

Aerodynamic Validation: An On-Track Study of a Formula Student Vehicle

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Abstract

Aerodynamic validation is essential in Formula Student, where CFD-based design decisions must be correlated with real on-track behaviour. This work presents an experimental and numerical assessment of the aerodynamic performance of the FST14 Formula Student prototype. The objective was to validate straight-line aerodynamic loads through on-track testing and compare the experimental estimates with CFD predictions for equivalent configurations, contributing to the correlation of numerical models with full-scale data. The experimental campaign used two approaches: constant-velocity tests for downforce estimation and coastdown tests for drag estimation. Vehicle response was measured through suspension potentiometers and pitot-based airspeed instrumentation, allowing aerodynamic loads to be reconstructed from ride-height variation and dynamic pressure. Dedicated calibrations and a MATLAB data-processing framework supported signal conditioning and parameter estimation. CFD simulations were carried out for representative operating points from the experimental dataset. The constant-velocity tests yielded $C_L A = 3.467\text{m}^2$, with axle-wise values of 1.602m^2 and 1.890m^2 , resulting in an aerodynamic balance of 46.20%, while the coastdown analysis produced $C_D A = 1.661\text{m}^2$. The CFD comparison reproduced the overall aerodynamic trends, but overpredicted the regression-based total, front, and rear downforce coefficients by 32.7%, 38.9%, and 25.2%, respectively, exceeding the typical lift-related numerical error previously reported for the adopted framework. The CFD prediction also indicated a more front-loaded balance of 50.9%. The discrepancies are plausibly linked to ride-height sensitivity, experimental uncertainty, geometry simplifications, boundary-condition assumptions, and steady RANS limitations. Overall, this work establishes a repeatable methodology for on-track aerodynamic validation in Formula Student and a structured workflow for aerodynamic development and simulation correlation.

Keywords: Race Car, Computational Fluid Dynamics, Constant Velocity Testing, Coastdown Testing, Downforce Estimation, Drag Estimation

1. Introduction

Aerodynamics has become one of the main performance drivers in motorsport, as the generation of downforce with limited drag is essential for increasing cornering speed, straight-line efficiency, and overall vehicle stability [1]. This importance is also evident in Formula Student (FS), an international engineering competition in which university teams design, manufacture, and compete with single-seater formula-style race cars. Since both on-track performance and engineering validation contribute to the competitiveness of a team, aerodynamic development must be supported not only by numerical predictions, but also by experimental evidence capable of validating the adopted design decisions.

Within FST Lisboa, aerodynamic development has increasingly relied on Computational Fluid Dy-

namics (CFD), mainly due to the cost, time, and resource limitations associated with experimental testing. However, CFD predictions depend on modelling assumptions, geometry simplifications, boundary conditions, and numerical setup choices. Without reliable validation, the correlation between numerical predictions and real-world performance becomes uncertain, making it difficult to ensure that aerodynamic designs translate effectively to the track [2].

Several validation efforts have previously been carried out within the team. Early wind-tunnel testing on FST06e investigated both a scaled rear wing and a reduced-scale full-vehicle model, but discrepancies with CFD predictions were affected by Reynolds-number differences, manufacturing limitations, and aeroelastic deformation [3]. Later, FST10e was studied through wind-tunnel test-

ing and on-track procedures, including constant-velocity and coastdown tests, although the uncertainty associated with the experimental setup and instrumentation limited direct quantitative comparison with numerical results [3, 4]. More recently, wind-tunnel testing of a scaled FST14 model showed consistent aerodynamic trends and reasonable agreement with CFD predictions, but non-negligible uncertainty remained [5].

Therefore, despite previous progress, FST Lisboa still lacked a robust full-scale on-track validation methodology capable of producing quantitative aerodynamic estimates under real operating conditions. The present work addresses this gap by developing and applying an on-track aerodynamic validation procedure to the FST14 prototype. The main objective is to estimate the aerodynamic loads of the vehicle in straight-line conditions and compare them with CFD predictions obtained for equivalent configurations.

2. On-Track Aerodynamic Estimation Methodology

The experimental validation procedure is based on indirect on-track aerodynamic estimation, in which the aerodynamic loads are inferred from the measured dynamic response of the vehicle rather than measured directly. This approach is particularly suitable for full-scale race-car testing, since on-track measurements include effects associated with real operating conditions, such as road surface irregularities, transient vehicle motion, environmental variations, and driver inputs [2]. In the present work, two complementary straight-line procedures are used: constant-velocity testing for downforce estimation and coastdown testing for drag estimation.

2.1. Constant-Velocity Downforce Estimation

Constant-velocity (CV) testing is used to estimate the aerodynamic downforce generated by the vehicle under quasi-steady straight-line conditions. During a CV segment, the vehicle is driven at approximately constant speed, so that longitudinal acceleration and the associated inertial load transfer are minimized. Under these conditions, changes in vertical wheel load can be mainly attributed to aerodynamic downforce, provided that steering input, braking, and throttle transients remain limited [6, 7].

The adopted approach reconstructs the vertical load variation at each corner wheel from suspension potentiometer measurements. The measured damper displacement is first expressed relative to an on-car baseline and then related to wheel displacement using the identified motion ratio,

$$MR_i = \frac{\Delta x_{d,i}}{\Delta x_{w,i}}, \quad (1)$$

where $i \in \{FL, FR, RL, RR\}$, $\Delta x_{d,i}$ is the damper displacement increment, and $\Delta x_{w,i}$ is the corresponding wheel displacement increment. The spring force is obtained from the measured spring force-displacement relation,

$$F_{\text{spring},i} = f_s(x_{s,i}), \quad (2)$$

and converted into wheel load through the suspension motion ratio,

$$F_i = F_{\text{spring},i} MR_i. \quad (3)$$

The front, rear, and total downforce are obtained by summing the reconstructed corner wheel contributions,

$$\begin{aligned} F_{L,F} &= F_{FL} + F_{FR}, \\ F_{L,R} &= F_{RL} + F_{RR}, \\ F_{L,T} &= F_{L,F} + F_{L,R}. \end{aligned} \quad (4)$$

Since the aerodynamic operating condition of a ground-effect vehicle is strongly influenced by ride height, the same processing chain is also used to estimate the dynamic front and rear ride heights. The tyre vertical force-displacement relation is inverted to estimate tyre deflection, which is combined with wheel displacement to reconstruct the instantaneous ride height,

$$RH_i = RH_{0,i} - (\Delta x_{w,i} + \delta_{\text{tyre},i}), \quad (5)$$

where $RH_{0,i}$ is the static reference ride height and $\delta_{\text{tyre},i}$ is the tyre vertical deflection. These ride-height estimates are later used to define the equivalent CFD operating points.

The aerodynamic load is related to dynamic pressure through

$$F_{L,j} = (C_{L,j} A) q, \quad q = \frac{1}{2} \rho v^2, \quad j \in \{T, F, R\}, \quad (6)$$

where q is the dynamic pressure, ρ is the air density, v is the vehicle airspeed, and j denotes total, front, or rear aerodynamic load. For the total vehicle contribution, $C_{L,T} A \equiv C_L A$. Applying the same regression independently to the front and rear axle loads provides $C_{L,F} A$ and $C_{L,R} A$, allowing the aerodynamic balance to be estimated as

$$AB = \frac{C_{L,F} A}{C_{L,F} A + C_{L,R} A} \times 100. \quad (7)$$

2.2. Coastdown Drag Estimation

Coastdown (CD) testing is used to estimate the aerodynamic drag-area coefficient. In this procedure, the vehicle is accelerated to a target speed and then allowed to decelerate freely without throttle or brake input. During this phase, the longitudinal deceleration results from the combined effect

of aerodynamic drag, rolling resistance, drivetrain losses, road grade, and wind. If the run is performed on a straight track and in opposite directions, first-order wind and grade effects can be reduced, following the general philosophy of established coastdown practices [8, 9, 10].

The resistive force is obtained from Newton's second law using the equivalent vehicle mass,

$$F_{\text{res}} = -m_{\text{eq}}a_x, \quad (8)$$

where a_x is the longitudinal acceleration and m_{eq} accounts for both translational mass and the rotational inertia of the wheels. The equivalent mass is written as

$$m_{\text{eq}} = m_t + \sum_i \frac{I_i \omega_i^2}{v^2}, \quad (9)$$

where m_t is the total vehicle mass, I_i is the rotational inertia of wheel i , ω_i is the corresponding angular speed, and v is the vehicle speed. This correction is included because part of the vehicle kinetic energy is stored in rotating components, meaning that the longitudinal deceleration cannot be interpreted using the translational mass alone.

The vehicle speed used in the regression is obtained from the pitot-derived airspeed corrected by the longitudinal wind component along the track direction,

$$v(t) = V_{\text{air}}(t) - w_{\parallel}(t), \quad w_{\parallel}(t) = \vec{w}(t) \cdot \hat{t}_{\text{track}}. \quad (10)$$

The resulting force-speed relation is then fitted using a second-order polynomial,

$$F_{\text{res}} = A_2 v^2 + A_1 v + A_0, \quad (11)$$

where the quadratic coefficient contains the aerodynamic drag contribution, while the remaining terms represent linear and constant resistance effects [11]. Neglecting residual wind and grade bias after bidirectional testing, the drag-area coefficient is obtained from

$$C_D A = \frac{2A_2}{\rho}. \quad (12)$$

For each accepted coastdown run, the polynomial coefficients in Equation (11) are determined by least-squares regression. The quadratic coefficient A_2 is then used to compute one run-wise value of $C_D A$, and the final drag-area estimate is obtained from the accepted set of runs. This formulation allows the drag-related coefficient to be identified directly from the reconstructed resistive-force and speed histories during the coastdown interval.

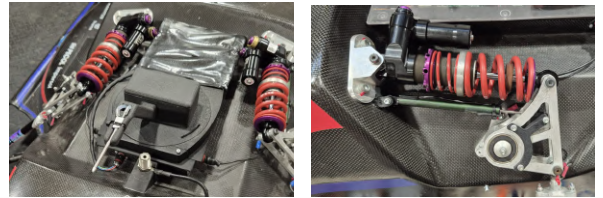
2.3. Instrumentation

The vehicle was instrumented with the signals required by the CV and CD estimation procedures. Suspension displacement was measured at the four corners using Variohm ELPM linear potentiometers mounted in parallel with the spring-damper assemblies, providing the primary input for the down-force reconstruction method. The pitot-static system, combined with an NXP MPXV7002 differential pressure transducer, was used to measure dynamic pressure and infer airspeed. Longitudinal acceleration was obtained from the onboard inertial system, while wheel-speed signals were obtained from the in-wheel motor/inverter telemetry and used in the equivalent-mass calculation for the coastdown analysis. In addition, throttle, brake, and steering signals were recorded to verify protocol compliance and support the segmentation of each run.

The approximate location of the main instrumentation is shown in Figure 1. The pitot assembly was mounted on the upper surface of the monocoque, ahead of the dashboard, to place the probe in a relatively unobstructed flow region while satisfying packaging constraints. The suspension potentiometers were installed at each corner, attached between the chassis and the moving rocker, so that damper motion could be measured throughout the test. The inertial unit was mounted close to the vehicle centre of gravity to reduce the influence of rigid-body rotations on the measured longitudinal acceleration.



(a) Approximate location of the main instrumentation on FST14.



(b) Pitot-tube assembly and suspension potentiometer installation.

Figure 1: Instrumentation layout and representative sensor installations used during the on-track campaign.

2.4. Calibration and Static Characterization

The experimental methodology requires the conversion of raw sensor signals into physical quantities

before the aerodynamic estimators can be applied.

The pitot-static system was used to obtain dynamic pressure and airspeed from the measured pressure difference, following the incompressible-flow relation between dynamic pressure and velocity. During calibration, the pitot tube was mounted in a controlled flow facility and compared against a manometric reference.

The reference dynamic pressure was obtained from the manometric head difference as

$$q_\infty = \Delta p_{\text{man}} \approx \rho_m g (l_1 - l_2), \quad (13)$$

where ρ_m is the manometric fluid density and $l_1 - l_2$ is the measured wetted-length difference between the reference pressure lines. A linear calibration law was then identified between the pitot sensor output and the reference pressure, as shown in Figure 2. This calibration was later used to convert the raw pitot signal into dynamic pressure during the on-track campaign.

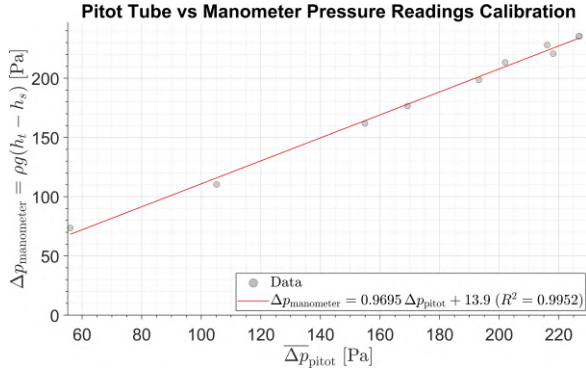
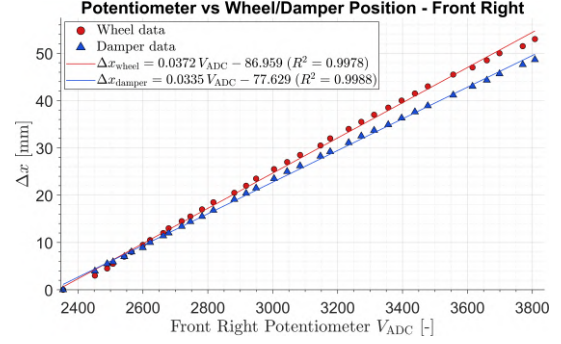
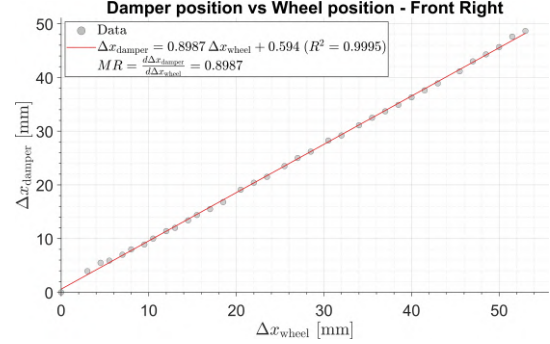


Figure 2: Pitot-system calibration against the manometric reference pressure.

The suspension potentiometers were calibrated through a static displacement procedure, in which wheel-side displacement was imposed incrementally and the corresponding damper displacement and raw potentiometer output were recorded. This procedure provided two required inputs for the CV load-reconstruction framework: the mapping between potentiometer output and physical damper/wheel position, and the motion ratio relating damper and wheel displacement. Since the same procedure was applied independently to all four corners, Figure 3 present the result for one representative corner only.



(a) Potentiometer output versus damper and wheel position.



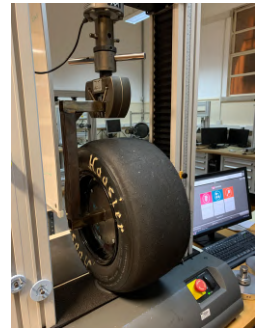
(b) Motion-ratio identification from the damper-wheel displacement relation.

Figure 3: Representative suspension calibration for one vehicle corner.

In addition to sensor calibration, the spring and tyre vertical force-displacement behaviours were characterized experimentally through quasi-static compression tests using an Instron 3369 universal testing machine. These tests provided the elastic-element inputs required to reconstruct wheel loads and dynamic ride heights from suspension displacement measurements. The physical test setups are shown in Figure 4.



(a) Spring compression test.



(b) Tyre vertical compression test.

Figure 4: Physical setup used for the quasi-static spring and tyre vertical characterization tests.

The measured spring and tyre responses were

not reduced to a single constant stiffness. Instead, the force–displacement relations were retained as lookup tables in the processing framework, allowing the load and ride-height reconstruction to account for the measured behaviour of the elastic elements. The corresponding characterization curves are shown in Figure 5.

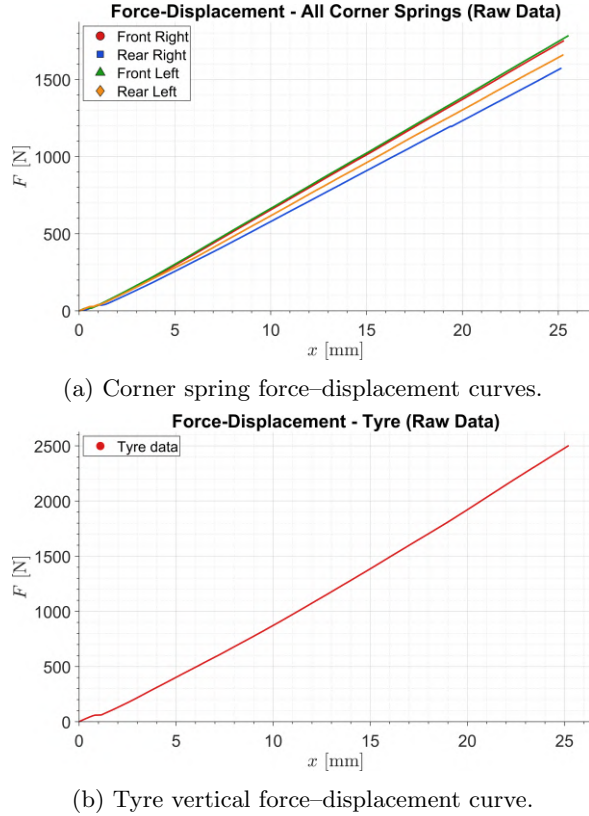


Figure 5: Static characterization of the spring and tyre vertical force–displacement behaviour used in the load-reconstruction framework.

These calibration and characterization procedures provide the required inputs for the aerodynamic estimation framework: dynamic pressure and airspeed from the pitot system, damper and wheel displacements from the suspension potentiometers, motion ratios from the damper–wheel displacement relation, and spring/tyre force–displacement laws for load and ride-height reconstruction.

2.5. Vehicle Setup

Before the on-track campaign, the vehicle was prepared in its full test configuration, including driver, battery, aerodynamic devices, instrumentation, and test tyres. This setup step was essential because the aerodynamic estimation procedure depends on suspension displacement measurements and on the assumption that the measured vertical response is dominated by aerodynamic loading. Ride height, corner weights, tyre pressure, and wheel alignment

were therefore verified before testing, since these quantities influence both the aerodynamic operating condition and the reconstruction of wheel loads [7].

The static load distribution was adjusted using corner scales, with the vehicle configured as close as possible to the final test condition. Cross-weight and ride-height checks were performed iteratively, since changes in pushrod shims affect both diagonal load distribution and vehicle attitude. The front and rear ride heights obtained from this procedure were then used as the static references for the later dynamic ride-height reconstruction.

Wheel alignment was also verified before testing, since toe and camber affect straight-line stability, tyre scrub, and parasitic tyre forces during the CV and CD segments. Toe was measured using a string reference aligned with the vehicle centreline, while camber was measured using a dedicated jig mounted to the hub assembly.

3. On-Track Aerodynamic Testing Campaigns

The experimental campaign was carried out with FST14, FST Lisboa’s electric Formula Student prototype. The vehicle is a four-wheel-drive race car equipped with a full aerodynamic package, independent double-wishbone suspension, pushrod-actuated spring–damper units, and Hoosier slick tyres, making it representative of the configuration to be validated in the present work. Prior to the campaign, the vehicle was prepared in its full test configuration, with the setup and instrumentation procedures described in Section 2.5

The on-track campaign was conducted on 17 October 2025 at Alverca Air Base, using a straight taxiway section suitable for bidirectional constant-velocity and coastdown testing. Figure 6 shows the test vehicle in the location where the campaign was conducted.



Figure 6: FST14 during the on-track aerodynamic test campaign.

The adopted straight-line test layout is shown in Figure 7.

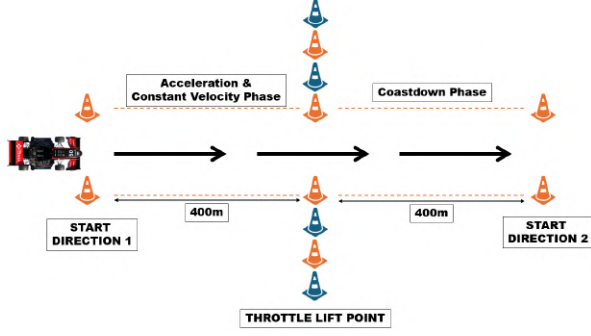


Figure 7: Straight-line test layout adopted for the constant-velocity and coastdown runs

Each pass was divided into an acceleration phase, a constant-velocity window, and a coastdown phase initiated at the throttle-lift marker. Runs were performed in opposite directions to reduce first-order wind and road-grade effects, following the general philosophy of standardized coastdown procedures adapted to the constraints of the campaign.

The vehicle was instrumented with the channels required for both aerodynamic estimation procedures. Suspension potentiometers were used to measure damper displacement at the four corners, while a pitot-static system provided dynamic pressure and airspeed. Longitudinal acceleration was obtained from the inertial system, and wheel-speed signals were used to support the coastdown equivalent-mass calculation. In addition, throttle, brake, and steering signals were recorded to verify protocol compliance and support run segmentation.

Environmental and vehicle-state monitoring was performed throughout the campaign to assess the consistency of the dataset. Ambient temperature, relative humidity, pressure, wind speed, and wind direction were obtained from the local meteorological station and interpolated to each run timestamp. These values were used to compute run-specific air density through the moist-air ideal-gas formulation, with uncertainty propagated from the atmospheric inputs [12]. Tyre pressure, tyre surface temperature, and track temperature were also monitored between opposite-direction pairs. Overall, the recorded conditions remained sufficiently stable for comparison between runs, although the telemetry range was insufficient for continuous live monitoring over the full track length.

4. On-Track Aerodynamic Testing Data Processing and Results

During post-processing, each log of recorded data was split into individual runs and segmented into acceleration, constant-velocity, and coastdown intervals required by the test protocol. Segmentation was based on vehicle speed, throttle position, brake position, and steering angle, ensuring that

only intervals compatible with the straight-line assumptions were retained. The raw signals were then converted into physical quantities using the calibration laws obtained for the pitot system and suspension potentiometers. Before conversion, the relevant signals were smoothed using a moving-average filter to reduce high-frequency measurement noise while preserving the low-frequency variations associated with vehicle motion. The processing workflows adopted for the constant-velocity and coastdown analyses are summarized in Figures 8a and 8b.

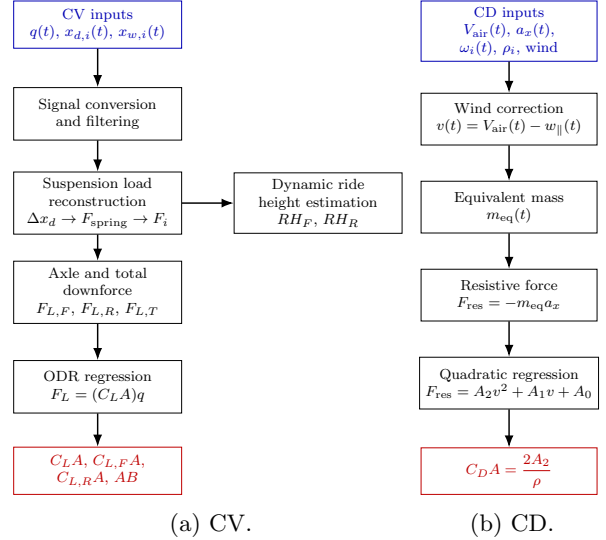


Figure 8: Processing workflows adopted for the aerodynamic estimation methodology: (a) constant-velocity downforce estimation and (b) coastdown drag estimation.

Representative processed signals for accepted constant-velocity and coastdown runs are shown in Figures 9 and 10. These figures illustrate the final quantities used by each branch of the methodology. For the constant-velocity analysis, the relevant signals include dynamic pressure, reconstructed front and rear downforce, total downforce, and ride-height evolution. For the coastdown analysis, the relevant quantities include corrected vehicle speed, longitudinal wind component, equivalent mass, longitudinal acceleration, and reconstructed resistive force. For the constant-velocity branch, each retained interval was treated as a quasi-steady operating condition. The representative dynamic pressure, reconstructed downforce, and ride-height quantities were therefore obtained as the mean value over the selected interval, while the corresponding scatter was quantified through the standard deviation of the processed signal [12]. These representative values defined the force-dynamic-pressure datasets used to identify the total, front, and rear lift-related aerodynamic coefficients.

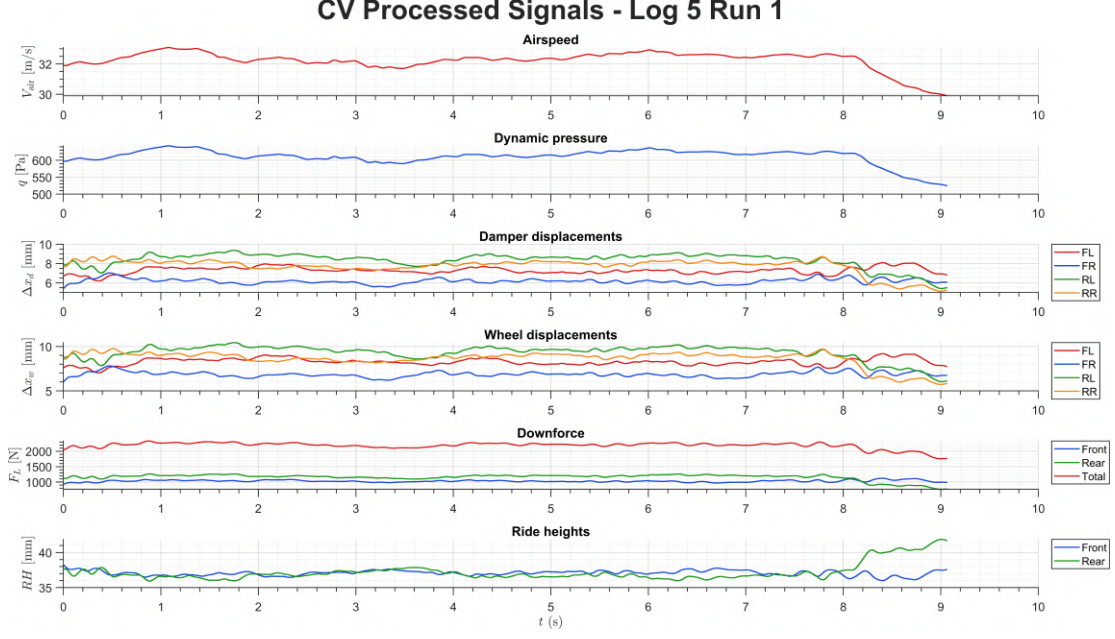


Figure 9: Representative processed constant-velocity signals for an accepted run.

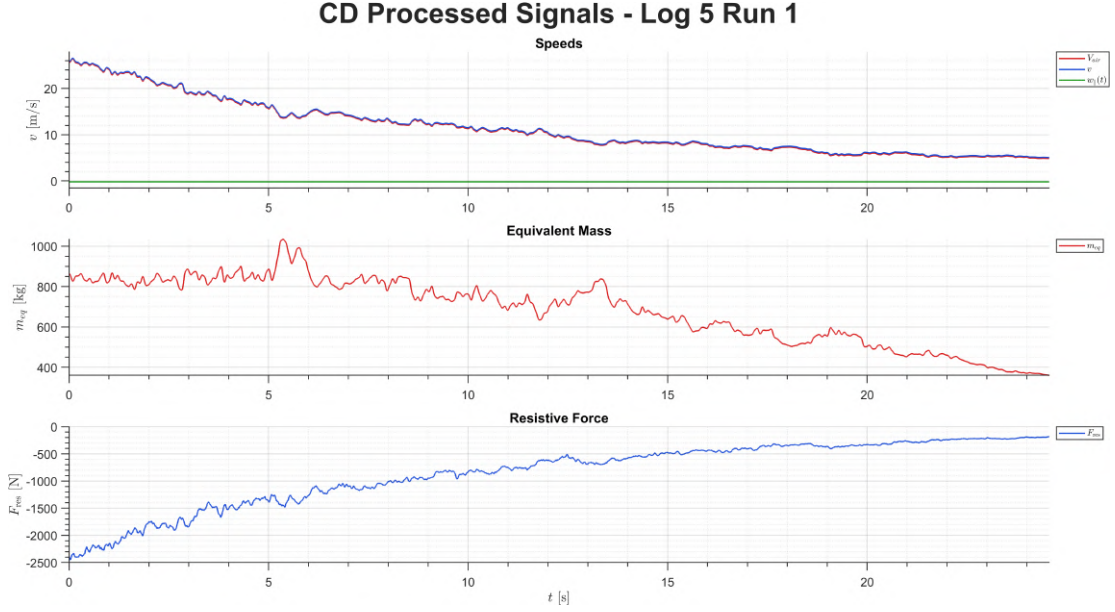


Figure 10: Representative processed coastdown signals for an accepted run.

Since both dynamic pressure and reconstructed downforce are affected by measurement uncertainty, the lift-related coefficients were identified using weighted orthogonal distance regression. This approach accounts for uncertainty in both regression coordinates and is therefore more appropriate than ordinary least squares for the present dataset [13]. The corresponding slopes define C_{LA} , $C_{L,FA}$, and $C_{L,RA}$, which are later compared directly with the CFD-derived regressions.

For the coastdown branch, the retained intervals were not reduced to a single representative value, since the vehicle speed and resistive force vary con-

tinuously during the deceleration phase. Instead, each accepted run provided a sequence of instantaneous speed-resistive-force samples. These data were fitted with a second-order polynomial using least-squares regression, and the quadratic coefficient was used to estimate the corresponding drag-area coefficient. Only runs whose fitted speed interval included 80 km h^{-1} were retained for the final drag evaluation, following the implementation criteria associated with SAE J1263 coastdown practice. A representative accepted coastdown regression is shown in Figure 11.

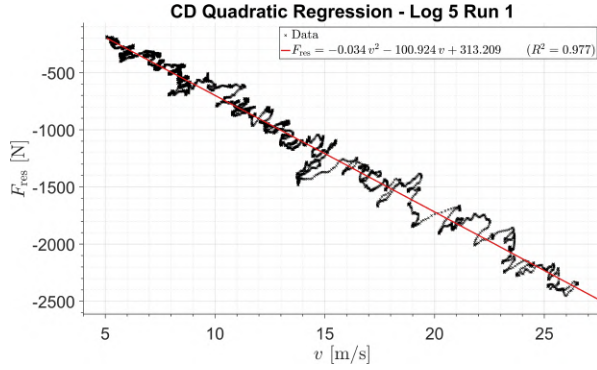


Figure 11: Representative coastdown regression used to identify the drag-area coefficient from the reconstructed resistive force.

The constant-velocity methodology yielded a total lift-related coefficient of $C_L A = 3.467 \pm 0.105 \text{ m}^2$, with front and rear contributions of $C_{L,F} A = 1.602 \pm 0.055 \text{ m}^2$ and $C_{L,R} A = 1.890 \pm 0.103 \text{ m}^2$, respectively. The corresponding aerodynamic balance was $46.20 \pm 1.60 \%$. From the accepted coastdown runs, the drag-area coefficient was estimated as $C_D A = 1.661 \pm 0.395 \text{ m}^2$. Combining both results gave an aerodynamic efficiency of $\eta_{\text{aero}} = 2.087 \pm 0.500$, with uncertainty propagated from the identified lift- and drag-related coefficients [12]. These quantities are summarized together with the CFD results in the following section for direct experimental–numerical comparison.

5. CFD Simulations and Comparison with Experimental Results

The numerical analysis was performed using the CFD methodology previously established by Santos [5] for the FST14 prototype, based on a simplified CFD-ready geometry prepared from the original CAD model and implemented in **Siemens STAR-CCM+**. The adopted setup was kept fixed throughout the present work, so that the numerical campaign focused on reproducing the experimental operating conditions rather than re-developing or re-validating the CFD model. The vehicle geometry was parametrized according to the framework developed by Carreira [4], allowing the front and rear ride heights measured experimentally to be imposed directly in the numerical model.

The CFD simulations were carried out for the 16 operating points retained from the constant-velocity dataset. These points were selected because each constant-velocity interval provides approximately steady values of airspeed, front ride height, rear ride height, and air density, making them directly compatible with the steady numerical framework. By contrast, the coastdown data were not simulated directly, since the vehicle speed and operating condition vary continuously throughout

the deceleration phase. The main characteristics of the adopted CFD setup are summarized in Table 1.

Table 1: Summary of the CFD setup adopted for the numerical correlation.

Item	Adopted setup
Software	Siemens STAR-CCM+
Flow model	Steady, incompressible, three-dimensional flow
Turbulence model	RANS $k-\omega$ SST, without transition model
Domain	Straight-line external aerodynamic half-domain
Ground/wheels	Moving ground and rotating wheels
Boundary conditions	Velocity inlet and pressure outlet
Varied inputs	U , RH_F , RH_R , ρ , and μ
Number of cases	16 constant-velocity operating points

For each simulation, the imposed inlet velocity, front ride height, rear ride height, and air density were taken from the corresponding processed constant-velocity run. The dynamic viscosity was computed from the interpolated ambient temperature using Sutherland’s law. The CFD output was post-processed in terms of total downforce and pitching moment, from which equivalent front and rear axle downforces were reconstructed. This allowed the numerical results to be compared directly with the experimentally reconstructed total, front, and rear aerodynamic loads.

The comparison was first performed at the regression level, using the same force–dynamic-pressure formulation adopted for the experimental constant-velocity analysis. For each aerodynamic contribution $j \in \{T, F, R\}$, the CFD force was fitted as $F_{z,j}^{\text{CFD}} = (C_L A)_j^{\text{CFD}} q$.

This regression treats the aerodynamic coefficients as approximately constant over the Reynolds-number range covered by the selected operating points. Therefore, variations of the aerodynamic response with Reynolds number are not explicitly modelled and are instead included in the residual scatter of the fitted relation. This assumption is considered acceptable for the present comparison, since the objective is to obtain an equivalent coefficient representative of the tested operating range rather than a Reynolds-resolved aerodynamic map.

Since the CFD outputs are deterministic numerical values evaluated at prescribed operating conditions, ordinary least squares was used for the numerical regressions. This contrasts with the experimental treatment, where weighted orthogonal distance regression was adopted to account for uncertainty in both dynamic pressure and reconstructed downforce. The resulting experimental and numerical regressions are compared in Figure 12.

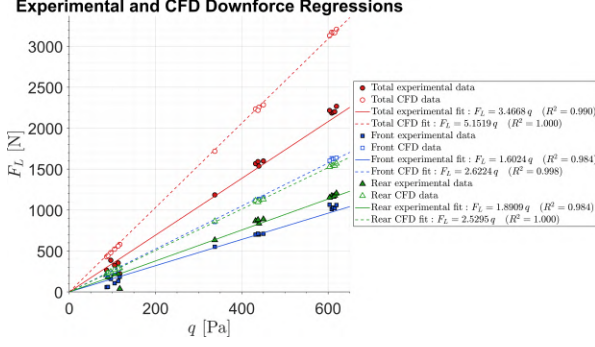


Figure 12: Comparison between experimental and CFD regressions of total, front, and rear downforce as functions of dynamic pressure.

The corresponding regression slopes are summarized in Table 2, together with the experimental drag-area coefficient and aerodynamic efficiency obtained from the coastdown analysis. The CFD comparison is only performed for the lift-related coefficients, since the numerical campaign reproduced the constant-velocity operating points and did not include direct coastdown simulations. The discrepancies reported in Table 2 should also be interpreted in light of the numerical error of the adopted CFD framework. For this setup, Santos estimated a numerical error of approximately 4.29% in C_L from the mesh convergence study, which provides a reference uncertainty level for the lift-related numerical predictions [5].

Table 2: Comparison between experimental and CFD aerodynamic results. Lift- and drag-area coefficients are given in m^2 .

Quantity	Experimental	CFD	Δ
$C_L A$	3.467 ± 0.105	5.152	+1.685
$C_{L,FA}$	1.602 ± 0.055	2.622	+1.020
$C_{L,RA}$	1.891 ± 0.103	2.530	+0.639
AB [%]	46.20 ± 1.60	50.9	+4.7
C_{DA}	1.661 ± 0.395	—	—
η_{aero}	2.087 ± 0.500	—	—

The comparison shows that the CFD model reproduces the qualitative linear dependence of aerodynamic force on dynamic pressure, but with consistently higher slopes for all three force components. The total lift-related coefficient predicted numerically is 5.152 m^2 , compared with the experimental value of $3.467 \pm 0.105 \text{ m}^2$, corresponding to an overprediction of 1.685 m^2 . This difference is substantially larger than the typical numerical error estimated by Santos for C_L , suggesting that the discrepancy cannot be attributed only to mesh-related numerical uncertainty. Since the comparison is based on the slope of the force-dynamic-

pressure relation, this difference indicates a systematic overprediction of aerodynamic load sensitivity, rather than an isolated mismatch at a specific operating point. As a result, the absolute force discrepancy increases with dynamic pressure.

The discrepancy is more pronounced at the front axle, where $C_{L,FA}$ is overpredicted by 1.020 m^2 , compared with 0.639 m^2 at the rear axle. This indicates that the CFD model not only overpredicts the total aerodynamic load, but also predicts a more front-biased load distribution, with aerodynamic balance increasing from 46.20 % experimentally to 50.9 % numerically. For a Formula Student vehicle, this is relevant because front-to-rear load distribution affects vehicle balance, tyre loading, and setup decisions. Therefore, the correlation must be assessed not only through total $C_L A$, but also through the axle-wise coefficients and aerodynamic balance.

A further hypothesis concerns the Reynolds-number range covered by the simulated operating points. Since the selected cases combine different airspeeds and ride heights, the numerical comparison is not performed at a single flow regime. The lowest-speed cases correspond to the lowest Reynolds numbers of the dataset, whereas the highest-speed cases approach $Re \approx 3.2 \times 10^6$, using the wheelbase as reference length. This may be relevant because aerodynamic devices operating close to the ground can be sensitive to Reynolds number and ground clearance, with transition, laminar separation bubbles, and separation onset affecting the resulting aerodynamic loads [14]. Since the present CFD setup is fully turbulent and does not include transition modelling, transitional effects in the real on-track flow could cause the numerical solution to maintain more attached flow and therefore predict higher downforce. This mechanism could contribute to the observed overprediction, although Reynolds number varies together with inlet velocity, dynamic pressure, ride height, and ground clearance, so its influence cannot be isolated without a dedicated sensitivity study.

Overall, the numerical model captures the main aerodynamic trend over the tested operating range, but with a systematic positive bias in total and front load that exceeds the typical lift-related numerical error reported for the adopted CFD framework. For a ground-effect-dominated Formula Student vehicle, these differences may result from ride-height sensitivity, geometry simplifications, boundary-condition assumptions, experimental uncertainty, and steady RANS modelling limitations [15]. The comparison supports the use of CFD for trend prediction and relative configuration studies, while reinforcing the need for full-scale experimental correlation before relying on numerical

results for absolute aerodynamic load estimation.

6. Conclusions

This work developed and applied a full-scale on-track aerodynamic validation methodology for the FST14 Formula Student prototype, covering vehicle setup, instrumentation, calibration, test execution, data processing, aerodynamic coefficient identification, and CFD correlation. The experimental campaign produced coherent aerodynamic estimates, with $C_L A = 3.467 \text{ m}^2$, $(C_{L,F} A) = 1.602 \text{ m}^2$, $(C_{L,R} A) = 1.890 \text{ m}^2$, $AB = 45.87\%$, and $C_D A = 1.661 \text{ m}^2$. The CFD comparison reproduced the correct qualitative increase of aerodynamic load with dynamic pressure, but overpredicted the force levels, with discrepancies of 32.7%, 38.9%, and 25.2% for total, front, and rear downforce, respectively, still exceeding the typical numerical error previously reported for this framework.

The main limitations were the reduced speed matrix caused by battery state of charge, limited telemetry range during testing, the absence of local wind measurements, and the restriction of the validation to straight-line conditions over a limited ride-height range. Additional uncertainty came from the use of meteorological-station wind data, the load reconstruction assumptions, and the steady CFD approach, which did not include yaw, steering, pitch variations, or transient ride-height effects. The coastdown data were also not directly compared with CFD because speed and vehicle state varied continuously.

Future work should extend the campaign to a denser matrix of ride heights, speeds, and aerodynamic configurations, supported by improved telemetry coverage, stronger test-day procedures, and direct on-site wind measurements. Further CFD studies should assess the sensitivity to ride height, pitch, yaw, steering, geometry simplifications, turbulence modelling, transition effects, and boundary-condition assumptions. These improvements would allow the methodology to evolve into a broader aerodynamic correlation framework for future FST Lisboa prototypes.

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