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Aerodynamic Design and Selection of NACA Airfoils for F1 Racing Cars Tailored Different Circuit Characteristics

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Abstract. Aerodynamic performance plays a decisive role in cornering speed and straight-line top speed for Formula 1 racing cars, and the selection of rear-wing airfoils directly dominates the critical trade-off between aerodynamic downforce and drag. This study constructs a computational-fluid-dynamics-based numerical simulation model taking NACA four-digit airfoils as research objects, and systematically investigates the influences of camber, thickness, and angle of attack on lift coefficient, drag coefficient, and lift-to-drag ratio. Simulation results indicate that camber contributes most to downforce enhancement, whereas thickness primarily controls drag characteristics; the drag coefficient increases by about (4-5) % with every 2 % growth in airfoil thickness. Corresponding airfoil selection strategies are proposed for three typical F1 circuits. The symmetric thin NACA 0008 is adopted for high-speed Monza to minimize drag; high-camber NACA 4412 is applied for technical Monaco to improve cornering performance; for mixed-layout Silverstone, NACA 4412 at (4-6)° angle of attack realizes balanced performance. The established mapping criteria between circuit characteristics and airfoil parameters can provide theoretical support for preliminary aerodynamic design and tuning of F1 rear-wing profiles.

Keywords: NACA airfoil, aerodynamics, track characteristics, airfoil selection, numerical simulation

1. Introduction

Aerodynamic performance is often the deciding factor that determines the overall competitiveness of a Formula 1 (hereinafter referred to as F1) racing car. In F1 vehicles, aerodynamic downforce determines the stability and cornering speed during high-speed turns. As F1 technical regulations keep evolving, aerodynamic development has become a priority focus area in team research. Statistical data indicate that the maximum lateral acceleration of an F1 car during racing can reach approximately 6g, and most of that load comes from the rear wing, underscoring its crucial role among vehicle components [1].

In recent years, researchers worldwide have conducted extensive investigations on the aerodynamic analysis and optimization of NACA airfoils. Liu et al. proposed an airfoil optimization framework based on Open FOAM and the Bayesian network, and found that the lift-to-drag ratio improved significantly with increasing thickness under single-objective optimization [2]. Chandan et al. employed the parametric finite element method to perform precise aerodynamic analysis of the

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NACA4415 airfoil, showing that higher-order computational schemes in simulating flow around airfoils [3]. McKay et al. systematically studied the influence of airfoil aerodynamic characteristics on vehicle performance and lap time, concluding that the maximum downforce condition yields optimal performance under most circuit operating conditions, whereas reducing downforce can lead to faster lap times under specific geometric configurations [4]. However, existing studies have largely focused either on airfoil optimization in isolation or on single-circuit scenario analysis, with limited in-depth discussion on how different circuit characteristics systematically determine airfoil selection criteria [5-7].

2. Numerical methods

2.1. Bacic information of NACA airfoil

In both theoretical studies and engineering practice of airfoil aerodynamic design, the four-digit NACA (National Advisory Committee for Aeronautics) airfoil series has been widely adopted as a benchmark profile in motorsport aerodynamics, owing to its concise parametric representation and favorable aerodynamic characteristics. The geometry of this airfoil family can be read directly from a four-digit code: the first digit gives the maximum camber as a percentage of the chord length, the second digit gives the position of maximum camber in tenths of the chord, and the last two digits gives the maximum thickness as a percentage of the chord. This simple coding makes modeling and performance estimation straightforward.

2.2. Selection of representative airfoils

The aerodynamic design of F1 racing car wings is all about a balance trade-off between downforce and drag, and this trade-off is physically embodied in the geometric parameters of the airfoil, particularly camber and thickness. Different circuit types impose distinct requirements on these two parameters: high-speed circuits favor small camber and small thickness to minimize drag, whereas technical circuits require large camber and moderate thickness to maximize downforce. Five representative airfoils from the NACA four-digit series are selected as the research subjects in this study. The specific geometric parameters are listed in the table below.

Table 1. Selection of airfoil geometric parameters

Type of airfoil	Maximum curvature f(%)	Maximum curvature position	Maximum thickness t (%)	Reason for selection
NACA0008	0	-	8	Symmetrical airfoil with extremely low drag
NACA0010	0	-	10	Symmetric airfoil, balancing low drag and structural strength
NACA0012	0	-	12	Symmetric airfoil, benchmark validation data source
NACA2410	2	0.4	10	Medium-camber thin airfoil, balanced downforce and drag

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Table 1. (continued)

NACA4412	4	0.4	12	High-camber medium-thickness airfoil, maximizing downforce

2.3. Geometric models

The geometric shapes of NACA0008, NACA0010, NACA0012, NACA2410, and NACA4412 airfoils were established using ANSYS—CFD, as shown in Figures 1–5.

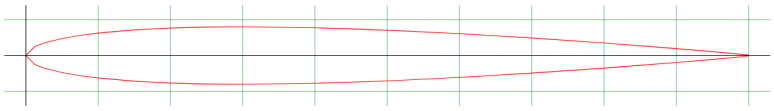


Figure 1. NACA0008 geometric model

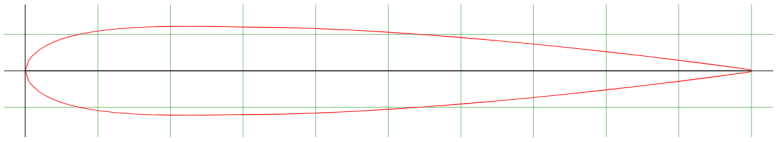


Figure 2. NACA0010 geometric model

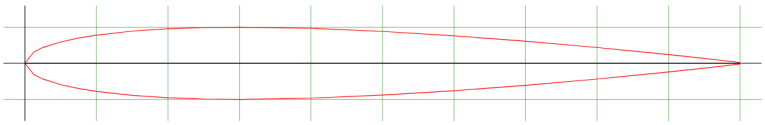


Figure 3. NACA0012 geometric model

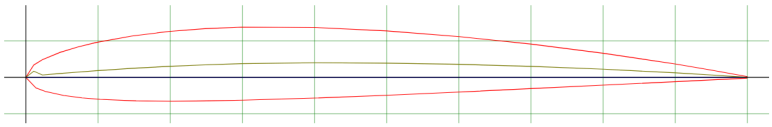


Figure 4. NACA2410 geometric model

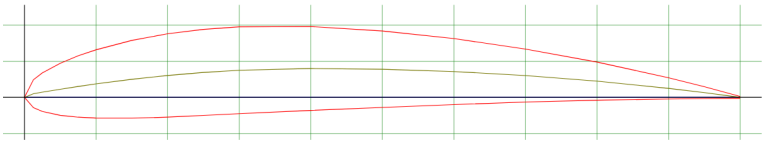


Figure 5. NACA4412 geometric model

2.4. Numerical simulation setup

This paper employs a steady-state Reynolds-averaged Navier–Stokes solver based on the finite volume method for aerodynamic computations. The computational domain is a rectangular region, with the inlet approximately 15 chord lengths upstream of the airfoil leading edge, the outlet approximately 20 chord lengths downstream of the trailing edge, and far-field boundaries located approximately 10 chord lengths above and below the airfoil. A structured mesh is used with

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refinement near the airfoil wall to ensure $y^+ \leq 1$, accurately capturing boundary layer flow. The k – w SST turbulence model is selected for its good predictive capability in adverse pressure gradient flows [6, 7]. The inflow Reynolds number is set to Re = 1.2 ×10-6 (based on chord length), with angle of attack ranging from (0–12)° and free-stream velocity Vx = 60m/s. Pressure–velocity coupling is handled using the SIMPLE algorithm, and spatial discretization employs second-order upwind schemes. Grid independence verification shows that when the mesh count exceeds approximately 1.5 ×105, variations in both lift and drag coefficients are below 1%; the final computational mesh used in this study comprises approximately 2×105cells.

To validate the numerical method, simulation results for the NACA 0012 airfoil at Re =1.2×106 and angles of attack of 4°and 8° are compared with published literature data; the relative deviations in lift coefficient and drag coefficient are both within 5%, demonstrating that the numerical method employed herein has sufficient computational accuracy.

3. Results and discussion

3.1. Influence of Airfoil geometric parameters on aerodynamic performance

3.1.1. Influence of camber

By comparing symmetric airfoils (NACA 0012) with cambered airfoils (NACA 2410, NACA 4412), the influence of camber on aerodynamic performance can be systematically examined. Table 2 lists the aerodynamic coefficients for the three airfoils at representative angles of attack.

Table 2. Comparison of aerodynamic coefficients for airfoils with different camber

Airfoil	f(%)	Angle of attack α (°)	C_l	C_d	C_l/C_d
NACA0012	0	4	0.44	0.0098	44.9
NACA0012	0	8	0.88	0.0136	64.7
NACA2410	2	4	0.66	0.0102	64.7
NACA2410	2	8	1.10	0.0140	78.6
NACA4412	4	4	0.88	0.0112	78.6
NACA4412	4	8	1.32	0.0150	88.0

This paper adopts an aerodynamic coordinate system; a negative C_l value indicates downward aerodynamic force (downforce). The absolute values in the table represent the magnitude of downforce.

At the same angle of attack, greater camber produces higher downforce. At α=4°, the symmetric airfoil yields C_l = -0.44, NACA 2410 approximately -0.66, and NACA 4412 up to -0.88. Increasing camber from 2% to 4% improves the absolute downforce by 33%.

Increased camber simultaneously raises drag. At the same angle of attack, the drag coefficient of NACA 4412 is approximately 12–14% higher than that of NACA 0012 (at α=4°, C_d increases from 0.0098 to 0.0112), an increment that significantly affects high-speed straight-line performance.

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NACA 2410 achieves its maximum lift-to-drag ratio of around79–80 within the 6–8° angle-of-attack range; NACA 4412 reaches a maximum of 98–100 in the 4–6° range. High-camber airfoils exhibit higher lift-to-drag ratio values and feature a wider optimal angle-of-attack range, providing greater flexibility for angle tuning. Some results similarly indicate that the lift coefficient increases with increasing camber ratio, accompanied by a rise in drag, consistent with the trends observed in this paper [8].

3.1.2. Influence of thickness

Lift characteristics: Thickness has little influence on lift, with the three airfoils exhibiting nearly identical lift coefficients at the same angle of attack, consistent with predictions from thin airfoil theory.

Drag characteristics: Thickness significantly affects drag. At, C_d =0.0089for NACA 0008, 0.0093 for NACA 0010, and 0.0098 for NACA 0012; for every 2% increase in thickness, the drag coefficient increases by 4–5%. This trend is primarily caused by increased pressure drag resulting from larger leading-edge radius and trailing-edge angle.

Lift-to-drag ratio and structural considerations: At similar lift coefficients, thinner airfoils exhibit higher aerodynamic efficiency due to lower drag. However, F1 wing profiles must withstand extremely high aerodynamic loads; thicker airfoils can accommodate stronger internal support structures and offer superior deformation resistance, so the actual selection must balance aerodynamic efficiency against structural stiffness. The study points out that the parametric expression of the mean camber line combined with thickness distribution for NACA four-digit airfoils can effectively enable viscous flow field analysis, providing a theoretical basis for thickness selection [9].

Table 3. Presents the aerodynamic coefficients for three symmetric airfoils at different angles of attack

Airfoil	Thickness t (%)	Angle of attack α (°)	C_l	C_d	C_l/C_d
NACA0008	8	4	-0.43	0.0089	48.3
NACA0008	8	8	-0.86	0.0127	69.3
NACA0010	10	4	-0.44	0.0093	47.3
NACA0010	10	8	-0.87	0.0131	66.4
NACA0012	12	4	-0.44	0.0098	44.9
NACA0012	12	8	-0.88	0.0136	64.7

3.2. Rear-wing selection and evaluation for tracks with different characteristics

Furthermore, multi-element airfoils represent the typical configuration of real-world F1 rear wings. Souza Dourado et al. performed optimization for two-dimensional multi-element F1 rear-wing profiles [10], while Gopaliya et al. numerically investigated flow interference within complete rear-wing assemblies [11]. Although this work concentrates on single-element airfoils to reveal fundamental aerodynamic principles, the obtained conclusions can still provide references for the primary-profile selection of multi-element rear wings. It should be noted that real F1 rear wings operate near the ground and encounter yawed inflow during cornering; existing experiments demonstrate that ground proximity alters aerodynamic performance of single-element wings [12], and yaw will induce asymmetric aerodynamic loads for multi-element wing-flap structures [13]. These ground-effect and yaw-related three-dimensional effects are excluded in this simplified two-

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dimensional model, and the subsequent comparative analysis only reflects relative performance trends of different airfoils.

3.2.1. High-speed track–Monza, Italy

The Monza circuit is a typical high-speed track, as shown in Figure 6. With a total length of 5.793 km, it includes 4 straights (total 3,100 m, accounting for 53.5%) and 11 corners, among which only Turns 1 and 2 are low-speed corners while the rest are high-speed.

The core objective of airfoil selection is to minimize drag. Segmented track lengths are listed in Table 4.

Using the cornering speed formula $V_{corner} = \sqrt{\frac{\mu g R}{1-\mu \cdot C_L \cdot \frac{0.5\rho A}{mg}}}$ (taking typical Monza track parameters: average corner radius R = 45m, tire friction coefficient μ=1.5, car mass m = 800kg, air density ρ=1.225kg/m3, reference area A=1.2m2, engine power P=600kw) and the straight-end speed formula $V_{end} = \left(\frac{2P}{\rho C_d A}\right)^{1/3}$, average straight speed $V_{avg} = \frac{V_{start}+V_{end}}{2}$,straight time $V_{avg} = \frac{V_{start}+V_{end}}{2}$, the cornering and straight-line performances of each airfoil are obtained as shown in Tables 5 and 6.

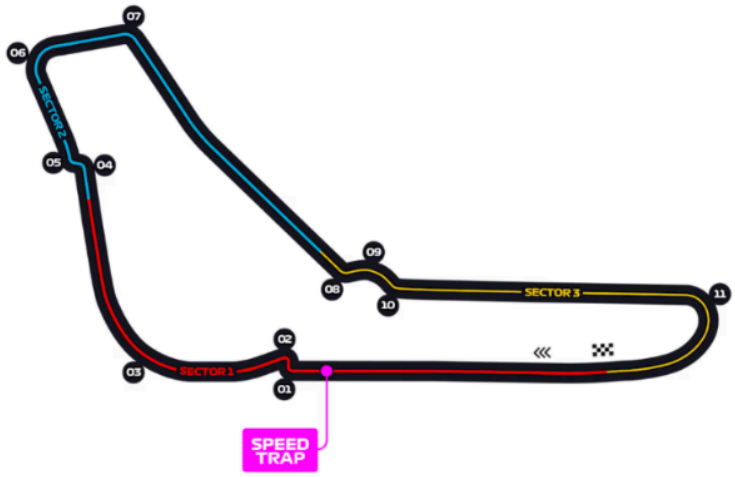


Figure 6. Schematic diagram of the Monza circuit

Table 4. Segment lengths and proportions of the Monza circuit

Segment	Count	Total length (m)	Proportion
Main straight	1	1120	19.3%
Back straight	1	980	16.9%
Lesmo straight	1	580	10.0%
Pre-Parabolica straight	1	420	7.3%
Total straights	4	3100	53.5%
Corners/deceleration sections	1	2693	46.5%

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Table 5. Cornering performance of each airfoil (Monza)

Airfoil	Cornering speed(km/h)	Total cornering time(s)
NACA0008	131.5	8.13
NACA0010	131.5	8.13
NACA0012	131.5	8.13
NACA2410	142.8	7.50
NACA4412	150.6	7.11

Table 6. Straight-line performance of each airfoil (Monza)

Airfoil	Straight-end speed (km/h)	Total straight time(s)
NACA0008	332.5	13.36
NACA0010	329.8	13.44
NACA0012	326.0	13.55
NACA2410	320.4	13.38
NACA4412	312.8	13.37

Combining cornering and straight-line times, with NACA 0008 as the baseline, the relative lap time differences for each airfoil are shown in Table 7.

Table 7. Total relative time differences

Airfoil	Relative time difference(s)
NACA0008	0
NACA0010	+0.2
NACA0012	+0.5
NACA2410	+0.8
NACA4412	+1.7

The results indicate that NACA 0008 achieves the highest straight-line speed due to its lowest drag; although it is slower in corners, its overall lap time remains optimal. NACA 0010 performs similarly with better structural strength, making it also a viable choice. Therefore, NACA 0008 or NACA 0010 is recommended for high-speed tracks.

3.2.2. Technical track – Monte Carlo, Monaco

The Monaco circuit is shown in Figure 7. With a total length of 3.337 km, it is the shortest and slowest track on the F1 calendar, featuring 12 corners and only approximately 600 m of total straight-line length (18% of the lap). The average speed is approximately 150 km/h, with a top speed not exceeding 290 km/h. The core objective of airfoil selection is to maximize downforce.

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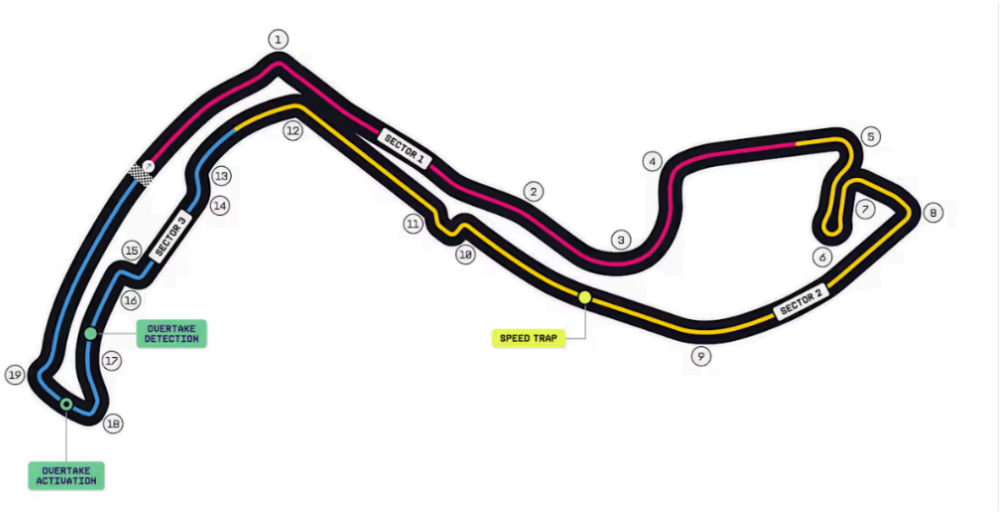


Figure 7. Schematic diagram of the Monaco circuit

The corner radii at Monaco vary significantly (Turn 1 approximately 8 m, others ranging from 15 to 40 m). This paper adopts an equivalent radius of R = 23.6 m (weighted average of 1 hairpin and 11 typical corners), approximates the corner path as semicircular (πR = 74 m), and takes a total straight length of 600 m. The computed cornering and straight-line performances for each airfoil are shown in Tables 8 and 9.

Table 8. Cornering performance of each airfoil (Monaco)

Airfoil	Cornering speed(km/h)	Total cornering time(s)
NACA0008	89.4	35.76
NACA0010	89.8	35.64
NACA0012	90.1	35.52
NACA2410	100.8	31.98
NACA4412	109.3	29.28

Table 9. Performance comparison of each airfoil (Monaco)

Airfoil	Straight relative time diff.	Corner relative time diff.(s)	Total time diff
NACA0008	0	0	0
NACA0010	+0.12	-0.12	0
NACA0012	+0.11	-0.24	-0.13
NACA2410	+0.30	-3.78	-3.48
NACA4412	+0.54	-6.48	-5.94

(Negative values indicate faster)

The advantage of NACA 4412 on this circuit is clear. Its cornering speed reaches 109.3 km/h—about 22% higher than NACA 0008's 89.4 km/h. Across 12 corners, that translates to roughly 6.5 seconds gained, while the drag penalty on straights costs only about 0.5 seconds. Gain nearly 6 seconds gap for each lap. For tight circuits like Monaco, the high-camber profile is clearly the better pick.

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3.2.3. Mixed track – Silverstone, UK

The Silverstone circuit, shown in Figure 8, stretches 5.891 km, with 8 effective corners and 2 main straights (total about 2,300 m, accounting for 39%). The corners cover high-speed (Copse, Maggotts), medium-speed (Stowe, Club), and low-speed (The Loop, Luffield) types. The average speed sits around 220 km/h, with top speeds exceeding 310 km/h. The core objective of selection is to maximize the lift-to-drag ratio C_l/C_d

(Figure 8 omitted in translation; caption: Fig. 8. Schematic diagram of the Silverstone circuit)

The calculations assume each airfoil operates at its angle of attack corresponding to the maximum lift-to-drag ratio; results are presented in Table 10.

Table 10. Performance comparison of each airfoil at the Silverstone circuit

Airfoil	Angle of attack α(°)	C_l/C_d	Cornering speed (km/s)	Straight speed(km/s)	Relative lap time (s)
NACA0008	8	69.3	148.6	284.2	0
NACA0010	8	66.9	149.2	281.4	+0.2
NACA0012	8	63.6	149.6	278.3	+0.5
NACA2410	6	83.9	160.8	286.5	-1.9
NACA4412	4	98.2	165.8	296.0	-3.2

(Negative values indicate faster)

The results show that NACA 4412 performs best at Silverstone, being approximately 1.3 seconds faster than NACA 2410 and about 3.2 seconds faster than NACA 0008. Its advantages are reflected in:

Balance of cornering speed and drag: At α =4° NACA 4412 achieves C_l/C_d = 98.2$, which is 42% higher than symmetric airfoils (approximately 69) and 17% higher than NACA 2410 (83.9). The large camber (f =4%) combined with a small angle of attack generates high downforce (C_l =-1.10) while drag remains at only 0.0112, yielding significant cornering benefits.

Superior straight-line speed: NACA 4412 achieves a top speed of 296.0 km/h, even higher than NACA 2410 at 286.5 km/h and NACA 0008 at 284.2 km/h. This is because it operates at a smaller angle of attack (4°vs. 6°), resulting in a lower drag coefficient. This indicates that the large-camber + small-angle combination can achieve a win–win situation of "fast in corners and fast on straights" on mixed tracks.

Broad high-efficiency range: NACA 4412 maintains a lift-to-drag ratio above 85 across the α = (2~6)°range, offering flexibility for fine-tuning according to track layout and weather conditions.

In summary, for Silverstone-type mixed tracks, NACA 4412 is recommended with the angle of attack controlled in the (4–6)° range; NACA 2410 can serve as a secondary alternative; symmetric airfoils, due to insufficient downforce and larger optimal angle of attack leading to higher drag, exhibit poor overall performance.

3.3. Summary of airfoil selection criteria

Based on the detailed analysis of the three track categories above, the airfoil selection criteria for different track characteristics are summarized in Table 11, which can serve as an engineering reference card for F1 teams to rapidly adjust wing configurations during the season.

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Table 11. Summary of airfoil selection criteria for different track characteristics

Track type	Representative circuit	Recommended airfoil	Recommended angle of attack (°)	Core design objective	Key performance metric	Secondary consideration
High-speed	Monza	NACA0008/0010	2~4	Minimize drag	Straight top speed	Structural strength (choose 0010)
Technical	Monaco	NACA4412	6~8	Maximize downforce	C_l	-
Mixed	Silverstone	NACA4412	4~6	Maximize lift-to-drag ratio	$C_l/C_d \geq 95$	Angle tuning flexibility

4. Conclusions

This paper systematically investigated the effects of camber, thickness, and angle of attack of NACA four-digit airfoils on aerodynamic performance through numerical simulation, and established airfoil selection criteria for three typical track categories. The main conclusions are as follows:

(1) Camber has the most significant effect on downforce; higher camber yields higher downforce but also increases drag. Thickness primarily affects drag; thinner airfoils provide higher aerodynamic efficiency but structural strength must also be considered.

(2) For high-speed tracks (e.g., Monza), NACA 0008 or NACA 0010 is recommended to minimize drag and achieve maximum straight-line speed. For technical tracks (e.g., Monaco), NACA 4412 is recommended to maximize downforce and significantly improve cornering speed. For mixed tracks (e.g., Silverstone), NACA 4412 is also recommended but with a smaller angle of attack (4–6)° to achieve an optimal balance between downforce and drag.

(3) NACA 4412 is not only suitable for technical tracks but also performs excellently on mixed tracks through proper angle-of-attack adjustment; its applicable range is broader than traditionally recognized.

(4) The track-characteristic-based airfoil selection and angle-of-attack tuning strategy established in this study can provide engineering reference for rapid design of F1 racing car wing configurations. Future work may further consider practical factors such as multi-wing interference, ground effect, and dynamic pitch to improve the engineering accuracy of the model.

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