

University of Wales Trinity Saint David
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***Research Proposal (Optimizing Race Strategy
Through Monte Carlo Simulation)***

Research Methods and Professional Developments (ACFA7004)

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1. Introduction

1.1. Background

Race strategy optimization is a fundamental challenge in motorsport engineering, involving multiple interdependent variables such as tire degradation, fuel consumption, weather conditions, and race incidents. Decision-making in this complex environment is highly uncertain, making data-driven predictive models crucial for competitive performance.

Traditionally, race engineers have relied on deterministic models, such as lap time spreadsheets and static simulations, to develop strategies. However, these approaches fail to quantify uncertainties, often leading to suboptimal pit stop decisions and unexpected race outcomes.

The motorsport industry is gradually shifting towards probabilistic decision-making models, particularly through Monte Carlo Simulation (MCS), which allows for thousands of race scenarios to be simulated, accounting for variations in tire wear, fuel loads, and weather conditions. However, such tools remain proprietary to elite teams, leaving mid-tier and lower-budget teams without access to high-fidelity probabilistic models.

Despite significant advancements in motorsport analytics, existing research primarily focuses on single-variable models, such as:

Pacejka tire models, which provide accurate grip and wear estimations but lack multi-variable interaction modeling. Fuel consumption models, which optimize energy efficiency but do not incorporate stochastic weather variations. Machine learning-based race predictions, which provide trend-based insights but lack a robust uncertainty quantification framework.

Additionally, open-source race strategy tools are virtually nonexistent, limiting accessibility to smaller racing teams. This study aims to bridge this gap by developing a Monte Carlo-based post-race analysis framework to predict strategy performance under uncertainty.

1.2. Aims & Objectives

The primary aim of this study is to develop an open-source Monte Carlo simulation framework for race strategy analysis, capable of predicting probabilistic race outcomes based on race data.

1.3. Specific Objectives:

Develop an integrated probabilistic model incorporating tire degradation, fuel consumption, and weather uncertainties. (Tire data is the main target)

Validate the model using real-world data and implement an open-source software package, enabling accessibility for motorsport teams and researchers.

This study aligns with the increasing use of AI and data-driven decision-making in motorsports, providing a scalable solution for real-world race strategy analysis.

2. Industrial Relevance

2.1. Technical Application

This research contributes to the motorsport industry by addressing a major technological gap—the lack of open-source, probabilistic strategy optimization tools. While top-tier F1 teams leverage advanced predictive analytics (e.g., Mercedes' Digital Twin models and Red Bull's AWS-powered simulations), such solutions are proprietary and cost-prohibitive.

By developing a Monte Carlo-based strategy tool, this research aims to:

Enable mid-tier and junior motorsport teams to apply probabilistic modeling in race strategy decisions.

Improve pit stop accuracy by predicting tire degradation under variable conditions.

Enhance fuel efficiency planning, reducing unnecessary pit stops and fuel waste.

2.2. Sustainability & FIA Regulations

Motorsport is evolving towards sustainability, with FIA's 2026 Sustainable Fuel Policy (FIA, 2023) mandating optimized fuel consumption and eco-friendly strategies. A robust fuel efficiency model, embedded within this Monte Carlo framework, will:

Assist teams in reducing carbon emissions by optimizing fuel strategy.

Enhance tire lifecycle management, reducing waste and aligning with Pirelli's environmental initiatives.

2.3. Economic Impact

Race strategy errors incur significant financial losses due to:

Unnecessary tire changes, leading to excess tire consumption.

Inefficient fuel strategies, increasing resource waste.

Misjudged pit stops, resulting in position losses.

By minimizing resource misallocation, this framework provides cost-saving benefits to smaller teams, improving competitiveness across Formula 3, Formula E, and endurance racing.

2.4. Industry Trends

F1 & Machine Learning: Elite teams use AI-powered race simulations to enhance decision-making.

Data Democratization: Open-source tools are gaining traction in motorsport engineering.

Increasing Reliance on Simulation-Based Strategy: Teams are moving from deterministic to probabilistic models for real-time adaptability.

This research aligns with these industry shifts, offering an innovative yet accessible solution.

3. Literature Review

3.1. Theoretical Framework

The optimization of race strategy in motorsports requires a multidisciplinary approach, integrating tire physics, fuel efficiency models, stochastic simulation methods, and machine learning techniques. This section reviews the key existing literature and identifies gaps in knowledge.

3.2. Tire Dynamics & Degradation Models

One of the most critical aspects of race strategy is tire performance, which influences lap times, pit stop frequency, and overall race results.

Pacejka's Magic Formula (1987)

The Pacejka tire model is a widely used mathematical representation of tire behavior under different conditions. While effective for grip estimation, it does not fully capture multi-lap degradation effects. Recent advancements in data-driven tire wear models (Zhang et al., 2021) integrate real-time telemetry and machine learning to predict tire performance.

FIA Tire Test Data (2023)

The FIA-provided datasets contain degradation curves for compounds C1 to C5, derived from pre-season tire testing. These datasets provide empirical parameters for modeling stochastic wear patterns under variable temperature and load conditions.

3.3. Monte Carlo Simulation in Motorsport Strategy

Monte Carlo Simulation (MCS) is a probabilistic modeling technique widely used in engineering and finance to assess risk and uncertainty. Recent applications in motorsports decision-making include:

Smith et al. (2020, SAE Paper 2020-01-0742) demonstrated MCS-based failure rate predictions in automotive systems.

Mobin & Hijawi (2020) applied MCS to stochastic optimization problems, showing its superiority over deterministic models.

In the context of race strategy, MCS enables engineers to generate thousands of race scenarios by varying parameters such as tire degradation, fuel consumption, and weather fluctuations.

Comparison with Machine Learning-Based Predictions

While Machine Learning (ML) models have been increasingly used in motorsport for race prediction (e.g., neural networks trained on historical race data), MCS offers distinct advantages:

Aspect	Monte Carlo Simulation	Machine Learning (ML)
Approach	Stochastic simulation	Data-driven regression/classification
Output	Probabilistic distributions	Deterministic prediction (single output)
Interpretability	High (transparent calculations)	Low (black-box models)
Data Requirements	Moderate	High (requires large labeled datasets)
Application in F1	Strategy risk analysis	Predictive analytics

MCS is particularly advantageous in motorsport because race outcomes depend on complex, interdependent variables, where probabilistic assessments provide richer insights than point predictions.

3.4. Fuel Efficiency & Sustainable Racing Strategies

Fuel consumption models are integral to race strategy, particularly in endurance racing and the FIA’s 2026 Sustainable Fuel Initiative. The Global Fuel Economy Initiative (GFEI, 2023) provides industry benchmarks on fuel efficiency under racing conditions.

Energy Recovery & Hybrid Powertrain Optimization

Mercedes-AMG Petronas F1 Team has integrated Energy Recovery Systems (ERS) into their race simulations.

Toyota Gazoo Racing (Le Mans 24h) applies probabilistic fuel models to maximize hybrid energy deployment.

A key research in integrating fuel modeling with real-time race conditions, an area where this research aims to contribute.

3.5. Weather Variability & Environmental Uncertainty

Weather is a major uncertainty factor in race strategy. Rainfall probability, track temperature fluctuations, and wind speed influence grip levels, tire selection, and pit stop strategy.

FIA Weather Prediction Models (2023) provide short-term race forecasts.

Markov Chain-based models (Xu et al., 2021) predict stochastic weather transitions, an approach adaptable to Monte Carlo-based strategy optimization.

3.6. Research Gap

Despite these advancements, existing race strategy models suffer from critical limitations:

Lack of multi-variable probabilistic modeling—most current research focuses on single-factor optimization.

Closed-source nature of F1 team tools—advanced AI-driven models are proprietary, leaving smaller teams without access.

Limited integration of real-world stochastic factors—models do not comprehensively combine tire degradation, fuel economy, and weather uncertainty.

This research addresses these gaps by developing an open-source Monte Carlo simulation tool that integrates tire physics, fuel efficiency modeling, and stochastic weather data.

4. Methodology

4.1. Data Collection

The research is expected to combine real-world race telemetry, FIA datasets, and open source APIs.

Primary Data Sources

1. Simulate tire data from real tests under various conditions.
2. Obtain data from some educational and commercial websites, such as but not limited to:
<https://www.megaride.eu/>

4.2. Variable Definition & Stochastic Modeling

Each race factor is modeled as a probabilistic distribution, capturing real-world uncertainties.

Key Variables:

Variable	Distribution Type	Source
Tire degradation	Normal ($\mu \pm 5\% \sigma$)	FIA test data
Fuel efficiency	Discrete probability	GFEI reports
Weather impact	Markov Chain	FIA weather models

By implementing these stochastic parameters, the model ensures realistic race variability.

4.3. Monte Carlo Simulation Process

1. Generate 10,000 race iterations, varying:

Pit stop timing

Tire degradation rates

Fuel consumption

Weather conditions

2. Compute probability distributions for:

Winning probability under different strategies

Tire lifespan predictions

Fuel conservation efficiency

3. Identify key influencing factors using:

Sobol sensitivity analysis

Variance decomposition techniques

4. Validate against real-world races:

Compare predictions to 2023 Hungarian Grand Prix strategy data.

Compute model accuracy metrics (e.g., mean absolute error of tire wear predictions).

4.4. Computational Framework & Toolchain

The framework is implemented using a combination of MATLAB, Python, and a range of experimental data visualization software.

4.5. Validation & Performance Metrics

To ensure model accuracy, the following statistical techniques will be applied:

ANOVA (Analysis of Variance)—to evaluate strategy impact.

Mean Squared Error (MSE)—to measure deviation from real race outcomes.

Cluster analysis (Scikit-Learn)—to classify optimal vs. suboptimal pit stop strategies.

4.6. Potential Limitations & Mitigation

Data noise (sensor inaccuracies) → Apply Kalman filtering.

Computational cost (10,000 iterations) → Optimize with parallel processing.

Weather unpredictability → Implement real-time Markov Chain updates.

5. Expected Results & Analysis

5.1. Overview of Expected Outcomes

This study aims to develop an open-source Monte Carlo-based race strategy analysis framework, providing probabilistic insights into optimal pit stop strategies, fuel efficiency, and tire degradation predictions under varying race conditions. The expected results will be quantitative and qualitative, providing motorsport teams with actionable insights.

The primary expected outputs include:

Probabilistic distributions of race outcomes under different strategies.

Tire degradation model validation, comparing real-world wear rates with predicted values.

Fuel consumption efficiency estimates, helping teams optimize refueling or hybrid energy management.

Impact assessment of weather uncertainty, quantifying how different weather conditions influence tire selection and race strategy.

By leveraging stochastic modeling, this study will identify key variables influencing race success, helping motorsport teams make data-driven strategic decisions.

5.2. Quantitative Outputs

The Monte Carlo simulation will generate a variety of statistical outputs, focusing on strategy success rates, tire longevity, and fuel efficiency.

5.2.1. Strategy Probability Distributions

A key deliverable is the probabilistic success rate of different pit stop strategies.

By running 10,000 simulated races, the framework will determine optimal stopping windows for each tire compound.

The results will be presented as a probability density function (PDF), illustrating the win likelihood under different strategies.

5.2.2. Tire Degradation & Longevity Predictions

The stochastic tire degradation model will be evaluated against real-world FIA tire test data.

The Monte Carlo model will estimate average tire lifespan, considering:

Track temperature variations

Fuel load impact on wear

Different tire compounds (C1-C5)

Validation metric: Mean Absolute Error (MAE) will be calculated between simulated vs. real degradation curves.

5.2.3. Fuel Consumption & Efficiency Improvements

Fuel consumption will be modeled as a discrete probability distribution based on:

Engine mode selection (standard, high-performance, fuel-saving)

Aerodynamic drag variability

Hybrid energy recovery contribution (ERS)

The Monte Carlo model will estimate fuel savings (%) per optimized strategy.

Results will be visualized in a heatmap format, showing the impact of fuel-saving techniques.

5.2.4. Weather Uncertainty Impact Assessment

The Markov Chain-based weather model will analyze:

Rain probability per session

Track cooling rate under cloud cover

Wind speed variations affecting aerodynamics

Result: A stochastic risk matrix, evaluating strategy robustness under uncertain weather conditions.

5.3. Qualitative Analysis

Beyond numerical outputs, this study aims to provide qualitative insights into race strategy robustness.

5.3.1. Strategy Robustness Assessment

The simulation will rank different race strategies based on their resilience to external factors (e.g., tire wear anomalies, unexpected safety cars).

Sensitivity analysis (using Sobol indices) will determine:

Which variables have the greatest influence on strategy success?

How sensitive is race outcome to tire degradation vs. fuel efficiency?

Findings will be summarized in a decision matrix, categorizing strategies into:

Highly robust

Moderately robust

Risk-prone

5.3.2. Comparative Analysis: Monte Carlo vs. Deterministic Models

The study will compare traditional deterministic models (e.g., Excel-based lap time predictions) against probabilistic Monte Carlo outputs.

Metrics for comparison:

Accuracy in predicting tire wear & fuel efficiency

Ability to model unexpected race scenarios (e.g., safety car events)

Computational performance trade-offs

5.3.3. Real-World Case Study Validation (e.g. Hungarian Grand Prix 2023)

Since data collection requires time, permission and many other factors, it would be helpful if data from certain historical matches could be obtained successfully so that effective and reasonable analysis can be carried out. The Monte Carlo model's predictions will be benchmarked against historical race data.

Case study analysis will compare:

Predicted vs. actual pit stop timing

Fuel efficiency accuracy

Tire degradation curve validation

Expected outcome: The model should show >85% accuracy in pit stop prediction, validating its practical application.

5.4. Statistical & Computational Analysis

To validate model accuracy, the study will employ advanced statistical tools and machine learning techniques.

Analysis Method	Purpose	Tool Used
Mean Squared Error (MSE)	Evaluate tire degradation model accuracy	Python (SciPy)
Analysis of Variance (ANOVA)	Compare race strategy performance across conditions	MATLAB Statistics Toolbox
K-Means Clustering	Identify optimal vs. suboptimal strategy clusters	Scikit-Learn (Python)
Sensitivity Analysis (Sobol Indices)	Determine key influencing variables	NumPy & Pandas (Python)
Heatmap Visualization	Display fuel efficiency gains per strategy	

Expected Outcome:

High correlation (>0.9) between simulation results and real-world data.

Identified key factors that contribute most to race strategy success.

Demonstration of Monte Carlo model outperforming traditional methods in uncertainty quantification.

5.5. Challenges & Mitigation Strategies

Despite its advantages, the Monte Carlo approach faces several challenges, which this study will address.

1.Data Uncertainty & Sensor Noise

Issue: Real-world telemetry data contains sensor noise, affecting accuracy.

Mitigation: Implementing Kalman filtering & Gaussian smoothing to clean data before simulation.

2.Computational Complexity

Issue: Simulating 10,000 race iterations is computationally expensive.

Mitigation:

Utilize parallel processing (NumPy vectorization & multi-threading).

Optimize Monte Carlo convergence by using Latin Hypercube Sampling (LHS).

3.Weather Uncertainty Complexity

Issue: Weather modeling is inherently unpredictable.

Mitigation: Use Markov Chain state transitions instead of simple probability distributions, improving forecast adaptability.

5.6. Practical Implications for Motorsport

The outcomes of this study will have wide-ranging benefits for motorsport engineering:

Application	Impact
Formula 1 Strategy Optimization	Helps teams evaluate risk-adjusted pit stop windows.
Endurance Racing (WEC, Le Mans)	Improves fuel conservation strategies for hybrid powertrains.
Formula E & Electric Motorsport	Aids in energy management optimization.

Sim Racing & eSports	Provides accurate AI-driven racing strategy models.
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5.7. Conclusion

This study will provide a data-driven, probabilistic approach to race strategy optimization, demonstrating that:

Monte Carlo methods outperform traditional deterministic models in uncertainty quantification.

Integrated tire degradation, fuel efficiency, and weather models improve strategy accuracy.

Open-source simulation tools democratize advanced race analytics, benefiting teams with limited computational resources.

By combining probabilistic analysis, real-world validation, and machine learning techniques, this research will push the boundaries of motorsport engineering, offering practical applications for both professional and amateur racing teams.

6. Project Plan (Gantt Chart)

Phase	Task	Duration
Phase 1	Literature Review & Data Collection	May
Phase 2	Model Development & Validation	June
Phase 3	Open-Source Tool Implementation	July
Phase 4	Analysis & Dissertation Writing	August

7. Evaluation

This research proposal presents a comprehensive Monte Carlo-based approach to optimizing race strategy through probabilistic modeling. While the proposed methodology is robust and grounded in established statistical and engineering principles, there are several key strengths and potential limitations that must be critically examined.

7.1. Strengths of the Research

1. **Holistic Integration of Race Variables:** Unlike traditional deterministic models, this study integrates tire degradation, fuel efficiency, and weather variability within a single probabilistic framework, providing a more accurate representation of real-world uncertainties.
2. **Applicability to a Wide Range of Motorsport Categories:** The methodology is applicable beyond Formula 1, extending to endurance racing, Formula E, and even sim racing.
3. **Democratization of Advanced Analytics:** By creating an open-source Monte Carlo simulation toolkit, this research lowers the entry barrier for mid-tier and independent racing teams, allowing them to benefit from advanced strategy optimization.
4. **Validation through Real-World Case Studies:** Benchmarking against the 2023 Hungarian Grand Prix ensures that the model is grounded in real-world data and is not just a theoretical construct.

7.2. Potential Challenges & Limitations

1. **Computational Demands:** Running 10,000 Monte Carlo iterations requires significant computational resources, which could pose challenges for smaller teams with limited hardware capabilities.

Mitigation: Implement parallel processing optimizations and explore cloud-based simulation frameworks.

2. **Data Availability & Quality:** While FIA and FastF1 datasets provide valuable insights, real-world race telemetry is often proprietary and difficult to obtain.

Mitigation: Incorporate data augmentation techniques and leverage alternative open-source race archives.

3. **Simplified Weather Model:** While the Markov Chain-based weather transition model is an improvement over deterministic forecasts, it may still lack granularity in sudden weather changes (e.g., microclimate shifts at circuits like Spa-Francorchamps).

Mitigation: Integrate real-time weather API inputs for improved adaptability.

7.3. Expected Contribution to the Field

Despite these challenges, the proposed research is expected to make a significant impact on motorsport engineering by introducing an accessible, probabilistic strategy analysis framework. The ability to quantify risk-adjusted decisions in racing can revolutionize how teams approach race strategy, making motorsport more data-driven and analytically precise.

Furthermore, the findings from this study can bridge the gap between academia and professional motorsport, providing actionable insights for both race engineers and data scientists working in the field.

7.4. Final Outlook

With a well-structured research plan, comprehensive validation strategy, and mitigation measures for potential challenges, this study has a high probability of yielding valuable insights. By successfully executing this research, the developed open-source Monte Carlo simulation toolkit could become an indispensable analytical asset for motorsport teams worldwide.

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