IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 11, November 2026

DOI: 10.17148/IJIREEICE.2026.141105

F1 Aerodynamic Design and Cornering Speed Visualizer: A Verified Lifting-Line Surrogate for Wing-Level Selection

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Abstract: The rear wing of a Formula 1 car trades cornering grip for straight-line speed, and choosing its level normally needs CFD, wind tunnels and lap simulation. This paper presents a lightweight, verified alternative: a lifting-line surrogate that maps five wing-geometry parameters (aspect ratio, angle of attack, slot gaps, camber and reference area) to downforce and drag coefficient areas, coupled to a steady-state cornering model with tyre load sensitivity and banking that a 50-step bisection solves for the maximum apex speed. Four wing specifications were simulated at five representative corners. The spread between the high-downforce and low-drag wings grows from 0.4 km/h at a 12 m hairpin to 48.8 km/h at a 140 m corner (293.6 against 244.8 km/h, up to 4.84 g), while the high-downforce car needs 546 kW against 331 kW of drag power at 320 km/h. The solver matches the closed-form solution to four decimal places and runs a full corner analysis in about 1.2 ms. A consistency check showed that the geometry model over-predicts the preset downforce by 25–33% and that its classification thresholds mislabel three of four presets; a recalibrated area of 0.741 m² and revised thresholds give four of four. The model is delivered as an interactive Flask application verified by 22 automated tests.

Keywords: Formula 1, aerodynamics, downforce, lifting-line theory, surrogate model, cornering speed, vehicle dynamics

I. INTRODUCTION

Formula 1 cars derive most of their cornering ability from aerodynamic downforce, which presses the tyres into the track and lets a modern ground-effect car corner at four to five times gravitational acceleration [1], [2]. Downforce costs drag, so teams change the rear-wing level from circuit to circuit, from high-downforce wings at Monaco to minimal wings at Monza. The choice is made with CFD [13], wind tunnels and lap-time simulation [9]–[11], tools that are expensive and unavailable to students.

Classical aerodynamics nevertheless captures the dominant trends cheaply. Lifting-line theory relates the lift of a finite wing to its aspect ratio and angle of attack [5], and high-lift theory explains how slotted multi-element wings delay stall [4]. Combined with a friction-circle tyre model [7], [8], such a surrogate can estimate how fast a car can take a corner with a given wing in about a millisecond. Surrogates, however, must be validated before they are trusted [12].

This paper makes four contributions: (1) a transparent wing surrogate with slot, camber and stall corrections and a configuration classifier; (2) a steady-state apex-speed solver with load sensitivity and banking, verified against a closed-form solution; (3) a systematic study of four wing levels at five corners, including sensitivity and grip-saturation analysis; and (4) a consistency check that exposes and corrects a calibration offset between the geometry model and the preset table. The model is deployed as an interactive web application.

II. RELATED WORK

Katz [1] reviewed race-car aerodynamics and showed that the downforce-to-drag ratio, not downforce alone, decides performance. Zhang et al. [2] surveyed ground-effect aerodynamics, in which the floor produces a large, efficient share of downforce, and Zerihan and Zhang [3] measured a wing in ground effect. Anderson [5] derives Prandtl's lifting-line result that the lift slope of a finite wing falls with aspect ratio and that induced drag is $C_L^2/(\pi e AR)$; Smith [4] explained why slotted elements raise maximum lift. Milliken and Milliken [7] and Pacejka [8] describe the friction limit of a tyre and its fall with vertical load. Siegler et al. [9], Brayshaw and Harrison [10] and Heilmeier et al. [11] showed that quasi-steady-state models capture cornering speeds at low cost. Forrester et al. [12] stress the validation of surrogates. None of these works links wing geometry directly to cornering speed in an interactive, verified tool.

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III. Aerodynamic and Vehicle Model

A. *Wing Surrogate*

Downforce and drag are the dynamic pressure times the coefficient areas $C_l \cdot A$ and $C_d \cdot A$:

$$q = \tfrac{1}{2}\rho V^2, \qquad L = q\,(C_L A), \qquad D = q\,(C_D A) \tag{1}$$

The 2-D lift slope 2π, reduced by a thickness factor 0.92 and raised by a slot factor $k_{slot} = 1 + 0.18n$ for n slot gaps, is corrected for aspect ratio AR with Oswald efficiency e = 0.85:

$$a = \frac{a_0}{1 + \dfrac{a_0}{\pi\, e\, AR}}, \qquad a_0 = 2\pi\,(0.92)\,k_{slot} \tag{2}$$

The lift coefficient is $C_L = a(\alpha - \alpha_0)k_{camber}$, with $\alpha_0 = -35c$ degrees and $k_{camber} = 1 + 3.2\ \max(0, c - 0.05)$ for camber ratio c. Above the stall angle $\alpha_s = 22° + 3°n$ the lift decays as $\exp[-6(\alpha - \alpha_s)]$. Drag combines profile, form and induced terms, with $C_{D0} = 0.028 + 0.065(c/0.12) + 0.015n$:

$$C_D = C_{D0} + 0.35 \sin^{2.2}\alpha + \frac{C_L^2}{\pi\, e\, AR} \tag{3}$$

$C_l \cdot A$ and $C_d \cdot A$ are the coefficients times the reference area (0.95 m²). Rules on $C_l \cdot A$ and α label the wing Monaco ($C_l \cdot A \geq 1.55$ m², or three slots at $\alpha \geq 18°$), Silverstone (≥ 1.35 m² and $\alpha \geq 15°$), Spa (≥ 0.85 m²) or Monza specification.

B. *Cornering Model*

A fixed underbody $C_l \cdot A$ of 1.95 m² and chassis $C_d \cdot A$ of 0.55 m² are added to the wing. For a 798 kg car [15] on a corner of radius R banked at θ, the normal force and the load-sensitive friction coefficient are

$$F_N = m\,g\cos\theta + q\,(C_L A)_{tot} + \frac{mV^2}{R}\sin\theta \tag{4}$$

$$\mu_{eff} = \mu[1 - k_s\,(F_N - mg)] \tag{5}$$

where $k_s = 8 \times 10^{-6}$ N^{-1} and μ_{eff} is clipped to $[1.1, 1.15\mu]$; the car holds the corner while $F_{req} = (mV^2/R)\cos\theta - mg\sin\theta \leq \mu_{eff} F_N$. A 50-step bisection between 25 and 380 km/h finds the limiting speed. For a flat corner with constant μ the limit is

$$V_{max}^2 = \frac{\mu\, m\, g}{\dfrac{m}{R} - \dfrac{1}{2}\rho\,\mu\,(C_L A)_{tot}} \tag{6}$$

which grows without bound once $\tfrac{1}{2}\rho\mu(C_l \cdot A)$ approaches m/R: downforce then rises as fast as the required force and the corner is grip-unlimited. Each wing is compared with a reference wing ($C_l \cdot A$ 1.75, $C_d \cdot A$ 0.46 m²); the corner-time difference is $L_c/(0.96V_{user}) - L_c/(0.96V_{ref})$ for arc length L_c.

IV. System Implementation

The model is a Python module with Pydantic result types, served by a Flask application in a four-layer architecture (presentation, application, physics, data). The Wing Designer page has sliders for the five inputs, preset buttons and a corner selector; every change triggers POST /api/analyze, which validates each field (HTTP 422 with per-field messages on failure) and returns coefficients, class, apex results, a speed trace, forces from 100 to 350 km/h and an illustrative 20 × 36 pressure-coefficient field (Fig. 1). A comparison page tabulates all presets at all corners. Thirteen engine tests and nine application tests (pytest) check physical trends, the closed-form limit, clamps, routes and validation.

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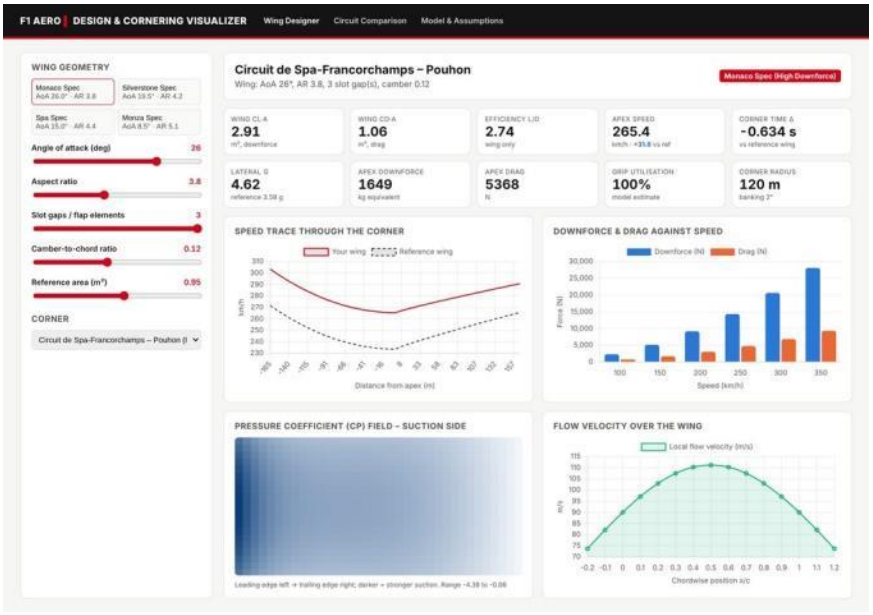


Fig. 1 Wing Designer: Monaco-spec geometry at Pouhon (265.4 km/h, +31.8 km/h).

V. Experimental Results

A. *Setup*

Four presets (Table I) were simulated at five representative corners: Monaco Grand Hotel Hairpin (R = 12 m), Monza Parabolica (90 m), Spa Pouhon (120 m), Silverstone Copse (140 m) and Suzuka 130R (200 m), with banking of 0–2° and μ = 1.55–1.70. Radii are estimates from public track maps. Runs used Python 3.13 on a CPU; one corner analysis takes 1.2 ms and one coefficient evaluation 1.3 μs.

TABLE I Wing Presets

Preset	$C_l \cdot A$	$C_d \cdot A$	L/D	AoA	Elem.
Monaco	2.25	0.72	3.12	26.0°	3
Silverstone	1.78	0.48	3.71	19.5°	2
Spa	1.42	0.38	3.74	15.0°	2
Monza	0.88	0.22	4.00	8.5°	1

B. *Apex Speed by Corner*

TABLE II Apex Speed (km/h) and Gain over Reference

Corner	Monaco	Silv.	Spa	Monza
Hairpin	50.0 (+0.2)	49.9 (+0.0)	49.8 (−0.1)	49.6 (−0.3)
Parabolica	185.6 (+7.2)	178.9 (+0.4)	174.0 (−4.4)	167.2 (−11.2)
Pouhon	247.1 (+13.5)	234.4 (+0.8)	225.2 (−8.4)	212.5 (−21.2)
Copse	293.6 (+18.5)	276.2 (+1.1)	263.2 (−11.9)	244.8 (−30.3)
130R	380.0 (+0.0)	380.0 (+0.0)	380.0 (+0.0)	348.3 (−31.7)

Table II shows that aerodynamics barely matters at the hairpin (49.6–50.0 km/h; 34–51 kg of downforce) but dominates fast corners: at Copse the Monaco wing reaches 293.6 km/h at 4.84 g against 244.8 km/h and 3.37 g for the Monza wing, and gains 0.206 s over the reference wing in one corner. The Monaco–Monza gap grows with radius (Fig. 2): 5.6 km/h at 50 m, 21.9 km/h at 100 m and 51.1 km/h at 150 m. At 130R three wings reach the 380 km/h ceiling: the corner is grip-unlimited and its speed would be set by engine power, which the model omits. Saturation begins at 192.5 m for the Monaco wing and 235 m for the Monza wing. On the straight the ranking reverses: at 320 km/h the Monaco-spec car needs 546 kW to overcome 6.1 kN of drag against 331 kW for the Monza spec.

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TABLE III APEX LOADS AT COPSE (R = 140 M)

Preset	g	DF (kg)	Drag (N)	Δt (s)
Monaco	4.84	1,744	5,173	−0.206
Silverstone	4.29	1,372	3,714	−0.013
Spa	3.89	1,125	3,044	+0.149
Monza	3.37	817	2,181	+0.405

Table III gives the loads behind these speeds. At Copse the Monaco-spec car carries 1,744 kg of downforce – 2.2 times its weight – and 5.2 kN of drag at the apex, while the Silverstone wing, whose coefficients differ from the reference wing by only 0.03 and 0.02 m², is within 1.1 km/h and 0.013 s of it.

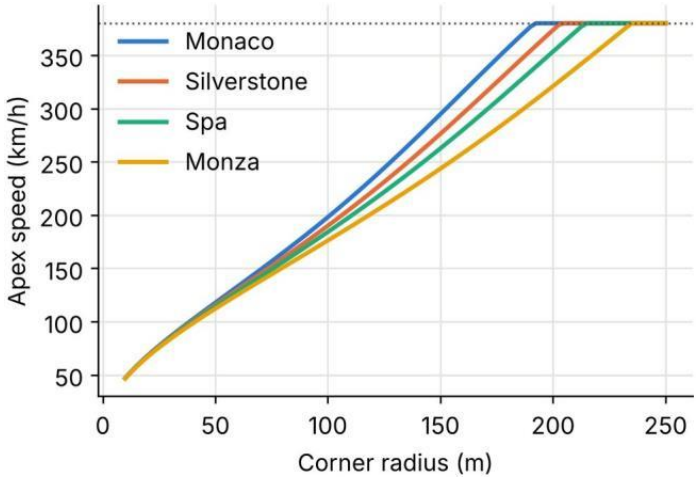


Fig. 2 Maximum apex speed against corner radius (μ = 1.65, flat).

C. *Wing Geometry Effects*

At AR = 4, $C_l \cdot A$ rises almost linearly with angle of attack until stall (Fig. 3); peak $C_l \cdot A$ grows from 2.47 m² at 25° with one slot to 3.47 m² at 31° with three, while the best L/D falls from 4.88 to 4.35 and occurs near 7°. Raising AR from 2 to 6 at 18° increases $C_l \cdot A$ from 1.43 to 2.38 m².

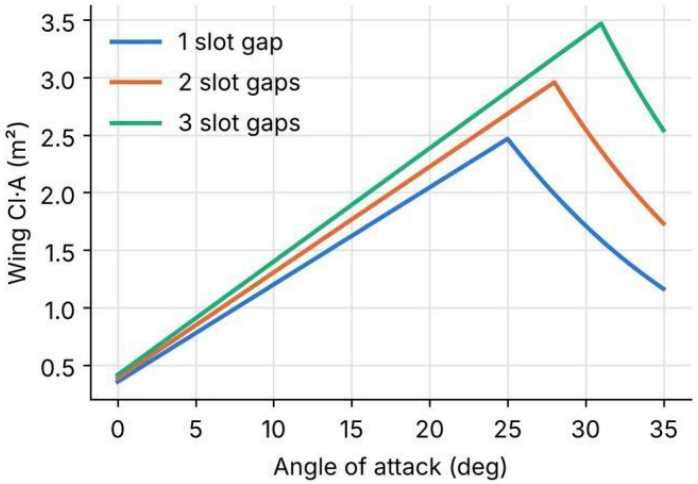


Fig. 3 Wing $C_l \cdot A$ against angle of attack for one to three slot gaps (AR = 4).

D. *Solver Verification*

With load sensitivity disabled on a flat corner (μ = 1.6, $C_l \cdot A$ 4.20 m²), the bisection result equals the closed-form speed to four decimals at all four radii (Table IV). With the full model, the force residual is below 0.001 N in all 17 grip-limited cases; the final bracket is 6.3×10^{-13} km/h. Load sensitivity is significant: the flat, constant-μ closed form gives 308.1 km/h for the Silverstone spec at Copse, against 276.2 km/h from the full model (which also includes 1.5° banking), where μ_{eff} falls from 1.70 to 1.51.

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TABLE IV BISECTION AGAINST CLOSED FORM (FLAT CORNER, FRICTION 1.6)

R (m)	Bisection	Closed form	|Error|
15	57.4982	57.4982	0e+00
50	117.0510	117.0510	0e+00
90	184.8192	184.8192	0e+00
140	320.0713	320.0713	0e+00

E. *Geometry–Preset Consistency*

TABLE V GEOMETRY MODEL AT PRESET GEOMETRY

Preset	Table	Model	Err.	Class
Monaco	2.25	2.91	+29%	Monaco
Silverstone	1.78	2.22	+25%	Monaco
Spa	1.42	1.83	+29%	Monaco
Monza	0.88	1.17	+33%	Spa

Evaluated at each preset's nominal geometry, the surrogate over-predicts $C_l \cdot A$ by 25–33% (Table V, Fig. 4) and assigns three presets too high a class (the Spa preset by two levels). A least-squares fit gives a reference-area scale of 0.78, i.e. 0.741 m², which brings all four $C_l \cdot A$ values within 3.8% of the table. The thresholds are a separate issue: even the table values are misclassified because the Silverstone preset (1.78 m²) exceeds the Monaco threshold. Thresholds midway between presets (2.0, 1.6 and 1.15 m²) classify all four table values and all four recalibrated values correctly. Corner results in Table II use the preset table and are unaffected.

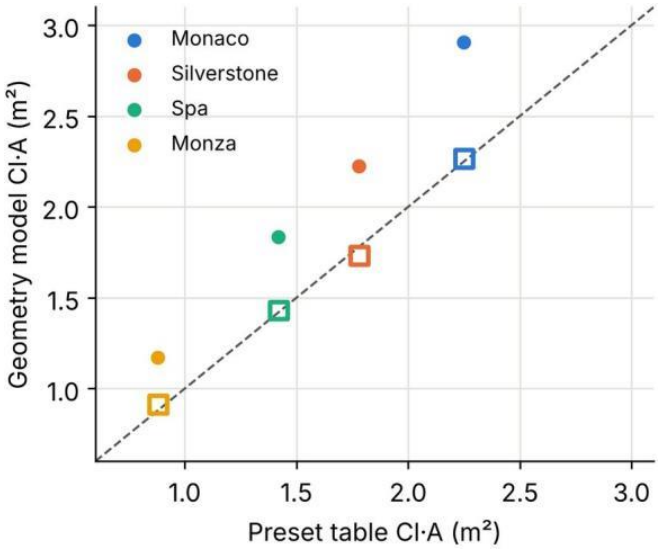


Fig. 4 Geometry-model $C_l \cdot A$ against the preset table; circles as coded, squares with the recalibrated area.

F. *Sensitivity*

A ±10% change around the Silverstone wing at Copse (276.2 km/h) moves the apex speed by −27.6/+28.7 km/h for grip, −27.0/+27.9 for radius, +20.5/−15.0 for mass and −13.5/+13.8 for total $C_l \cdot A$ (Fig. 5); air density acts identically to $C_l \cdot A$. The 2026 minimum mass of 768 kg would add 7.0 km/h.

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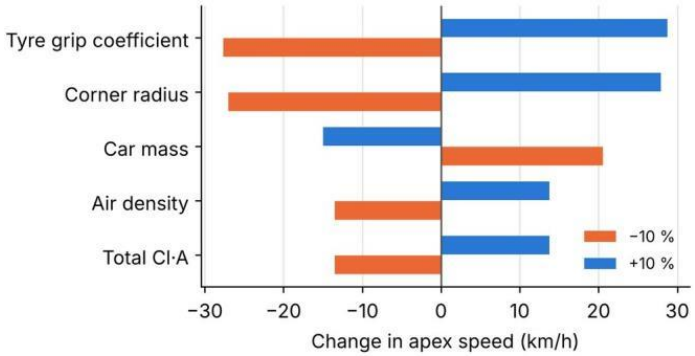


Fig. 5 Sensitivity of apex speed at Copse to ±10% input changes.

VI. Discussion and Limitations

The surrogate reproduces the expected physics – stall, aspect-ratio and slot effects, the V^2 growth of downforce and grip saturation – and lateral accelerations of 2.4–5.7 g in corners of 90 m and above, consistent with ground-effect Formula 1 cars [1]. Absolute coefficients remain estimates: the model is not calibrated to CFD, corner data are representative, and power, braking and DRS are not modelled. Two implementation details limit its range: the effective friction is floored at 1.1, so any surface with $\mu < 1.1$ yields the same speed (132.5 km/h at R = 90 m), and the grip-utilisation metric saturates at 100% in all fast corners. The pressure field is an analytic illustration, not a flow solution.

VII. Conclusion and Future Work

A lifting-line wing surrogate coupled to a verified bisection cornering solver makes the downforce–drag trade-off of Formula 1 measurable in about a millisecond. The study quantified how wing level matters with corner radius, identified grip-unlimited corners, and – through a consistency check – found and corrected a 25–33% calibration offset and misplaced classification thresholds. Future work will calibrate the surrogate against open CFD data, extend it to a full-lap quasi-steady-state simulation with power and DRS, and add the 2026 car model.

Acknowledgment

The authors thank G. Karthiha, Assistant Professor (O.G), and Dr. P. Chitra, Professor and Head, Department of Computer Science and Engineering (Emerging Technologies), SRM Institute of Science and Technology, Vadapalani Campus, for their guidance and support.

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