

University of Wales Trinity Saint David  
Wales Institute of Science & Art



Research Proposal – Development of a VI-Grade Model of the MCR Racing  
Car for Lap Time Simulation

---

Research Methods and Professional Developments ACAFA7004



(University of Wales Trinity Saint David, 2024)

Diego Alexander Valencia Flores  
2405760  
March 3, 2025

## Contents

|       |                                                                      |    |
|-------|----------------------------------------------------------------------|----|
| 1     | Introduction .....                                                   | 4  |
| 1.1   | Historical Context .....                                             | 4  |
| 1.2   | Aims of the Research .....                                           | 6  |
| 1.3   | Expected to achieve through the research .....                       | 7  |
| 2     | Industrial Relevance .....                                           | 9  |
| 2.1   | Importance of study in the stream of Motorsport Engineering .....    | 9  |
| 3     | Literature Review.....                                               | 10 |
| 3.1   | Previous models and work/research .....                              | 10 |
| 3.1.1 | ADVISOR.....                                                         | 11 |
| 3.1.2 | RAPTOR .....                                                         | 12 |
| 3.1.3 | VESIM.....                                                           | 14 |
| 3.1.4 | P-SAT .....                                                          | 15 |
| 3.1.5 | Limitations of the models.....                                       | 17 |
| 4     | Proposed Methodology .....                                           | 19 |
| 4.1   | Data acquisition .....                                               | 19 |
| 4.1.1 | Additional Data Collection if Required.....                          | 21 |
| 4.2   | Vehicle Model Setup .....                                            | 22 |
| 4.3   | Validation .....                                                     | 22 |
| 4.4   | Performance Optimization .....                                       | 23 |
| 4.4.1 | Selection of Factors and Response Variable .....                     | 23 |
| 4.4.2 | Factor Screening using Factorial or Fractional Factorial Design..... | 24 |
| 4.4.3 | Constructing the Box Behnken Experimental Design .....               | 24 |
| 4.4.4 | Running the Simulation in VI-CarRealTime .....                       | 24 |
| 4.4.5 | Response Surface Methodology (RSM) and Statistical Analysis .....    | 25 |
| 4.4.6 | Identifying the Optimal Setup and Validation .....                   | 25 |
| 3.    | Results Collection & Analysis .....                                  | 26 |
| 4.    | Project Planning/Timescales .....                                    | 27 |
| 4.    | Evaluation.....                                                      | 28 |

|            |                                                                                                                   |    |
|------------|-------------------------------------------------------------------------------------------------------------------|----|
| 5          | Reference list.....                                                                                               | 29 |
| Figure 1   | First FEM article published in 1956 (Turner at al., 1956).....                                                    | 4  |
| Figure 2   | Lotus Driving Simulator - Technical Bulletin (1966) (Haigh, 2024).....                                            | 5  |
| Figure 3   | DiM400 Driver-in-the-loop Simulator Rig & VI-CarRealTime Simulator Software (Vi-grade.com, 2025) .....            | 5  |
| Figure 4   | Box-Behnken Design (Develve.net, 2022) .....                                                                      | 6  |
| Figure 5   | Example Response Surface and contour plots using Box-Behnken design (Habibi, Mohammadi and Kamankesh, 2017) ..... | 7  |
| Figure 6   | ADVISOR ´s series HEV block diagram ´s top level (Wipke, Cuddy and Burch, 1999).....                              | 11 |
| Figure 7   | ADVISOR 2.0 Vehicle Input Screen (Wipke et al., 1999) .....                                                       | 12 |
| Figure 8   | Engine and Vehicle Thermal Management System(Berry et al., 2002) .....                                            | 13 |
| Figure 9   | FLOWMASTER2 Thermal Management Model Showing varying levels of system detail (Berry et al., 2002) .....           | 14 |
| Figure 10  | Schematic of the integrated vehicle system (Assanis et al., 2000) .....                                           | 14 |
| Figure 11  | Vehicle system in Simulink - Vehicle Engine SIMulation (VESIM) (Assanis et al., 2000) .....                       | 15 |
| Figure 12  | PSAT single shaft parallel hybrid (Rousseau and Pasquier, 2001).....                                              | 16 |
| Figure 13  | PSAT-PRO model and real physical systems .....                                                                    | 17 |
| Figure 14  | Vehicle Model Interface VI-CarRealTime (www.vi-grade.com, 2025).....                                              | 22 |
| Table 1    | Example Table of information provided by the racing team of the race car.....                                     | 19 |
| Table 2    | Proposed Gantt.....                                                                                               | 27 |
| Equation 1 | The Response Surface Model - Second order polynomial function.....                                                | 25 |

# 1 Introduction

## 1.1 Historical Context

Vehicle simulation has evolved significantly from its early reliance on mechanical testing to advanced computational modelling. In the mid-20<sup>th</sup> century, vehicle testing primarily depended on physical prototypes and experimental methods. However, the introduction of computer-aided designs (CAD), finite element analysis (FEA) or finite element method (FEM) in the 1950s and 1970s revolutionized the field, enabling engineers to simulate car behaviour under different conditions. Knowing that the first article on FEM was published in 1956 (Turner et al., 1956).

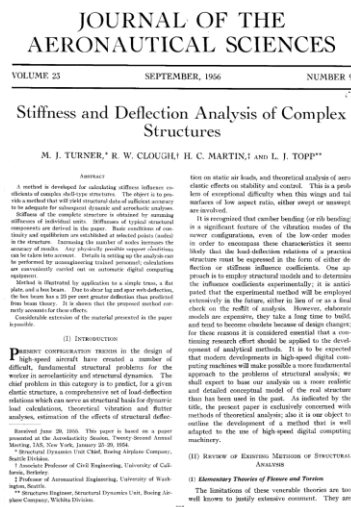


Figure 1 First FEM article published in 1956 (Turner et al., 1956)

By the 1980s and 1990s, real-time simulations and driver-in-the-loop systems became standard, enhancing the accuracy of vehicle dynamics representation. But even before they became the standard in the automotive or motorsport industry the DIL simulators for racing applications have been around for quite some time. Colin Chapman Lotus founder by 1966, already experienced the pinnacles of motor racing success, having won the Formula One world championship. Ever-eager to promote Lotus's engineering capabilities, Chapman decided to take a swing at manufacturing driving simulators and in 1965 and 1966 it was reported that around 20 of Lotus simulators were produced and sold (Haigh, 2024).

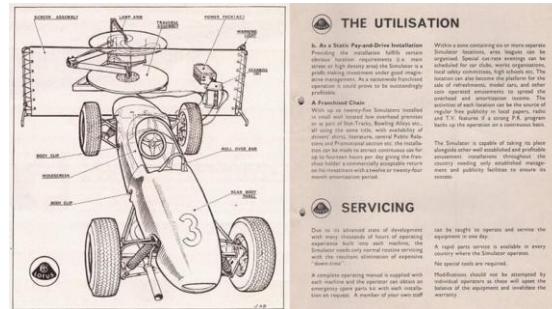


Figure 2 Lotus Driving Simulator - Technical Bulletin (1966) (Haigh, 2024)

In recent years, significant advancements have been made in driving simulators, particularly in Driver-in-the-Loop (DIL) simulation. VI-grade has been at the forefront of these developments, creating fully customizable DIL simulators, including the latest DiM400 and higher models. These simulators, part of the DiM family, integrate state-of-the-art technologies to enhance driving simulation fidelity. They retain VI-grade's signature architecture, featuring a lower stage that translates and rotates in a plane—representing chassis and tire-roadway dynamics—coupled with an upper stage equipped with a six-degree-of-freedom mechanism (Vi-grade.com, 2025).

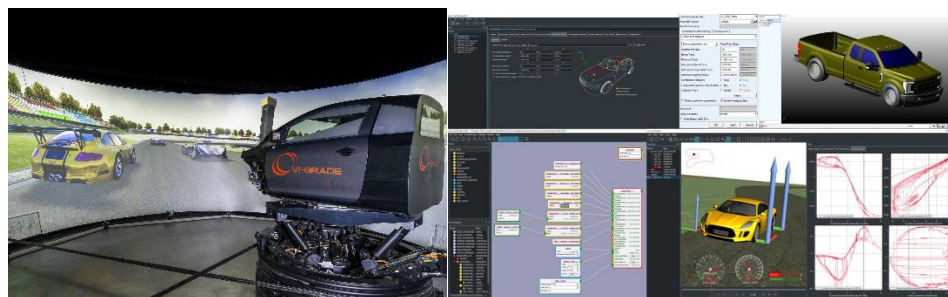


Figure 3 DiM400 Driver-in-the-loop Simulator Rig & VI-CarRealTime Simulator Software (Vi-grade.com, 2025)

Beyond hardware, VI-grade has also developed VI-CarRealTime, a real-time vehicle simulation environment that enables a streamlined development process from concept to sign-off. This software utilizes a simplified vehicle model, allowing vehicle dynamics engineers to efficiently conduct large-scale Design of Experiments (DOE) and multi-objective optimization studies. The ability to rapidly evaluate various design configurations makes VI-CarRealTime a powerful tool for accelerating vehicle development (Vi-grade.com, 2025).

## 1.2 Aims of the Research

The intended research focuses on developing a VI-Grade Driver-Out-of-the-Loop (DOL) simulation model using VI-CarRealTime to predict the kinematic and dynamic behaviour of the MCR race car model. This will be achieved by incorporating real vehicle data, including front and rear damper and spring rates, tire position, camber, toe, anti-roll bar rates, and suspension geometry.

Once the vehicle model is fully configured and accurately replicates the race car's behaviour in simulation, the next step will involve performance optimization. This will be conducted using a Design of Experiments (DOE) approach, specifically the Box-Behnken (BBD) statistical method / Response Surface Methodology (RSM) (Lamidi et al., 2022). This method will be used to analyse three key changing factors and assess their impact on the response variable—lap time—to determine the optimal vehicle setup.

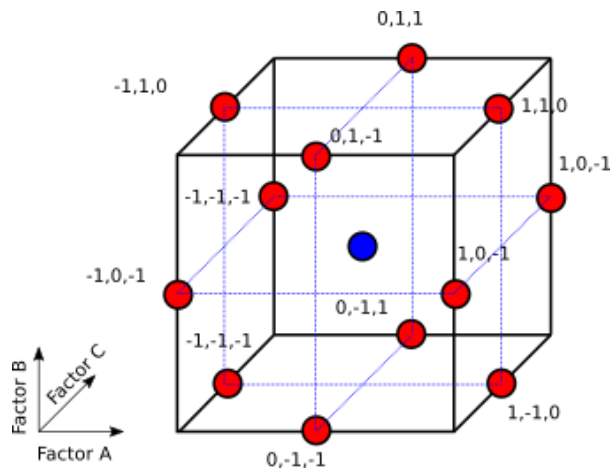


Figure 4 Box-Behnken Design (Develve.net, 2022)

The Box-Behnken DOE is a multivariable optimization tool and independent quadratic design involved in the factorial or fractional design (www.itl.nist.gov, n.d.), in which the levels of all variables are changed simultaneously. The first step of multivariable optimization is accomplished by screening the factors studied using a full factorial or fractional factorial design, to obtain the significant effects of the analytical system (Zolgharnein, Shahmoradi and Ghasemi, 2013).

After determining the significant factors, the optimum operating conditions are attained by using more complex experimental designs such as the Doehlert Matrix (DM), central composite designs (CCD), and three-level designs like the Box-Behnken Design (BBD) (Ferreira et al., 2007).

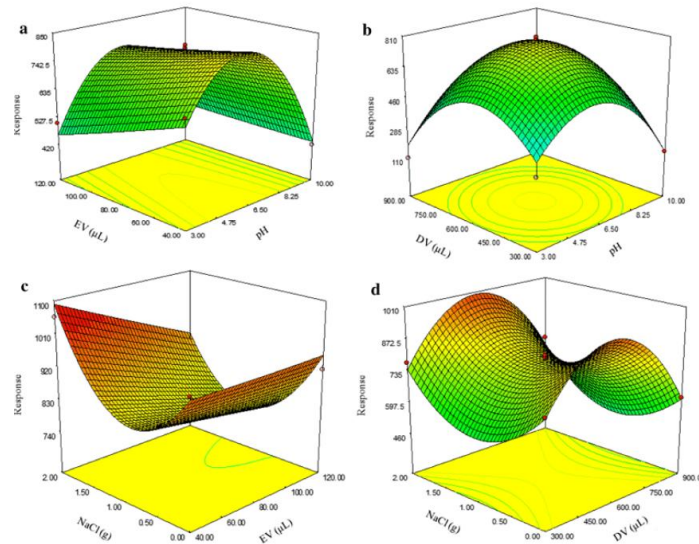


*Figure 5 Example Response Surface and contour plots using Box-Behnken design (Habibi, Mohammadi and Kamankesh, 2017)*

The Box-Behnken Design is particularly useful in response surface methodology (RSM) as it optimizes variables efficiently while reducing the number of experimental runs compared to full factorial designs, making it a widely used approach for high-accuracy optimization in engineering applications.

### 1.3 Expected to achieve through the research

The primary expected outcome of this research is to develop one or more optimized race car setups that yield the best lap time for each track tested. Initially, the research aims to establish an optimal baseline setup for a representative track from the racing season. However, with further refinement, the goal is to tailor setups for multiple tracks, allowing for improved adaptability across different circuit conditions.

Additionally, this research aims to produce a fully functional VI-Grade VI-CarRealTime simulation model of the MCR race car, capable of accurately predicting its dynamic behaviour. A successful implementation of this model will not only validate its predictive accuracy but also serve as a tool for real-time setup evaluation. If time permits, an interactive testing framework could be developed, enabling rapid setup validation at the university workstation. This would allow for on-the-fly adjustments to vehicle parameters, facilitating pre-event preparation before race weekends.

As a final step, the Design of Experiments (DOE) approach will be leveraged to refine the lap time optimization process. By analysing key variables such as suspension settings, aerodynamic balance, and tire characteristics, the research aims to determine the most influential parameters affecting lap time. The Box-Behnken statistical method will be used to quantify these effects, systematically identifying the most effective configurations. The goal is to generate data-driven, optimized setups that enhance vehicle performance across different conditions, providing a competitive advantage in real-world racing scenarios.

## 2 Industrial Relevance

### 2.1 Importance of study in the stream of Motorsport Engineering

Driver-Out-of-the-Loop (DOL) simulation has become essential in motorsport engineering, enabling faster vehicle development, performance optimization, and reduced reliance on costly track testing. The use of VI-CarRealTime in this research aligns with industry trends, where simulation-driven methodologies are now integral to professional motorsport teams.

This study demonstrates how real-time simulation, and optimization can refine vehicle dynamics before track testing. Motorsport teams across disciplines—Formula 1, endurance racing, GT series, and single-make championships—increasingly rely on lap time simulation and setup optimization to maximize performance within limited testing opportunities.

By incorporating real vehicle data into a validated simulation environment, this research enhances the industry's ability to predict and refine race car behavior, leading to more efficient development cycles. The application of Design of Experiments (DOE) for lap time optimization provides a structured approach to evaluating setup changes systematically.

Beyond this study, the findings will directly benefit MCR Racing, which competes in Sports 2000, ensuring the car operates at peak performance and efficiency throughout the season. The methodologies developed could also be adapted for broader engineering applications.

## 3 Literature Review

### 3.1 Previous models and work/research

Over the past few decades, the development of driving simulators has been a key focus in motorsport and automotive engineering, driven by the need for cost-effective testing, performance optimization, and safety improvements. As mentioned in the introduction, simulation technology has evolved significantly, moving from basic computational models to highly sophisticated Driver-in-the-Loop (DIL), Driver-Out-of-the-Loop (DOL), and Hardware-in-the-Loop (HIL) simulations (AB Dynamics, 2023).

From the early 2000s onward, private companies, coalitions of manufacturers, and governmental bodies have played a crucial role in advancing simulation technology. These efforts have resulted in the creation of standardized models, used both in research and industry, to refine vehicle dynamics, optimize performance, and accelerate development processes.

While DIL simulations focus on real-time human interaction with virtual vehicle models, DOL simulations prioritize purely computational modelling, often incorporating vast amounts of real-world vehicle data to enhance predictive accuracy. More advanced approaches, such as HIL simulations, introduce physical hardware components into the simulation loop, enabling real-world validation of control strategies, powertrain systems, and vehicle dynamics (Baglione et al., 2008).

Although this research does not explore a novel area, it builds upon a well-established foundation of simulation-based vehicle development, an area that has been significantly advanced by automotive manufacturers, motorsport teams, and governmental research bodies. These previous contributions have played a crucial role in refining vehicle dynamics simulations for both road and race car applications, providing valuable insights that will guide the methodology and implementation of this study.

### 3.1.1 ADVISOR

Throughout this evolution 5 notable simulation models have emerged as industry benchmarks, shaping the modern approach to vehicle simulation and performance analysis. One of the earliest and most significant models was Advanced Vehicle Simulator (ADVISOR) now having ADVISOR 2.1 (Wipke, Cuddy and Burch, 1999).

Developed in November 1994, ADVISOR was initially designed as an analysis tool to support the U.S. Department of Energy (DOE) in understanding Hybrid Electric Vehicle (HEV) technology. Through collaborations with major automotive manufacturers such as Ford, General Motors, and Chrysler, ADVISOR evolved into a versatile simulation platform widely used by researchers and engineers (Wipke et al., 1999).

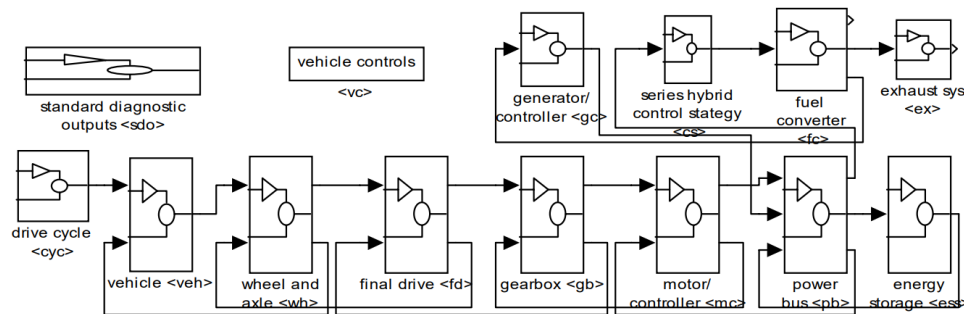


Figure 6 ADVISOR's series HEV block diagram's top level (Wipke, Cuddy and Burch, 1999)

The primary function of ADVISOR was to analyse vehicle powertrains, with a focus on power flow interactions between components. By simulating driving cycles, such as the Federal Urban Driving Schedule, the model could evaluate fuel consumption and tailpipe emissions. Additionally, ADVISOR allowed engineers to perform performance simulations, such as determining 0-60 mph acceleration times or assessing a vehicle's maximum grade-climbing capability at a given speed (Wipke et al., 1999).

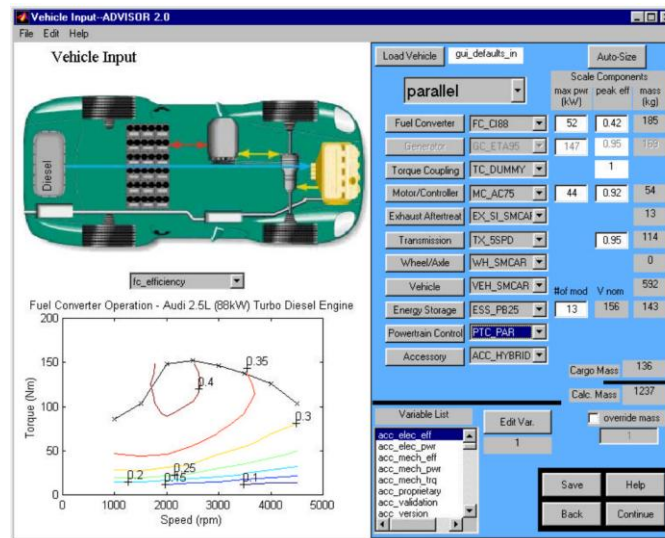


Figure 7 ADVISOR 2.0 Vehicle Input Screen (Wipke et al., 1999)

To achieve its objectives, ADVISOR relied on a discrete-step approximation of vehicle behaviour. This method treated each time step as a steady-state condition, enabling the use of efficiency maps and power usage models based on laboratory-derived steady-state tests.

However, due to its reliance on steady-state assumptions, ADVISOR had inherent limitations—it could not capture short-duration drivetrain dynamics, such as driveline vibrations or electric field oscillations. Despite these limitations, ADVISOR was a pioneering tool that laid the groundwork for more advanced real-time vehicle simulation models, including those used in motorsport applications today (Wipke et al., 1999).

### 3.1.2 RAPTOR

As the automotive industry has progressed, vehicle manufacturers have increasingly relied on simulation tools to predict vehicle performance early in the development process. A significant portion of these simulations has been developed using MATLAB/Simulink, a widely adopted modelling and simulation environment for control system design and vehicle dynamics analysis. One such tool is RAPTOR (Rapid Automotive Performance Simulator), a Toolkit for Optimization and Reporting, co-developed by Southwest Research Institute (SwRI) and DaimlerChrysler (Baglione et al., 2008).

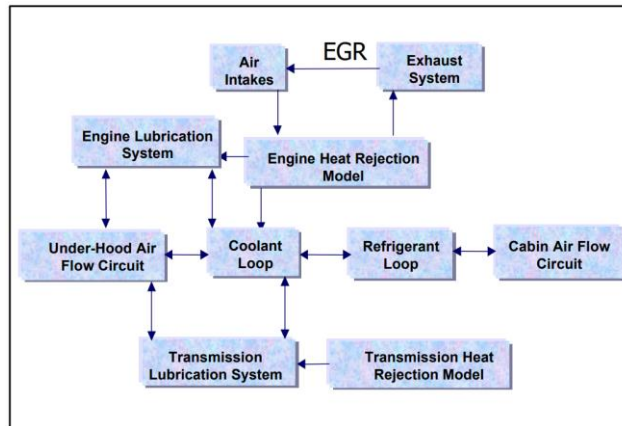


Figure 8 Engine and Vehicle Thermal Management System(Berry et al., 2002)

RAPTOR is designed to facilitate component sizing and selection, evaluate control algorithms, and predict vehicle performance and fuel economy (Berry et al., 2002). By incorporating detailed vehicle parameters, this simulation tool provides a comprehensive assessment of powertrain and drivetrain efficiency under various operating conditions.

Typical input parameters for RAPTOR include:

1. Vehicle mass
2. Frontal area
3. Engine performance maps
4. Transmission and differential losses
5. Tire rolling resistance

With this data, RAPTOR can simulate Full Load Performance metrics (Berry et al., 2002) such as:

1. Theoretical top speed
2. Acceleration performance

Additionally, the software can estimate Part Load Fuel Consumption across different driving conditions, enabling engineers to optimize fuel efficiency (Berry et al., 2002).

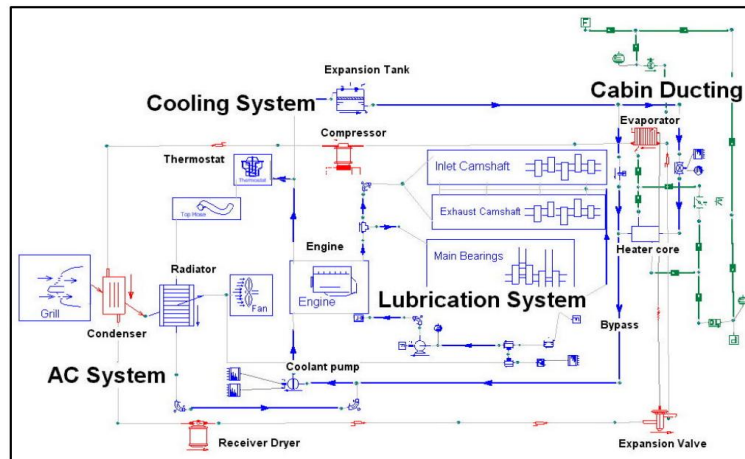


Figure 9 FLOWMASTER2 Thermal Management Model Showing varying levels of system detail (Berry et al., 2002)

By integrating detailed vehicle models with advanced optimization techniques, RAPTOR has become a valuable tool in the automotive and motorsport industries. It allows engineers to analyse, refine, and optimize vehicle designs before physical testing, ultimately reducing development costs and enhancing performance predictions.

### 3.1.3 VESIM

Since 1994, the University of Michigan, in collaboration with the University of Iowa, Wayne State University, and the University of Wisconsin at Madison, has established an Automotive Research Centre (ARC) ([arc.engin.umich.edu](http://arc.engin.umich.edu), n.d.) dedicated to the development and validation of advanced ground vehicle simulations. This initiative has led to the creation of the Vehicle Engine SIMulation (VESIM), an integrated simulation platform designed to analyse vehicle dynamics and engine performance (Assanis et al., 2000).

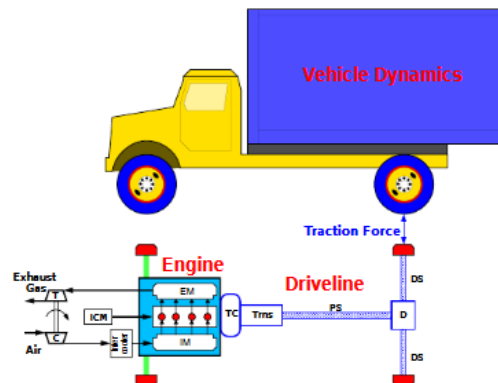


Figure 10 Schematic of the integrated vehicle system (Assanis et al., 2000)

The VESIM vehicle model consists of two main components that describe the dynamic behaviour of the vehicle in both longitudinal and heave directions. The core simulation modules—including the cylinder, transmission, and vehicle dynamics—are programmed using FORTRAN and C. These modules are then converted into MEX file format, enabling their integration into SIMULINK as a functional simulation module (Assanis et al., 2000).

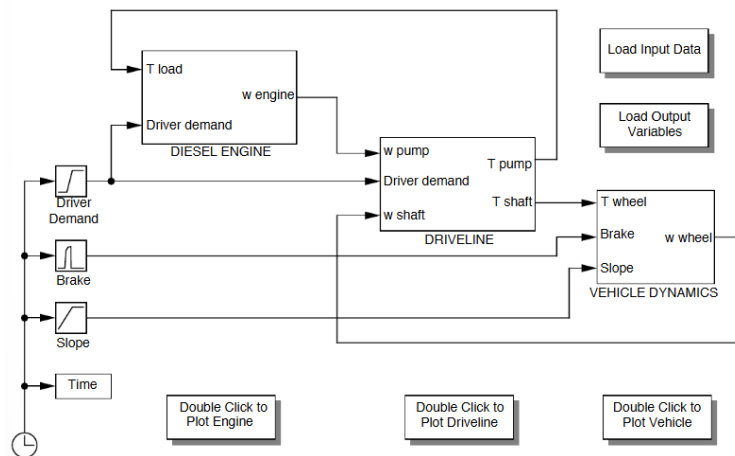


Figure 11 Vehicle system in Simulink - Vehicle Engine SIMulation (VESIM) (Assanis et al., 2000)

The SIMULINK solver package is responsible for the simultaneous integration of all vehicle modules, allowing for a comprehensive and dynamic simulation environment. This fully integrated approach enables researchers to analyse vehicle performance under various operating conditions, making VESIM a valuable tool for the study of ground vehicle dynamics, engine behaviour, and powertrain optimization (Assanis et al., 2000).

### 3.1.4 P-SAT

PSAT is a powerful modelling tool that allows users to realistically evaluate not only fuel consumption but also vehicle performance. One of its most important characteristics is that it operates under real-world conditions, using real command-based inputs from the driver, making it a Driver-in-the-Loop (DIL) simulation. PSAT is developed in MATLAB/Simulink/Stateflow (Rousseau et al., 2006), providing a flexible and scalable simulation environment.

The software supports the simulation of a wide range of vehicle applications, including two-wheel drive, four-wheel drive, and heavy-duty vehicles (Rousseau et al., 2006). It features multiple-option component model libraries, allowing users to select the appropriate level of modelling based on the specific requirements of a simulation. This modular approach enables researchers and engineers to customize simulations for various powertrain architectures and driving conditions.

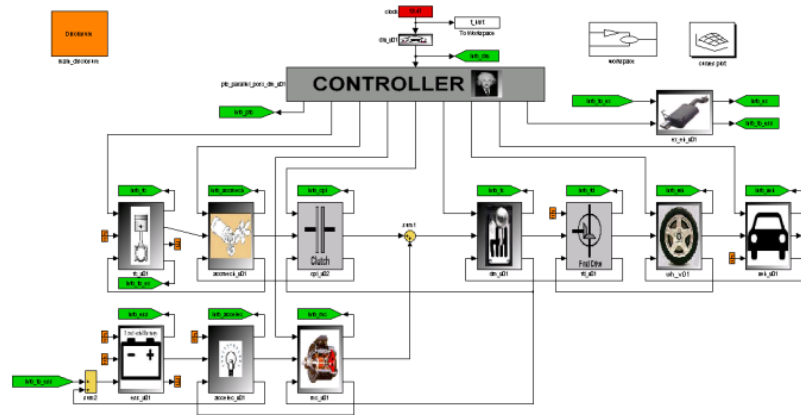


Figure 12 PSAT single shaft parallel hybrid (Rousseau and Pasquier, 2001)

Numerous studies have utilized PSAT to support U.S. Department of Energy (DOE) research activities, contributing to advancements in powertrain optimization and fuel (Rousseau et al., 2006). Additionally, PSAT has been extensively validated using production and prototype test data from Argonne National Laboratory's (ANL) Advanced Powertrain Research Facility (APRF). Its extension, PSAT-PRO, has further enabled Rapid Control Prototyping, providing an efficient framework for testing and refining powertrain control strategies (Rousseau and Pasquier, 2001).

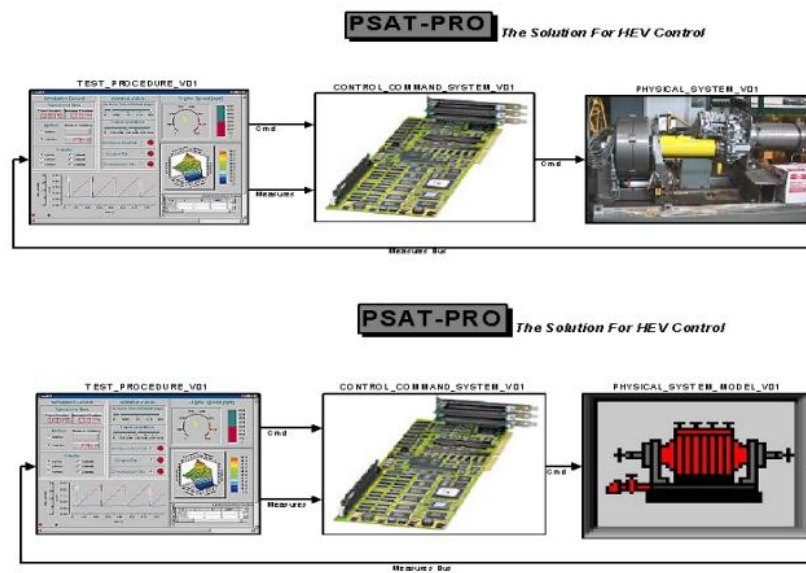


Figure 13 PSAT-PRO model and real physical systems

By incorporating realistic driver inputs and validated powertrain models, PSAT serves as a valuable tool for powertrain development, optimization, and validation, supporting the transition toward more efficient and sustainable vehicle technologies.

### 3.1.5 Limitations of the models

The simulation models reviewed in this section serve as references, all incorporating Driver-Out-of-the-Loop (DOL) aspects. However, a key difference is their reliance on MATLAB/Simulink environments, which provide a flexible computational framework for defining and calculating custom response variables through mathematical manipulation.

In contrast, VI-CarRealTime offers a comprehensive range of predefined parameters but lacks the flexibility to create new variables or custom equations. Its closed-environment structure limits modifications to adjustments within existing parameters, restricting the ability to implement custom control strategies or alternative vehicle dynamics models. Unlike MATLAB/Simulink, where equations can be freely adjusted, VI-CarRealTime constrains modeling to its predefined framework.

However, this limitation is balanced by efficient post-processing, where all required outputs are available in proper units, minimizing additional data manipulation. Despite reduced modeling flexibility, VI-CarRealTime remains a validated tool in motorsport, offering a structured and efficient approach to setup optimization and performance testing, making it well-suited for applications where quick and reliable simulation results are prioritized.

## 4 Proposed Methodology

This section outlines the methodological approach that will be used to develop and validate a Driver-Out-of-the-Loop (DOL) simulation model using VI-CarRealTime. The methodology will follow a structured proceed that includes data acquisition, vehicle model setup, validation, and performance optimization.

### 4.1 Data acquisition

The accuracy of the simulation model relies heavily on the quality and completeness of the input data. This research as mentioned above will use real-world-vehicle data from the MCR race car to ensure that the VI-CarRealTime model accurately replicates the car's physical behaviour. This data will be given by the team in their own format which the task in hand will be accurately inputting and adjusting the data in the model later. For further understanding the data provided by the racing team is as follows.

Table 1 Example Table of information provided by the racing team of the race car

| MATLAB variable:        | Description:                            | Value:      | Unit:          |
|-------------------------|-----------------------------------------|-------------|----------------|
| <b>INPUTS</b>           |                                         |             |                |
| <b>INPUTS:</b>          |                                         |             |                |
| Ax                      | Longitudinal Acceleration               | 0.280       | G              |
| Ay                      | Lateral Acceleration                    | 1.240       | G              |
| v                       | Speed                                   | 30.000      | m/s            |
| <b>CONSTANTS</b>        |                                         |             |                |
| <b>GEOMETRY:</b>        |                                         |             |                |
| TrackF                  | Front Track                             | 1.500       | m              |
| TrackR                  | Rear Track                              | 1.475       | m              |
| WheelB                  | Wheelbase                               | 2.600       | m              |
| <b>MASSES:</b>          |                                         |             |                |
| FL_M                    | FL Corner Mass                          | 148.000     | kg             |
| FR_M                    | FR Corner Mass                          | 124.000     | kg             |
| RL_M                    | RL Corner Mass                          | 197.000     | kg             |
| RR_M                    | RR Corner Mass                          | 215.000     | kg             |
| MsF                     | Front Sprung Mass                       | 228.367     | kg             |
| MsR                     | Rear Sprung Mass                        | 358.367     | kg             |
| MusF                    | Front Unsprung Mass                     | 43.033      | kg             |
| MusR                    | Rear Unsprung Mass                      | 53.033      | kg             |
| <b>WHEELS:</b>          |                                         |             |                |
| RR                      | Tyre Rolling Radius                     | 0.265       | m              |
| Wh                      | Wheel Centre Height                     | 0.265       | m              |
| <b>SUSPENSION DATA:</b> |                                         |             |                |
| hF                      | Front Roll Centre Height                | 0.012       | m              |
| hR                      | Rear Roll Centre Height                 | 0.070       | m              |
| h_Increase_F            | Roll Centre Height Increase Coeff Front | 1.231       | -              |
| h_Increase_R            | Roll Centre Height Increase Coeff Rear  | 1.182       | -              |
| H                       | CoG Height above Roll Centre            | 0.350       | m              |
| H_plus_h                | CoG Height                              | 0.300       | m              |
| <b>SPRING RATES:</b>    |                                         |             |                |
| KsF                     | Spring Rate Front                       | 39053.28421 | N/m            |
| KsR                     | Spring Rate Rear                        | 67538.95831 | N/m            |
| MR_F                    | Motion Ratio Front                      | 0.883       | -              |
| MR_R                    | Motion Ratio Rear                       | 0.924       | -              |
| KwARBF                  | Front ARB Rate                          | 63000.000   | N/m            |
| KwARBR                  | Rear ARB Rate                           | 53000.000   | N/m            |
| <b>Bump_Knee_Point</b>  |                                         |             |                |
| Bump_Knee_Point         | Bump Knee Point                         | 37.75       | mm/s           |
| Rebound_Knee_Point      | Rebound Knee Point                      | -37.75      | mm/s           |
| <b>AERO DATA:</b>       |                                         |             |                |
| CiF                     | Front Coefficient of Lift               | 0.400       | -              |
| CiR                     | Rear Coefficient of Lift                | 0.400       | -              |
| Area                    | Frontal Area                            | 1.317       | m <sup>2</sup> |

This format is well structured as well as it includes track test results or manufacturers specifications which are key vehicle parameters.

The main data categories which can be gathered include:

- **Suspension Geometry:** Determines how the vehicle responds to cornering forces and affects handling characteristics.
  - Camber
  - Toe
  - Caster
  - Anti-roll Bar Stiffness
  - Roll Centres
  - Instantaneous Centres
- **Spring & Damper Characteristics:** Influences the car's ability to absorb road irregularities and maintain stability under high-speed cornering and braking conditions.
  - Spring Stiffness (rates)
  - Damper Compression/Rebound Settings
  - Bump Stops
- **Vehicle Mass and Weight Distribution:** These affects load transfer, braking efficiency and overall dynamic response.
  - Total Weight
  - Front-to-Rear Weight Distribution
  - Centre of Gravity Height
  - Corner Weight
- **Tire Parameters:** Crucial information for understanding how the car interacts with the track surface.
  - Tire Grip Levels
  - Slip Angles
  - Pressure Sensitivity (if known)
  - Temperature-dependent behaviour (if known)
  - Wear Characteristics (if known)
- **Powertrain Characteristics:** Crucial parameters which can give top speed and power delivery characteristics.
  - Engine Power
  - Torque Curves
  - Transmission Gear Ratios

- Differential Settings
  - Throttle Response Mapping
- Aerodynamic Properties: Playing a critical role in achieving high-speed stability and cornering performance.
  - Drag Coefficients
  - Downforce Levels
  - Centre of Pressure Position (if known)
  - Impact of Adjustable Aero Components (e.g., Wings, Diffusers, Underbody Elements (if any and if known))

All this data will be processed and formatted to match the input structure required by VI-CarRealTime, ensuring proper integration into the simulation model.

#### 4.1.1 Additional Data Collection if Required

Given the circumstances of this research, there is a possibility that some necessary vehicle data may not be readily available. If critical parameters are missing or incomplete, additional on-track or workshop testing may be conducted as needed to supplement the dataset. This would involve installing new sensors or strain gauges on the MCR race car to measure key dynamic properties such as suspension loads, aerodynamic forces, and tire temperatures, particularly if their inclusion is found to enhance the correlation between the simulation model and the real car.

The decision to conduct additional data collection will be based on the performance of the initial VI-CarRealTime model. If the model indicates significant gaps in the available data, targeted testing sessions will be conducted to address these deficiencies. This ensures that the simulation remains as accurate as possible, refining the model only when necessary to capture key response factors that cannot be effectively replicated using the existing dataset.

## 4.2 Vehicle Model Setup

Once the necessary data is acquired, the MCR Race Car model will be constructed within VI-CarRealTime by configuring its existing predefined simulation parameters to match real vehicle's specifications. Unlike MATLAB/Simulink-based models, where new mathematical relationships can be defined, VI-CarRealTime requires all vehicle properties to fit within its existing framework of parameters. This means that the focus will be on accurately inputting and adjusting the available variables e.g., suspension, tire, aerodynamic, and drivetrain parameters rather than developing new variables or equations. Also, the aim is to be able to predict the race car behaviour and be as close as possible to the real values.

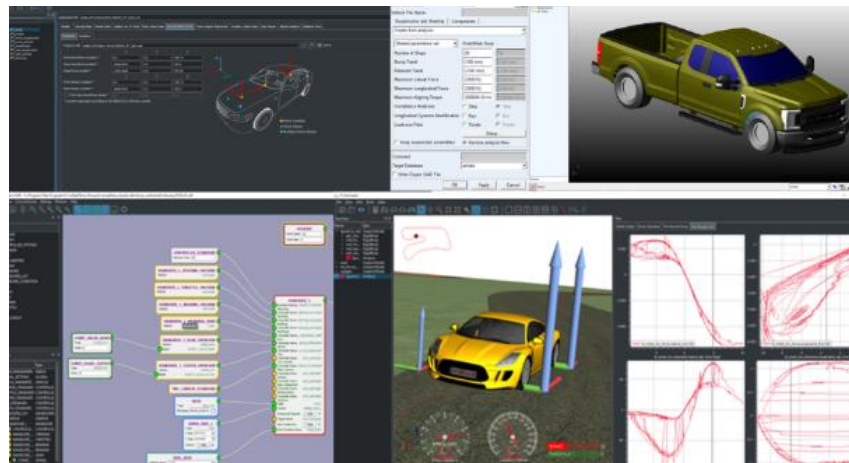


Figure 14 Vehicle Model Interface VI-CarRealTime ([www.vi-grade.com](http://www.vi-grade.com), 2025)

## 4.3 Validation

To ensure the accuracy and reliability of the simulation, the VI-CarRealTime model will be compared against real-world telemetry data collected from the MCR Race Car during track testing. The validation process will compare simulated outputs with actual performance metrics to confirm that the simulation reflects real-world conditions as closely as possible.

The validation process will involve:

- Lap Time Comparison – Simulated lap times will be compared to actual race data to assess overall performance accuracy
- Cornering Speeds and Lateral G-Forces – The model's turning performance will be verified by matching real-world g-force reading with the simulated data

- Acceleration and Braking Profiles – Simulated 0-100 km/h times, braking distances, and longitudinal acceleration curves will be matched against real-world data to ensure powertrain and braking system accuracy
- Suspension and Load Transfer Analysis – Vertical load distribution and roll stiffness effects will be evaluated to confirm that the suspension and weight transfer behaviour aligns with real-world dynamics.

## 4.4 Performance Optimization

Once the VI-CarRealTime model is validated, the next step is to optimize the race car setup to achieve the lowest lap time using a Design of Experiments (DOE) methodology, specifically the Box-Behnken Design (BBD). The BBD is a multivariable optimization tool and an independent quadratic design that allows for the simultaneous variation of multiple factors to analyse their effects on a chosen response variable—in this case, lap time.

This statistical approach is particularly useful within Response Surface Methodology (RSM) as it efficiently optimizes multiple variables while minimizing the number of experimental runs required compared to full factorial designs. Given the constraints of VI-CarRealTime, which only allows for predefined parameter adjustments, BBD provides an effective framework to systematically test and optimize the most influential setup parameters.

The approach taken in this research is similar to that of Aslan and Cebeci (2007), who applied the Box-Behnken experimental design and RSM for modelling the grindability of coal. Their study involved three independent variables (Bond work index, grinding time, and ball diameter) and used BBD to establish functional relationships between these factors and the response variable (d80, the particle size at which 80% of the material passes through a sieve). Their findings demonstrated that the BBD method provides statistically reliable models and efficiently predicts optimal conditions with minimal experimental runs (Aslan and Cebeci, 2007).

### 4.4.1 Selection of Factors and Response Variable

The first step is defining the independent variable (factors) that will be adjusted and the response variable that will be measured:

- Independent Variables (factors): Three key setup parameters will be selected based on their influence on vehicle performance. These may include:

- Spring and damper stiffness (affecting weight transfer and handling balance)
- Tire camber settings (impacting grip and cornering efficiency)
- Aerodynamic balance (modifying the front-to-rear downforce ratio)
- Response Variable: The primary metric to be optimized is lap time, as it directly determines performance improvements.

#### 4.4.2 Factor Screening using Factorial or Fractional Factorial Design

Before applying the Box Behnken Design, a factor screening step will be performed using either a full factorial or fractional factorial design. To prevent unnecessary computational effort on factors that have minimal impact.

1. Identify the most significant setup parameters influencing lap time
2. Eliminate non-influential factors that may not contribute significantly to performance improvement
3. Reduce the complexity of the optimization process, ensuring the only key variables are included in the final DOE

#### 4.4.3 Constructing the Box Behnken Experimental Design

After determining the significant factors, a Box-Behnken experimental design will be constructed. The BBD is a three-level design that systematically evaluates interactions between the selected setup parameters while reducing the number of required simulations.

- Each factor is tested at three levels: low (-1), medium (0), and high (+1)
- The experiment consists of a predetermined number of simulations, ensuring that data collection is structured and statistically valid

#### 4.4.4 Running the Simulation in VI-CarRealTime

Once the test matrix is defined, each selected setup configuration will be simulated in VI-CarRealTime to measure its effect on lap time.

- The car will be virtually driven through the selected track layout under identical conditions (same weather, track surface, and fuel load).

#### 4.4.5 Response Surface Methodology (RSM) and Statistical Analysis

The recorded data will be analysed using Response Surface Methodology (RSM) to:

1. Fit a quadratic regression model to describe how lap time responds to changes in the selected factors
2. Identify interaction effects between variables
3. Determine the optimal setup configuration that minimizes lap time while maintaining vehicle stability and performance balance

As demonstrated in previous studies, the response surface model will be expressed as a second-order polynomial function, incorporating linear, quadratic, and interaction effects to capture the complexity of the system being optimized.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} x_i x_j + \varepsilon$$

*Equation 1 The Response Surface Model - Second order polynomial function*

Where **y** presents the lap time,  $x_i$  are the independent variables (setup parameters), and **b** coefficients are determined using statistical regression (Aslan and Cebeci, 2007). This mathematical model will allow for the visualization of response surfaces (3D plots) showing the effects front and rear spring rates as well as Anti Roll Bar.

#### 4.4.6 Identifying the Optimal Setup and Validation

Once the optimal configuration is determined from the RSM analysis, this setup will be re-tested in VI-CarRealTime to validate the results

- The optimized parameters will be applied to the race car simulation, and a final lap time comparison will be made to ensure that expected improvements are realized
- If discrepancies exist, adjustments will be made, and additional fine-tuning maybe required

### 3. Results Collection & Analysis

The primary data expected to be collected in this research will be quantitative and will originate from the VI-CarRealTime simulations of the MCR race car. The collected data will include lap times, cornering speeds, longitudinal and lateral accelerations, suspension travel, aerodynamic loads, and tire forces for each tested setup configuration. This data will be structured in numerical tables and graphical outputs, allowing for direct comparison across different simulation runs.

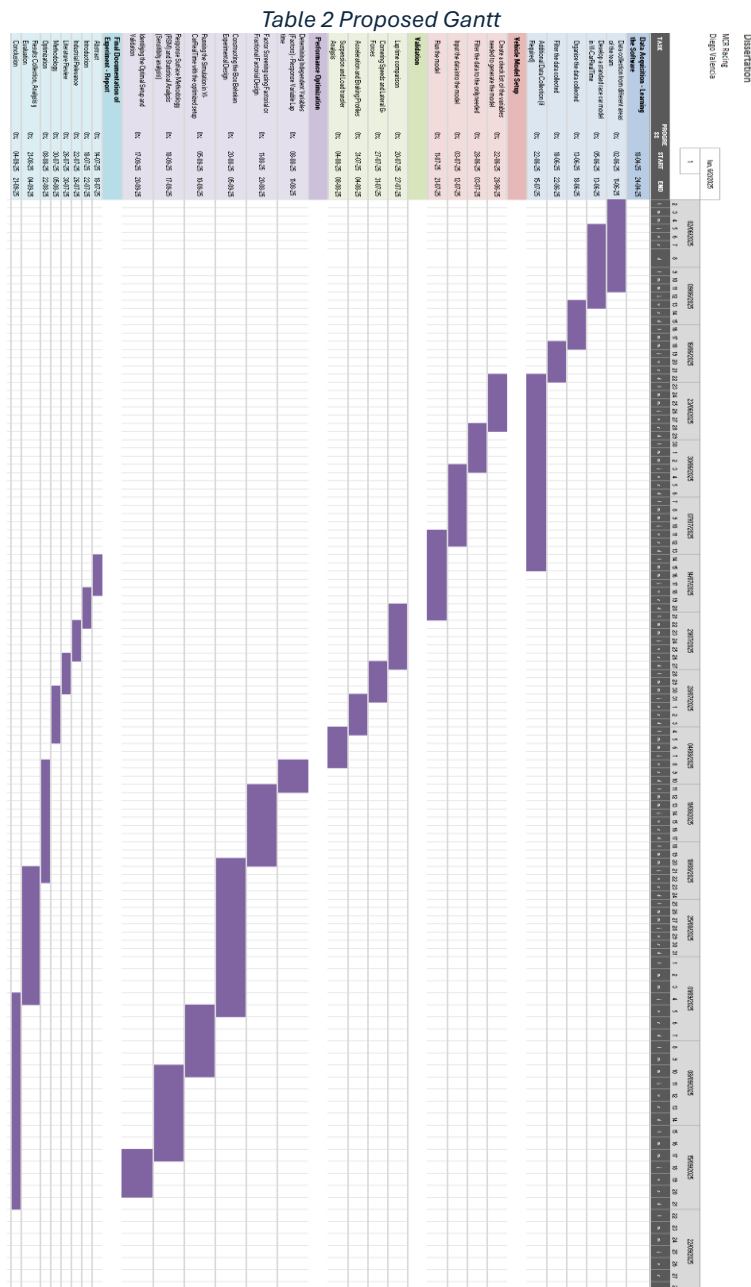
Since the data is generated within a predefined simulation environment, minimal additional processing will be required; however, it may need to be formatted for statistical analysis in MATLAB or Excel to facilitate response surface modelling and Design of Experiments (DOE) validation.

The primary metrics for assessing this data will be lap time improvements, consistency in vehicle handling, braking efficiency, and aerodynamic balance. The DOE approach will allow for statistical correlation between setup parameters and their effect on lap time, helping to determine the optimal setup within the tested parameter space. Potential challenges in data collection or analysis may arise from simulation constraints in VI-CarRealTime, such as limited customization options for certain vehicle behaviours.

Additionally, if the simulation results do not align with real-world expectations, adjustments to input parameters or additional validation through external datasets may be required. Ensuring the simulation model's accuracy will be crucial to drawing meaningful and reliable conclusions from the collected data.

## 4. Project Planning/Timescales

The project is structured into key phases and organized in a Gantt Chart (Kumar, 2005): Data Acquisition (June-July 2025), Vehicle Model Setup (July 2025), Validation (July-August 2025), and Performance Optimization using DOE (August-September 2025). The final report will be compiled in September 2025, ensuring a structured approach to simulation, analysis, and optimization of the MCR race car.



## 4. Evaluation

This research aims to develop a Driver-Out-of-the-Loop (DOL) simulation model using VI-CarRealTime to optimize the MCR race car setup. By implementing a Box-Behnken DOE approach, the study will provide data-driven insights into how Front Spring Rates, Rear Spring Rates, and Front Anti-Roll Bar affect lap times. Given its structured methodology and reliance on validated simulation techniques, this research is expected to contribute valuable knowledge to motorsport engineering, particularly in simulation-driven setup optimization.

The chosen methods are designed to generate high-quality quantitative data, including lap times, cornering speeds, and aerodynamic loads, ensuring accurate performance evaluation. The Box-Behnken DOE methodology allows for an efficient and statistically validated approach to optimizing vehicle setups while minimizing unnecessary simulations. However, the complexity of the Box-Behnken model poses a challenge, as it requires careful selection of input parameters and meticulous data interpretation to ensure reliable results. Additionally, VI-CarRealTime's predefined parameters limit full customization, meaning that adjustments beyond its framework cannot be introduced. To mitigate this, iterative parameter tuning and model validation will be conducted, ensuring the simulation accurately reflects real-world conditions. If necessary, additional data collection using on-track testing may be performed to enhance model accuracy.

Despite these limitations, this research has been carefully planned to maximize its success and impact within motorsport simulation and performance engineering. The findings will contribute directly to the race team, offering a structured approach to setup optimization that can be applied before race weekends, helping to refine suspension and aerodynamic configurations without excessive track testing. By integrating real-world data, validated simulation techniques, and statistical optimization, the study will provide meaningful, applicable results. If successful, this research will serve as a valuable reference for race teams and engineers, demonstrating how simulation-based optimization can enhance vehicle performance, reduce testing costs, and improve race preparation efficiency.

## 5 Reference list

1. Algal Research (2021). *Box-Behnken Design - an overview* | *ScienceDirect Topics*. [online] [www.sciencedirect.com](http://www.sciencedirect.com). Available at: <https://www.sciencedirect.com/topics/engineering/box-behnken-design> [Accessed 27 Feb. 2025].
2. An, F. and Rousseau, A. (2001). Integration of a Modal Energy and Emissions Model into a PNGV Vehicle Simulation Model, PSAT. *SAE Technical Papers*. [online] doi:<https://doi.org/10.4271/2001-01-0954>.
3. appeal.admin (2023). *XiL testing: The end of prototype vehicle testing?* | *AB Dynamics*. [online] AB Dynamics. Available at: <https://www.abdynamics.com/xil-testing-the-end-of-prototype-vehicle-testing/> [Accessed 27 Feb. 2025].
4. arc.engin.umich.edu. (n.d.). *Automotive Research Center*. [online] Available at: <https://arc.engin.umich.edu/> [Accessed 27 Feb. 2025].
5. Aslan, N. and Cebeci, Y. (2007). Application of Box–Behnken design and response surface methodology for modeling of some Turkish coals. *Fuel*, [online] 86(1-2), pp.90–97. doi:<https://doi.org/10.1016/j.fuel.2006.06.010>.
6. Assanis, D.N., Filipi, Z., Gravante, S., Grohnke, D., Gui, X., Louca, L.S., Rideout, G., Stein, J.L. and Wang, Y. (2000). Validation and Use of SIMULINK Integrated, High Fidelity, Engine-In-Vehicle Simulation of the International Class VI Truck. *SAE Technical Papers*. doi:<https://doi.org/10.4271/2000-01-0288>.
7. Baglione, M., Duty, M., Ni, J. and Assanis, D. (2008). REVERSE DYNAMIC OPTIMIZATION METHODOLOGY FOR MAXIMIZING POWERTRAIN SYSTEM EFFICIENCY. *IFAC Proceedings Volumes*, [online] 40(10), pp.17–24. doi:<https://doi.org/10.3182/20070820-3-US-2918.00005>.
8. Berry, A., Blissett, M., Steiber, J., Tobin, A.T. and Mcbroom, S.T. (2002). A New Approach to Improving Fuel Economy and Performance Prediction through Coupled Thermal Systems

- Simulation. *SAE technical papers on CD-ROM/SAE technical paper series*. [online] doi:<https://doi.org/10.4271/2002-01-1208>.
9. Chris Mack (2016). *Lecture71 (Data2Decision) Response Surface Modeling*. [online] YouTube. Available at: <https://www.youtube.com/watch?v=3PW5YTRtt7w> [Accessed 2 Mar. 2025].
  10. Develve.net. (2022). *Box-Behnken design*. [online] Available at: <https://develve.net/Box-Behnken%20design.html> [Accessed 27 Feb. 2025].
  11. Dias, C., Landre, J., Freire, L., Cotta, H.M. and Oliveira, M.G. (2024). Braking system analysis with the aid of a dynamic vehicle simulator with nine degrees of freedom. *Australian Journal of Mechanical Engineering*, pp.1–10. doi:<https://doi.org/10.1080/14484846.2024.2338318>.
  12. Electrical Engineering Education (2022). *Step by Step Modelling of Car Suspension System | Modelling Depths Explained | Machine Dynamics*. [online] YouTube. Available at: <https://www.youtube.com/watch?v=7PHNGSQZ8Zg> [Accessed 12 Feb. 2025].
  13. Ferreira, S.L.C., Bruns, R.E., Ferreira, H.S., Matos, G.D., David, J.M., Brandão, G.C., da Silva, E.G.P., Portugal, L.A., dos Reis, P.S., Souza, A.S. and dos Santos, W.N.L. (2007). Box-Behnken design: An alternative for the optimization of analytical methods. *Analytica Chimica Acta*, [online] 597(2), pp.179–186. doi:<https://doi.org/10.1016/j.aca.2007.07.011>.
  14. Frings, A. and Ewbank, D. (2022). Optimizing the Vehicle Development Process by Combining Driving Simulators and Virtual Test Driving. *Proceedings*, pp.61–72. doi:[https://doi.org/10.1007/978-3-662-64550-5\\_4](https://doi.org/10.1007/978-3-662-64550-5_4).
  15. Garje Mohankumar, Anup and Sawanth, Sai Kishan (2022). *Driver subjective feedback study during crosswind gusts on driving simulator for high speed straight line driving*. [online] Chalmers.se. Available at: <https://odr.chalmers.se/items/657eb1fe-6542-4d23-9370-117e037e395b> [Accessed 12 Feb. 2025].
  16. Genta, G. and Genta, A. (2016). *Road Vehicle Dynamics: Fundamentals Of Modeling And Simulation*. [online] Google Books. Available at:

- [https://books.google.co.uk/books?hl=en&lr=&id=U-uxDgAAQBAJ&oi=fnd&pg=PR7&dq=vehicle+simulations+history&ots=QFkyY67uZp&sig=Ef0ftstCiTrjexlRTxgKd2l7dso&redir\\_esc=y#v=onepage&q=vehicle%20simulations%20history&f=false](https://books.google.co.uk/books?hl=en&lr=&id=U-uxDgAAQBAJ&oi=fnd&pg=PR7&dq=vehicle+simulations+history&ots=QFkyY67uZp&sig=Ef0ftstCiTrjexlRTxgKd2l7dso&redir_esc=y#v=onepage&q=vehicle%20simulations%20history&f=false) [Accessed 27 Feb. 2025].
17. Habibi, H., Mohammadi, A. and Kamankesh, M. (2017). Hydroxymethylfurfural in fruit puree and juice: preconcentration and determination using microextraction method coupled with high-performance liquid chromatography and optimization by Box–Behnken design. *Journal of Food Measurement and Characterization*, [online] 12(1), pp.191–199. doi:<https://doi.org/10.1007/s11694-017-9630-2>.
  18. Haigh, I. (2024). *A Brief History of Motorsport Driving Simulators*. [online] Ansiblemotion.com. Available at: <https://www.ansiblemotion.com/automotive-driver-in-the-loop-simulation-articles/a-brief-history-of-motorsport-driving-simulators> [Accessed 26 Feb. 2025].
  19. Konrad Technologies (2022). *Driver-in-the-loop (DIL) with Sensor Fusion Test from VI Grade and Konrad Technologies*. [online] YouTube. Available at: <https://www.youtube.com/watch?v=wk5dvNShyJo> [Accessed 12 Feb. 2025].
  20. Kumar, P. (2005). *Effective Use of Gantt Chart for Managing Large - ProQuest*. [online] www.proquest.com. Available at: <https://www.proquest.com/docview/220442584?pq-origsite=gscholar&fromopenview=true&sourcetype=Scholarly%20Journals> [Accessed 2 Mar. 2025].
  21. Lamidi, S., Olaleye, N., Bankole, Y., Obalola, A., Aribike, E. and Adigun, I. (2022). *Applications of Response Surface Methodology (RSM) in Product Design, Development, and Process Optimization*. [online] www.intechopen.com. Available at: <https://www.intechopen.com/chapters/83621> [Accessed 27 Feb. 2025].
  22. Lin, C.-C., Filipi, Z., Wang, Y., Louca, L., Peng, H., Assanis, D. and Stein, J. (2001). Integrated, Feed-Forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies . *Automotive Research Center*. [online] Available at: [https://www.researchgate.net/profile/Loucas\\_Louca/publication/2514663\\_Integrated\\_Feed-](https://www.researchgate.net/profile/Loucas_Louca/publication/2514663_Integrated_Feed-)

- Forward\_Hybrid\_Electric\_Vehicle\_Simulation\_in\_SIMULINK\_and\_its\_Use\_for\_Power\_Management\_Studies/links/0deec523063d683886000000/Integrated-Feed-Forward-Hybrid-Electric-Vehicle-Simulation-in-SIMULINK-and-its-Use-for-Power-Management-Studies.pdf?\_sg%5B0%5D=started\_experiment\_milestone&origin=journalDetail&\_rtd=e30%3D [Accessed 27 Feb. 2025].
23. Mack, C. (2018). *Online Statistics Course Materials*. [online] Lithoguru.com. Available at: <https://www.lithoguru.com/scientist/statistics/course.html> [Accessed 2 Mar. 2025].
  24. Marcel Butschle (2023). *Factorial vs fractional vs response surface designs | when to use what?* [online] YouTube. Available at: <https://www.youtube.com/watch?v=78B2KmJ6OvY> [Accessed 2 Mar. 2025].
  25. Markel, T., Brooker, A., Hendricks, T., Johnson, V., Kelly, K., Kramer, B., O’Keefe, M., Sprik, S. and Wipke, K. (2002). ADVISOR: a systems analysis tool for advanced vehicle modeling. *Journal of Power Sources*, 110(2), pp.255–266. doi:[https://doi.org/10.1016/s0378-7753\(02\)00189-1](https://doi.org/10.1016/s0378-7753(02)00189-1).
  26. Maylor, H. (2019). Beyond the Gantt Chart: Project Management Moving On. *European Management Journal*, [online] 19(1), pp.92–100. doi:[https://doi.org/10.1016/s0263-2373\(00\)00074-8](https://doi.org/10.1016/s0263-2373(00)00074-8).
  27. Newman, M. (2023). *Speed Up Your Development With Raptor and CarSim’s Integration*. [online] New Eagle. Available at: <https://neweagle.net/blog/speed-up-your-ev-development-with-raptor-and-carsims-cutting-edge-integration/> [Accessed 27 Feb. 2025].
  28. Nikolett Szpisják-Gulyás, Al-Tayawi, A.N., Z. Horváth, Zs. László, Szabolcs Kertész and Cecília Hodúr (2023). Methods for experimental design, central composite design and the Box–Behnken design, to optimise operational parameters: A review. *Acta Alimentaria*, 52(4), pp.521–537. doi:<https://doi.org/10.1556/066.2023.00235>.
  29. Paul Allen (2020). *Response Surface Methodology*. [online] YouTube. Available at: <https://www.youtube.com/watch?v=LBVPxeqirPE> [Accessed 2 Mar. 2025].

30. Pettersson, P., Jacobson, B., Bruzelius, F., Johannesson, P. and Fast, L. (2020). Intrinsic differences between backward and forward vehicle simulation models. *IFAC-PapersOnLine*, [online] 53(2), pp.14292–14299.  
doi:<https://doi.org/10.1016/j.ifacol.2020.12.1368>.
31. Rousseau, A., Jun Soo Kwon, Sharer, P., Sylvain Pagerit and M. Duoba (2006). Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT. doi:<https://doi.org/10.4271/2006-01-0667>.
32. Rousseau, A. and Pasquier, M. (2001). Validation of a Hybrid Modeling Software (PSAT) Using Its Extension for Prototyping (PSAT-PRO) . *Global Powertrain Congress*. [online] Available at:  
<https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=8216fcf030f50def6e21ef5f8b603e2421f31ffa> [Accessed 28 Feb. 2025].
33. Science Roast (2020). *Response Surface Methodology (RSM) analysis in minitab*. [online] YouTube. Available at: [https://www.youtube.com/watch?v=ge52U\\_nrVFA](https://www.youtube.com/watch?v=ge52U_nrVFA) [Accessed 2 Mar. 2025].
34. Steiber, J., Trader, A., Treichel, B., Tsujimoto, D., Reese, R., Bedard, M. and Musial, M. (2006). Development of an Engine Test Cell for Rapid Evaluation of Advanced Powertrain Technologies using ModelControlled Dynamometers. *SAE Transactions*, [online] 115, pp.715–720. doi:<https://doi.org/10.2307/44700102>.
35. The Open Educator (2017). *Response Surface Methodology Basic, the Central Composite Design Explained*. [online] YouTube. Available at:  
<https://www.youtube.com/watch?v=zBXPBAuX-Us> [Accessed 2 Mar. 2025].
36. The Open Educator (2020a). *Box Behnken Response Surface Methodology RSM Design and Analysis Example using Minitab & MS Excel*. [online] YouTube. Available at:  
<https://www.youtube.com/watch?v=m1eTI9zWkcs> [Accessed 2 Mar. 2025].
37. The Open Educator (2020b). *Multiple Response Optimization Explained with Example using Minitab Response Surface Methodology RSM*. [online] YouTube. Available at:

<https://www.youtube.com/watch?v=ZDSgdN1DhzY&list=PLJx1An1zOedhfB0WMJT1yaV35FoYe3Miv> [Accessed 2 Mar. 2025].

38. Turner, M.J., Clough, R.W., Martin, H. and Topp, L.J. (1956). Stiffness and Deflection Analysis of Complex Structures. *Journal of the Aeronautical Sciences*, [online] 23(9). Available at:  
[https://www.ce.memphis.edu/7117/notes/presentations/papers/Turner%20et%20al%20\(1956\)%20Stiffness%20and%20deflection%20analysis%20of%20complex%20structures.pdf](https://www.ce.memphis.edu/7117/notes/presentations/papers/Turner%20et%20al%20(1956)%20Stiffness%20and%20deflection%20analysis%20of%20complex%20structures.pdf) [Accessed 26 Feb. 2025].
39. Vi-grade.com. (2025). *Cable-driven DiM DYNAMIC Simulator* | Vi-grade. [online] Available at: [https://www.vi-grade.com/en/products/cable-driven\\_dim\\_dynamic\\_simulator/](https://www.vi-grade.com/en/products/cable-driven_dim_dynamic_simulator/) [Accessed 26 Feb. 2025].
40. Wipke, K., Cuddy, M., Bharathan, D., Burch, S., Johnson, V., Markel, A. and Sprik, S. (1999). *Advisor 2.0: A Second- Generation Advanced Vehicle Simulator for Systems Analysis*. [online] Available at: <https://www.nrel.gov/docs/fy99osti/25928.pdf> [Accessed 27 Feb. 2025].
41. Wipke, K.B. and Cuddy, M.R. (n.d.). *Using an Advanced Vehicle Simulator (ADVISOR) to Guide Hybrid Vehicle Propulsion System Development*. [online] Nrel.gov. Available at: <https://www.nrel.gov/docs/legosti/fy96/21615.pdf> [Accessed 27 Feb. 2025].
42. Wipke, K.B., Cuddy, M.R. and Burch, S.D. (1999). ADVISOR 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach. *IEEE Transactions on Vehicular Technology*, 48(6), pp.1751–1761. doi:<https://doi.org/10.1109/25.806767>.
43. www.itl.nist.gov. (n.d.). 5.3.3.6.2. *Box-Behnken designs*. [online] Available at: <https://www.itl.nist.gov/div898/handbook/pri/section3/pri3362.htm> [Accessed 27 Feb. 2025].
44. www.vi-grade.com. (2025). *VI-CarRealTime* | Vi-grade. [online] Available at: <https://www.vi-grade.com/en/products/vi-carrealtime/> [Accessed 26 Feb. 2025].

45. Xiao, D., Hu, Y. and Sun, X. (2024). Real-Time Detection of Anomalous Driving Behavior Using Generative Adversarial Networks and Behavior Prediction Models. *IEEE*, [online] pp.252–255. doi:<https://doi.org/10.1109/eiect64462.2024.10867154>.
46. Zolgharnein, J., Shahmoradi, A. and Ghasemi, J.B. (2013). Comparative study of Box–Behnken, central composite, and Doehlert matrix for multivariate optimization of Pb (II) adsorption onto Robinia tree leaves. *Journal of Chemometrics*, [online] 27(1-2), pp.12–20. doi:<https://doi.org/10.1002/cem.2487>.