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

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Dedicated to my mom, my dad, my sister, my grandparents and girlfriend.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

Validação aerodinâmica é essencial em Formula Student, onde resultados CFD devem ser correlacionadas com o comportamento em pista. Este trabalho apresenta uma avaliação experimental e numérica do protótipo FST14. O objetivo foi validar cargas aerodinâmicas em linha reta por ensaios em pista e comparar estimativas experimentais com previsões CFD para configurações equivalentes, contribuindo para correlacionar modelos numéricos com dados à escala real.

A campanha combinou ensaios a velocidade constante para estimar downforce e ensaios de coast-down para estimar resistência aerodinâmica. A resposta do veículo foi medida por potenciômetros de suspensão e tubo de Pitot, permitindo reconstruir cargas aerodinâmicas a partir da altura ao solo e pressão dinâmica. Calibrações e uma metodologia em MATLAB apoiaram o condicionamento dos sinais e a estimação de parâmetros. As simulações CFD foram realizadas para pontos experimentais representativos.

Os ensaios a velocidade constante resultaram em $C_L A = 3.467\text{m}^2$, com valores por eixo de 1.602m^2 e 1.890m^2 , e balanço aerodinâmico de 46.20%; os ensaios de coastdown produziram $C_D A = 1.661\text{m}^2$. A comparação CFD reproduziu as tendências globais, mas sobrestimou os coeficientes de downforce total, dianteira e traseira em 32.7%, 38.9% e 25.2%, respectivamente, excedendo o erro numérico típico previamente reportado. A previsão CFD indicou ainda um balanço mais dianteiro de 50.9%.

As discrepâncias estão plausivelmente associadas à sensibilidade à altura ao solo, incerteza experimental, simplificações geométricas, condições de fronteira e limitações de RANS estacionário.

No geral, são estabelecidos uma metodologia repetível para validação aerodinâmica em pista e um fluxo estruturado para desenvolvimento aerodinâmico e correlação com simulações.

Palavras-chave: Carro de Competição, Dinâmica de Fluidos Computacional, Ensaios a Velocidade Constante, Ensaios de Coastdown, Estimativa de Downforce, Estimativa de Resistência Aerodinâmica

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 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

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Nomenclature

Greek symbols

α	Road inclination angle or toe angle, depending on context
β	Regression slope or auxiliary coefficient, depending on context
χ^2	Chi-squared statistic
Δ	Difference or increment
δ	Deflection or steering angle, depending on context
η	Efficiency
γ	Camber angle
μ	Dynamic viscosity
ν	Degrees of freedom
ω	Angular speed
ρ	Density
σ	Standard deviation
τ	Time interval or dwell time
θ	Angular direction

Roman symbols

A	Reference area
a	Acceleration
AB	Aerodynamic balance
A_0, A_1, A_2	Polynomial coefficients of the coastdown resistive-force model
C_D	Drag coefficient
C_L	Lift coefficient

F	Force
f	Force–deflection relation
f_0, f_1	Rolling-resistance coefficients
g	Gravitational acceleration
I	Rotational inertia
J	Regression objective function
K	Stiffness
L	Wheelbase or characteristic length
l	Length or measured distance
M	Moment
m	Mass
MR	Suspension motion ratio
N	Number of samples or data points
p	Pressure
q	Dynamic pressure
R	Specific gas constant or resistance term, depending on context
Re	Reynolds number
RH	Ride height or relative humidity, depending on context
R^2	Coefficient of determination
S	Static load or Sutherland constant, depending on context
T	Temperature
U	Inlet velocity
u	Standard uncertainty
$\mathbf{u}$	Velocity vector
V	Velocity magnitude or voltage, depending on context
v	Vehicle speed relative to the air
w	Wind speed contribution
X	Regression design matrix

x	Displacement
y	Observation vector

Subscripts

0	Static, initial, reference, or constant condition
ADC	Analog-to-digital converter
aero	Aerodynamic quantity
air	Air
amb	Ambient condition
CD	Coastdown
CFD	Computational Fluid Dynamics prediction
CV	Constant velocity
D	Drag
d	Damper or dry-air component, depending on context
F	Front axle
FL	Front-left corner
FR	Front-right corner
i	Run, corner, or generic index
∞	Free-stream condition
j	Regression dataset index
k	Sample index
L	Lift or downforce
m	Manometric fluid or mass-related quantity, depending on context
man	Manometer
max	Maximum value
min	Minimum value
O	Reference origin
$\parallel$	Component parallel to the track direction
pitot	Pitot sensor

R	Rear axle
ref	Reference condition
res	Resistive
RL	Rear-left corner
RR	Rear-right corner
s	Spring
T	Total
track	Track
tyre	Tyre
v	Water-vapour component
w	Wheel, when used as a displacement subscript
wind	Wind
x	Longitudinal direction
y	Lateral or pitch-axis direction, depending on context
z	Vertical direction

Superscripts

$\overline{(\cdot)}$	Mean or filtered quantity
CFD	Numerical prediction obtained from CFD
$\hat{(\cdot)}$	Estimated or fitted quantity
-1	Inverse relation
T	Transpose

Glossary

AB	Aerodynamic Balance
ADC	Analog-to-Digital Converter
AHRS	Attitude and Heading Reference System
APPS	Accelerator Pedal Position Sensor
BPS	Brake Pedal Sensor
CAD	Computer-Aided Design
CAN	Controller Area Network
CD	Coastdown
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
CV	Constant Velocity
DEM	Department of Mechanical Engineering
DNS	Direct Numerical Simulation
DRS	Drag Reduction System
FS	Formula Student
FSG	Formula Student Germany
FVM	Finite Volume Method
GNSS	Global Navigation Satellite System
INS	Inertial Navigation System
IST	Instituto Superior Técnico
LES	Large Eddy Simulation
LNEC	Laboratório Nacional de Engenharia Civil
MPE	Mean Percentage Error
ODR	Orthogonal Distance Regression
RANS	Reynolds-Averaged Navier–Stokes
RMSE	Root Mean Square Error
SAE	Society of Automotive Engineers
SoC	State of Charge
SST	Shear Stress Transport
UTM	Universal Testing Machine

Chapter 1

Introduction

This chapter serves as an introduction to this research, outlining its objectives, expected deliverables, and the significance of the topic. By providing a structured framework, it ensures a clear understanding of the research direction and its relevance within the broader context of Formula Student (FS).

1.1 Motivation and Relevance

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. This importance is also evident in FS, an international engineering competition in which university teams design, manufacture, and compete with single-seater formula-style race cars [1]. The events are divided into static disciplines, namely engineering design, cost and manufacturing, and business presentation, and dynamic disciplines, including acceleration, skidpad, autocross, endurance, efficiency, and track drive. Since dynamic events account for 675 of the total 1000 points available, vehicle performance on track is a central factor in achieving competitive results [2].

Although success on track is an important objective, it is not the sole determinant of a team's performance. Engineering design and validation, especially in the context of the Engineering Design event, play a pivotal role in the final score of a team. This is where aerodynamic development becomes especially relevant, as teams are expected to demonstrate well-funded engineering methodologies and decisions, but also validation of their concepts.

In professional motorsports, aerodynamic testing benefits from access to advanced facilities like wind tunnels and track instrumentation. In contrast, FS teams often rely heavily on Computational Fluid Dynamics (CFD) due to budget and resource limitations. Currently, the overreliance on CFD simulations often means that teams lack proper procedures and methodologies for experimental validation through wind tunnels and/or on-track testing. Without reliable validation, the correlation between CFD predictions and real-world performance weakens, making it challenging to ensure aerodynamic designs translate effectively to the track. This can lead to suboptimal setups that impact vehicle performance and race strategy.

This limitation is evident across the FS community, including at FST Lisboa, the FS team from Instituto Superior Técnico (IST). Despite employing quite advanced CFD workflows, the team lacks robust on-track validation procedures due to limitations in instrumentation and testing methodology. As a result, there is a gap between theoretical aerodynamic performance and real-world results.

Therefore, the primary motivation for this thesis is to bridge that gap by developing a cost-effective and reliable on-track validation methodology. By collecting accurate aerodynamic performance data and correlating it with CFD predictions, this work aims to improve the credibility of simulation results and support more effective engineering design justifications. The expected outcome is a methodology that not only improves FST Lisboa's aerodynamic understanding but also serves as a valuable asset during the Engineering Design event, helping the team stand out in an increasingly competitive field.

1.2 Formula Student Aerodynamics

Nowadays, spotting an aeroless prototype in a FS competition paddock is a rare sight. As aerodynamic devices have become a staple in prototype design, teams continuously refine their aerodynamic packages to maximize performance.

Aerodynamics in FS is governed primarily by two main force components [3]:

- **Downforce (F_L)** – aerodynamic force that acts approximately perpendicular to the incoming airflow and to the direction of vehicle motion. This force is directed towards the ground, increasing the normal loads on the tyres and therefore improving their force-generation capability:

$$F_L = \frac{1}{2} \rho v^2 C_L A \quad (1.1)$$

where F_L is the aerodynamic downforce, ρ is the air density, v is the vehicle speed relative to the air, C_L is the lift coefficient associated with downforce generation, and A is the reference area.

- **Drag (F_D)** – aerodynamic force that acts approximately parallel to the incoming airflow and opposite to the direction of vehicle motion. It therefore represents the aerodynamic resistance that the vehicle must overcome as it moves through the air:

$$F_D = \frac{1}{2} \rho v^2 C_D A \quad (1.2)$$

where F_D is the aerodynamic drag force and C_D is the drag coefficient, which characterizes the aerodynamic resistance associated with the vehicle geometry and flow conditions. As in Equation (1.1), ρ is the air density, v is the vehicle speed relative to the air, and A is the reference area. The term $\frac{1}{2} \rho v^2$ corresponds to the dynamic pressure, often denoted by q .

A useful performance parameter derived from these two forces is the aerodynamic efficiency (η_{aero}),

which expresses how much downforce is generated per unit of drag. It is commonly defined as

$$\eta_{\text{aero}} = \frac{F_L}{F_D} = \frac{C_L}{C_D}. \quad (1.3)$$

Teams typically prioritize optimizing downforce, as the nature of FS tracks, characterized by tight corners and slalom sections demands high levels of grip, making drag a secondary concern. The practical implementation of these aerodynamic principles in prototypes rely on specific aerodynamic devices designed to generate and control downforce efficiently. Similarly to any other component of the prototype, their design is subjected to tight constraints and regulations, as per the Formula Student Germany (FSG) 2025 Rules and Regulations [2]. Although there are slight differences between prototypes, aerodynamic packages within FS are fundamentally divided into four sub-assemblies:

- **Front Wing:** Positioned at the very front of the car, is designed to generate downforce efficiently. Its primary role, however, is to direct airflow in a way that benefits the overall package;
- **Underbody:** This component accelerates airflow beneath the car, creating a low-pressure area that enhances downforce;
- **Side Wings:** These are the aerodynamic components located on the sides of the car. They contribute to downforce and help manage airflow in alignment with the car's aerodynamic design;
- **Rear Wing:** Situated at the back of the car, the rear wing generates significant downforce. However, its position relative to the incoming airflow also results in considerable drag, making it less efficient in terms of aerodynamic performance.



Figure 1.1: Aerodynamic elements of the FST14 prototype

These aerodynamic elements (Figure 1.1) work collectively to generate downforce and manage airflow around the vehicle and their impact becomes most apparent when considering how performance on track is fundamentally limited by tyre grip. Forces responsible for accelerating, braking and cornering are transmitted through the tyres of a racecar. As such, the ultimate determinant to maximize vehicle performance is to equally maximize the grip interaction between the tyres and the road surface. While the optimization of grip is an intricate subject, dependent on multiple factors and design decisions, namely suspension design, FS teams found in aerodynamic development an answer.

Increasing the normal load on a tyre through aerodynamic force without the undesirable addition of mass and consequent inertia, which are usually a hindrance to performance, effectively expands the tyre's performance envelope or friction ellipse. Since friction force is proportional to normal load, the maximum available grip is increased allowing for higher cornering speeds, shorter braking distances and improved acceleration capabilities [4]. The effects of added downforce are illustrated in the diagram in Figure 1.2.

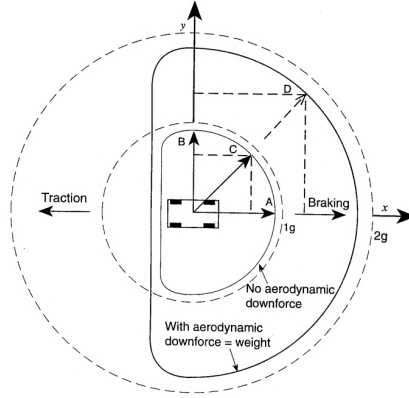


Figure 1.2: Effect of added aerodynamic downforce on the tyre's maximum performance envelope [4]

The effects of aerodynamics on performance are directly analyzed by the FST Lisboa Vehicle Dynamics department, primarily through lap time simulations using the team's in-house developed Quasi-Steady-State point mass simulator. This simulator models the vehicle as a single point mass traveling along a predefined track layout. By entering parameters such as vehicle C_L and C_D , the team can evaluate how aerodynamic changes impact lap times across various dynamic events and ultimately predict the team's overall points in FS competitions.

For this study, considering the interdependence of C_L and C_D , the team input a range of possible (C_L, C_D) pairs into the simulator. These pairs were derived from trends observed across the extensive CFD simulations conducted during the FST13 design phase. The impact of varying C_L/C_D on total competition points is illustrated in Figure 1.3.

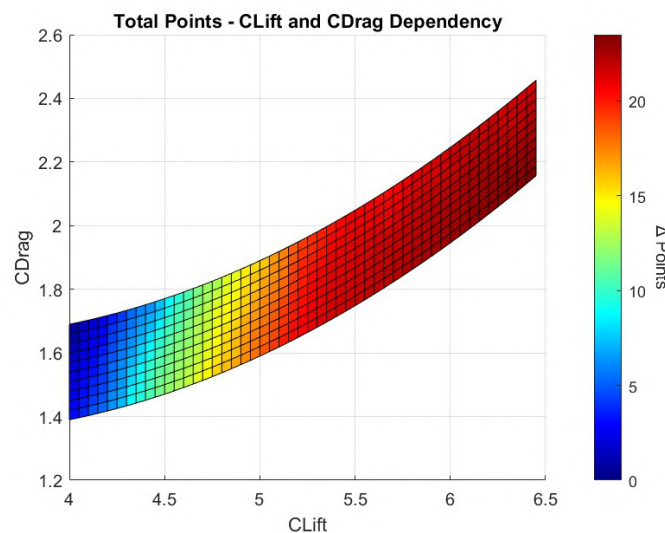


Figure 1.3: Effect of aerodynamic performance on total points

The results in Figure 1.3 demonstrate how even small errors in the predicted aerodynamic coefficients can significantly impact total competition points, reinforcing the need for accurate validation beyond CFD.

1.3 Aerodynamic Validation

Aerodynamic validation methods are essential to ensure that computational predictions accurately reflect real-world performance. While CFD provides detailed aerodynamic estimates, its results must be experimentally assessed to account for modeling assumptions and simplifications, particularly because full-scale aerodynamic measurements under real operating conditions do not necessarily reproduce the same conditions observed in controlled testing environments [5]. Validation techniques typically include wind tunnel testing, where scaled or full-size models are tested under controlled conditions, and on-track testing, which measures aerodynamic forces directly on the vehicle in dynamic conditions. Additionally, flow visualization techniques, such as tuft testing provide qualitative insights into airflow patterns, helping identify areas of separation, vortices, and regions of high turbulence.

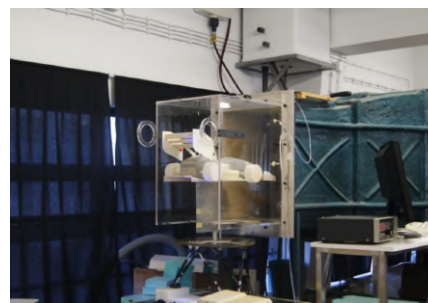
Within FSTLisboa, there have been several attempts at validating results originating from CFD as an attempt to establish these simulations as trustworthy tools to reflect on-track performance.

FST Lisboa's first wind tunnel testing campaign coincided with the development of the team's first-ever aerodynamic package. During the design phase of FST06e, a 40% scale model of the rear wing was tested in the Low-Speed Wind Tunnel at IST (Figure 1.4a). The primary objective was to study the effect of varying endplate sizes on lift; however, unexpected discrepancies between CFD predictions and experimental results were observed. These deviations were largely attributed to differences in Reynolds number, as the wing was originally designed for a higher Reynolds number than what was achieved in the wind tunnel. Tests were conducted at 10m/s , resulting in a Reynolds number nearly four times lower than the full-scale value, leading to altered flow characteristics and affecting the validity of the results [6].

Subsequently, a 25% scale model of the complete FST06e was 3D printed (Figure 1.4b) and tested. However, due to weight limitations imposed by the aerodynamic force balance, the model had to be manufactured with extremely thin 1 mm surfaces. This led to significant aeroelastic deformations, making it more challenging to draw direct comparisons with CFD predictions [6].



(a) Rear wing model



(b) Full-scale model

Figure 1.4: FST06e wind tunnel testing [6]

One of the team's latest wind tunnel testing effort was led by Jaime Pacheco as a key component of his master's thesis. This involved the full manufacturing and testing of a 1/3 scale model of FST Lisboa's 10th prototype, the FST10e, in the aeroacoustic closed-section wind tunnel at IST's Aerospace Laboratory. Although the numerical data successfully captured the general trends observed experimentally, the high uncertainty associated with the apparatus prevented a reliable quantitative comparison between the CFD results and wind tunnel measurements [6].

The first and only attempt at on-track aerodynamic testing was carried out during the FST10e's testing phase as part of Miguel Carreira's master's thesis. This involved conducting coast-down and constant velocity tests on track. However, much like the previous wind tunnel testing campaigns, high experimental uncertainties, which arised from poor methodologies and instrumentation, preventing any viable quantitative comparisons with numerical results [7].

More recently, the work of Santos represented the most recent aerodynamic experimental validation effort carried out within FST Lisboa. His thesis focused on the aerodynamic study of the FST14, with particular emphasis on the side elements, combining CFD simulations with wind tunnel testing of a specifically manufactured 1:3 scale model. As illustrated in Figure 1.5, the experimental campaign was conducted in the closed-circuit wind tunnel at Laboratório Nacional de Engenharia Civil (LNEC) and included global force and moment measurements, surface static pressure measurements, and tuft-based flow visualization. Although the experimental setup was still affected by non-negligible uncertainty, the results showed consistent aerodynamic trends and reasonable agreement with the numerical predictions, further reinforcing the credibility of the CFD methodology adopted within the team as a design tool [8].



Figure 1.5: FST14 wind tunnel experimental campaign [8]

Given the critical role of aerodynamics in shaping a prototype's overall performance envelope, bridging the gap between CFD simulations and real-world performance becomes essential to ensure both accuracy and efficiency in the design process. Despite previous validation attempts within the team, as outlined in this chapter, FST Lisboa still lacks a robust methodology with proper instrumentation capable of delivering accurate on-track data. This data is crucial for assessing the modelling accuracy of the CFD setup and simulations.

1.4 Objectives and Deliverables

The primary objective of this work is to validate the aerodynamic performance of the FST14 prototype through on-track testing and to correlate the resulting experimental estimates with Computational Fluid Dynamics (CFD) predictions for the same operating conditions, thereby assessing the modelling accuracy of the adopted CFD model. To this end, the prototype is subjected to straight-line constant-velocity and coastdown tests, from which lift- and drag-related aerodynamic quantities are identified using data acquired from suspension potentiometers, a pitot tube, and the remaining vehicle instrumentation.

A secondary objective is to provide FST Lisboa with a structured and replicable methodology for straight-line aerodynamic validation. This includes the full chain of activities required to obtain reliable aerodynamic estimates, namely vehicle preparation and setup, instrumentation and sensor calibration, static characterization of the relevant suspension and tyre parameters, on-track test execution, data processing, aerodynamic coefficient identification, and comparison with CFD results. By documenting these procedures in a consistent manner, the present work aims to provide the team with a validation framework that can be reused and further refined in future prototype development cycles.

Throughout the course of this work, the following main deliverables are produced:

- A documented vehicle setup and preparation methodology for straight-line aerodynamic testing, including ride-height control, load distribution, and wheel-alignment verification;
- A documented instrumentation and calibration methodology, including pitot-tube calibration, suspension-potentiometer calibration, and motion-ratio identification;
- Static characterization of the spring and tyre vertical force–displacement behaviour required for wheel-load reconstruction;
- An on-track testing campaign under monitored environmental, vehicle, and track conditions;
- A complete data-processing framework implemented in MATLAB for run segmentation, signal conversion, downforce estimation from constant-velocity data, and drag estimation from coastdown data;
- A correlation between CFD and on-track results, including point-by-point comparison and regression-based assessment of the modelling error.

1.5 Relevance to Aerospace Engineering

Although developed in the context of Formula Student, the methodology presented in this work addresses challenges that are also encountered throughout the aerospace industry. Modern aircraft and spacecraft rely extensively on CFD during the design process to evaluate aerodynamic performance and support engineering decisions. However, numerical predictions must ultimately be correlated with experimental data to ensure that the simulated behaviour accurately represents real operating conditions.

Experimental validation is therefore an essential stage of aerodynamic development. Across the aerospace sector, numerical models are routinely assessed through wind tunnel campaigns, flight testing, or other experimental techniques before being used with confidence for design optimisation, certification, or operational analyses. Developing reliable validation methodologies is consequently as important as improving the numerical models themselves.

The approach explored in this work reflects this engineering philosophy by combining computational predictions with full-scale experimental measurements to assess aerodynamic performance under representative operating conditions. While CFD provides a cost-effective and accessible research platform, the principles of experimental validation, uncertainty quantification, and model correlation are directly transferable to broader aerospace engineering applications.

1.6 Thesis Outline

This thesis is divided into seven chapters.

Chapter 1 introduces the context and motivation of the work, discusses the role of aerodynamics and aerodynamic validation in FS, and presents the objectives and deliverables.

Chapter 2 reviews the main approaches used in aerodynamic performance evaluation, with particular focus on the two methodologies most relevant to the present work: experimental on-track testing and CFD.

Chapter 3 describes the preparation of the on-track aerodynamic validation campaign. It presents the experimental prototype, the theoretical basis of the adopted downforce- and drag-estimation methodologies, the test procedures and vehicle pre-requisites, the instrumentation and its calibration, the static characterization of the spring and tyre behaviour, and the final vehicle setup procedure.

Chapter 4 presents the on-track testing campaigns carried out for the present work. It describes the testing facility, the practical implementation of the straight-line protocol, the execution of the runs, and the monitoring of the environmental, vehicle, and track conditions under which the data were acquired.

Chapter 5 details the post-processing of the experimental data and the corresponding aerodynamic results. It includes raw-signal segmentation, calibration-based signal conversion, implementation of the constant-velocity and coastdown processing frameworks, presentation of the processed data, and identification of the experimental lift-related coefficients, drag-area coefficient, and aerodynamic efficiency.

Chapter 6 presents the CFD simulations performed for the selected operating conditions and compares the numerical results with the experimental estimates. The adopted numerical setup, the definition of the simulated cases, the post-processing of the CFD results, and the validation against experimental data through point-by-point and regression-based comparisons are discussed.

Chapter 7 summarizes the main achievements of the work and presents recommendations for future developments, with emphasis on the refinement and extension of the aerodynamic validation methodology.

Chapter 2

Aerodynamic Performance Evaluation

Aerodynamic performance evaluation is commonly supported by three main approaches: wind tunnel testing, on-track testing, and CFD simulations. Together, these methods form a complementary framework for aerodynamic development, since each provides a different perspective on the flow physics and vehicle behavior. While CFD enables detailed flow-field analysis and rapid design iteration, experimental methods are required to assess how well the numerical predictions represent real operating conditions.

Although these three pillars are often regarded as part of a complete aerodynamic validation framework, wind tunnel testing is not the focus of the present thesis. Instead, this chapter concentrates on the two approaches most directly relevant to the objectives of this work: CFD and experimental on-track testing, highlighting their principles, advantages, limitations, and, most importantly, the need for their combined use in a reliable aerodynamic evaluation process.

2.1 On-Track Experimental Testing

On-track testing remains one of the most direct and reliable approaches for evaluating the real-world aerodynamic performance of a race car. It serves as the final validation stage in the development process, where the vehicle is evaluated under conditions that closely replicate those encountered in competition conditions. Testing on-track introduces dynamic variables such as road surface irregularities, transient vehicle motion, environmental effects, and driver inputs, all of which influence the aerodynamic loads acting on the vehicle in ways that cannot always be reproduced through simulations or controlled wind-tunnel testing alone [5, 9].

Methodologies employed in an on-track testing environment can generally be divided into two main categories: direct measurement techniques, in which sensors and instruments are used to measure aerodynamic-related quantities directly; and indirect measurement techniques, in which aerodynamic performance is inferred from the measured dynamic response of the vehicle. In the present work, the emphasis is placed on the latter approach, specifically on the estimation of performance-related aerodynamic parameters, such as downforce and drag, rather than on the direct characterization of local flow features or detailed aerodynamic phenomena.

2.1.1 Constant Velocity for Downforce Estimation

Constant Velocity (CV) testing is a widely used method for the experimental determination of a vehicle's aerodynamic downforce under real-world conditions. It is particularly suited to FS applications due to its low-cost nature and ease of implementation, as it allows teams to validate the aerodynamic performance of their prototype using track testing and relatively simple instrumentation, often already present on the vehicle [10].

The method consists of accelerating the vehicle to a predetermined speed and maintaining that speed over a straight and flat section of track. During this phase, data is acquired from the suspension system to estimate the vertical forces acting on the wheels. These forces result from the combination of vehicle weight and aerodynamic downforce generated at that specific speed and ride height. Because downforce is highly dependent on ride height, maintaining precise control over the vehicle's vertical dynamics is crucial to the test's validity [11].

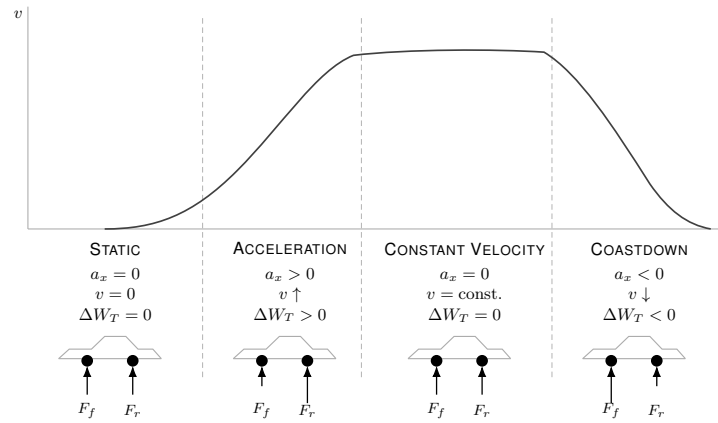


Figure 2.1: Schematic representation of the phases of a typical CV run

As illustrated in Figure 2.1, the run is composed of four distinct stages: the static condition where the vehicle is at rest, the acceleration phase which introduces positive weight transfer, the constant speed phase where inertial forces become negligible and downforce can be isolated, and the deceleration phase which introduces negative weight transfer. Only the CV segment is suitable for aerodynamic assessment, as it ensures that longitudinal acceleration is null and thus inertial effects are minimized.

The downforce estimation relies on measuring the vertical loads at the wheels and comparing them to the static values. These loads can be obtained either through the use of strain gauges mounted in the suspension or, more commonly in FS applications, through the measurement of damper deflections using potentiometers [7, 11]. Knowing the motion ratios and spring stiffnesses of the suspension allows for a direct calculation of vertical forces. When the total downforce is known and the corresponding dynamic pressure is measured, the lift coefficient can also be obtained. This approach not only yields the total downforce, but also allows for the estimation of aerodynamic balance by assessing the load distribution between the front and rear axles, thereby providing insight into the longitudinal position of the aerodynamic centre of pressure [10].

To maximize measurement accuracy and eliminate as many external influences as possible, several

guidelines must be followed during vehicle setup [11]:

- Springs and dampers should be set as soft as reasonably possible to minimize vertical load variation from bumps;
- The presence of bump rubbers or packers should be eliminated as they introduce non-linearities in the suspension response;
- Anti-roll bars should be disconnected to ensure that each wheel moves independently and reflects local load changes without cross-axle coupling;
- The tests should be conducted in both directions on the track to reduce the influence of wind direction and road slope.

2.1.2 Coastdown Testing for Drag Estimation

Coastdown (CD) testing is a widely accepted method for the experimental determination of a vehicle's aerodynamic drag under real-world conditions, and is particularly attractive in FS due to its low-effort and low-cost nature [12]. Since the procedure can usually be carried out with minimal instrumentation, often limited to vehicle speed measurement, it provides a practical means of experimentally assessing the road-load characteristics of the full-scale prototype without the need for complex test setups [11].

The method consists of accelerating the vehicle to a predetermined speed and then allowing it to decelerate freely without throttle or brake input. During this deceleration period, the vehicle speed is monitored as a function of time, from which the resistive forces acting on the vehicle can be estimated and the drag contribution subsequently identified through suitable fitting procedures [13]. A typical velocity–time graph, which illustrates the principle behind the CD procedure, is shown in Figure 2.2.

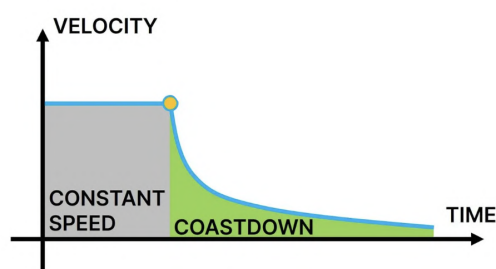


Figure 2.2: CD testing principle [14]

The Society of Automotive Engineers (SAE) has established standardized procedures for conducting CD tests. In the present context, the general methodology is referenced through test specification developed in partial accordance with the SAE J1263 norm, while the SAE J2263 norm formalizes the determination of vehicle road-load force over the speed range from 115 km/h to 15 km/h [15, 16].

According to these procedures, the CD test should be conducted on a flat, straight, and smooth test track, under low-wind conditions. The vehicle is accelerated to the target speed and then allowed to coast down over the prescribed speed interval while the relevant quantities, such as vehicle speed,

time, and ambient conditions, are recorded. To reduce the influence of wind and road gradient, tests are performed in both directions and the results are averaged, in line with established on-road drag-determination practice [16–18].

These procedures also define a set of initial conditions and prerequisites that should be satisfied [15]:

- The tests should be carried out at ambient temperatures between 5 °C and 38 °C;
- Tests shall not be run during foggy conditions;
- Tests shall not be conducted when average wind speeds exceed 16 km/h or when peak wind speeds exceed 20 km/h;
- Roads shall be dry, clean, smooth, and straight;
- Tires shall have accumulated a minimum of 160 km prior to CD testing;
- Tires should have at least 75% of the original tread depth remaining;
- Vehicle tires should be inflated to the manufacturer's recommended cold inflation pressure, corrected for the difference between ambient and soak temperature.

2.2 Computational Fluid Dynamics

Computational Fluid Dynamics has become one of the most powerful and widely used tools in aerodynamic development. It allows engineers to simulate the behaviour of air as it flows around a body by solving, in approximate form, the governing equations of fluid motion [19]. Through these simulations, it becomes possible to visualize pressure distributions, identify flow separation, and estimate aerodynamic forces in a fully virtual environment [20]. This reduces the dependence on early-stage physical prototypes and gives teams the freedom to explore a wide range of design alternatives in a cost-effective manner.

Within the FS context, CFD plays a central role in the aerodynamic design process. It is frequently used to evaluate the performance of aerodynamic components under different operating conditions, such as ride heights, velocities, and yaw angles. This level of flexibility is particularly valuable because physical testing opportunities are often limited by time, cost, instrumentation availability, and track access.

However, while CFD is an extremely powerful tool, it is not infallible. At the Reynolds numbers typically encountered by FS cars, the flow is predominantly turbulent, making the direct resolution of all relevant flow scales impractical for routine design work. Therefore, affordable simulations require additional modelling assumptions, with one of the most important choices being the mathematical approach used to represent turbulence, such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), or Reynolds-Averaged Navier–Stokes (RANS) methods [21].

These approaches involve different compromises between physical resolution and computational cost. As a result, the meaning and impact of turbulence modelling depend on the selected approach,

being especially central in RANS-based simulations, which remain widely used in vehicle aerodynamic development due to their comparatively affordable computational cost [22].

Therefore, the accuracy and quality of CFD predictions depend on several critical factors, including the selected modelling approach, the turbulence model, mesh refinement, numerical schemes, and the accuracy of the applied boundary conditions [20]. Simulation results must therefore be interpreted with care. Without validation, there is no guarantee that a configuration which appears promising in the digital domain will perform equivalently on track.

2.2.1 Governing Equations of Fluid Motion

At the core of CFD lie the Navier–Stokes equations, which govern the motion of viscous fluids [19]. These equations represent the conservation laws of physics: mass, momentum, and energy. For incompressible, Newtonian fluids under isothermal conditions, which is often a valid assumption in FS aerodynamic simulations, the governing equations simplify to the following form [19].

$$\nabla \cdot \vec{u} = 0 \quad (2.1)$$

This equation states that mass is conserved in an incompressible flow, where $\vec{u}$ is the velocity vector of the fluid.

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} + \vec{f} \quad (2.2)$$

Here, ρ is the fluid density, p is the static pressure, μ is the fluid dynamic viscosity, and $\vec{f}$ represents any external forces acting on the fluid (e.g., gravity). The left-hand side includes both local and convective acceleration terms, while the right-hand side represents pressure, viscous, and body forces.

Equations (2.1) and (2.2) are discretized and solved numerically. This involves subdividing the domain into a computational mesh and applying numerical schemes such as the Finite Volume Method (FVM) to approximate the differential operators. The solution is iteratively computed until convergence criteria are met, providing velocity, pressure, and derived quantities such as aerodynamic forces [20].

2.2.2 Turbulence Modeling and Near-Wall Treatment

Most real-world flows, particularly around bluff bodies like a FS car, are turbulent. Accurately capturing this turbulent behavior is one of the greatest challenges in CFD.

Most commonly, turbulence is modeled using the RANS approach [23]. RANS decomposes the instantaneous velocity field into a mean component and a fluctuating component into the Navier–Stokes equations and applying time-averaging introduces new terms called the Reynolds stresses. These represent the influence of turbulent fluctuations on the mean flow and require closure through turbulence models [19].

To close the RANS equations, various turbulence models are available. The most common in vehicle aerodynamics include [20, 24]:

- $k-\varepsilon$ model: Widely used for its robustness and simplicity, suitable for free shear flows but less accurate near walls;
- $k-\omega$ model and Shear Stress Transport (SST) variant: Provides better accuracy in near-wall regions and is often preferred for external aerodynamics due to its balance of stability and fidelity.

These models solve two additional transport equations, one for the turbulent kinetic energy k and another for its dissipation rate ε or specific dissipation rate ω . The treatment of flow near solid surfaces is especially important in aerodynamic studies, as this is where boundary layers form and most drag originates. Depending on mesh resolution and turbulence model, engineers choose between [25]:

- Wall functions: Semi-empirical formulas used when the mesh is coarse near the wall (typically targeting $30 < y^+ < 300$).
- Low-Reynolds models or fully resolved walls: Require fine mesh resolution ($y^+ \approx 1$) and directly solve the boundary layer without wall function approximations.

Correctly modeling this near-wall behavior is crucial for capturing both pressure and viscous drag components, as well as for reliable downforce estimation. In FS, CFD simulations often rely on the RANS framework with the SST $k-\omega$ model, as it provides a good trade-off between computational cost and near-wall accuracy [25]. The careful selection of turbulence model and wall treatment ensures reliable aerodynamic predictions, especially when validated against wind tunnel or on-track data. This allows teams to simulate and understand flow behavior over wings, diffusers, and underbodies, guiding informed design choices early in development.

2.2.3 Numerical Simulation Workflow

A CFD analysis is composed of a sequence of well-defined steps that begins with the selection of an appropriate mathematical model and ends with the interpretation of results [25]. Each stage in this workflow contributes to the overall quality and physical reliability of the simulation, although not all stages affect the solution in the same way. In particular, it is useful to distinguish between aspects that primarily define the modelling accuracy of the simulation and those that primarily affect its numerical accuracy. Figure 2.3 summarizes this process through a simplified schematic.

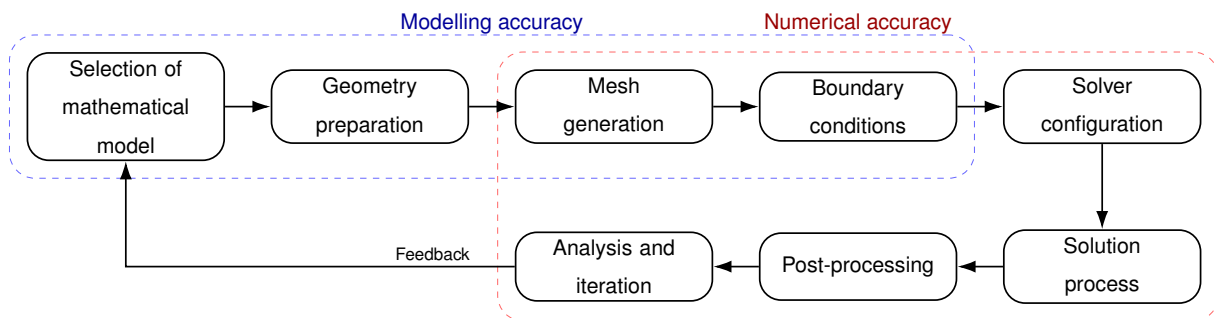


Figure 2.3: Simplified CFD workflow adopted for the numerical analysis

The workflow begins with the selection of the mathematical model, followed by geometry preparation, mesh generation, the definition of boundary conditions, and solver configuration. The numerical solution is then obtained iteratively until a converged state is reached, after which the relevant flow quantities and integrated aerodynamic forces are extracted in post-processing. Finally, the results are assessed and, if necessary, the setup is refined through further iterations of the geometry, mesh, boundary conditions, or numerical settings [20, 26].

From the point of view of modelling accuracy, the most influential stages are the selection of the mathematical model, geometry preparation, and the prescription of boundary conditions, since these determine how closely the simulation setup represents the real physical problem. By contrast, numerical accuracy is primarily governed by mesh generation, solver configuration, and the solution process, as these control the discretization quality, convergence behaviour, and the extent to which the chosen mathematical model is solved accurately. Post-processing and analysis then provide the basis for assessing both sources of error and guiding subsequent refinements.

Chapter 3

On-Track Aerodynamic Testing Preparation

This chapter describes the preparation of the on-track aerodynamic testing campaign, encompassing the definition of the experimental platform, the estimation methodologies, and the practical implementation required to ensure reliable data acquisition.

3.1 Experimental Prototype

This section introduces the experimental platform on which the straight-line aerodynamic testing campaign is conducted. The tests shall be carried out on the FST Lisboa's electric FS prototype, FST14. FST14 is a four-wheel-drive electric race car built around a composite monocoque chassis and equipped with a full aerodynamic package, representative of contemporary Formula Student design practice [27].

The chassis consists of a carbon-fibre sandwich monocoque with a honeycomb core, providing a lightweight and stiff structural backbone for both suspension and aerodynamic load paths. In race-ready condition, FST14 has a mass of approximately 205 kg, with the Centre of Gravity (CG) located at approximately 300 mm above the ground. Propulsion is provided by four AMK electric motors, supplied by a self-developed accumulator with a nominal energy capacity of 5.9 kWh, enabling a top speed of approximately 117 km/h. [27, 28]

FST14 features independent double-wishbone suspension at both the front and rear axles, with carbon-fibre tubular wishbones. The spring–damper units are actuated via pushrods and rocker mechanisms, enabling compact packaging and well-defined motion ratios between wheel and damper displacement. The rear axle is equipped with a torsional anti-roll bar integrated into the suspension assembly. This architecture provides precise wheel control and well-defined kinematics, while maintaining low unsprung mass. Tyre contact is ensured through Hoosier competition slicks, specified as 16.0×7.5 –10 R20, which are widely adopted in FS and play a central role in the vehicle's dynamics and on-track behaviour. [27]

Aerodynamically, the vehicle carries a full downforce-generating package composed of front and rear

wings and associated bodywork elements, forming the baseline platform to be evaluated in the present work [27]. A representative view of the experimental prototype is shown in Figure 3.1.



Figure 3.1: FST14 at FSG2025 [@FSG-Haindl]

3.2 Fundamentals of Methodologies for Aerodynamic Estimation

With the experimental platform defined in Section 3.1, this section presents the aerodynamic estimation framework adopted in this work. The theoretical models used to estimate drag and downforce from straight-line CV and CD data are introduced, and the required measured/identified inputs are summarised at the end of the section.

3.2.1 Downforce Estimation

Referring back to Section 2.1.1, downforce estimation of a vehicle involves submitting it to a phase of straight-line CV, typically at sufficiently high speed so that aerodynamic effects manifest clearly in the vertical loads [10, 29].

During a CV segment, the longitudinal acceleration is approximately null ($a_x \approx 0$), hence no longitudinal inertial load transfer is added/subtracted to the front and rear tyre loads. Under these conditions, the total vertical loads at the front (F_F) and rear (F_R) axles can be written as [30]

$$F_F = S_{FL} + S_{FR} + F_{LF}, \quad (3.1a)$$

$$F_R = S_{RL} + S_{RR} + F_{LR}, \quad (3.1b)$$

where S_{FL} , S_{FR} , S_{RL} and S_{RR} are the static (reference) loads at the front-left, front-right, rear-left and rear-right tyres, respectively, and F_{LF} and F_{LR} are the aerodynamic downforce contributions at the front and rear axle.

Therefore, downforce estimation stems from the variation of wheel loads relative to their static values, since aerodynamic downforce appears as an additional vertical force transmitted through the suspension. These incremental loads can be inferred from the elastic deflections of the suspension elements

measured during the CV phase [29]. In the most general case, the spring response is not strictly linear; instead, the spring force follows a measured force–deflection law,

$$F_{\text{spring}} = f_s(\Delta x_s), \quad (3.2)$$

where Δx_s is the spring deflection (compression taken as positive). A displacement-dependent (tangent) spring stiffness can be defined locally as

$$K_s(\Delta x_s) \equiv \frac{dF_{\text{spring}}}{d\Delta x_s}. \quad (3.3)$$

If the spring response is approximately linear over the operating range of interest, Equation (3.2) reduces to the familiar Hooke’s law approximation $F_{\text{spring}} \approx K_s \Delta x_s$ with constant K_s [3].

Since damper motion and wheel motion are not equivalent, suspension kinematics are characterised by a motion ratio (MR), which relates a small change in damper displacement Δx_d to the corresponding wheel-centre displacement Δx_w [31],

$$MR = \frac{\Delta x_d}{\Delta x_w}. \quad (3.4)$$

Assuming the spring deflection is measured at the damper line of action, the spring force can be translated into wheel load through the kinematic leverage of the suspension. Under quasi-static vertical equilibrium, the incremental wheel load transmitted to the tyre contact patch can be written as

$$F_{\text{wheel}} = F_{\text{spring}} \cdot MR, \quad (3.5)$$

and the axle load is obtained by summing the two corresponding wheel loads of that axle [32].

In addition to suspension compliance, the tyres themselves act as elastic elements and can exhibit a nonlinear vertical response. The tyre behaviour is therefore represented by a measured force–deflection relation,

$$F_{\text{wheel}} = f_{\text{tyre}}(\delta_{\text{tyre}}), \quad (3.6)$$

so that the tyre deflection is obtained by inversion, $\delta_{\text{tyre}} = f_{\text{tyre}}^{-1}(F_{\text{wheel}})$. Analogously, a local (tangent) tyre stiffness may be defined as

$$K_{\text{tyre}}(\delta_{\text{tyre}}) \equiv \frac{dF_{\text{wheel}}}{d\delta_{\text{tyre}}}. \quad (3.7)$$

Only in the linear special case does Equation (3.6) reduce to $\delta_{\text{tyre}} \approx F_{\text{wheel}}/K_{\text{tyre}}$ [33, 34].

Since ride height is defined as the vertical distance between a chassis reference plane and the ground, it is influenced by both tyre compression and wheel-centre vertical motion induced by suspension travel, reflecting the coupled nature of aerodynamic operating condition and suspension state in high-downforce race cars [35]. Denoting by $\Delta x_{w,i}$ the wheel-centre displacement at corner i relative to the chassis (compression positive), the instantaneous dynamic ride height at corner i can be expressed as

$$RH_i = RH_{0,i} - (\Delta x_{w,i} + \delta_{\text{tyre},i}), \quad (3.8)$$

where $RH_{0,i}$ is the static ride height in the reference condition. Using Equation (3.4), the wheel-centre displacement can be written as $\Delta x_{w,i} = \Delta x_{d,i}/MR_i$ [30, 32, 33].

Aerodynamic downforce is obtained from the incremental vertical loads measured at the wheels during CV operation. Defining the aerodynamic-induced (incremental) wheel loads as

$$F_i \equiv F_{\text{wheel},i}, \quad i \in \{FL, FR, RL, RR\}, \quad (3.9)$$

the downforce at the front and rear axles becomes

$$F_{L_F} = F_{FL} + F_{FR}, \quad (3.10a)$$

$$F_{L_R} = F_{RL} + F_{RR}, \quad (3.10b)$$

and the total downforce is

$$F_{L_T} = F_{L_F} + F_{L_R}. \quad (3.11)$$

The vertical load path and the sign conventions adopted for the estimated spring and wheel loads are summarised in the quarter-car free-body diagram of Figure 3.2. In this schematic, the vehicle corner is represented by a two-mass system, the sprung (suspended) mass m_s , which corresponds to the portion of chassis/aerodynamic package supported by the suspension, and the unsprung mass m_u , which represents the wheel–upright assembly and associated components below the suspension spring [30, 32]. The aerodynamic contribution at that corner, $F_{L,i}$, acts downward on the sprung mass, increasing the vertical load transmitted through the suspension. The suspension spring element connects m_s to m_u and develops an internal spring force $F_{\text{spring},i}$ that acts on the two masses with equal magnitude and opposite direction. An increase in aerodynamic loading produces an increase in spring compression, which is measured through the spring displacement Δx_s (shown in blue). The tyre is modelled as a second elastic element between the unsprung mass and the ground, whose compression is denoted by δ_{tyre} (also shown in blue). The resulting vertical force transmitted at the contact patch is the reconstructed wheel load $F_{\text{wheel},i}$ [30, 32].

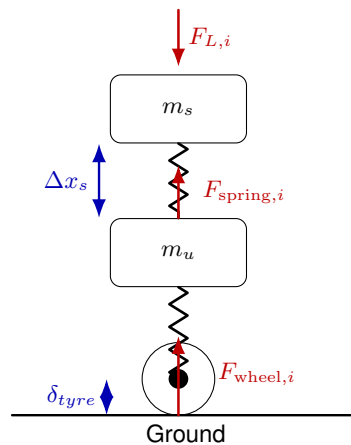


Figure 3.2: Quarter-car diagram for corner i

Beyond the reconstruction of F_{LF} , F_{LR} , and F_{LT} for each CV segment, aerodynamic performance can also be identified through the classical linear dependence of aerodynamic lift on dynamic pressure. From Equation (1.1),

$$F_L = \frac{1}{2} \rho v^2 C_L A, \quad (3.12)$$

and introducing the dynamic pressure as $q \equiv \frac{1}{2} \rho v^2$, the relation can be written in the linear form [4]

$$F_L = (C_L A) q. \quad (3.13)$$

This formulation enables the identification of the lift-area coefficient ($C_L A$) from the slope of the force–dynamic-pressure regression. The same approach can be applied independently to the front and rear axle contributions, yielding

$$F_{LF} = (C_{L,F} A) q, \quad (3.14a)$$

$$F_{LR} = (C_{L,R} A) q, \quad (3.14b)$$

from which not only the total aerodynamic loading but also its front–rear distribution can be quantified [7]. In this framework, the aerodynamic balance is obtained directly from the identified axle slopes as

$$AB = \frac{C_{L,F} A}{C_{L,F} A + C_{L,R} A} \times 100 [\%]. \quad (3.15)$$

The estimation of these quantities requires the set of measured signals and calibrated parameters summarized in Table 3.1. These inputs are needed to determine the dynamic pressure and to convert the measured suspension response into the corresponding aerodynamic wheel loads used in the regression procedure.

Table 3.1: Measured signals and calibrated parameters required for $C_L A$ estimation from the CV regression procedure

Quantity	Symbol
Airspeed	v
Air density	ρ
Suspension displacement (per corner)	Δx_d
Spring force–deflection relation (or stiffness), per corner	$f_s(\Delta x_s)$
Motion ratio (per corner)	MR
Tyre force–deflection relation (or stiffness), per corner	$f_{\text{tyre}}(\delta_{\text{tyre}})$

3.2.2 Drag Estimation

Referring back to Section 2.1.2, drag estimation of a vehicle involves subjecting it to a CD phase, in which the vehicle is first accelerated to a target speed and then allowed to decelerate freely without throttle or braking input, so that the longitudinal resistive forces can be inferred from the measured speed decay [12, 13]. This procedure isolates the resistive forces acting on the vehicle.

Assuming that deceleration is mainly attributed to aerodynamic drag, proportional to the vehicle's speed (v) squared and other resistances (R), which for simplicity sake, one can assume as constant throughout the motion, the vehicle's motion during CD can be described resorting to Newton's second law, whose governing equation [36] is:

$$m \frac{dv}{dt} = - \left(R + \frac{1}{2} \rho C_D A v^2 \right) \quad (3.16)$$

Rearranging the equation by separating the variables, and through implicit differentiation and normalization, one obtains:

$$v = \frac{v_0}{\beta} \tan \left[\left(1 - \frac{t}{t_0} \right) \tan^{-1}(\beta) \right]; \quad (3.17)$$

where $\beta = v_0 \left(\frac{\rho C_D A}{2R} \right)^{1/2}$, v_0 is the velocity at the beginning of CD and t_0 is the total CD time [37].

In summary, this analytical solution to the two-term drag model describes a non-linear deceleration profile, where velocity decreases progressively over time. At the initial moment $t = 0$, the vehicle begins at its maximum speed v_0 . As time approaches the total CD duration $t \rightarrow t_0$, the argument of the tangent function tends to zero, and velocity smoothly converges to zero [37].

The resulting velocity-time curve is monotonically decreasing, exhibiting a steep slope at the start due to the dominant aerodynamic drag at higher speeds. As the vehicle slows, other resistance becomes the primary retarding force, leading to a progressively flatter slope, resulting in a concave-upward curve, which is easily verifiable in Figure 2.2. Therefore, in a given CD test, continuous monitoring of the vehicle's velocity over time can be sufficient for estimating its drag characteristics by fitting the recorded data to an appropriate deceleration model [13], such as the one in Equation (3.17). However, this approach presents challenges due to the inherent complexity of the function, making regression fitting difficult. As such, a more robust and simplified regression-based method is often preferred in practical road-load identification studies [12, 17].

The idea behind this simplified method is to perform a 2nd-order polynomial regression of the longitudinal resistive force as a function of vehicle speed. Following the approach of Preda et al. [38], and consistently with established CD-based drag identification methods [13, 17], the resistive force (F_{res}) is obtained from Newton's second law and fitted as

$$F_{\text{res}} \equiv -m_{\text{eq}} a_x = A_2 v^2 + A_1 v + A_0 \quad (3.18)$$

where m_{eq} is the equivalent mass and the minus sign ensures $F_{\text{res}} > 0$ during CD ($a_x < 0$).

Resorting back to Equation (3.16) and breaking it down, the force balance during CD can be written as

$$\frac{dv}{dt} = - \frac{(R_R + R_G + R_A)}{m_{\text{eq}}} \quad (3.19)$$

where R_R , R_G and R_A are the rolling, grade and air resistances, respectively.

Rolling resistance accounts for internal friction losses (f_0) and tyre rolling resistance (f_1), while grade

resistance accounts for possible terrain inclination (α) and air resistance equates to aerodynamic drag, accounting for a possible wind speed (w):

$$R_R = m_t g (f_0 + f_1 v) \cos \alpha \quad (3.20a)$$

$$R_G = m_t g \sin \alpha \quad (3.20b)$$

$$R_A = \frac{1}{2} \rho_{\text{air}} C_D A (v + w)^2 \quad (3.20c)$$

Equivalent mass (m_{eq}) arises from the distinction between the rotational and translational components of the kinetic energy (E_k) in the vehicle's energy balance. The rotational term ($E_{k,\text{rot}}$) includes the energy necessary to increase the rotational speed of the drivetrain and wheels (ω_i) against their inertial resistance (I_i), whereas the translational term ($E_{k,\text{trans}}$) accounts for the energy required to accelerate the total mass of the vehicle (m_t) linearly. Together, these components define an equivalent mass (m_{eq}) that captures the total kinetic energy as if it were purely translational:

$$E_k = E_{k,\text{rot}} + E_{k,\text{trans}} = \frac{1}{2} m_t v^2 + \sum_i \frac{1}{2} I_i \omega_i^2 = \frac{1}{2} m_{\text{eq}} v^2 \Rightarrow m_{\text{eq}} = m_t + \sum_i \frac{I_i \omega_i^2}{v^2} \quad (3.21)$$

Substituting Equations (3.20) into Equation (3.19) and expanding $(v + w)^2$, one obtains

$$\frac{dv}{dt} = -\frac{1}{m_{\text{eq}}} \left\{ \left(\frac{1}{2} \rho_{\text{air}} C_D A \right) v^2 + (m_t g f_1 \cos \alpha + \rho_{\text{air}} C_D A w) v + \left(m_t g (f_0 \cos \alpha + \sin \alpha) + \frac{1}{2} \rho_{\text{air}} C_D A w^2 \right) \right\} \quad (3.22)$$

Multiplying Equation (3.22) by $-m_{\text{eq}}$ yields the resistive-force form of Equation (3.18), from which the polynomial coefficients can be identified as

$$A_2 = \left(\frac{1}{2} \rho_{\text{air}} C_D A \right) \quad (3.23a)$$

$$A_1 = (m_t g f_1 \cos \alpha + \rho_{\text{air}} C_D A w) \quad (3.23b)$$

$$A_0 = \left(m_t g (f_0 \cos \alpha + \sin \alpha) + \frac{1}{2} \rho_{\text{air}} C_D A w^2 \right) \quad (3.23c)$$

Equations (3.23) showcase the influence that wind speed and ground grade have on the CD resistance. To mitigate these effects, the tests are executed in both directions of the same straight track. Neglecting residual wind and grade bias, and manipulating Equations (3.23), the resistance coefficient can be obtained as

$$C_D A = \frac{2A_2}{\rho_{\text{air}}} \quad (3.24)$$

The estimation of $C_D A$ from the CD procedure requires a reduced set of measured signals and known vehicle parameters, summarized in Table 3.2.

Table 3.2: Signals and parameters required for $C_D A$ estimation from CD regression.

Quantity	Symbol
Vehicle speed)	v
Longitudinal acceleration	a_x
Air density	ρ_{air}
Total vehicle mass	m_t
Wheel rotational speed (per wheel)	ω_i

3.3 Testing Procedures and Vehicle Pre-Requisites

Building upon the CV and CD methodologies introduced in Section 2.1 and the aerodynamic force estimation fundamentals established in Section 3.2, this section consolidates the practical pre-requisites required to execute an on-track campaign with consistent, repeatable results. The intent is to ensure that measured effects are dominated by aerodynamics.

3.3.1 Run Protocol and Track Layout

Each aerodynamic validation pass shall be executed as a straight-line, bidirectional run composed of three consecutive phases: acceleration up to the target speed, a CV window, and a CD to near rest. A run is considered complete once vehicle speed decreases below 16 km/h.

During the CV window, the driver shall stabilise the car at a given target speed with minimal steering input. The campaign is intentionally conducted over several distinct target speeds, rather than a single plateau, so that each CV segment provides one (q, F_L) operating point and the combined dataset supports identification of $C_L A$ through the linear $F_L - q$ relationship of Equation (3.13).

The transition from CV to CD is defined by a dedicated corridor marker, denoted the throttle lift point. At this location, the driver shall lift off the accelerator in a consistent manner, initiating CD without any additional driver inputs. This marker therefore delineates the end of the CV window and the start of the CD phase, and provides a repeatable reference for segmenting the data during post-processing.

Immediately after the throttle lift point, the CD phase shall begin, with no throttle or brake input and minimal steering activity, so that deceleration is driven by aerodynamic drag and rolling resistance.

To reduce first-order wind and grade effects, runs shall be executed in both directions. Bidirectional parity shall be enforced by retaining an equal number of runs runs per direction. If an imbalance occurs due to rejected runs or operational interruptions, excess runs from the over-represented direction shall be discarded. A minimum of 12 valid runs shall be retained for analysis, corresponding to six valid runs per direction.

This protocol draws inspiration from SAE J1263-style CD practice, while being adapted to the campaign constraints and objectives [15].

After completing a pass in one direction, the vehicle shall exit the corridor, loop back, and repeat the same sequence in the opposite direction; no data from turnaround segments shall be used for analysis.

The intended corridor geometry is illustrated in Figure 3.3, including the acceleration, CV, and CD zones, the colour coding, and the stop/restart lines used between opposite-direction passes.

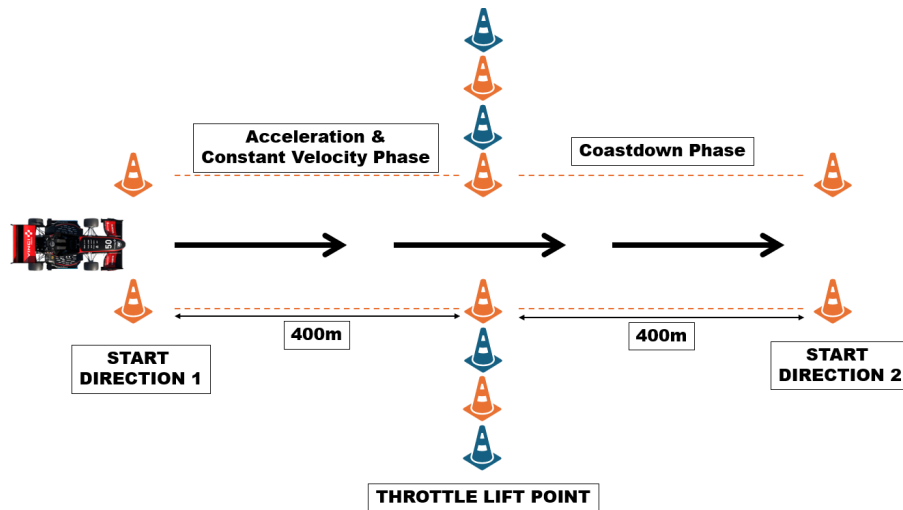


Figure 3.3: Testing track layout adopted for straight-line CV and CD runs

3.3.2 Vehicle Configuration and Setup Philosophy

The vehicle shall be configured such that the measured response in straight-line CV and CD segments is dominated by aerodynamic effects. Prior to the first valid run, the car shall be brought to a ready-to-race condition at full test weight, including the driver and all instrumentation. Total mass and static mass distribution shall be balanced, measured and documented [11].

All aerodynamic devices shall be installed in a specified configuration, with mounting positions and incidence angles explicitly defined and recorded. This includes the front and rear wings and any additional devices relevant to the setup under test [11]. The objective is to enforce a repeatable geometric state that can be directly correlated with simulation, while ensuring that run-to-run variation is not driven by untracked assembly differences. Unless otherwise stated, the baseline aerodynamic configuration shall be defined with the rear wing main flaps set to its no-Drag Reduction System (DRS) incidence (wing closed) - Figure 3.4a. For reference, the opposing DRS-open state is shown in Figure 3.4b.



(a) Rear wing with DRS closed (no-DRS incidence)
[@FSG-Partenfelder]



(b) Rear wing with DRS open
[@FSG-Partenfelder]

Figure 3.4: Rear wing DRS states

The front wing should be mounted in the second-highest of its four discrete height positions, which the team identified as the most suitable compromise between aerodynamic performance and straight-line stability, while maintaining sufficient ground clearance to avoid front wing ground contact. The front wing mounting brackets are highlighted in Figure 3.5, with their intended mounting position shown in detail.

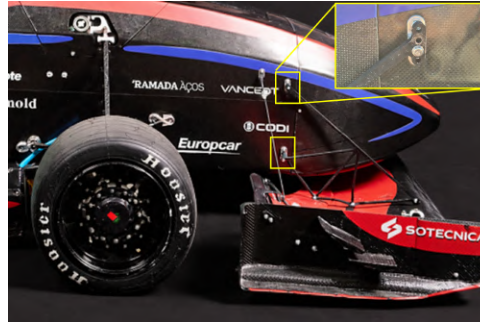


Figure 3.5: Front wing mounting position [Adapted from @FSG-Grobe]

The suspension shall be prepared to keep the wheel load–displacement relationship as linear as practicable over the CV/CD windows and to reduce sensitivity to track roughness, since the effective aerodynamic operating condition in a high-downforce car depends not only on the external flow state but also on the suspension response of the vehicle [35]. Springs and dampers should therefore be set as soft as reasonably possible, bump rubbers/packers shall be removed to avoid hard-stop behaviour that would introduce strongly non-linear stiffness and anti-roll bars shall be disconnected to minimise cross-axle coupling, allowing each wheel to respond independently and reducing the likelihood of roll influence during minor steering corrections [11].

The mechanical baseline shall be established in the workshop and recorded per corner, including camber, toe, and ride-height.

For straight-line aerodynamic testing, camber is preferably set to zero (or close) so that the tyre remains as vertical as possible. This minimizes camber-induced lateral force generation (camber thrust) during rectilinear motion and better preserves the assumption that the measured wheel displacement is predominantly associated with vertical tyre and suspension compliance, rather than with parasitic lateral tyre effects [39].

A slight front toe-in may be utilized to improve directional stability and reduce the tendency of the vehicle to wander during the CV and CD segments. Since toe settings affect tyre scrub and straight-line behaviour, only a small toe-in should be used, prioritizing stability without introducing unnecessary rolling resistance or tyre wear [40].

For CD validity, regenerative braking shall be disabled so that the vehicle decelerates passively under aerodynamic drag and rolling resistance, rather than under non-aerodynamic drivetrain torque. The vehicle should have accumulated a minimum of 160 km prior to the campaign, and the tyres shall have retained at least 75% of the original tread depth at the start of testing. Finally, tyres shall be inflated to the team nominal cold pressure of 0.8 bar.

In this sense, the vehicle preparation and control settings are selected to follow the same general phi-

losophy as SAE J1263-style CD practice [15], while remaining tailored to the constraints and objectives of the present campaign.

3.3.3 Environmental and Procedural Requirements

Testing shall be conducted on a dry, clean, smooth, and straight road surface, with its grade remaining approximately constant along the measurement corridor.

Ambient conditions shall be monitored throughout the campaign. Ambient temperature should lie within 0°C to 38°C, with any data acquired outside this band flagged for review. Runs shall not be performed under foggy conditions; if fog develops during an opposite-direction pair, the testing shall be suspended and the affected pair discarded. Wind shall be assessed before each opposite-direction pair, and testing shall not proceed when mean wind exceeds approximately 16 km/h or when the maximum gusts exceed approximately 20 km/h. If a pair is executed and later found to violate these limits, the pair shall be discarded.

These environmental requirements are taken from SAE J1263 CD practice [15] and are adopted in the present campaign as acceptance criteria to preserve repeatability and limit uncontrolled wind and grade bias.

3.3.4 Instrumentation and Data Collection

Instrumentation and data collection shall be executed so that CV and CD datasets are reliable, synchronized, and directly usable in post-processing. Sensors should be calibrated in the workshop using traceable procedures, and acquisition channel time-bases shall be synchronized to a common clock.

At minimum, the vehicle shall be equipped with a pitot tube (airspeed), suspension potentiometers on all four corners (wheel and/or damper displacement), an Attitude and Heading Reference System (AHRS) (longitudinal acceleration), brake and throttle position sensing, and steering angle sensing. High-frequency data shall be recorded consistently across channels for each run. Sampling rates shall be sufficient for CV/CD estimation (as guidance, ≥ 100 Hz for vehicle state channels). Each run shall be trimmed into acceleration, CV, and CD segments before analysis, and turnaround segments shall be excluded by construction.

Environmental and tire conditions shall be logged at the start of opposite-direction pairs to support pair-level acceptance and correction. Ambient and track temperature, barometric pressure, and wind speed/direction shall be recorded at the beginning of each run; similarly, tire pressure and temperature should be measured and recorded at the beginning of each pair. Finally, after every opposite-direction pair, on-site responsible shall confirm protocol compliance and signal credibility: no throttle/brake during CD, minimal steering during CV/CD, steady CV pitot behavior, and continuous, plausible potentiometer traces. Any rejected pair shall be re-run immediately while conditions remain comparable, preserving the integrity and repeatability of the final dataset.

3.4 Data Acquisition Systems

This work leverages pre-existing sensors, focusing on calibration, data acquisition and the suitability of each channel for aerodynamic inference according to the required inputs in Tables 3.1 and 3.2.

3.4.1 Overview of Instrumentation and Sensors

Linear potentiometers for suspension travel — *Variohm ELPM* (Figure 3.6(a))

Suspension displacement at each corner is measured using *Variohm ELPM* linear position sensors. These are conductive-plastic linear potentiometric transducers in which a spring-loaded wiper moves along a resistive track, converting linear stroke into a proportional electrical signal [41]. In the context of this work, these sensors provide the core input for CV downforce estimation, as the measured damper displacements are later converted into vertical wheel loads through the calibrated suspension and tyre relations described previously (Table 3.1).

Brake and accelerator pedal rotary sensors — *Piher MSC-360* (Figure 3.6(b))

Driver pedal positions are monitored using *Piher MSC-360* contactless Hall-effect rotary sensors. A diametrically magnetised rotor generates a rotating magnetic field, from which an internal Hall integrated circuit estimates the absolute angular position and produces an electrical output proportional to pedal displacement [42]. In this testing campaign, these signals are used primarily for run screening and segmentation. CV intervals are retained only when pedal input remains stable and braking is absent, while CD runs are rejected whenever unintended throttle or brake application is detected. Accordingly, these channels serve to enforce the assumptions underlying the estimators rather than appearing directly as variables in Tables 3.1 and 3.2.

Steering-wheel angle sensor — *Piher PSC-360G2* (Figure 3.6(c))

Steering angle is measured using a *Piher PSC-360G2* Hall-effect absolute angle sensor in end-of-shaft configuration, which allows continuous mechanical rotation while providing an absolute electrical angle over the configured span [43]. Similarly to the pedal sensors, the steering signal is treated as a validation variable rather than as a direct regression input. Its main role is to verify straight-line running conditions and to exclude intervals with excessive steering activity, thereby protecting the assumptions of one-dimensional longitudinal motion used in the aerodynamic estimators.

Inertial Navigation System (INS) — *Movella Xsens MTi-680G* (Figure 3.6(d))

Vehicle kinematics and attitude are provided by a *Movella Xsens MTi-680G* INS. Through Global Navigation Satellite System (GNSS)/inertial fusion, the unit supplies longitudinal acceleration a_x together with roll, pitch, and yaw information [44]. Among these outputs, the longitudinal acceleration is the only

quantity used directly in the aerodynamic estimation framework presented in this work, entering the CD regression as one of the required inputs (Table 3.2).

Pressure transducer for pitot-tube airspeed measurement — *NXP MPXV7002* (Figure 3.6(e)–(f))

Airspeed is measured indirectly using a pitot-static probe, which provides the pressure difference between total pressure, p_t , and static pressure, p_s . Under the incompressible-flow assumption, this differential pressure corresponds to the dynamic pressure and allows airspeed to be reconstructed as $v = \sqrt{2\Delta p / \rho_{\text{air}}}$, with $\Delta p = p_t - p_s$ [45]. The differential pressure is acquired using an *NXP MPXV7002* integrated piezoresistive pressure sensor, whose output is approximately linear with pressure over its specified range, enabling Δp to be reconstructed directly from the measured analogue voltage and supply level [46].

The sensor is connected to the pitot-static probe through two silicone tubes, respectively linked to the total-pressure and static-pressure ports, so that the transducer measures Δp directly. The probe itself is mounted on an external support specifically designed for this campaign and manufactured by 3D printing, allowing the sensing head to be positioned in free-stream flow while maintaining a rigid attachment to the vehicle. The corresponding assembly (Figure 3.6(f)) includes a mounting interface to the vehicle, the structural support for the probe and tubing routing, and an enclosure that houses the sensor and associated acquisition electronics, thereby ensuring both mechanical protection and stable electrical integration.

Inverters and wheel–motor package for wheel-speed monitoring — *AMK KW26-S5-FSE-4Q* and *AMK DD5-14-10-POW* (Figure 3.6(g)–(h))

In contrast with the previously described external instrumentation, the inverter and motor package is an intrinsic subsystem of the vehicle powertrain. In addition to propulsion control, the *AMK KW26-S5-FSE-4Q* inverter package provides drivetrain telemetry through the vehicle Controller Area Network (CAN) network, including motor rotational speeds and instantaneous motor torques. FST14 is equipped with four *AMK DD5-14-10-POW* in-wheel motors, such that each motor is directly coupled to its corresponding wheel. The measured motor speeds can therefore be converted directly into wheel rotational speeds ω_i , enabling wheel-speed monitoring at each corner throughout a run. Within the present work, these signals are required to evaluate the equivalent mass term adopted in the CD formulation (Table 3.2).

The main instrumentation and drivetrain components employed throughout the campaign are summarized in Figure 3.6.



Figure 3.6: Main instrumentation and drivetrain components used in the aerodynamic testing campaign

3.4.2 Instrumentation and Sensors Placement

The pitot-static probe assembly is mounted on the upper surface of the monocoque, immediately ahead of the vehicle dashboard, where the flow is expected to be relatively unobstructed and representative of free-stream conditions. As shown in Figure 3.7a, the 3D-printed support base is bolted to the monocoque using four fasteners, re-using existing drilled holes associated with the front electronics box lid interface. This location provides a practical compromise between exposure to clean airflow and packaging constraints on the vehicle.

Linear potentiometers are mounted at each corner, as illustrated in Figure 3.7b, which shows the front-right corner. Each potentiometer is installed in parallel with the damper, where one end is rigidly fixed to the monocoque structure, while the opposing end is attached to the moving rocker. This arrangement allows the potentiometer rod to extend and retract freely with rocker rotation, providing a direct measurement of suspension motion throughout compression and extension of the damper/spring assembly.

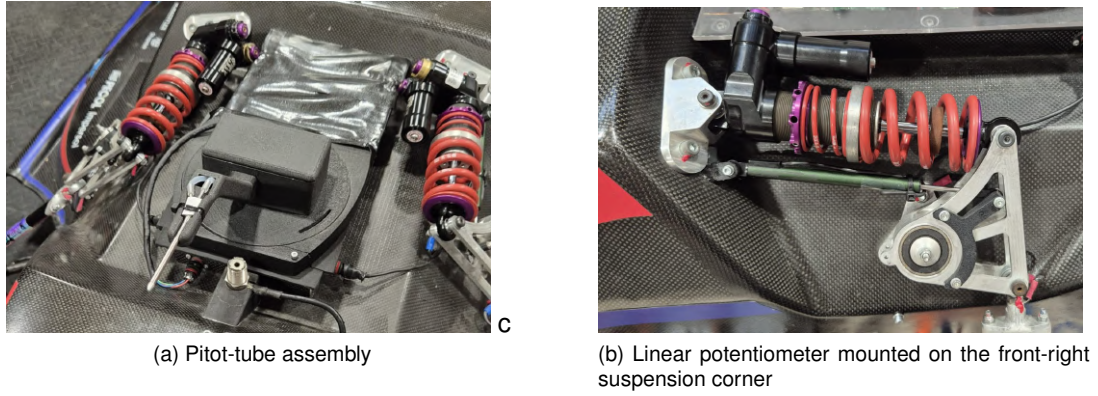


Figure 3.7: Instrumentation installed on FST14 for on-track aerodynamic testing

The INS is rigidly mounted to the monocoque at its base, underneath the driver's seat, as close as practicable to the combined vehicle–driver CG. In this location, the sensor is positioned near the CG of the system, which minimises the contribution of rigid-body rotational components to the measured linear accelerations. This placement is therefore well suited for acquiring the longitudinal acceleration signal a_x used in the CD identification framework. A schematic overview of the instrumentation layout is provided in Figure 3.8, which summarises the approximate mounting locations of the sensors and subsystems described above on the vehicle.



Figure 3.8: Schematic overview of the approximate mounting locations of the instrumentation used in the on-track campaign

3.4.3 Calibration Procedures

The calibration procedures described in this section establish the transfer functions required to convert raw sensor outputs into physical quantities used throughout the on-track aerodynamic estimation. In particular, the pitot system is calibrated to relate the dynamic-pressure sensor output to the reference dynamic pressure in controlled flow conditions, while the suspension potentiometers are calibrated to map Analog-to-Digital Converter (ADC) voltage to damper and wheel positions and to identify the corner motion ratios from a static stepwise procedure.

Pitot tube calibration

The pitot system was calibrated in a controlled flow facility located at the *Laboratório de Aerodinâmica e Mecânica dos Flúidos*, IST.

During calibration, the pitot tube was mounted inside the test section using a rigid clamp to ensure repeatable probe positioning and alignment with the incoming flow direction, as shown in Figure 3.9. The pitot differential-pressure sensor output, denoted Δp_{pitot} , was recorded simultaneously with the reference pressure measurements obtained from the multi-manometer. For each steady fan setting, the multi-manometer provides the wetted lengths l_1 and l_2 associated with tubes 2 and 3, respectively. The difference between these two pressure lines defines the incoming-flow dynamic pressure, q_∞ [45], which is obtained from the manometric head difference (Δp_{man}), for a manometric fluid of density $\rho_m = 750 \text{ kg/m}^3$, as [47]:

$$q_\infty = \Delta p_{\text{man}} = p_t - p_\infty \approx \rho_m g (l_1 - l_2). \quad (3.25)$$

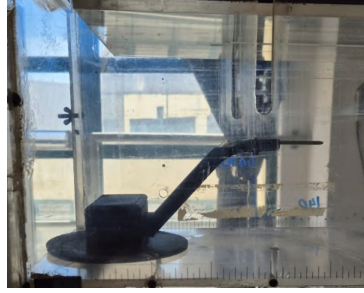


Figure 3.9: Pitot tube mounted and clamped inside the test section during calibration

A set of steady operating points was acquired by varying the fan setting following a pyramid sequence, progressively increasing the fan command up to a maximum setting and subsequently decreasing it back down to a minimum. For each operating point, p_t and p_∞ were obtained from the multi-manometer and the corresponding pitot sensor input was taken as the mean of the logged signal over an approximately 30 s steady interval.

A linear calibration law was identified to map the pitot sensor output to the reference dynamic pressure: $\Delta p_{\text{man}} = a \Delta p_{\text{pitot}} + b$, where a and b are obtained from a least-squares regression. The resulting fit is shown in Figure 3.10, with the identified coefficients.

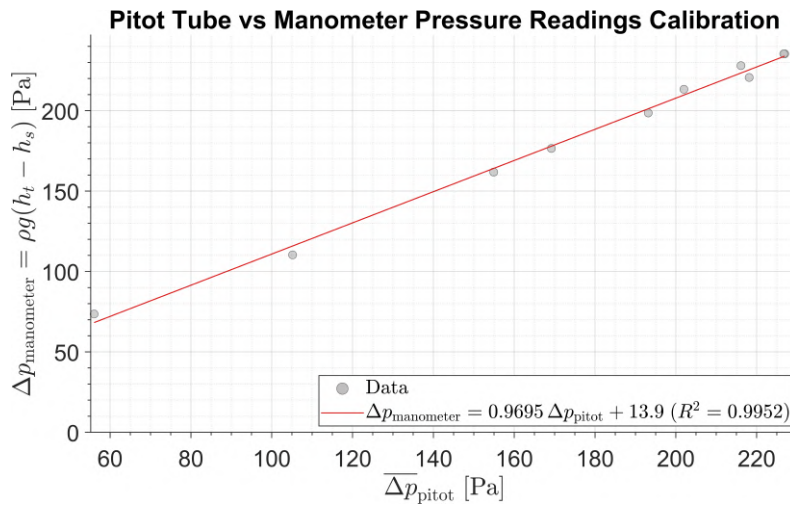


Figure 3.10: Reference manometer pressure Δp_{man} versus time-averaged pitot sensor output $\overline{\Delta p_{\text{pitot}}}$

Potentiometers calibration

The linear potentiometers were calibrated in the FST Lisboa workshop through a static, stepwise suspension displacement procedure. In essence, each corner was displaced incrementally and, at each imposed step, the corresponding damper position was measured with a caliper ruler while the raw potentiometer output (ADC voltage) was logged and time-averaged over approximately 10–15 s. This yielded an empirical mapping between raw potentiometer signal and physical damper position, which was subsequently used to reconstruct damper motion. The same dataset also allowed the corner motion ratio to be obtained by relating imposed wheel travel to measured damper travel. Both the calibrated damper position x_d and the corner motion ratio MR constituted required inputs to the aerodynamic estimation framework, as summarised in Table 3.1.

Before the calibration, the vehicle was prepared in a controlled manner: the car was raised and supported under the monocoque on rigid stands so that the wheels could be removed and the suspension could be articulated safely. The wheels were removed and, crucially, the spring was removed from the damper so that the suspension could be moved through its available travel without spring preload influencing the measurements and without requiring excessive force to raise the corner for insertion of additional plates; the damper was then reattached to the rocker/bellcrank using the original hardware.

For each corner, the wheel-side assembly was raised in discrete increments by stacking calibrated plates under the corner (Figure 3.11(a)). The resting condition on the support was taken as the zero reference for wheel travel, and each additional plate thickness was measured and recorded as an incremental wheel-displacement step. At every step, the damper stroke was measured with the caliper ruler aligned as parallel as possible to the damper axis (Figure 3.11(b)), and the potentiometer ADC voltage was averaged over the acquisition window. This sequence was repeated until the available damper stroke was exhausted.



(a) Wheel-side assembly supported on stacked calibrated plates



(b) Damper-stroke measurement using a caliper ruler

Figure 3.11: Static setup used for potentiometer calibration

The raw step data $\{x_d, x_w\}$ for all corners, as well as the averaged V_{ADC} potentiometer time histories acquired over each 10–15 s window, are provided in Appendix A. The final calibration output for each corner was therefore a set of paired measurements $\{V_{ADC}, x_d\}$, from which a calibration function $x_d = f(V_{ADC})$ was identified. Figures 3.12a–3.12d show, for each corner, the measured wheel and damper position as a function of the potentiometer ADC output together with the identified linear calibration fits.

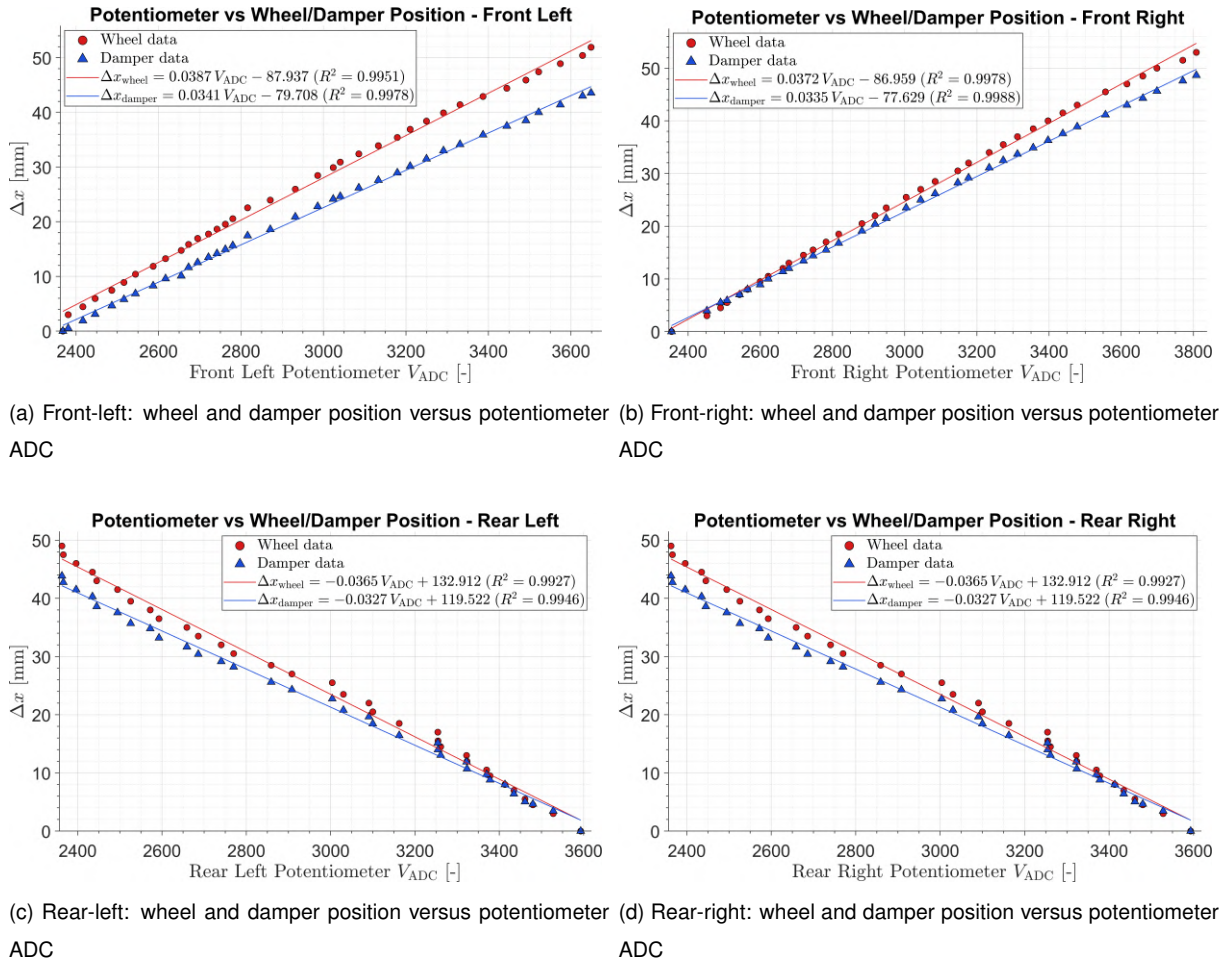
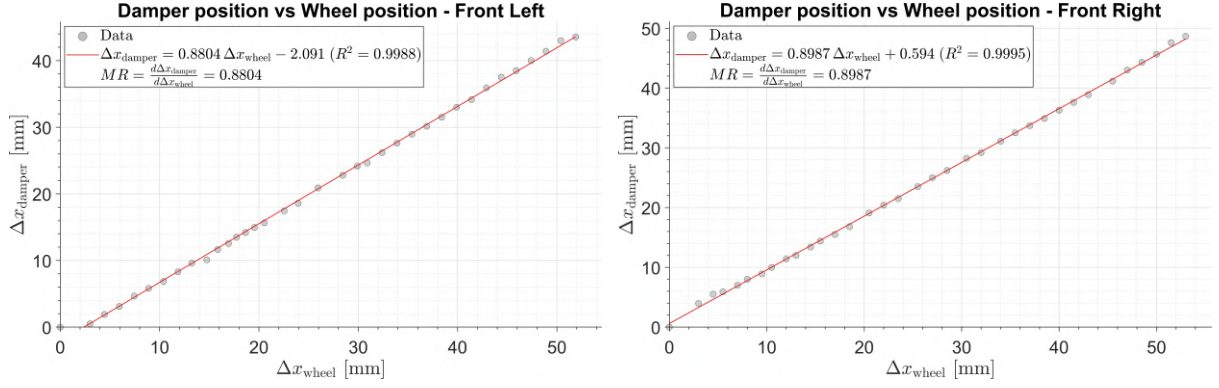
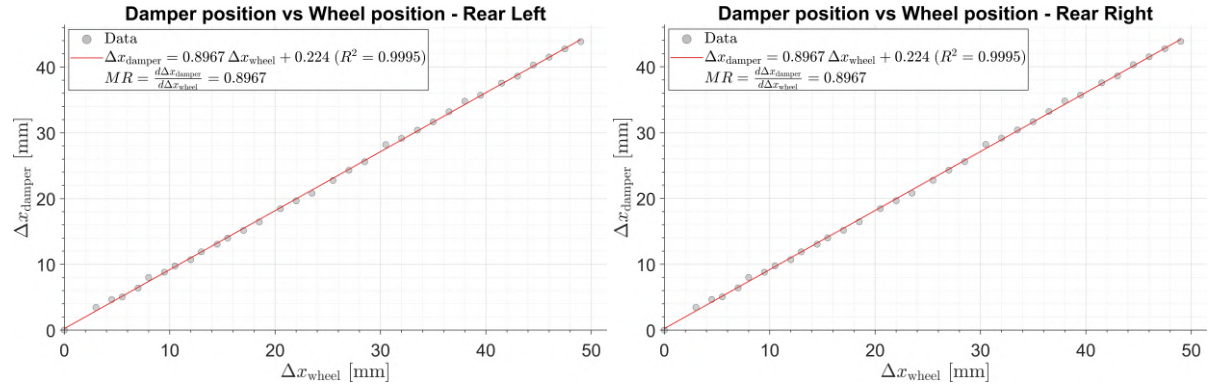


Figure 3.12: Potentiometer calibration curves for all corners: measured wheel and damper position versus potentiometer ADC output, including linear fits

In parallel, wheel travel was obtained from the cumulative plate thickness x_w , allowing the motion ratio to be estimated from the measured increments as a single representative value over the relevant operating range. This approach assumes that the imposed plate-stack height is a faithful approximation for vertical wheel travel and that the wheel-to-damper geometric ratio is approximately constant over the displacement range relevant to the operating window, so that a single best-fit slope provides a representative motion ratio. Figures 3.13a–3.13d report the linear relation between damper and wheel displacement used to extract the motion ratio for each corner.



(a) Front-left: damper position versus wheel position (linear fit) (b) Front-right: damper position versus wheel position (linear fit)



(c) Rear-left: damper position versus wheel position (linear fit) (d) Rear-right: damper position versus wheel position (linear fit)

Figure 3.13: Motion ratio identification for all corners from the linear relation between damper and wheel position

3.5 Static Characterization of Stiffness Parameters

As previously identified in Table 3.1, both the corner spring behaviour and tyre vertical behaviour constitute required inputs for the CV C_{LA} estimation pipeline.

Quasi-static compression tests were conducted to characterise the vertical response of each corner spring and the tyre. In this context, quasi-static testing refers to slow, approximately steady loading under displacement control at a low loading rate on a static/quasi-static tension–compression testing machine, as opposed to dynamic testing, such that inertial and dynamic effects are negligible [48]. Consequently, the measured response is governed primarily by the equilibrium force–displacement relation. Under this assumption, rather than reducing the behaviour to a single effective stiffness, the measured force–displacement data are retained and later used directly as a lookup table.

Experimental tests were carried out at the *LEM² - Laboratório de Ensaios Mecânicos e de Materiais* (ACPMME/Department of Mechanical Engineering (DEM)), IST, using an *Instron 3369* electromechanical Universal Testing Machine (UTM) [49], operating in displacement control and recording force through the machine load cell. For all configurations, the same general procedure was adopted, where the specimen (spring or tyre assembly) was mounted between rigid interfaces, ensuring proper alignment with

the machine axis, and compressed under a displacement ramp up to the target stroke (approximately 25 mm). A small preload was applied to ensure stable contact and remove any slack, after which force and displacement were zeroed [50]. The acquisition rate was set to 500 Hz, by default [49].

3.5.1 Spring Stiffness Characterization

To enable wheel-load reconstruction during CV runs, the vertical response of each corner spring was identified experimentally and retained in the form of a measured force–deflection law, $f_s(\Delta x_s)$ (Equation (3.2)). The components characterised are the motosport grade coil springs, from a company called H&R Springs, bought for the FST13 prototype (predecessor to FST14) and retained for compatibility with the damper package utilised in FST14: RF070–36–070 at the front axle and RF080–36–375LBS at the rear axle. These correspond to the softest available springs that satisfy the damper interface and packaging constraints, in line with the setup philosophy for straight-line aerodynamic testing (Section 3.3.2), where suspension settings are selected as soft as reasonably possible.

Each spring was tested individually under axial compression, using flat, parallel plates to promote uniform load introduction and minimise bending. Force–displacement data were recorded from the unloaded condition up to approximately 25 mm of compression (compression taken as positive, consistent with the sign convention adopted in Figure 3.2).

The experimental setup used for spring stiffness characterization is shown in Figure 3.14, with the respective measured datasets of all four corners presented together in Figure 3.15.



Figure 3.14: Instron 3369 UTM configured for quasi-static spring vertical compression testing

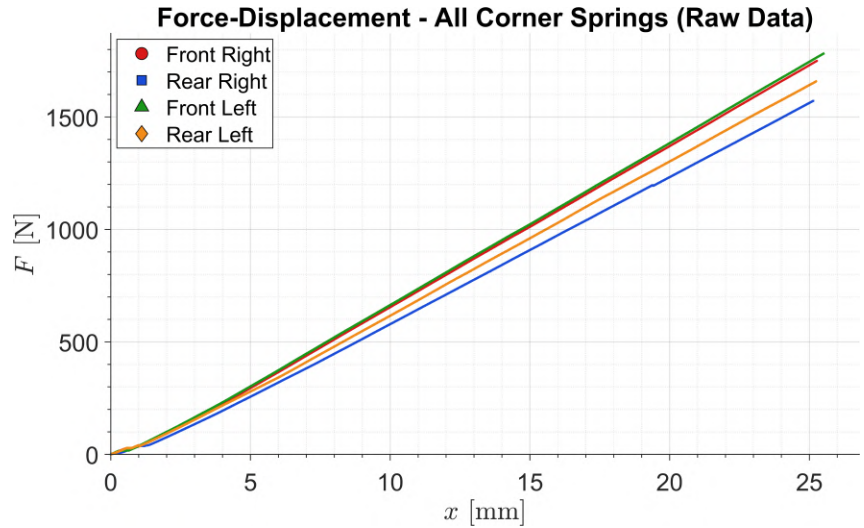


Figure 3.15: Corner spring force–displacement curves (measured data points) for all four corners

Although the curves are predominantly linear over the tested range, the on-track processing does not collapse the spring behaviour to a single constant stiffness, K_s . Instead, for each corner $i \in \{FL, FR, RL, RR\}$, the recorded force–displacement points $\{(x_i, F_i)\}$ are stored as the nonlinear elastic characteristic of the component. For an arbitrary compression x , the corresponding force is obtained by interpolation of the measured data.

In the data-processing pipeline, the spring force is therefore evaluated as $F_{\text{spring},i} = f_s(\Delta x_{s,i})$ by interpolating the experimental force–deflection data at the instantaneous spring deflection (Equation (3.2)). The measured laws $f_s(\Delta x_s)$ therefore constitute a direct input to the CV C_{LA} estimation pipeline, as listed in Table 3.1.

3.5.2 Tyre Vertical Stiffness Characterization

The tyre vertical response was characterised via quasi-static compression of the wheel–tyre assembly, to identify the measured relation $f_{\text{tyre}}(\delta_{\text{tyre}})$ required by the processing framework of Section 3.2.1 (Equations (3.6)–(3.7)). Unlike the spring tests, tyre testing is highly sensitive to alignment; therefore, a dedicated jig was designed and manufactured to ensure that the applied load was transmitted purely vertically through the wheel centre, avoiding off-axis loading that would otherwise bias the measured force–displacement response.

The jig comprises three steel square tubes welded into a stiff C-shaped frame. One end integrates a circular flange that is fixed to the wheel using the 12-bolt pattern, ensuring rigid constraint of the rim. On the opposite end, an extrusion is incorporated to provide a straight gripping surface for the UTM clamp, allowing the machine to apply compressive load along the intended vertical axis.

The experimental setup used for tyre vertical characterization is shown in Figure 3.16, while the measured tyre force–displacement response is shown in Figure 3.17, exhibiting an approximately linear trend over most of the tested stroke, with a mild stiffening tendency at higher compressions.



Figure 3.16: Instron 3369 UTM configured for quasi-static tyre vertical compression testing

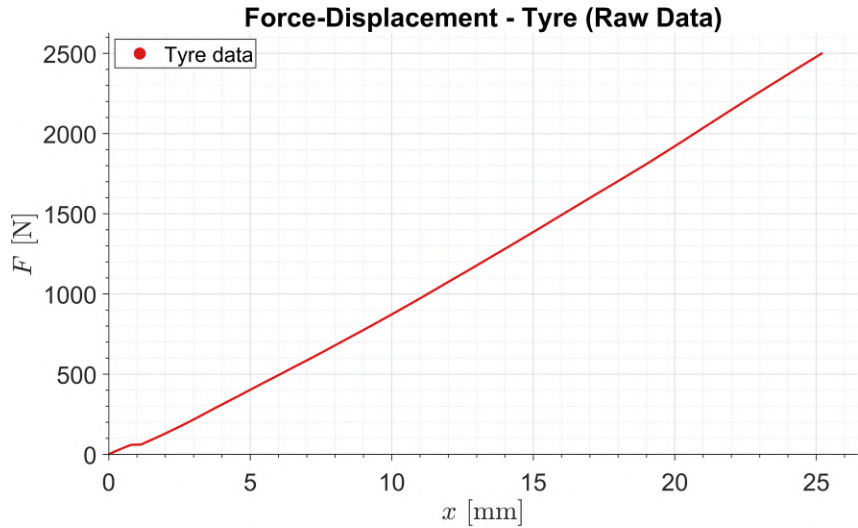


Figure 3.17: Tyre force–displacement curve (measured data points) from quasi-static Instron compression test

In the subsequent processing pipeline, the tyre behaviour is retained as a lookup table rather than reduced to a constant stiffness. The recorded force–displacement points $\{(\delta_j, F_j)\}$ are stored as the nonlinear elastic characteristic of the tyre: for an arbitrary force F_{wheel} , the deflection δ_{tyre} , is obtained by interpolation of the measured data. This measured tyre law is one of the required inputs listed in Table 3.1.

3.6 Vehicle Setup

Section 3.3.2 defined the geometric, alignment and load-distribution requirements to be satisfied before aerodynamic testing. The present section describes the workshop procedure used to implement and verify those requirements.

Since aerodynamic force estimation relies on suspension displacement measurements and CD deceleration analysis, the static setup must ensure controlled ride height, cross-weight distribution and wheel alignment. The procedure was therefore divided into two stages: load distribution and ride height control, followed by wheel alignment and final verification.

3.6.1 Load Distribution and Ride Height Control

The first stage established a common reference plane and the target static load state. Before placing the vehicle with driver on the scales, the four platforms were individually levelled to remove artificial load transfer caused by floor unevenness.

Once a common reference plane had been established, the vehicle was positioned on four independent corner scales in full aerodynamic testing configuration, with tyres at operating pressure, aerodynamic devices installed, springs and dampers mounted, battery installed, and steering centred, as shown in Figure 3.18.



Figure 3.18: Vehicle positioned on corner scales during static setup

Cross-weight balance was evaluated as $\Delta W_{\text{cross}} = |(W_{FL} + W_{RR}) - (W_{FR} + W_{RL})|$, with the requirement $\Delta W_{\text{cross}} \leq 5$ kg. Load redistribution was achieved by adjusting pushrod shim stacks, which alter static wheel position and therefore the diagonal load distribution. Since these adjustments also affect ride height, the procedure was iterative.

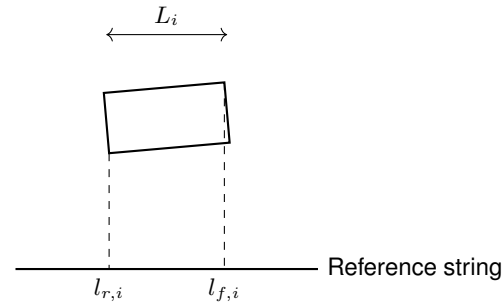
After cross-weight convergence, the vehicle was placed on the workshop floor and the front and rear ride heights were measured at predefined chassis reference points. The minimum ground clearance was verified to satisfy $h_{\text{min}} \geq 30$ mm, in accordance with FSG 2025 Rule T2.2. The rake was then verified by requiring the absolute difference between front and rear ride height, normalised by their mean ride height, to remain below 5%. Cross-weight balancing and ride height verification were repeated until all constraints were satisfied simultaneously.

3.6.2 Wheel Alignment and Final Verification

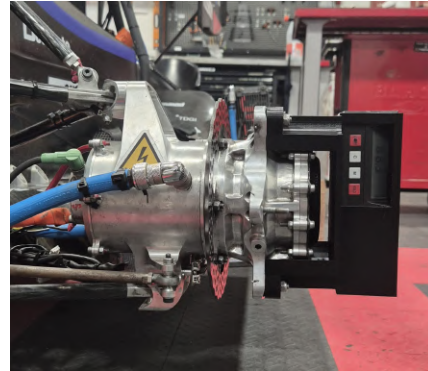
Once the static load state and ride heights had been stabilised, wheel alignment was adjusted. Since toe and camber tuning requires wheel removal and suspension access, the vehicle must be supported on stands. To preserve the suspension geometry corresponding to the final static ride height, the installed length of each damper was first recorded with the vehicle resting on the floor. The spring-damper assemblies were then replaced by rigid dummy dampers set to the same installed length, thereby maintaining the correct suspension position during alignment.

Toe alignment was measured using a custom string alignment kit that establishes a longitudinal reference parallel to the vehicle centreline through tensioned strings supported by front and rear beams. For each wheel i , the distances between the reference string and the front and rear measurement points were denoted $l_{f,i}$ and $l_{r,i}$, respectively. With L_i representing the longitudinal separation between these points, the toe angle was computed as $\alpha_i = \arctan\left(\frac{l_{f,i} - l_{r,i}}{L_i}\right)$. The measured value was then corrected through toelink shims, adjustment until the prescribed toe setting was obtained.

Camber was measured using a 3D-printed jig bolted directly to the hub face, providing a repeatable mounting interface for a calibrated digital inclinometer, as shown in Figure 3.19. After zeroing the inclinometer against a horizontal chassis reference, camber was obtained from $\gamma_i = 90 - \theta_{\text{inclinometer}}$. The measured camber was subsequently adjusted by modifying the shim stack at the suspension mounting interface until the target value was reached.



(a) Toe angle inference from string-to-wheel measurements



(b) Camber measurement jig mounted to the hub assembly

Figure 3.19: Wheel alignment measurement methods used during setup

After alignment, the spring-damper assemblies were reinstalled and the vehicle was returned to the scales to confirm that cross-weight distribution and ride heights remained within tolerance. The final static configuration used for aerodynamic testing is summarised in Figure 3.20, including corner weights, alignment values and shim configurations for traceability. Note that mass and corner weight values account for the driver.

Quantity		Value
Mass		274.65 kg
RH_F		49 mm
RH_R		51 mm

Rear Right	
Quantity	Value
Corner weight	70.1 kg
Toe	-0.13°
Camber	-1.2°
Pushrod shims	2 mm
Toe link shims	4 mm
Camber bracket shims	3.5 mm

Front Right	
Quantity	Value
Corner weight	67.35 kg
Toe	0.3°
Camber	-1.1°
Pushrod shims	3 mm
Toe link shims	4 mm
Camber bracket shims	3.5 mm



Rear Left	
Quantity	Value
Corner weight	72.7 kg
Toe	0.3°
Camber	-1.1°
Pushrod shims	3 mm
Toe link shims	5 mm
Camber bracket shims	3.5 mm

Front Left	
Quantity	Value
Corner weight	64.5 kg
Toe	-0.12°
Camber	-1.1°
Pushrod shims	2 mm
Toe link shims	5.5 mm
Camber bracket shims	2 mm

Figure 3.20: Final static configuration prior to aerodynamic testing

Chapter 4

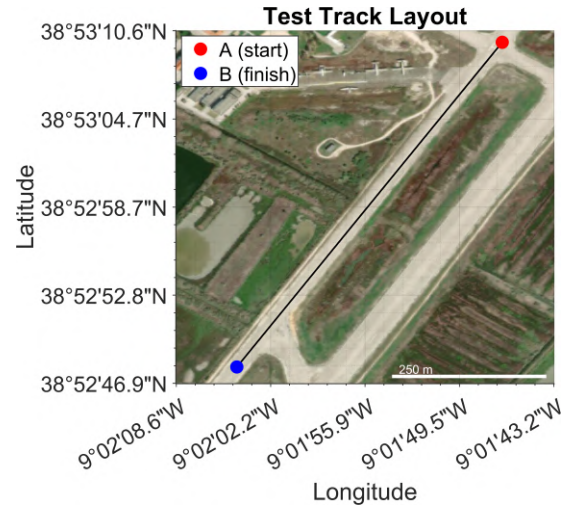
On-Track Aerodynamic Testing Campaigns

This chapter presents the on-track testing campaign carried out to obtain the experimental data used to validate the aerodynamic models and CFD predictions associated with the FST14 prototype. It first describes the testing facility and the straight-line protocol implemented during the campaign, including the practical adaptations required on the test day. It then documents the overall execution of the runs, the operational conditions under which the data were collected, and the monitoring of the main environmental, vehicle, and track variables used to assess the consistency and validity of the recorded dataset.

4.1 Testing Facility

The on-track testing campaigns were conducted during the 17th October 2025 at the Alverca Air Base, located within the Alverca Military Complex (Portugal). An overall aerial view of the base is provided in Figure 4.1a, which contextualises the available runway infrastructure within the test site.

All runs were performed on the taxiway, which offers close to 2.5 km of usable asphalt for straight-line testing. A detailed view of the utilised runway strip is shown in Figure 4.1b, where the tested segment is highlighted and the start (A) and finish (B) reference markers used in the campaign are indicated.



(a) Alverca Air Base within the Alverca Military Complex (Portugal) (b) Runway segment used for testing, with the start (A) and finish (B) reference markers indicated [51]

Figure 4.1: Overview of testing facility

The geometric definition of the testing direction used in subsequent analysis is based on the two reference markers identified in Figure 4.1b. Their geographic coordinates, corresponding to point A (start line) and point B (finish line), are reported in Table 4.1.

Table 4.1: Geographic coordinates of the start and finish reference points used to define the track direction.

Track point	Latitude	Longitude
A (start line)	38°53'09.83" N	9°01'46.65" W
B (finish line)	38°52'47.98" N	9°02'04.52" W

4.2 Procedural Overview

The campaign was executed to follow, as closely as operationally possible, the procedures and pre-requisites defined in Section 3.3. In particular, the straight-line run protocol described in Section 3.3.1 was implemented on the test day, such that each pass comprised acceleration up to the target speed, a CV window, and a CD phase. The CV–CD transition was defined by a dedicated on-track reference (throttle lift point), providing a repeatable driver cue for consistent execution.

The intended corridor geometry and operational sequence were implemented according to the track layout of Figure 3.3. Although the taxiway offers a substantially longer available straight, the corridor was assembled to reproduce the planned acceleration/CV zone, the downstream CD zone, and the stop/restart references between opposite-direction passes. The corridor was laid out using a measuring wheel (odometer) to place the key longitudinal references and to maintain the intended distances between markers; during track assembly, a centreline reference was established and used as a visual guide to keep the corridor straight and consistent over the full measurement length. An example of the

corridor assembly procedure and the definition of the throttle lift point marker are shown in Figures 4.2 and 4.3, respectively.



Figure 4.2: Track assembly using a measuring wheel (hodometer)



Figure 4.3: Dedicated throttle lift point markers defining the CV-CD transition

The on-track campaign comprised a total of 16 runs (8 paired passes). In line with the rationale in Section 3.3.1, namely, to collect CV data over several distinct target speeds such that each CV segment provides one (q, F_L) operating point, the original plan was to test five motor-speed limitations (8000 rpm, 11 000 rpm, 14 000 rpm, 17 000 rpm and 20 000 rpm), with three opposite-direction pairs per limitation. In practice, the available battery State of Charge (SoC) did not allow completion of the full matrix, and the final dataset comprised 6 runs at an 8000 rpm limitation, 6 runs at an 20 000 rpm limitation, and 4 runs at an 17 000 rpm limitation. Across all runs, the power demand was kept constant at 60 kW, and torque limitations were kept unchanged by using the same vehicle control configuration adopted for the acceleration event, avoiding run-to-run variability associated with changes in drivetrain settings.

The vehicle setup and operating philosophy defined in Section 3.3.2 was adopted prior to the first valid run and maintained throughout the campaign. In practice, the vehicle state used on the test day corresponded to the final, workshop-established configuration resulting from the preparation and setup procedure detailed in Section 3.6. The car was therefore brought to a ready-to-run condition at full test weight with the driver and instrumentation installed, and the aerodynamic package was kept in a defined configuration. In accordance with the setup procedure, tyres were inflated to the nominal cold pressure of 0.8 bar prior to the first run. Furthermore, control settings relevant to CD validity were enforced, in particular disabling regenerative braking so that the vehicle decelerated passively during the CD phase under aerodynamic drag and rolling resistance. A representative example of the vehicle positioned at the start line (point A) during the final pre-run checks is shown in Figure 4.4.



Figure 4.4: Vehicle positioned at point A (start line)

Operationally, the team was stationed near reference point A (start line), which served as the campaign hub for run preparation and post-run checks. As the vehicle returned to point A after each pass, tyre pressure and tyre temperature were monitored together with track temperature. Tyre pressure was measured using a handheld tyre pressure gauge (Figure 4.5), while both tyre surface temperature and track temperature were assessed using a thermal imaging camera (Figure 4.6); these tools were readily available within the team workshop and were therefore adopted for the between-run monitoring procedure.



Figure 4.5: Tyre pressure monitoring using a handheld pressure gauge



Figure 4.6: Tyre temperature monitoring using a thermal imaging camera

Finally, instrumentation and data collection were carried out in line with the requirements of Section 3.3.4, ensuring that the channels required for CV/CD segmentation and aerodynamic estimation were recorded in a synchronised dataset suitable for post-processing. It should be noted, however, that the pre-intended continuous monitoring of sensor signals and on-site plausibility checks could not be fully implemented, since the telemetry link did not provide sufficient range over the full corridor length; once the vehicle was sufficiently far from the operational hub (point A), live data reception was lost and continuous real-time analysis was therefore not possible.

4.3 Campaign and Vehicle Conditions State Monitoring

As described in Section 4.2, the campaign was organised around repeated opposite-direction passes with the vehicle returning to the operational hub at point A after each pair of runs. This operational loop enabled systematic between-run checks of vehicle and track conditions at point A. The present section therefore summarises the vehicle status records gathered during these checks (tyre pressure, tyre/track surface temperature) and the atmospheric conditions obtained from the local meteorological station. For the latter, environmental data were associated to each run individually by using the recorded run timestamps (hours and minutes), so that the corresponding set of atmospheric variables could be linked to each pass. These records provide context for the raw sensor signals and the subsequent aerodynamic estimates.

4.3.1 Environmental Conditions

As established in the environmental and procedural requirements of Section 3.3.3, atmospheric conditions are relevant both as acceptance criteria and as inputs to the aerodynamic estimation. Because ambient conditions were not logged on-board, ambient temperature (T_{amb}), relative humidity (RH), barometric pressure (p_{amb}), and wind speed/direction (V_{wind} , θ_{wind}) were obtained from the local meteorological station. Station measurements were then associated to each pass using the recorded run timestamps (hours and minutes). Since the station data were available only at an hourly cadence, the atmospheric state at the start of each run was estimated by linear interpolation between the two nearest station records.

For temperature, humidity, pressure, and the corresponding air density, these interpolated values were assigned on a per-run basis and treated as constant over the run. By contrast, for the CD analysis, the wind data were additionally evaluated as a time-varying profile over the duration of each CD segment, so that the wind component along the vehicle path could be determined continuously during the run.

Table 4.2 summarises the station readings at the timestamps that bracket the on-track runs and are therefore used as the reference points for the linear interpolation performed to estimate the atmospheric conditions at the start of each run.

Table 4.2: Meteorological station records at reference timestamps.

Time	T_{amb}	RH	p_{amb}	V_{wind}	θ_{wind}
	[°C]	[%]	[hPa]	[km h ⁻¹]	[°]
17:00	27.0	42.0	1013.0	9.0	190
18:00	26.2	40.0	1013.8	14.0	305
19:00	22.2	54.0	1014.4	18.4	316

Using the reference station records of Table 4.2 together with the timestamp of each pass, the atmospheric state at the start of each run was estimated by linear interpolation between the two nearest station entries. The resulting per-run environmental inputs associated to each of the 16 runs are reported in Table 4.3.

Table 4.3: Atmospheric conditions associated with each run from linear interpolation of the meteorological-station records in Table 4.2

Run	Time	T_{amb}	RH	p_{amb}	V_{wind}	θ_{wind}	Run	Time	T_{amb}	RH	p_{amb}	V_{wind}	θ_{wind}
		[°C]	[%]	[hPa]	[km h ⁻¹]	[°]			[°C]	[%]	[hPa]	[km h ⁻¹]	[°]
1	17:40	26.5	40.7	1013.5	12.3	266.7	9	18:02	26.1	40.5	1013.8	14.1	305.4
2	17:42	26.4	40.6	1013.6	12.5	270.5	10	18:04	25.9	40.9	1013.8	14.3	305.7
3	17:46	26.4	40.5	1013.6	12.8	278.2	11	18:07	25.7	41.6	1013.9	14.5	306.3
4	17:48	26.4	40.4	1013.6	13.0	282.0	12	18:08	25.7	41.9	1013.9	14.6	306.5
5	17:51	26.3	40.3	1013.7	13.2	287.8	13	18:12	25.4	42.8	1013.9	14.9	307.2
6	17:53	26.3	40.2	1013.7	13.4	291.6	14	18:13	25.3	43.0	1013.9	15.0	307.4
7	17:56	26.3	40.1	1013.7	13.7	297.3	15	18:16	25.1	43.7	1014.0	15.2	307.9
8	17:59	26.2	40.0	1013.8	13.9	303.1	16	18:17	25.1	44.0	1014.0	15.2	308.1

It should be noted that the values of V_{wind} and θ_{wind} reported in Table 4.3 correspond to the interpolated atmospheric state at the start of each run and are therefore used as run-level reference values. For the CD processing framework, however, wind speed and direction are not treated as fixed scalars over the entire segment. Instead, a time-varying wind profile is constructed over each CD interval by mapping the CD timestamps to absolute clock time and interpolating the meteorological-station records accordingly. This yields $V_{\text{wind}}(t)$ and $\theta_{\text{wind}}(t)$ throughout the run, from which the longitudinal wind component along the vehicle direction of motion is subsequently obtained.

For a given CD run, the meteorological-station wind records were interpolated in time over the run duration to obtain

$$V_{\text{wind}} = V_{\text{wind}}(t), \quad \theta_{\text{wind}} = \theta_{\text{wind}}(t). \quad (4.1)$$

The vehicle direction of motion is defined from the track geometry using the coordinates of the start and end reference points reported in Table 4.1. Denoting by $\mathbf{S}_A = (x_A, y_A)$ and $\mathbf{S}_B = (x_B, y_B)$ the coordinates of points A and B, respectively, the unit vector along the track is obtained as

$$\hat{\mathbf{t}}_{\text{track}} = \frac{\mathbf{S}_B - \mathbf{S}_A}{\|\mathbf{S}_B - \mathbf{S}_A\|}. \quad (4.2)$$

For runs performed in the opposite direction, the orientation of this vector is reversed accordingly. This definition ensures that the track-direction unit vector always aligns with the instantaneous direction of vehicle motion for the considered run.

The wind vector is reconstructed from its interpolated magnitude and direction as

$$\mathbf{w}(t) = -V_{\text{wind}}(t) \begin{bmatrix} \cos \theta_{\text{wind}}(t) \\ \sin \theta_{\text{wind}}(t) \end{bmatrix}, \quad (4.3)$$

where θ_{wind} follows the meteorological convention [52], denoting the direction from which the wind originates. The minus sign is therefore required so that $\mathbf{w}(t)$ represents the actual wind velocity vector, pointing in the direction toward which the air is moving.

The longitudinal wind component ($w_{\parallel}(t)$) along the vehicle path is then obtained by projection of the wind vector onto the track direction,

$$w_{\parallel}(t) = \mathbf{w}(t) \cdot \hat{\mathbf{t}}_{\text{track}}. \quad (4.4)$$

This quantity represents the effective headwind/tailwind contribution acting along the direction of motion during the CD segment and is used in the speed correction described later in Section 5.2.2, consistently with the need to account for the sensitivity of on-road aerodynamic measurements to real environmental conditions [9].

With respect to the acceptance criteria defined in Section 3.3.3, the recorded atmospheric conditions indicate that the temperature requirement was satisfied throughout the test window. Specifically, T_{amb} remained within the 0°C to 38°C band for all runs (Tables 4.3). Regarding wind, the interpolated mean wind speed V_{wind} associated to each run ranged from approximately 12.3 km h^{-1} to 15.2 km h^{-1} (Table 4.3). Therefore, the criterion on mean wind speed ($V_{\text{wind}} \leq 16 \text{ km h}^{-1}$) was satisfied for all runs. The

gust criterion (maximum gusts below 20 km h^{-1}) cannot be verified from the available dataset, since the meteorological station records used in Tables 4.2 and 4.3 provide only discrete mean values at hourly cadence and do not include gust information. Finally, fog and surface condition constraints were addressed operationally during the session; no fog was observed during the run window and the runway surface was dry and clean, so no runs were discarded on these grounds.

Using the interpolated atmospheric variables in Table 4.3, an air-density value was computed for each run. For run i , the interpolated ambient temperature $T_{\text{amb},i}$, relative humidity RH_i , and barometric pressure $p_{\text{amb},i}$ were first used to determine the vapour ($P_{v,i}$) and dry-air ($P_{d,i}$) partial pressures [53]. The air density was then computed from the ideal-gas relation for a moist-air mixture as [54]:

$$\rho_i = \frac{P_{d,i}}{R_d T_{K,i}} + \frac{P_{v,i}}{R_v T_{K,i}}, \quad (4.5)$$

where $R_d = 287.058 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific gas constant of dry air and $R_v = 461.495 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific gas constant of water vapour. Therefore, the density values listed in Table 4.4 were obtained directly by substituting, for each run, the interpolated values of $T_{\text{amb},i}$, RH_i , and $p_{\text{amb},i}$ from Table 4.3 into Equation (4.5).

To quantify the uncertainty associated with this calculation, a relative uncertainty of 1% was assigned to the main atmospheric inputs entering the density evaluation. Assuming these input quantities to be independent, the standard uncertainty in air density was obtained through first-order uncertainty propagation [55]:

$$u_{\rho,i} = \sqrt{\left(\frac{\partial \rho}{\partial p_{\text{amb}}} u_{p,i}\right)^2 + \left(\frac{\partial \rho}{\partial RH} u_{RH,i}\right)^2 + \left(\frac{\partial \rho}{\partial T_K} u_{T,i}\right)^2}. \quad (4.6)$$

The $\rho_i \pm u_{\rho,i}$ values reported in Table 4.4 were obtained in this manner for each run and then rounded to four decimal places. Since the atmospheric conditions varied only slightly throughout the test session, the resulting density uncertainties remain nearly constant from run to run.

Table 4.4: Air density assigned to each run through moist-air calculations, together with the corresponding propagated absolute uncertainty

Run	Time	$\rho \pm u_\rho$ [kg m ⁻³]	Run	Time	$\rho \pm u_\rho$ [kg m ⁻³]
1	17:40	1.1725 ± 0.0118	9	18:02	1.1745 ± 0.0119
2	17:42	1.1726 ± 0.0118	10	18:04	1.1751 ± 0.0119
3	17:46	1.1729 ± 0.0118	11	18:07	1.1759 ± 0.0119
4	17:48	1.1731 ± 0.0118	12	18:08	1.1761 ± 0.0119
5	17:51	1.1733 ± 0.0118	13	18:12	1.1772 ± 0.0119
6	17:53	1.1735 ± 0.0118	14	18:13	1.1774 ± 0.0119
7	17:56	1.1737 ± 0.0118	15	18:16	1.1782 ± 0.0119
8	17:59	1.1739 ± 0.0118	16	18:17	1.1785 ± 0.0119

4.3.2 Vehicle and Track Conditions

As previously mentioned, a structured set of vehicle and track condition checks was performed at the operational hub, point A, between successive opposite-direction run pairs. The monitoring procedure

and instrumentation used for tyre pressure, tyre surface temperature, and track surface temperature measurements were described in Section 4.2. The present subsection therefore focuses on the recorded values and their evolution throughout the testing campaign.

Monitoring these parameters was important to verify that variations in measured suspension displacement, longitudinal deceleration, or inferred aerodynamic forces were not significantly affected by unintended changes in the vehicle or track state. In particular, tyre pressure and tyre temperature influence both the effective vertical stiffness of the tyre and the rolling resistance contribution during CD. Track temperature also provides relevant context for tyre thermal behaviour between runs. The recorded trends were therefore used to assess whether the campaign was conducted under sufficiently stable conditions to support comparison between passes and limit non-aerodynamic sources of bias.

The run-by-run evolution of tyre pressure, tyre surface temperature, and track surface temperature is summarised in Table 4.5 and shown graphically in Figure 4.7. The measurements were taken before every second run, corresponding to the checks performed between opposite-direction run pairs.

Table 4.5: Tyre surface temperatures, track surface temperature, and tyre pressures measured at point A before each monitored run pair

Before Run	Time	Tyre temperatures				Track temperature	Tyre pressures			
		T_{FL}	T_{FR}	T_{RL}	T_{RR}	T_{track}	p_{FL}	p_{FR}	p_{RL}	p_{RR}
		[°C]	[°C]	[°C]	[°C]	[°C]	[bar]	[bar]	[bar]	[bar]
1	17:39	35.6	38.0	36.2	31.7	33.7	0.80	0.80	0.80	0.80
3	17:45	32.6	32.7	34.5	33.8	31.3	0.80	0.80	0.80	0.80
5	17:50	32.9	32.3	34.3	34.8	30.3	0.80	0.80	0.80	0.85
7	17:55	32.4	31.9	34.6	34.5	30.5	0.80	0.80	0.80	0.85
9	18:01	33.5	32.1	35.5	35.3	30.3	0.85	0.80	0.80	0.85
11	18:06	33.5	32.9	35.5	34.6	29.7	0.85	0.80	0.80	0.85
13	18:11	33.9	33.1	34.1	35.5	28.9	0.85	0.80	0.80	0.85
15	18:15	32.9	32.0	34.4	34.8	28.9	0.80	0.80	0.80	0.85

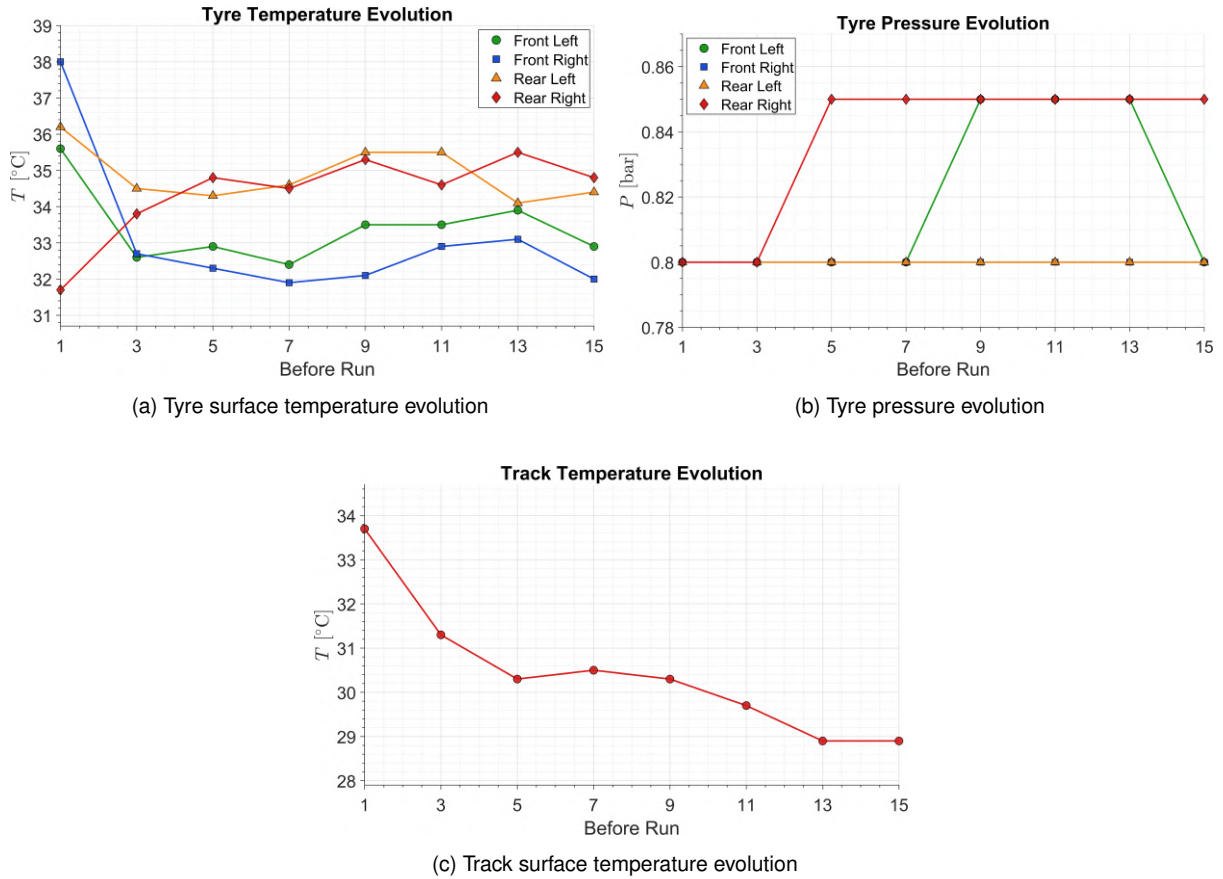


Figure 4.7: Evolution of the monitored vehicle and track condition variables throughout the testing campaign

Tyre surface temperatures showed an initial peak before Run 1, followed by a rapid decrease and a relatively stable evolution over the remaining measurements. Apart from this first value, the corner-to-corner spread remained limited and no sustained drift was observed, supporting the repeatability of tyre thermal conditions between run pairs.

Track surface temperature decreased gradually from 33.7°C before Run 1 to 28.9°C before Runs 13 and 15, consistent with the ambient-temperature trend reported in Table 4.3. This gradual cooling provides context for possible small variations in tyre recovery and CD deceleration.

Tyre pressures remained within a narrow range of 0.80 bar to 0.85 bar, with only minor corner-dependent variations. Therefore, pressure-induced changes in tyre stiffness and rolling resistance are expected to be secondary, while the recorded values support the stability of the vehicle state during the campaign.

Overall, the condition monitoring results indicate that tyre pressures remained stable and that tyre and track thermal states evolved smoothly during the campaign. The tyres were allowed to cool sufficiently between run pairs to maintain comparable operating conditions, while the remaining gradual thermal trends were retained as contextual information for interpreting scatter in the aerodynamic estimates. These observations support the validity of comparing opposite-direction run pairs under the assumption that non-aerodynamic influences were limited and did not exhibit abrupt or uncontrolled variation.

Chapter 5

On-Track Aerodynamic Testing Data Processing and Results

This chapter presents the processing of the on-track test data and the resulting aerodynamic estimates. Starting from the raw measured signals acquired during the testing campaigns, the data are segmented, converted into calibrated physical quantities, and processed through the CV and CD estimation frameworks developed in MATLAB.

5.1 Raw Sensor Data and Run Segmentation

With the testing facility, procedures, and campaign conditions established in Sections 4.1–4.3, the analysis begins with the raw on-track logs and their segmentation into the phases required by the straight-line test protocol. The objective of this step is to identify, for each run, the start and end times of the acceleration, CV, and CD intervals, such that only the CV and CD portions are retained for the subsequent aerodynamic processing.

Data acquisition followed a paired-run logging convention. As described in Section 4.1, runs were executed as opposite-direction pairs ($A \rightarrow B$ followed by $B \rightarrow A$). After completing each pair, the vehicle returned to point A for checks and was powered down; consequently, each log file contains the data corresponding to two runs. In post-processing, each log file is first split into its two run instances and then segmented into phases.

Segmentation relies on a subset of the recorded channels, referenced here by their raw acquisition names:

- Vehicle speed reference ($V_{ref}(t)$): identified from the four wheel-speed channels `amk_actual_speed0--3`, averaged into a single speed trace $V_{ref}(t)$ after unit conversion.
- Driver inputs ($APPS(t)$, $BPS(t)$): protocol compliance is assessed using the Accelerator Pedal Position Sensor (APPS) and Brake Pedal Sensor (BPS) channels, recorded as `te_main_APPS` and `te_main_BPS`, respectively, and interpreted as $APPS(t)$ and $BPS(t)$, respectively.

- Steering demand ($\delta(t)$): straight-line behaviour is verified using the steering angle signal `steering_angle`, denoted $\delta(t)$.
- Other raw channels (processed later): signals such as the pitot tube readings `diff_pressure`, the suspension potentiometer channels `fl/fr/r1/rr_pot_adc` and the longitudinal acceleration from the IMU channel `accX` are shown in the raw overview for completeness but are kept in raw form at this stage and converted into physical quantities only in the next section through the calibration procedures.

To ensure that the extracted CV and CD segments comply with the intended straight-line protocol (Section 3.3.1), a set of segmentation acceptance criteria was applied during trimming and phase boundary detection. Table 5.1 summarises the corresponding rules and threshold values used throughout this procedure.

Table 5.1: Acceptance criteria used for trimming/segmentation and protocol-compliance checks

Criterion	Rule / condition	Value
Straight-line trimming	$V_{ref}(t) > V_{min}$	$V_{min} = 5 \text{ km/h}$
	$ \delta(t) < \delta_{max}$	$\delta_{max} = 5^\circ$
Throttle lift confirmation	$APPS(t) < APPS_{min}$	$APPS_{min} = 2 \%$
	dwel time below threshold $\geq \tau_{min}$	$\tau_{min} = 1.0 \text{ s}$
Coast-down compliance	$APPS(t) \leq APPS_{min}$	$APPS_{min} = 2 \%$
	$BPS(t) \leq BPS_{min}$	$BPS_{min} = 2 \%$
CV stability	$ V_{ref}(t) - V_{ref} < \Delta V_{CV}$	$\Delta V_{CV} = 1 \text{ km/h}$
	$ \delta(t) < \delta_{max}$	$\delta_{max} = 5^\circ$
Run termination	$V(t) < V_{end}$	$V_{end} = 16 \text{ km/h}$

Following the definition of the segmentation criteria, a manual trimming and phase-identification process was carried out for each run. This step was performed using a dedicated visualisation software (PlotJuggler), which allows for the synchronous inspection of all recorded channels and facilitates precise identification of phase transitions. Appendix B provides an example visual representation of these signals in PlotJuggler, for a given log.

For each log file, the relevant signals described above were visualised and analysed jointly. The trimming process consisted of isolating the time interval corresponding to valid straight-line motion, removing portions of the data affected by vehicle manoeuvring, start-up transients, or post-run deceleration outside the defined protocol. Within this trimmed interval, the phase boundaries were identified by applying the acceptance criteria summarised in Table 5.1.

The resulting segmentation yields, for each run, the set of phase bounds:

$$[t_{acc,start}, t_{acc,end}], \quad [t_{CV,start}, t_{CV,end}], \quad [t_{CD,start}, t_{CD,end}]$$

which are subsequently used to extract the CV and CD datasets for aerodynamic processing.

Figure 5.1 provides a visual representation of the segmentation result for a given log, showing the raw channels (using acquisition names) together with the extracted phase intervals for each of the two runs contained in the file. Equivalent raw-signal overviews for the remaining log files are provided in Appendix B.

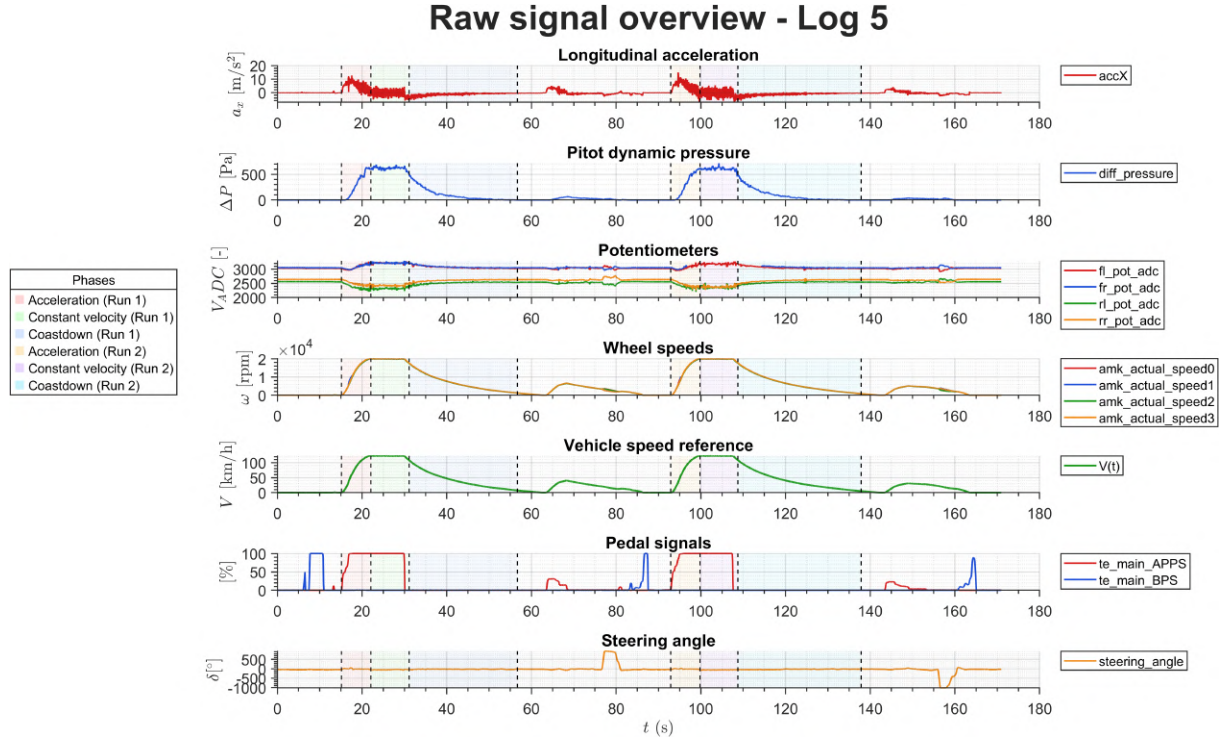


Figure 5.1: Representative raw signal overview for Log 4 (two opposite-direction runs), with the extracted intervals highlighted

5.2 Data Processing

The next stage of the analysis consists of processing the retained run data into the aerodynamic quantities of interest. This is carried out in two steps. First, the relevant raw sensor outputs are converted into calibrated physical signals using the transfer functions identified in Section 3.4.3. Second, these converted signals are introduced into the CV and CD analysis frameworks.

5.2.1 Calibration Based Conversion of Raw Signals

The first step of the post-processing consists of conditioning and converting the segmented raw sensor signals into the physical quantities required by the aerodynamic estimation procedures. Before applying the calibration laws identified in Section 3.4.3, the raw signals were first smoothed using a moving-average filter to reduce high-frequency measurement noise [56]. For a generic signal x_k , the filtered value $\bar{x}_k$ is given by

$$\bar{x}_k = \frac{1}{N_w} \sum_{j=0}^{N_w-1} x_{k-j}, \quad (5.1)$$

where N_w is the moving-average window size in samples. The value of N_w was selected according to the expected bandwidth of each signal, such that the averaging window was large enough to attenuate measurement noise while remaining short enough to preserve the physical variations relevant to the analysis [57].

After smoothing, the pitot differential pressure signal is converted into calibrated dynamic pressure, while the raw potentiometer outputs are converted into calibrated damper and wheel displacement histories. These conversions are applied separately to the CV and CD intervals identified during the segmentation procedure. In the CV branch, the calibrated dynamic pressure and suspension displacement signals constitute the direct inputs to the downforce estimation framework. In addition, the pitot-derived airspeed is also included in this conversion path. While it is not used directly within the downforce processing framework, it is retained as a relevant quantity for the subsequent comparison with CFD simulation results. In the CD branch, the pitot-derived dynamic pressure is further transformed into airspeed, which is then used in the drag-identification procedure. The corresponding conversion paths are summarised in Figures 5.2 and 5.3, which explicitly indicate the retained time windows for each branch together with the calibration laws applied from Figures 3.10 and 3.12.

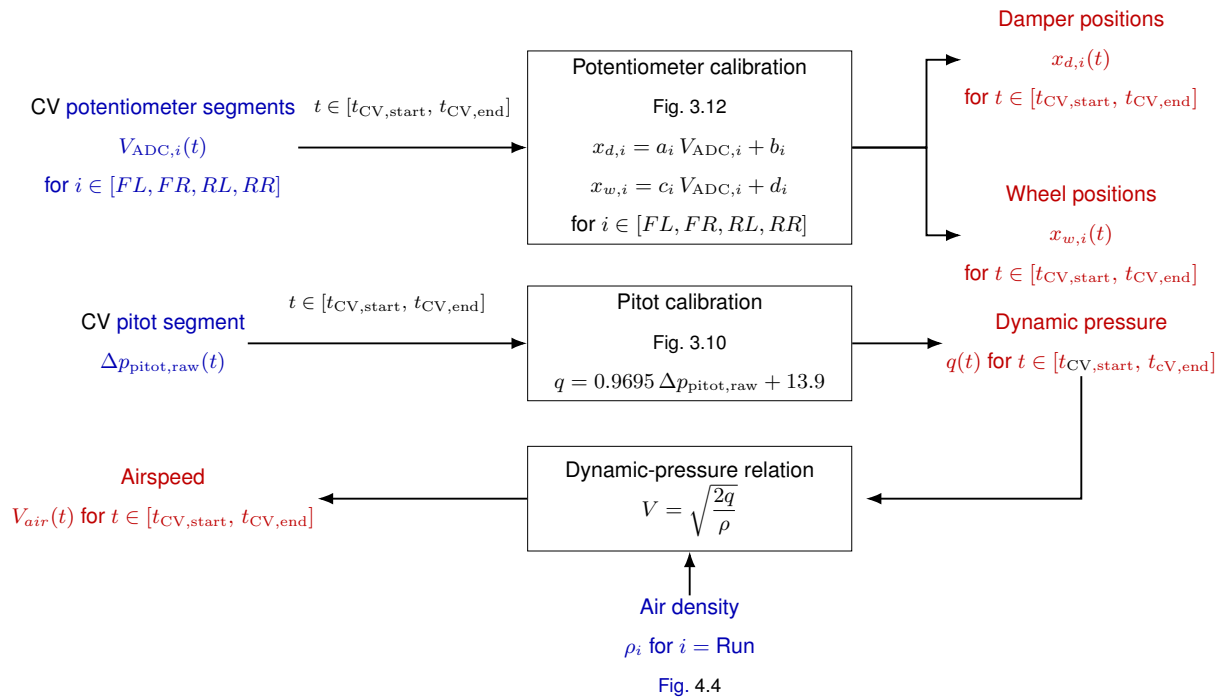


Figure 5.2: Calibration based conversion of segmented raw signals into the physical quantities used in the CV processing branch, for a given run

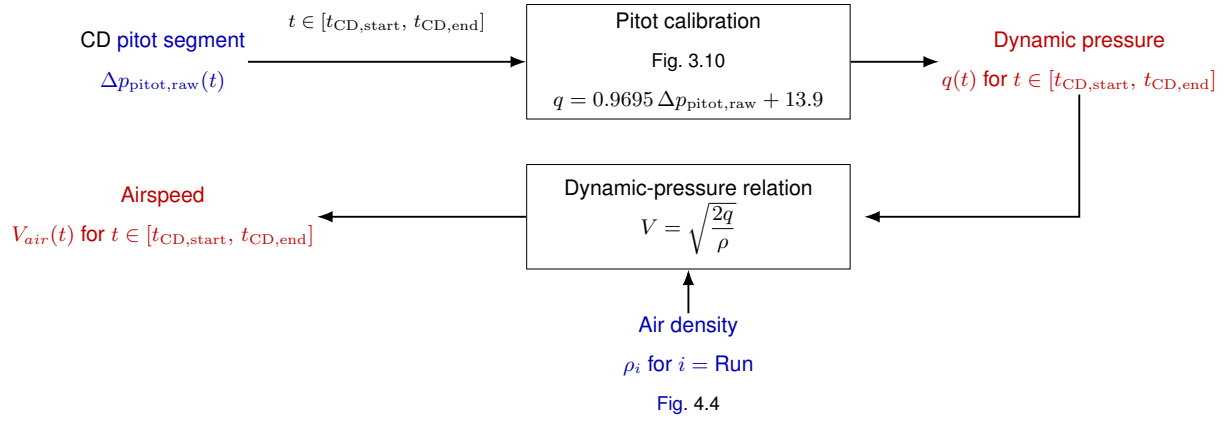


Figure 5.3: Calibration based conversion of segmented raw signals into the physical quantities used in the CD processing branch, for a given run

5.2.2 Aerodynamic Estimation Processing Frameworks

After signal calibration, the retained data are introduced into aerodynamic estimation frameworks implemented in MATLAB. These frameworks correspond to the algorithmic procedures developed for the CV and CD analyses, through which the measured data are transformed into estimates of the aerodynamic quantities of interest. The following sections present the processing approach used for each method.

Constant Velocity

The CV segments are processed to estimate aerodynamic downforce, dynamic ride heights, and the associated aerodynamic coefficients. This procedure combines the measured suspension response with the identified suspension and tyre characteristics in order to reconstruct the vertical load path at each corner and, subsequently, at axle and vehicle level.

The required inputs for this framework are summarised in Table 3.1. The complete processing chain is presented in Figure 5.4, where each transformation block corresponds directly to the governing equations introduced in Section 3.2.1. In addition to the main force-reconstruction path, the figure also makes explicit the origin of the required inputs by referencing the corresponding processed signals, calibration curves, tables, and setup quantities from which they are obtained.

A further preprocessing step is required before the spring force law can be applied. The calibrated damper displacement signals obtained from the vehicle do not share the same zero reference as the spring force–displacement curves identified in the static characterization. Accordingly, the measured damper displacement is first expressed as an increment relative to the car baseline, while a static spring-compression baseline is obtained from the static wheel load, motion ratio, and inverse spring law. These two contributions are then combined to define the total spring compression used in the spring-force evaluation.

From this point, the spring force and wheel load are reconstructed at each corner, after which the front- and rear-axle downforce and the total downforce are obtained. In parallel, the reconstructed wheel loads are used with the tyre force–deflection relation to determine tyre deflection, which is then

combined with the calibrated wheel displacement and the static ride height reference to estimate the dynamic ride height at each corner. Finally, the reconstructed total, front, and rear axle downforce values are regressed against dynamic pressure in order to estimate C_{LA} , $C_{L,FA}$, and $C_{L,RA}$.

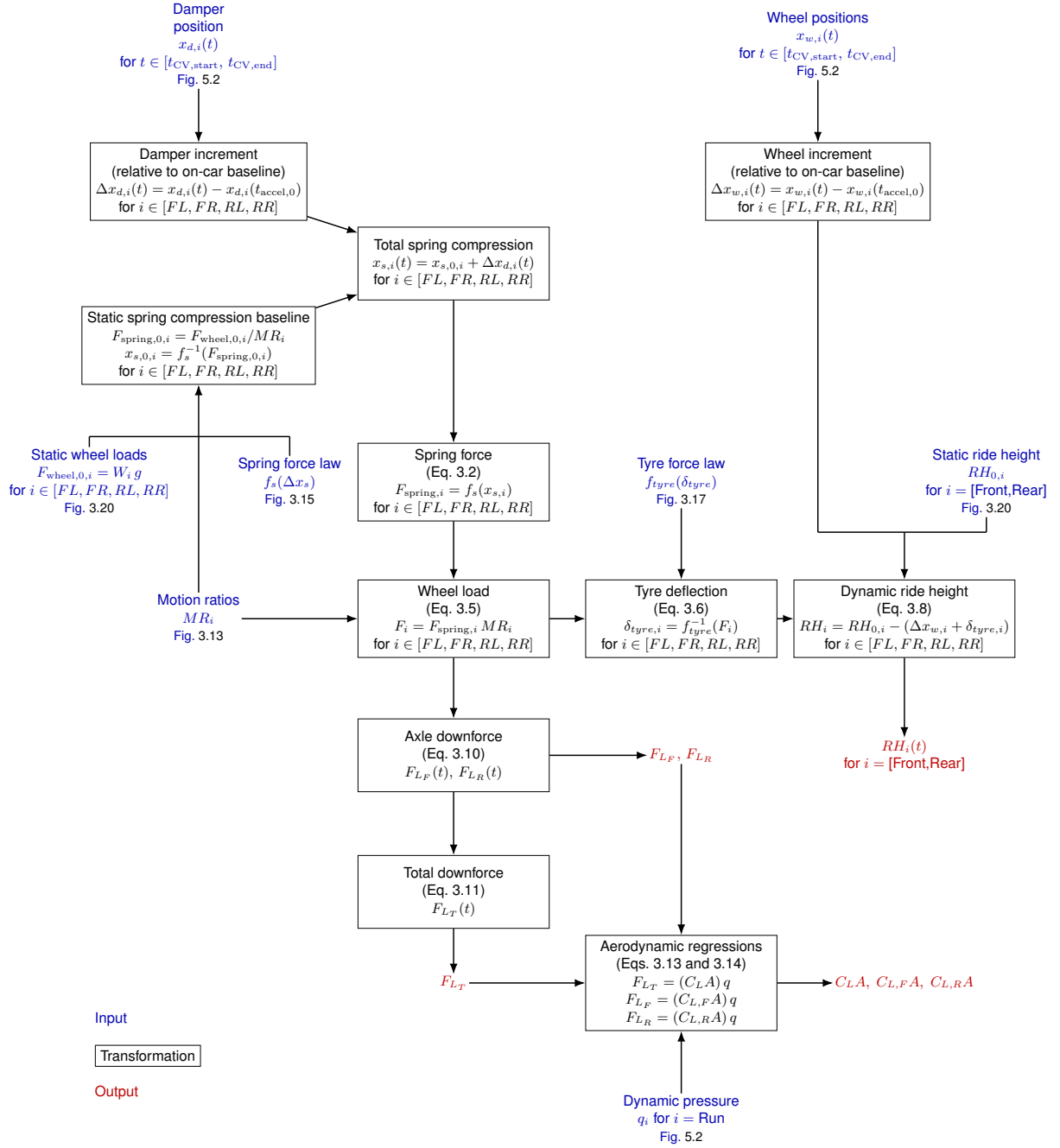


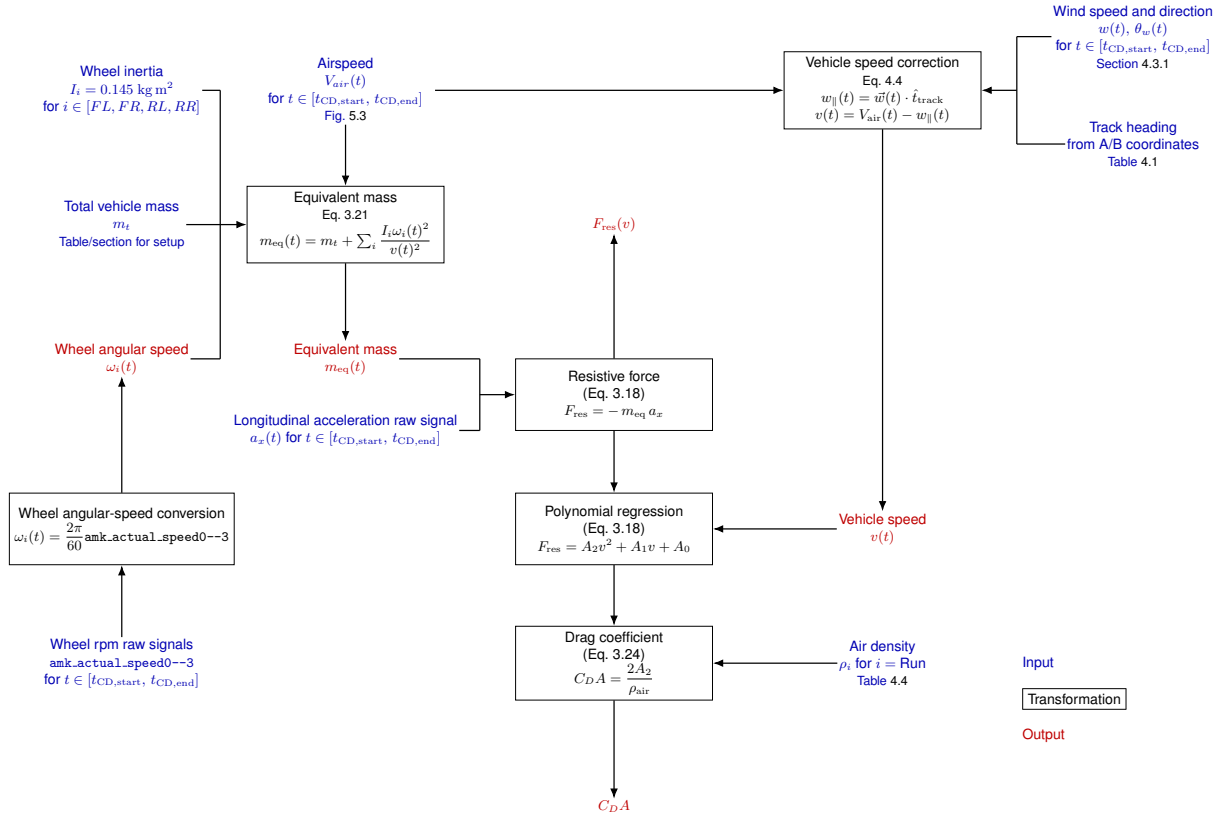
Figure 5.4: CV aerodynamic processing framework for a given run

Coastdown

In parallel with the CV analysis, the CD segments are processed to estimate the aerodynamic drag area and rolling-resistance coefficients. This procedure uses the vehicle free-deceleration response to characterise the longitudinal resistive forces acting during straight-line motion.

Figure 5.5 presents the adopted processing framework, with each block corresponding to the governing equations introduced in Section 3.2.2. The required inputs are summarised in Table 3.2, and their origin is explicitly indicated in the figure.

Before entering the main processing chain, the raw longitudinal-acceleration and wheel-speed signals are smoothed through a moving-average operation in order to reduce high-frequency measurement noise, as equally employed on Section 5.2.1. The procedure then begins with the reconstruction of the resistive force from the longitudinal acceleration and the equivalent mass. The latter includes both the total vehicle mass and the rotational inertia contribution of the wheels, obtained from the wheel-speed signals. Since the wheel rotational inertia was not measured experimentally, its value was approximated from the CAD model and introduced as a fixed parameter in the equivalent-mass calculation. In parallel, the vehicle speed is determined by correcting the pitot-derived airspeed for wind effects based on the measured wind conditions and track heading. The resistive force is then fitted as a function of vehicle speed using a second-order polynomial. The fitted coefficients are finally used, together with the air density and vehicle mass, to estimate C_DA .



5.3 Processed Data

With the processing frameworks established in Figures 5.4 and 5.5, the next stage of the results chapter consists of examining the processed signals obtained from each methodology. The purpose of this section is to present representative time histories for the main quantities involved in the CV and CD processing chains, and to identify the quantities retained for the subsequent aerodynamic analysis and comparison with CFD.

Table 5.2 summarises the main processed quantities whose time histories are presented for each branch of the analysis.

Table 5.2: Processed quantities selected for time-history presentation in the CV and CD branches

Branch	Time histories
CV	$V_{\text{air}}(t), q(t), \Delta x_{d,i}(t), \Delta x_{w,i}(t), F_{L_T}(t), F_{L_F}(t), F_{L_R}(t), RH_F(t), RH_R(t)$
CD	$V_{\text{air}}(t), w_{\parallel}(t), v(t), a_x(t), m_{\text{eq}}(t), F_{\text{res}}(t)$

5.3.1 Constant Velocity Processed Signals

For the CV methodology, the processed quantities of interest follow from the framework shown in Figure 5.4. In particular, the retained interval $[t_{\text{CV,start}}, t_{\text{CV,end}}]$ is illustrated through representative time histories of airspeed ($V_{\text{air}}(t)$), dynamic pressure ($q(t)$), damper and wheel displacements ($\Delta x_{d,i}(t)$, $\Delta x_{w,i}(t)$), reconstructed downforce ($F_{L_T}(t)$, $F_{L_F}(t)$, $F_{L_R}(t)$), and dynamic ride heights ($RH_F(t)$, $RH_R(t)$).

Since this portion of each run is intended to represent quasi-steady straight-line motion, the corresponding time histories are expected to remain approximately constant throughout the selected segment. The remaining variation is mainly associated with measurement noise, local pavement irregularities and suspension response to small disturbances. Under this quasi-steady assumption, the principal processed quantities used in the later aerodynamic regressions can be reduced to representative scalar values for the run.

Accordingly, for the CV methodology, the value retained for later analysis is taken as the arithmetic mean of the processed signal over the retained interval, while the associated uncertainty is quantified through the standard deviation of that same time history. This treatment is adopted only for the CV branch, for which the analysed quantities are expected to remain approximately stationary within the selected segment. It is therefore not introduced as a general uncertainty definition for the full chapter, nor directly extended to the CD methodology, where the processed quantities evolve continuously during the deceleration event.

For a generic processed quantity $x(t)$ sampled over a CV segment containing N samples, the representative value is defined as [58]:

$$\bar{x} = \frac{1}{N} \sum_{k=1}^N x_k, \quad (5.2)$$

while the associated uncertainty [55] is taken as the standard deviation of the same time history [59]:

$$u_x = \sigma_x = \sqrt{\frac{1}{N} \sum_{k=1}^N (x_k - \bar{x})^2}. \quad (5.3)$$

Figure 5.6 shows representative processed time histories for a CV run, including airspeed dynamic pressure, damper and wheel displacements, reconstructed downforce, and dynamic ride heights over the retained interval. The corresponding plots for the remaining runs are provided in Appendix C.1.

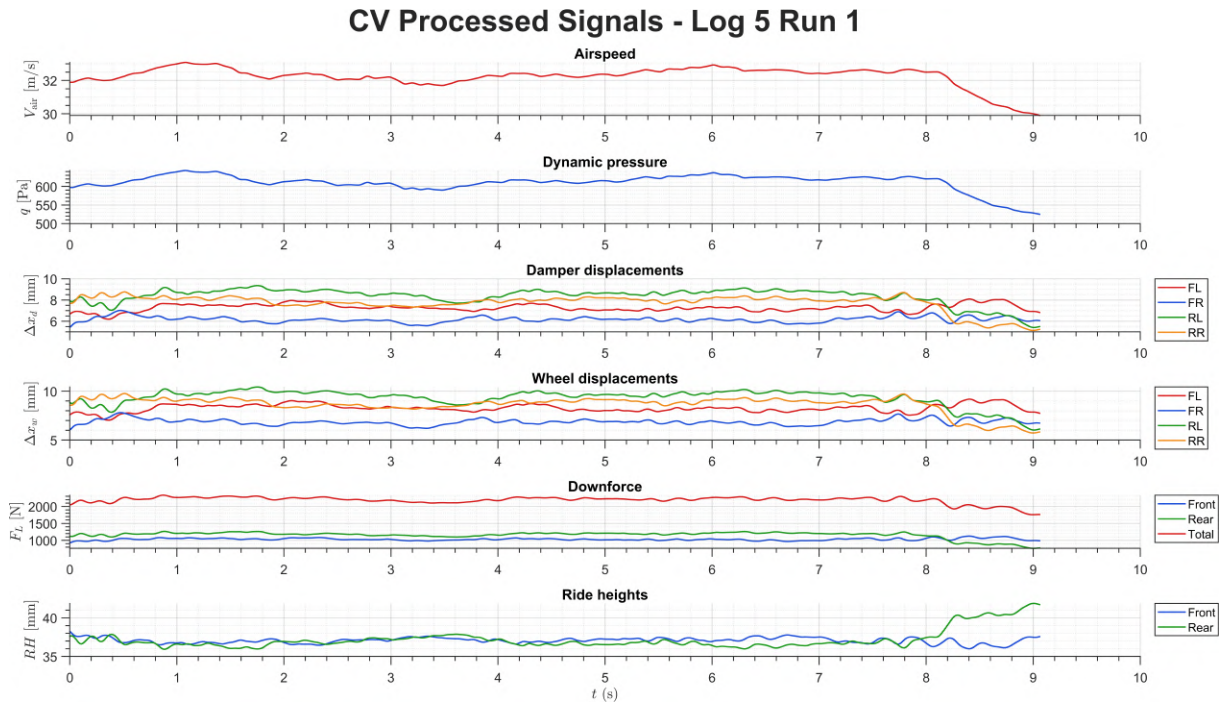


Figure 5.6: Representative processed time histories for a CV run (Log 5 Run 1 - Run 9)

To complement the graphical representation, Table 5.3 summarises the representative CV quantities obtained for all analysed runs. For each run, the value reported for each quantity corresponds to the segment mean over the retained CV interval, while the associated uncertainty is taken as the standard deviation of the mean for a given corresponding time history, according to Equations (5.2) and (5.3).

Table 5.3: Representative CV quantities for all analysed runs. Each entry is reported as mean $\pm$ standard deviation over the retained interval

Run	q [Pa]	V_{air} [m s ⁻¹]	F_{L_F} [N]	F_{L_R} [N]	F_{L_T} [N]	RH_F [mm]	RH_R [mm]
1	117.19 $\pm$ 3.86	14.138 $\pm$ 0.233	184.6 $\pm$ 15.1	38.7 $\pm$ 13.7	223.3 $\pm$ 28.7	46.84 $\pm$ 0.18	50.52 $\pm$ 0.17
2	86.69 $\pm$ 3.10	12.160 $\pm$ 0.219	58.4 $\pm$ 16.3	207.6 $\pm$ 15.5	266.0 $\pm$ 31.8	48.32 $\pm$ 0.19	48.49 $\pm$ 0.19
3	113.51 $\pm$ 5.91	13.912 $\pm$ 0.360	133.5 $\pm$ 16.4	220.2 $\pm$ 14.1	353.7 $\pm$ 30.4	47.44 $\pm$ 0.19	48.34 $\pm$ 0.17
4	89.64 $\pm$ 4.33	12.362 $\pm$ 0.301	60.9 $\pm$ 20.0	176.8 $\pm$ 18.1	237.8 $\pm$ 38.1	48.29 $\pm$ 0.23	48.86 $\pm$ 0.22
5	96.32 $\pm$ 6.70	12.813 $\pm$ 0.446	159.2 $\pm$ 19.7	227.3 $\pm$ 19.8	386.4 $\pm$ 39.5	47.14 $\pm$ 0.23	48.25 $\pm$ 0.24
6	105.15 $\pm$ 4.52	13.387 $\pm$ 0.286	106.2 $\pm$ 18.1	218.5 $\pm$ 18.0	324.8 $\pm$ 36.2	47.76 $\pm$ 0.21	48.36 $\pm$ 0.22
7	337.36 $\pm$ 15.38	23.976 $\pm$ 0.548	551.4 $\pm$ 35.8	633.5 $\pm$ 27.6	1184.9 $\pm$ 63.4	42.55 $\pm$ 0.42	43.42 $\pm$ 0.32
8	608.42 $\pm$ 10.71	32.195 $\pm$ 0.284	1010.6 $\pm$ 42.5	1174.0 $\pm$ 60.1	2184.7 $\pm$ 102.5	37.32 $\pm$ 0.48	36.96 $\pm$ 0.71
9	611.60 $\pm$ 22.22	32.271 $\pm$ 0.598	1030.3 $\pm$ 30.4	1163.0 $\pm$ 97.2	2193.3 $\pm$ 127.6	37.07 $\pm$ 0.35	37.12 $\pm$ 1.16
10	603.39 $\pm$ 22.96	32.047 $\pm$ 0.619	1065.4 $\pm$ 48.2	1150.3 $\pm$ 101.9	2215.8 $\pm$ 150.1	36.69 $\pm$ 0.55	37.24 $\pm$ 1.21
11	615.33 $\pm$ 22.87	32.351 $\pm$ 0.599	1023.7 $\pm$ 34.9	1177.3 $\pm$ 47.1	2201.0 $\pm$ 82.1	37.14 $\pm$ 0.40	36.95 $\pm$ 0.55
12	619.31 $\pm$ 17.12	32.452 $\pm$ 0.452	1061.1 $\pm$ 46.7	1205.9 $\pm$ 45.4	2266.9 $\pm$ 92.1	36.74 $\pm$ 0.53	36.58 $\pm$ 0.54
13	439.53 $\pm$ 15.59	27.327 $\pm$ 0.483	701.0 $\pm$ 48.4	835.8 $\pm$ 33.3	1536.7 $\pm$ 81.7	40.82 $\pm$ 0.56	41.03 $\pm$ 0.40
14	431.76 $\pm$ 13.39	27.081 $\pm$ 0.422	700.0 $\pm$ 37.1	866.5 $\pm$ 39.7	1566.6 $\pm$ 76.8	40.87 $\pm$ 0.43	40.61 $\pm$ 0.47
15	449.96 $\pm$ 18.76	27.637 $\pm$ 0.574	710.3 $\pm$ 35.8	888.5 $\pm$ 43.4	1598.8 $\pm$ 79.2	40.71 $\pm$ 0.41	40.39 $\pm$ 0.52
16	437.42 $\pm$ 9.72	27.246 $\pm$ 0.303	711.3 $\pm$ 38.8	880.1 $\pm$ 39.4	1591.4 $\pm$ 78.2	40.73 $\pm$ 0.45	40.45 $\pm$ 0.47

These representative values constitute the experimental dataset used in the CV analysis. In particular, the mean values of dynamic pressure and reconstructed downforce define the data points used in the experimental regressions from which $C_{L,A}$, $C_{L,F,A}$, and $C_{L,R,A}$ are identified, while the corresponding ride-height values provide the basis for defining the operating conditions considered in the CFD simulations.

5.3.2 Coastdown Processed Signals

For the CD methodology, the processed quantities of interest follow from the framework shown in Figure 5.5. In particular, the retained interval $[t_{CD,start}, t_{CD,end}]$ is illustrated through representative time histories of airspeed ($V_{air}(t)$), longitudinal wind component ($w_{||}(t)$), ground speed ($v(t)$), equivalent mass ($m_{eq}(t)$), and reconstructed resistive force ($F_{res}(t)$).

Unlike the CV branch, the CD segment does not correspond to a quasi-steady operating condition. During this phase, the vehicle undergoes a continuous deceleration, so that the processed quantities evolve systematically with time rather than fluctuating about an approximately constant value. As a result, the CD data are not reduced to a single representative scalar per run through a segment mean. Instead, the retained interval is interpreted as a continuous deceleration event from which a sequence of valid instantaneous samples is extracted for the later drag-identification procedure.

The representative role of the CD processed signals is therefore different from that of the CV branch.

Rather than condensing each run into one mean value and one uncertainty, the CD methodology retains the full time evolution of the deceleration event, since the subsequent aerodynamic identification is based on the functional relation between resistive force and vehicle speed over the entire interval.

Figure 5.7 shows representative processed time histories for a CD run, including airspeed, longitudinal wind component, ground speed, equivalent mass, and reconstructed resistive force over the retained interval. The corresponding plots for the remaining runs are provided in Appendix C.2.



Figure 5.7: Representative processed time histories for a CD run (Log 5 Run 1 - Run 9)

These processed time histories constitute the experimental dataset used in the CD analysis. In particular, the retained instantaneous pairs of ground speed and reconstructed resistive force define the data used in the subsequent regressions from which the drag-related aerodynamic coefficient is identified.

5.4 Aerodynamic Performance Estimation

This section presents the final identification of the aerodynamic coefficients from the processed experimental data. The CV data are used to estimate the lift-related coefficients through regression, while the CD data are used to estimate the drag-related coefficient. The following subsection focuses on the estimation of C_{LA} and C_{DA} from the representative CV and CD quantities introduced previously.

5.4.1 Estimation of C_{LA} from Constant Velocity Data

The final step of the CV processing framework shown in Figure 5.4 corresponds to the aerodynamic regressions block. At this stage, the reconstructed total, front and rear downforce signals are combined with the dynamic-pressure signal in order to identify the lift related aerodynamic coefficient.

For each analysed run i , the resulting values used as regression inputs are those listed in Table 5.3, from which the data points $(q_i, F_{L_T,i})$, $(q_i, F_{L_F,i})$, and $(q_i, F_{L_R,i})$, together with their associated uncertainties $(u_{q,i}, u_{F_{L_T,i}})$, $(u_{q,i}, u_{F_{L_F,i}})$, and $(u_{q,i}, u_{F_{L_R,i}})$. Denoting the representative dynamic pressure by q_i , and the representative total, front and rear downforce values by $F_{L_T,i}$, $F_{L_F,i}$ and $F_{L_R,i}$, respectively, the regression model is written as

$$F_{L,j,i} = \beta_j q_i, \quad j \in \{T, F, R\}, \quad (5.4)$$

with

$$\beta_T = C_L A, \quad \beta_F = (C_{L,F} A), \quad \beta_R = (C_{L,R} A). \quad (5.5)$$

The regression is constrained to pass through the origin, consistently with Equation (3.13), so that the aerodynamic load vanishes when $q = 0$.

Since both the representative dynamic pressure and the reconstructed downforce are affected by experimental uncertainty, the coefficient identification is performed through weighted Orthogonal Distance Regression (ODR). Unlike ordinary least squares, which assumes that the independent variable is known exactly and minimizes only the vertical deviations in the dependent variable, ODR treats both variables as subject to measurement error. The fit is therefore obtained by minimizing the weighted sum of the squared orthogonal distances between the experimental points and the fitted model, so that uncertainties in both coordinates are explicitly accounted for. This formulation is particularly appropriate in the present case, since neither the representative dynamic pressure nor the reconstructed downforce can be regarded as error-free, and their respective uncertainty levels should be reflected in the regression procedure [60, 61].

For each dataset, the fitted slope is obtained by minimizing

$$J(\beta_j) = \sum_{i=1}^{N_r} \frac{(F_{L,j,i} - \beta_j q_i)^2}{u_{F_{L,j,i}}^2 + \beta_j^2 u_{q,i}^2}, \quad (5.6)$$

where N_r is the number of runs used in the regression. This procedure is applied independently to the total, front and rear datasets, yielding $\hat{\beta}_T$, $\hat{\beta}_F$ and $\hat{\beta}_R$ [60, 61].

The uncertainty of each fitted slope (u_{β_j}) was estimated from the local curvature of the objective function at the optimum, consistently with the asymptotic covariance formulation adopted in weighted orthogonal distance regression. Under this interpretation, the uncertainty associated with the identified parameter is related to the inverse curvature of the objective function in the vicinity of the minimum, while the overall scale of the estimate is set by the residual variance of the fit [60, 61]. For the present single-parameter regression problem, this yields

$$u_{\beta_j} = \sqrt{\chi_{\nu,j,\text{red}}^2 \frac{2}{\left. \frac{\partial^2 J}{\partial \beta_j^2} \right|_{\beta_j = \hat{\beta}_j}}} \quad (5.7)$$

where

$$\chi_{\nu,j,\text{red}}^2 = \frac{J(\hat{\beta}_j)}{\nu}, \quad \nu = N_r - 1. \quad (5.8)$$

The final experimental estimates are therefore reported as

$$(C_L A) = \hat{\beta}_T \pm u_{\beta_T}, \quad (C_{L,F} A) = \hat{\beta}_F \pm u_{\beta_F}, \quad (C_{L,R} A) = \hat{\beta}_R \pm u_{\beta_R}. \quad (5.9)$$

For completeness, a coefficient of determination based on the vertical residuals is also reported as a graphical indicator of the agreement between the measured points and the fitted trend,

$$R_j^2 = 1 - \frac{\sum_{i=1}^{N_r} (F_{L,j,i} - \hat{\beta}_j q_i)^2}{\sum_{i=1}^{N_r} (F_{L,j,i} - \bar{F}_{L,j})^2}. \quad (5.10)$$

Figure 5.8 presents the culmination of the methodology described above. Using the representative CV quantities reported in Table 5.3, the total, front and rear reconstructed downforce values are plotted against the corresponding representative dynamic pressure, and the fitted zero-intercept weighted ODR lines are superimposed for each dataset. The resulting slopes provide the experimental estimates of $(C_L A)$, $(C_{L,F} A)$, and $(C_{L,R} A)$.

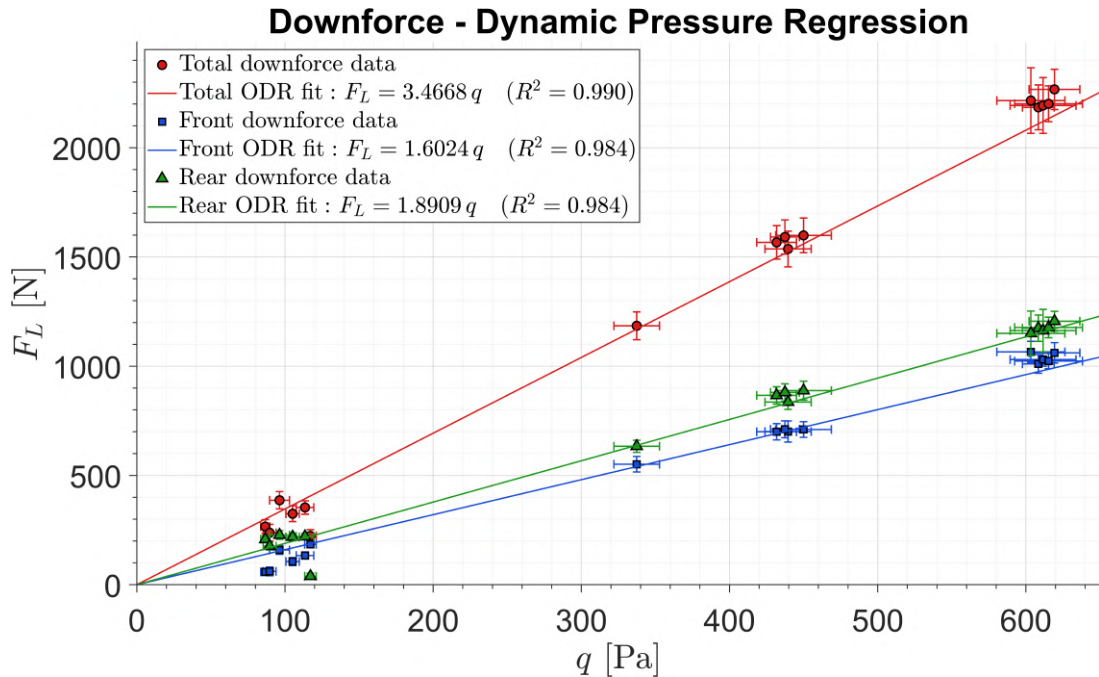


Figure 5.8: Experimental CV regressions used to identify $C_L A$, $(C_{L,F} A)$, and $(C_{L,R} A)$

The final experimental estimates obtained from the regressions are summarised in Table 5.4. Besides the total, front and rear lift-related coefficients, the corresponding aerodynamic balance is also reported, computed from Equation (3.15). These quantities constitute the final experimental aerodynamic results from the CV methodology.

Table 5.4: Final experimental lift-related aerodynamic coefficients identified from the CV weighted orthogonal distance regressions, together with the corresponding aerodynamic balance.

Quantity	Experimental result
$C_L A$	$3.467 \pm 0.105 \text{ m}^2$
$(C_{L,F} A)$	$1.602 \pm 0.055 \text{ m}^2$
$(C_{L,R} A)$	$1.890 \pm 0.103 \text{ m}^2$
AB	$46.20 \pm 1.60 \%$

5.4.2 Estimation of $C_D A$ from Coastdown Data

The final step of the CD processing framework shown in Figure 5.5 corresponds to the polynomial regression and coefficient-extraction blocks. At this stage, the reconstructed resistive-force signal is combined with the corrected vehicle-speed signal in order to identify the drag-area coefficient from each CD run.

For each analysed run i , the regression dataset is formed by the retained sample pairs $(v_{i,k}, F_{\text{res},i,k})$, where $v_{i,k}$ is the corrected vehicle speed and $F_{\text{res},i,k}$ is the reconstructed resistive force at sample k , with $k = 1, \dots, N_i$. Following the formulation introduced in Section 3.2.2, the resistive force is modelled as a second-order function of speed,

$$F_{\text{res},i,k} = A_{2,i} v_{i,k}^2 + A_{1,i} v_{i,k} + A_{0,i}, \quad (5.11)$$

where the quadratic coefficient $A_{2,i}$ contains the aerodynamic drag contribution, while $A_{1,i}$ and $A_{0,i}$ represent the linear and constant rolling-resistance terms. Although the fit also provides estimates of f_1 and f_0 , the present subsection focuses on the identification of $C_D A$.

For each run, the polynomial coefficients are obtained through a standard least-squares regression of Equation (5.11). Defining

$$\mathbf{p}_i = [A_{2,i} \quad A_{1,i} \quad A_{0,i}]^T, \quad \mathbf{y}_i = \begin{bmatrix} F_{\text{res},i,1} \\ F_{\text{res},i,2} \\ \vdots \\ F_{\text{res},i,N_i} \end{bmatrix}, \quad \mathbf{X}_i = \begin{bmatrix} v_{i,1}^2 & v_{i,1} & 1 \\ v_{i,2}^2 & v_{i,2} & 1 \\ \vdots & \vdots & \vdots \\ v_{i,N_i}^2 & v_{i,N_i} & 1 \end{bmatrix}, \quad (5.12)$$

the fitted coefficient vector is

$$\hat{\mathbf{p}}_i = (\mathbf{X}_i^T \mathbf{X}_i)^{-1} \mathbf{X}_i^T \mathbf{y}_i. \quad (5.13)$$

following the usual least-squares solution for linear models in the parameters [62].

The corresponding coefficient uncertainty is obtained from the residual variance,

$$s_i^2 = \frac{1}{N_i - 3} \sum_{k=1}^{N_i} \left[F_{\text{res},i,k} - \left(\hat{A}_{2,i} v_{i,k}^2 + \hat{A}_{1,i} v_{i,k} + \hat{A}_{0,i} \right) \right]^2, \quad (5.14)$$

which gives

$$\text{Cov}(\hat{\mathbf{p}}_i) = s_i^2 (\mathbf{X}_i^T \mathbf{X}_i)^{-1}, \quad u_{A_{2,i}} = \sqrt{[\text{Cov}(\hat{\mathbf{p}}_i)]_{11}}. \quad (5.15)$$

as the standard covariance estimate for the fitted coefficients [62].

The run-wise drag-area coefficient is then obtained as

$$(C_{DA})_i = \frac{2\hat{A}_{2,i}}{\rho_i}, \quad (5.16)$$

where the air-density value ρ_i and corresponding uncertainty $u_{\rho,i}$ are taken from Table 4.4. The associated uncertainty in $(C_{DA})_i$ follows from first-order propagation of the uncertainties in $\hat{A}_{2,i}$ and ρ_i ,

$$u_{(C_{DA})_i} = \sqrt{\left(\frac{2}{\rho_i} u_{A_{2,i}}\right)^2 + \left(\frac{2\hat{A}_{2,i}}{\rho_i^2} u_{\rho,i}\right)^2}. \quad (5.17)$$

following the law of propagation of uncertainty [55].

Since the CD procedure yields one drag-area estimate per run, only runs satisfying certain acceptability criteria were retained for the final coefficient evaluation. In the present work, only runs whose fitted speed interval included 80 km h^{-1} were retained for the final drag-area evaluation, in line with CD implementation criteria suggested by SAEJ1263 norms [63]. Denoting the set of accepted runs by $\mathcal{A}$, with cardinality N_a , the final experimental drag-area estimate is taken as the arithmetic mean of the accepted run-wise values,

$$\overline{C_{DA}} = \frac{1}{N_a} \sum_{i \in \mathcal{A}} (C_{DA})_i. \quad (5.18)$$

The uncertainty associated with the final averaged estimate is taken as the combination of two statistically distinct contributions: the uncertainty of the mean associated with the repeatability of the accepted run-wise estimates, quantified by $s_{C_{DA}}/\sqrt{N_a}$, and the propagated uncertainty associated with the individual run regressions, combined in quadrature over the accepted set. Under the assumption that the accepted run estimates are independent and that the run-to-run repeatability and within-run regression uncertainties may be treated as separate contributors, the variance of the final mean is therefore written as the sum of these two terms: [64].

$$u_{\overline{C_{DA}}} = \sqrt{\frac{s_{C_{DA}}^2}{N_a} + \frac{1}{N_a^2} \sum_{i \in \mathcal{A}} u_{(C_{DA})_i}^2}, \quad s_{C_{DA}} = \sqrt{\frac{1}{N_a} \sum_{i \in \mathcal{A}} [(C_{DA})_i - \overline{C_{DA}}]^2}, \quad (5.19)$$

Figure 5.9 illustrates the culmination of the CD methodology for one representative accepted run. The reconstructed resistive-force samples are plotted against the corrected vehicle speed, and the fitted quadratic regression is superimposed. From this fit, the corresponding run-wise value of C_{DA} is obtained directly from the CD data. The equivalent regressions for the remaining accepted runs are provided in Appendix C.3.

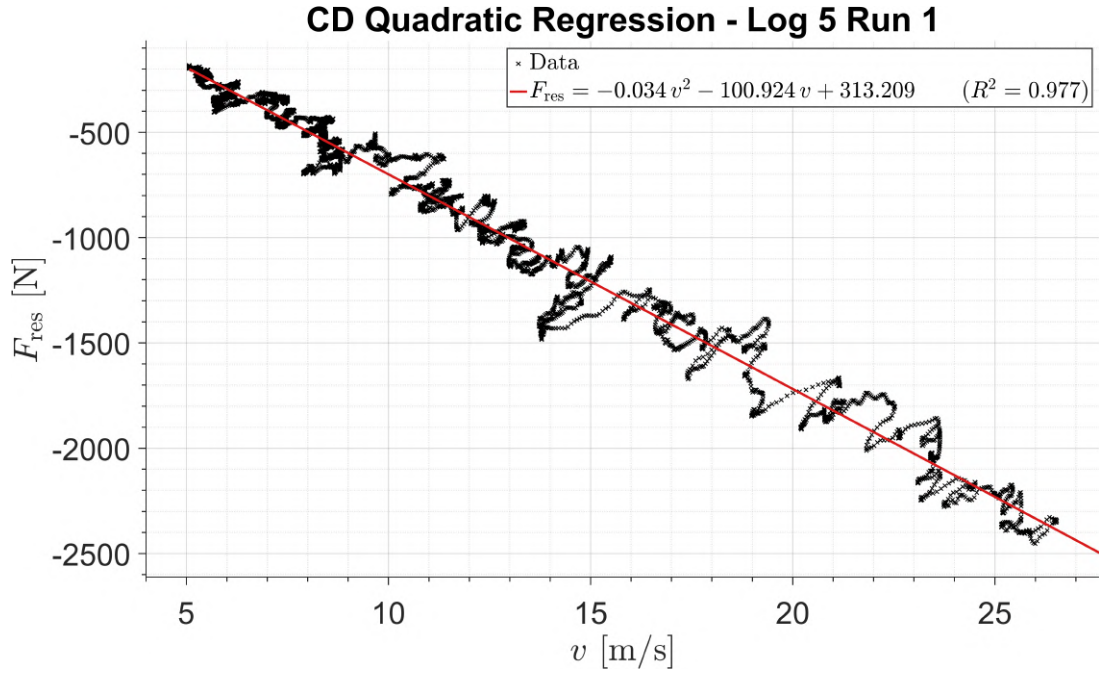


Figure 5.9: Representative CD regression for one accepted run, showing the reconstructed resistive-force data and the fitted quadratic model used to identify the corresponding run-wise value of $C_D A$

The final experimental estimate obtained from the accepted CD runs is summarised in Table 5.5. This quantity constitutes the final drag-related aerodynamic result identified from the CD methodology.

Table 5.5: Final experimental drag-area coefficient identified from the accepted CD regressions

Quantity	Experimental result
$C_D A$	$1.661 \pm 0.395 \text{ m}^2$

5.4.3 Estimation of Aerodynamic Efficiency

Following the identification of the lift-related coefficient $C_L A$ from the CV methodology and of the drag-area coefficient $C_D A$ from the CD methodology, the aerodynamic efficiency can be evaluated as a derived performance parameter. Recalling Equation (1.3), aerodynamic efficiency (η_{aero}) is defined as the ratio between downforce and drag coefficients.

The associated standard uncertainty is obtained by first-order propagation of the uncertainties in $C_L A$ and $C_D A$, assuming these quantities to be independent [55]. The final experimental aerodynamic efficiency is summarised in Table 5.6. This quantity provides a compact measure of the trade-off between the downforce generated by the aerodynamic package and the associated drag penalty.

Table 5.6: Final experimental aerodynamic efficiency obtained from the identified values of $C_L A$ and $C_D A$, with uncertainty propagated from the corresponding standard uncertainties.

Quantity	Experimental result
η_{aero}	2.087 ± 0.500

Chapter 6

Computational Fluid Dynamics Simulations and Comparison with Experimental Results

The purpose of the present chapter is not to redevelop or re-verify the numerical model through a new assessment of geometry preparation, domain sensitivity, wall modeling alternatives, or mesh convergence. Instead, the objective is to apply an existing CFD framework to the operating conditions considered in this study and to compare the resulting numerical aerodynamic loads with the experimental estimates obtained from the on-track testing campaign. Accordingly, the fixed characteristics of the adopted numerical methodology are first summarized, followed by the definition of the case-dependent simulation matrix and the comparison between numerical and experimental results.

6.1 Reference Numerical Setup

The CFD simulations performed in the present work adopt the numerical framework previously established by Santos [8] for the aerodynamic assessment of the same Formula Student prototype under straight-line conditions, using *Siemens Star-CCM+*. The adopted framework also includes the CFD-ready vehicle geometry prepared in the reference work from the original CAD model in *Siemens NX*, together with the associated simplifications introduced for numerical analysis. An overview of the simplified FST14 CAD model used in the simulations is presented in Figure 6.1.

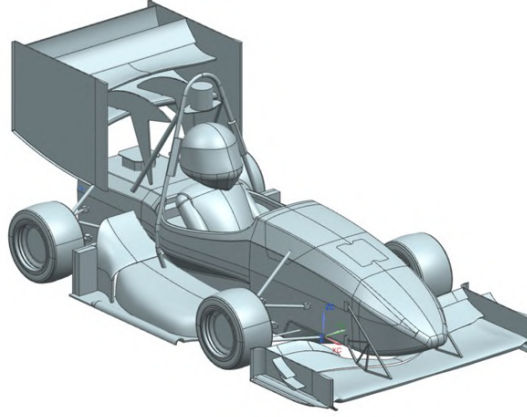


Figure 6.1: Overview of the simplified CFD-ready CAD model of the FST14 vehicle [8]

The main geometric, modeling, boundary-condition, and mesh-related characteristics inherited from the reference work are compiled in Table 6.1.

Table 6.1: Reference CFD setup adopted from Santos [8] and used throughout the present simulation campaign

Parameter group	Adopted value / model
Geometry details	Full aerodynamic package retained; minor components with negligible external aerodynamic relevance removed; locally simplified wheel assemblies; driver model included; tire contact patches represented through local downward extrusion; wing trailing edges thickened for improved mesh quality
Flow model	Steady, three-dimensional, incompressible flow; no transition model; RANS $k-\omega$ SST turbulence model; all y^+ wall treatment
Solver settings	Coupled flow solver; implicit tree wall-distance evaluation; Venkatakrishnan limiter; cell quality remediation enabled
Computational domain	Straight-line external aerodynamic half-domain; domain dimensions of $50 \times 7 \times 10$ m; symmetry plane at vehicle centerline
Boundary conditions	Velocity inlet; pressure outlet with $p = 0$ Pa relative; moving ground with $U_{\text{ground}} = U_{\text{inlet}}$; no-slip vehicle walls with fixed wall velocity $U = 0$ m/s; rotating wheels; far-field boundaries defined according to the reference setup
Turbulence boundary values	Turbulence intensity $TI = 0.01$; turbulence viscosity ratio $\mu_t/\mu = 10$
Mesh strategy	Surface wrapper, polyhedral volume mesh, and prism layers; volumetric refinement boxes around the full car and aerodynamic devices; adopted mesh level $h_i = 1.5$; $N_f = 5.79 \times 10^6$ surface faces

Throughout the present work, the numerical setup summarized in Table 6.1 is kept fixed across all simulations, with only the operating conditions associated with each case being updated, as described in the following section.

6.2 Selection and Implementation of Numerical Cases

This section defines the CFD cases considered in the present study and describes how the corresponding operating conditions are imposed in the numerical model. The objective of the simulation campaign is to generate a numerical dataset under conditions that are directly comparable with the on-track results, so that the discrepancy between CFD predictions and experimentally estimated aerodynamic quantities can be assessed consistently. To achieve this, the selected numerical cases must correspond to operating conditions that are both well defined in the experimental dataset and readily reproducible within the adopted steady CFD framework.

6.2.1 Basis for Case Selection

The numerical simulations are based on the 16 representative points retained from the constant-velocity analysis. This choice was made because, within each retained constant-velocity interval, the quantities required to define the numerical operating condition may be regarded as approximately constant. In particular, the representative values of airspeed, front ride height and rear ride height are already available for each run from the processed constant-velocity dataset, as summarized in Table 5.3. Air density is also assigned on a run-by-run basis from the moist-air calculations presented in Table 4.4. As such, each constant-velocity point can be represented numerically by a single set of geometric and flow inputs, which is fully compatible with the steady CFD framework adopted in the present work.

By contrast, the coastdown methodology is associated with a continuously evolving operating condition, most notably due to the progressive variation in vehicle speed throughout each run. Its direct numerical reproduction would therefore be less straightforward, requiring either a transient CFD formulation or the discretization of each coastdown run into several operating points. For this reason, the constant velocity dataset provides a more suitable basis for the present CFD-to-experiment comparison, while also remaining consistent with the quasi-steady assumptions underlying the experimental downforce estimation.

6.2.2 Implementation in the Parametric Numerical Model

The geometrical implementation of the simulation cases is based on the CFD-ready model of the FST14 vehicle adopted by Santos [8], whose geometry is parameterized according to the framework developed by Carreira [7]. In this parametric formulation, the vehicle attitude can be adjusted through front ride height, rear ride height, roll, steering and yaw, allowing efficient geometric reconfiguration for CFD analyses. In the present work, only the front and rear ride heights are varied from case to case, since these are the parameters required to reproduce the operating conditions associated with the selected constant-velocity points. The remaining parametric inputs are kept fixed at their straight-line reference values, with roll, steering and yaw set to zero throughout the full simulation campaign.

For each run, the front and rear ride heights imposed geometrically in the CFD model are taken from the representative values reported in Table 5.3. The inlet velocity is prescribed from the corresponding

representative airspeed reported in the same table.

In addition to the geometrical inputs and inlet velocity, the air density and dynamic viscosity must also be prescribed as fluid properties in the CFD solver, since they directly define the flow medium associated with each simulation case. Air density is assigned from the moist-air calculations summarized in Table 4.4. In addition, the dynamic viscosity of air is evaluated for each run from the interpolated ambient temperature reported in Table 4.3, using Sutherland's law [65],

$$\mu_i = \mu_{\text{ref}} \left(\frac{T_i}{T_{\text{ref}}} \right)^{3/2} \frac{T_{\text{ref}} + S}{T_i + S}, \quad (6.1)$$

where T_i is the absolute ambient temperature associated with run i , $\mu_{\text{ref}} = 1.716 \times 10^{-5} \text{ Pa s}$, $T_{\text{ref}} = 273.15 \text{ K}$, and $S = 111 \text{ K}$.

The corresponding Reynolds number was computed using the vehicle wheelbase as reference length,

$$Re_i = \frac{\rho_i U_i L_{\text{ref}}}{\mu_i}, \quad (6.2)$$

with $L_{\text{ref}} = 1.54 \text{ m}$.

For clarity, the complete set of operating conditions, flow properties, and corresponding Reynolds numbers used to define the 16 CFD cases is summarized in Table 6.2.

Table 6.2: Operating conditions and flow properties used to define the CFD simulations

Run	RH_F	RH_R	U	ρ	μ	Re
	[mm]	[mm]	[m s ⁻¹]	[kg m ⁻³]	[$\times 10^{-5} \text{ Pa s}$]	[$\times 10^6$]
1	46.84	50.52	14.138	1.1725	1.8444	1.384
2	48.32	48.49	12.160	1.1726	1.8440	1.191
3	47.44	48.34	13.912	1.1729	1.8440	1.363
4	48.29	48.86	12.362	1.1731	1.8440	1.211
5	47.14	48.25	12.813	1.1733	1.8435	1.256
6	47.76	48.36	13.387	1.1735	1.8435	1.312
7	42.55	43.42	23.976	1.1737	1.8435	2.351
8	37.32	36.96	32.195	1.1739	1.8430	3.158
9	37.07	37.12	32.271	1.1745	1.8425	3.168
10	36.69	37.24	32.047	1.1751	1.8416	3.149
11	37.14	36.95	32.351	1.1759	1.8407	3.183
12	36.74	36.58	32.452	1.1761	1.8407	3.193
13	40.82	41.03	27.327	1.1772	1.8392	2.694
14	40.87	40.61	27.081	1.1774	1.8388	2.670
15	40.71	40.39	27.637	1.1782	1.8378	2.729
16	40.73	40.45	27.246	1.1785	1.8378	2.691

6.3 Post-Processing of Numerical Results

Once the 16 CFD simulations were completed, the resulting aerodynamic loads were post-processed to obtain a numerical data set directly comparable with the quantities previously estimated from the constant-velocity experimental analysis. All cases correspond to straight-line symmetric simulations, with no imposed roll, yaw, or steering and differing only in front and rear static ride height. Accordingly, the post-processing adopted here follows directly the reporting logic implemented in the FST Lisboa STAR-CCM+ macro, in which each case is solved as a symmetric half-car model and the reported force and moment are subsequently interpreted on a full-vehicle basis.

For each converged case, two primary quantities were retained from the CFD solution: the total aerodynamic downforce ($F_{z,tot}^{CFD}$) and the aerodynamic pitching moment about the model reference origin ($M_{y,O}^{CFD}$). The downforce was obtained by integrating the pressure and wall-shear stress contributions over the selected vehicle surfaces and projecting the resulting aerodynamic force onto the negative vertical direction, so that a positive value corresponds to downward force. The pitching moment was obtained from the corresponding moment of the aerodynamic force distribution about the vehicle pitch axis. In the post-processing chain, the reported values correspond to the mean of the last ten monitor samples.

In the present straight-line formulation, the reference origin used for the pitching-moment report is taken as the front-axle reference for the equivalent axle-load decomposition, which is consistent with the aerodynamic-balance expression implemented in the numerical reporting macro. Under this convention, the total aerodynamic load is represented by equivalent front and rear axle downforce contributions, $F_{z,F}^{CFD}$ and $F_{z,R}^{CFD}$, satisfying

$$F_{z,T}^{CFD} = F_{z,F}^{CFD} + F_{z,R}^{CFD}. \quad (6.3)$$

The corresponding moment equilibrium about the front axle is

$$\sum M_{y,O} = 0 \Rightarrow M_{y,O}^{CFD} + F_{z,R}^{CFD} L = 0, \quad (6.4)$$

where $L = 1.54m$, corresponding to the wheelbase, since it is the longitudinal separation between the front and rear axle application lines of the equivalent loads. Hence,

$$F_{z,R}^{CFD} = -\frac{M_{y,O}^{CFD}}{L}, F_{z,F}^{CFD} = F_{z,T}^{CFD} + \frac{M_{y,O}^{CFD}}{L}. \quad (6.5)$$

This procedure yields, for each ride-height configuration, a set of total, front and rear aerodynamic downforce values directly comparable with those reconstructed from the constant-velocity experimental analysis. Since the main purpose of the numerical results is their direct comparison with the experimental estimates, the final CFD dataset is presented later in a combined table that includes both numerical and experimental quantities for each configuration.

6.4 Validation Against Experimental Results

This section presents the validation of the CFD results against the aerodynamic quantities previously estimated from the constant-velocity experimental analysis. The comparison is performed first at the level of the individual operating points used in the simulation campaign, through a direct point-by-point assessment of the numerical and experimental downforce estimates. Subsequently, the CFD dataset is used to formulate numerical force–dynamic-pressure regressions for the total, front, and rear aerodynamic contributions, which are then compared with the corresponding experimental regressions. This procedure allows the agreement between both approaches to be assessed both locally, for each simulated condition, and globally, in terms of the overall aerodynamic trends.

6.4.1 Point-by-Point Comparison

Table 6.3 compares the CFD-predicted and experimentally reconstructed aerodynamic downforces for the 16 operating points retained from the validation dataset. Rather than viewing each row as an isolated force comparison, the table is more meaningfully interpreted as an indication of how well the numerical model reproduces the aerodynamic response of the car across the tested ride-height range.

This point is particularly relevant for a high-downforce race car, for which ride height is itself one of the dominant aerodynamic parameters. Both the overall downforce level and its front–rear distribution are strongly affected by the ground-effect regime, so that relatively small variations in vertical position and attitude can produce appreciable changes in aerodynamic load and balance [66, 67]. Since aerodynamic performance in this regime is also strongly coupled to suspension state and to the effective operating condition of the vehicle, the discrepancies reported in Table 6.3 should not be interpreted only as local force-prediction errors, but also as indicators of how closely the CFD model reproduces the ride-height sensitivity observed experimentally [35, 68].

The operating points listed in Table 6.2, where the front and rear ride heights and the corresponding airspeeds used in the CFD campaign are summarized, help place this comparison in context. Runs 1–6 correspond to the highest ride-height and lowest-speed conditions of the dataset, while runs 7–12, by contrast, correspond to the lowest ride-height and highest-speed conditions. On the other hand, runs 13–16 lie in an intermediate region, with aerodynamic load in this regime is strongly dependent on both dynamic pressure and vertical position.

The CFD front and rear downforces were obtained from the total downforce and pitching moment about the front-axle reference using the post-processing relations introduced previously. To account for the uncertainty associated with the experimental force reconstruction, the relative discrepancy in Table 6.3 is reported as an interval rather than as a single value. In this way, the table shows not only the nominal force mismatch, but also how that mismatch varies within the experimental uncertainty window.

Table 6.3: Comparison between CFD and experimental downforce quantities retained for the regression analysis. Experimental values are reported as central estimate $\pm$ uncertainty. The relative discrepancy is reported as an interval

Run	Total downforce			Front downforce			Rear downforce		
	$F_{z,T}^{\text{CFD}}$	F_{L_T}	Δ	$F_{z,F}^{\text{CFD}}$	F_{L_F}	Δ	$F_{z,R}^{\text{CFD}}$	F_{L_R}	Δ
	[N]	[N]	[%]	[N]	[N]	[%]	[N]	[N]	[%]
1	580.7	223.3 $\pm$ 28.7	130.4–198.4	286.9	184.6 $\pm$ 15.1	43.7–69.3	293.8	38.7 $\pm$ 13.7	460.6–1075.1
2	429.5	266.0 $\pm$ 31.8	44.2–83.4	207.1	58.4 $\pm$ 16.3	177.2–391.9	222.4	207.6 $\pm$ 15.5	–0.3–15.8
3	561.0	353.7 $\pm$ 30.4	46.1–73.5	272.8	133.5 $\pm$ 16.4	82.0–132.9	288.3	220.2 $\pm$ 14.1	23.0–39.9
4	443.6	237.8 $\pm$ 38.1	60.8–122.1	214.5	60.9 $\pm$ 20.0	165.1–424.3	229.2	176.8 $\pm$ 18.1	17.6–44.4
5	480.1	386.4 $\pm$ 39.5	12.7–38.4	233.7	159.2 $\pm$ 19.7	30.6–67.5	246.4	227.3 $\pm$ 19.8	–0.3–18.7
6	522.4	324.8 $\pm$ 36.2	44.7–81.0	251.8	106.2 $\pm$ 18.1	102.6–185.8	270.6	218.5 $\pm$ 18.0	14.4–34.9
7	1718.0	1184.9 $\pm$ 63.4	37.6–53.2	854.2	551.4 $\pm$ 35.8	45.5–65.7	863.9	633.5 $\pm$ 27.6	30.7–42.6
8	3171.3	2184.7 $\pm$ 102.5	38.7–52.3	1632.6	1010.6 $\pm$ 42.5	55.0–68.6	1538.7	1174.0 $\pm$ 60.1	24.7–38.1
9	3163.8	2193.3 $\pm$ 127.6	36.3–53.2	1622.6	1030.3 $\pm$ 30.4	53.0–62.3	1541.2	1163.0 $\pm$ 97.2	22.3–44.6
10	3129.6	2215.8 $\pm$ 150.1	32.3–51.5	1601.9	1065.4 $\pm$ 48.2	43.9–57.5	1527.6	1150.3 $\pm$ 101.9	22.0–45.7
11	3165.2	2201.0 $\pm$ 82.1	38.6–49.4	1622.7	1023.7 $\pm$ 34.9	53.3–64.1	1542.6	1177.3 $\pm$ 47.1	26.0–36.5
12	3207.5	2266.9 $\pm$ 92.1	36.0–47.5	1639.6	1061.1 $\pm$ 46.7	48.0–61.6	1567.9	1205.9 $\pm$ 45.4	25.3–35.1
13	2254.4	1536.7 $\pm$ 81.7	39.3–54.9	1135.4	701.0 $\pm$ 48.4	51.5–74.0	1119.0	835.8 $\pm$ 33.3	28.8–39.4
14	2233.4	1566.6 $\pm$ 76.8	35.9–49.9	1118.9	700.0 $\pm$ 37.1	51.8–68.8	1114.6	866.5 $\pm$ 39.7	23.0–34.8
15	2284.5	1598.8 $\pm$ 79.2	36.1–50.3	1153.1	710.3 $\pm$ 35.8	54.6–71.0	1131.4	888.5 $\pm$ 43.4	21.4–33.9
16	2217.5	1591.4 $\pm$ 78.2	32.8–46.5	1119.7	711.3 $\pm$ 38.8	49.3–66.5	1097.8	880.1 $\pm$ 39.4	19.4–30.6

The uncertainty-aware comparison in Table 6.3 confirms that the CFD model overpredicts the aerodynamic load throughout almost the entire dataset. All total-force and front-force discrepancy intervals remain strictly positive, as do all but two of the rear-force intervals. Only Runs 2 and 5 at the rear axle produce discrepancy bands that marginally cross zero, indicating that these two low-load rear-force cases are the only operating points for which the CFD prediction can be considered approximately consistent with the experimental estimate once uncertainty is taken into account.

The interval formulation also makes clear that the most extreme percentage differences are concentrated in the low-load cases, where the reconstructed experimental force is small and the denominator effect becomes dominant. This is particularly evident for Run 1 at the rear axle, for which the experimental rear downforce is only 38.7 ± 13.7 N. In this case, the corresponding discrepancy interval extends from about 461% to 1075%, not because the absolute force mismatch is exceptionally large in the context of the full dataset, but because the reference experimental force is itself very small. The uncertainty-based representation therefore helps distinguish between genuinely large absolute mismatches and inflated relative differences caused by low denominator values.

To summarize the full dataset with global descriptors, the Mean Percentage Error (MPE) and the

Root Mean Square Error (RMSE) were evaluated from the central experimental estimates only,

$$\text{MPE} = \frac{1}{N} \sum_{i=1}^N \frac{F_i^{\text{CFD}} - F_i^{\text{Exp}}}{F_i^{\text{Exp}}} \times 100, \text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (F_i^{\text{CFD}} - F_i^{\text{Exp}})^2}, \quad (6.6)$$

where $N = 16$ for the present dataset. The resulting values are reported directly in the legend of Figure 6.2.

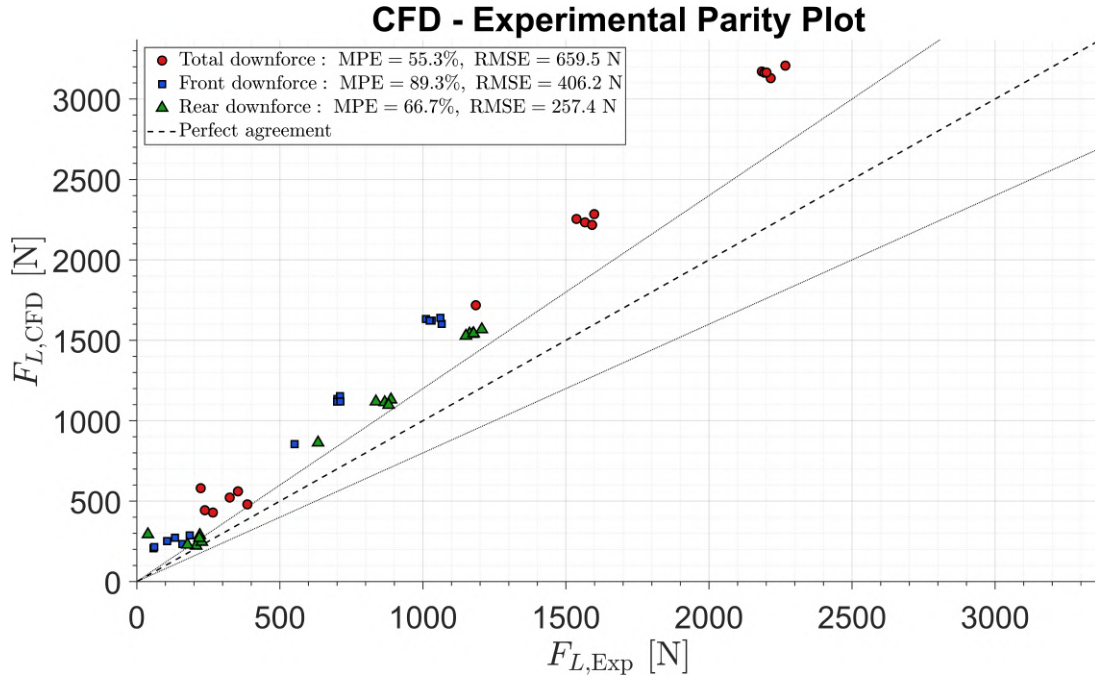


Figure 6.2: Parity plot comparing CFD and experimentally reconstructed total, front, and rear downforce values for the 16 validation operating points. The dashed line represents perfect agreement, while the dotted lines indicate $\pm 20\%$ deviation from parity

The total-force comparison yields $\text{MPE} = 55.3\%$ and $\text{RMSE} = 659.5 \text{ N}$, while the corresponding values are 89.3% and 406.2 N for the front axle and 66.7% and 257.4 N for the rear axle. Since all central discrepancies are positive, the MPE values can be interpreted directly as measures of systematic over-prediction [69]. In practical terms, the MPE quantifies the average relative bias of the CFD predictions with respect to the experimental estimates, showing that the numerical model overpredicts total downforce by about 55% on average, with an even larger relative bias at the front axle and a smaller, though still substantial, bias at the rear axle. The RMSE complements this interpretation by expressing the typical magnitude of the discrepancy in absolute force units. It therefore shows that the disagreement is not only large in relative terms, but also substantial in absolute terms, especially for total downforce. Considered together, these two metrics indicate that the observed mismatch is not primarily the result of a few isolated outliers, but rather of a persistent and systematic bias in the CFD predictions. Moreover, the fact that the front axle exhibits the largest MPE, while the total-force RMSE remains the largest in absolute terms, further supports the conclusion that the CFD model is affected simultaneously by a global over-prediction of aerodynamic load and by an overestimation of the front aerodynamic contribution relative to the rear.

Figure 6.2 also ties the point-by-point analysis together in a compact way. All data points lie above the parity line, immediately confirming that the CFD model systematically overpredicts aerodynamic load for the total, front, and rear datasets. The rear-force points remain closest to the parity line, whereas the front-force points are consistently farther away, which is fully consistent with the discrepancy intervals reported in Table 6.3. The parity plot therefore reinforces the conclusion that the disagreement is not only a global force-level offset, but also a bias in aerodynamic balance, with the CFD model tending to predict a more front-loaded load distribution than that reconstructed experimentally.

The operating-point distribution reported in Table 6.2 also helps explain how these discrepancies are organized.

For the lowest ride-height and highest-speed cases, namely Runs 7–12, the discrepancy intervals remain comparatively compact despite the stronger ground-effect regime: the total-force intervals remain bounded within about 32–53%, the front-force intervals within about 44–69%, and the rear-force intervals within about 22–46%. This is an important result, because these runs correspond to the part of the ride-height envelope where the aerodynamic response should be most sensitive. If the CFD model were failing to reproduce ride-height sensitivity altogether, a more irregular or rapidly diverging pattern would be expected in this region. Instead, the errors remain relatively coherent, which is more consistent with a systematic offset in force level and balance than with a complete loss of ride-height sensitivity.

The intermediate ride-height cases, Runs 13–16, show a very similar behavior. Their total-force discrepancy intervals remain between about 33 and 55%, while the front-force and rear-force intervals remain within roughly 49–74% and 19–39%, respectively. This again suggests that, once the aerodynamic loading becomes appreciable, the CFD model reproduces the qualitative trend of increasing downforce with decreasing ride height, but does so at a consistently higher force level than that inferred experimentally.

By contrast, the highest ride-height and lowest-speed conditions, namely Runs 1–6, exhibit the widest discrepancy intervals. In this region the aerodynamic signal is weakest, so moderate absolute mismatches are amplified when expressed as relative differences. This is particularly visible for the front axle in Runs 2 and 4, and for the rear axle in Run 1. The uncertainty-aware intervals are useful here because they show that the apparent severity of the percentage mismatch is partly a consequence of the low aerodynamic load level itself, rather than evidence of a qualitatively different aerodynamic trend.

The Reynolds-number distribution may also provide additional context for this behaviour. The lowest-speed cases correspond to the lowest Reynolds numbers of the dataset, while the highest-speed cases approach $Re \approx 3.2 \times 10^6$. This range is relevant because previous studies on inverted wings in ground effect have shown that aerodynamic performance can depend on both Reynolds number and ground clearance, with the laminar separation bubble and the onset of separation also being sensitive to these parameters [70]. Since the adopted numerical setup assumes a fully turbulent RANS formulation without transition modelling, possible differences between the numerical and real boundary-layer states may therefore vary across the tested operating range.

At the lower Reynolds-number conditions, viscous effects, transition, and local separation may have a stronger influence on the effective aerodynamic performance of individual devices. If the real on-track

flow contains transitional regions, laminar separation bubbles, or less energetic boundary layers than those represented by the fully turbulent numerical model, the CFD solution may tend to maintain more attached flow and consequently predict higher aerodynamic loads. This provides a plausible contribution to the observed overprediction, particularly in cases where the aerodynamic signal is weaker and the force reconstruction is more sensitive to uncertainty. The importance of this mechanism is also supported by studies showing that forcing or modelling boundary-layer transition can significantly alter the aerodynamic forces of wings operating in ground effect [71].

Nevertheless, this interpretation should be regarded as a possible contributing factor rather than a direct conclusion. In the present dataset, Reynolds number varies simultaneously with inlet velocity, dynamic pressure, ride height, and ground-effect intensity. Therefore, its influence cannot be isolated from the other operating parameters without a dedicated Reynolds-number sensitivity study.

Overall, the combined evidence from Table 6.3 and Figure 6.2 indicates that the CFD model captures the qualitative increase in aerodynamic load across the tested ride-height range, but with a clear positive bias in downforce level and a tendency to predict a more forward aerodynamic balance than that inferred from the experimental data. In the context of a ground-effect-dominated race car, this suggests that the main limitation of the present numerical model is not an inability to reproduce the general aerodynamic trends with ride height, but rather a systematic overprediction of both the magnitude and the longitudinal distribution of the aerodynamic loads.

6.4.2 Numerical Regression Formulation and Comparison with Experimental Regression

Beyond the direct point-by-point comparison presented previously, it is also informative to compare the CFD dataset and the experimental dataset at the regression level, using the same force–dynamic-pressure framework adopted in the CV analysis. This provides a more global view of the agreement between both approaches, since it allows the comparison to be made not only at the level of the individual operating points, but also in terms of the overall aerodynamic trend represented by the force response to dynamic pressure.

This comparison is particularly relevant because the regression slope condenses the behaviour of the dataset into an effective aerodynamic coefficient for the tested configuration and operating range. In this sense, the regression-based comparison complements the local point-by-point analysis. While the latter indicates how well each simulated operating point reproduces the corresponding experimental estimate, the former reveals whether the CFD model captures the overall force sensitivity to dynamic pressure in a consistent manner.

With the CFD results expressed in terms of total, front, and rear aerodynamic downforce, a numerical regression can therefore be formulated on the same basis adopted for the experimental treatment. For each run i , the numerical forces $F_{z,T,i}^{\text{CFD}}$, $F_{z,F,i}^{\text{CFD}}$, and $F_{z,R,i}^{\text{CFD}}$ are taken from Table 6.3, while the corresponding representative dynamic pressure q_i is taken from Table 5.3. Although the latter originates from the experimental processing, it also defines the operating condition imposed in the corresponding CFD

case, and is therefore the appropriate normalization variable for the numerical regression.

For each aerodynamic contribution $j \in \{T, F, R\}$, the numerical force is related to dynamic pressure through

$$F_{z,j}^{\text{CFD}} = (C_L A)_j^{\text{CFD}} q. \quad (6.7)$$

Accordingly, the CFD estimates of $(C_L A)_T^{\text{CFD}}$, $(C_L A)_F^{\text{CFD}}$, and $(C_L A)_R^{\text{CFD}}$ are obtained as the slopes of linear regressions of aerodynamic force against dynamic pressure, constrained to pass through the origin. For each dataset, the fitted slope is identified through ordinary least squares.

This formulation is directly comparable with the experimental treatment, for which the same force–dynamic-pressure relation was adopted, although the experimental slopes were identified through weighted ODR to account for measurement uncertainty. By contrast, the CFD outputs are deterministic numerical results evaluated at prescribed operating conditions, so an ordinary least-squares fit is sufficient for the numerical dataset. The resulting total, front, and rear numerical regressions can therefore be compared directly against the corresponding experimental regressions.

Figure 6.3 presents this comparison by superimposing the experimental and numerical regressions for the total, front, and rear aerodynamic force components as functions of dynamic pressure.

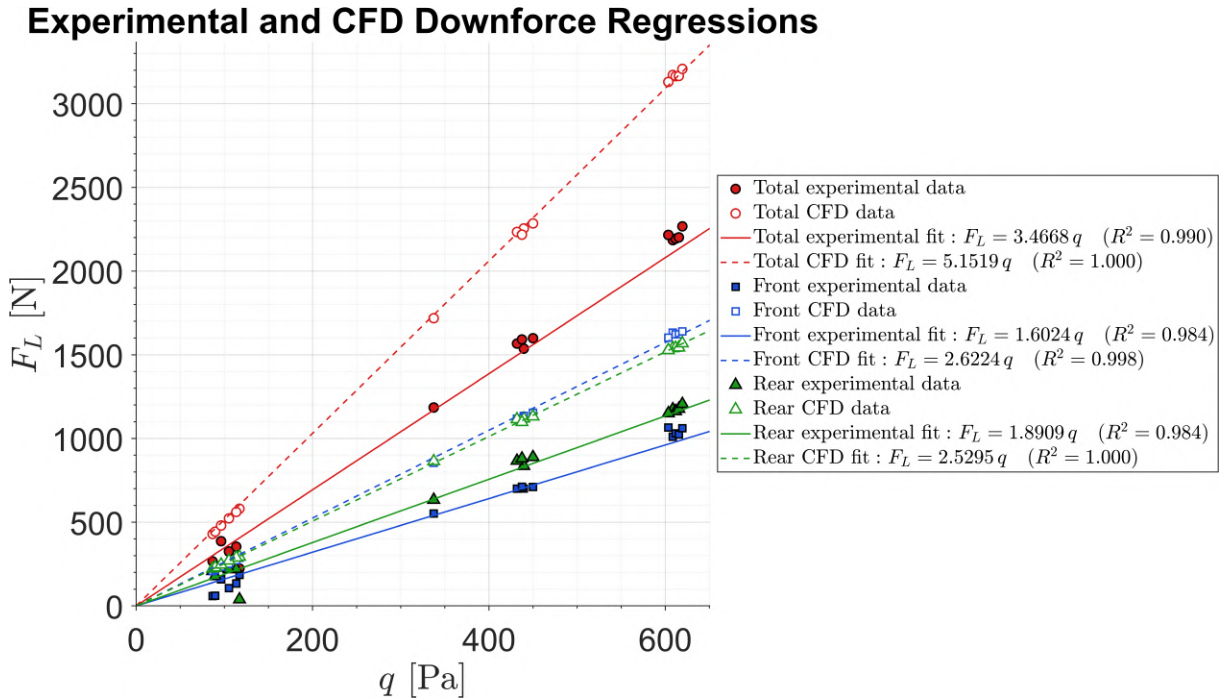


Figure 6.3: Comparison between the experimental and CFD regressions of total, front, and rear downforce as functions of dynamic pressure

The corresponding fitted slopes, which represent the experimental and numerical estimates of $(C_L A)$, $(C_{L,F} A)$, and $(C_{L,R} A)$, are summarized in Table 6.4, together with the associated regression-based aerobalance, defined as the front aerodynamic load fraction. The table also reports the absolute and relative differences between the experimental and numerical results, so that the comparison can be made not only in terms of total, front, and rear aerodynamic sensitivity to dynamic pressure, but also in terms of the predicted longitudinal distribution of downforce. These differences should be interpreted in light of

the numerical error of the adopted CFD framework, for which Santos estimated approximately 4.29% in C_L from the mesh convergence study [8].

Table 6.4: Comparison between the experimental and CFD estimates of the lift-related aerodynamic coefficients obtained from the force–dynamic-pressure regressions

Quantity	Experimental	CFD	Δ	Δ [%]
$(C_L A)$	3.4668 m ²	5.1519 m ²	1.6851 m ²	32.7
$(C_{L,F} A)$	1.6024 m ²	2.6224 m ²	1.0200 m ²	38.9
$(C_{L,R} A)$	1.8909 m ²	2.5295 m ²	0.6386 m ²	25.2
AB	46.2 %	50.9 %	4.7 %	9.2

The comparison shows that the CFD model reproduces the same qualitative linear dependence of aerodynamic force on dynamic pressure as the experimental dataset, but with consistently steeper slopes for all three force components. This indicates that the numerical model captures the overall trend of increasing downforce with increasing dynamic pressure, yet overestimates the magnitude of that sensitivity over the tested operating range. The fact that the numerical and experimental regressions remain approximately parallel in Figure 6.3, especially for the axle-wise components, suggests that the disagreement is not associated with a change in the basic aerodynamic trend, but rather with a systematic upward shift in the predicted force response.

The total-force regression provides the most compact measure of this behaviour. From Table 6.4, the CFD estimate of $(C_L A)$ exceeds the experimental regression slope by 1.6851 m², which corresponds to a relative difference of 32.7% with respect to the CFD value. This difference is substantially larger than the 4.29% numerical error estimated by Santos, suggesting that the discrepancy cannot be attributed only to mesh-related numerical uncertainty. Therefore, when the dataset is reduced to a single global descriptor, the numerical model still predicts a substantially stronger downforce response to dynamic pressure than that inferred from the experimental data.

The axle-wise regressions refine this interpretation. The front-force regression exhibits the largest relative discrepancy, with $(C_{L,F} A)^{\text{CFD}}$ exceeding the experimental estimate by 1.0200 m², or 38.9%, whereas the rear-force regression shows a smaller, though still substantial, difference of 0.6386 m², corresponding to 25.2%. This shows that the CFD model not only overpredicts the overall aerodynamic load, but also overestimates the front contribution more strongly than the rear one. The same tendency was already suggested by the parity plot and by the point-by-point comparison, but the regression slopes show that it is embedded in the global force–dynamic-pressure response of the numerical dataset rather than being limited to specific runs.

This conclusion is further reinforced by the aerobalance comparison. Defining aerobalance as the front aerodynamic load fraction, the experimental regression yields 46.2%, whereas the CFD regression yields 50.9%, corresponding to a difference of 4.7 percentage points, or 9.2% relative to the CFD value. The numerical model therefore predicts not only a higher total aerodynamic load, but also a more front-biased load distribution. In the context of a Formula Student vehicle, such a shift in aerodynamic balance

is significant, since relatively small changes in front/rear load partition can alter the vehicle response appreciably. The regression-based aerobalance comparison therefore confirms, in a compact way, that the main deficiency of the numerical model is not limited to force magnitude alone, but also extends to the longitudinal distribution of downforce.

From a physical point of view, these results suggest that the main limitation of the numerical model lies less in reproducing the existence of the aerodynamic trend itself, and more in reproducing its magnitude and longitudinal partition. Since the aerodynamic response of a Formula Student car is strongly ride-height dependent, this mismatch must be interpreted in light of the fact that the CFD cases and the experimental runs correspond to the same nominal operating conditions, but not necessarily to exactly the same effective aerodynamic state. Small differences in effective front and rear ride height, tyre deflection, suspension state, or local flow structures can alter the front/rear force balance appreciably, even if the nominal straight-line condition appears equivalent. In that sense, the regression comparison should not be interpreted as a purely abstract fit comparison, but as an integrated measure of how well the CFD model reproduces the experimentally observed aerodynamic behaviour across the tested straight-line operating envelope.

Another important aspect visible in Figure 6.3 is that the CFD data remain very tightly aligned, yielding regression coefficients with R^2 values essentially equal to unity, whereas the experimental datasets exhibit a slightly larger but still small scatter. This is expected, since the CFD outputs are deterministic evaluations at prescribed operating points, while the experimental forces are reconstructed quantities affected by measurement noise, parameter uncertainty, and unavoidable run-to-run variability. The high linearity of both datasets therefore supports the appropriateness of the force–dynamic-pressure framework itself, while the slope offset quantifies the residual disagreement between numerical prediction and experimental observation.

Overall, the numerical regressions show that the CFD model reproduces the correct qualitative force trend with dynamic pressure, but with systematically higher total, front, and rear aerodynamic sensitivities than those inferred experimentally, with the total-load discrepancy exceeding the typical lift-related numerical error reported for the adopted CFD framework. This behaviour is not unexpected for the adopted statistically steady RANS setup, particularly since no transition model was included. Under these assumptions, the numerical model may represent the boundary-layer state and separated-flow behaviour in a more idealised manner than occurs on track, contributing to higher predicted aerodynamic loads. The total-force regression remains the closest in relative terms, whereas the front-force regression shows the largest deviation, and the aerobalance comparison confirms that the numerical model predicts a more front-loaded aerodynamic state than that observed experimentally. Accordingly, the regression comparison reinforces the conclusion drawn from the point-by-point analysis: over the tested operating range, the CFD model is affected by a systematic overprediction of aerodynamic load, combined with a tendency to overestimate the front share of that load.

Chapter 7

Conclusions

7.1 Achievements

The main objective of the present work was to validate the aerodynamic performance of the FST14 prototype through on-track testing and to correlate the resulting experimental estimates with CFD predictions obtained for the same operating conditions. A secondary objective was to provide FST Lisboa with a structured and reproducible methodology for straight-line aerodynamic validation, covering vehicle preparation, instrumentation, calibration, test execution, data processing, and numerical comparison. In this respect, the thesis fulfilled both a validation objective and a methodological one, by establishing a complete workflow that can be reused and refined in future development cycles.

From the experimental point of view, the adopted methodology proved capable of producing coherent aerodynamic estimates from full-scale on-track measurements. The constant-velocity analysis yielded a total lift-related aerodynamic coefficient of $C_{LA} = 3.467 \pm 0.105 \text{ m}^2$, together with axle-wise values of $(C_{L,FA}) = 1.602 \pm 0.055 \text{ m}^2$ and $(C_{L,RA}) = 1.890 \pm 0.103 \text{ m}^2$, corresponding to an aerodynamic balance of $AB = 45.87 \pm 1.60\%$. In parallel, the coastdown analysis led to a final drag-area estimate of $C_{DA} = 1.661 \pm 0.395 \text{ m}^2$, from which an aerodynamic efficiency of $\eta_{\text{aero}} = 2.087 \pm 0.500$ was obtained. Taken together, these results constitute the main experimental aerodynamic characterization produced in this thesis and confirm that meaningful aerodynamic coefficients can be identified on track using relatively accessible instrumentation, provided that the preparation, calibration, and processing stages are conducted carefully.

Beyond the numerical values themselves, an important achievement of this thesis lies in the fact that these results were obtained through a complete and documented procedure. The present work therefore not only reports a set of aerodynamic coefficients for one campaign, but also delivers a practical validation framework that can be reproduced by the team in future prototypes. This is particularly relevant in the context of FST Lisboa, where previous aerodynamic validation efforts had already demonstrated the value of experimental work, but were still limited by uncertainty, instrumentation constraints, or insufficient methodological robustness for a stronger quantitative comparison with numerical data.

A further achievement of the present work is that, together with the wind-tunnel campaign carried

out previously on the same prototype, it allowed FST14 to become the first FST Lisboa car assessed through the three principal aerodynamic performance assessment fronts: CFD, wind-tunnel testing, and on-track testing. This constitutes an important milestone within the team, extending the validation effort to full-scale operating conditions.

From the numerical point of view, the CFD campaign successfully reproduced the experimentally observed straight-line operating conditions through steady simulations parameterized by ride height and speed. The comparison with the on-track estimates showed that the numerical model captured the correct qualitative trend of aerodynamic-force increase with dynamic pressure, although the agreement was not equally strong for all quantities. At the regression level, the CFD model yielded $(C_L A)_{\text{CFD}} = 5.1519 \text{ m}^2$, $(C_{L,FA})_{\text{CFD}} = 2.6224 \text{ m}^2$, and $(C_{L,RA})_{\text{CFD}} = 2.5295 \text{ m}^2$, corresponding to differences of 1.6851 m^2 , 1.0200 m^2 , and 0.6386 m^2 relative to the experimental estimates, or relative discrepancies of 32.7%, 38.9%, and 25.2%, respectively. The regression-based aerodynamic balance was also more front-biased in CFD, with $AB_{\text{CFD}} = 50.9\%$, corresponding to a difference of 4.7 percentage points relative to the experimental result.

In interpretative terms, the present results suggest that the adopted CFD setup is capable of reproducing the general aerodynamic behaviour of the car in straight-line conditions, but still exhibits discrepancies that exceed the typical lift-related numerical error previously reported for this framework. Since Santos estimated a numerical error of approximately 4.29% in C_L , the differences observed here cannot be attributed only to mesh-related numerical uncertainty. For a high-downforce Formula Student vehicle, this is particularly important, since aerodynamic loads are strongly sensitive to ride height and small differences in effective operating condition may lead to appreciable differences in both total force and aerodynamic balance. Accordingly, the present work supports CFD as a valuable design and trend-analysis tool, while reinforcing the need for on-track validation before using the model confidently for quantitative setup decisions.

Overall, the present thesis achieved its main objective by experimentally estimating the straight-line aerodynamic performance of FST14, performing a directly comparable CFD campaign, and quantifying the discrepancy between both approaches. In this sense, it contributes both a practical validation framework and a first quantitative basis for assessing the numerical accuracy of the straight-line CFD model currently adopted within FST Lisboa.

7.2 Limitations and Future Work

Although the main objectives of the present work were achieved, several opportunities remain for improving the methodology and aerodynamic understanding that can be extracted from it. The thesis should therefore be regarded as a first step toward a broader and more mature on-track aerodynamic validation capability, rather than as a fully exhaustive characterization of the vehicle behaviour.

A first limitation of the present work is that the experimental validation was restricted to a limited number of straight-line operating points and essentially to a single aerodynamic configuration. Although this was sufficient to identify the main lift- and drag-related parameters and to perform a first CFD

correlation exercise, it does not yet provide a complete aerodynamic map of the vehicle. Future work should therefore extend the campaign to a denser matrix of front and rear ride heights, speeds, and aerodynamic configurations, allowing the sensitivity of downforce, drag, and aerodynamic balance to be assessed directly for validation, setup definition, and vehicle-dynamics integration.

A second limitation concerns the campaign implementation and environmental characterization. Practical constraints affected the originally intended procedure, including limitations in the achievable speed matrix and the lack of sufficiently long-range live telemetry for continuous real-time signal verification. These aspects contribute to the experimental uncertainty through reduced repeatability, limited real-time detection of signal anomalies, and possible variability in the selected analysis windows. Future campaigns would benefit from more robust test-day infrastructure, tighter procedural control, immediate plausibility checks, and a larger repeatable dataset. Direct on-site wind measurements with higher temporal resolution, including gust information, would also reduce one of the main uncertainty sources in the coast-down analysis, where the final result remains comparatively sensitive to environmental correction.

Further improvements are also possible at the level of instrumentation. The external pitot-tube support, although practical and functional, was not ideal from the standpoint of packaging, and therefore represents a possible source of uncertainty in the dynamic-pressure measurement. Future work could refine this installation and investigate more aerodynamically neutral mounting solutions. Likewise, although the present methodology relies successfully on suspension-displacement-based load reconstruction, the conversion from measured suspension travel to aerodynamic load remains dependent on calibration quality, tyre stiffness characterization, and suspension modelling assumptions. Complementary sensing solutions could therefore be explored to strengthen confidence in the inferred wheel loads, including more direct load-measurement approaches.

On the numerical side, the present comparison was limited to steady straight-line CFD simulations with fixed yaw, roll, and steering, using nominal operating conditions derived from the representative experimental points. This is appropriate for a first validation study, but it introduces modelling uncertainty because the simulations do not fully represent the variations in vehicle attitude and flow conditions experienced on track. Additional uncertainty is associated with the steady RANS assumptions, the absence of transition modelling, and the sensitivity of ground-effect flows to small changes in operating condition. Future CFD work should therefore investigate the influence of pitch, yaw angle, steering input, transient ride-height changes, and boundary-condition assumptions. The adoption of transitional turbulence models, through hybrid RANS-LES approaches if computational resources allow, could also improve the prediction of separation, transition, and unsteady flow structures. Once a broader experimental map becomes available, the numerical model could be validated over a wider operating envelope, providing a stronger basis for assessing how accurately CFD captures the aerodynamic behaviour of the vehicle.

Finally, the methodology developed here opens the door to a more integrated use of aerodynamic validation within the team development process. Future work should connect the validated aerodynamic data more directly to lap-time simulation, setup optimization, and aerodynamic design decisions, so that validation becomes an active part of the development loop rather than an isolated post-design exercise.

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Appendix A

Sensor Calibration Raw Data

This Appendix showcases raw data relevant to the calibration procedures of the pitot tube and linear potentiometers.

A.1 Pitot Tube Calibration Raw Data

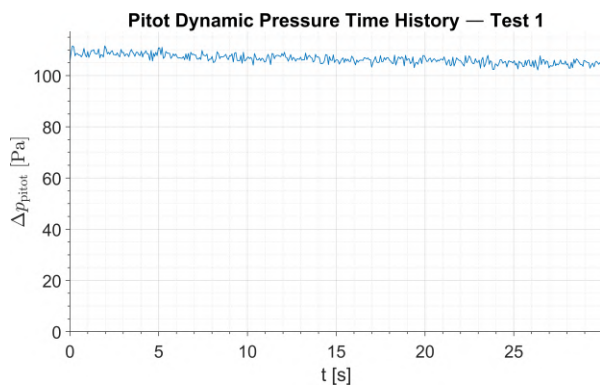


Figure A.1: Pitot dynamic pressure time history — Test 1

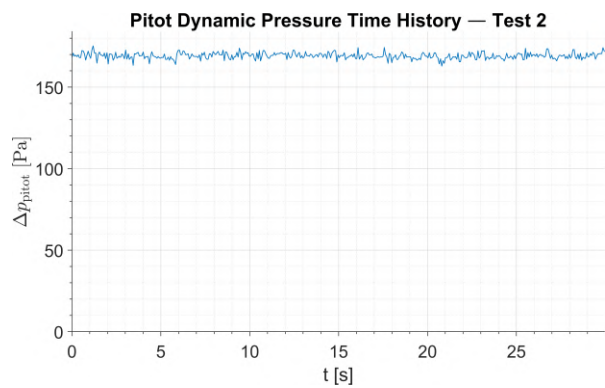


Figure A.2: Pitot dynamic pressure time history — Test 2

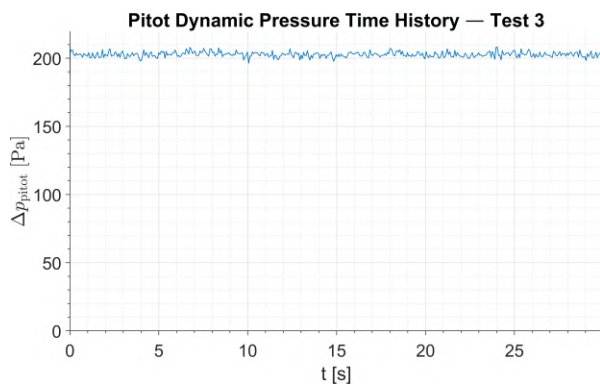


Figure A.3: Pitot dynamic pressure time history — Test 3

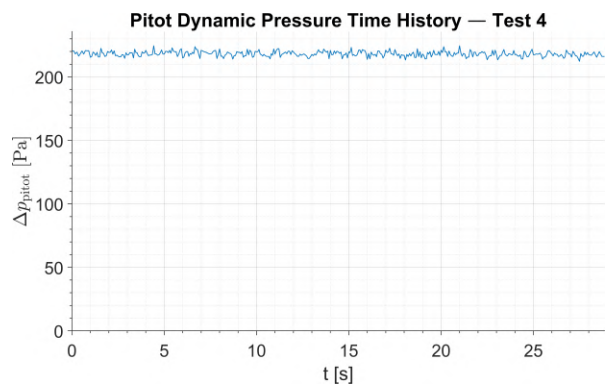


Figure A.4: Pitot dynamic pressure time history — Test 4

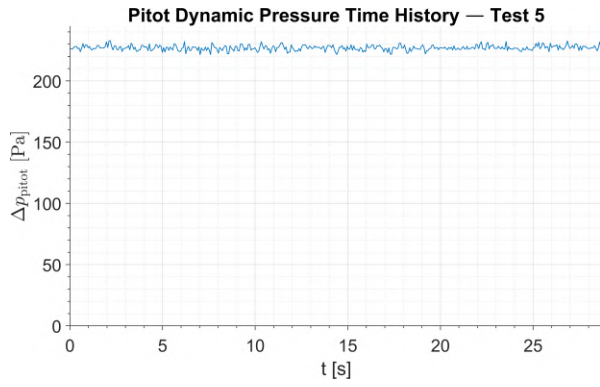


Figure A.5: Pitot dynamic pressure time history — Test 5

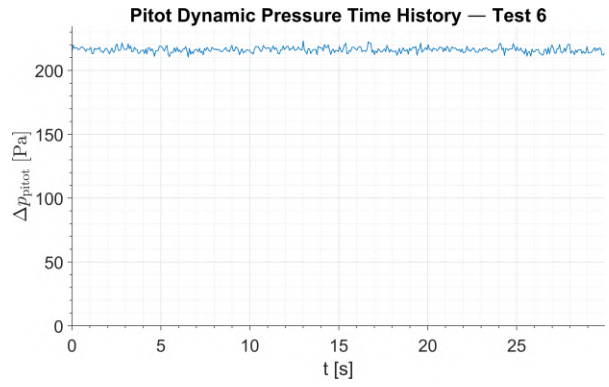


Figure A.6: Pitot dynamic pressure time history — Test 6

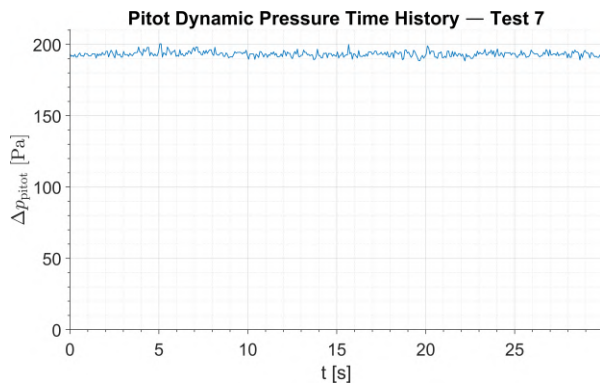


Figure A.7: Pitot dynamic pressure time history — Test 7

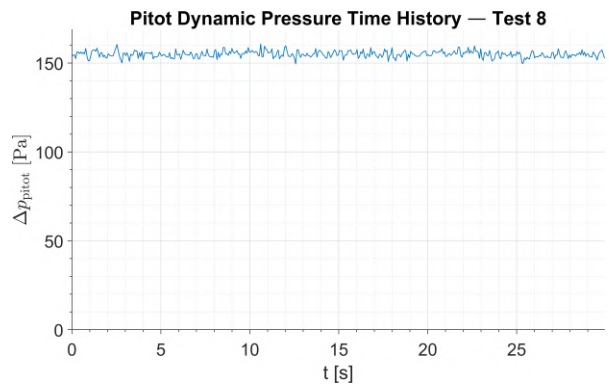


Figure A.8: Pitot dynamic pressure time history — Test 8

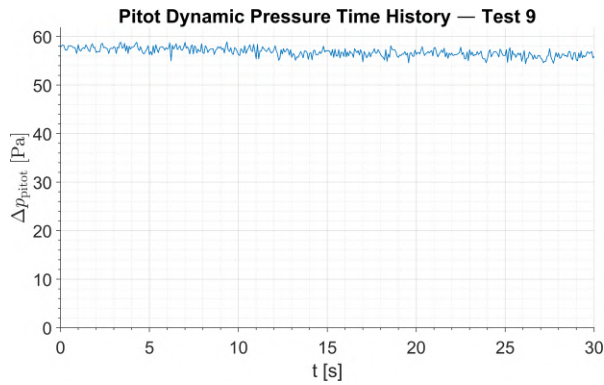


Figure A.9: Pitot dynamic pressure time history — Test 9

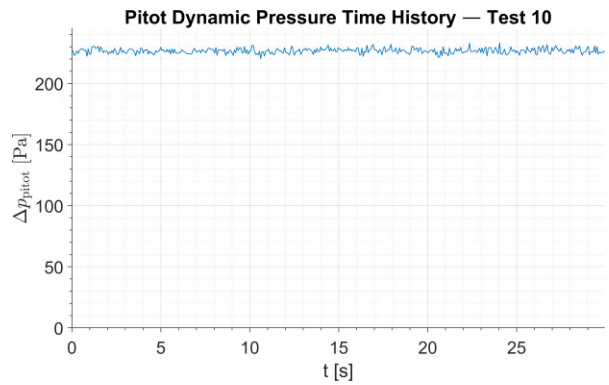


Figure A.10: Pitot dynamic pressure time history — Test 10

A.2 Linear Potentiometers Calibration Raw Data

Table A.1: Raw potentiometer calibration data for the FL corner

Point	V_{ADC} [-]	Δx_{wheel} [mm]	Δx_{damper} [mm]
full droop	2368.065	0.00	0.00
1	2381.001	3.00	0.50
2	2416.578	4.45	1.90
3	2446.297	5.95	3.10
4	2486.740	7.45	4.65
5	2533.151	8.95	6.30
6	2588.634	10.45	7.90
7	2649.745	11.95	9.50
8	2711.549	13.45	11.00
9	2774.073	14.95	12.65
10	2833.869	16.45	14.00
11	2894.560	17.95	15.35
12	2953.891	19.45	16.75
13	3013.836	20.95	18.10
14	3072.295	22.45	19.55
15	3126.652	23.95	20.80
16	3180.326	25.45	22.05
17	3233.932	26.95	23.35
18	3286.593	28.45	24.60
19	3334.254	29.95	25.70
20	3384.458	31.45	26.95
21	3430.158	32.95	28.05
22	3477.534	34.45	29.20
23	3523.641	35.95	30.35
24	3566.074	37.45	31.40
25	3607.184	38.95	32.40
26	3649.312	40.45	33.45
27	3687.452	41.95	34.45
28	3722.157	43.45	35.35
29	3756.991	44.95	36.25
30	3788.846	46.45	37.15
31	3816.071	47.95	37.95
32	3844.877	49.45	38.75
33	3869.945	50.45	39.40
34	3887.910	51.20	40.25
35	3904.054	51.90	43.55

Table A.2: Raw potentiometer calibration data for the FR corner

Point	V_{ADC} [-]	Δx_{wheel} [mm]	Δx_{damper} [mm]
full droop	2680.113	0.00	0.00
1	2711.673	3.00	1.45
2	2743.918	4.55	2.20
3	2771.209	5.55	3.25
4	2798.500	7.05	4.05
5	2816.139	8.90	5.80
6	2544.051	10.40	6.85
7	2587.029	11.85	8.30
8	2617.003	13.25	9.60
9	2655.009	14.75	10.10
10	2672.842	15.85	11.65
11	2694.827	16.95	12.55
12	2721.067	17.75	13.50
13	2741.702	18.65	14.20
14	2762.026	19.55	14.95
15	2780.061	20.55	15.65
16	2815.923	22.55	17.45
17	2870.976	23.95	18.60
18	2931.673	25.95	20.90
19	2985.879	28.45	22.80
20	3041.126	30.45	23.55
21	3074.168	31.95	24.30
22	3102.695	33.45	25.05
23	3124.533	35.00	25.75
24	3152.294	36.50	26.50
25	3178.676	38.00	27.30
26	3207.755	39.50	28.05
27	3233.440	41.00	28.85
28	3253.236	42.50	29.55
29	3270.204	44.00	30.30
30	3289.936	45.50	31.05
31	3307.336	47.00	31.80
32	3320.573	48.50	32.55
33	3335.711	50.00	33.25
34	3346.933	51.50	34.00
35	3360.235	53.00	34.80

Table A.3: Raw potentiometer calibration data for the RL corner

Point	V_{ADC} [-]	Δx_{wheel} [mm]	Δx_{damper} [mm]
full droop	3593.107	0.00	0.00
1	3528.085	3.00	3.45
2	3479.661	4.50	4.65
3	3460.969	5.50	5.05
4	3434.603	7.00	6.40
5	3390.379	8.50	7.60
6	3355.974	10.00	8.80
7	3324.155	11.50	10.05
8	3291.223	13.00	11.30
9	3255.464	14.50	12.55
10	3225.827	16.00	13.80
11	3203.190	17.50	15.05
12	3177.364	19.00	16.30
13	3152.835	20.50	17.50
14	3129.093	22.00	18.65
15	3106.889	23.50	19.85
16	3085.138	25.00	21.10
17	3064.241	26.50	22.25
18	3044.825	28.00	23.45
19	3024.821	29.50	24.70
20	3006.294	31.00	25.85
21	2987.673	32.50	27.00
22	2970.010	34.00	28.15
23	2952.891	35.50	29.30
24	2936.362	37.00	30.40
25	2920.336	38.50	31.60
26	2905.148	40.00	32.75
27	2890.476	41.50	33.85
28	2876.257	43.00	35.00
29	2862.388	44.50	36.10
30	2848.753	46.00	37.20
31	2835.786	47.50	38.35
32	2823.272	49.00	43.85

Table A.4: Raw potentiometer calibration data for the RR corner

Point	V_{ADC} [-]	Δx_{wheel} [mm]	Δx_{damper} [mm]
full droop	3593.107	0.00	0.00
1	3528.085	3.00	3.45
2	3479.661	4.50	4.65
3	3460.969	5.50	5.05
4	3434.603	7.00	6.40
5	3390.379	8.50	7.60
6	3355.974	10.00	8.80
7	3324.155	11.50	10.05
8	3291.223	13.00	11.30
9	3255.464	14.50	12.55
10	3225.827	16.00	13.80
11	3203.190	17.50	15.05
12	3177.364	19.00	16.30
13	3152.835	20.50	17.50
14	3129.093	22.00	18.65
15	3106.889	23.50	19.85
16	3085.138	25.00	21.10
17	3064.241	26.50	22.25
18	3044.825	28.00	23.45
19	3024.821	29.50	24.70
20	3006.294	31.00	25.85
21	2987.673	32.50	27.00
22	2970.010	34.00	28.15
23	2952.891	35.50	29.30
24	2936.362	37.00	30.40
25	2920.336	38.50	31.60
26	2905.148	40.00	32.75
27	2890.476	41.50	33.85
28	2876.257	43.00	35.00
29	2862.388	44.50	36.10
30	2848.753	46.00	37.20
31	2835.786	47.50	38.35
32	2823.272	49.00	43.85

Appendix B

On-Track Raw Data

This appendix gathers the representative raw signal overview of four of the extracted logs and complements the representative example presented in Section 5.1.

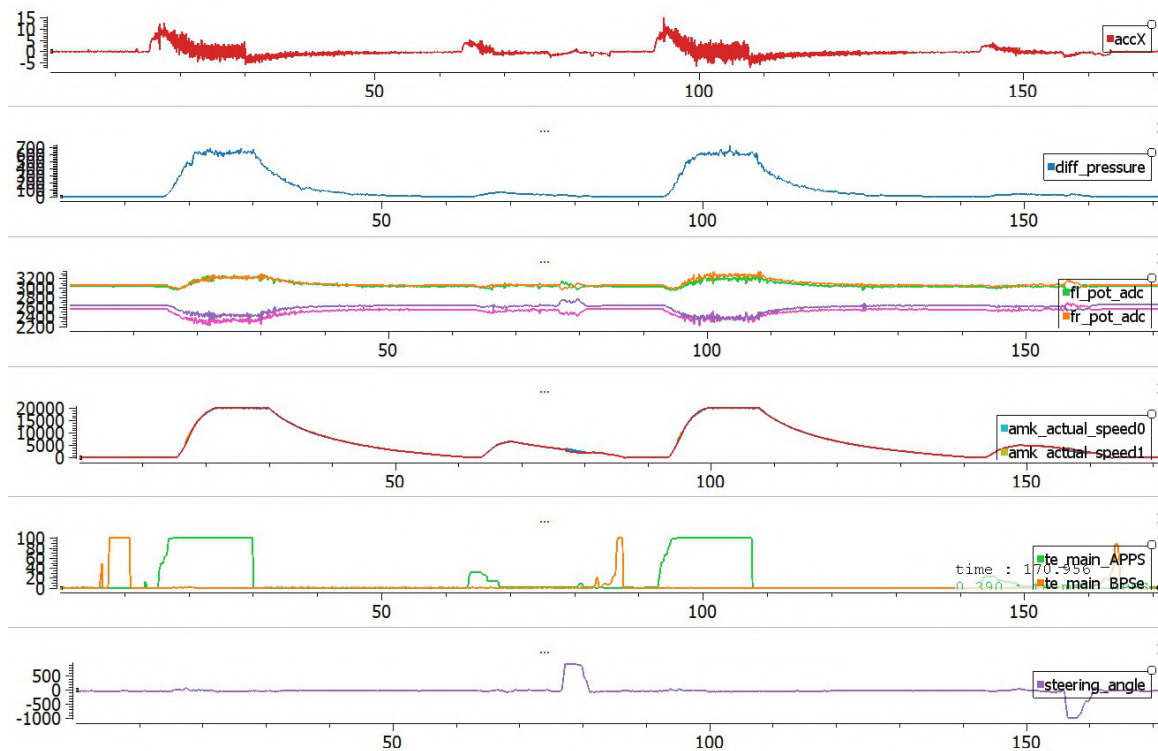


Figure B.1: Overview of the raw logged signals as visualised in the PlotJuggler software environment

Raw signal overview - Log 4

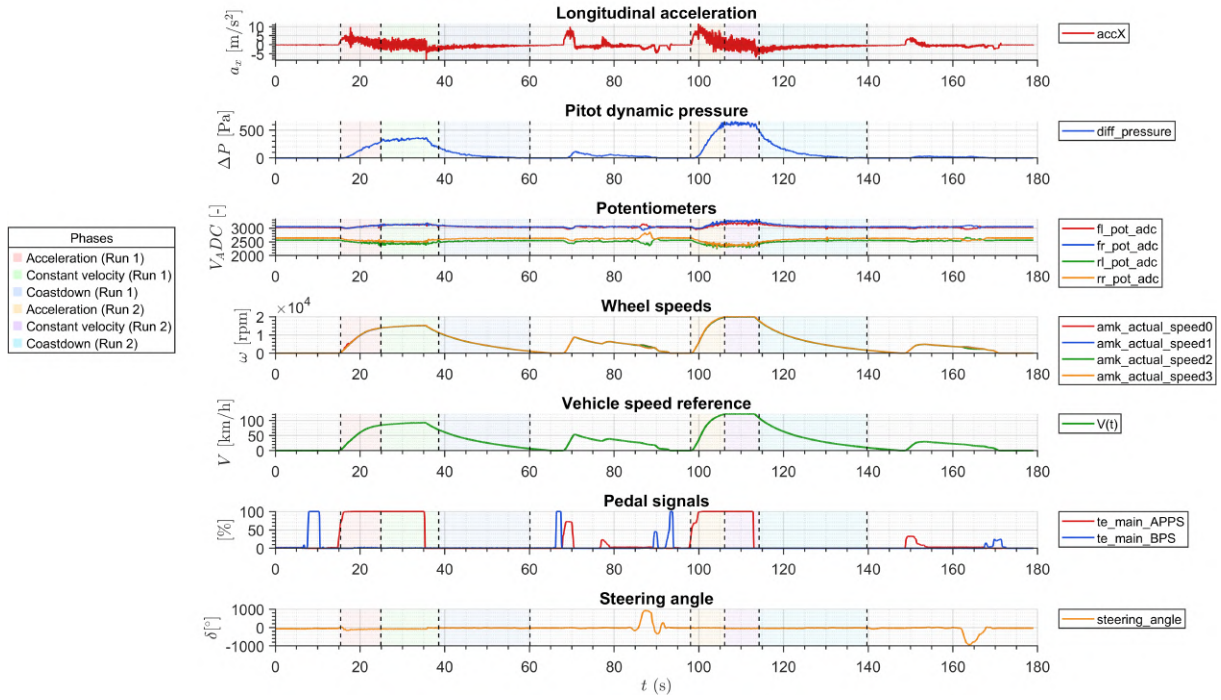


Figure B.2: Representative raw signal overview for Log 4 (two opposite-direction runs), with the extracted intervals highlighted.

Raw signal overview - Log 6

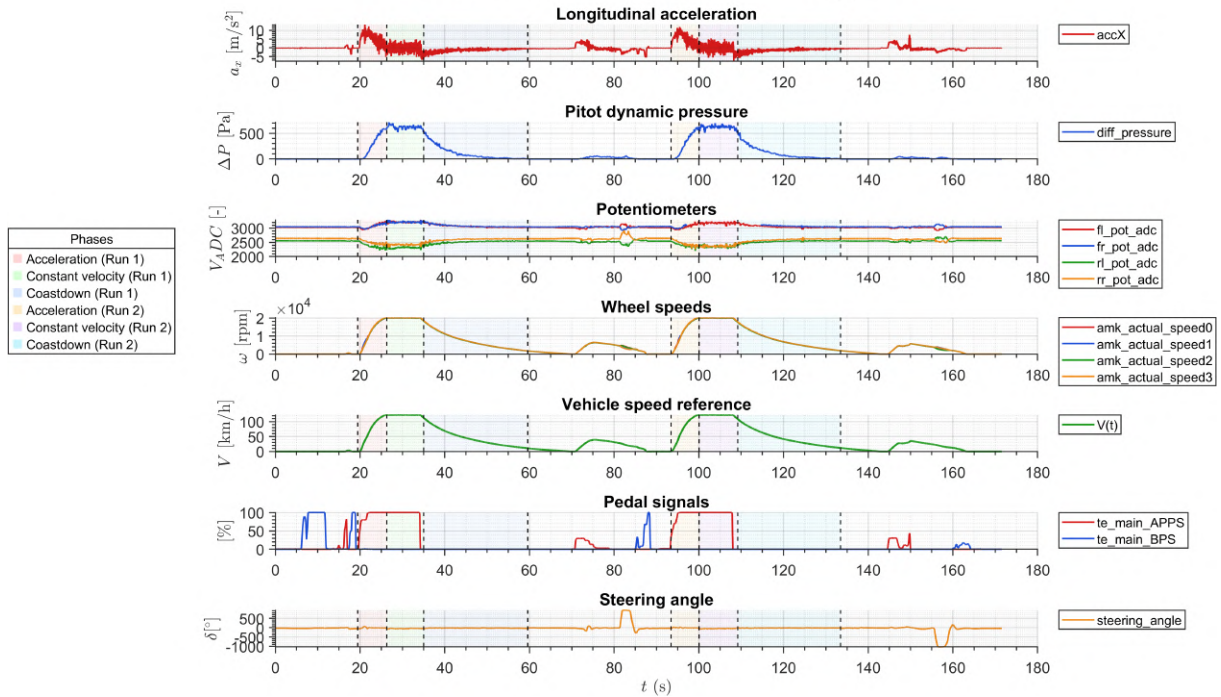


Figure B.3: Representative raw signal overview for Log 6 (two opposite-direction runs), with the extracted intervals highlighted.

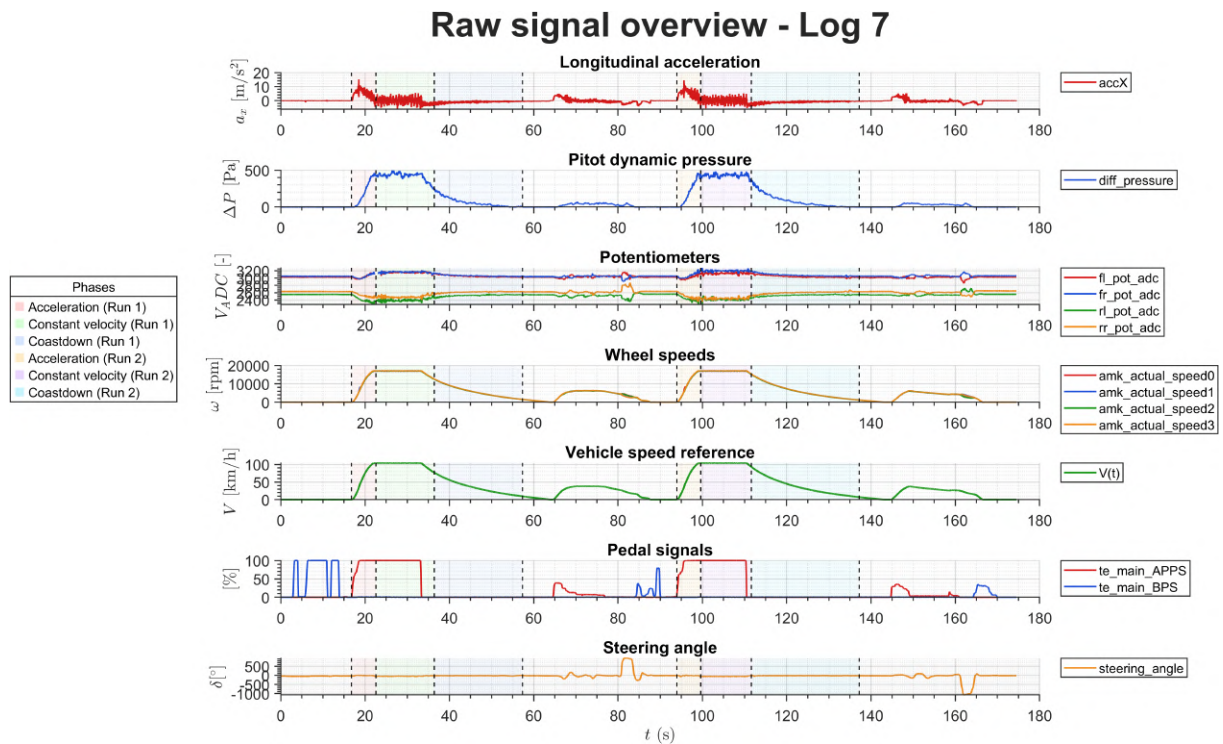


Figure B.4: Representative raw signal overview for Log 7 (two opposite-direction runs), with the extracted intervals highlighted.

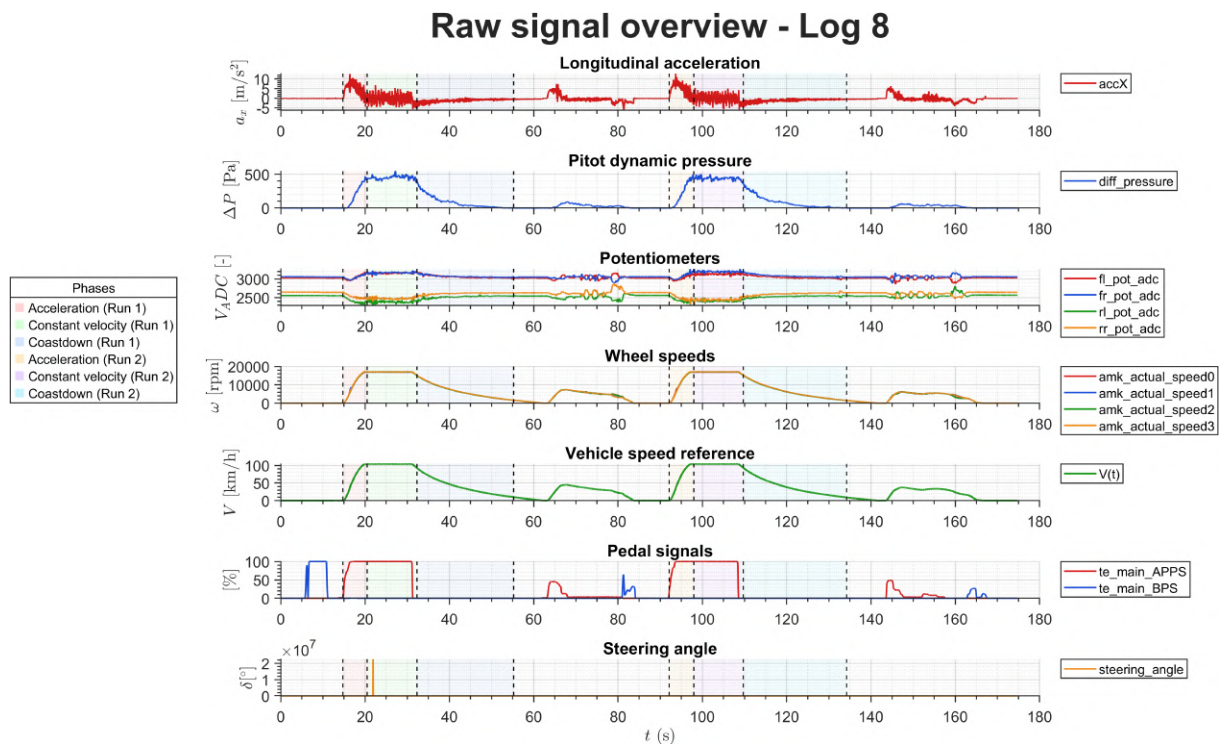


Figure B.5: Representative raw signal overview for Log 8 (two opposite-direction runs), with the extracted intervals highlighted.

Appendix C

On-Track Processed Data

This appendix gathers the processed time-history plots obtained for some of the on-track tests and complements the representative examples presented in Section 5.3. It also gathers some of the coast-down quadratic runs for accepted runs, which complements the regression presented in Section 5.4.2.

C.1 Constant Velocity Processed Time Histories

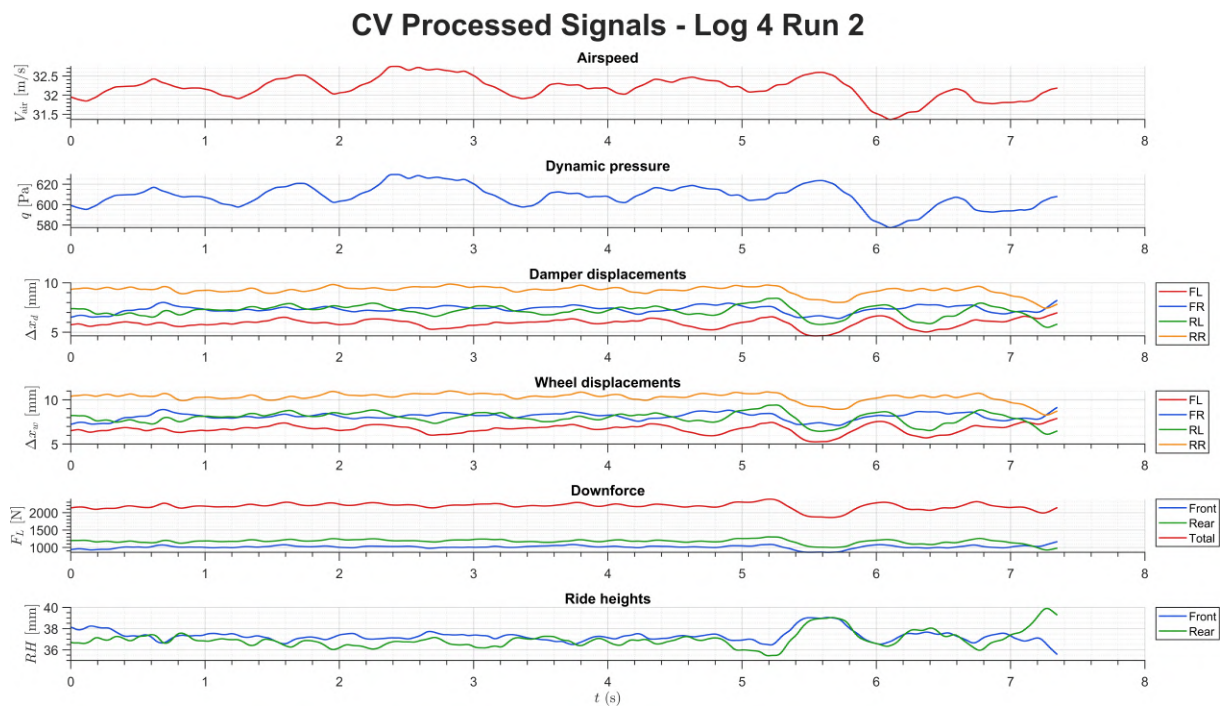


Figure C.1: Processed constant-velocity time history for Log 4 Run 2 – Run 8

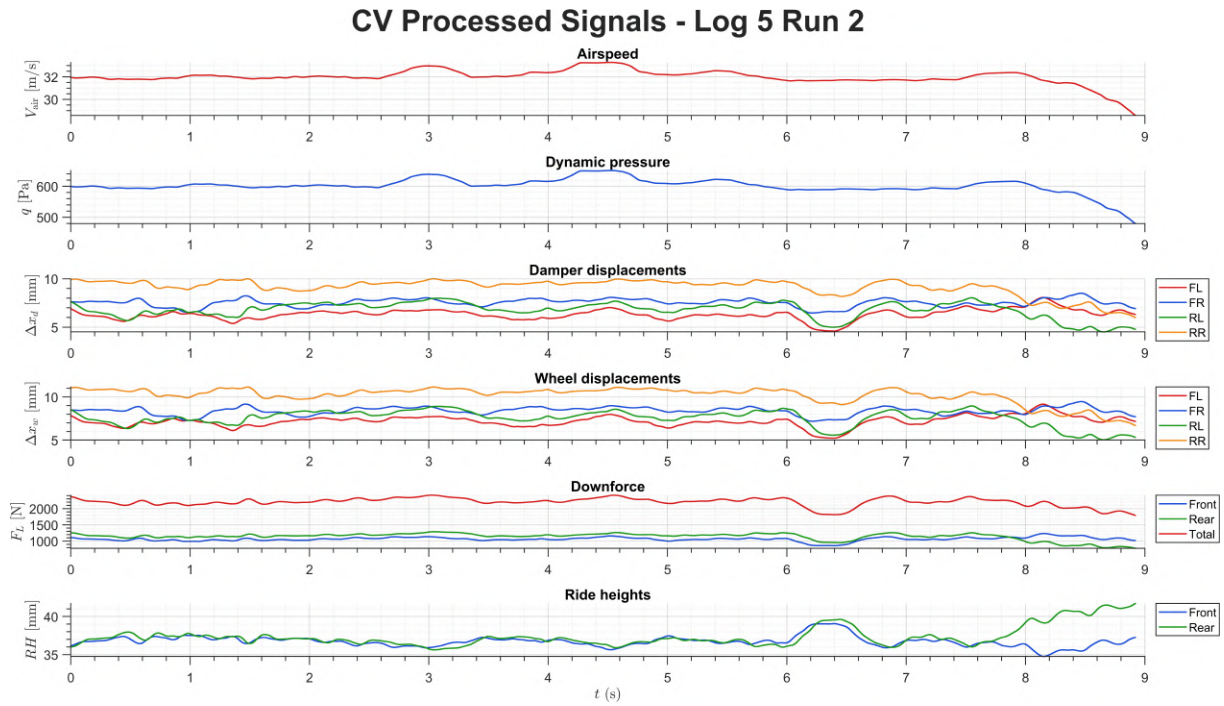


Figure C.2: Processed constant-velocity time history for Log 5 Run 2 – Run 10

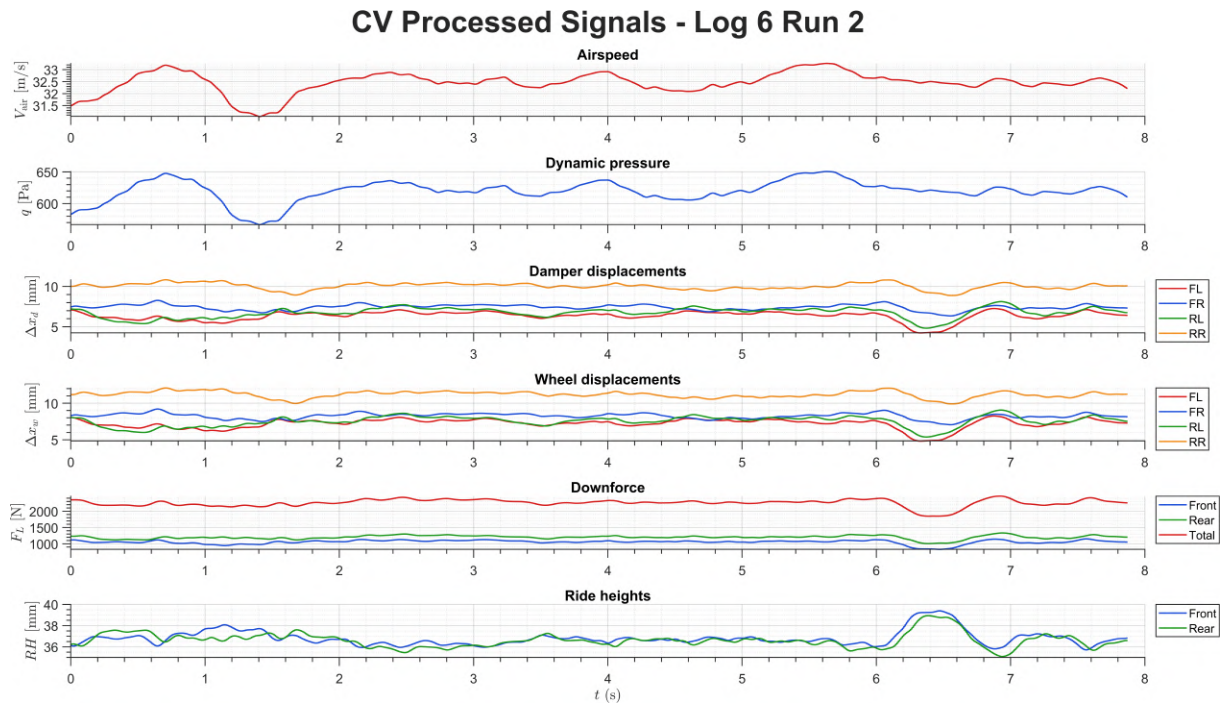


Figure C.3: Processed constant-velocity time history for Log 6 Run 2 – Run 12

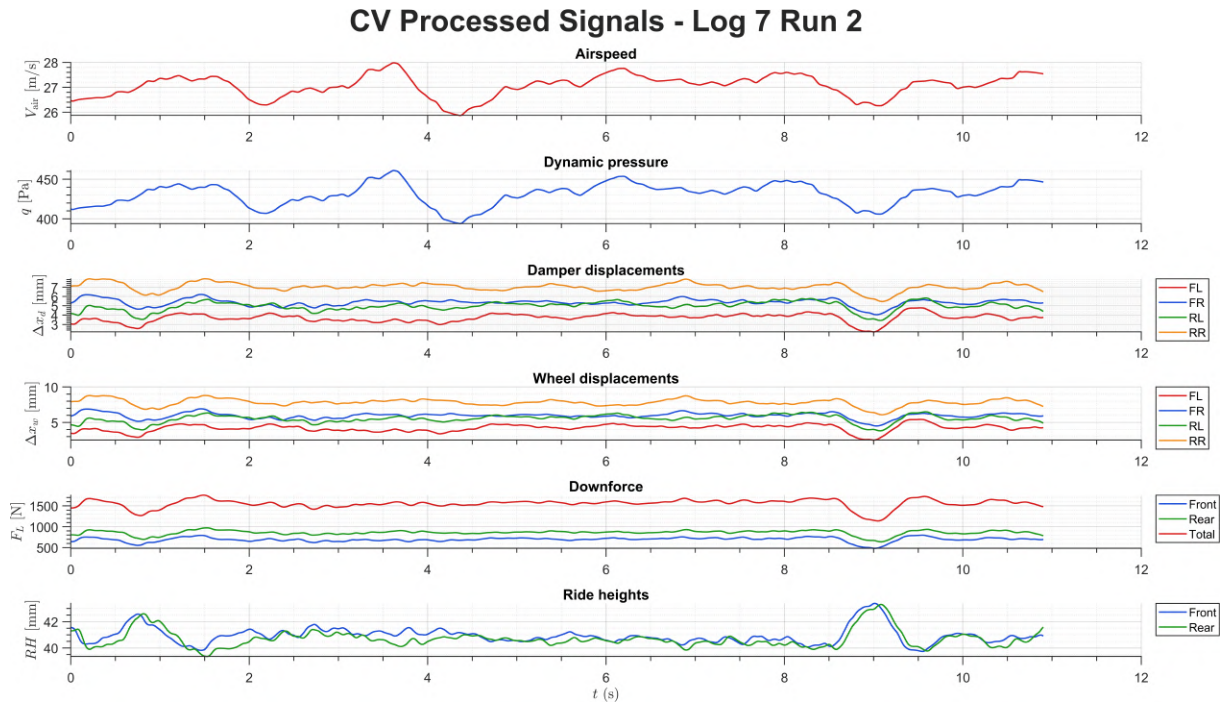


Figure C.4: Processed constant-velocity time history for Log 7 Run 2 – Run 14

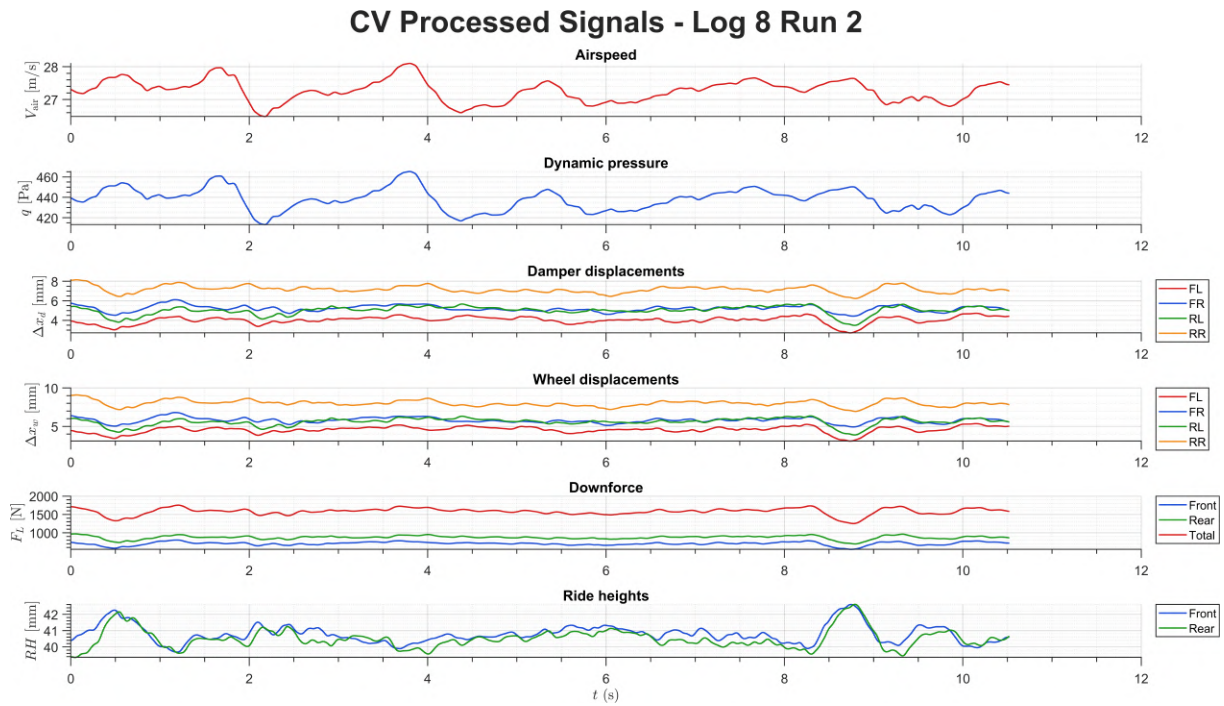


Figure C.5: Processed constant-velocity time history for Log 8 Run 2 – Run 16

C.2 Coastdown Processed Time Histories

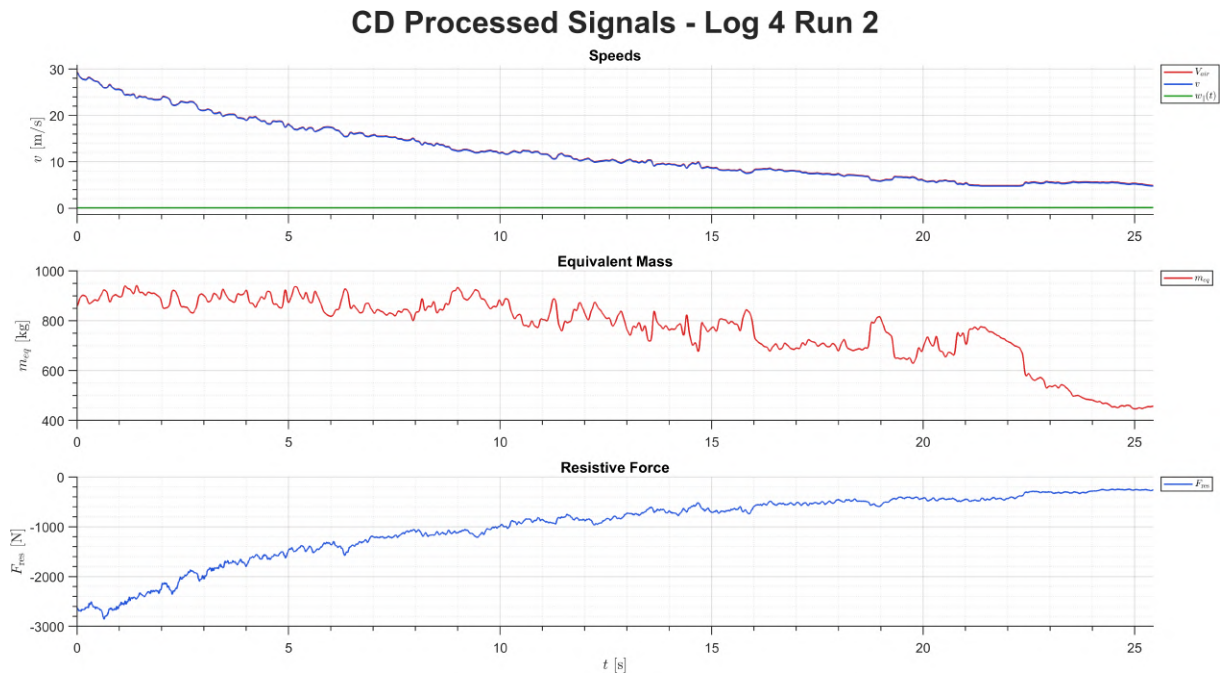


Figure C.6: Processed coastdown time history for Log 4 Run 2 – Run 8

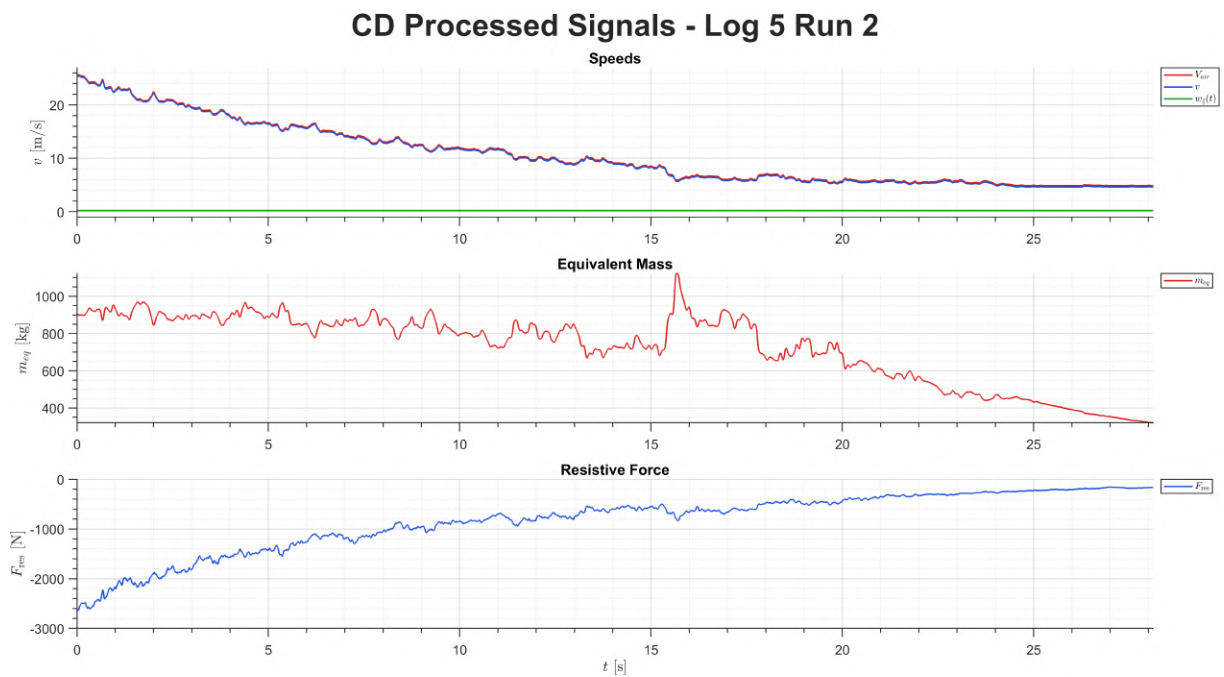


Figure C.7: Processed coastdown time history for Log 5 Run 2 – Run 10

CD Processed Signals - Log 6 Run 2

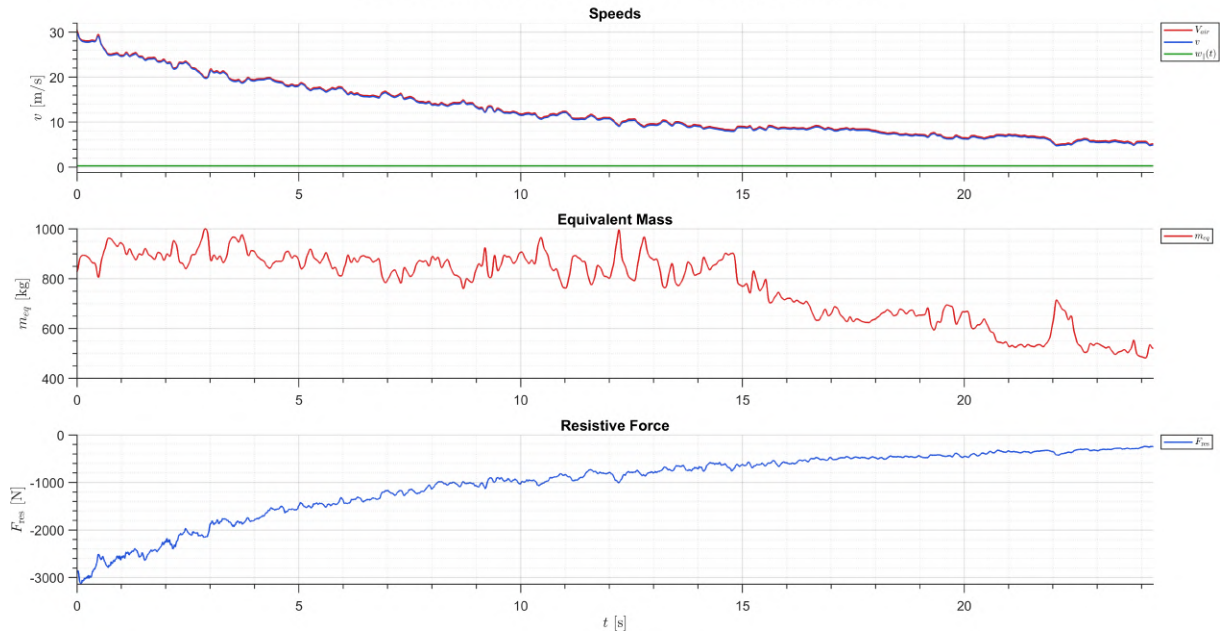


Figure C.8: Processed coastdown time history for Log 6 Run 2 – Run 12

CD Processed Signals - Log 7 Run 2

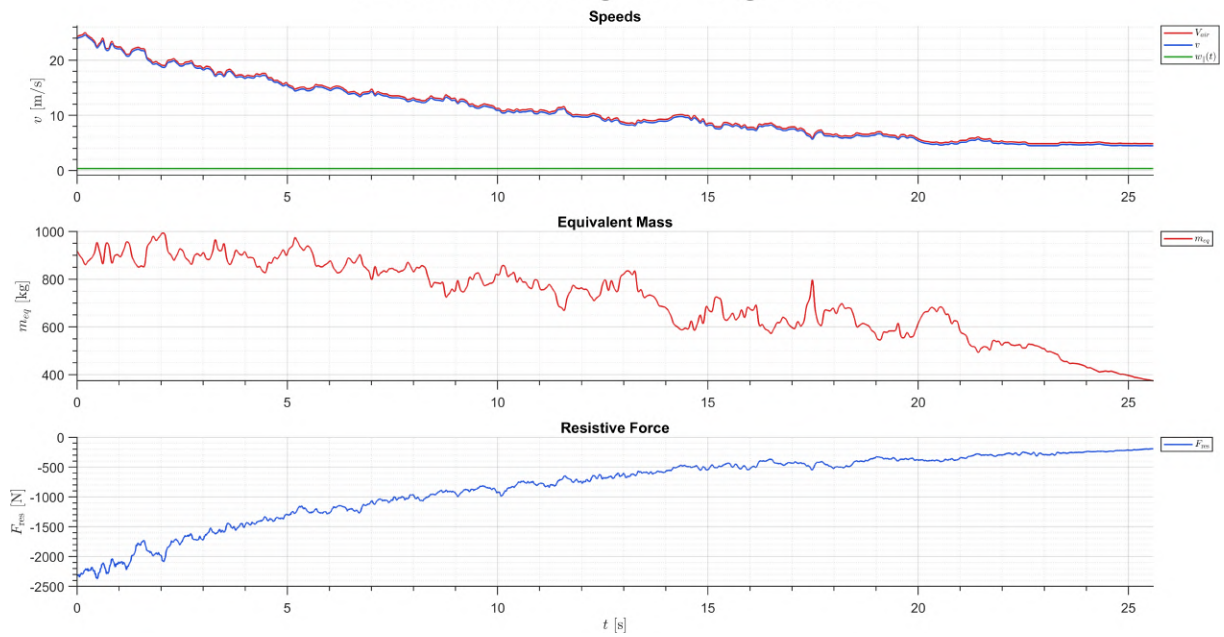


Figure C.9: Processed coastdown time history for Log 7 Run 2 – Run 14

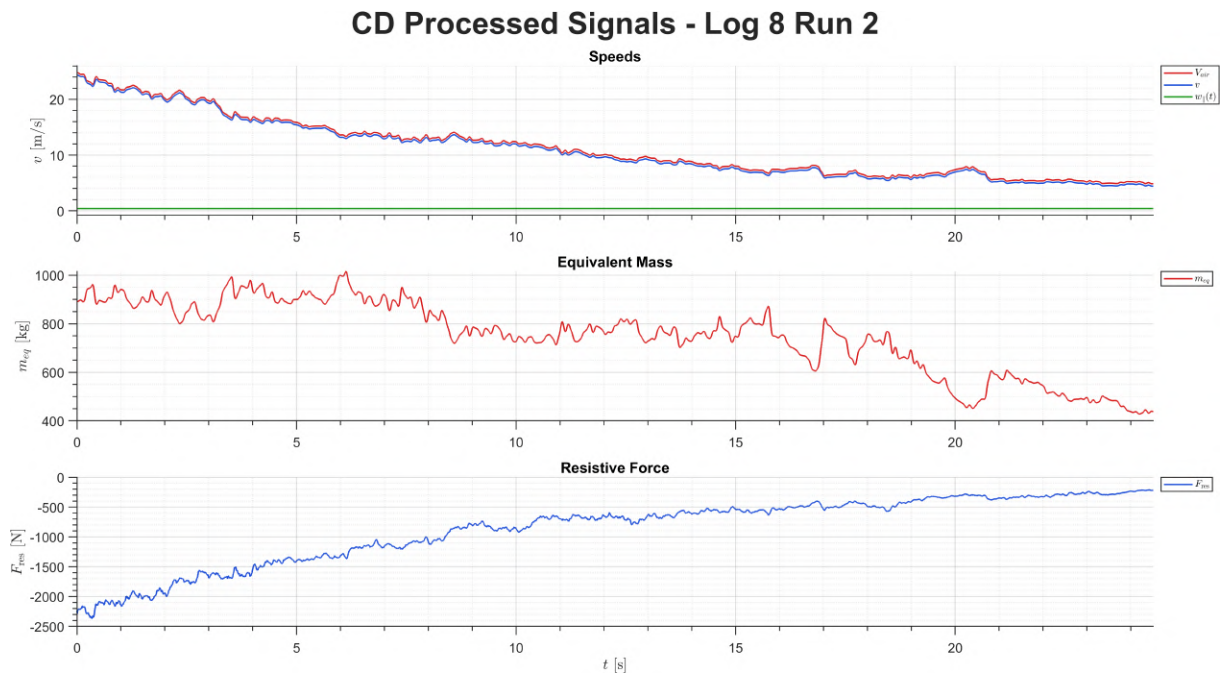


Figure C.10: Processed coastdown time history for Log 8 Run 2 – Run 16

C.3 Coastdown Quadratic Regressions for Accepted Runs

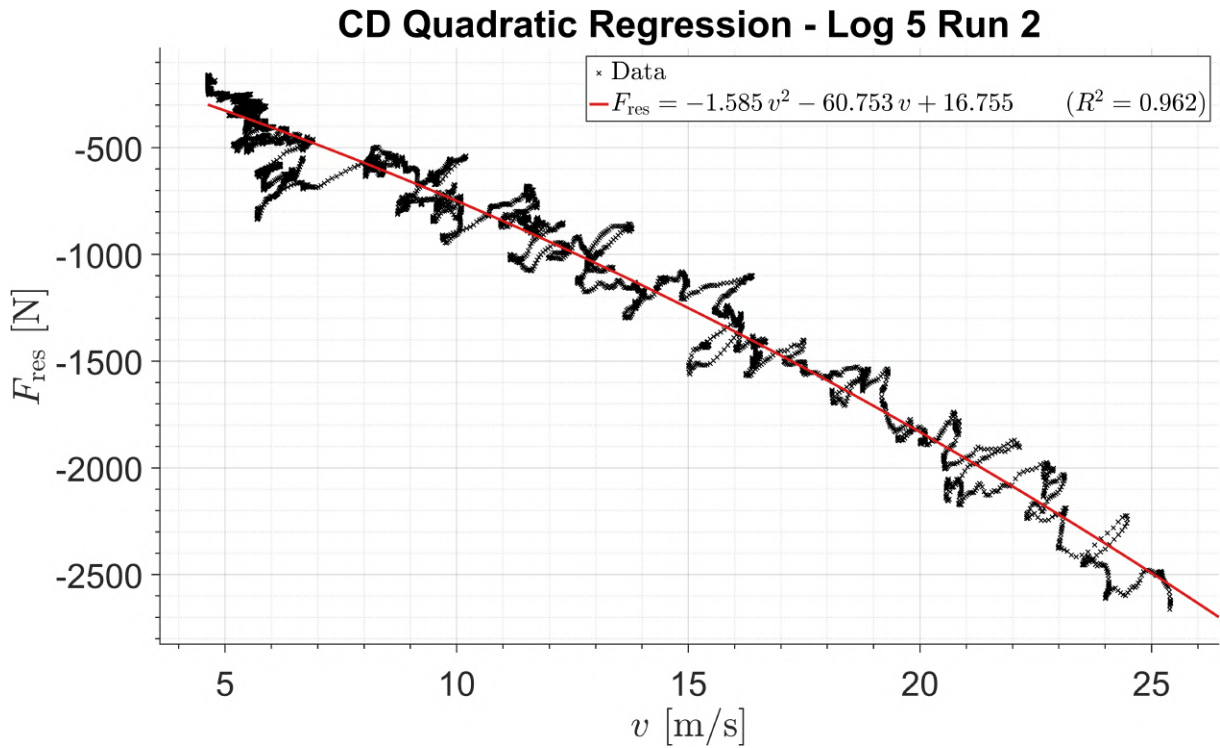


Figure C.11: Quadratic coastdown regression for Log 5 Run 2 – Run 10

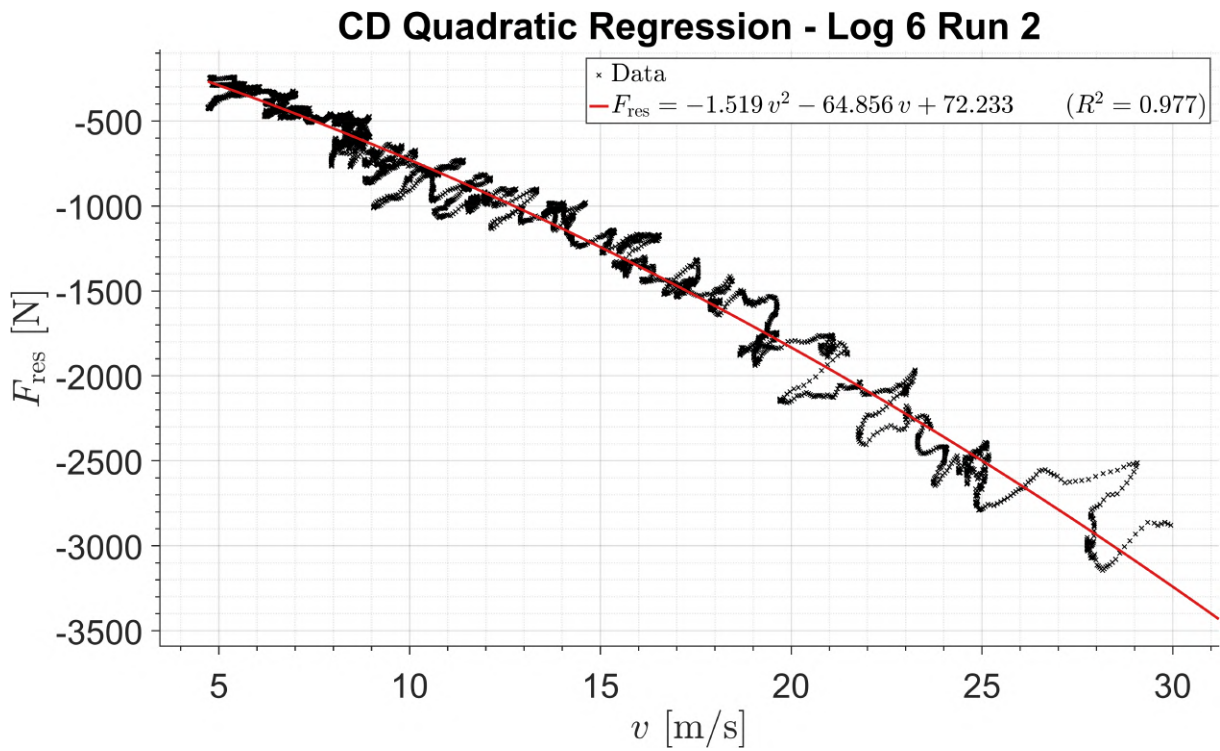


Figure C.12: Quadratic coastdown regression for Log 6 Run 2 – Run 12

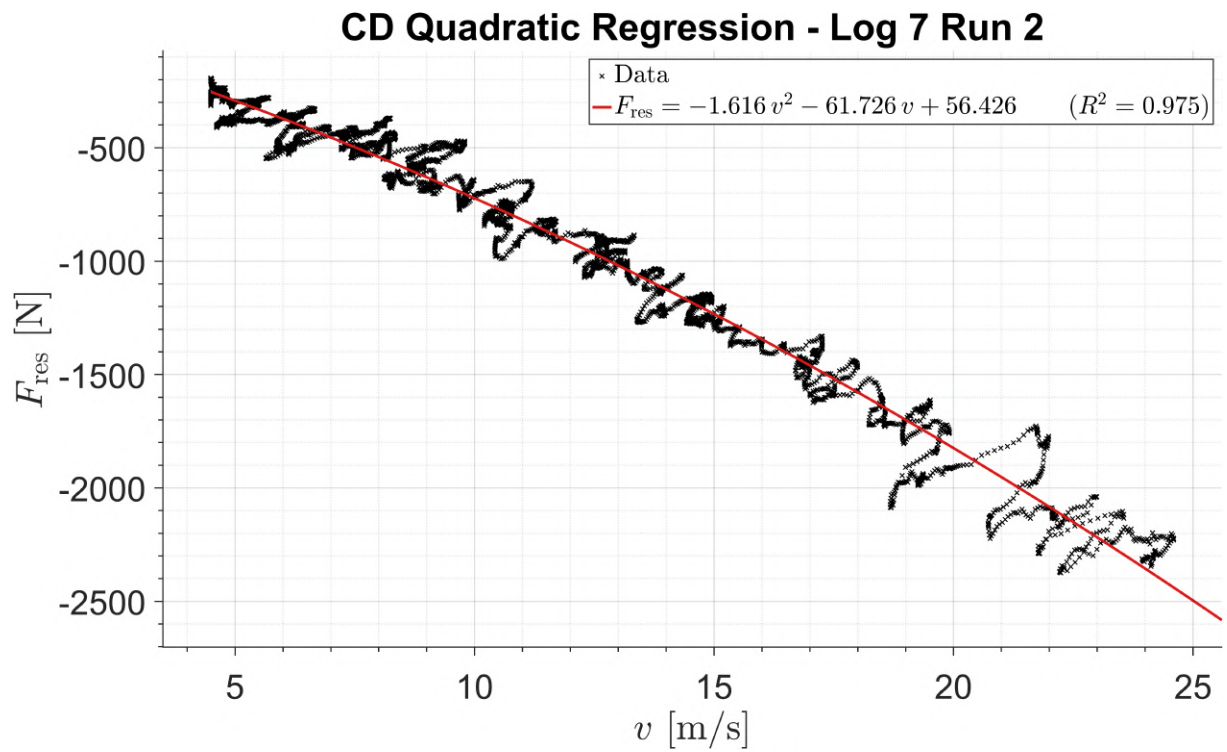


Figure C.13: Quadratic coastdown regression for Log 7 Run 2 – Run 14

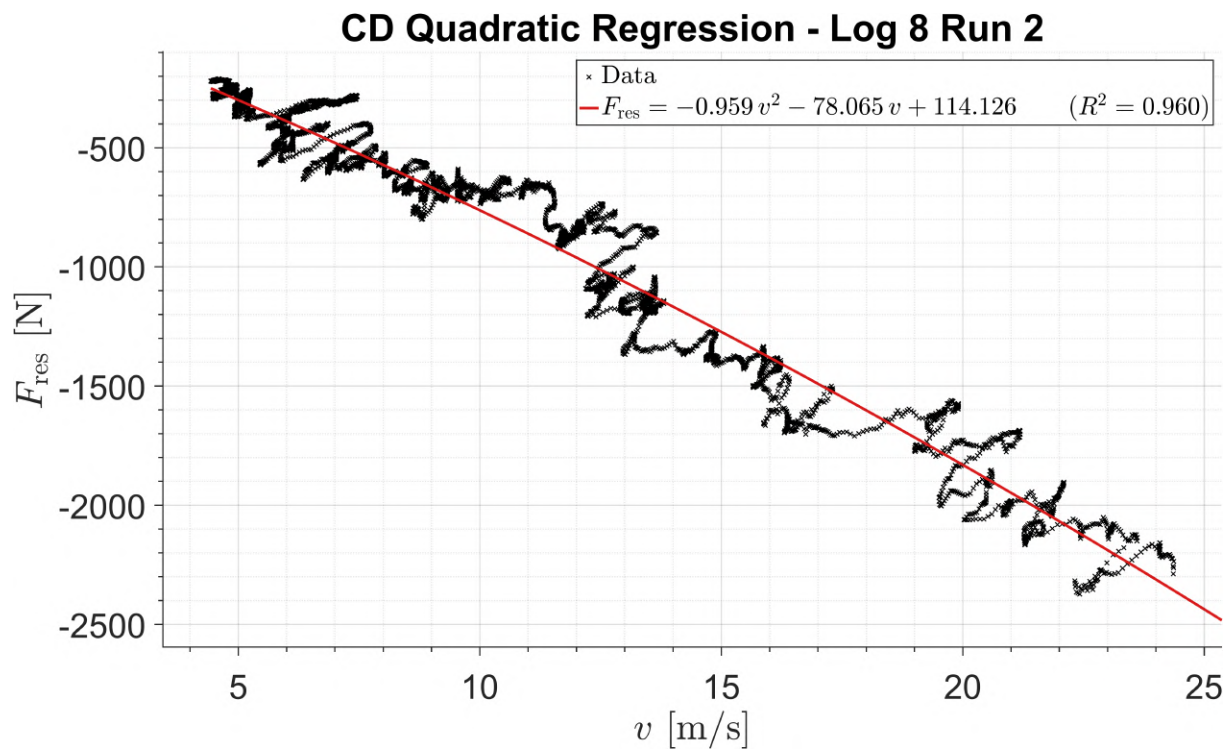


Figure C.14: Quadratic coastdown regression for Log 8 Run 2 – Run 16