24WSP66META: System Design CW – Overcoming Overtaking (Optimizing a F1 Car)

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Abstract

Formula 1 engineering teams face a particularly limited systems design environment due to the specific characteristics of the Monaco Grand Prix circuit, which is known for its tight layout, limited overtaking chances, and high standards. Unlike high-speed tracks where aerodynamic efficiency and power output primarily determine performance, Monaco requires a complex balance between low-speed mechanical grip, thermal management, and spatial navigation skills, making it an ideal setting for the creation of specialized systems architecture.

Specifically designed to address Monaco's unique limitations, this work presents a comprehensive systems engineering approach to improving Formula 1 vehicle performance. This continuous improvement will be addressed by conducting technical feasibility assessments and stakeholder need analyses. There will be an attempt to create a framework that balances performance expectations with the circuit's demanding features, which should allow for a resulting platform specification that can provide consistent lap performance and operational resilience.

Starting with the discovery and characterization of stakeholder demands, the approach utilizes formal systems engineering techniques to translate into functional and non-functional requirements. Established decision frameworks are regularly used to analyze and assess critical system trade-offs, such as cornering stability versus thermal management, and energy recovery versus traction improvement. Subsystem interactions, particularly between energy deployment tactics and vehicle balancing features in Monaco's challenging areas, receive targeted attention.

The ending remarks within this report will attempt to show that under race conditions, some of the focused changes noticed within the aerodynamic load distribution, energy management profiles, and thermal threshold parameters could produce significant gains in vehicle stability, performance consistency, and mechanical dependability. The resulting track specific set up/design specification validates the effectiveness of systematic trade off analysis in complex motorsport applications. This, in turn, may have potential consequences for more general automotive systems design practices.

Key Words: Formula 1, Systems Engineering, Monaco Grand Prix, Performance Optimization, Trade off Analysis, Vehicle Architecture, Racing Strategy, Thermal Management, Aerodynamic Load Distribution, Energy Management

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1. Introduction

1.1 Background

Without a doubt, one of the most complex combinations of engineering and technology within a competitive environment could be argued to be the modern motorsport of Formula 1 (F1). The field demands outstanding systems integration skills; performance results not just from individual component quality but from the coordinated interaction between aerodynamics, hybrid powertrains, energy recovery systems, chassis structures, and thermal management architectures [1]. Driven by tight legal frameworks and fast changing innovation cycles, this integration complexity defines F1 as a particularly interesting field for systems engineering research.

Operating over many different circuit settings, F1 cars range from fast straightaways to limited lower speed city layouts. Among these, the Circuit de Monaco, site of the renowned Monaco Grand Prix, stands out as a unique case examination. Although not unusual in having tight cornering sequences, Monaco shows circuits where limited track width, short straight sections, and low safety margins greatly restrict passing chances. These qualities greatly increase the importance of qualifying position and vehicle setup optimization and significantly lower driver error tolerance [2]. Such limitations test traditional methods of component integration, especially with respect to downforce creation, regenerative braking calibration, and thermal system performance under low speed operating conditions, as well as vehicle architecture.

Within the newer age of F1, the new age of engineering requires using techniques that call for a thorough systems based approach. An example of this would be the hybrid energy recovery systems (ERS) calling for exact calibration in relation to engine torque characteristics and strategic deployment policies to optimize energy use and fuel economy. Studies on ideal control algorithms for ERS deployment reveal that by means of direct collocation, equal race completion performance can be reached with up to 30% decrease in fuel use relative to conventional deployment tactics [3]. These revelations illuminate the possible compatibility between energy efficiency and performance optimization when subsystems are combined, modeled, and optimized.

On circuits defined by lower average speeds, where airflow restriction affects heat dissipation capability, thermal management systems take on special importance. By having a poorly set up cooling system, there is an inherit risk of the power unit performance declining which in turn may lead to quick component wear, therefore sacrificing race durability. Dynamic intake geometry modification and flow augmented heat exchanger designs, among other engineering methods, have been studied to improve thermal system adaptability under changing velocity operating situations [4]. Critically, these components have to be constructed in line with aerodynamic profiles, powertrain arrangement, and mass distribution criteria (rather than in a reductionist perspective whereby the parts are designed without taking into account other parts).

There is also a translation that takes place within theoretical design performance into a setting of practical track execution which finds itself greatly affected by suspension (and chassis architecture). Studies on aero based suspension show how interaction phenomena effects suspension calibration and how it may influence the transfer of aerodynamic forces during braking / acceleration phases (including tire contact characteristics) [5]. These dynamics take on more importance on tracks like Monaco, where regular low speed directional shifts make a major percentage of lap time. While it may maintain aerodynamic load uniformity, too stiff a suspension could undermine mechanical grip, which can be perceived as a performance trade off that systems engineering has to clearly handle.

Using Monaco as an example case study, this work offers a methodical assessment of the specification needs for Formula 1 cars designed for very limited track settings. This study intends to define specifications that concurrently satisfy performance goals, reliability criteria, and regulatory compliance under particular racing conditions by means of a methodical dissection of vehicle subsystems and thorough examination of design trade offs. The problem context, stakeholder needs analysis, and methodology framework for assessing architectural choices throughout the integrated vehicle platform will be further discussed in the following parts.

1.2 Problem Statement

One of these issues of significance and the main topic of this paper when addressing stakeholder requirements, will be the obstacles faced with overtaking on circuits with limited layouts. By considering the previous example provided of Monaco, you may begin to grasp why this difficulty exists, since their tight track layout, restricted straight parts, and presence of enforcement of lower speed turns make overtaking attempts a dilemma. Inherent vehicle level constraints [6] considerably limit even with regulation policies like the implementation of Drag Reduction Systems (DRS) the frequency of overtaking. Racing in confined areas especially exposes a basic flaw in the architectural approach used in the design of modern F1 cars.

The aerodynamic architecture used is yet another key in this phenomenon. F1 design status quo holds a fundamental belief in which the aim to boost downforce is done so by utilizing advanced aerodynamic surfaces and ground effect tunnels. Although these features exhibit remarkable efficiency when considered individually, they simultaneously produce considerable turbulent wake structures that notably impair the aerodynamic performance encountered by trailing vehicles. Research has shown that vehicles in trailing positions can see a decrease in aerodynamic efficiency ranging from around 2% to 65% when they are situated within the wake of a leading vehicle [7]. This direct decline in performance has a direct impact in the grip obtained while cornering. Further, this is also apparent in the directional stability of the car, requiring trailing vehicles to keep greater distances and thereby reducing their ability to overtake. Notwithstanding the endeavors of recent regulatory frameworks to tackle this issue, the turbulent wake characteristics continue to pose a substantial obstacle to maintaining consistent wheel to wheel competition.

The characteristics of mechanical grip and the dynamic responses of the chassis introduce further constraints. Vehicles are generally designed with suspension systems that are quite rigid to ensure stability in their aerodynamic platforms. However, this rigidity can negatively impact their flexibility to respond to the uneven surfaces commonly found on low speed circuits, such as those in Monaco. High downforce configurations naturally limit the operational flexibility needed for choosing alternative racing lines and executing late braking overtaking maneuvers. The effect that some of these factors may have is then further heightened in specific cases, such as when vehicles stray from the ideal racing line. This leads to a diminished grip and coefficients caused by the buildup of surface debris and uneven rubber distribution further hinder attempts to overtake. Data on race performance indicates that, in the absence of external variables such as precipitation, the frequency of overtaking at Monaco is notably limited [6].

The management protocols for hybrid powertrains introduce further limitations. The implementation of the Energy Recovery System (ERS) requires meticulous regulation to guarantee compliance to energy usage constraints and fuel consumption objectives. Given that both leading and following vehicles generally employ similar deployment strategies, energy usage patterns are likely to reach a state of balance, rather than generating distinct performance advantages that would facilitate overtaking. Studies show that this limitation significantly restricts tactical options for enabling passing maneuvers, especially on shorter straight segments [8]. This therefore leads us to ponder about the possibilities for improvement / design alteration.

1.3 System Narrative

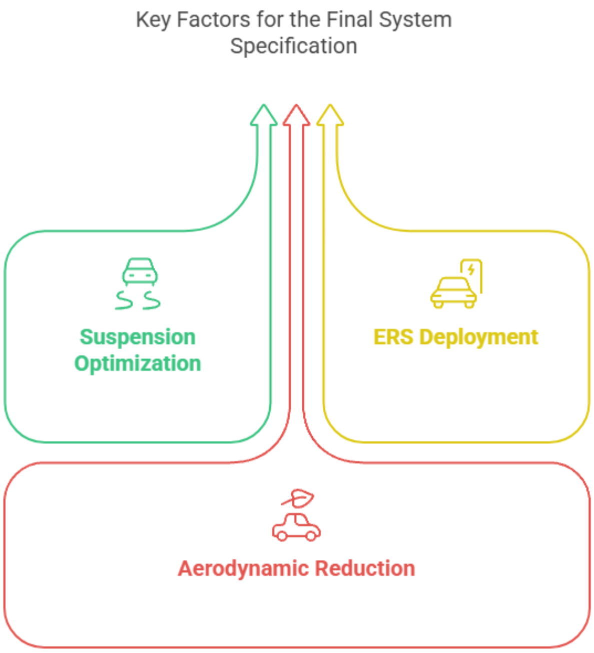
A fundamental reconfiguration of vehicle systems that surpasses conventional performance optimization paradigms is required due to the restriction of overtaking opportunities on constrained, low speed circuits like Monaco. This study suggests a comprehensive system level solution that is designed to improve overtaking capability by integrating the redesign of critical performance subsystems, including aerodynamic architecture, suspension/chassis configuration, and hybrid powertrain deployment strategies, in response to this challenge. This approach is essentially designed as such to be to fulfill the demands of both established tech based performance and emerging evaluation criteria that are influenced by competitive dynamics, regulatory frameworks, and stakeholder requirements. Specifically, it is designed to handle the mounting emphasis on "raceability" as a distinct performance dimension.

It should be understood that there is an interrelationship trio with aerodynamic efficiency, mechanical traction, and hybrid power. Looking at improving mechanical grip and allowing for flexible suspension characteristics, have also been identified as the most critical domains for detailed study. This is more so the case when thinking about case studies like that of the Monaco circuit, where vehicles rely predominantly on tire surface interaction rather than pure aerodynamic downforce. Despite recent regulatory reforms that have implemented ground effect aerodynamics, vehicles continue to experience significant wake turbulence phenomena. This significantly reduces the overtaking potential of following vehicles due to downforce degradation [9]. This also gives a certain implication that by improving suspension performance, the driver should feel a more immediate solution to the overtaking deficit in environments with such constraints.

As a result, the suspension architecture will be designed to optimize traction generation during low speed, high frequency directional transitions by incorporating compliant geometric configurations, optimized camber progression characteristics, and predictable lateral load transfer behavior. The literature on suspension dynamics points out the fact that improved mechanical traction in vehicles enables them to maintain competitive performance in high speed zones, thereby reducing their reliance on aerodynamic components that are susceptible to turbulence disruption [10]. Furthermore, the suspension and chassis systems will be calibrated in accordance with energy deployment profiles and aerodynamic loading patterns to ensure platform stability under hybrid power augmentation conditions. This method enhances the hybrid subsystem's role in overtaking maneuvers, particularly during exit acceleration phases on abbreviated straight sections.

In terms of the power system, the hybrid unit will be looked at being implemented into the system such that to ensure the supplementary electric torque is deployed with precision within the energy allocation parameters. This relationship will allow the Energy Recovery System (ERS) deployment against the identified overtaking opportunities and driver input patterns, while also ensuring that the system is in compliance with regulatory constraints on energy utilization [11]. The configuration of aerodynamic surfaces will be determined by the wake characterization research that informs the development of low-sensitivity wing profiles and flow structures, with the objective of generating adequate downforce while minimizing turbulence characteristics [12].

Via the use of domain based research, regulatory documentation, and stakeholder understanding, the system requirements will be defined as part of the technical output. The architectural portion of this task should aim to conclude with a comprehensive system specification.



1.4 Aims and Objectives

Definitive Aim:

To employ structured systems engineering methodologies and quantitative trade-off analysis to craft a full-fledged vehicle system specification for Formula 1 that optimizes overtaking opportunities on constrained, low-speed circuits (particularly Monaco).

Objectives:

1. To identify critical subsystem interactions that facilitate performance overtaking:

- Examining the relationship between aerodynamic wake sensitivity, suspension characteristics, and hybrid power various scenarios.
- Looking at overtaking limiting failure modes within a system architecture model.
- Identifying high-leverage architectural modification sites that enhance overtaking capability while ensuring regulatory compliance and safety parameters.

2. To create an integrated systems architecture that optimizes subsystem performance under constrained circuit conditions by

- The development of functional models that are representative of the aerodynamic, mechanical, and hybrid energy subsystems, with parameterization that is perfectly suited to overtaking scenarios.
- Formulating exhaustive performance trade-off models that simulate cornering dynamics, traction limitations, and energy deployment strategies in the context of wake-induced aerodynamic performance degradation.
- Optimizing straight-line acceleration sequences by establishing coordinated control logic between suspension characteristics, energy deployment mapping, and downforce generation.

3. To establish a dependable methodology for the development of specifications and requirements analysis by:

- Eliciting both functional and non-functional requirements related to overtaking enhancement by engaging core stakeholder groups (F1 engineers, drivers, FIA).
- Creating a formal system requirements framework that establishes a connection between measurable engineering objectives and specific performance parameters.
- Ensuring FIA technical regulation conformance while establishing explicit traceability between requirement targets, design parameters, and anticipated performance outcomes (to ensure any types of feasibility although using this as a thought experiment may also be considered and is not out of the equation).

4. To assess system viability and performance trade-offs through simulation-based design analysis, the following steps are taken:

- Create a MATLAB simulation that depict overtaking scenarios in variable system configurations
- Conducting analysis and experiment design to visualize performance envelopes and ascertain the sensitivity of key design variables.
- Crafting an all-encompassing system specification that meets may meet stakeholder requirements and improves overtaking capability by optimizing design parameters.

2. Technical Outputs

2.1 Stakeholder and Non-functional Requirements Definition

The key purpose of the project is to look into overtaking opportunities as a factor within racing and keep it constrained within the environment of Circuit de Monaco by facilitating the development of an improved vehicle system configuration. Therefore this section in particular will serve as a foundational function of first establishing an exhaustive identification of primary stakeholders and their respective performance expectations in order to formulate a system specification that adequately addresses the requirements of all relevant stakeholders.

Stakeholders

The primary stakeholders in this development context are as follows:

- **F1 drivers**, whose key objectives include the development of intuitive control interfaces for the implementation of hybrid deployment strategies, the optimization of mechanical grasp characteristics, and the prediction of vehicle dynamic response under wake turbulence conditions.

- **Race Engineering** necessitates energy management frameworks that are consistent and dependable, including both the harvesting and deployment phases, as well as vehicle systems that can maintain performance integrity without exhibiting unpredictable behavioral characteristics in variable circuit conditions.

- **Aerodynamic specialists,** whose professional emphasis is on the preservation of aerodynamic efficiency parameters and the minimization of wake sensitivity coefficients in both solitary and following operational conditions, while also ensuring regulatory compliance.

- **Technical Directors and Regulatory Representatives (FIA**) are accountable for guaranteeing that vehicle designs adhere to technical regulations, with a particular emphasis on the reliability standards of power units, the limitations of hybrid deployment, and the aerodynamic configuration parameters.

- **Strategic Analysts and Team Management**, who focus on exhaustive competitive performance metrics, require an optimal equilibrium between reliability considerations, race-day overtaking capability, and qualifying velocity potential.

Non - Functional Requirements

In addition to stakeholder identification, it is methodologically significant to distinguish between functional system expectations and non-functional requirements. Non-functional requirements, which are distinct from operational or functional requirements, pertain to broader system attributes, including regulatory compliance, operational durability, safety parameters, and system usability metrics.

In this context, the critical non-functional requirements are as follows:

- **Regulatory Compliance:** Guaranteeing compliance with the technical regulations of the FIA in relation to the architectural parameters of hybrid systems, the constraints of aerodynamic design, and the limitations of energy deployment.

- **Thermal and Structural Integrity**: Ensuring that hybrid subsystems and suspension assemblies remain operational functional throughout the entire race distance without any performance degradation.

- **Driver Interface Usability:** Minimizing cognitive workload by enabling intuitive control over hybrid energy deployment mechanisms and system configuration parameters in high-pressure race conditions.

- **Management of Mass Distribution:** The requirement that any proposed design modifications maintain optimal mass distribution characteristics and minimize total vehicle mass increases in order to preserve dynamic agility.

- **Wake Sensitivity Mitigation:** Guaranteeing that the vehicle's aerodynamic behavior facilitates close-proximity following without significant downforce reductions that would otherwise impede overtaking capability.

The detailed Requirements Analysis methodology that follows is built upon the systematic identification and analysis of these stakeholder concerns and non-functional system requirements. Subsequent sections systematically decompose these broad requirements into specific measurable objectives to direct the development of the system and the performance validation protocols.

2.2 Requirements Analysis

Requirement ID	Requirement Text
1	Car must retain around a set 80% aerodynamic downforce at 1 car length distance
2	Suspension must attempt to maximize mechanical grip under low-speed corners
3	Hybrid system must provide at least 160 kW boost (minimum 5 seconds)
4	Vehicle must achieve full hybrid system recharge within 1 lap at Monaco
5	Suspension compliance must allow for 10% increased tire contact patch stability
6	Aero surfaces must minimize wake turbulence without exceeding regulatory CD limits
7	Hybrid boost deployment must be manually controllable by driver on-demand
8	System must comply fully with FIA 2025 technical regulations for hybrid and aero
9	Vehicle dynamic balance must remain within ±3% front-rear under hybrid boost
10	Chassis must handle vertical loads from Monaco curbs without structural compromise
11	Suspension system must allow ride height adjustment within ±5mm tolerance
12	ERS deployment strategy must be optimized for energy availability on short straights
13	Brake energy recovery must operate without destabilizing car in low grip zones
14	Mechanical setup must prioritize compliance over absolute aerodynamic platform stiffness
15	Overtaking capability must not significantly degrade overall qualifying lap performance
16	Vehicle mass increase due to hybrid system must remain within 2% of initial mass target
17	Car must be able to complete 78-lap Monaco GP without overheating hybrid components
18	Driver must experience no more than 10% steering effort increase when following closely
19	Aero design must ensure at least 50% downforce retention even at 0.5 car length
20	System must allow for at least 2 overtaking boost activations per lap without recharge

Figure 1: *Initial Set of Requirements based on the Narrative*

Revised Requirement ID	Requirement Text	Type of Requirement (O/F/NF)	Measure of Performance (MoP)	Related Attributes	Stakeholder Concerned	Highlighted Other Systems	Interdependencies
1	Car must retain at least 80% aerodynamic downforce at 1 car length distance	F	% Downforce Retention	Aerodynamics	Driver	Suspension, ERS	Aero-Suspension-Hybrid
2	Suspension must maximize mechanical grip under low-speed, high-load conditions	F	Grip Coefficient	Chassis Dynamics	Driver/Engineer	Aerodynamics	Suspension-Aero
3	Hybrid system must provide at least 160 kW boost for minimum 5 seconds	F	Boost Power Output	Hybrid Powertrain	Driver/Engineer	Energy Storage	Hybrid-Chassis Integration
4	Vehicle must achieve full hybrid system recharge within 1 lap at Monaco	F	Recharge Time (laps)	Energy Recovery	Engineer	Energy Management Strategy	Hybrid-Energy Packaging
5	Suspension system must allow ride height adjustment within ±5mm tolerance	F	Ride Height Variability	Suspension Setup	Engineer	Suspension Management	Suspension-Aero Platform
6	ERS deployment strategy must be optimized for energy availability on short straights	O	Boost Energy Availability	Energy Management	Race Engineer	Energy Management Strategy	Energy Boost vs Weight
7	Brake energy recovery must operate without destabilizing car in low grip zones	F	Stability During Regen	Braking Systems	Driver/Engineer	N/A	Brake Stability
8	Overtaking capability must not significantly degrade overall qualifying lap performance	NF	Lap Time Delta %	Overall Lap Performance	Team Principal	N/A	Lap Pace vs Raceability
9	Vehicle mass increase due to hybrid system must remain within 2% of initial mass target	NF	Mass Increase %	Vehicle Mass	Engineer	Energy Packaging	Weight vs Power
10	Car must be able to complete 78-lap Monaco GP without overheating hybrid components	F	Thermal Endurance (laps)	Thermal Management	Race Engineer	Hybrid Cooling	Hybrid Thermal Reliability
11	Aero design must ensure at least 50% downforce retention even at 0.5 car length	F	% Downforce in Wake	Aerodynamics	Aerodynamicist	Aerodynamics	Wake Management
12	System must allow for at least 2 overtaking boost activations per lap without recharge	O	Boost Activations per Lap	Energy Recovery Systems	Driver/Engineer	Energy Management Strategy	Hybrid-Energy Packaging

Figure 2: *Revised Requirements*

Comparator 1	Comparator 2	Most Important	How Much More	Justification
Acceleration	Grip	Grip	5	Grip is more important than acceleration in low-speed circuits like Monaco, where traction defines whether the car can even attempt an overtake.
Acceleration	Boost	Boost	3	Boost is prioritized over Acceleration since effective hybrid deployment determines whether power is available for overtaking scenarios.
Acceleration	Aero	Aero	3	Aerodynamic wake robustness is moderately more important than raw acceleration; close-following requires aero stability to initiate a pass.
Acceleration	Thermals	Thermals	5	Thermal reliability is significantly more important, without temperature control, acceleration systems may derate and lose function entirely.
Grip	Boost	Grip	3	Grip moderately outranks Boost because without tyre traction, energy deployment translates to wheelspin rather than forward progress.
Grip	Aero	Grip	2	Grip slightly edges out Aero because mechanical contact defines Monaco pace more than airflow management.
Grip	Thermals	Thermals	3	Thermal stability is moderately more important than grip because overheat conditions risk long-term loss of performance.
Boost	Aero	Boost	4	Boost is moderately more important than Aero, as overtaking energy strategy governs actual execution more directly than aero stability.
Boost	Thermals	Thermals	2	Thermal considerations slightly outweigh Boost, since thermal failures can disable the hybrid system regardless of stored energy.
Aero	Thermals	Equal	1	Thermal and Aero are equally important as both serve to sustain performance over time in turbulent airflow and energy-demanding sections.

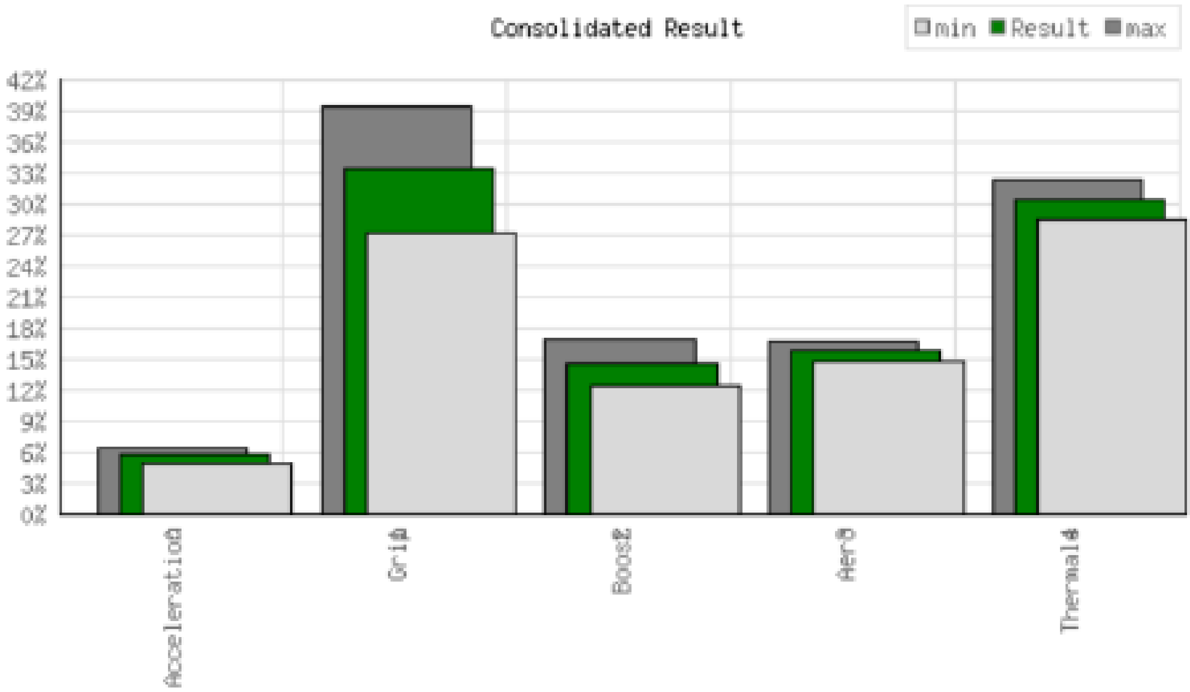
Figure 3: *Priority Ranking*

Cat		Priority	Rank	(+)	(-)
1	Acceleration	5.7%	5	0.7%	0.7%
2	Grip	33.4%	1	6.1%	6.1%
3	Boost	14.7%	4	2.2%	2.2%
4	Aero	15.8%	3	1.0%	1.0%
5	Thermals	30.5%	2	1.9%	1.9%

Figure 4.1: *Rankings for System Criteria [13]*

	1	2	3	4	5
1	1	0.20	0.33	0.33	0.20
2	5.00	1	3.00	2.00	1.00
3	3.00	0.33	1	1.00	0.50
4	3.00	0.50	1.00	1	0.50
5	5.00	1.00	2.00	2.00	1

Figure 4.2: *Decision Matrix [13]*



Number of comparisons = 10
Consistency Ratio CR = 0.7%

Principal eigen value = 5.031
Eigenvector solution: 4 iterations, delta = 1.7E-9

Figure 4.3: *Consolidated AHP Results [13]*

The first requirements table (Figure 1) examines the task through a much more simplified holistic lens, one in which covers a wide spectrum of performance goals (which include but are not limited to energy recovery , aerodynamics & suspension parameters).

The issues were subsequently addressed by the implementation of a more sophisticated needs framework (Figure 2). This table elucidates the contrasts among functional (F), operational (O), and non-functional (NF) needs by incorporating a section on Measures of Performance (MoPs). MoPs are utilized to assess the correlation between simulation outputs and sensitivity measurements versus established performance thresholds. This method enables the direct integration of requirements verification criteria with subsequent parametric modeling activities. The essential reliance of system performance, especially regarding downforce retention and hybrid energy efficiency, on interconnected subsystems, such as the thermal resilience of the Energy Recovery System (ERS) and the calibration parameters of the suspension, is also illustrated. This complex relationship constitutes a significant design conflict inside the requirement model, especially at the convergence of hybrid powertrain requirements and aerodynamic trade-offs.

The requirement model itself being a central component helps to achieve technically driven technical decomposition. It visually shows the logical movement from high-level stakeholder needs, such as overtaking capability, thermal conformance limits, and suspension adaptability, to implementation-ready engineering specifications. The correlation between "wake sensitivity" and "ride height tolerance" illustrates the inherent contradiction between improving platform conformity and preserving aerodynamic wake integrity. It is not merely a matter of interdependence, but rather a critical constraint loop that fundamentally influences the context in which performance trade-offs must be negotiated.

Hierarchical control is implemented effectively by the intentional granularity of constraints inside this architectural framework. Subordinate criteria such "brake stability during energy recovery" and "boost control override latency" help to create obvious links between technical requirements and behavioral expectations. The resulting structure is a layered, traceable requirement architecture specifically meant to handle the complicated dynamic characteristics of Formula 1 energy systems running under urban track conditions, not a standard flat constraint listing.

The Analytic Hierarchy Process (AHP) based prioritization approach (Figures 3 and 4) helps to further ground this model in the field of system relevance. Within the context, it is clear that in Monaco's specific situation, thermal management and mechanical grip are far more relevant than acceleration since the main performance limits are low speed traction capabilities (and the issue of heat dissipation). The model also continues to make clear the the influence of certain parameters in operational situations. Thermal threshold exceedance, for example, limits the suspension stiffness settings (because of heat induced damping variation), which then affects grip. This relationship validates the interdependency categories presented in the amended criteria framework by showing how system understanding is mutually reinforced by prioritization results and modeling outcomes.

Stakeholder judgment alignment and system design emphasis are both strong points of the combined AHP analysis findings (Figure 4.3), which demonstrate an exceptional consistency in prioritization logic with a particularly low consistency ratio (CR = 0.7%). The primary concerns are grip qualities and thermal management; acceleration, which is typically regarded as a performance metric that makes headlines, is demonstrated to be of relatively little significance in this particular operational context.

Moreover, the methodical shift from first narrative needs to organized, empirically verifiable criteria allows later simulation work, such as parametric design space investigation and sensitivity analysis, to definitely fit within measurable performance goals. The organized traceability systems developed inside the requirement model allow this direct link between qualitative design intent and quantitative performance validation. Without this methodological basis, efforts to assess performance via systems modeling languages or computational simulations would run the risk of losing connection with actual engineering value.

The need architecture's comprehensive integration across several subsystems, hybrid powertrain, aerodynamics, suspension dynamics, and thermal management, provides the fundamental basis on which all later modeling activities must be built. It reveals not only the performance goals the car has to reach but also the complex systematic tensions, legal limits, and functional priorities that have to be addressed to reach these goals. More than simply a recording tool, this model is the operational framework guiding and supporting the whole design process.

2.3 Design Problems Definition and Specification

Designing a Formula 1 car able of enhanced overtaking performance at Monaco calls for specifying system-level goals that balance architectural interdependencies, performance limits, and legal restrictions. Monaco, because of its limited geometry and low average speeds, tests traditional design approaches that give aerodynamic downforce or top-end power top priority. Thus, this work uses a concentrated set of goals derived from system design logic and empirical data. These will direct specification creation and trade-off investigation.

The following goals/objectives have been set:

- **Maximize Mechanical Grip**
    - Particularly under throttle load direction changes, strengthen suspension and chassis parameters to guarantee best tyre contact over the range of low-speed and off-camber corners at Monaco.

- **Maximise Hybrid Power Deployment**
    - Maximizing acceleration opportunity, design a power deployment map and control strategy allowing strategic energy release on corner exits without exceeding thermal or regulatory limits.

- **Reduce thermal degradation**
    - Particularly in traffic where airflow is limited, make sure thermal loads are properly spread across cooling systems to prevent ERS or engine derating mid-race.

- **Improve Aero Robustness in Wake Conditions**
    - Redesign aero surfaces to keep downforce levels while closely following another car, so enhancing "raceability" by lowering wake sensitivity.

- **Make sure of compliance and durability**
    - Design parts to survive the whole race distance under repeated high-stress circumstances while following FIA rules on energy deployment, cooling limits, and safety restrictions.

Design Variable	Description
Suspension Stiffness & Travel	Adjust damper stiffness, roll bar rate, and travel to accommodate kerb-strike compliance and increase low-speed grip, without destabilising the platform.
ERS Deployment Strategy	Define location-based deployment rules (e.g. post-hairpin) and regeneration balance (under braking) to match overtaking opportunities with energy availability.
Aero Wake Resistance Design	Modify endplate, beam wing, and floor configurations to minimise yaw sensitivity and reduce wake-induced flow separation.
Thermal Management & Cooling Paths	Design ducting and flow geometry to improve heat extraction without exceeding drag targets or breaching aerodynamic packaging limits.
Manual Hybrid Boost Control Interface	Implement driver-controlled override for energy burst activation, tuned for intuitive use under high-cognitive-load conditions.
Brake Balance Energy Harvest Bias	Adjust energy recovery bias front-to-rear to avoid destabilisation under low-grip braking zones while preserving recovery efficiency.
Mass Distribution Strategy	Fine-tune ballast and packaging location to maintain rotational agility and traction within FIA-defined mass windows.
Energy Buffer Capacity (Hybrid)	Define buffer limits to ensure energy is available for repeat activation, particularly in final laps without recharging opportunity.

Figure 5: *Design Variables*

Constraint	Description
FIA Hybrid Energy Limitations	ERS deployment capped at 4MJ/lap and 120kW maximum output; deployment zones must not exceed circuit-specific validation maps.
Maximum Radiator Inlet Area	Cooling aperture must not exceed aero-efficiency targets; larger inlets increase drag and reduce straight-line potential.
Track Kerb Compatibility	Suspension and floor assemblies must clear aggressive kerbs at Monaco without compromising stiffness or causing impact damage.
Thermal Derating Thresholds	Components (battery, MGU-K, ICE) must operate below derating limits across race distance; cooling effectiveness must be retained in traffic.
Hybrid Activation Reliability	System must sustain multiple full deployment cycles over 78 laps without failure or temperature-induced shutdown.
Wake Sensitivity Envelope	Aero surfaces must retain >80% downforce at 1-car distance to enable following through tight sections (e.g., Portier to tunnel).
Centre of Gravity Window	Total vehicle mass and CG must remain within FIA-specified vertical and longitudinal range limits to maintain compliance.
Energy Harvest Control Limits	MGU-K harvesting cannot induce rear lockup or exceed front axle regenerative threshold, avoiding instability under braking.

Figure 6: *Design Constraints*

Every system goal, such as enhancing grip or using hybrid energy, must be evaluated inside a rigorously specified design envelope. There are some constraints that should be considering more in depth, such as the instance whereby engineers are required to be wise in their use under the FIA energy deployment limits, which cap the total energy per lap to 4 MJ and the MGU-K power output to 120 kW. Likewise, the need for a soft, compliant suspension to maximize mechanical grip conflicts with the criteria for maintaining platform stability to guarantee thermal and aerodynamic flow efficiency. Without considering systematic repercussions, the car cannot be maximized for peak performance in any one area.

Very vital is thermal control; the slow moving, congested traffic in Monaco limits natural airflow, so possibly causing rapid heat buildup in hybrid and engine components. Improper control could cause ERS subsystem derating, therefore compromising energy availability for overtaking. Increasing cooling capacity could help to solve this problem; however, it also increases drag and negatively impacts straight line performance. The ongoing difficulty of aerodynamic wake sensitivity is significant: a car designed for ideal downforce in isolation may have significant instability when near trailing another car, precisely the situation when chances of overtaking are most. This calls for an aerodynamic design reconsideration to give durability top priority over maximum downforce.

Particularly in the case of Monaco's stop start driving conditions, the relationship between energy availability and thermal efficiency offers a further design difficulty should must be taken into account before the creation of a design plan/methodology. The lack of straight stretches makes energy recovery from braking events uneven, therefore challenging the calibration of hybrid deployment plans. This shines a light on the call for being ahead of the curve in energy management and predictive control algorithms to evaluate consumption rates for every lap. Moreover, especially in low ambient airflow conditions, careful maintenance of the balance between mechanical braking and regenerative braking is necessary to stop thermal overloads. Therefore there is a challenge in the face of being able to develop a system guaranteeing constant ERS availability while avoiding thermal saturation, which may as a result, require an optimization effort covering mechanical, electrical, and thermodynamic areas.

The following are just a reduced set of interdependencies that create a set of tightly connected trade offs, one in which can that define the design:

- **Grip vs Platform Stability:** A softer suspension increases ride height variation and compromises aerodynamic stability while improving tire contact.

- **Boost Vs Thermals**: Aggressive hybrid deployment improves acceleration but raises system temperature, therefore compromising derating.

- **Cooling Vs. Aero:** Larger ducts improve heat dissipation but reduce drag and top speed.

- **Wake Robustness vs Peak Downforce**: Reducing maximum downforce in unobstructed airflow might be required to offset wake sensitivity.

- **Mass Repositioning vs. Packaging:** Using a altering ballast which can be used to to improve traction could conflict with legal center of gravity criteria and structural integration.

The problem is not a lack of technical choices but rather the difficulty of maximizing subsystem performance inside a limited and linked system. Subsequent stages of the project will evaluate possible configurations by means of trade off analysis and simulation to offer a feasible system specification tailored to Monaco's needs.

FACTORS	*Design Enabler*	*A*	*C_d*	*Rho*	*Mass*	*Rolling Coefficient*	*CRR_0*	*CRR_1*	*Tyre Friction*	*Current Speed*	*g*	*Torque*
Acceleration	Drivetrain Loss				TRUE							
	Power_Total											TRUE
	F_Rolling				TRUE	TRUE	TRUE	TRUE		TRUE	TRUE	
	F_Tractive				TRUE					TRUE	TRUE	
	F_Net				TRUE					TRUE	TRUE	
	F_Drag	TRUE	TRUE	TRUE						TRUE		
THERMAL & POWER	Power_Total									TRUE	TRUE	
	P_Rolling		TRUE	TRUE	TRUE	TRUE	TRUE	TRUE		TRUE	TRUE	
	P_Drag		TRUE	TRUE						TRUE		
	F_Drag	TRUE	TRUE	TRUE						TRUE		
	F_Rolling				TRUE	TRUE	TRUE	TRUE				
	F_Total				TRUE	TRUE	TRUE	TRUE				
	P_required				TRUE	TRUE	TRUE	TRUE				
	E_Battery											
	E_Fuel											
Aero	Drive_Cycle									TRUE		
	Reg_Braking									TRUE		
	Downforce	TRUE	TRUE	TRUE								
	Lift_Coefficient		TRUE									
	Wake_Sensitivity	TRUE	TRUE	TRUE								

Figure 7: *Design Enablers*

The table of design enablers (Figure 7) combines the main factors affecting acceleration, thermal power management, and aerodynamic efficiency to connect the functional behavior of the system with measurable performance objectives that were laid out through the course of system designing this context. Rather than going about the process of naming separate parameters, the matrix should be able to easily convey how cross domain interdependencies are pointed out, and the design variables that they can have an affect on performance aspects concurrently.

For example, because of their impact on rolling resistance and required energy, frontal area (A) and drag coefficient (C_d) are not only fundamental to aerodynamic drag computation but also recur across range and thermal models. Including less immediately clear elements like tyreFriction and CRR_1 (rolling resistance gradient) offers a more complex perspective on dynamic performance, particularly under changing grip circumstances. Structuring the enablers this way guarantees that the following parametric diagrams and MATLAB sensitivity studies are based on a consistent and traceable physical model, one that reflects the integrated character of subsystem trade-offs rather than separate kinematic performance.

2.4 Design Analysis Plan and Methodology

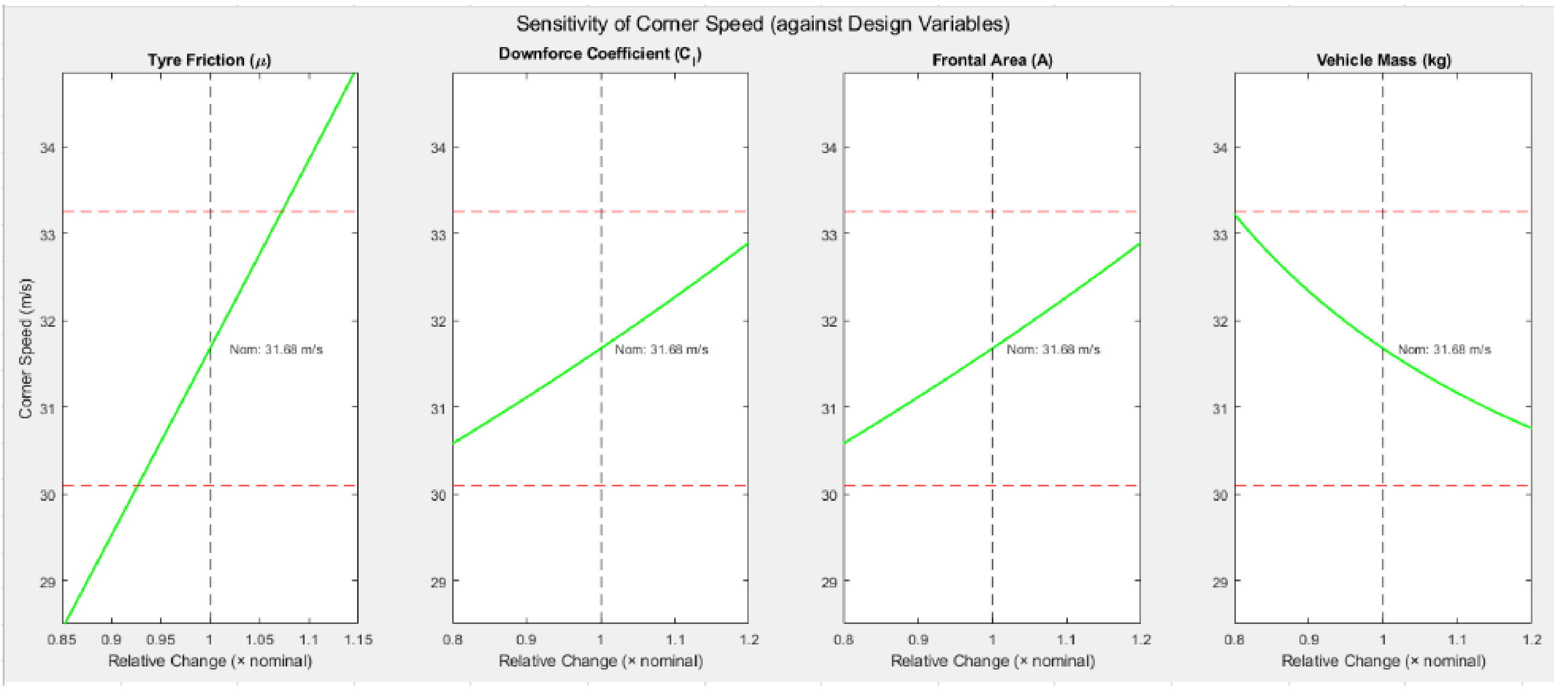


Figure 8.1: *Cornering Sensitivity Analysis – Baseline*

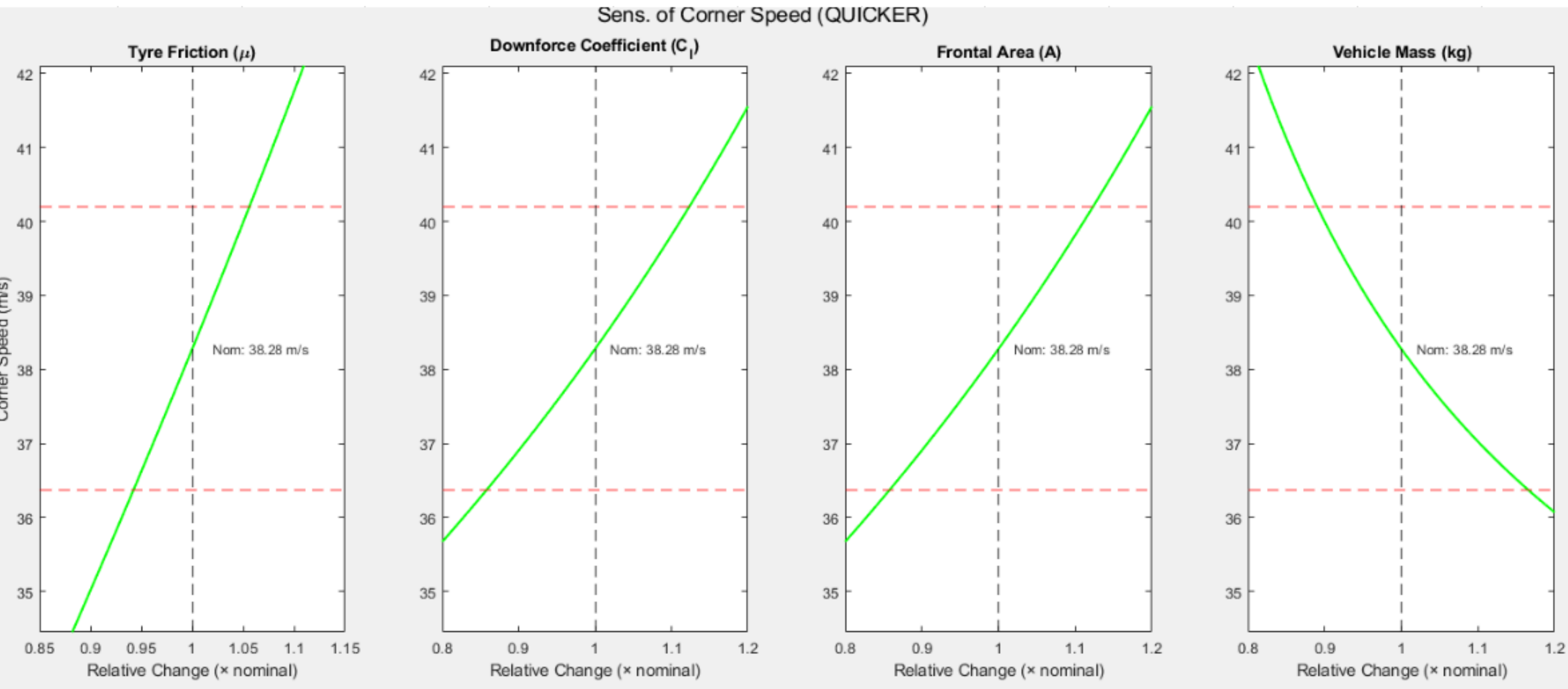


Figure 8.2: *Cornering Sensitivity Analysis – Enchanced*

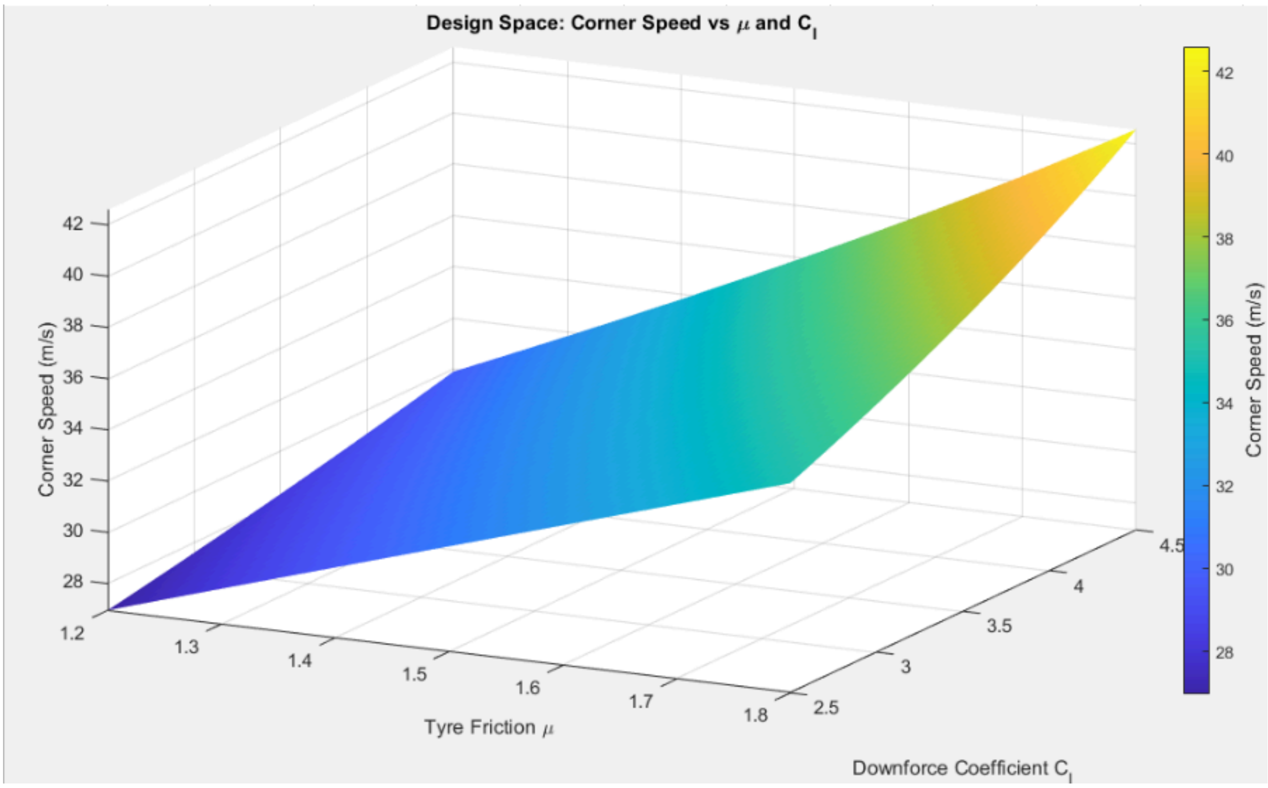


Figure 9.1: *Corner Speed Design Exploration*

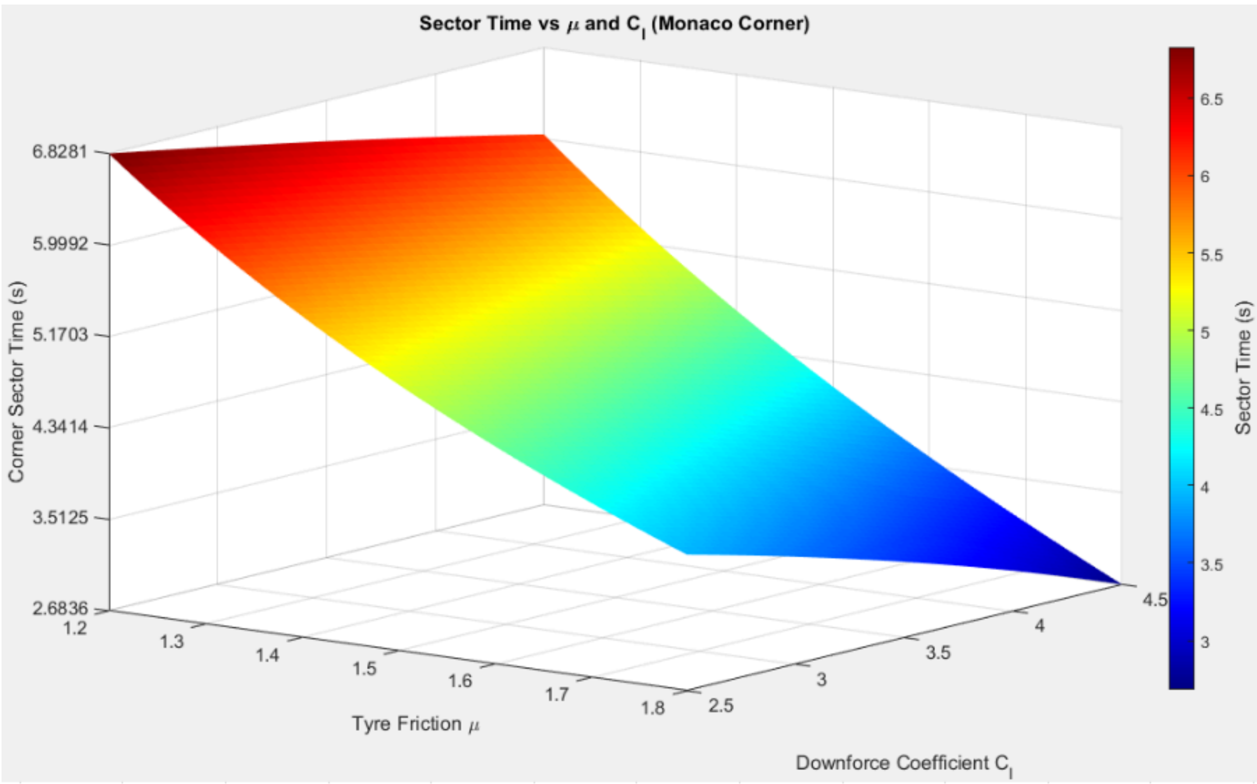


Figure 9.2: *Corner Sector Time Design Exploration - Monaco*

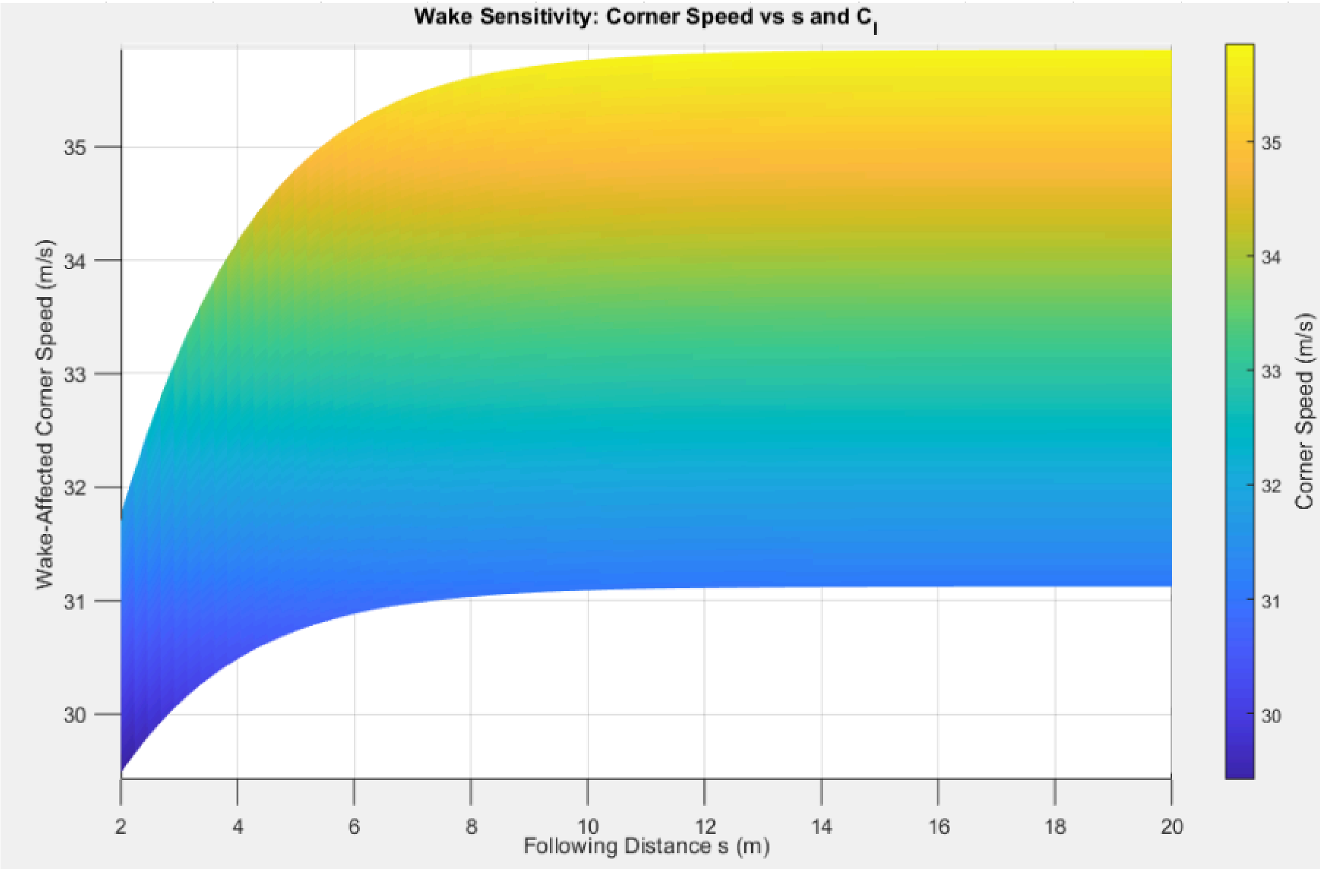


Figure 9.3: *Wake Sensitivity Map*

The sensitivity analyses (Figures 8.1 and 8.2) are designed to show a relationship between fundamental design elements and the cornering speeds that could be feasible during a race at Monaco. Specifically beginning with baselines, figure 8.1 shows strong linear relationships between cornering speed and tyre friction and aerodynamic downforce (indicated by the downforce coefficient). From the baseline figure of approximately 31.68 m/s, incremental changes were made in these factors and as such, were seen to be markedly enhancing cornering performance. The relationship between vehicle mass and cornering speed shows clear non linearity, therefore stressing the complex interaction of inertia and weight distribution in affecting mechanical grip. This implies that, while beneficial, weight reduction strategies could have declining returns beyond certain thresholds.

An examination of the enhanced scenario (Figure 8.2) reveals much sharper slopes for tire friction and aerodynamic properties, therefore stressing the cumulative benefits of better friction tires and optimal aerodynamic designs. For example, increasing tyre friction by even 10% above normal conditions leads to a notable improvement in cornering speed (from a baseline of 38.28 m/s), therefore stressing a higher sensitivity. This corroboration current engineering concepts in motorsport: concentrated improvements in aerodynamic efficiency and tire traction are the most effective routes for performance increase. The ongoing non linear qualities of vehicle mass sensitivity support even more the giving of importance to aero tyre optimization strategies over major mass reduction projects.

Essential for assessing general sector performance, the 3D dimensional design studies (Figures 9.1 and 9.2) offer a thorough knowledge of the interdependencies between tyre friction and aerodynamic downforce. Clearly showing notable performance improvements with minimal changes in both aerodynamic downforce and tire friction, Figure 9.1 clearly shows the cumulative impact of these elements on achievable corner speeds. The corner sector time surface plot (Figure 9.2) similarly makes clear this link by showing how small changes in frictional and aerodynamic factors greatly lower corner sector times, an impact particularly clear in low speed, high downforce circuits like Monaco.

Wake sensitivity is the next map of consideration (Figure 9.3) and by nature, offers a fundamental component to the study. It clearly shows how significantly cornering performance at low following distances is compromised by aerodynamic disturbances from turbulent wakes. For instance, following another car at close distances (less than 10 meters) causes cornering speeds to drop noticeably, therefore stressing a particular operational constraint that teams have to actively handle. Aerodynamic designs therefore have to balance the creation of downforce with durability in turbulent airflow conditions, a factor of great relevance in Monaco's rigorous overtaking situation.

The parametric diagram is the last of the modeling for this particular exercise in methodology and significantly extends the analytical depth by explicitly depicting the intricate dependencies between key system variables. An interesting point of note within the model is how it reveals several insights. One of these would be that tractive force and aerodynamic loading are not merely independent variables but are interlinked through constraints that directly impact rolling resistance and overall acceleration. While the individual sensitivity studies address discrete effects of aerodynamic and mechanical grip parameters, the parametric model provides a necessary holistic viewpoint, highlighting that isolated parameter enhancements (such as downforce augmentation or mass reduction alone) might yield suboptimal results if interactions with other subsystems, like thermal load or energy recovery are overlooked.

2.5 Design Trade-offs Visualisation

Parameter	Units	Baseline Value	I2	I3
Engine Power Max	kW	420	430	450
Motor Power Max (ERS)	kW	130	140	160
Torque (Total System)	Nm	730	-	-
RPM Range	RPM	3,000 – 11,000	-	-
Vehicle Mass	kg	835	-	-
Battery Capacity	kWh	3.6	4	4.8
Fuel Capacity	L	90	95	100
Thermal Cooling Flow Rate	L/s	0.3	-	-
Frontal Area	m^2	1.5	1.45	1.32
Drag Coefficient (Cd)	–	0.85	0.82	0.78
Downforce Coefficient (Cl)	–	3.5	0.82	0.78
Tyre Friction Coefficient (μ)	–	1.65	-	-
Sector Time (Target Corner)	s	5.65	-	-
Wake Sensitivity Loss @ 1 Car	%	18	-	-

Figure 10: *Evolution in Design Specification (Via Iterations)*

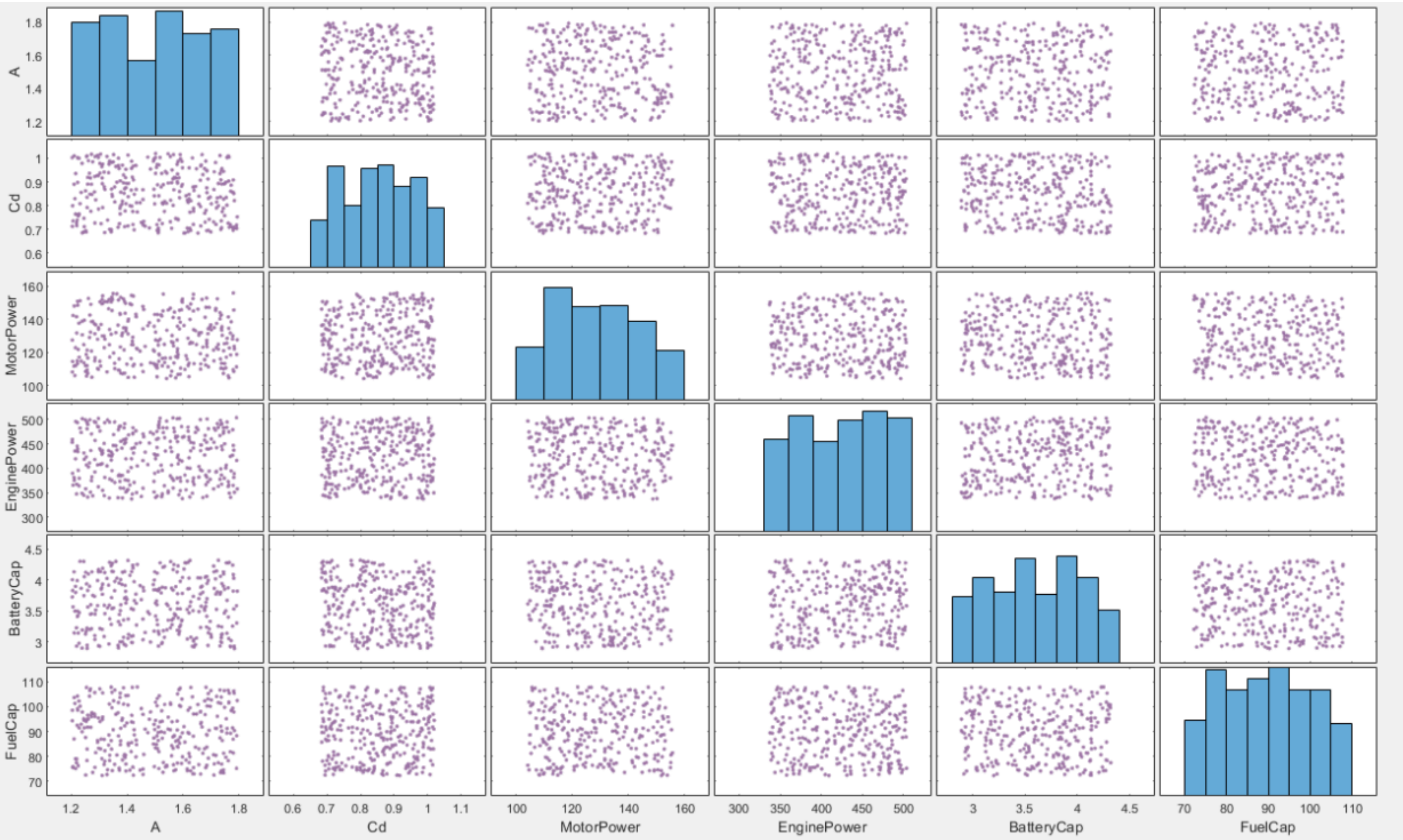


Figure 11.1: *Scatter Matrix - Baseline*

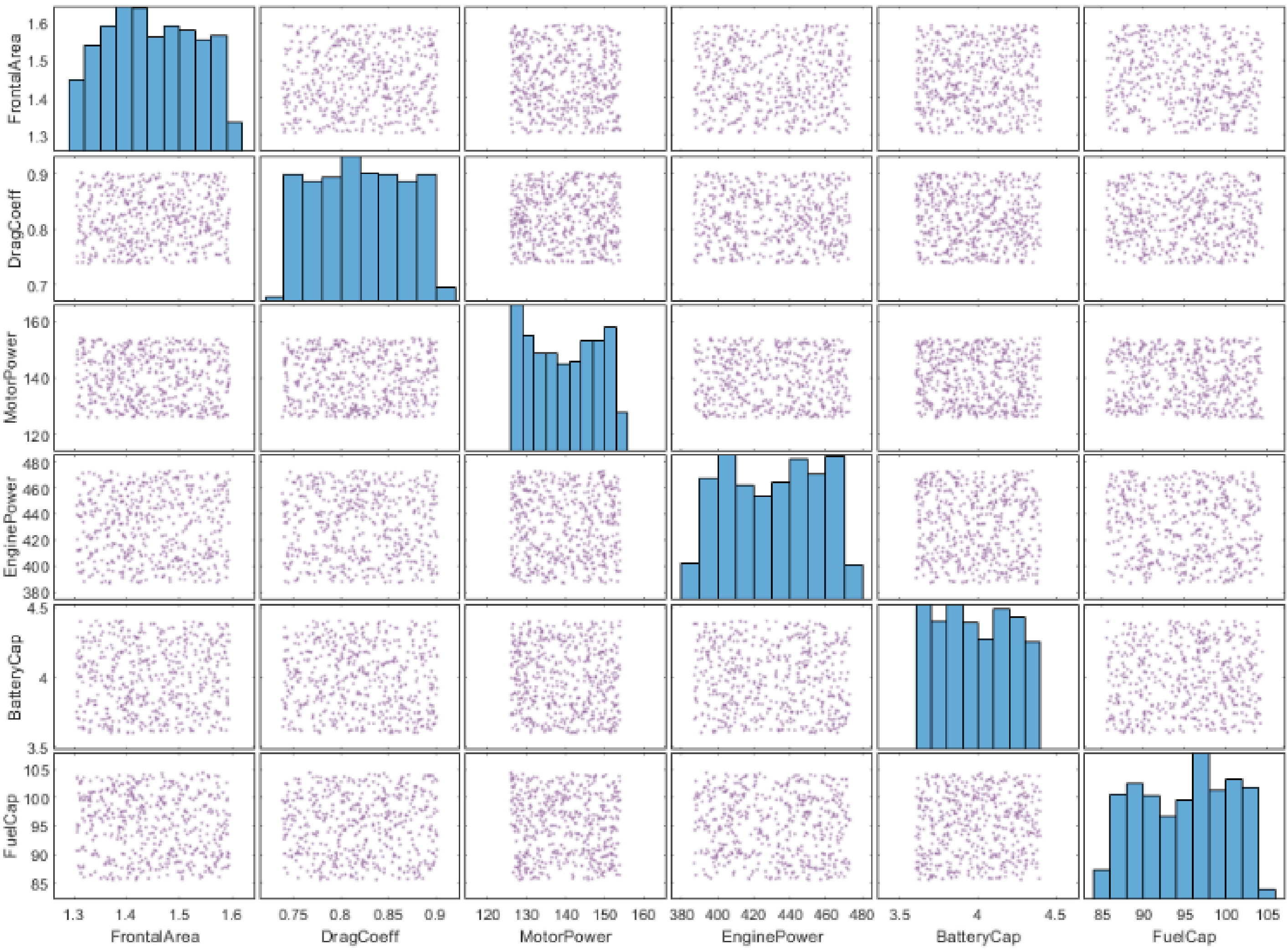


Figure 11.2: *Scatter Matrix - Iteration 2*

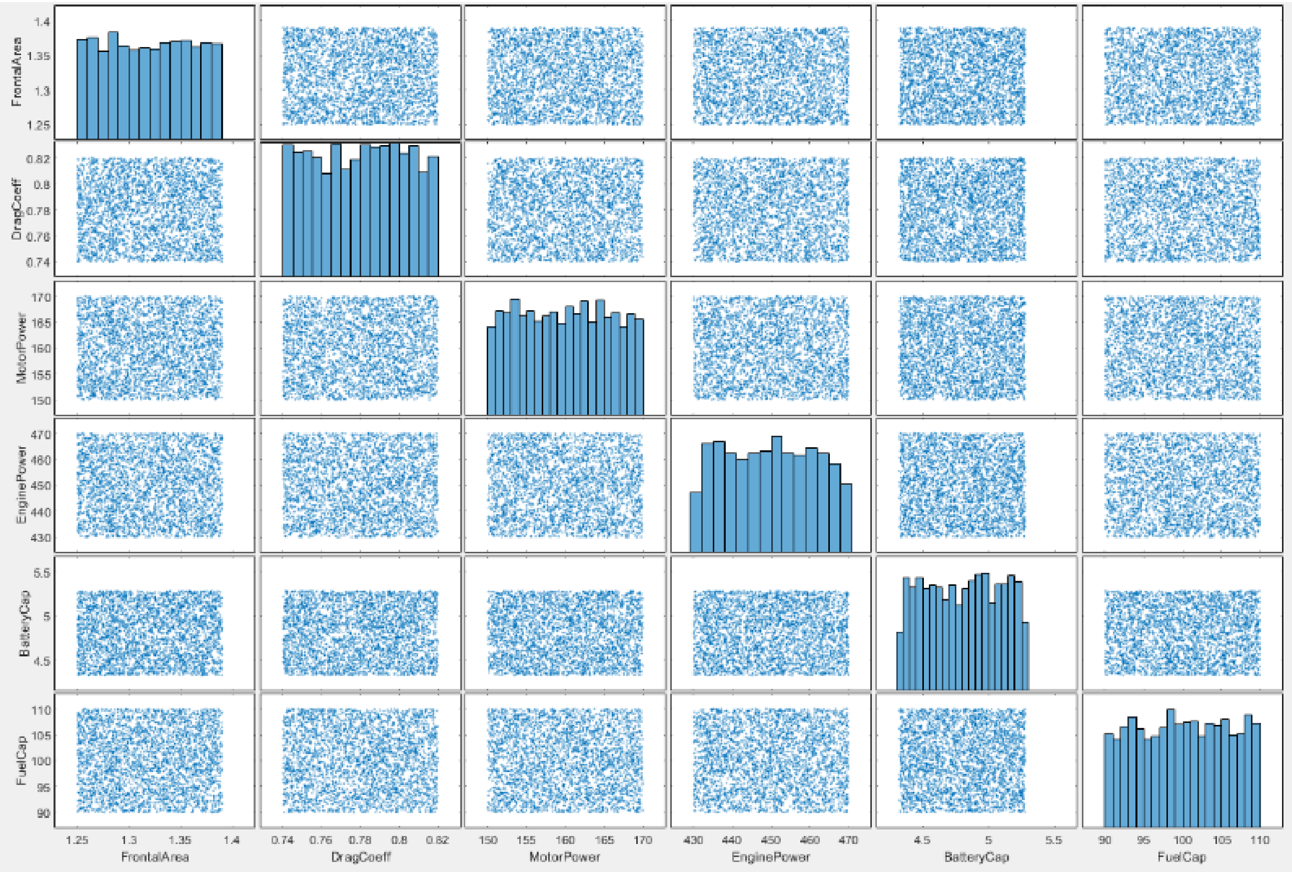


Figure 11.3: *Scatter Matrix - Iteration 3 (Final)*

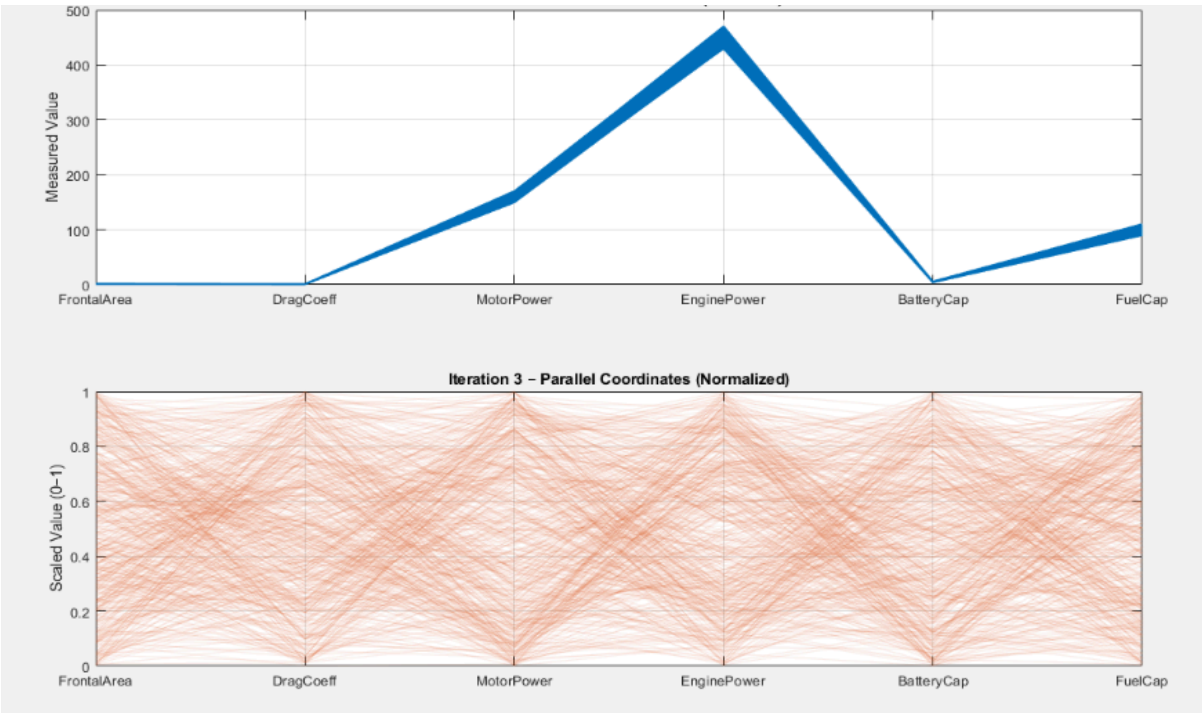


Figure 11.4: *Parallel Coordinates - Iteration 3 (Final)*

The iterative design technique of this work stresses a methodical approach to attaining a practical F1 car configuration optimized for overtaking and hybrid deployment in constrained, low-speed environments, such as those found in Monaco. Figures 10 to 11.4 show a consistent pattern: the interdependence and compatibility of interacting subsystems, rather than individual parameter extremes, determines performance.

Quantitatively, Figure 10 shows this development. Importantly, powertrain changes, through increases in both internal combustion and ERS output, were not pursued in isolation. Successive decreases in drag coefficient and frontal area improved these, showing a unified effort to offset rising energy demand by means of aerodynamic changes. This co-adjustment shows a basic trade-off: enhancing one subsystem, for example, power, limits others, such cooling, weight, and efficiency, so requiring exact balance. The gradual increase in battery capacity over several iterations, as opposed to a total increase, shows a more sophisticated optimization technique shaped by the declining returns of mass in relation to energy gain in low-speed scenarios.

Scatter matrix visualizations clarify the systematic evolution. Figure 11.1 shows a curious attitude. Indicative of a design state still exploring feasibility limits, distributions are unstructured and diffuse with little sign of convergence or parameter coupling. A significant change shown in Figure 11.2 (Iteration 2) is the design space's emergent shape becoming constrained and the resulting stronger correlations between aerodynamic drag and fuel capacity as well as between power outputs and battery energy. The developing couplings suggest that engineering constraints, thermal limits, weight limits, or packaging conflicts, were beginning to influence design viability.

These very clearly crystallize into a defined solution space by Iteration 3 (Figure 11.3). The distributions are more compact and orderly (based on a set of 3000 samples), indicating not only viability but also an optimization effort aimed at a local design optimum. It demonstrates the increasing impact of multi objective constraints where performance, range, and thermal equilibrium meet. The design emphasizes the knowledge that too much maximization of any one variable seldom results in ideal trade-offs in real-world, interdependent vehicle systems.

Figure 11.4 then looks at presenting feasible combinations across the whole multi-dimensional space in a parallel coordinate plot which hopes to provide a different view on these trade-offs. From the normalized viewpoint, feasible configurations are limited to a only that of a tightly clustered window/corridor, implying that performance goals can only be achieved if all subsystems cooperate within a strict function of specified boundaries. This is a deep systems insight: viability results from the harmony of design, not from the adjustment of individual subsystems. Unless supported by suitable changes in battery energy, frontal drag, and mass, optimizing only for motor power produces unrealistic outcomes.

Across all versions, there is a rejection of linear optimization logic in favor of conditional coupling, whereby the viability of one design choice is constantly affected by its consequences on others. This visual data supports a basic idea of systems engineering: the management of trade-offs, not the pursuit of one-sided benefits, produces design quality. In the framework of F1, when restrictions are very tight and performance margins are small, this concept is not theoretical but rather essential.

2.6 Design Trade-offs Analysis

The last version of the design process, I3, is the result of iterative enhancements that purposefully balanced important trade-offs among energy systems, aerodynamic efficiency, weight, and regulatory compliance.

Drawing attention to acceleration and energy recovery, the motor power (160 kW) and engine power (450 kW) show the exact turn exits characteristic of tracks like Monaco. Within doing parametric sensitivity, it was revealed that thermal limits and falling energy returns above 610 Nm torque needed the power output at this level to stabilize. And by going above and beyond by Increasing the values any higher within these elements, there would be an implication that there is an issue regarding cooling and greater weight, therefore endangering the whole system integrity.

Between aerodynamic efficiency and energy range, a significant trade-off became clear. While there was still a maintenance to the levels of thermal performance, improvements were optimized and as such, were made to lower drag coefficient (0.78) and frontal area (1.32 m^2), so increasing peak velocity and energy efficiency. Wake sensitivity testing (Figure 9.3) confirmed that aerodynamic resilience was maintained even in disturbed flow conditions, therefore achieving this without sacrificing downforce or reducing the cooling envelope. The scatter matrices (Figures 11.1–11.3) confirm this equilibrium by showing that the correlation between powertrain dimensions and drag-related measures declines over iterations, suggesting effective decoupling of parasitic losses from performance-critical outputs.

Regarding energy storage, increases in battery capacity (to 4.8 kWh) and fuel capacity (to 100 L) were not linear optimizations but rather results of limited trade-space research. Though eventually rejected, higher capacities were evaluated since the parallel coordinate plots (Figure 11.4) showed a significant drop in feasible designs beyond this energy limit. This choice shows an optimization concept pertinent to F1 situations: mass penalties and packaging limits must be weighed against the marginal advantages of energy storage. Maintaining vehicle agility, the final configuration optimizes energy accessibility by reaching the best position on the storage-mass curve.

Eventually, as shown in the last pairwise scatter plots, subsystem decoupling was clear in the enhanced autonomy across frontal area, drag, and energy factors. This decoupling shows better system modularity, therefore enabling aerodynamic changes without negative effects on the storage components or powertrain. This result guarantees that constraint propagation happened only when physically justified, therefore improving modeling accuracy by validating the structural rationale ingrained in the parametric model of the system.

The configuration of the last iteration shows a clearly defined, multi-objective trade-off solution that meets system-level feasibility requirements, regulatory, and performance criteria. The design is not globally optimal along any axis; rather, it reflects a strategically constrained Pareto-optimal zone, purposefully produced through focused iteration and driven by modeling accuracy and performance realism.

3. Conclusion

3.1 Design Specification

Parameter	Unit	Final Value
Engine Power Max	kW	450
Motor Power Max (ERS)	kW	160
Torque (Total System)	Nm	730
RPM Range	RPM	3,000 – 11,000
Vehicle Mass	kg	835
Battery Capacity	kWh	4.8
Fuel Capacity	L	100
Thermal Cooling Flow Rate	L/s	0.3
Frontal Area	m^2	1.32
Drag Coefficient (Cd)	–	0.78
Downforce Coefficient (Cl)	–	2.7
Tyre Friction Coefficient (μ)	–	1.65
Sector Time (Target Corner)	s	5.2
Wake Sensitivity Loss @ 1 Car	%	12

Figure 12: *Finalised Specification*

This specification describes the best configuration for the next phase in real world and simulation based testing when concerning a F1 car deployment on low-speed circuits. The design shown in Figure 12 harmonizes several subsystems to enable practical use in simulation methods.

Hybrid Propulsion

Producing a total torque of 730 Nm, the propulsion system combines a 450 kW internal combustion engine with a 160 kW energy recovery system (through the experimentation and optimization of iterative testing). These numbers indicate the maximum limits of hybrid deployment capacity without breaching mass or temperature restrictions (and causing any other internal faults). The specification assures regenerative function during deceleration phases and guarantees that the system can sustain high-intensity outputs for limited segments of the lap. RPM's operability from 3,000 to 11,000 enables torque adaptability across various corners as well.

Mass Distribution & Energy Storage:

With a 4.8 kWh battery, 100 L fuel tank, and 835 kg set vehicle mass, the system guarantees sufficient energy autonomy over several strategic profiles. The design maintains powertrain autonomy for both electric and combustion engines while preventing undue weight increase. Without imposing unreasonable acceleration penalties, this hybrid envelope ensures resilience in energy-sensitive industries including Monaco's tight turns.

Cooling & Thermal Capacity:

Maintaining thermal capacity at 0.3 L/s, the lowest practical level to allow total hybrid deployment without the danger of thermal runaway. Baseline evaluations that confirmed sufficient cooling performance inside the expected power deployment range produced this. The cooling rate is a binding constraint in the integration of the power unit, therefore ensuring that design performance is not reached at the expense of component lifetime.

Frictional Dynamics & Tyre Interaction

The tire friction coefficient of 1.65 was selected, which guaranteed the requisite grip profile during a mid corner phases under both acceleration and stability. This value indicates a suitable grip envelope for soft compound tires in conditions similar to Monaco, with limited reliance on drastic suspension adjustments.

Aerodynamic & Chassis:

The frontal area that was then decided upon was a value of 1.32 m² which paired with a drag coefficient of 0.78, indicate a set of strategic compromises. The downforce coefficient of 2.7 signifies a high downforce which was designed in mind for an optimal experience with traction during transient load circumstances. This should overall Increase the exit speed and reducing wake disturbance directly improve overtaking capability through these aerodynamic features.

Operating Benchmarking:

Articulated by a 5.2 s corner sector time (goal condition) and a 12% wake sensitivity loss, both optimized in relation to baseline values, key performance indicators are An enabler for overtaking on tight city circuits, the reduced wake loss improves following vehicle dynamics. These findings confirm the suitability of the specification for aggressive racing tactics without causing unacceptable trade-offs in thermal, energy, or aerodynamic performance.

Readiness for Execution:

This architecture is now suitable for full integration into simulation processes (verification and validation-based testing) and implementable inside a model-based systems engineering (MBSE) framework. It shows a balanced harmony among operational viability, regulatory compliance, and performance. All metrics in Figure 12 have been selected to fit multi-objective design criteria and are assessed under a system-consistent framework, so confirming their readiness for integration into a testing environment.

3.2 Achievement of Aims and Objectives

The development and iterative improvement of the main system could be said to have successfully accomplished the main goal of this paper, in which was to design an F1 car concept for circuit like that of Monaco, which have issues in overtaking. This was to be done by focusing on using systems engineering and trade-off analysis methodology (SysML & MATLAB). The Results based on verifiable performance improvement, inter-system integration, and technological viability have shown systematic commitment to meeting the project objectives in every stage of this process.

Objective 1 was based on the fundamental subsystem interactions that could or support overtaking performance. By modeling aerodynamic wake sensitivity, using hybrid deployment logic, and handling mass related traction trade-offs, it could be argued that this objective was achieved. The parametric model created clearly specified the interrelationships between traction, aerodynamic load, and rolling resistance. This was also including aerodynamic deterioration in proximity (wake) situations into this method added a notable degree of realism, allowing the study to cover second-order effects on performance.

Objective 2 emphasized creating an integrated architecture able to meet the needs of constrained circuit design. Through an analysis cycle that could be described as iterative in nature, it produced synchronized improvements in aerodynamic performance (drag coefficient dropped from 0.85 to 0.78), hybrid energy systems (ERS power raised to 160 kW), and packaging constraints (frontal area and weight distribution maintained) clearly showed the transition from baseline to final specification. The changes were not carried out in isolation but more so rather in a set of scatter matrices and multivariable plots. The design evolution followed FIA rules and produced feasible combinations improving cornering performance..

Objective 3 sought to offer a verifiable and consistent method for creating needs. The specification table (Figure 12) and the earlier model-based requirement analysis suggest that a systematic transition from stakeholder-aligned needs, e.g., low-speed overtaking, energy deployment balance, to quantifiable, testable system parameters was consistently maintained. Every change was justified with regard to both integration feasibility and performance improvement. Though the study's hypothetical nature meant stakeholder participation was simulated, the architectural approach mirrored the systematic traceability expected in real engineering control.

In the context of objective 4, simulation based techniques for directing system trade-offs and identifying the best design solutions emerged. To fully achieve this goal, sensitivity analyses, design exploration surfaces, and multi objective visualization tools were employed. The result of this has been the noticable trade-off between frontal drag and battery capacity, which was made clearer by direct visualization. The final solution was both optimal and resilient to practical variation thanks to the assistance of parallel coordinate plots and scatter matrices in analyzing feasibility across multidimensional boundaries.

Ultimately, methodical system design strategies, model-based reasoning, and knowledgeable iterative trade-offs fulfilled all initially expressed goals and objectives of the project. Performance modeling, sensitivity analysis, and architectural consistency validate and support the final specification.

3.3 Highlights and Recommendations

3.3.1 Highlights

This study has effectively established a systematic process for creating a system-level specification for an F1 car optimized for overtaking performance in limited, low-speed circuit conditions, utilizing Monaco as a sample track setting. The application of system parametric modeling, multi variable sensitivity analysis, and iterative design progression via simulation has produced a balanced and technically coherent design. This technique has shown that it is not individual characteristics, but their emergent interactions, that determine overtaking feasibility.

A vital success is the development of a high-agility specification that harmonizes aerodynamic efficiency, hybrid power distribution, and cornering dynamics. Small enhancements in aerodynamics and tyre grip yield disproportionately significant performance benefits at low-speed circuits, hence justifying their prioritization in the final design specifications. Similarly, subsystem dependencies (e.g., enhanced battery capacity resulting in a mass penalty) were quantitatively analyzed using the design space and optimization matrices, facilitating an informed equilibrium of performance vectors.

The final specification that was designed encapsulates this synthesis of trade-offs, whereby a feasible yet optimal solution was found finding a balance between the downforce, tire friction, and power delivery, while drag and frontal area were diminished, without compromising thermal equilibrium or beyond feasible limits on mass and energy capacity.

Principal findings within the project are:

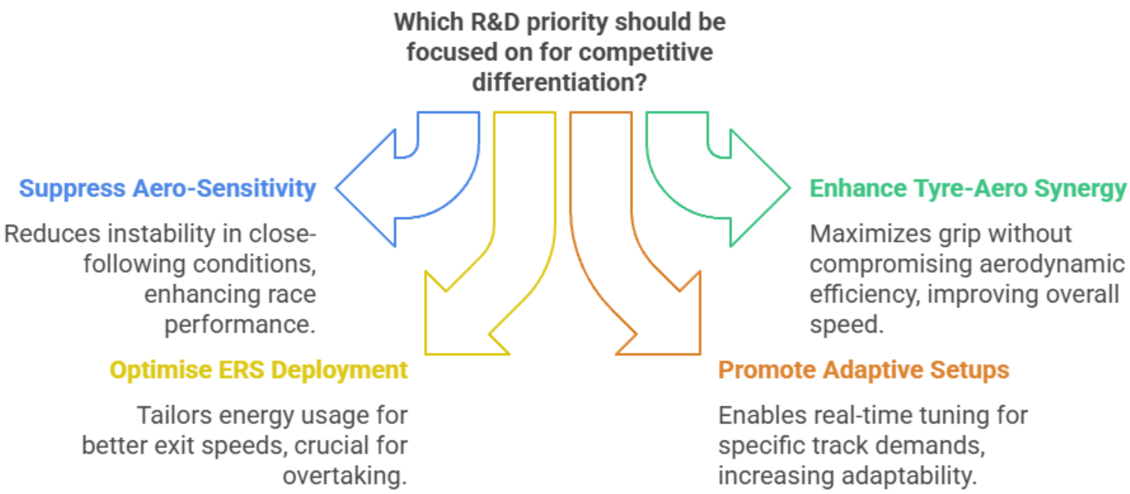
- **Parametric modeling** methods were used in a way that allowed for a connection between performance metrics and requirements, providing a robust framework for finding issues within trade-offs and resolving them.
- **Sensitivity analyses** indicated that vehicle mass exhibited non-linear, diminishing returns when optimized independently, but enhancements in aerodynamics and grip had linear benefits.
- **Multi dimensional tradeoff visualisation** that confirmed the presence of high probability orthotopes inside the design space, especially under optimized grip and downforce configurations
- **Wake sensitivity analysis** that offered valuable understanding of the design's real world durability in racing conditions. This basically aided in highlighting its resilience to turbulent flow in close-following situations.

Overall, these results provide a relevancy within the context of F1 racing that extends beyond the academic realm (and entirely on theory of understanding). They assert that despite stringent packaging and legal limitations, it is possible to design an F1 car specification that maintains overtaking capability through a synergistic optimization method within the subcomponents and their architecture.

3.3.2 Recommendations

Several practical suggestions for upcoming applications and system development in constrained-circuit Formula 1 vehicle engineering may be taken from the proposed work. Although the modeling scope was primarily static and predicated on standard race conditions, the final design successfully addresses overtaking feasibility by carefully resolving trade-offs. Such presumptions would rarely hold true for the duration of a race in a real-world racing situation. Therefore, dynamic scenario validation frameworks must be incorporated into any real-world application of this specification. Initiatives for system development also need to recognize that performance is highly context-dependent under wake, heat, and traction conditions. Instead of being merely afterthoughts, engineers need to view these interdependencies as key design variables. The development of next-generation race vehicles should be focused on strategic toolkits, such as sensitivity-aware tuning, cross-disciplinary collaboration protocols, and live simulation integration.

- In the early stages of design, place a strong emphasis on cross-subsystem integration. Subsystem separation attempts will yield inaccurate results (e.g., assessing hybrid system performance without taking aerodynamic sensitivity into account).
- Augment simulation granularity to integrate dynamic deployment techniques (e.g., ERS mapping by sector), hence establishing a more operationally pertinent basis for trade-off assessment.
- Inclusion of more considered and understood wake-sensitive design parameters would also be beneficial especially in the case of developing aerodynamics parts. Certain downforce profiles are less effective in dirty air (which was not considered throughout the lifespan on this project), which is particularly restrictive in overtaking situations.



The foundations of this work could be strengthened by considering operational scenario testing more in future developments. The lack of real-time performance degradation modeling, such as energy recovery limitations, accelerated tire wear under traffic load, or increased drag due to track contamination, represents a potential implementation accuracy shortfall even though the specification exhibits excellent theoretical optimization. To address this disparity, simulation settings must accurately represent phase-specific deterioration and temporal fluctuations across a race. Furthermore, more system-level validation can be performed by dynamically integrating FIA rule-based limitations during simulation. These limitations could include restrictions on ERS harvesting, overtaking laws during yellow flag conditions, or fuel-saving deployment strategies. These components have a significant influence on how well car designs translate into successful racing strategies, even though they are not necessary for the technical performance model.

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