Statistical Analysis of Tire Performance and Pit Strategy in Formula 1 Racing

https://youtu.be/GwiF1hZk91Q

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1. Introduction

Formula 1 car racing is considered to be at the pinnacle of motor sport, characterized by high-speed competition, high-tech innovation, and tactical driving. Of all the many aspects of car racing under such stringent conditions, tire compounds represent an important variable that can end up greatly determining a team's performance over a event. Every tire compound, namely Soft, Medium, and Hard, has different qualities that dictate traction, longevity, and overall lap performance. It is pivotal that any team interested in optimizing their competitive approach and enhancing their chances of winning really understand these aspects.

A Formula 1 car's performance is not only determined by engine output and aerodynamic aspects but also to a great extent by tires. Softer tires, for instance, provide better traction, leading to faster lap times, but are prone to wear quickly, leading to an increased number of pit stops. Harder tires, on the other hand, have greater durability, albeit at the expense of slower lap speeds. This delicate dance between speed and longevity is central to racing strategy, which highlights a close study of tire performance.

2. Objectives

The main objectives of this work are stated as below. First, it aims to examine in-depth the effect of different tire compounds, namely Soft, Medium, and Hard, on both stability and consistency of lap times over segments of a race. Understanding this relationship is important since softer tires tend to offer better traction and faster lap times but soon degrade, which can lead to greater inconsistency in lap times and a higher chance of performance loss.

Secondly, we aim to discover optimal pit stop strategies tailored to different meteorological conditions. Meteorological conditions play a major role in determining the dynamics of a race, including tire wear, traction, and optimal times of performing a pit stop. By modelling possible pit stop times under different weather conditions, our study aims to identify patterns thereof that can be used for strategic purposes, such as optimal times for tire compound changes or altering driving habits.

3. Literature Review

The effect of tire compounds on competitive performance has been rigorously analysed in motorsport-related studies. Smith et al. (2019) showed that softer tire compounds lead to faster lap times, but this comes with increased wear and unpredictability. Jones and Lee (2021) carefully explored this trade-off further, highlighting that speed has to be weighed against durability in tire choice.

Academic study of pit stop strategies has also become an important field of study. Brown and Patel (2020) highlighted that weather conditions play an important aspect in planning stops, suggesting that poor weather could necessitate earlier or more often stops. Survival analysis methodologies, such as Kaplan-Meier estimators, have also been used efficiently to study stopping times and predict optimal stopping times (Garcia et al., 2018).

Time series decomposition methods have been applied in lap time series analyses to detect underlying patterns and periodic effects due to tire wear-out and track development (Wang & Chen, 2022). This study extends these concepts by using a varied range of sources of information together with a large suite of statistical methods to provide an all-encompassing view of tire performance and pit stop strategies.

4. Methodology

4.1 Data Sources

The data used for this study was carefully compiled from two main sources, thus ensuring a complete and diversified dataset for analysis:

The Ergast Developer API serves as an exhaustive database of historical information relevant to Formula 1 racing. It allows for users to access information regarding lap times, information relating to tire types, timing of pit stops, and classification of weather conditions, from 2000 to 2023. Such completeness of dataset allows for advanced analysis of performance of every race over time, thus enabling effective comparative assessments between different seasons and tracks.

Kaggle Data: A supplementary dataset with weather conditions for Formula 1 racing from 2018 to 2023 has been used. This dataset includes relevant variables like temperature, humidity, and rainfall, which are useful for understanding the role that weather conditions play on tire performance as well as pit stop planning. Adding weather information adds another layer of complexity to the analysis so that deeper insight can be derived from the dynamics that exist under racing conditions.

4.2 Data Preparation

Data cleaning and preparation procedures played a significant role in ensuring accuracy and useability of these datasets. Data loading and preprocessing procedures that were carried out are demonstrated in the following code segments:

```r
# Load necessary libraries
library(dplyr)
library(jsonlite)
library(httr)

# Load tire data
tyre_data <- read.csv("C:/Users/Priyanka/mangrulkarp_final_project/Tyre

# Load weather data
weather_data <- read.csv("C:/Users/Priyanka/mangrulkarp_final_project/F

# Convert Rainfall to logical
weather_data$Rainfall <- as.logical(weather_data$Rainfall)
```

During this step, tire and meteorological information were brought into R, and rainfall was converted to a logical data type to improve analytical efficacy. This step was vital to enable easy filtration and scrutiny of weather conditions that are relevant to racing activities. Data from multiple sources were cleaned, transformed, and merged to create a cohesive dataset for analysis. Timestamp formats were standardized, tire compound labels normalized, and missing values handled appropriately.

The merging process was carried out using key identifiers such as RaceID, DriverID, and lap number to align lap times, pit stops, and weather data. Inconsistencies due to accidents or safety car periods were identified and excluded to avoid any skew in the results.

4.3 Quantitative Method

It employs a range of established statistical methods to analyze the data, choosing each according to its relevance to the questions under study.

The Analysis of Variance (ANOVA) is a statistical approach applied to examine and evaluate the mean lap times of different tire compounds. ANOVA allows for the detection of significant differences in lap times due to tire choice, providing substantial insight into differences in performance attributes of different compounds under different conditions.

Kaplan-Meier Survival Analysis: This approach is applied so that an investigation can be done on the timing of pit stops, ultimately enabling an evaluation of meteorological conditions' influence on pit strategies. The use of Kaplan-Meier estimator offers significant information regarding a driver's likelihood of needing a pit stop at various laps, which is imperative in creating efficient racing strategies.

Time series decomposition is a method used by teams to identify trends of tire degradation over the course of a race. Through the examination of variations in tire performance during a race, teams can make data-driven decisions on the optimal timing of pit stops and tire compound choice.

5. Statistical Methodologies

5.1 Analysis of Variance (ANOVA)

A statistical analysis using ANOVA was conducted to investigate whether there are significant differences between means and variances of lap times in different tire compounds. This analytical method allows for an investigation of whether any differences between lap times are of statistical relevance, providing valuable information on each tire compound's performance qualities. The code snippet below describes the application of the ANOVA methodology:

The ANOVA testing clearly confirmed significant differences ($p < 0.001$) in both mean values and variances of lap times between different tire compounds. Post-hoc Tukey's HSD tests then showed significant differences between pairs, with Soft yielding the quickest though least consistent lap times, Medium finding an optimal balance between pace and consistency, and Hard providing the slowest times though with maximum stability.

```r
anova_model <- aov(Lap_Time ~ Tyre_Compound, data = race_data)
summary(anova_model)

# Post-hoc test
TukeyHSD(anova_model)
```

5.2. Kaplan-Meier Survival Analysis

The timing of pit stops was studied using survival analysis, with a pit stop being defined as an event and time being measured by the number of laps driven before stopping. It allows for comparison between different pit stop strategies under different weather conditions. The code snippet below demonstrates building a survival object with fitted Kaplan-Meier curves:

```r
library(survival)
library(survminer)

# Create survival object
race_data$pit_event <- ifelse(race_data$Pit_Stop == 1, 1, 0)
surv_obj <- Surv(time = race_data$Lap, event = race_data$pit_event)

# Fit Kaplan-Meier curves by weather condition
fit <- survfit(surv_obj ~ Weather_Condition, data = race_data)

# Plot survival curves
ggsurvplot(fit, data = race_data, pval = TRUE, conf.int = TRUE,
           legend.title = "Weather Condition",
           xlab = "Lap Number",
           ylab = "Probability of No Pit Stop")
```

Kaplan-Meier plots showed a longer dryness duration compared with the higher frequencies of pit stops due to inclement weather. Median numbers of laps to do pit stops were significantly reduced under rainy conditions, thus highlighting weather effects on pit stop strategies.

5.3 Time-Series Decomposition

Decomposition by Seasonal-Trend Loess (STL) was applied to separate lap times into individual stints, enabling extraction of trend (degradation), seasonality, and residuals. Decomposition by STL aids better visualization of changes in lap times over a stint.

Use of STL decomposition is presented in the following code snippet:

```
library(forecast)

# Example for a single stint
stint_lap_times <- race_data %>%
  filter(DriverID == "driverX", RaceID == "raceY", Stint == 1) %>%
  arrange(Lap) %>%
  pull(Lap_Time)

# Convert to time series object
ts_lap_times <- ts(stint_lap_times, frequency = 5)  # frequency chosen

# STL decomposition
decomp <- stl(ts_lap_times, s.window = "periodic")
plot(decomp)
```

Decomposition by STL revealed that there was a rising trend across stints with a strong trend of degradation for Soft tire compounds, moderate for Medium tires, and nearly not perceptible by eye for Hard tires. Decomposition by STL provides vital information on tire performance reduction over time, which helps teams to take apt decisions on optimum pit stop times.

5.4 Mixed-Effects Model

In an effort to account for individual drivers' variation in lap times, a Linear Mixed-Effects Model (LMM) was implemented using the lme4 package. This modelling was important because each driver covers many laps, which violates the independence premise underlying standard statistical models. By specifying tire compound as a fixed effect and driverId as a random intercept, the model effectively controls for tire compound's actual effect on lap performance. Analysis showed that, after controlling for individual driver effects, Soft tires were associated with an average of 2.07 additional seconds per lap compared with Medium tires.

```
output$mixedModelSummary <- renderPrint({
  df <- lap_data() %>% filter(driverId %in% input$driverId)
  df <- assign_tyre_compound(df, tyre_data, input$season, input$round)
  df <- df %>% filter(!is.na(compound))
  if (nrow(df) < 2) return(cat("Not enough data for a mixed model.\n"))
  model <- lmer(time_sec ~ compound + (1 | driverId), data = df)
  summary(model)
})
```

This effect was statistically significant (t = 5.85), and the model was able to account for random performance variation between drivers. The residual variance (0.709 seconds) reflects significant between-driver variation in laps. By including random effects, the model represents improved generalizability and reduces over-attribution of variation in lap times to tire compounds. This, in turn, enhances the reliability of the model for use in practical racing environments, especially in comparing strategies between drivers. Implementation of the model in real time with the Shiny app allowed for dynamic feedback for each individual race and driver choice.

6. Analysis

6.1 Lap Time Analysis

An analysis of lap times was carried out using the collected data on laps. This involved representing lap time trends for every driver over the course of a race. The following code snippet demonstrates the process used for graphical presentation of lap times:

```
output$lapTrendPlot <- renderPlot({
  req(lap_data(), input$driverId)
  df <- lap_data() %>% filter(driverId %in% input$driverId)

  ggplot(df, aes(x = lap, y = time_sec, color = driverId)) +
    geom_line(size = 1) +
    labs(title = "Lap Time Trends", x = "Lap", y = "Lap Time (s)", color =
    theme_minimal()
})
```

Such an approach enables an easy comparison between lap times across different drivers, thus highlighting differences in performance and tire management. Combined with total laps driven, it is possible to detect patterns and significant deviations that could reflect tire wear, or tactical stops. ANOVA analysis showed significant differences between both mean lap times and variances between different tire compounds ($p < 0.001$). Soft tires showed the fastest average lap times but at the expense of high variance, reflecting rapid decay. Medium compounds showed a balance of speed with stability, with Hard tires showing both lowest lap times but highest stability.

The findings reaffirm theoretical trade-offs developed in previous literature and highlight the importance of choosing compounds that are particularly adapted to racing conditions and tactical strategies.

6.2 Tire Composition's Influence

ANOVA was applied to evaluate the effect of tire compounds on lap times. This analytical method allows us to detect if differences in lap times resulting from different tire compounds are significant.\

```
output$anovaSummary <- renderPrint({
  df <- lap_data() %>% filter(driverId %in% input$driverId)
  summary(aov(time_sec ~ compound, data = df))
})
```

The observations from ANOVA provide insightful information on which tire compounds are yielding optimal performance, thus guiding tire selection strategies for teams. From an understanding of which variations in lap times are statistically significant, teams can make informed decisions about the choice of tire compounds to use in future races. Time series decomposition showed a consistent rise in lap times over the stints, consistent with tire wear phenomenon. Degradation was found to be maximum for Soft compounds, intermediate for Medium compounds, and least for Hard tires. Seasonal components captured lap time fluctuations possibly related to traffic or track evolution, while residuals accounted for random noise and driver-specific factors.

6.3 Pit Stop Analysis

The information related to pit stops was analyzed using Kaplan-Meier survival analysis to help understand the timing of pit stops under different weather conditions. Understanding this is critical for designing effective pit strategies:

```
output$kmPlot <- renderPlot({
  pit_df <- gather_pit_data(input$season, input$round)
  fit <- survfit(Surv(time = pit_df$lap, event = pit_df$event) ~ condition,
  plot(fit, col = c("red", "black"), lwd = 2)
})
```

The Kaplan-Meier plots generated from this analysis illustrate the survival probabilities for drivers requiring pit stops under varying conditions, thus providing critical information for developing race strategies. By illustrating the probability of pit stops for different laps, teams are better able to anticipate the ideal moment to initiate their strategies based on the changing nature of the race. Kaplan-Meier survival analysis revealed significant differences in pit stop timing between varying weather conditions. In dry conditions, longer stints between pit stops were indicated by longer medians between laps, indicating extended stints. Wet conditions, however, required earlier and more frequent pit stops due to tire adjustments necessitated by changes in track surface. Hazard rate analysis revealed an increased risk for pit stops under conditions of changing weather, emphasizing the strategic complexities that teams face in changing environments.

7. Conclusion

This study performs an exhaustive empirical examination of tire performance and pit stop tactics in Formula 1 racing based on a large dataset with advanced analytical tools. It demonstrates that tire compounds play an important role in determining lap time consistency and rates of wear, with Soft tires providing better speeds at the expense of stability, while Hard tires provide better longevity at a slower speed. Additionally, under meteorological conditions, the timing of pit stops is greatly influenced by weather, with rainy conditions requiring earlier and more stops.

It combines ANOVA, survival analysis, and time-series decomposition techniques to present an overall view of tire and pit strategy optimization. Practical application of findings from this study holds important implications for racing organizations seeking increased performance by adopting data-based decision-making techniques.

8. Limitations

While exhaustive, this analysis does have some shortcomings. Alas, despite the vast range of available data, there could be undetected inconsistencies or holes, especially in respect to weather information and tire compounds. Uniformity is assumed in each lap by the study; however, differences in traffic flows, driving behavior, and time under a safety car inject uncertainty that cannot be fully controlled.

In addition, survival analysis treats pit stops independently; however, in practice, tactical team decision-making, together with activity by opposing drivers, imposes complex interdependencies. Disaggregated time-series data lead to overall decline patterns being revealed; however, these fail to adequately characterize contextual factors like track temperature or mechanical issues.

9. References

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