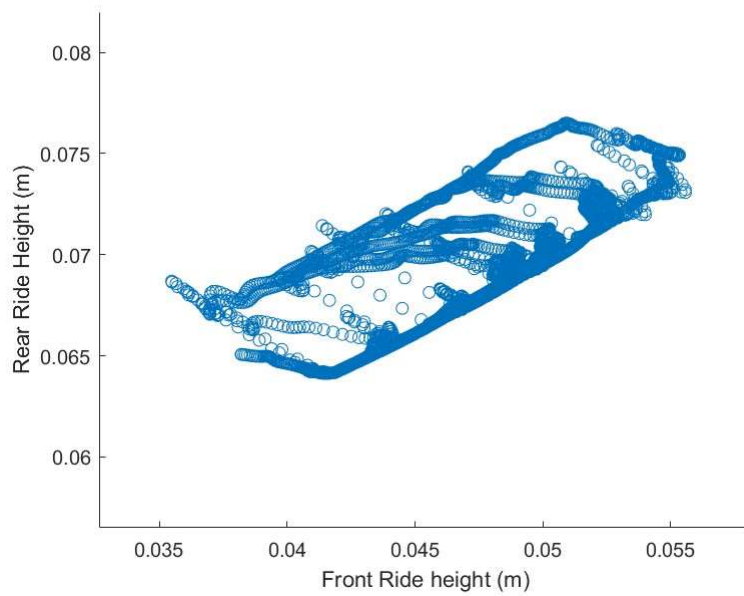


Figure 9-62: Set Up 1 - Aerodynamic Forces for Max Performance: Base Set Up Scatter Plot Zoomed

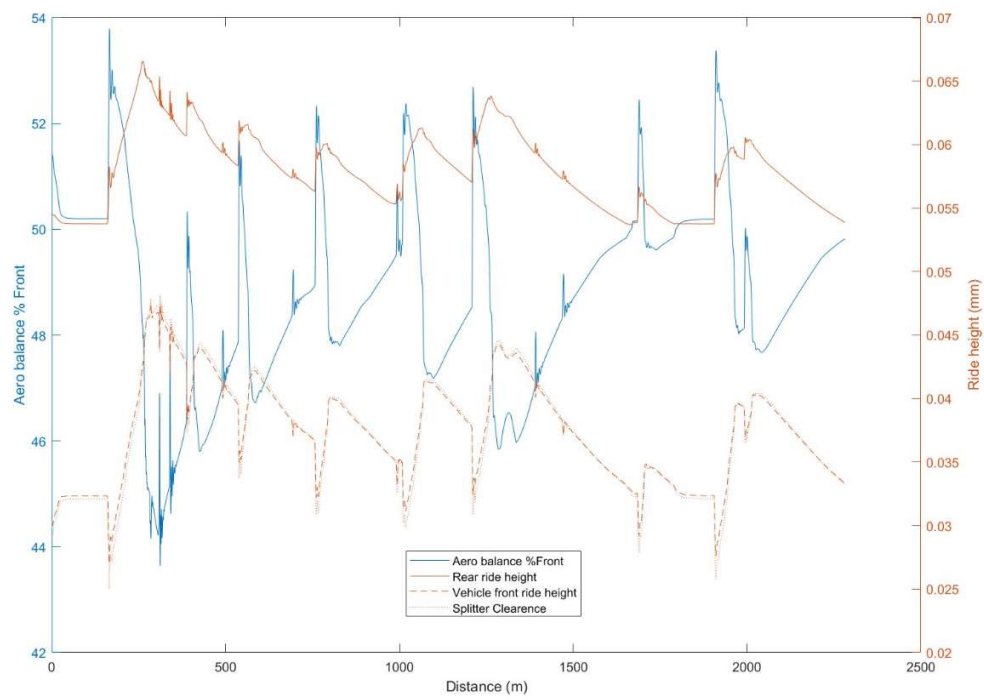


Figure 9-63: Set Up 2 - %Front Aero Balance for Max Performance

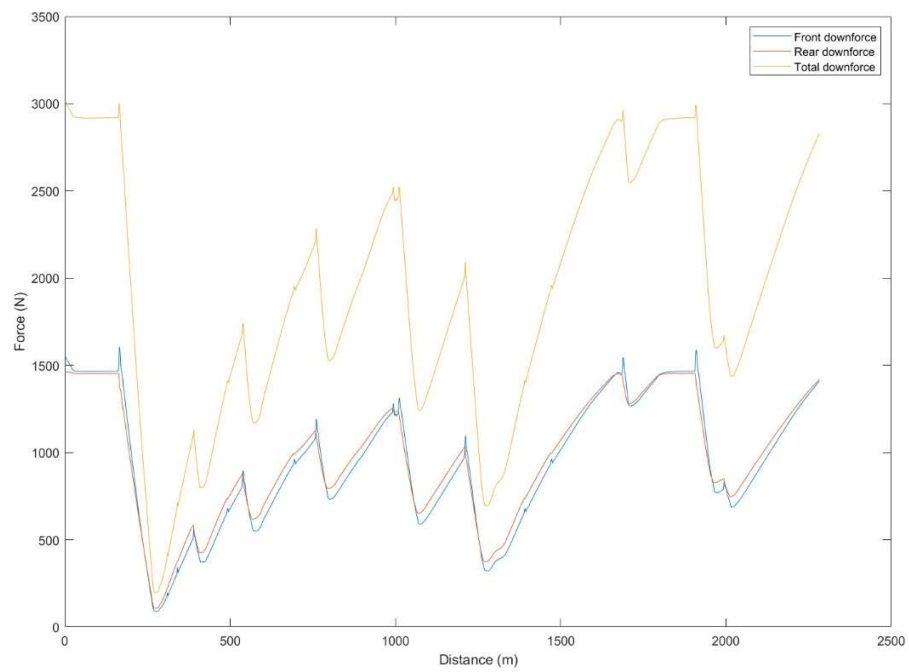


Figure 9-64: Set Up 2 - Aerodynamic Forces for Max Performance

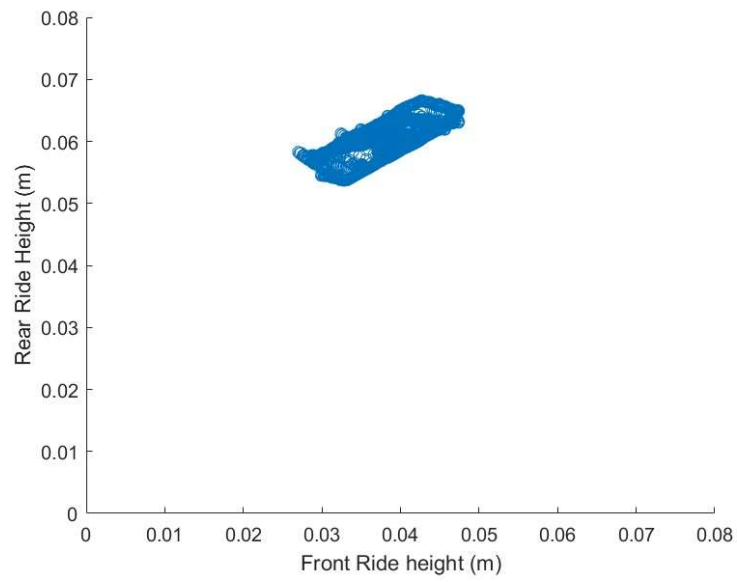


Figure 9-65: Set Up 2 - Scatter plot

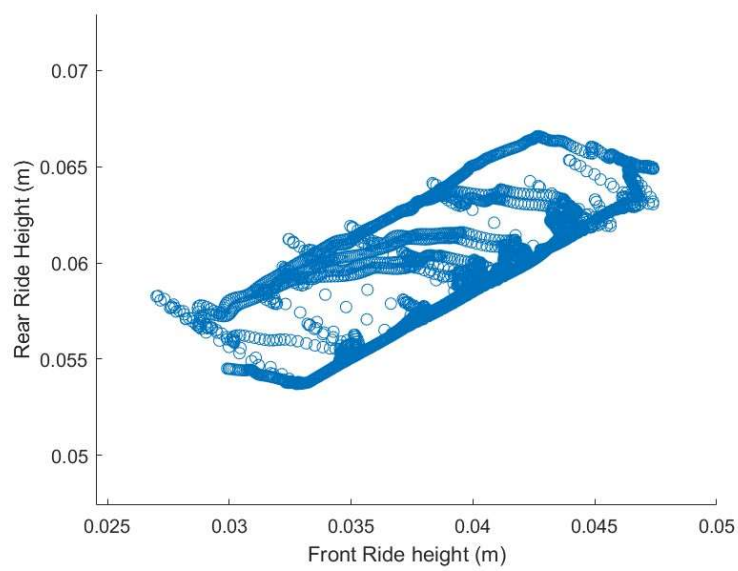


Figure 9-66: Set Up 2 - Scatter plot zoomed

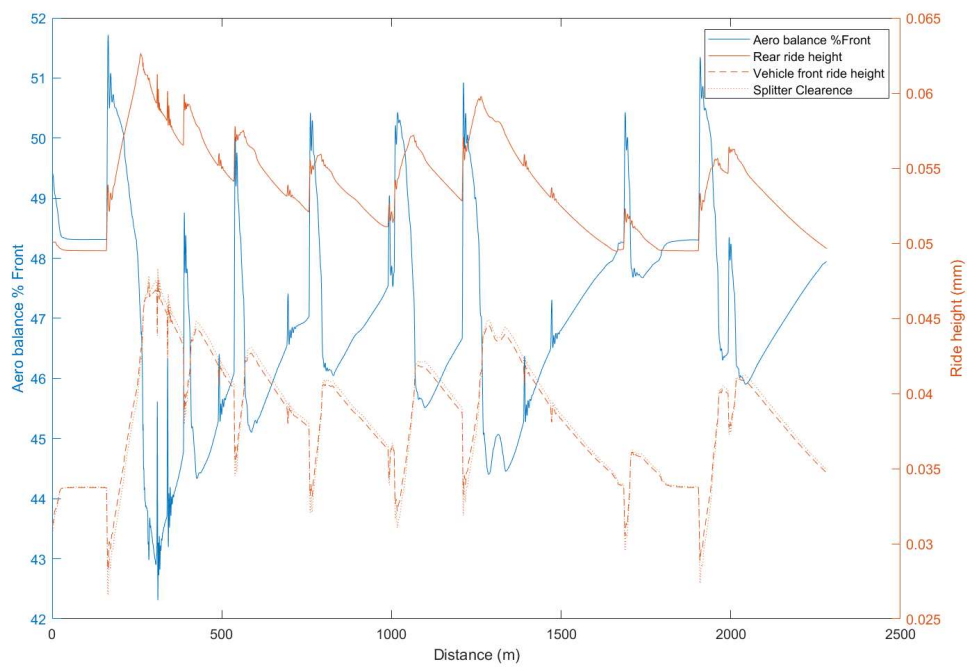


Figure 9-67: Set Up 3 - %Front Aero Balance for Max Performance

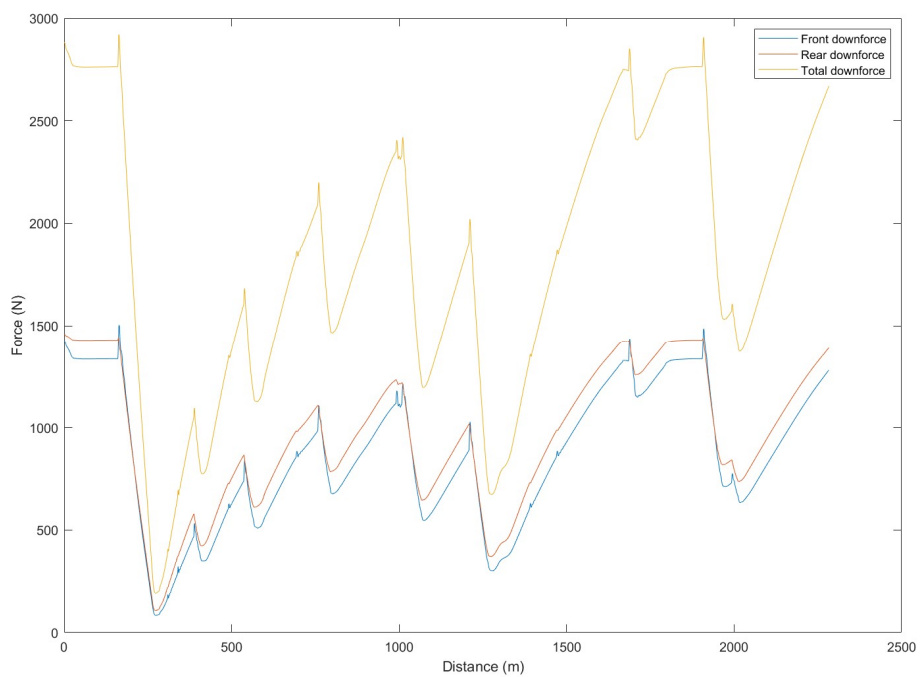


Figure 9-68: Set Up 3 - Aerodynamic Forces for Max Performance

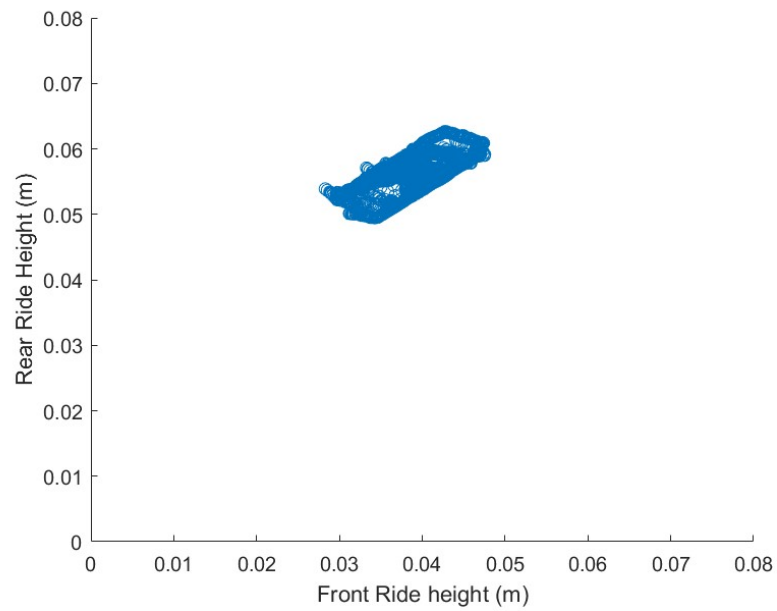


Figure 9-69: Set Up 3 - Scatter plot

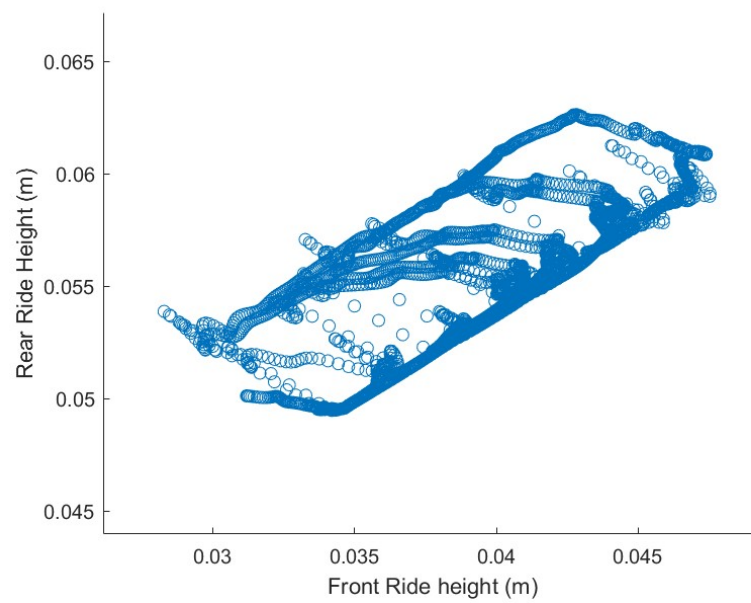


Figure 9-70: Set Up 3 - Scatter plot zoomed

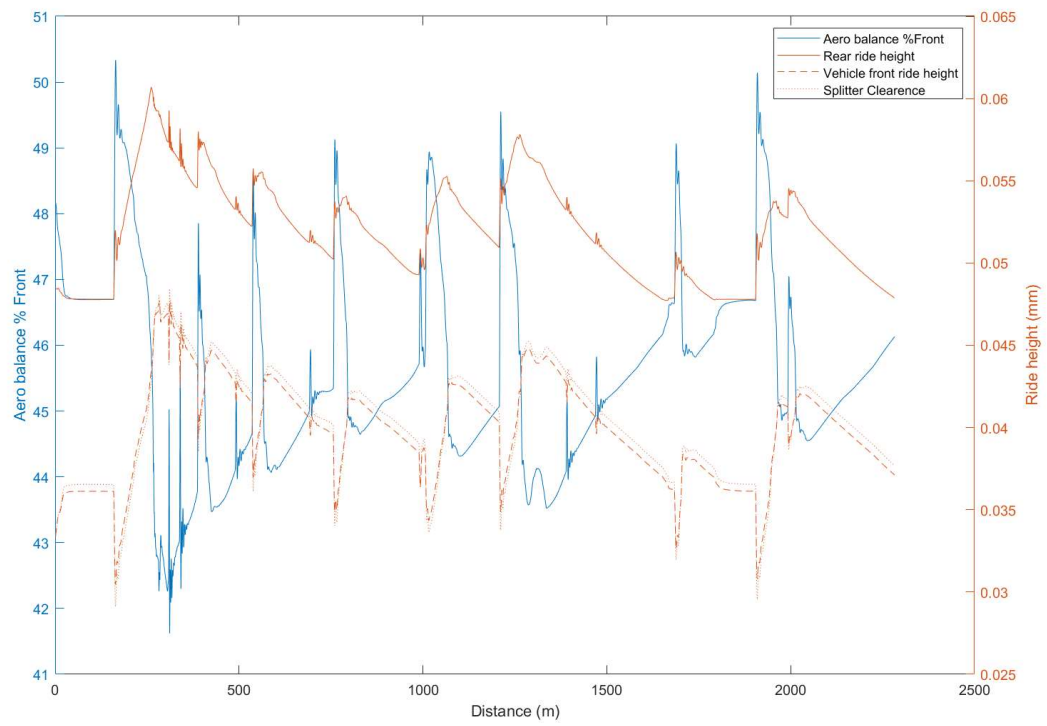


Figure 9-71: Set Up 4 - %Front Aero Balance for Max Performance

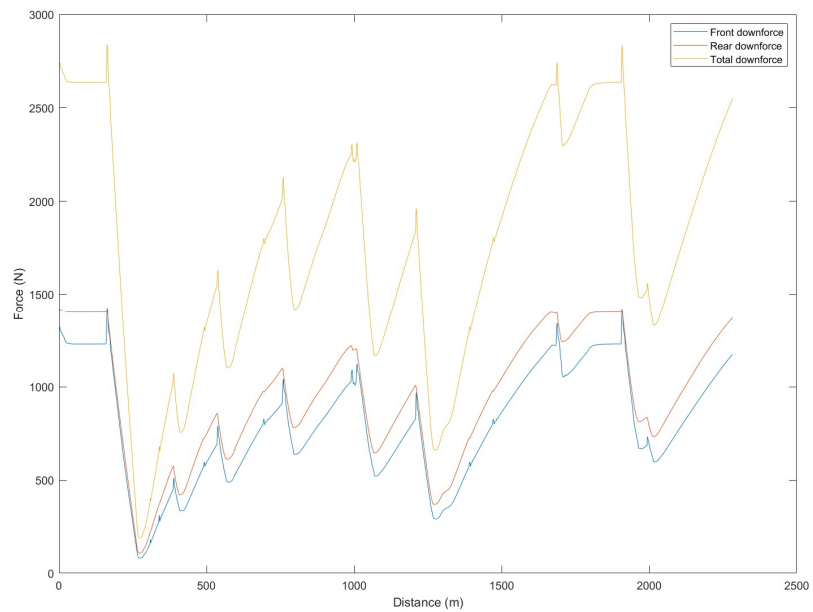


Figure 9-72: Set Up 4 - Aerodynamic Forces for Max Performance

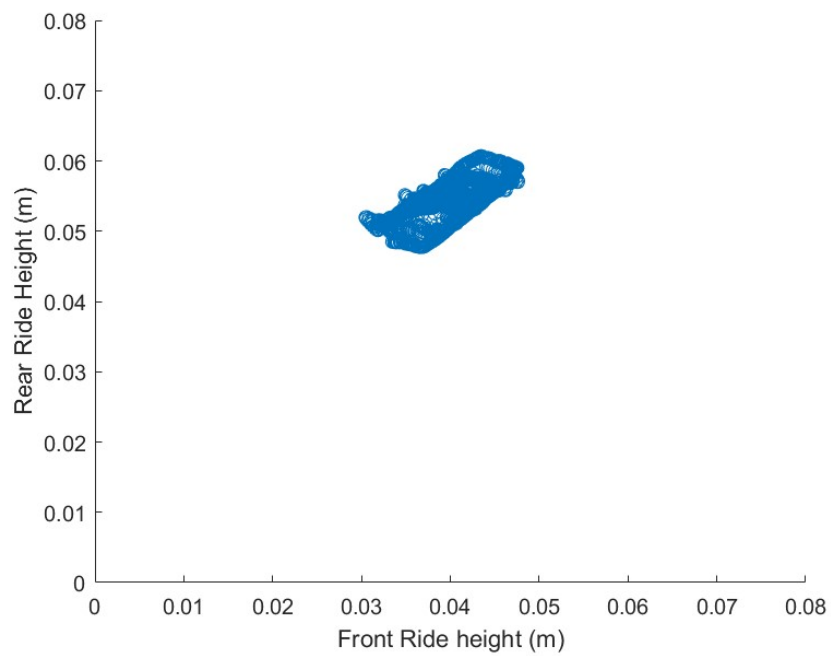


Figure 9-73: Set Up 4 - Scatter plot

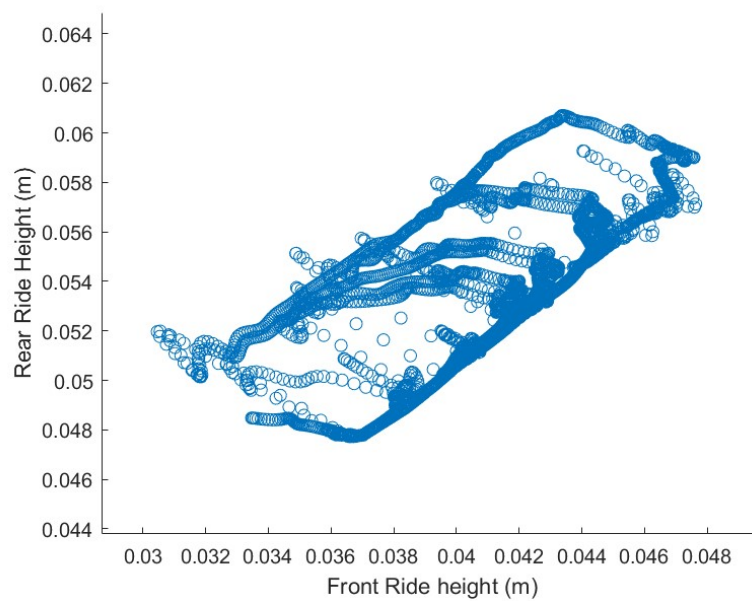


Figure 9-74: Set Up 4 - Scatter plot zoomed

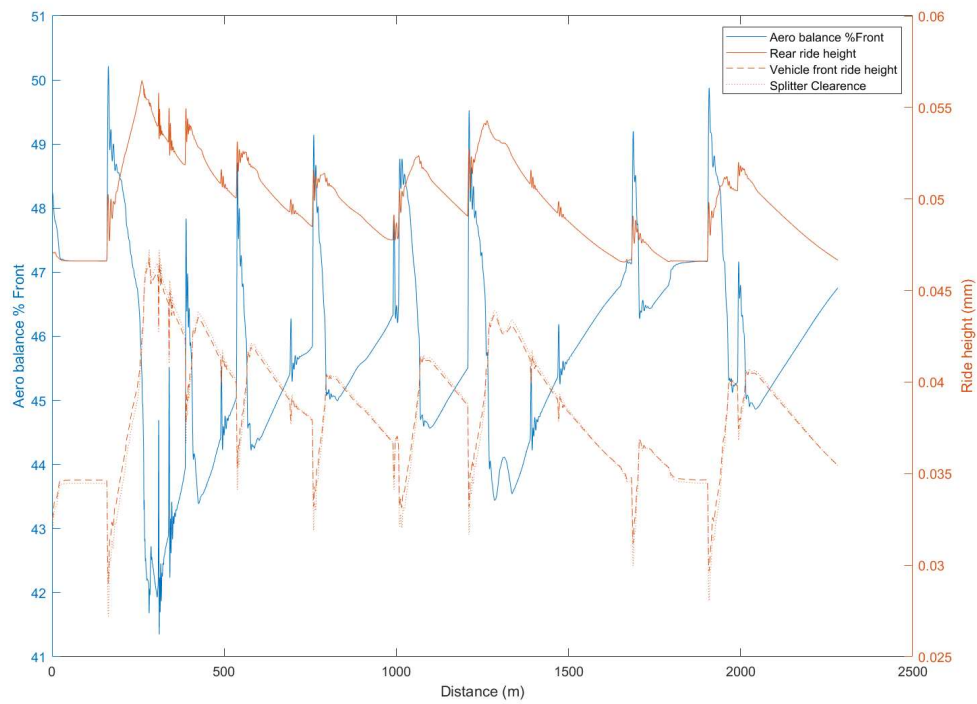


Figure 9-75: Set Up 5 - %Front Aero Balance for Max Performance

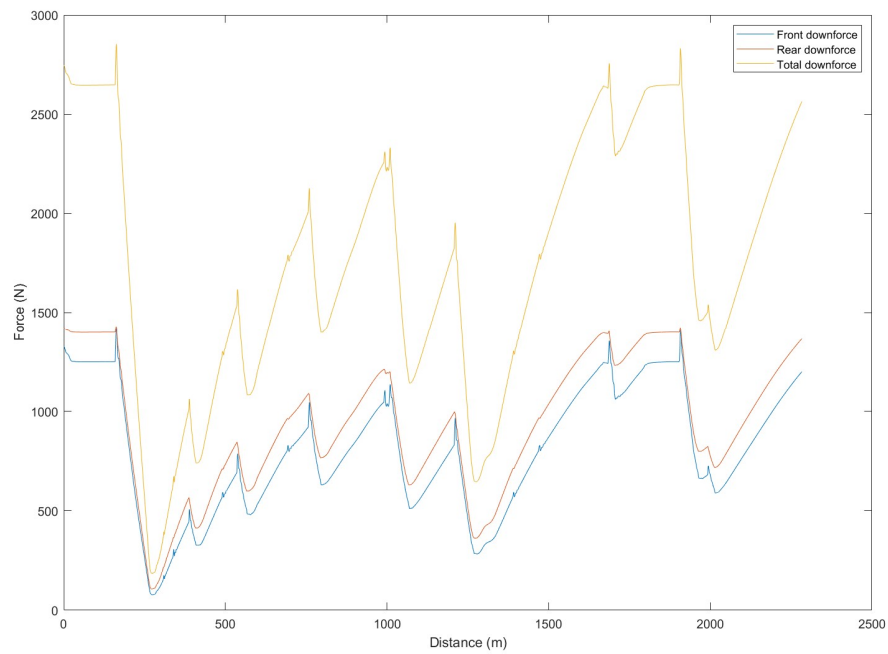


Figure 9-76: Set Up 5 - Aerodynamic Forces for Max Performance

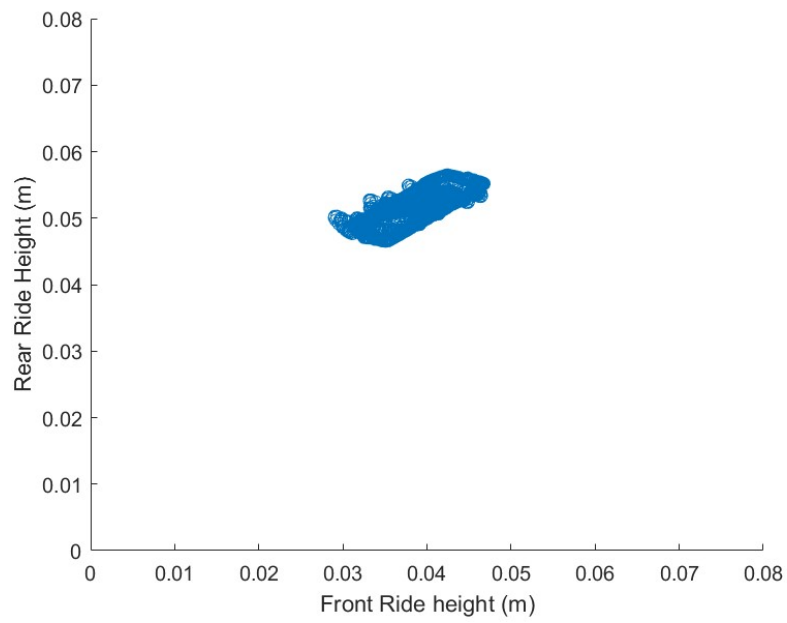


Figure 9-77: Set Up 5 - Scatter plot

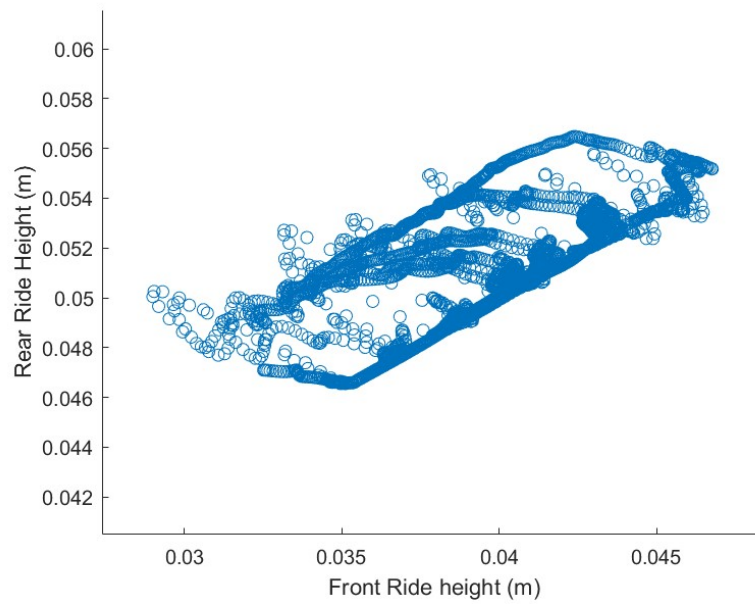


Figure 9-78: Set Up 5 - Scatter plot zoomed

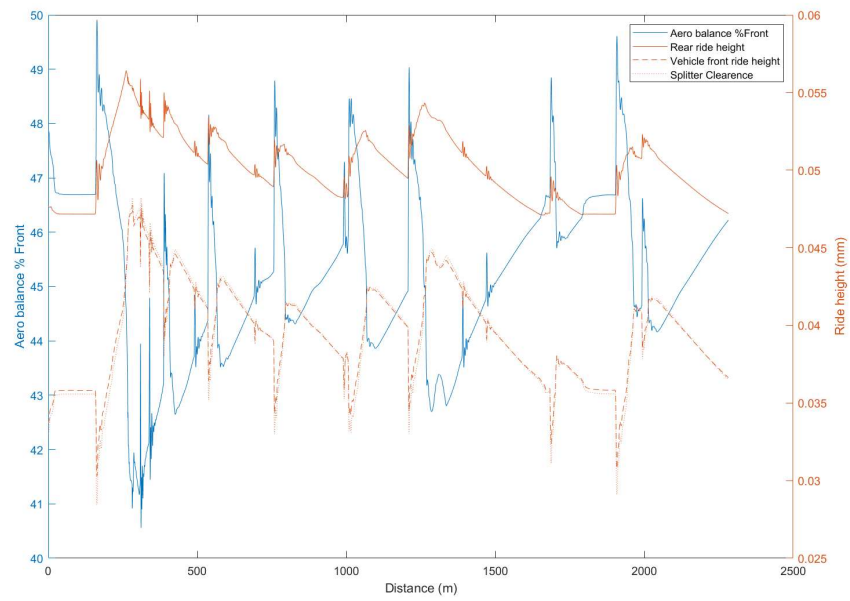


Figure 9-79: Set Up 6 - %Front Aero Balance for Max Performance

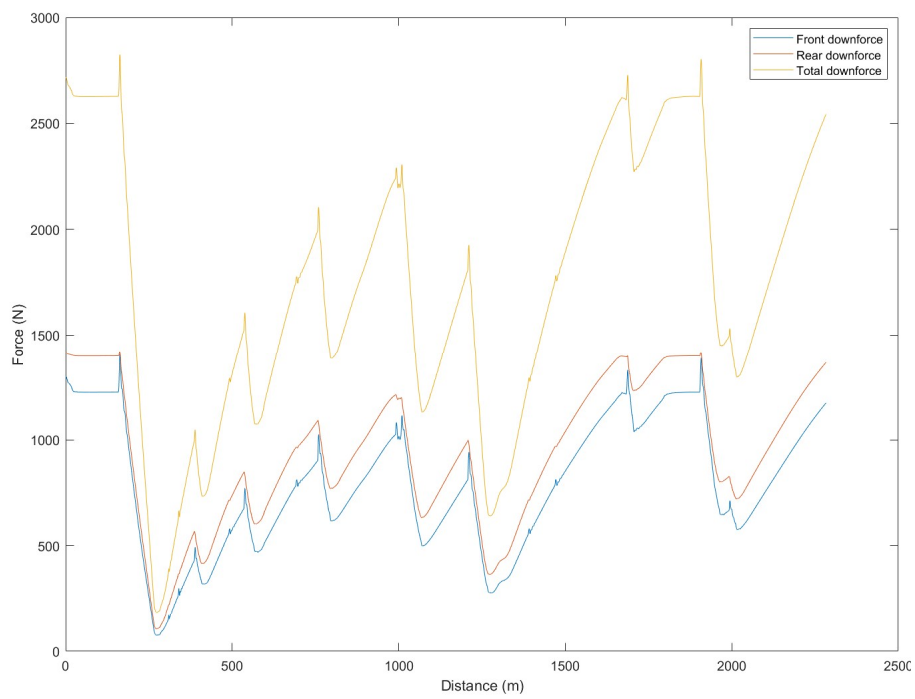


Figure 9-80: Set Up 6 - Aerodynamic Forces for Max Performance

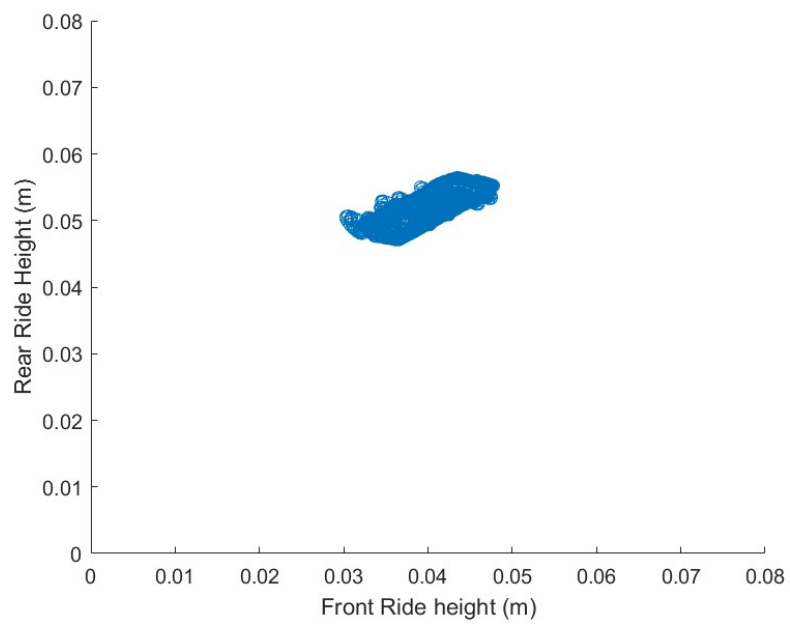


Figure 9-81: Set Up 6 - Scatter plot

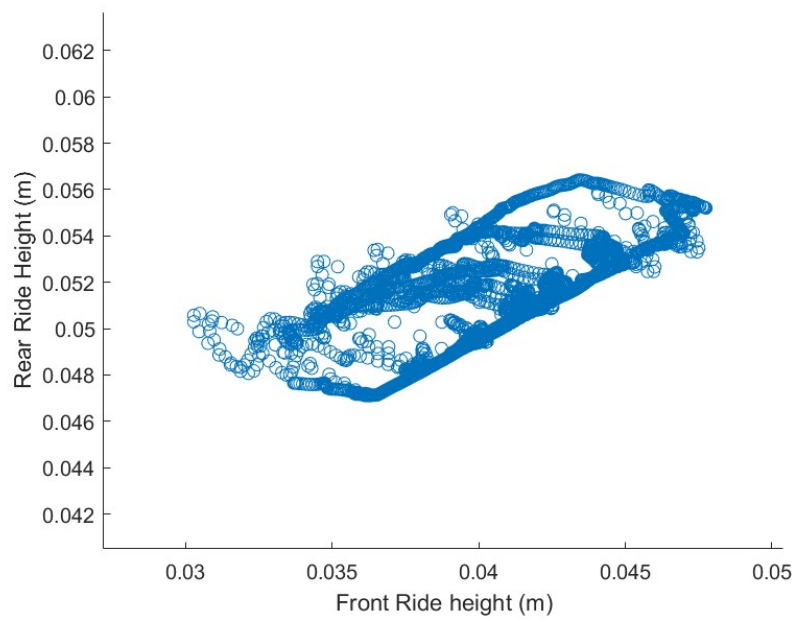


Figure 9-82: Set Up 6 - Scatter plot zoomed