

CRANFIELD UNIVERSITY

RENAN FRANCISCO SOARES

WAKE CHARACTERISATION AND SIMULATION FOR
GROUND VEHICLES

SCHOOL OF AEROSPACE, MANUFACTURING AND
TRANSPORT
PhD in Aerospace

PhD
Academic Year: 2015 - 2020

Supervisor: Prof. Kevin Garry
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ABSTRACT

This project aims to develop a generic, adaptable device able to emulate the distinct aerodynamic wake characteristics corresponding to different closed-wheel automotive vehicle categories, avoiding the use of a full-body vehicle model(s). The intention is to reduce complexity in both wind tunnel experimental testing and computational simulation, enhancing the capability of experimental facilities to study interference effects between vehicles in close proximity (*e.g.* platoon formation, drafting) and allowing faster build, meshing and computation time for CFD studies.

The overall approach uses both computational and experimental investigations on generic automotive configurations (*e.g.* DrivAer models), particularly in relation to wake development and detailed flow structures. CFD simulations are mainly used for preliminary flow analysis and aerodynamic design, while the wind tunnel established the experimental, benchmark datasets.

The three standard DrivAer vehicle configurations were adopted for studies relating to passenger cars, while the proposed 4th configuration (‘high-performance’) was developed and proposed as a benchmark model for race car aerodynamics. Two extensive, experimental wake datasets on the four DrivAer configurations have been created, the first using a pressure-based technique (total pressure rake), and the second applying an image-based method (Stereoscopic Particle Image Velocimetry). Additional experimental analyses support each wake dataset, such as (i) investigation of the effects of experimental conditions, (ii) Reynolds number characteristics and (iii) statistical analysis.

These automotive wake benchmarks were used as the basis for the development of a conceptual wake generator, which is intended to be adaptable and able to

generate representative wakes equivalent to automotive bodies. The development and key aerodynamic characteristics of this device are outlined, and each configuration experimentally validated using wind tunnel data.

The complex wake structures associated with each of the four vehicle configurations are categorised, and the resulting wake emulator is seen to be capable of reproducing the key features within the wake development region of interest (*i.e.* $0.666 < x/W < 1.33$, where x/W is the distance behind the vehicle normalised by the DrivAer model width, W). This thesis is concluded with the proposal of a wake generator device as a new tool to support further development on automotive aerodynamics.

Keywords:

Automotive aerodynamics; bluff-body wake generator; PIV wake database; total pressure wake database; CFD design.

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LIST OF ABBREVIATIONS

General terms

BL, BLC	[Ground] Boundary Layer [Control system]
BL1	1 st -stage Boundary Layer Control system
BL2	2 nd -stage Boundary Layer Control system
CAD	Computer-aided design
CFD	Computational Fluid Dynamics
CORD	Cranfield Online Research Data
CUDA	Compute Unified Device Architecture (Nvidia)
LIC	Line Integral Convolution
LSC	Least Squares Quadratic
NACA	National Advisory Committee for Aeronautics
NASCAR	National Association for Stock Car Auto Racing
PIV	Particle Image Velocimetry
SPIV	Stereoscopic Particle Image Velocimetry
RANS	Reynolds-Averaged Navier Stokes
RMIT	Royal Melbourne Institute of Technology
SAE	Society of Automotive Engineers
TU Berlin	Technische Universität Berlin
TUM	Technische Universität München

DrivAer model nomenclature

E	Estateback car model
F	Fastback car model
hp	High-performance aero pack
hpF	High-performance, Fastback car model
N	Notchback car model
S	smooth underbody; <i>also</i> Sutherland constant (<i>fluid mechanics</i>)
wM	with side mirrors
woM	without side mirrors
wW	with wheels

$w_o W$	without wheels
wTS	with top strut
$GSon$	ground simulation
$GSo ff$	no ground simulation
$y\{S\}\{AN\}d$	Yaw angle notation: AN: (two-digit angle), $S = \begin{cases} n, & AN < 0 \\ p, & AN \geq 0 \end{cases}$

Other nomenclature

$\sqrt{A}$	reference length, based on the base area squared root
A_{ref}	reference area
$A\#$	PIV acquisition area, number #
c	aerofoil cord
CS	[car] model scale
H	reference height
h	mesh refinement level
h_c	gap clearance, ride height
L	reference length
$P\#$	cross-flow plane, number #
W	reference width; wheel track
wr	wheel radius
wb	wheelbase
x_o	coordinate position of the vehicle leading point
x_F	coordinate position of the front wheel's axle
x_R	coordinate position of the rear wheel's axle
γ	vehicle yaw angle to coordinate system
ω_w	local rotation rate on wheels

Aerodynamic parameters

C_D	drag coefficient
C_L	lift coefficient
C_P	pressure coefficient
C_{P_t}	total pressure coefficient
$C_{P_{tL}}$	total pressure loss coefficient

I	turbulence intensity
M	Mach number
M_w	molecular weight
n	number of moles; <i>also</i> number of samples (<i>statistics</i>)
P	pressure
P_∞	environmental, reference pressure
P_d	dynamic pressure
P_s	static pressure
P_t	total pressure
R	Universal Gas Constant
Re	Reynolds number
S	Sutherland constant; <i>also</i> smooth underbody (<i>DrivAer geometry</i>)
T	temperature
T_o	reference temperature (Sutherland's law)
U	velocity
U_∞	reference velocity; freestream magnitude
U_{GS}	relative ground movement
$\overrightarrow{U_y + U_z}$	cross-plane velocity vector
V	volume
ε	turbulent dissipation
κ	turbulent kinetic energy
ρ	density
μ	dynamic viscosity; <i>also</i> true mean (<i>statistics</i>)
μ_o	reference viscosity (Sutherland's law)
μ_t	eddy viscosity
ν	kinematic viscosity

Normalised parameters

H_b	normalised vehicle body height
y^+	normalised [dimensionless] wall distance
y^*	normalised width (cross-flow plane, horizontal direction)
z^*	normalised height (cross-flow plane, vertical direction)
u/U_∞	normalised velocity
x/L	normalised x -coordinate
y/W	normalised y -coordinate
z/H	normalised z -coordinate

Statistical parameters

ΔCI	confidence interval [range, delta]
df	degree of freedom
e	margin of error
n	number of samples; <i>also</i> number of moles (<i>fluid mechanics</i>)
s	sample standard deviation
s^2	sample variance
$t_{\alpha,df}$	t-student distribution coefficient
Z_{α}	Z-score [distribution coefficient]
α	significance level
μ	true mean; <i>also</i> dynamic viscosity (<i>fluid mechanics</i>)
σ	standard deviation
σ^2	variance

Miscellaneous symbols

$ x $	absolute value
$\sim$	approximately
$\bar{x}$	averaged value
$^{\circ}$	degree
Δ	difference or range
$\#$	[identification] number

Chapter 1.

INTRODUCTION

The automotive industry generally relies on effective synergy between experimental and computational tools, combining the strengths of both approaches. A process, typically referred to as a ‘wind tunnel-CFD correlation’, usually overlaps the investigation cases between those approaches.

The key advantage of a wind tunnel facility is the ability to investigate flow characteristics using the real fluid in a controlled environment. The complexity present in a ‘true, on-road’ condition is simplified and allows an analysis isolating parameters of interest. Additionally, an automated model setup can quickly assess the vehicle performance at different conditions and positions (*e.g.* cross-flow sensitivity and optimisation of ride height). Unfortunately, a process of aerodynamic design only based on experiments would require building a physical model for every geometric variation being considered, making an experimental-only approach time consuming and financially challenging.

A computational approach is routinely used as an alternative design tool, where design solutions can be exploited and quantified in a virtual environment. The growth of hardware processing power and improvement of numeric methods have been boosting the gains from CFD simulations. The main advantage lies on the cost-benefit ratio, where a relatively good flow prediction can be achieved while avoiding experimental costs (*e.g.* body manufacturing and wind tunnel time) [1] [2] [3] [4]. However, note that simulations are based on mathematical models that, whilst intended to represent the real fluid, are subject to errors from (i) the mathematical model itself, (ii) numeric discretisation of equations, and (iii)

representation of the ‘real-world’ environment (*i.e.* fidelity of boundary conditions); which can have an accumulative effect on simulations that are both unpredictable and difficult to control. The validation of CFD modelling is a key-step to enhance and quantify the accuracy and reliability of the numeric results, and for that, a well-known baseline case likely to be required for assessing the numerical modelling. This also highlights the dependence of the CFD approach to a ‘trustful’ reference dataset & CAD geometry; a gap that wind tunnel can fulfil as the main experimental dataset source.

Regarding automotive design, most of the current design approaches for ground vehicles are focused only on the performance optimisation of a single model. While this approach simplifies the design process, the environment disturbances that a given vehicle would be exposed to in practice are mostly ignored, thus subtracting critical aerodynamic interferences such as vehicle-to-vehicle proximity ([Figure 1](#)).

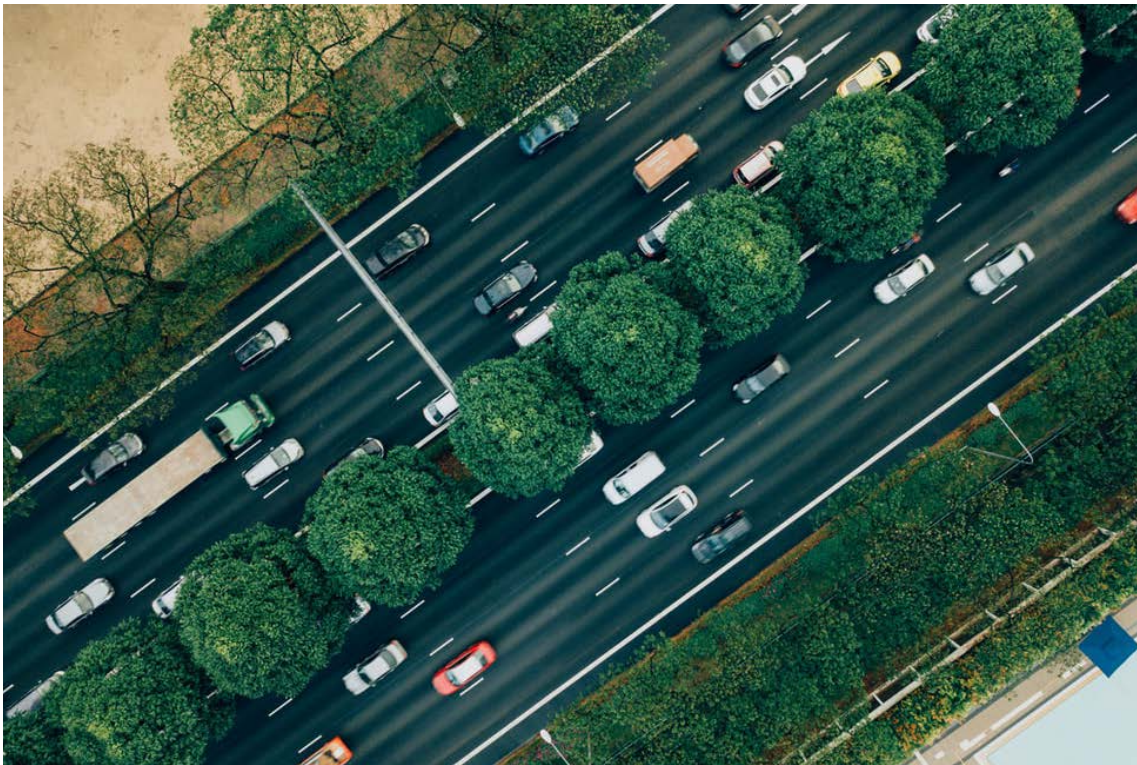


Figure 1. Vehicles are often exposed to traffic formation, creating a mutual aerodynamic interference. (source: [Unsplash](#)).

To illustrate this point, a group of preliminary CFD simulations¹ were carried out in order to illustrate that, for instance, the cooling flow of a passenger vehicle can be impacted in close proximity (Figure 2), while a high-performance race car usually has the aerodynamic balance significantly changed when moving in the wake of a leading car (Figure 3).

Another aspect for consideration is the current attention being given to autonomous vehicles. It is likely that the contemporary understanding of the expression ‘traffic jam’ will be changed in a mid-term future due to interacting vehicles in a network. Even though public acceptance may take years or decades to be fully satisfied, the technology continues to be developed and already offered commercially (*e.g.* Tesla car models).

There are research investigations currently in progress evaluating on-road, platooning formation for passenger cars – a line of vehicles following each other in close proximity, ideally at a constant pace. The manoeuvre has already been used by goods vehicles with human drivers, where the focus is on aerodynamic drag reduction and therefore fuel savings. However, autonomous vehicles may execute the manoeuvre more efficiently and this may also be applicable to other types of vehicles, while ensuring safety and constant-moving traffic.

This project anticipates a near future where ground vehicles, specially passenger cars, will be mostly dominated by autonomous and interconnected vehicles, usually at close-proximity and in constant-moving traffic lines. In such a scenario, the aerodynamic interaction between vehicles must be considered in the design process, and therefore, the current experimental and computational tools should be optimised for this goal.

¹ The simulations presented in Figure 2 and Figure 3 were carried out following the CFD cost-effective methodology found in Chapter 3.

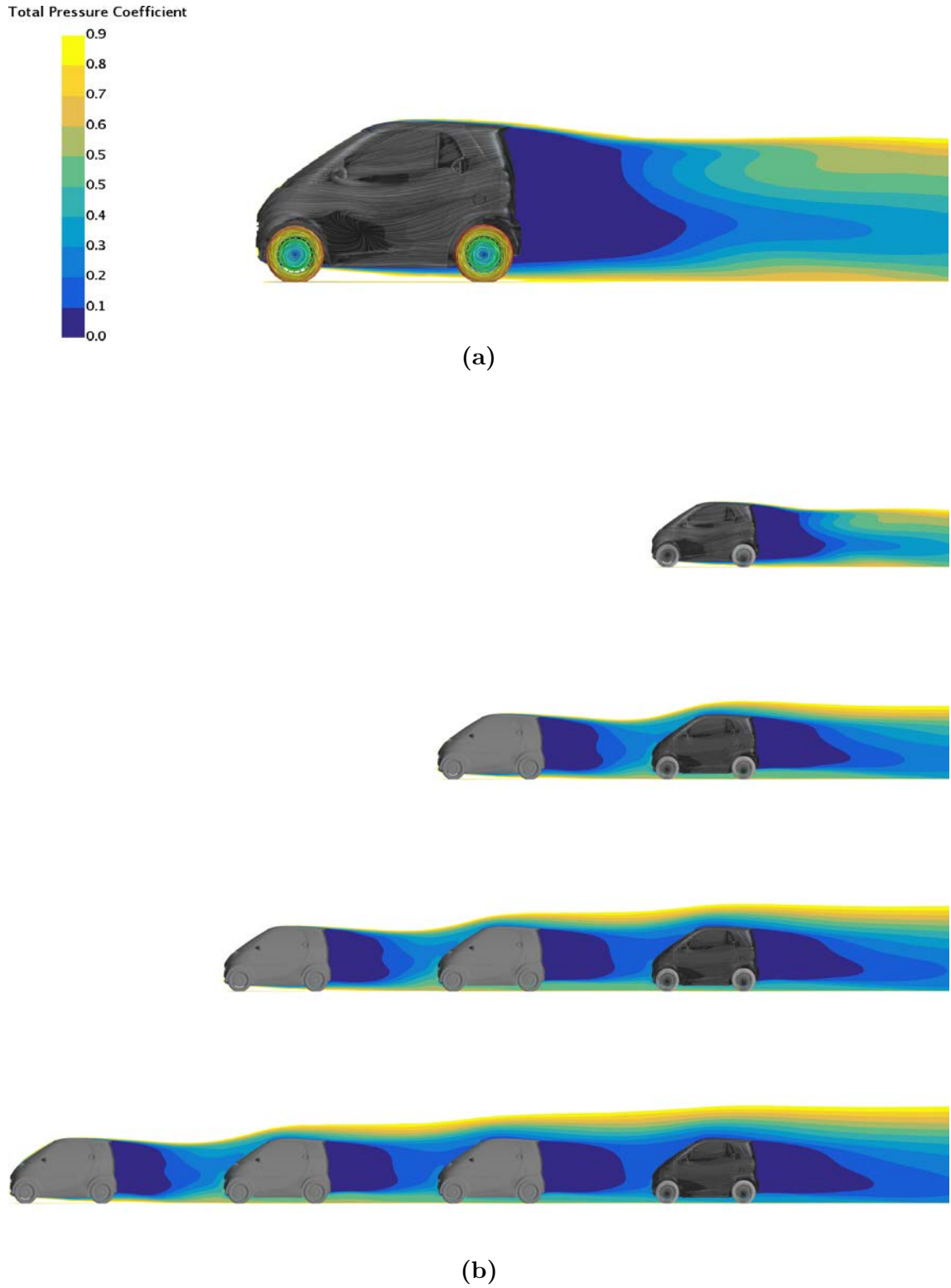
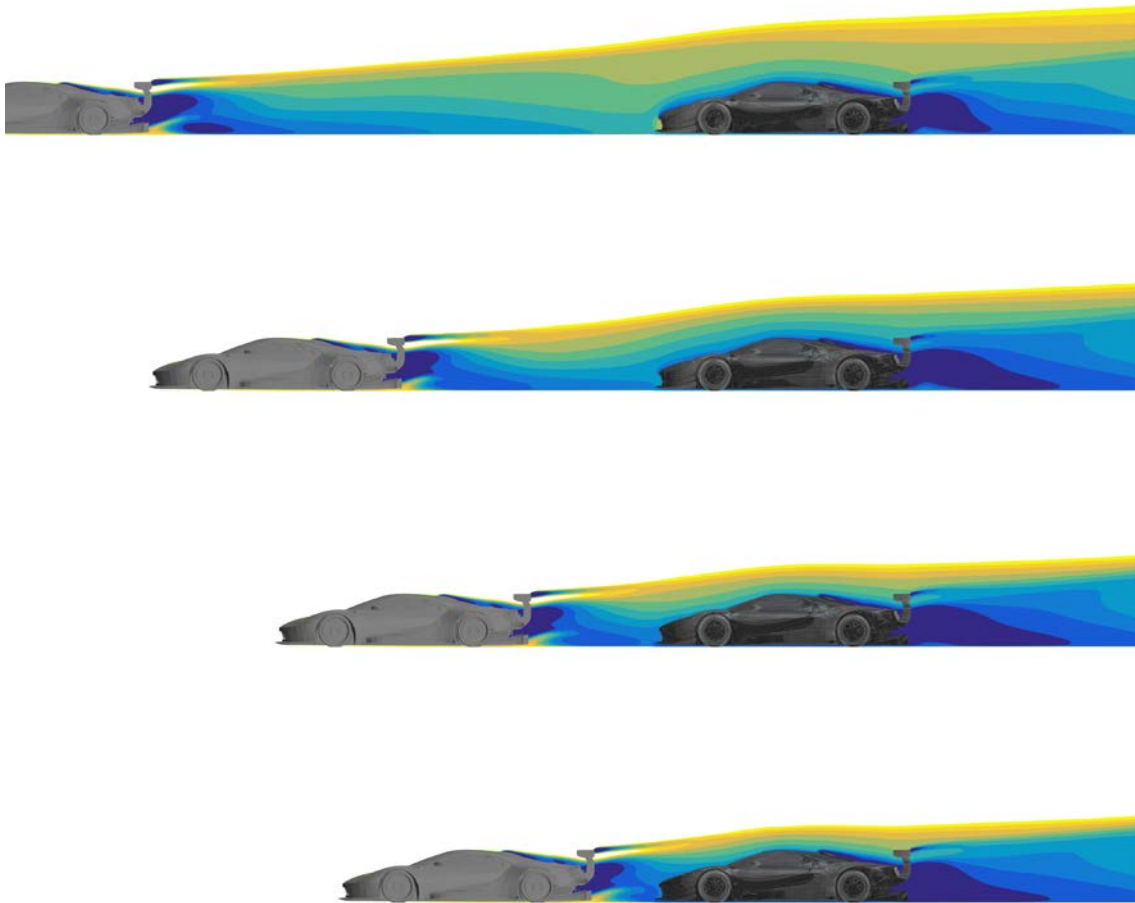


Figure 2. Wake visualisation of platooning formation (compact car model). (a) Isolated, single passenger car; and (b) same vehicle joining a 2-, 3-, and 4-vehicle platoon formation.

C_{p_t} contours at symmetry plane between 0 (dark colour) to 0.9 (light colour).



(a)



(b)

Figure 3. Wake visualisation of drafting approaching manoeuvre between race cars. (a) Isolated, single race car; and (b) same vehicle approaching an identical model from $x/L = 2.00$ to $x/L = 0.25$.

C_{pt} contours at symmetry plane between 0 (dark colour) to 0.9 (light colour).

Most current wind tunnel facilities are unable to accommodate multiple full-body vehicle models (at a relevant scale) due to working section length limitations. Indirectly, this also impacts the quality of CFD development in relation to this topic, since adequate validation process for vehicle platooning would require established, experimental references.

The development of an automotive wake generator device could potentially simplify the current process of using a controlled, wind tunnel environment for testing car models exposed to representative automotive wakes. Therefore, the proposal for a standard wake generator – capable of reproducing representative wake characteristics for different vehicle configurations – could make wind tunnels fit for the forecasted demand of data for platooning aerodynamics, expanding the tools available related to future aerodynamic vehicle design.

1.1 AIM AND OBJECTIVES

This project aims to develop a standard but adaptable device able to reproduce distinct wake characteristics corresponding to different closed-wheel automotive vehicle categories without replication of a full-body vehicle.

This will reduce complexity in both experimental testing and computational simulation, enhancing the capability of experimental facilities to study interference effects between vehicles and allowing faster build, meshing and computational time for CFD studies.

There are two requisites for the development of a potential wake generator device:

- i. Full-body model references.
- ii. Experimental database of respective automotive wakes.

The DrivAer model [5] configurations represent three automotive categories, all related to passenger models, while there is no relevant representation of a high-performance vehicle. In consequence, this project adopted two policy points followed:

- i. Design of an additional DrivAer configuration by implementing an aerodynamic add-on kit (*i.e.* proposal of a 4th DrivAer model: high-performance fastback).
- ii. Focus on the simplicity and cost-effectiveness of (i) simulations and (ii) experiments, as well as the aerodynamic solutions proposed for further experimental and computational implementation.

From the perspective of professional skills, the researcher pursues the strengthening of knowledge in automotive aerodynamics. The goals in the professional perspective are:

- i. To increase the understanding of flow phenomena in automotive aerodynamics.
- ii. To acquire knowledge in experimental techniques and tools for wind tunnel test methodologies.
- iii. To develop an alternative tool for further automotive development in near-proximity and platooning formation.

1.2 RESEARCH METHODOLOGY AND LIMITATIONS

This section presents the initial guidelines adopted for the research project and gives a summary of technical limitations.

1.2.1 Research Scope

The overall research methodology is divided into two main parts:

- Part I:* *Investigation of wakes generated on full-body vehicles.*
- Part II:* *Investigation of wakes emulated on a novel device.*

The goal of the first is to investigate computationally (e.g. CFD) and experimentally (e.g. wind tunnel) automotive models, and compile a database of wake development of four full-body vehicle shapes corresponding to a respective automotive category: fastback (F), notchback (N), estateback (E), and a high-performance fastback (hpF). The latter part focuses on a simple and adaptable wake generator, including test, simulation, and database compilation of wakes development emulated with the proposed device.

1.2.2 Research Phases

The initial plan defined three research phases as *Part I*, while *Part II* consists of another two phases. The expected milestone of each phase is:

Phase I: Produce a validated CFD procedure for automotive wake simulation at realistic levels of working section blockage (Figure 4).

Phase II: Design a high-performance DrivAer Fastback configuration with an appropriate level of drag, downforce, balance, and wake characteristics (Figure 5).

Phase III: Compile experimental-based wake characteristics of the four vehicles categories generated on full-body cases (Figure 6).

Phase IV: Design of a simple, adaptable wake generator (Figure 7).

Phase V: Compile experimental-based wake development of four vehicles categories emulated on the experimental device (Figure 8).

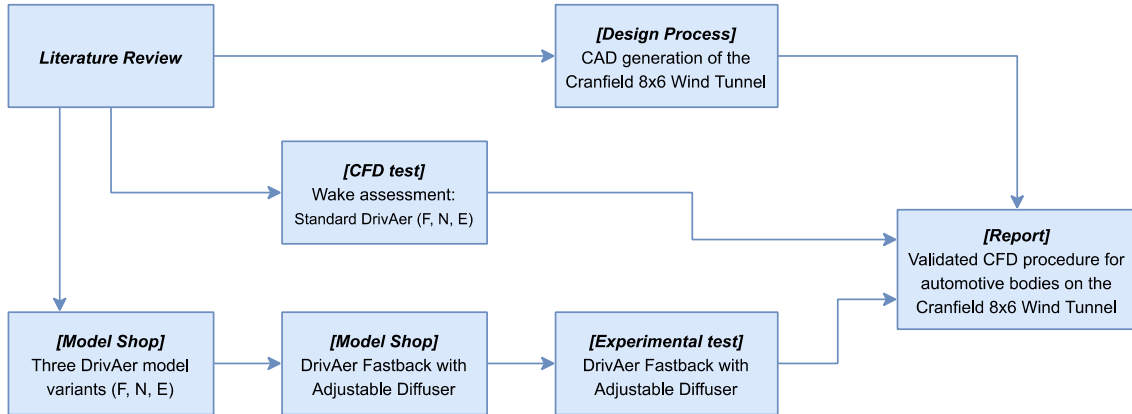


Figure 4. Methodology, Phase I: Validated CFD procedure for modern automotive shapes.

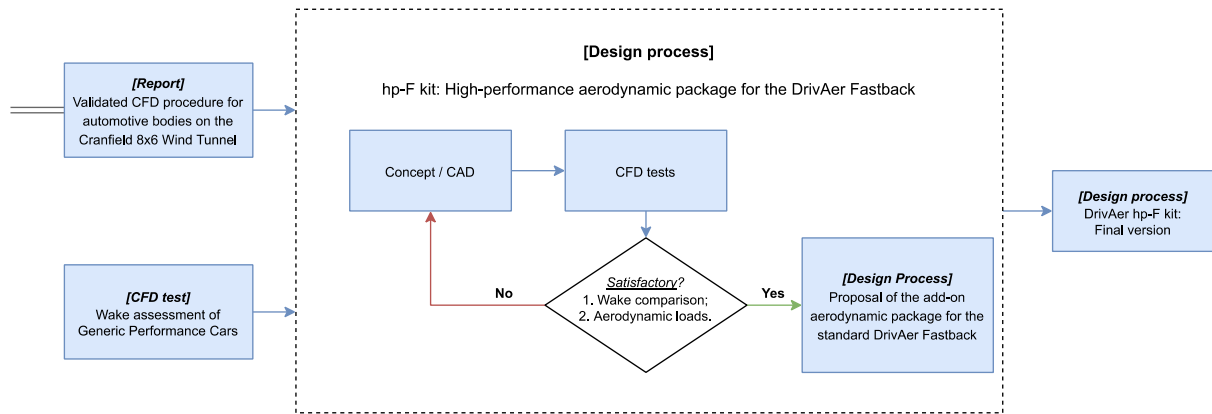


Figure 5. Methodology, Phase II: Design of a high-performance DrivAer Fastback configuration.

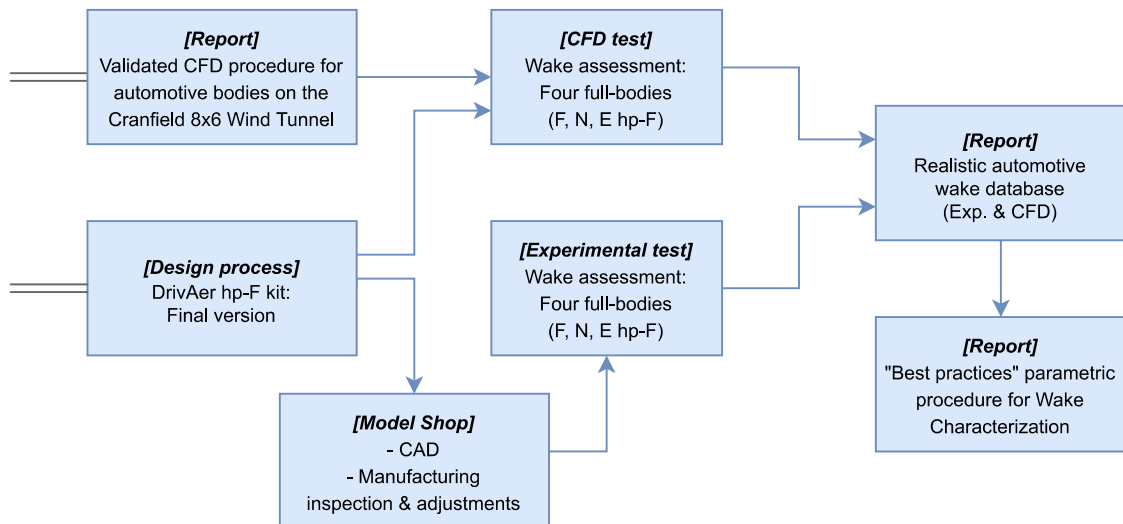


Figure 6. Methodology, Phase III: Extensive wake assessment of full-body vehicle shapes.

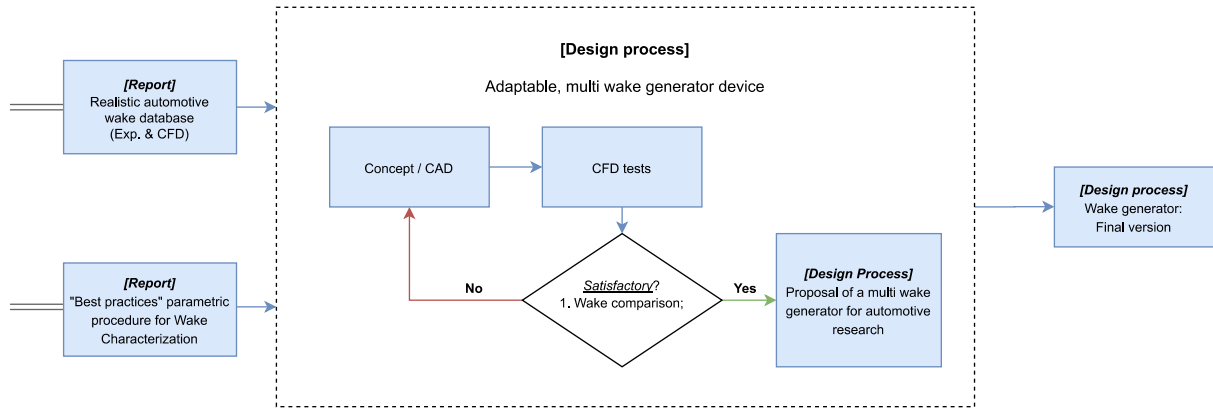


Figure 7. Methodology, Phase IV: Design of a wake generator.

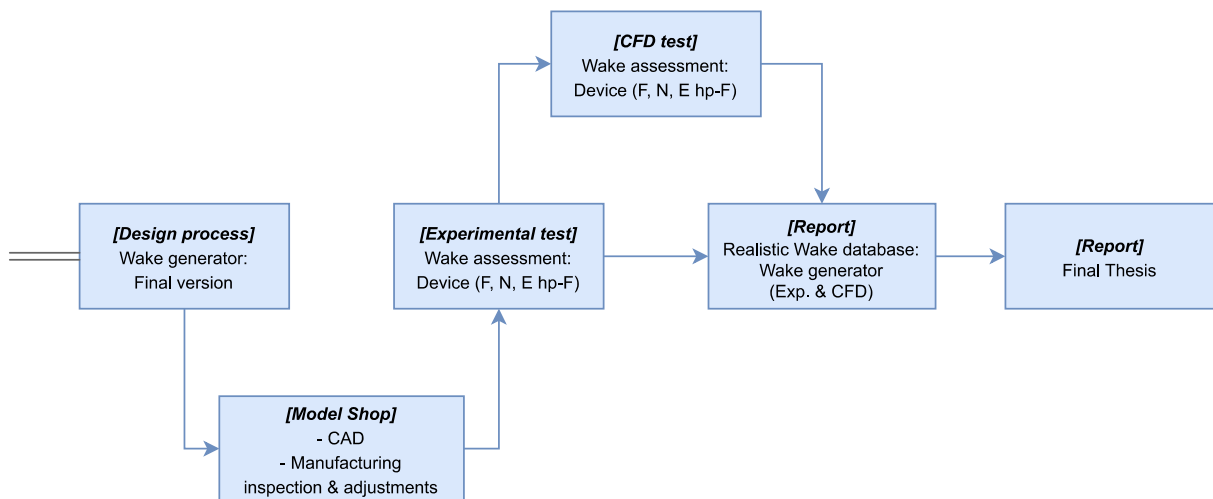


Figure 8. Methodology, Phase V: Wake assessment of the device and thesis conclusion.

1.2.3 Fundamental Design Guidelines

A few guidelines are adopted on the research project plan in order to increase the challenge and the range of applicability of achievable results. These can be summarised over different activities, as follows:

Wake Generator:

- I. Develop a cost-effective, easy-to-use solution for automotive wake emulation (necessary).
- II. Ensure compact dimensions and design simplicity (necessary).
- III. Achieve an adaptable and/or adjustable device for non-stop wind tunnel test routines (ideal).

Experiments, Simulations:

- IV. Ensure cost-effective use of both wind tunnel and computational resources (necessary).

High-performance benchmark model:

- V. Consider the DrivAer Fastback car model as a baseline for the development of a high-performance vehicle benchmark (ideal).
- VI. Ensure that this benchmark model can generate a representative wake of a race car model (necessary).

1.3 THESIS OUTLINE

Following this introduction chapter, *Chapter 2* contains a discussion on the technical literature related to (i) wake characterisation, (ii) automotive benchmark models and (iii) bluff-body wake generators.

Chapter 3 presents the validation of CFD simulations, divided into (i) mesh sensitivity, (ii) correlation to passenger vehicles and (iii) correlation to race car models.

Chapter 4 addresses the experimental assessment of automotive wakes using a pressure-based technique: total pressure rake. A preliminary analysis of the wind tunnel and acquisition resolution is presented. The main experimental campaign provides a wake database of four vehicle models in terms of total pressure coefficient.

Chapter 5 reports the wake characteristics of the same vehicle models but using an image-based measuring technique – Stereoscopic Particle Image Velocimetry (SPIV). The results of the main experimental campaign are presented as a wake database of four vehicle models in terms of 3D velocity fields.

Chapter 6 introduces the design process of a wake generator device. The design process is divided into three phases: (i) proof-of-concept, (ii) investigation of concepts, and (iii) investigation of an adaptable, multi-wake generator body.

Chapter 7 reports the experimental assessment of the wake generator using a total pressure rake, in a similar manner to full-body models (see *Chapter 6*). A wake database for the device shapes is presented.

Chapter 8 summarises the research project and provides recommendations for future investigations.

Additional materials are presented in the Appendix, as follows:

- Wake pathlines of models using CFD validation ([Appendix A](#)).
- Wake development from a single-seater racing car in different ground conditions ([Appendix B](#)).
- Detailed-based CFD assessment of the wind tunnel experimental conditions ([Appendix C](#)).
- Proposal of an active-controlled design for wind tunnel experiments ([Appendix D](#)).
- Dimensional drawings of the wake generator configurations for (i) modular concept, (ii) adaptable concept for zero-yaw use, and (iii) further development suggestion for adaptable, yaw-variant concept ([Appendix E](#)).

Chapter 2.

LITERATURE REVIEW

This chapter presents a summary of the literature, which is split into (i) wake characterisation of automotive configurations, (ii) current automotive benchmark (*i.e.* DrivAer car model), and (iii) use of bluff bodies as wake generators.

2.1 WAKE CHARACTERISATION OF AUTOMOTIVE SHAPES

Most significant and pioneering studies in this field were performed by Ahmed *et al.* [6], who presented a study of the wake structures of automotive shapes (Figure 9). Three vehicle categories were investigated (*e.g.* fastback, notchback, and estateback shapes), and the results were achieved by experimental testing of the $\frac{1}{4}$ scale models, on a stationary wall, at freestream velocity equal to 60m/s (*i.e.* $Re = 4.3 \times 10^6$). The velocity fields in respective wakes were assessed with a nine-hole pressure probe, while flow visualisation required an emulsion of aluminium oxide and kerosene as well as a plane positioned close to the rear. The main results were (i) the identification of the near-wake flow structure, mainly from the oil-flow technique, and (ii) the wake development up to one-car length downstream shown by velocity field and total pressure contours in planes orthogonal to the velocity axis.

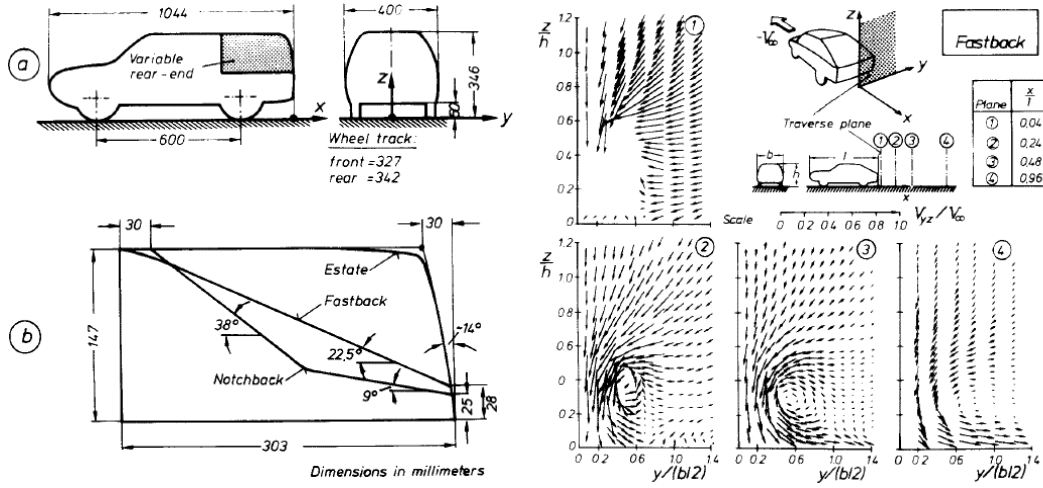


Figure 9. Study on the wake structures of automotive shapes performed by Ahmed [6].

Onorato *et al.* [7] investigated the relation between wake structure, drag, and body geometry using simplified bodies. A series of body shapes, from a streamlined to a simplified vehicle-like body, were evaluated based on modular parts. This approach demonstrated simple but effective in an experimental test at 40 m/s , using a model scale of $1/4.25$, that of a 1986's passenger car. A nine-hole total pressure probe evaluated a wake plane of each configuration using an automated transverse, while an external balance acquired the drag force. It was identified that including windshield inclination produced a raising of the wake, which was associated with a drag coefficient increase of nominally 4%. The authors found that a bluff-body (model M4, $C_d = 0.176$) had a total pressure distribution with a local minimum of $C_{pt} = 0.1$, while the most drag-efficient body (model M1, $C_d = 0.071$) showed a smaller wake area and local minimum of $C_{pt} = 0.4$. This publication illustrates the importance of understanding the wake characteristics in automotive aerodynamics, while highlighting the use of a total pressure probe as a simple but efficient tool.

Computer simulations were limited in the 1990s, and experimental studies were the primary source of technical knowledge in this field. Fukuda *et al.* [8] exemplify

the evolution of CFD application on wake assessment. In order to achieve an improvement of vehicle aerodynamics via wake control, the authors measured the pressure distribution, aerodynamic forces, and the near wake. Based on the experimental velocity field and rudimentary simulation, it is seen that a modified, fastback rear-end shape achieves improved aerodynamic performance by changing the near-wake development.

Subsequent numerical studies proved a substantial source of new understanding as a result of the technological evolution of computational resources. Keogh *et al.* [9] investigated the aerodynamic effects of a cornering manoeuvre on the forces and wake development. The author’s approach identifies significant flow phenomena in the wake development of ground vehicles. However, the lack of a wake assessment of modern automotive shapes meant that the study was focused on the Ahmed body [6] for validation of computational tools and wake comparison, rather than the latest reference body: the DrivAer car model [5].

The scientific investigation of automotive wakes has seen growing interest in one of the state-of-art experimental approaches: the image-based technique ‘Particle Image Velocimetry’ (PIV). This technique consists of measuring displacements of particles (usually known as ‘seeds’) in a flow, which can be converted into velocity vectors field [10].

Cogotti *et al.* [11] presented one of the earliest relevant PIV-based automotive applications at the Pininfarina Wind Tunnel. The authors showed that the technique was feasible for the study of automotive wakes, where full-scale vehicles were tested.

PIV studies are yet being carried out using simplified bodies, but with purpose of wake studies of hatchback geometries [12], investigation of near-wall flows [13] and technique *per se* for automotive aerodynamics [14], and study of wake bi-stability of a squareback model [15]. The later exemplified the use of tomographic

PIV. Another hardware configuration is the stereoscopic PIV (SPIV), where multiple cameras assess an identical flow section and estimate the spatial (3D) seeding displacement, therefore providing a 3D velocity vector field [10]. For high-performance vehicles, SPIV (Stereoscopic PIV) has already been in the interest of motorsport industry for over a decade, as highlighted by Nakagawa *et al.* [16], reporting experimental investigation around a Toyota F1 2008 car.

2.2 AUTOMOTIVE BENCHMARK: DRIVAER CAR MODEL

Heft *et al.* [5] presented the DrivAer reference model: a vehicle body with interchangeable rear-ends, as well as with different underfloor configurations and an option for an external rear-mirror (Figure 10). Their experimental tests investigated a 40% scale model regarding: (i) drag coefficient as a function of the length-based Reynolds number (Re); (ii) drag coefficient of the 36 configurations tested experimentally; and (iii) axial pressure distribution on the upper, lateral, and lower surfaces for several configurations, as well as the pressure distribution on the windshield, side and rear windows. Note that those drag results are corrected to remove rolling resistance from wheels on the moving belt.

A preliminary version of the model had been illustrated in earlier publications [17]. For instance, Wojciak *et al.* [18] [19] [20] explored the unsteady aerodynamic flow phenomena on the notchback model. Both experiments and simulations addressed a time-dependent flow generated by the sinusoidal yaw oscillation on the 50% scale car model, where the oscillation varied from $1Hz$ to $4Hz$, and yaw angle from $\pm 1^\circ$ to $\pm 5^\circ$. A Reynolds number dependence study up to 1.2×10^7 is included in Wojciak *et al.* [18]. The key results were (i) the identification of a delayed reaction of the wake flow near 15% of the oscillation period tested, (ii)

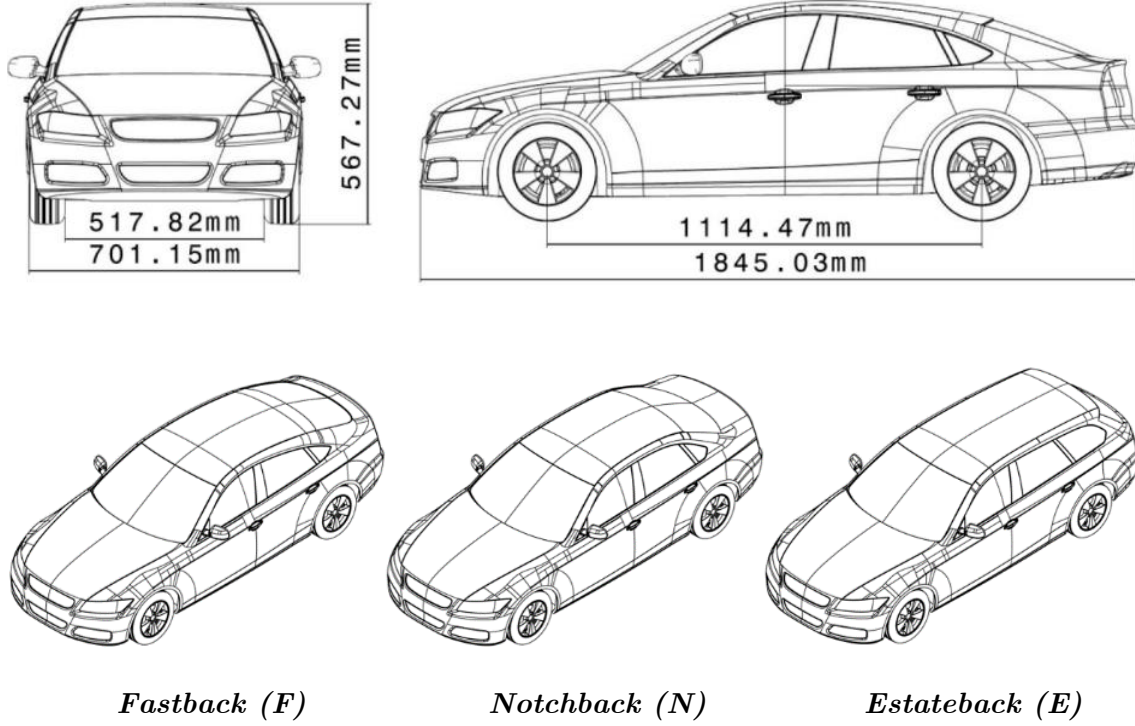


Figure 10. DrivAer car model (as presented by Helf *et al.* [5]): 40%-scale body dimensions and three rear-end configurations: Fastback, Notchback, and Estateback.

comparison of unsteady to quasi-steady aerodynamics forces and moments, and (iii) wake topology.

Strangfeld *et al.* [21] and Wieser *et al.* [22] focus on the experimental aerodynamic forces and pressure distributions using 25% scale models at TU Berlin's wind tunnel. A 50% scale version was used only on the preliminary version of the model [18] [19] [20], which had a rounded rear-end surface.

Computational-based published studies using DrivAer models are mostly focused on (i) validation of computational tools (*e.g.* CFD techniques) based on real-case experiments, and (ii) assessment of automotive aerodynamics beyond experimental constraints (*e.g.* wind tunnel blockage). Researchers have also shown the advantages and limitations of CFD approaches (*e.g.* RANS, URANS, DES, and

LES) and alternatives in overturning modelling challenges such as (a) relative wheel movement, (b) meshing & finite domain constraints, and (c) effects of environmental unsteadiness.

The most recent geometry pack (2015, [23]) included internal components in order to expand the investigation to internal flows. A constantly growing number of publications adopting the model proved that it became the relevant benchmark in a similar fashion to what the Ahmed bodies did a few decades ago.

2.3 BLUFF-BODY WAKE GENERATORS

Relatively few authors have addressed the concept of a leading-vehicle wake generator. Soso *et al.* [26] investigated experimentally the effect of a race car wake on the aerodynamic performance of a following wing in ground effect. The race

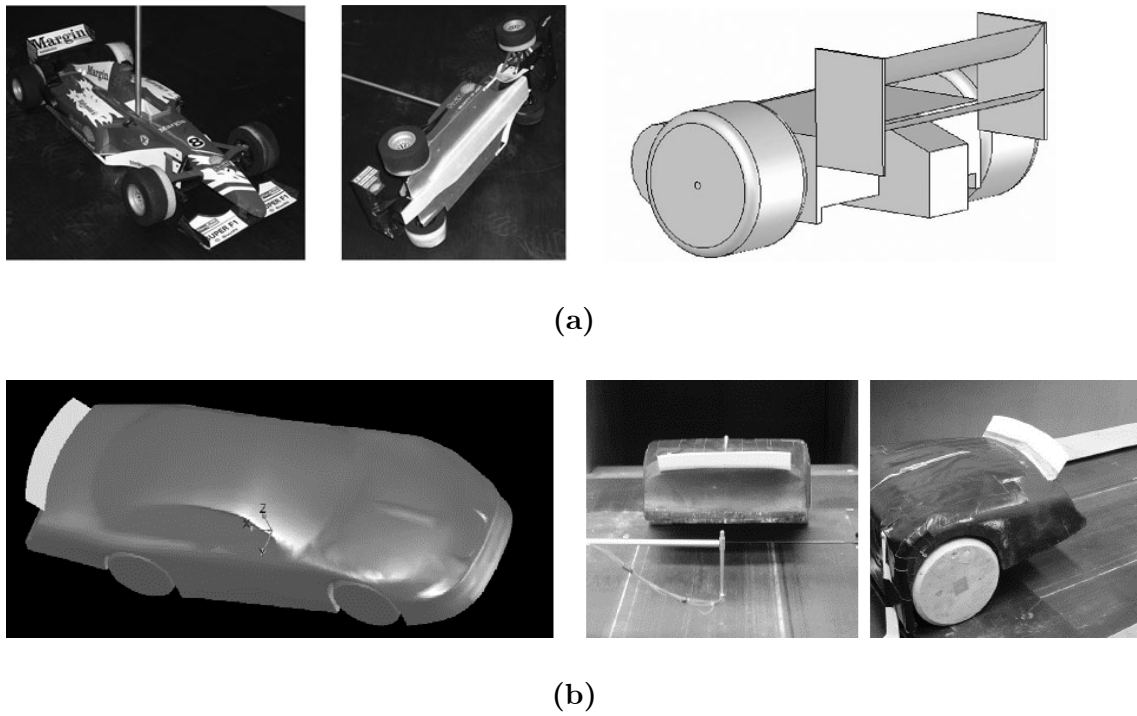


Figure 11. Bluff-body wake generators of performance cars.
 (a) Wilson *et al.* [24], (b) Dominy *et al.* [25].

car body was simplified to a bluff body with a rounded front surface, diffuser and mounted wing. Despite the fact the wake generated was not assessed in detail and was probably oversimplified, the results on the wing were in line with the known influence of a realistic race car wake (*e.g.* pair of counter-rotating vortices coupled with a strong upwash stream, [27] [28] [29]).

Figure 11 illustrates the work of Wilson *et al.* [24] and Dominy *et al.* [25], which demonstrated that bluff-bodies could be applied for the emulation of ground vehicle wakes in an experimental environment.

Wilson *et al.* [24] reported work intended to design and test a wake generator able to create an accurate representation of wake flow generated from a F1 car model. The wind tunnel-based study involved (i) a wake survey on a 1/6 scale 2006 F1 car model in two planes downstream the model, then (ii) designing and testing

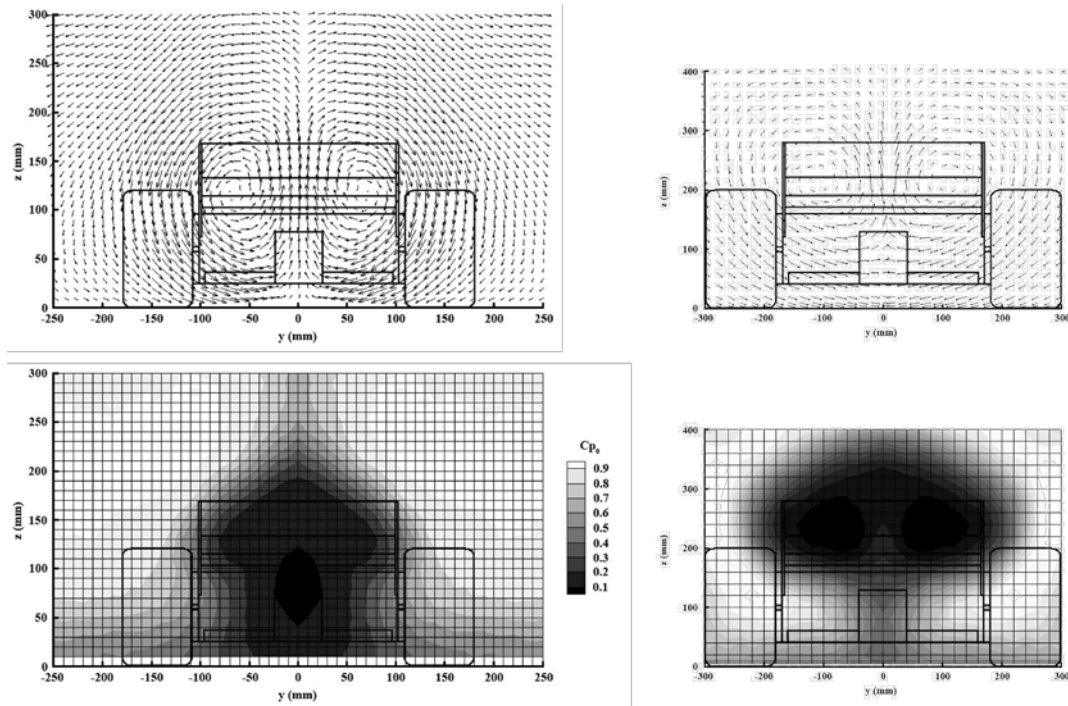


Figure 12. On the challenge of wake emulation (Wilson *et al.* case [24]). A full-body model (left column) and respective wake generator (right column) have a significant difference in the total pressure at $x/L = 0.50$, even though similar velocity fields are produced.

the simplified wake generator. The contrast of ‘stagnation pressure’ (*i.e.* total pressure) between the model and the wake generator at the same plane illustrates the challenge of a high-quality wake generation, albeit the secondary flow was acceptable in magnitude and position (Figure 12).

Dominy *et al.* [25] employed CFD simulation in order to obtain a wake dataset, which led to the design of a bluff-body wake generator, and respective experimental test. The wake comparison between the simulation of a full-scale NASCAR car and a respective, physical bluff-body indicated a correlation between the main flow phenomena.

A wake generator study was presented by Ebrahim *et al.* [30] relating to vehicle platooning aerodynamics using computational simulation. The interaction between two Ahmed bodies was evaluated, and a two-parameter (*e.g.* length and gap) analysis was performed on the leading body in order to shorten it as much as possible while sustaining similar wake characteristics. The outcomes reinforce the use of a CFD approach as a useful tool for optimisation of a bluff-body wake generator.

Chapter 3.

VALIDATION OF CFD SIMULATIONS FOR AUTOMOTIVE APPLICATIONS

This chapter addresses the validation of the CFD simulation method adopted for three-dimensional, realistic vehicle bodies. For passenger car models, this process was based on the following experimental database: Heft *et al.* [5], Collin *et al.* [31], Wieser *et al.* [22]; all using the DrivAer model. Their experiments were carried out using different wind tunnel types, model setup configurations and at different Reynolds numbers (*e.g.* geometric scales and freestream condition). An additional section addresses the wake of race car aerodynamics, considering the work of Watts *et al.* [27], and Newbon *et al.* [28].

The author is aware that differences in the experimental approach – such as ground simulation, working section, blockage, freestream turbulence level, physical model rig, and the wind tunnel type itself, can significantly impact the data. Therefore, a compilation of validation cases targets not only a specific case but also a range of conditions.

The aim of this chapter is to propose a robust, cost-effective CFD setup based on RANS modelling, that is able to simulate steady-state, aerodynamic phenomena on automotive applications. Supplementary details can also be found in the published SAE technical paper [32].

3.1 GLOBAL METHODOLOGY

3.1.1 Numerical Setup

CFD simulations for validation purposes were performed using Star-CCM+, double-precision, version 11.02. The CFD setup is an optimised approach based partly on previous studies, see [33] [34] [35] [36] [37], where results led to conclude that a RANS modelling approach using (at least) 2nd-order *Realisable k - ϵ two-layer* as turbulence model can be cost-effective in terms of computational resources in studies of external automotive aerodynamics.

A segregated flow solver is chosen for higher robustness against numerical instabilities, while constant density is an acceptable assumption for this application due to the low Mach number (*i.e.* $M < 0.15$, [38]).

Turbulence properties are modelled by *Realisable k - ϵ two-layer*: an improved version turbulence model from the k - ϵ group. All numeric gradients are calculated

Table 1. Cost-effective CFD setup summary.

Feature	Description
Time regime	steady-state
Equation of State	constant density
Fluid (air):	
Reference density	$\rho = 1.184 \text{ kg/m}^3$
Reference dynamic viscosity	$\mu = 1.855 \times 10^{-5} \text{ Ns/m}^2$
Reference temperature	$T = 298 \text{ K}$
Flow Solver	segregated
Flow regime	turbulent
Turbulence model	Realisable k - ϵ two-layer
Gradient order	2 nd -order, Hybrid Gauss-LSQ

with 2nd-order using *Hybrid Gauss-LSQ* method. *All y^+ Wall Treatment* is applied on a set of prism layers (see meshing details at [section 3.2.4 ‘Meshing Strategy’](#)). It is a cost-efficient approach when compared to fully calculated boundary layers.

3.1.2 Vehicle Model and Flow Parameters

The standard coordinate system origin is placed identically to the DrivAer CAD geometries – the centre point of the front wheel axle. It agrees with the definition presented in Katz [1], Barnard [39], and Hucho [40]: the $+ve$ x -coordinate is in the downstream direction, while $+ve$ z -coordinate is in the lift direction and positive y -coordinate starts from the symmetry plane ([Figure 13](#)).

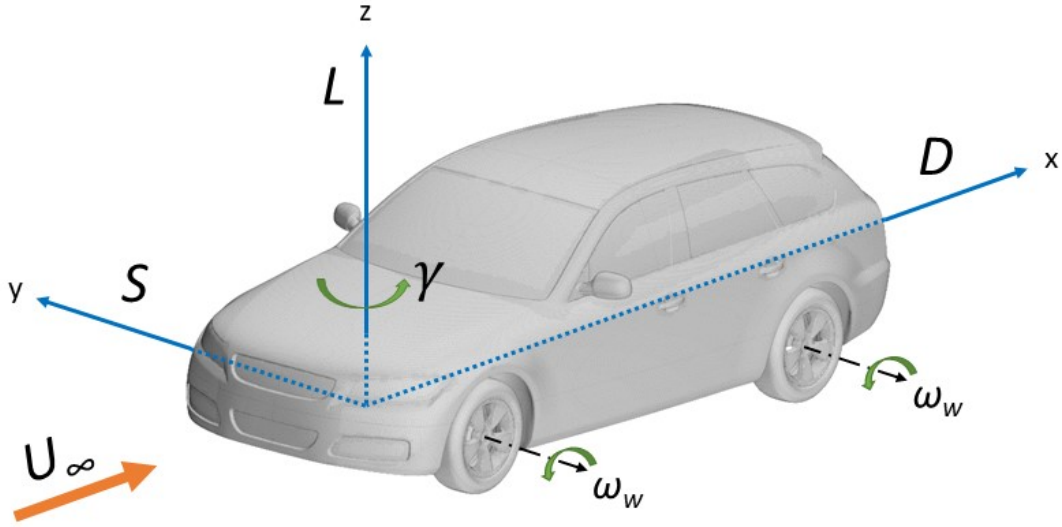


Figure 13. Coordinate system adopted for automotive applications.

[Table 2](#) summarises the normalised parameters for spatial and flow dynamics. All geometric parameters have been parametrised as a function CS (*i.e.* car scale factor) in order to create a normalised reference for further studies. [Table 3](#) presents the normalised definition of DrivAer dimensions and physical size for versions used at TUM [5], Audi [31], and TU Berlin [22].

Table 2. List of normalised parameters.

Parameter	Symbol	Definition
Normalised x -coordinate	x/L	$(x - 0.8075 \text{ CS}) / L$
Normalised y -coordinate	y/W	y/W
Normalised z -coordinate	z/H	z/H
Normalised velocity	u/U_∞	u/U_∞
Drag coefficient	C_D	$F_D / (\rho_\infty A_{ref} U_\infty^2 / 2)$
Lift coefficient	C_L	$F_L / (\rho_\infty A_{ref} U_\infty^2 / 2)$
Pressure coefficient	C_P	$P / (\rho_\infty U_\infty^2 / 2)$
Total pressure coefficient	C_{p_t}	$\frac{P}{\rho_\infty U_\infty^2 / 2} + \left(\frac{u}{U_\infty}\right)^2$
Total pressure loss coefficient	$C_{p_{t_l}}$	$(1 - C_{p_t})$

Table 3. Parametric dimensions for DrivAer car models.

Parameter	Symbol	Definition	DrivAer TUM, DrivAer Audi	DrivAer TU Berlin	
Car scale	CS	—	40 %	25 %	
Reference length	L	$4.6126 \times CS$	1.8450	1.15315	m
Front end (x -position)	x_o	$-0.8075 \times CS$	[-0.323, 0, 0]	[-0.202, 0, 0]	m
Front wheels axle position	x_F	0	[0, 0, 0]	[0, 0, 0]	m
Rear wheels axle position	x_R	$2.7861 \times CS$	[1.1145, 0, 0]	0.696525	m
Reference height	H	$1.4182 \times CS$	0.5673	0.3546	m
Reference width; Wheel track	W	$1.7529 \times CS$	0.7012	0.4382	m
Wheel radius	wr	$0.3180 \times CS$	0.1272	0.0795	m
Wheelbase	wb	$2.7862 \times CS$	1.1145	0.6966	m
Reference area	A_{ref}	$2.1605 \times CS^2$ (full-car, F)	0.1728 (half-car)	0.0675 (half-car)	m^2

3.1.3 Wheel Modelling

Wheel contact patches on the ground surface were necessary for both physical and computational reasons. The first is due to the need to replicate the physical fluid phenomena around the wheel-surface (*e.g.* realistic pressure distribution and corresponding ‘horse-shoe’-like vortex structures). The second is related to the eventual numeric instability generated on poor quality cells close to the tangent contact of perfectly rounded wheels on a plane surface [34] (*e.g.* ‘needle’-like cells: elements where aspect ratio can be measured in orders magnitude).

Two approaches were considered as follows: (a) to create a fixed plane tangential to the tyres as the ground plane and move the wheel axis downwards through the ground plane, then subtract the wheel volume below the surface to create a contact patch; or (b) fix the position of the body and wheels, and move the ground plane upwards crossing the wheel surfaces. Even though both approaches would provide identical tyre patches, the first approach would change the position of the

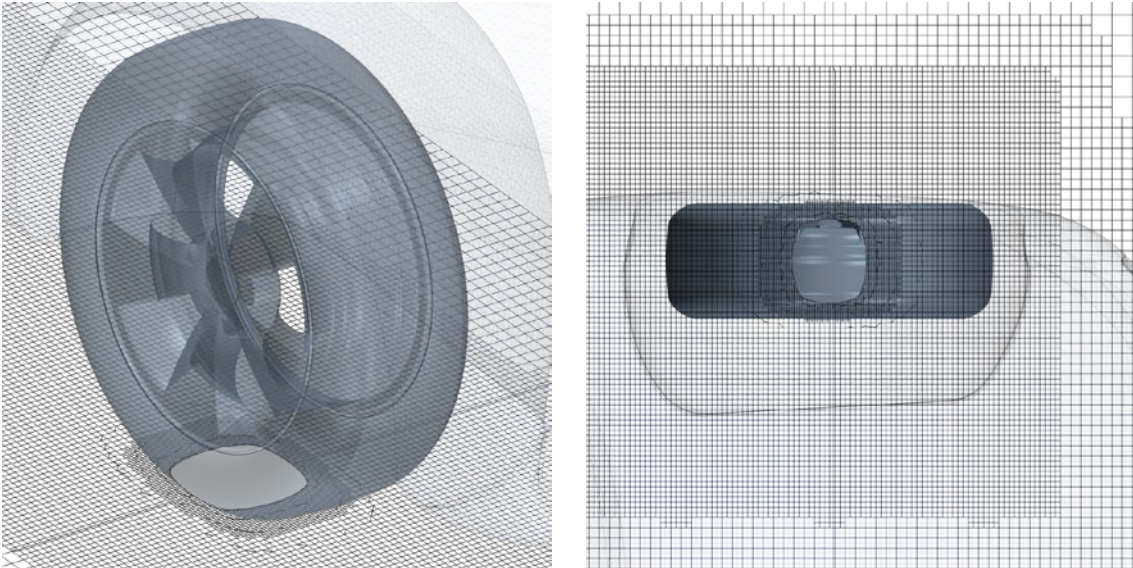


Figure 14. Frontal tyre contact patch for DrivAer model. The feature emulates a more realistic deformation and improves numerical robustness due to meshing quality.

wheel inside the wheelhouse, and it is known to be a region of significant drag generation.

As a result, solution *b* chosen was since the positioning between the wheel surface and respective wheel cavity is sustained, whereas a small reduction in the body ground clearance (*e.g.* near $0.01m$ for a full-scale model) may result in a small increase in ground effect (*i.e.* increase of local flow velocity coupled to a pressure reduction). This issue is acceptable in order to maintain the geometry inside the wheel cavity and the related fluid dynamics from such regions. Therefore, the standard ground plane for the DrivAer model is hereafter defined as $0.219H$ (normalised by the vehicle height, H) below the front wheel axle (*e.g.* $0.31m$ for a full-scale model).

3.2 NUMERICAL VALIDATION, PART I: On the Meshing Sensitivity of Numerical Simulation

This section addresses the analysis of the mesh sensitivity regarding the optimisation of CFD setup based on [33] [34] [37] [41] [42]. Results will assist in understanding the simulation sensitivity of automotive bodies and enhance the meshing strategy for final validation cases.

3.2.1 Experimental References

In the initial proposal of the DrivAer model Heft *et al.* [5] included a collection of experimental results and cited the availability of all related CAD models.

The scope of the current CFD validation exercise is mostly focused on the sensitivity of the computational approach to different car categories, represented by the Fastback, Notchback, and Estateback rear-ends (denoted by F , N , and E , respectively). While interchanging the rear body provides a representation of those car categories, other features form a standard configuration, which includes: side mirrors (wM), a smooth underbody (S) and detailed wheels and tyres (wW). Table 4 summaries the vehicle components employed.

Unfortunately, the mounting system was often underestimated and rarely detailed in previous related publications. Figure 15 shows the main body held by an aerodynamic-profile overhead support strut, while the wheels are supported individually and detached from the main body.

An inherent experimental bias from that mounting configuration is expected on the measurement of pressure distribution on the upper surface. For instance, a higher-pressure zone on the wing-like leading edge and residual wake are phenomena that potentially can occur, and for a suitable validation purpose it

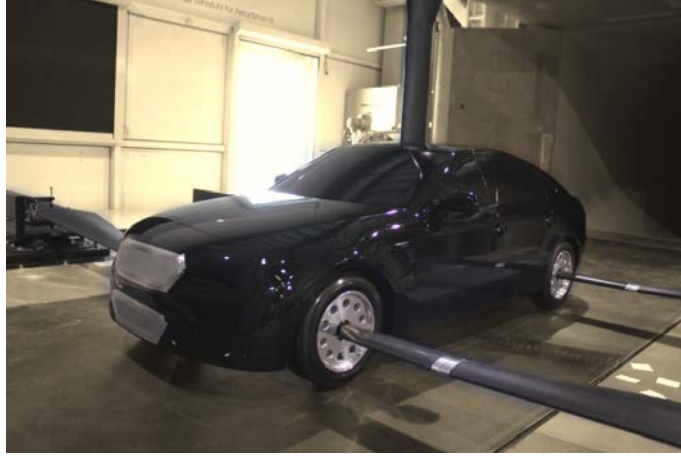
Table 4. DrivAer model configurations.: TUM (Heft *et al.* [5]) and Audi (Collin *et al.* [31]) versions.

Component	Description	Notation
Rear end	Fastback, Notchback, Estateback	F, N, E
Underbody	Smooth underbody	S
Mirrors	Standard mirror	wM
Wheels	Smooth version: generic rims and with slick tyres	wW
Strut ²	with Top Strut (NACA 0025)	wTS

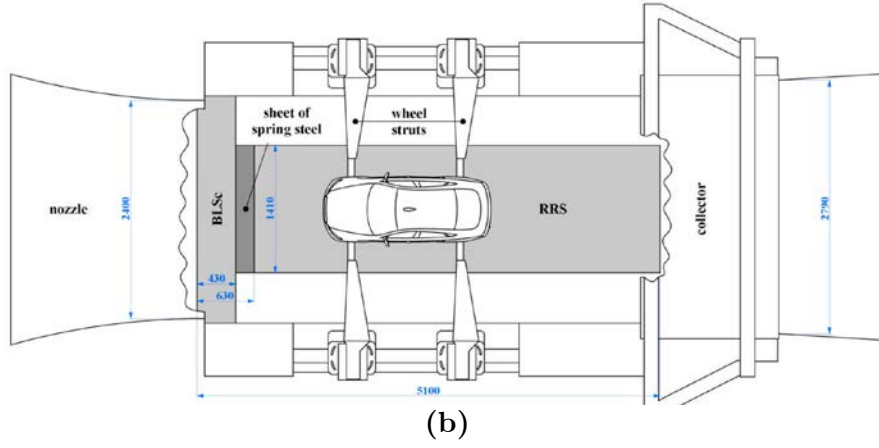
should not be ignored (*i.e.* adequate computational representation of physical conditions).

For this reason, the computational simulations for this specific case include a generic overhead support. An analysis of published images illustrating the experimental apparatus led to a design of a simplified NACA 0025 regular strut with $c = 0.375m$, where the leading edge is positioned at $x = 1.393m$ on the original full-scale DrivAer coordinate system.

² Details of the top strut was not described in the respective experimental reference [5] [43]. A reverse-engineering of the strut geometry properties were done based on image analysis.



(a)



(b)

Figure 15. Illustrations of the experimental setup tested by Helf *et al.* [5].
(a) photo [5] and sketch [43] of the experimental setup.

3.2.2 Numerical Fluid Domain

Air properties were estimated in order to provide flow similarity to the experimental freestream condition approximately to $Re = 5.2 \times 10^6$ (based on vehicle length). Flow similarity for the working fluid with a density equal to 1.184 kg/m^3 and dynamic viscosity of $1.855 \times 10^{-5} \text{ Ns/m}^2$ required a freestream speed equivalent to 44.2 m/s . A Mach number of 0.13 supported the assumption of incompressible flow.

Table 5. CFD setup summary.

Feature	Description
Domain simplification	half-symmetrical three-dimensional
Time regime	steady-state
Equation of State	constant density
Fluid (air):	
Reference density	$\rho = 1.184 \text{ kg/m}^3$
Reference dynamic viscosity	$\mu = 1.855 \times 10^{-5} \text{ Ns/m}^2$
Reynolds Number	$Re = 5.2 \times 10^6$
Flow Solver	segregated
Flow regime	turbulent
Turbulence model	Realisable $k\text{-}\varepsilon$ two-layer
Gradient order	2 nd -order, Hybrid Gauss-LSQ

For both TUM (Heft *et al.* [5]) and Audi (Collin *et al.* [31]) DrivAer experimental tests, their blockage effects are assumed as negligible because they were performed in $\frac{3}{4}$ open test sections, which provide less interference compared to a closed test section. Symmetry simplification for the numerical domain has been adopted for computational cost-effectiveness due to (i) the steady-state approach and (ii) the model symmetry at zero-yaw position.

These wind tunnel and model conditions led to the definition of a numerical fluid domain over the symmetric half-body as a rectangular block $13L$ (*i.e.* vehicle length, L) long with height of $7H$ from the ground and width equal to $5.7W$ (*i.e.* vehicle width, W) from the symmetry plane (Figure 17). The flow inlet was placed $2L$ upstream of the coordinate origin (*i.e.* the vehicle frontal axle, Figure 13).

3.2.3 Numerical Boundary Conditions

The minimum-blockage effect of the fluid domain allows a simplification of the boundary conditions. A velocity-constant freestream is set at the inlet surface, while a pressure-constant outlet is set at the downstream surface. Both top and side domain surfaces are set for mirroring properties (*i.e.* symmetry condition), based on the assumption of minimum disturbances in the farfield. The symmetry condition is convenient to be applied at the symmetry domain surface only because the modelling considers averaged, steady-state flow behaviour (*i.e.* no assessment of flow in time-dependent modelling).

Ground simulation for ground vehicles implies the following pertinent features that are modelled: (i) relative movement between the body and ground surface, and (ii) relative rotation of the wheels. The first can be simply modelled as a sliding wall moving underneath the vehicle, with the same relative velocity as the vehicle in relation to the ground, but in the opposite direction. However, the second requirement is more complex.

Wheel modelling in automotive aerodynamics remains a challenge for CFD techniques due to the complexity of the geometry and motion relative to the surrounding flow. Regarding the aim of adopting a cost-effective steady-state solution, earlier experience in this topic [33] [34] [35] [37] indicated that imposing a velocity field on the wheel surface, as a function of the wheel rotation rate and radial position, can be an acceptable approach since it emulates the main effects of the wheel relative motion (*e.g.* boundary layer generation on a ‘sliding-wall’ surface interacting with the surrounding flow at the wheel cavity). Considering this approach, illustrated in [Figure 16](#), circumvents the requirement to compute a time-dependent wheel motion, which would require re-meshing the domain for each time-step and an unsteady simulation.

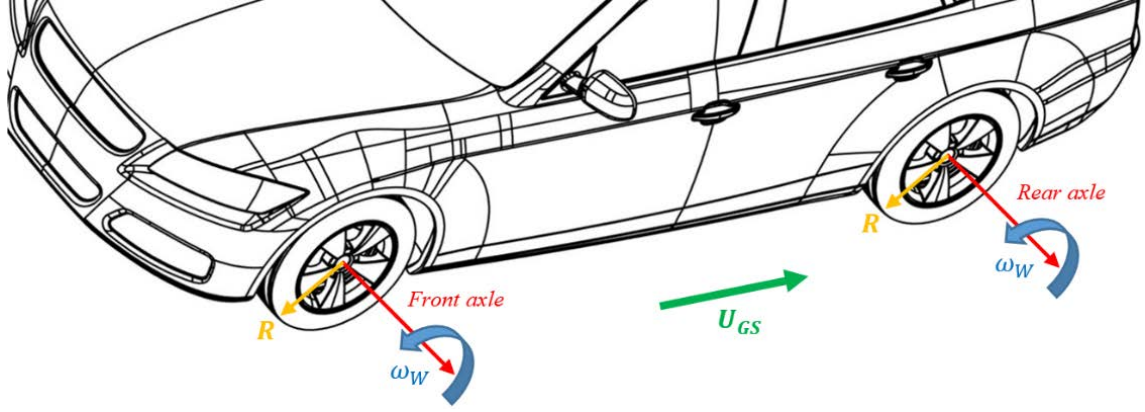


Figure 16. Sketch of kinematic motion references adopted for time-averaged ground simulation [34] [37].

Two boundaries are created to represent each pair of wheels (front and rear). A tangential velocity field on each wheel surface is imposed by applying a local rotational rate (ω_w) on each pair of wheels, calculated as the ratio of relative ground velocity (U_{GS}) and wheel radius (R). Parameters of each boundary are presented and summarised in Table 6.

Table 6. Boundary conditions.

Boundary	Condition	Parameters
Inlet	velocity-inlet	$U_{\infty} = 44.2 \text{ m/s}$; $I = 0.5\%$; $\mu_t/\mu = 2$
Outlet	pressure-outlet	$P_{\infty} = 0 \text{ Pa}$; $P_{abs} = 101325 \text{ Pa}$
Car body	wall	no-slip condition
Sym	symmetry	
Farfield	symmetry	
Ground	wall	no-slip, ground movement at $U_{GS} = 44.2 \text{ m/s}$
Wheels	wall	no-slip, local rotation rate at $\omega_w = 347.5 \text{ rad/s}$

3.2.4 Meshing Strategy

The meshing strategy complies with the goal of maximising the cost-effective use of computational resources during processing (*e.g.* RAM, storage memory, and processing time). The mesher model (Table 7) used in the Star-CCM+ package is based on a trimmed cell type, with instructions for surface remesher and automatic surface repair.

Table 7. Global mesher model.

Feature	Description
Cell type	Trimmed cell mesher
Surface remesher (trigger)	face quality <0.10
Automatic surface repair (trigger)	face quality <0.05
Prism layers function:	
Stretching function	Geometric progression
Distribution mode	Wall thickness
Boundary march angle	50 degrees
Minimum thickness allowed	10% base size

Table 8 summarises the mesher configuration used for the vehicle surface surroundings, mostly defined as a function of *base size* (*i.e.* a 1-D dimensional reference) as a global variable to scale faces and volumes with respective coefficients. Since the domain core and farfield cells also have mesh dimensions scaled to the base size, the entire mesh control can be reduced to a single driving parameter.

Note that not only prism layer distribution, specifically the first layer, but also the freestream, impacts the y^+ magnitude over no-slip surfaces like the vehicle body and ground reference. In order to ensure similar wall function estimation over different freestreams, the prism layer thickness is defined as a function of

freestream magnitude to avoid the buffer layer zone in the boundary layer, generally defined between $5 < y^+ < 30$, which could be poorly solved.

Table 8. Global criteria of meshing generation.

Feature	Description
Base size (reference edge size)	$h \times CS$ [mm]
Target	100% base size
Minimum	50% base size
 <i>Vehicle surface</i>	
Surface Curvature	36 points per circle
Surface Growth rate	1.2
Auto-repair minimum proximity	0.01
Prism layers:	
Stretching function	Geometric progression
Distribution mode	Wall thickness
Boundary march angle	50°
Minimum thickness allowed	10% base size
Total thickness	150% base size
Number of layers	4
Near-wall thickness	$0.025/U_\infty$
Maximum core/prism transition ratio	5
 <i>Domain's surfaces and core</i>	
Maximum cell size	20000% base size
Inlet, Outlet, Farfield surfaces:	
Target surface size	20000% base size
Minimum surface size	20000% base size
Surface growth rate	1.5
Prism layer	Disabled
Ground surface:	
Target surface size	20000% base size
Minimum surface size	100% base size
Surface growth rate	1.5
Prism layer	2 layer, $0.18/U_\infty$ (first layer)

The prism layer thickness is defined as a function of the freestream in order to maintain the same y^+ distribution across differences in meshing refinement or Reynolds number (as a result of changes in relative air speed or vehicle scale).

Most of the discretised domain obeys global criteria of meshing size distribution. However, dedicated spatial resolution control is used in regions where turbulent, separated flows were expected:

- i. Near-wake core, from:
 - vehicle's bluff body
 - side mirrors
- ii. Farfield wake development, from:
 - vehicle's bluff body end
 - rear bumper corner
 - side mirrors
- iii. High recirculation zone:
 - frontal and rear wheel-related features
(e.g. tyre and wheel cavities)

Several detail-orientated refinement regions were also applied to geometry-sensitive regions surrounding all vehicle models. These control regions involve: (i) front bumper edge, (ii) frontal stagnation zone, (iii) top strut root, (iv) hood-windshield gap, (v) frontal grid, (vi) A-pillar vortex, connected to (vii) upper lateral edge, then (viii) upper rear-end edge ([Figure 17](#)). The purpose is an improved estimation of flow gradients with enough resolution enough to suppress mesh sensitivity, also resulting in more accurate pressure distribution and respective load components.

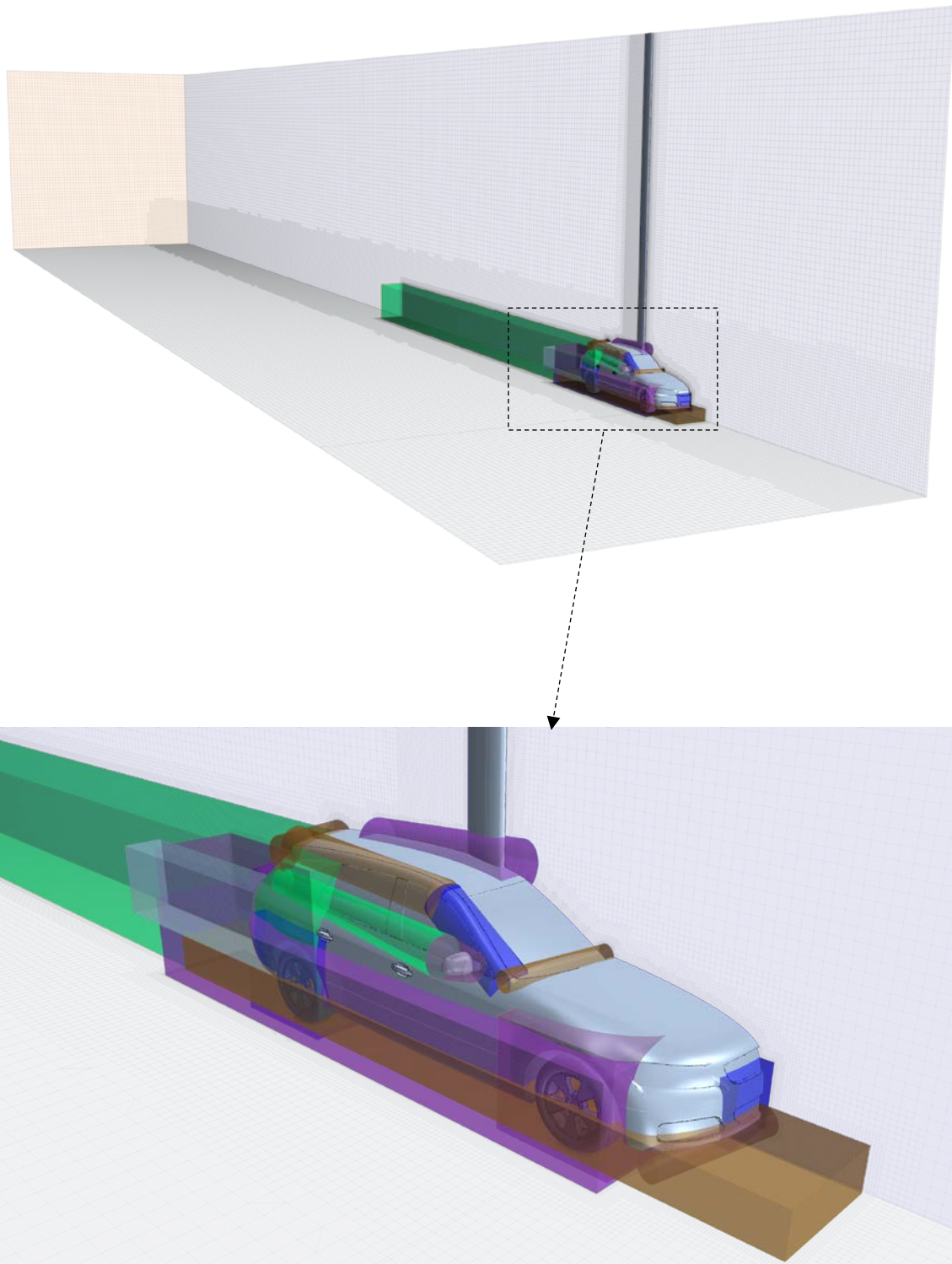


Figure 17. Independent refinement control for meshing optimisation in Star-CCM+ over a DrivAer Estateback case (*ESwMwW*)

3.2.5 Mesh Sensitivity Analysis

A relevant parameter for optimisation of the CFD results and computational resources is the spatial discretisation (*i.e.* mesh distribution and resolutions) required to emulate the experimental test with acceptable correlation. Considering that vehicles behave like a bluff-body and produce a large turbulent wake, the drag coefficient is a significant parameter in automotive aerodynamics, and one of the most sensitive and challenging properties for numerical prediction.

As a result, the mesh sensitivity of the DrivAer simulations was analysed in terms of drag coefficient, C_D , as a function of the mesh refinement level h (*i.e.* a scalar definition for mesh density control proposed in [32]). It means that h is a driving variable to relevant parts of the domain discretisation, like surfaces, core volumes, and local refinement controls.

Two independent experimental references (TUM [5] and Audi [31]) were used to evaluate the simulation accuracy and the mesh size sensitivity, summarised in Figure 18. Note that the first cited experiment [5] suggests a $C_D = 0.243$, while the latter [31] indicates $C_D = 0.251$, a difference of 8 counts ($\sim 3.3\%$) between tests.

The coarser mesh, $h = 50$, provided the largest discrepancies to the experimental references [5] [31]. The entire model assembly (body + wheels + strut) is overestimating the references by 34.0% (Heft *et al.* [5]) and 29.7% (Collin *et al.* [31]), respectively. Reducing the mesh refinement level by half, $h = 25$, decreases the difference of the numerical results to 13.0% (Heft *et al.* [5]) and 9.4% (Collin *et al.* [31]).

Numerical simulations for a mesh with $h < 15$ provide results within a range of 5% difference to experimental references. For $h = 15$, the simulation overpredicts the drag coefficient by 5.1% (Heft *et al.* [5]) and 1.7% (Collin *et al.* [31]). However,

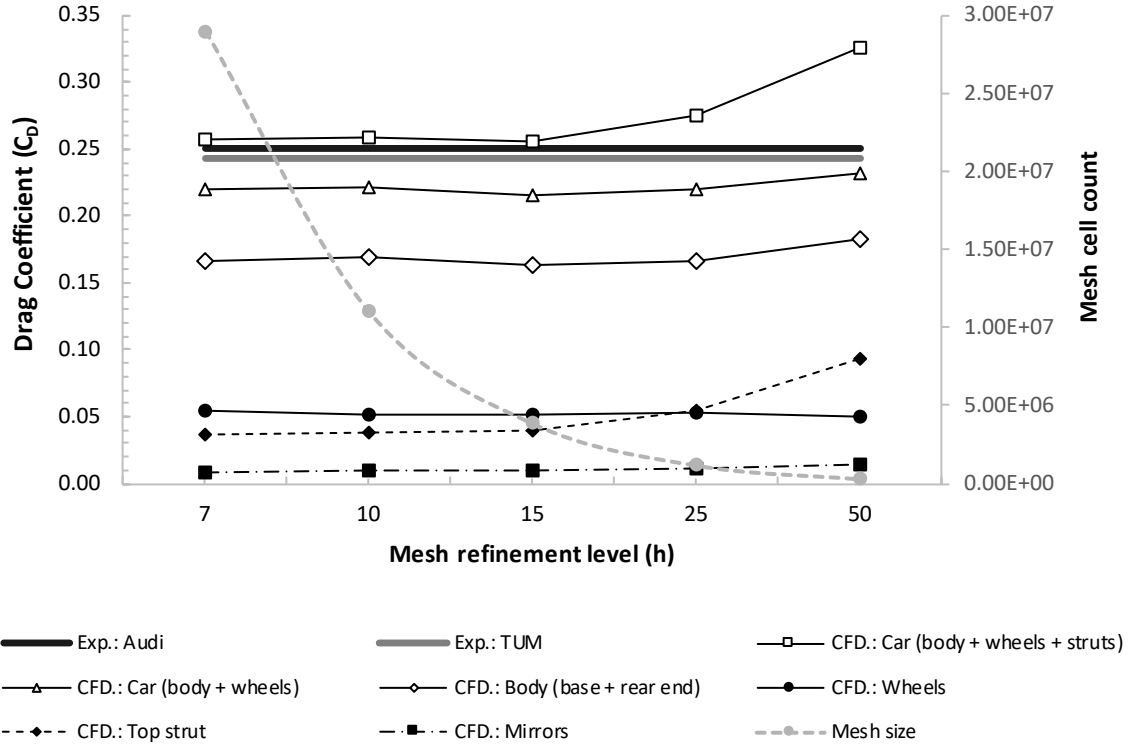


Figure 18. Mesh sensitivity for DrivAer Fastback: drag coefficient as a function of mesh refinement level (h).

when $h = 10$ the difference increases to 6.6% and 3.2%, respectively. The most refined mesh case, $h = 7$, differs by 5.6% (Heft *et al.* [5]) and 2.3% (Collin *et al.* [31]).

In summary, the mesh sensitivity reflected by the drag coefficient was significant between $15 < h < 50$, with a clear trend of convergence proportional to the reduction of the mesh refinement level. An asymptote range starts from $h = 15$, where further reduction in h only provides a residual fluctuation in the results.

In terms of cost-effectiveness, a mesh with $h = 15$ can deliver an enough level of accuracy in C_D (*i.e.* 2% to 5%) while requiring almost three times less computational resources than similar results (*e.g.* $h = 7$). Therefore, meshing applications on automotive bodies will be based on a maximum mesh refinement level of $h = 15$, corresponding to a cell count of 3.86 million cells over a half-symmetric domain.

3.3 NUMERICAL VALIDATION, PART II: On the Correlation to Passenger Vehicle References

This section summarises the analysis of numerical simulation cases compared to equivalent, published experimental data. The goal is to validate and estimate the capability of the CFD methodology as a tool for automotive aerodynamics, which will be employed in subsequent studies related to the development of the wake emulator.

3.3.1 CASE I – DrivAer experiment with an overhead strut, with ground simulation: Analysis on Pressure Distribution

The surface static pressure distribution of each standard DrivAer rear-body variation – Fastback, Notchback, and Estateback – were assessed over the upper and lower surface simulated, using the same body configuration and applying ground simulation (*i.e.* *SwMwW*, *GSon*). These results are compared to published experimental data obtained by Heft *et al.* [5] and Collin *et al.* [31] at TUM and Audi’s wind tunnels, respectively.

While the CFD simulation of all DrivAer configurations has been undertaken, not all configurations have been tested experimentally to obtain the surface static pressure distribution. Numerical results, shown in [Figure 19](#) to [Figure 21](#), are compared to the most suitable reference available for each case.

Note that as previously explained, the experiments required an overhead strut connected to the model on the symmetry plane. The issue is not only a spatial gap in the upper surface pressure data but also in the influence that the strut has on the adjacent pressure tappings. The strut is included in numerical simulations in order to replicate the experimental condition.

Numerical results for the surface static pressure distribution is analysed as time-averaged results on both the upper and lower surface over all three main vehicle models with acceptable accuracy (*e.g.* $\Delta C_p < 0.05$); however, with particularities as described below.

Significant differences are only found in specific locations on the surface, mainly on geometry steps like those at: (i) the bonnet’s leading edge; the roof’s (ii) leading and (iii) trailing edges; and (iv) the rear-end corner. These local protuberances generate peak deviations to $0.40C_p$ in comparison to experimental references.

Such differences are not considered to be ‘errors’ in the pressure prediction. Experimental results indicate that probes might not have been concentrated in areas of high-gradient flow due to geometric details, therefore not capturing those local pressure peaks accurately. To illustrate this point, both the Fast- and Notchback models have pressure fluctuations at the rear window edges, mainly on the rearmost step, but the respective pressure probes did not have enough resolution to capture the phenomenon.

Based on the experimental data available [5], it can be concluded that the surface static pressure coefficient distribution can be calculated with accuracy in the range of $\Delta C_p \pm 0.06$ on regions of low-gradient (*e.g.* continuous surfaces with large curvature). Small regions of local, high-gradient peaks may suffer more substantial differences, estimated to be $\overline{\Delta C_p} = 0.20$ for most cases.

Note that adding the top model mounting strut to the numerical domain makes it possible to identify the experimental interference that results from this configuration. All cases show a pressure recovery from the roof leading edge towards the strut leading edge, where a local region of stagnation is expected. A top strut impacts the flow adjacent to the upper surface by $\Delta C_p = 0.80$ within an upstream distance of the half-strut cord. The aerofoil-like wake has a mild, positive increment of $\Delta C_p < 0.20$ within a range of a half-strut cord downstream.

In terms of the underbody surface static pressure distribution, both the simulation and Heft *et al.* [5] results agree over the majority of the surface, but conflicting trends are found under the front bumper zone (*i.e.* $x/L < -0.05$).

Figure 19 shows that simulation and experiment suggest a divergent trend for static pressure distribution. The simulation shows that $C_p \approx -0.05$ is found after the bumper's leading edge that reduces $C_p \approx -0.50$ when reaching the front-wheel axle. Experimental results of Heft *et al.* [5] ('□' symbol) suggest that the pressure distribution can be referred to as a plateau of $\overline{C_p} \approx -0.45$. Comparing with a second experimental reference (Collin *et al.* [31], '♦' symbol), the numerical prediction was thought to be erroneous, whereas only on that specific region (*i.e.* $x/L < -0.05$).

Collin *et al.* [31] experimental results not only contradicted the first reference but support the numerical outcome. The pressure curve trend is in accordance with CFD results, with an offset of $\Delta C_p < 0.1$ in the range of $-0.13 < x/L < -0.05$.

It is unclear why those experimental data disagree in this specific region. A bi-stable flow condition is unlikely since the flow is subjected to a contraction and therefore acceleration, leading to the conclusion that both Collin *et al.* [31] experiment and CFD simulations have reflected the time-averaged flow condition more accurately underneath the front bumper. Apart from this issue, the experimental results differ by $\overline{\Delta C_p} < 0.05$ along the entire underbody profile, while agreeing with CFD results.

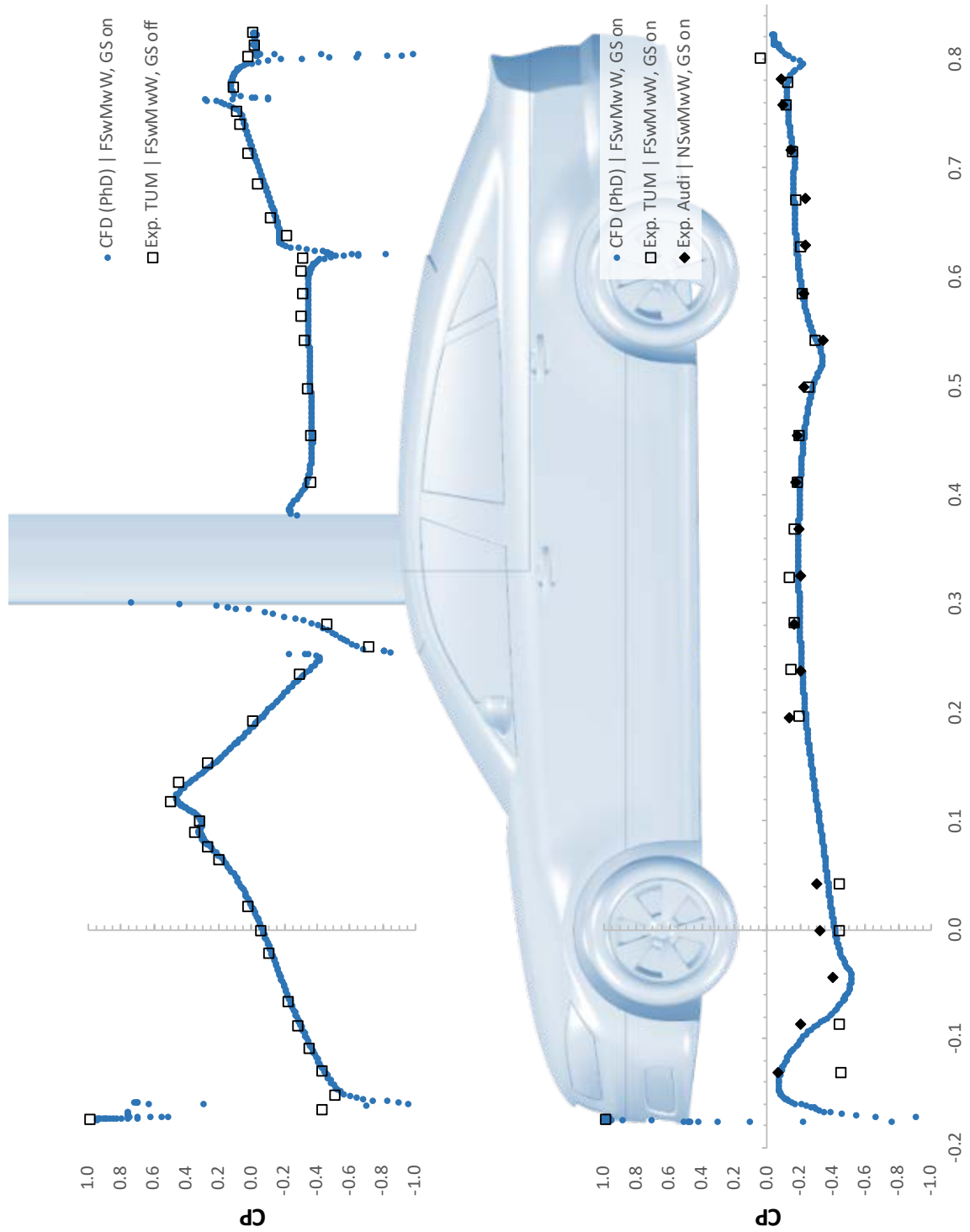


Figure 19. CFD validation, case I: C_p distribution on DrivAer Fastback (FSwMwW).

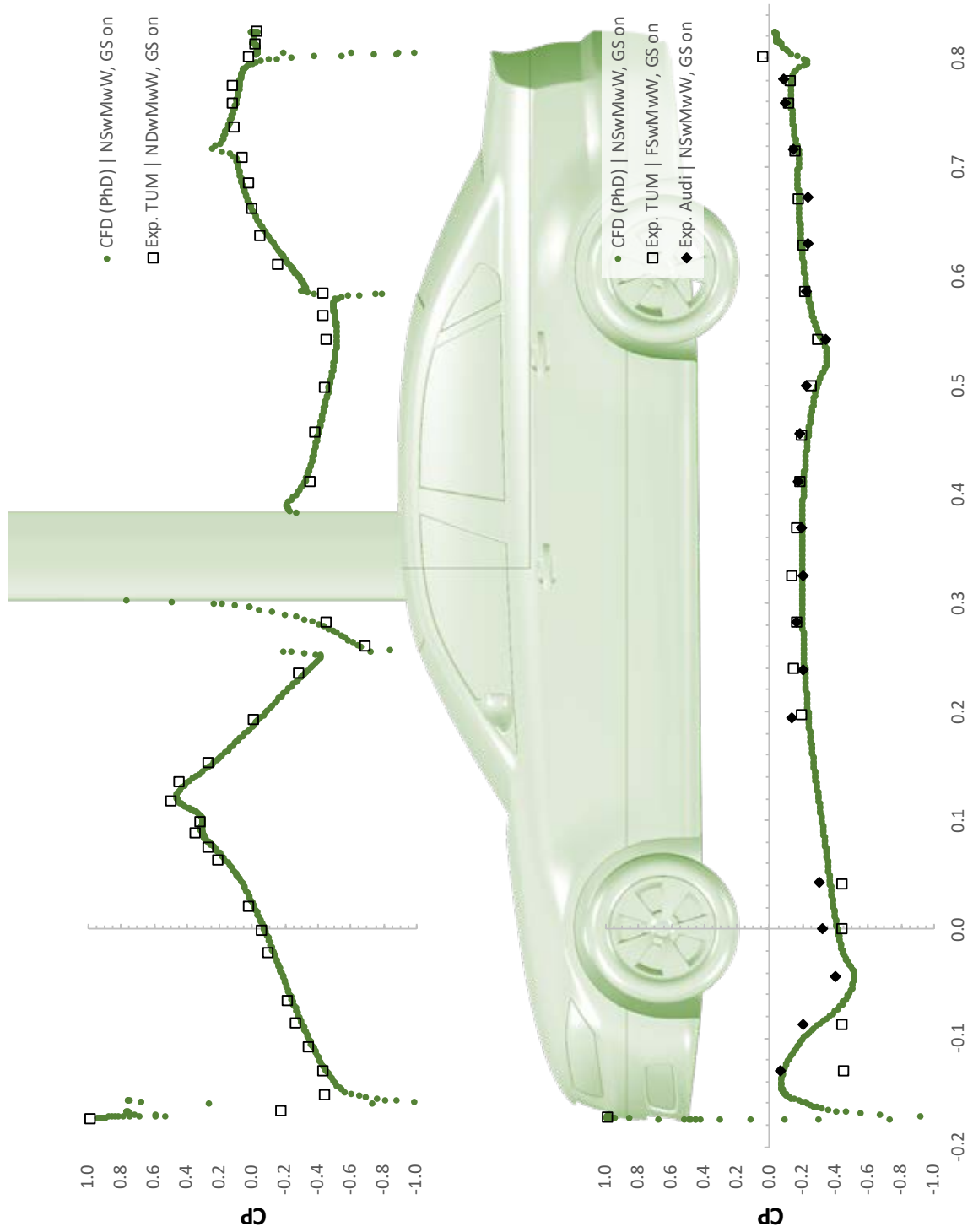


Figure 20. CFD validation, case I: C_p distribution on DrivAer Notchback (NSwMwW).

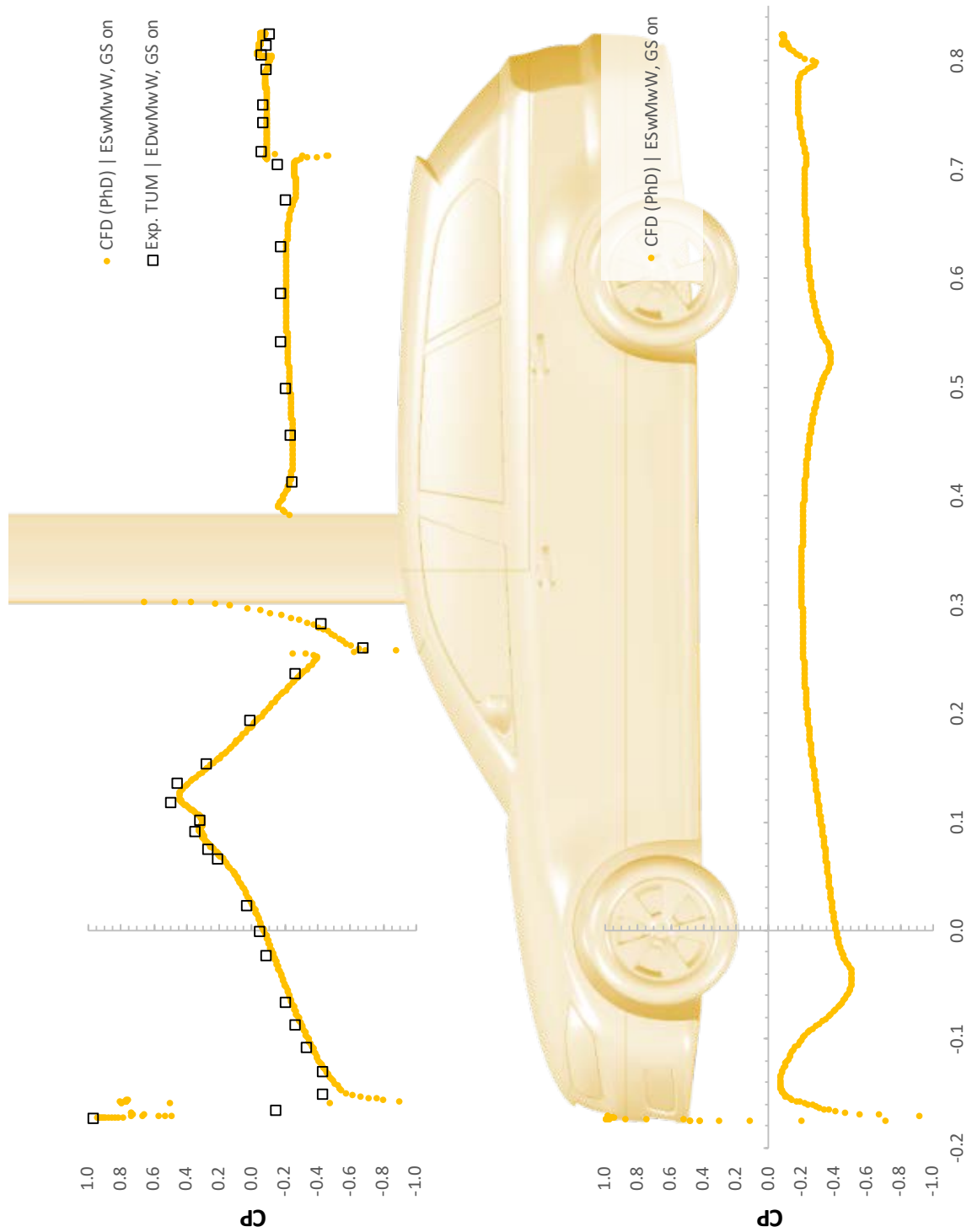


Figure 21. CFD validation, case I: C_p distribution on DrivAer Estateback (ESwMwW).

In terms of the numerical pressure data, [Figure 22](#) assists with the assessment of the pressure distribution on the DrivAer rear-body variants.

The lower surface has almost identical results for all three vehicle configurations, indicating that the performance of the standard DrivAer smooth underbody (*S*) with ground simulation (*GSon*) is nearly independent of the upper body geometry. While the Fastback and Notchback models are virtually identical, the Estateback model has a minor offset gradually growing from $x/L = 0.4$ to 0.6 , then a constant of $\Delta C_p \cong -0.05$ until the underbody end (see [Figure 22](#), $x/L > 0.6$).

In addition to the underbody surface, the entire forebody generates a pressure distribution which is seen to be independent of the rear-body geometry. The bluff-body shape allows the flow – and respective characteristics – to behave nearly independent of minor geometry changes on the rear-end.

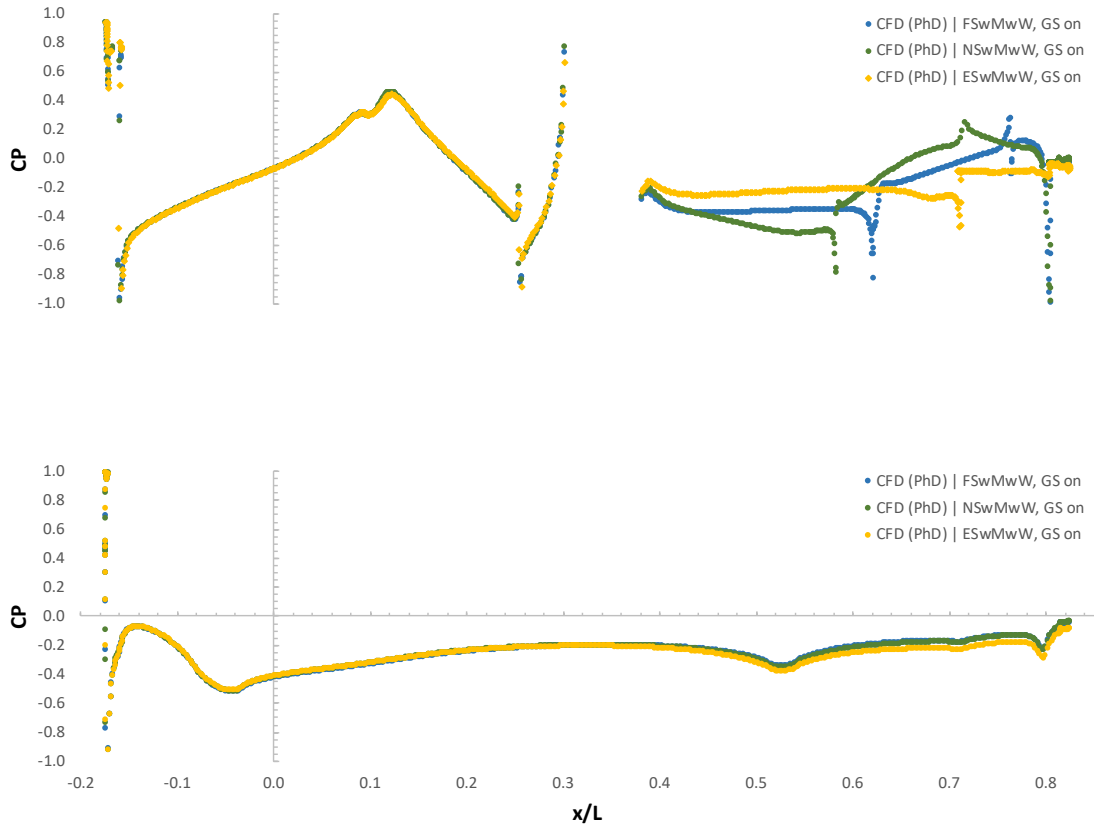


Figure 22. CFD validation, case I: Numerical results over the three standard DrivAer variations (*-SwMwW* configurations, *GSon*).

3.3.2 CASE II – DrivAer experiment with no overhead strut and non-rotating-wheels, fixed ground: Analysis on Oil-flow and Surface Pressure Mapping

Wieser *et al.* [22] provide an experimental analysis of the surface static pressure distribution on both Fast- and Notchback DrivAer models. A quarter-scaled body was mounted using non-rotating wheels to the turntable floor, leading to a no-ground simulation (*GSoff*) condition.

In contrast to the experiments of Heft *et al.* [5] and Collin *et al.* [31], this method avoids using an overhead strut with its corresponding interference. Wieser *et al.* [22] describe the wind tunnel cross-section as being $2m \times \sqrt{2}m$; recreated in CFD simulation, as illustrated in Figure 23.

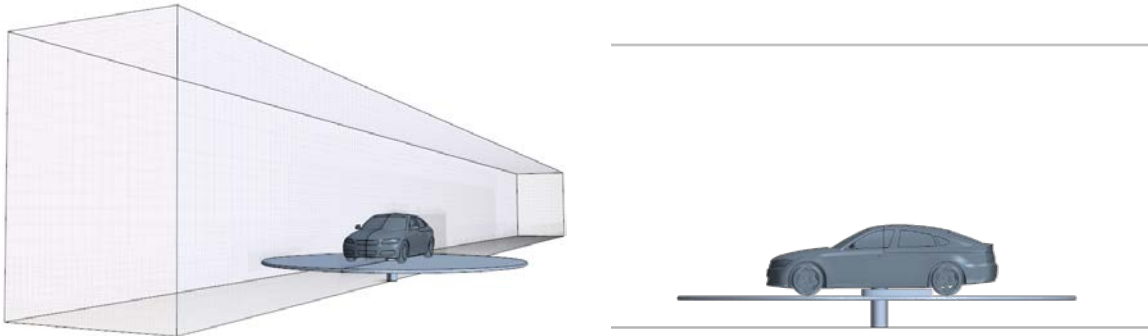


Figure 23. Illustration of the numerical fluid domain used for CFD validation based on Wieser *et al.* [22] experimental study.

The majority of the numerical simulation and meshing strategies presented in this chapter and used for *Case I* (section 3.3.1) were tailored for the specific experimental domain (*e.g.* closed-test section configuration) and flow conditions (*e.g.* Reynolds number). Vehicle model features are listed in Table 9, while

numerical configuration and boundary conditions are summarised in Table 10 and Table 11, respectively.

Table 9. DrivAer model features: TU Berlin [22].

Component	Description	Notation
Rear end	Fastback, Notchback	F, N
Underbody	Smooth underbody	S
Mirrors	Standard mirror	wM
Wheels	Detailed version: detailed rims and grooved tyre	wW

Table 10. CFD setup summary.

Feature	Description
Domain simplification	half-symmetrical three-dimensional
Time regime	steady-state
Equation of State	constant density
Fluid (air):	
Reference density	$\rho = 1.184 \text{ kg/m}^3$
Reference dynamic viscosity	$\mu = 1.855 \times 10^{-5} \text{ Ns/m}^2$
Reynolds Number	$Re = 3.2 \times 10^6$
Flow Solver	segregated
Flow regime	turbulent
Turbulence model	Realisable $k\text{-}\varepsilon$ two-layer
Gradient order	2 nd -order, Hybrid Gauss-LSQ

Table 11. Boundary conditions.

Boundary	Condition	Parameters
Inlet	velocity-inlet	$U_\infty = 41 \text{ m/s}; \quad I = 0.5\%; \quad \mu_t/\mu = 2$
Outlet	pressure-outlet	$P_\infty = 0 \text{ Pa}; \quad P_{abs} = 101325 \text{ Pa}$
Car body	wall	no-slip condition
Wheels	wall	no-slip condition
Sym	symmetry	
Wind tunnel walls (except ground floor)	symmetry	
Ground and Turntable	wall	no-slip condition

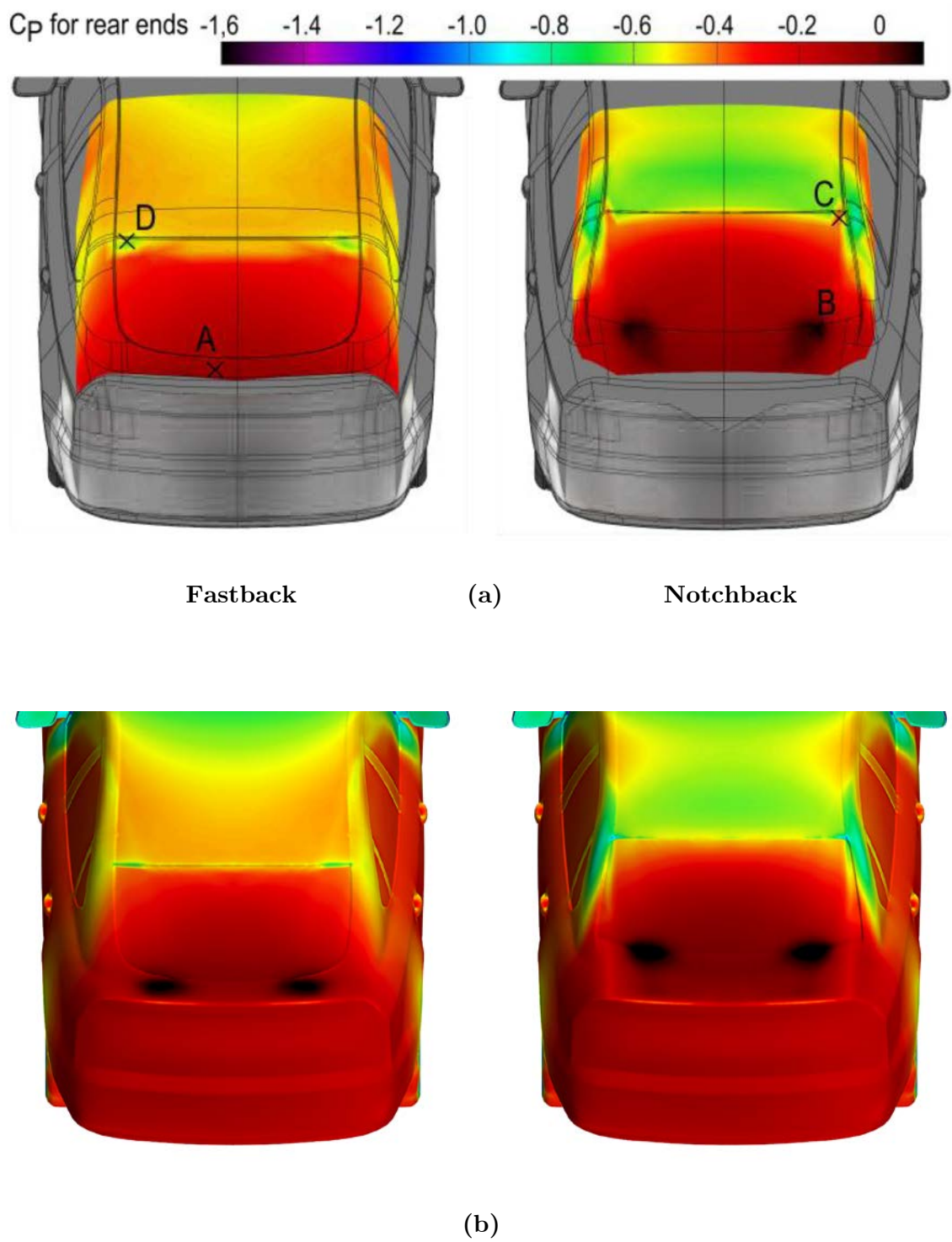


Figure 24. CFD validation, case II: pressure coefficient (C_p) magnitude on DrivAer Fastback ($FSwMwW$) and Notchback ($NSwMwW$).
 (a) experimental reference ([22], edited) and (b) CFD simulation.

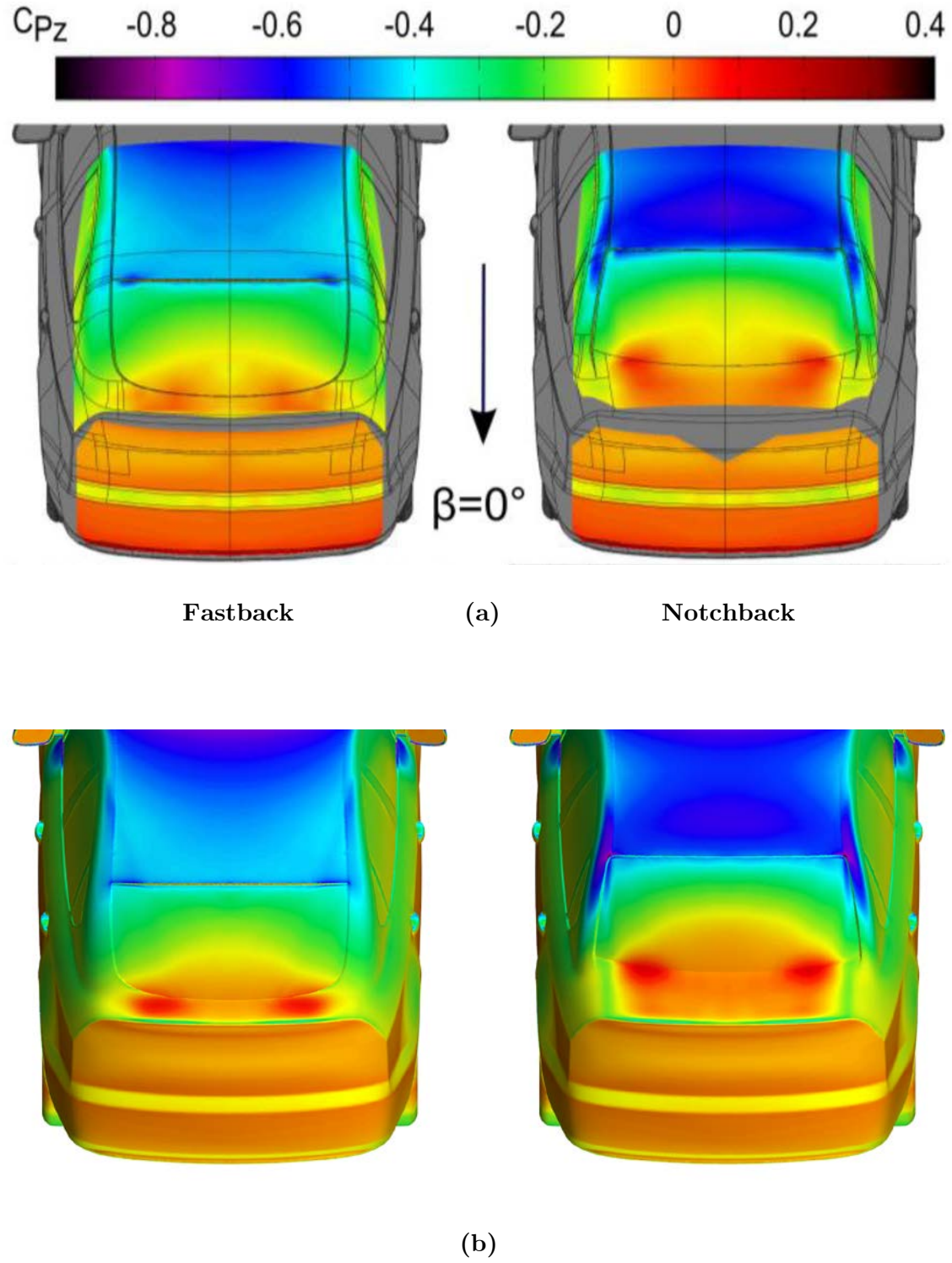
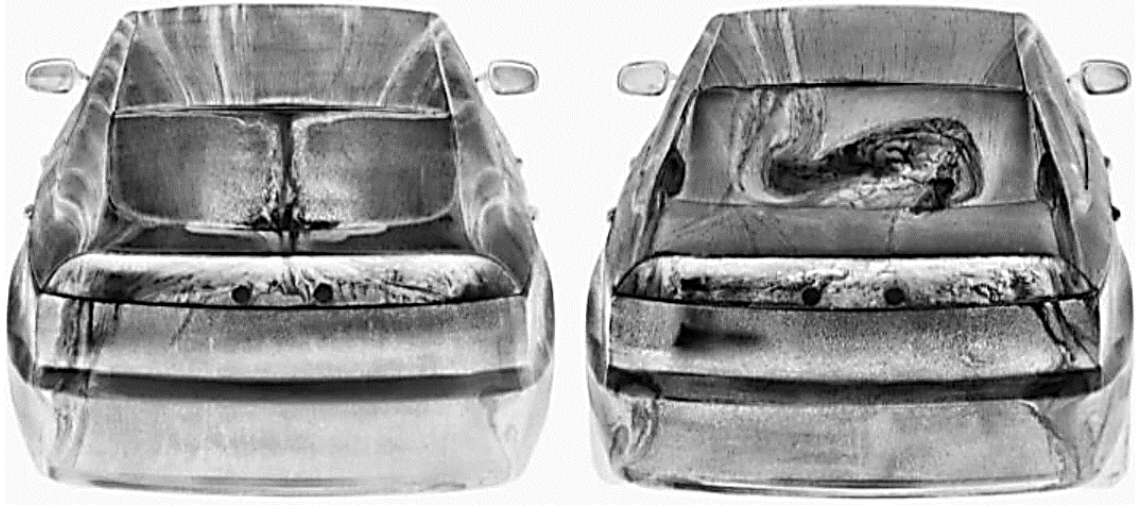


Figure 25. CFD validation, case II: z -direction pressure coefficient (C_{p_z}) on DrivAer Fastback (FSwMwW) and Notchback (NSwMwW).
(a) experimental reference [22] and (b) CFD simulation.



Fastback

(a)

Notchback



(b)

Figure 26. CFD validation, case II: flow visualisation on DrivAer Fastback (*FSwMwW*) and Notchback (*NSwMwW*) surface.

(a) experimental oil-flow [22] (edited) and (b) CFD simulation (LIC shear stress vector field).

The numerical results are compared to the corresponding experimental data and indicate a correlation with the surface static pressure coefficient distribution in both magnitude and z-oriented decomposition (i.e. $P \times \vec{n}_z$, where $\vec{n}_z$ is the z-component of a local surface normal vector, [22]).

Figure 24 shows that the numerical approach can predict the pressure coefficient, C_p , on the vehicle surface within a difference of $\overline{\Delta C_p} < 0.05$. To illustrate this, experiments revealed that the Notchback model has the maximum peak of $C_p = 0.08$, while simulation captures the feature by $\Delta C_p = 0.04$. A larger discrepancy of $\Delta C_p \cong 0.1$ is found on the fastback maximum peak ($C_p = 0.02$). However, the difference may not be completely due to CFD solver.

The maximum peak region on each rear-body model (Figure 24), found in numerical results, are highlighted over the experimental model with pressure taps in Figure 27. While a pressure tap is near to the C_p peak region for the Notchback case (Figure 27, upper-right), the feature on the Fastback model (Figure 27, upper-left) might not have been acquired adequately due to the distance between pressure tappings near to the C_p peak region.

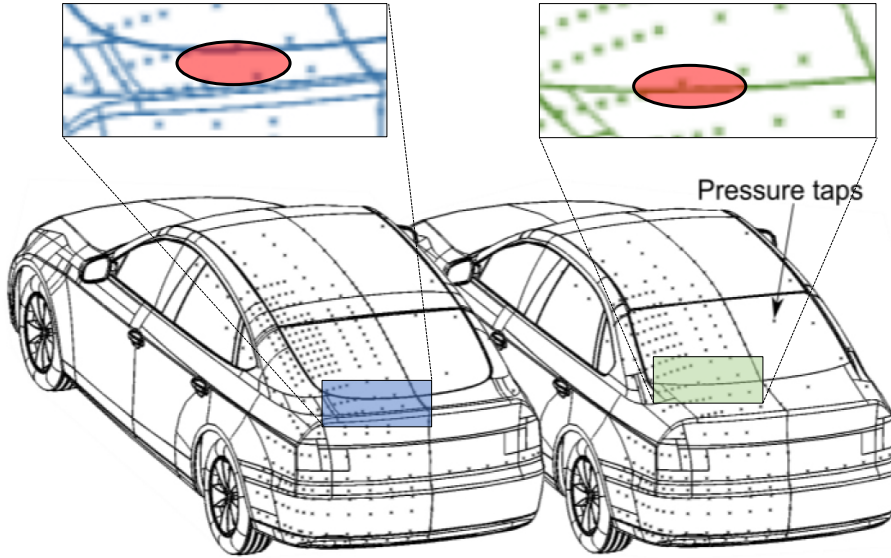


Figure 27. Numerical local peak regions highlighted on experimental models with pressure tapping positions ([22], edited).

Figure 25 shows a comparison between the experimental reference of by Wieser *et al.* [22] and corresponding simulation as a function of z-oriented decomposition of the pressure coefficient (C_{p_z}) [22]. Both numerical and experimental pressure distributions highlight similar features, such as: (i) C-pillar flow acceleration, (ii) rear-base recovery, and (iii) regions of local C_{p_z} peaks.

The pressure distribution on both models, simulated by CFD, differ from the respective experiment [22] by less than $0.1C_{p_z}$ on the roof surface – a significant region for the resultant lift; although, better calculated on the Fastback case ($\overline{\Delta C_{p_z}} < 0.05$).

Regarding flow visualisation, the surface oil-flow technique is one of the most basic experimental tools. It usually employs a solution of small solid particles diluted in a solvent dragged along by flow friction, which form streamline patterns once the solvent evaporates and/or advects as a result of the flow. Comparable results can be generated with the CFD simulation by plotting the line integral convolution (LIC) of sheer stress vectors on the body surface.

Figure 26 shows that most of the observations from the CFD simulation are confirmed by experimental oil-flow results. The steady, upper flow over the roof of both vehicle models is well-predicted, combined with a lateral inward motion surrounding the roof’s lateral edges. Traces of A-pillar vortices can also be found, though weak and not completely clear. Both models share another feature: a vortex core leaving the rear bumper corners at its vertical centre, aligned to the lateral edge.

On the Fastback model (Figure 26, left-hand side), the simulation results seem to agree almost entirely to the trends exposed by oil-flow; the flow around the C-pillar is similar, likewise is the correlation on the rear-end surface. A liquid accumulation is found at the symmetry plane, indicating that the oil-flow solution had been dragged to this region. While a local low-speed flow did not advect or

evaporate the solvent, gravity drove the mixture to the forward-facing step from the rear window edge.

The Notchback configuration exhibits flow characteristics that are exposed by both experimental and numerical techniques (Figure 26, at right). Compared to the Fastback model, the Notchback's larger inclination of the rear window leads to flow separation on the C-pillar, which generates coherent vortex structures found along the lateral edges. The boot-step surface on the simulated Notchback rear-body also shows good correlation with experimental test data. Although the latter surface displays blurred streamline pattern (Figure 26, Notchback experiment), they are visible on the model's left-hand side located at approximately a quarter of the rear window width. The main discrepancy between simulation and experiment is found in the flow characteristics captured over the Notchback rear window region.

Both the CFD simulation and the experimental data show the upper flow moving downstream with significant inwards motion along the rear-body surface. However, the simulation suggests a small recirculation on the boot-step surface towards the rear window centre, which drives flow separation and vortex structures leaving the central region.

In relation to the experimental data (Figure 26, Notchback experiment), an asymmetric flow structure was identified with the following trajectory: (i) flow starts from the upper left-end side and runs down along the rear window, but (ii) it is collected before reaching the lower edge and (iii) a strong, lateral motion conveys the flow higher and to the opposite side; then (iv) this seems to be in conflict with the inward motion and finally is streamed to the lower window edge.

A reason for these differences may be the nature of each approach: while the adopted CFD method provided a time-averaged prediction of the flow condition(s), the "exposure time" of the oil-flow technique is uncertain because it

depends on (a) mixing concentration and (b) local flow speed, which varies over a surface of interest.

In the experimental case analysed, the solvent may have evaporated very quickly and resulted in a “frozen” time-step of the flow condition. However, this hypothesis is unlikely because the wind tunnel model is exposed to the freestream during the run-up to the required velocity and, therefore, it would be unrealistic to expect the solvent to have dried that quickly.

The most likely explanation is a small asymmetry in the model relative to the freestream, not in the geometry *per se* but as a result of a small yaw misalignment. Since publications [44] [45] [46] [47] lead to the conclusion that the notchback geometry has a weak flow instability over the rear-body, any residual yaw deviation may bias its instabilities equilibrium. If it tends to be stable in one of the flow states, the surface oil-flow mixture would capture a stable feature coherent over time, such as that captured on the experimental reference [31].

Therefore, the experimental oil-flow visualisation technique may not be directly compatible with steady-state CFD simulations on surfaces exposed to strong instabilities (*e.g.* blurry patterns) and/or low-speed flow (*e.g.* streamlines driven by gravity or an extensive drying period).

3.4 NUMERICAL VALIDATION, PART III: On the Correlation to Race Car studies

The objective addressed in this section is to test the robustness of the adopted CFD methodology to capture the wake characteristics from an additional automotive class: the single-seater race car. An indirect but important outcome is the analysis of the wake evolution from this class of ground vehicle, in alignment with the research scope.

Even though wind tunnel data [27] is available relating to the wake development of race car configurations, there was no access to the corresponding CAD geometry. Consequently, a precise numerical reproduction of the experiment and its condition could not be carried out. As an alternative, a qualitative analysis of the CFD tool can be performed using another generic, but similar, CAD model of a race car, then comparing the correlations between these simulations and the reference cases.

3.4.1 Reference Cases

Watts *et al.* [27] published experimental data regarding the wake characteristics from a ¼ scale single-seater race car model; which was tested at $Re = 2.4 \times 10^6$ on a stationary ground plane. The results highlighted an important mechanism in the wake of this automotive category, as described by the authors:

“wake structure is dominated by a pair of counter-rotating vortices which combine with low speed flow from the diffuser to generate a highly turbulent field.” [27]

Although the CAD geometry is not available, data can still be compared to the performance of a similar vehicle model and be used to assess the capability of a CFD simulation to capture the aerodynamic wake behaviour.

Newbon *et al.* [28] investigate the wake simulation of an open-wheel race car with slight differences to the model used by [27]. Their study is further evidence of the wake characteristics of high-performance vehicles, which corroborates the study of Watts *et al.* [27].

Thus, both results [27] [28] from two different geometries (Figure 28 and Figure 29) are used to qualitatively evaluate the CFD simulation of the wake prediction from high-performance configurations.

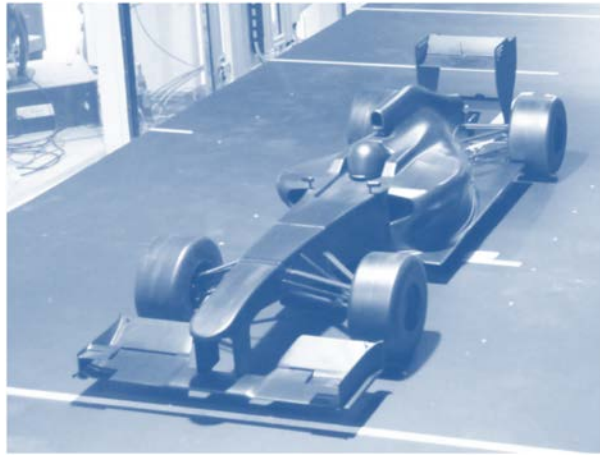


Figure 28. Qualitative validation, reference I: 25%-scale experimental model on stationary floor condition (*GSoff*), Watts *et al.* [27].
Rear wing design: higher double-element with short span (0.58 *W*; 0.40 *W*).

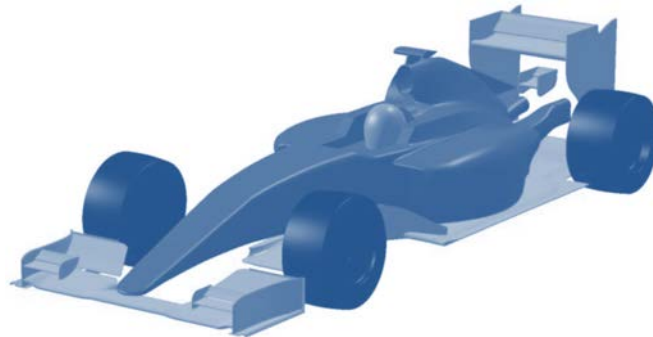


Figure 29. Qualitative validation, reference II: 25%-scale numerical model on moving ground condition (*GSon*), Newbon *et al.* [28].
Rear wing design: lower double-element with longer span (0.47 *W*; 0.54 *W*).

3.4.2 Baseline Geometry

The baseline geometry resulted from modifying an open-source, generic CAD model: Formula 1 FE4 (Gonzalez [48]). This required (i) repairs of external surfaces, (ii) simplification of wheel features, and (iii) reconstruction of surfaces related to internal flow exhaust & intake (Figure 30).

The resulting geometry is a race car model that is $4.606m$ long from nose to rear wing endplate, with underfloor nose-down by 0.7° . When placing the ground plane $10mm$ above the z -origin [9], the minimum ground clearance is found to be $43.5mm$ at the leading edge of the underbody flat plate. The elevated ground plane generated a tyre patch of $144 \times 279mm$ and $198 \times 322mm$ for the front and rear wheels, respectively. Table 12 provides the parametric dimensions of the baseline body.

Table 12. CAD parametric dimensions.

Parameter	Symbol	Definition	
Car scale	CS	—	
Reference length	L	$4.606 \times CS$	m
Front end (nose-tip)	x_o	$[0, 0, 0.435] \times CS$	m
Front wheels axle position	x_F	$[0.936, 0.804, 0.289] \times CS$	m
Rear wheels axle position	x_R	$[4.224, 0.804, 0.287] \times CS$	m
Reference height (excl. top camera wing)	H	$0.869 \times CS$	m
Reference width; wheel track	W	$1.608 \times CS$	m
Gap clearance (foremost underfloor plate tip)	h_g	$43.5 \times CS$	mm
Wheel radius	WR	$0.288 \times CS$	m
Wheelbase	WB	$3.288 \times CS$	m
Reference area (full-car projected area)	A_{ref}	$1.0772 \times CS^2$	m^2

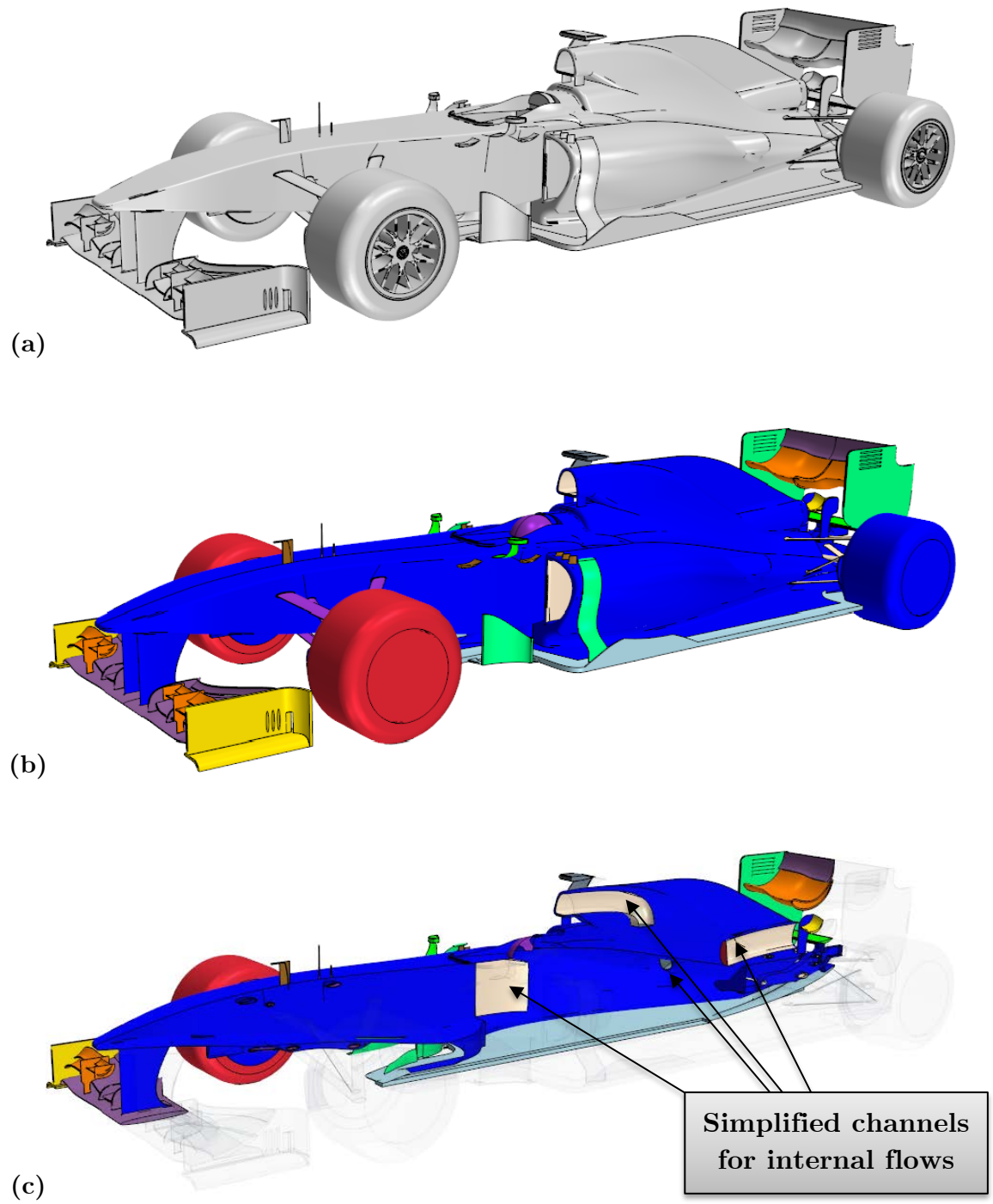


Figure 30. Baseline CAD model of a single-seater race car. (a) original by [48] and (b) edited CAD model, and (c) highlight of simplified internal channels. Rear wing design: high double-element with short span ($0.56 W$; $0.48 W$).

3.4.3 Numerical Fluid Domain

The numerical fluid domain was designed for a full-scale vehicle and adopted a plane of symmetry along the axial centreline, illustrated in Figure 31. The downstream left-hand side of the symmetric domain is a block $20.2L$ long with height of $10.5H$ from the ground and width equal to $8.7W$ from the symmetry plane. Vehicle positioning is done by placing the model $5L$ downstream of the flow inlet.

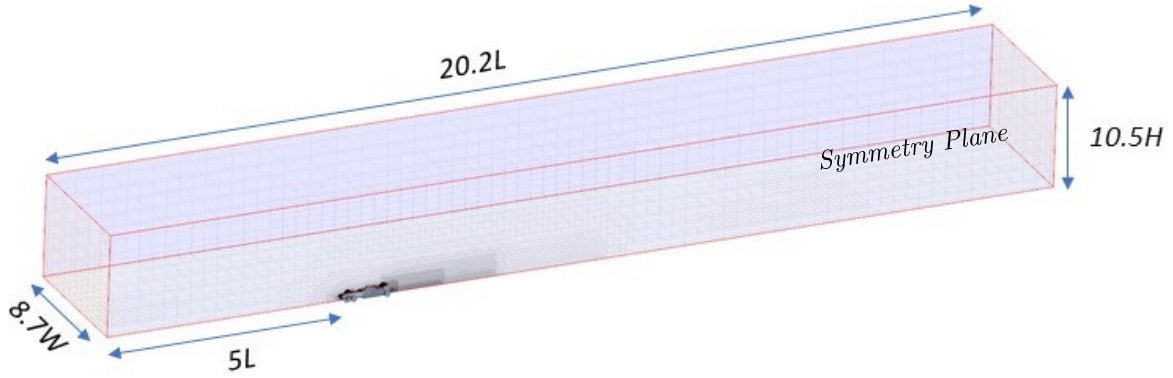


Figure 31. Numerical fluid domain used for simulation of a race car model.

Table 13. CFD setup summary.

Feature	Description
Domain simplification	half-symmetrical three-dimensional
Time regime	steady-state
Equation of State	constant density
Fluid (air):	
Reference density	$\rho = 1.184 \text{ kg/m}^3$
Reference dynamic viscosity	$\mu = 1.855 \times 10^{-5} \text{ Ns/m}^2$
Reynolds Number (experimental reference)	$Re = 2.4 \times 10^6$
Flow Solver	segregated
Flow regime	turbulent
Turbulence model	Realisable $k-\epsilon$ two-layer
Gradient order	2 nd -order, Hybrid Gauss-LSQ

Table 14. Boundary conditions, Part I: constant surfaces

Boundary	Condition	Parameters
Inlet	velocity-inlet	$U_{\infty} = 12 \text{ m/s}; \quad I = 1.0\%; \quad \mu_t/\mu = 2$
Outlet	pressure-outlet	$P_{\infty} = 0 \text{ Pa}; \quad P_{abs} = 101325 \text{ Pa}$
Car body	wall	no-slip condition
Wheels	wall	(see Table 15)
Sym	symmetry	
Wind tunnel walls (except ground floor)	symmetry	
Ground and Turntable	wall	(see Table 15)

Table 15. Boundary conditions, Part II: ground simulation.

Feature	no Ground Simulation (<i>woGS</i>)	with Ground Simulation (<i>wGS</i>)
Ground	no-slip, stationary wall	no-slip, ground movement: $U_{GS} = 12 \text{ m/s}$
Wheels	no-slip, stationary wall	no-slip, local rotation rate: $\omega_w = 94.3 \text{ rad/s}$

Two ground conditions were employed in the CFD simulations. No ground simulation condition (*GSoff*) was used to compare results with Watts *et al.* [27], while ground simulation (*Gson*) is appropriate for Newbon *et al.* [28] case.

Note that ground simulation involves imposing (*i*) relative movement on the ground surface, and (*ii*) local rotational rate at each wheel axle that will generate a velocity field on the wheel surface from stagnation (*e.g.* wheel axle position) to ground relative velocity (*e.g.* outer tyre surface), illustrated in Figure 32.

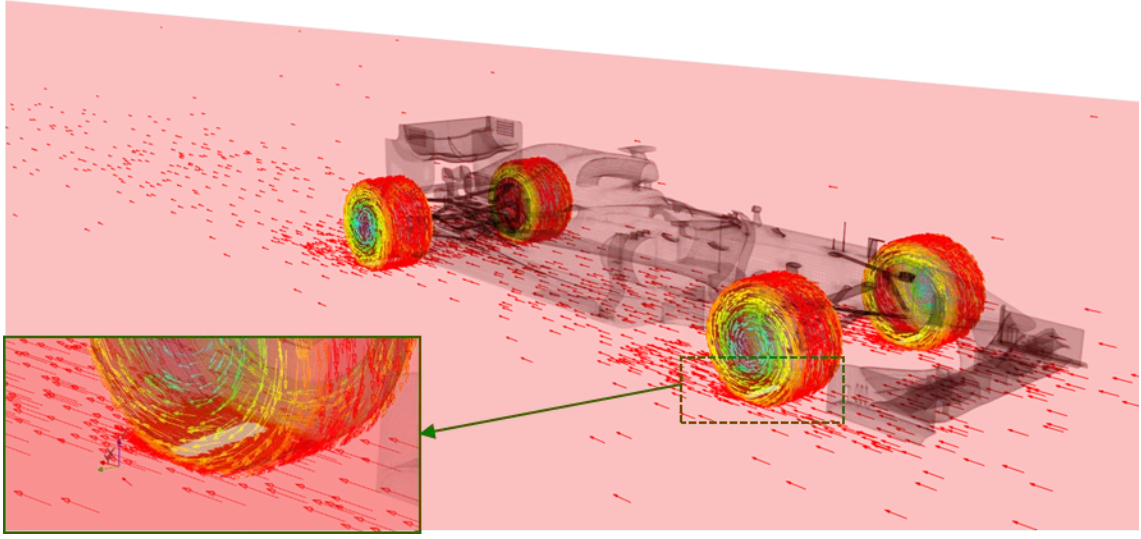


Figure 32. Ground simulation approach applied on the ground and wheels boundaries.

The meshing process followed the approach described in [section 3.2.4 ‘Meshing Strategy’](#); however, with some specific amendments. This type of vehicle requires extra attention to details to obtain an acceptable numerical simulation, since the detail-oriented features can alter or generate flow structures that have a significant impact on the overall flow field. The influence of wheels is increased, in view of the substantial contribution to resultant drag, while the underfloor and wings are crucial for downforce generation.

[Figure 33\(a\)](#) highlights a number of refinement control regions with independent meshing resolution used to optimise the mesh density. Those in contact with the vehicle surface are on (i) front and (ii) rear tyres; front wing (iii) endplate and (iv) trailing edge; rear wing (v) trailing edge and (vi) near wake; (vii) mirrors; (viii) cockpit and helmet; (ix) sidepod and (x) rear exhaust flows. A further four control regions were placed along the expected wake trace.

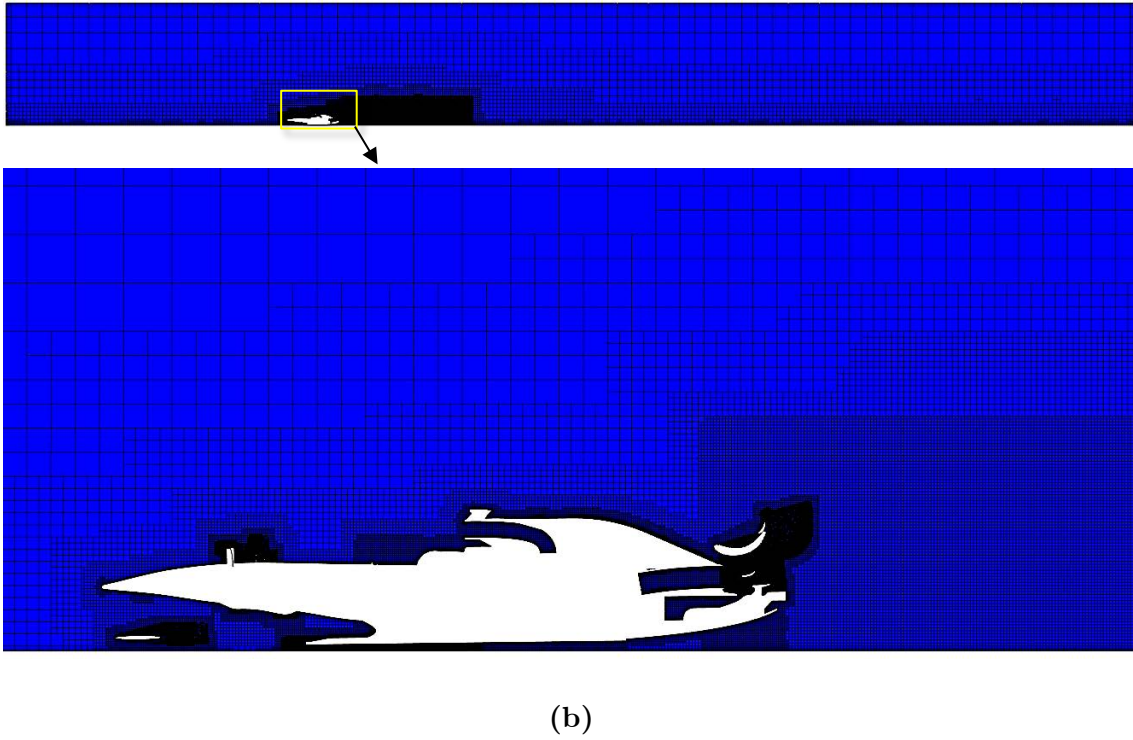
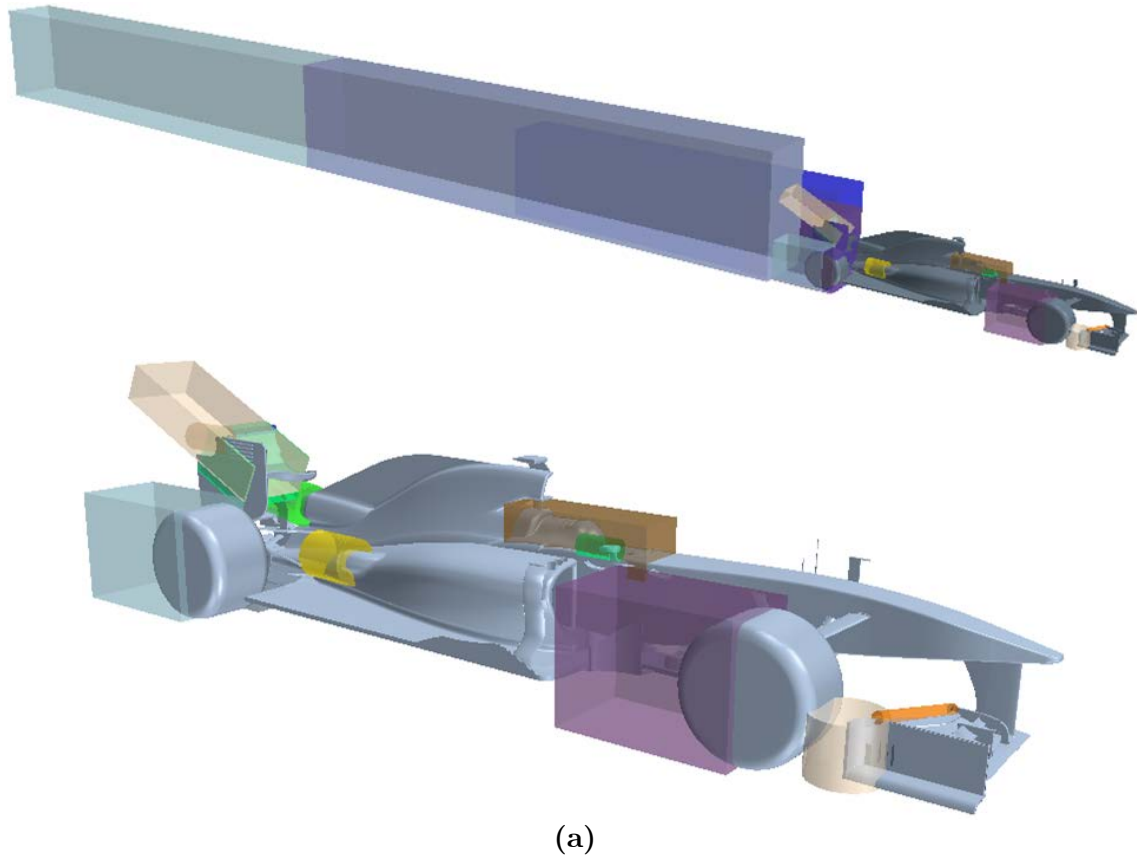


Figure 33. Meshing process. Illustration of (a) refinement control regions, and (b) symmetry-plane slice of the resulting mesh.

3.4.4 CASE I – Watts *et al.* [27] experimental study, GSoff: Wake Velocity Distribution

This first reference case [27] provides experimental data for velocity magnitude over two cross-flow planes in the wake, at $x/L = 0.50$ and $x/L = 1.00$ downstream of the vehicle. Adopting $U = 0.9U_\infty$ as a criterion for identification of the wake trace topology, the numerical simulation shows that the wake generated from the baseline model adopted has characteristics analogous to the reference case, including (i) a column of large momentum loss, (ii) ‘mushroom-like’ wake topology, and (iii) evidence of the ground floor boundary layer.

At $x/L = 0.50$ (see Figure 34), both the experiment and simulation show that the wake has a large velocity deficit of nearly $0.50U_\infty$. The region of larger momentum loss is concentrated at the symmetry plane, which extends from the diffuser and extends beyond the height of the rear wing assembly.

Watts *et al.* [27] describe a ‘mushroom-like’ wake topology, which can be found when evaluating the momentum loss up to $0.25U_\infty$. A similar feature is found in the simulation of the baseline model within a similar region.

Another feature is present on both wakes: rear wingtip vortices. A pair of velocity loss regions, related to vortex cores, can be found next to the rear wing and forms the recirculation mechanism that shapes the base of the cited ‘mushroom-like’ trace described above.

Figure 35 presents the velocity magnitude at $x/L = 1.00$. Both experiment and simulation agree that the central zone of the rear base is no longer the region of highest velocity deficit at $x/L = 1.00$. The region has experienced an intense momentum recovery and weakly connect the upper wake trace to the ground boundary layer.

The experimental data suggests that the main region of momentum loss appears above the rear wing projection; where the velocity deficit reaches approximately $0.25U_\infty$. The corresponding CFD results on the baseline exhibits the similar flow distribution, whereas the velocity deficit on the upper trace is higher: $0.35U_\infty$.

The wingtip vortex cores are no longer discrete on both cases at $x/L = 1.00$, although the lower pair of lateral recirculation region gives an indication of their position. It seems that wingtip cores have not moved laterally but vertically by $\Delta z^* \cong 0.15$ on both experimental [27] and simulation car models from $x/L = 0.50 \rightarrow 1.00$.

The most significant difference in the flow features between cases is found for the ground boundary layer. In the experimental data [27], the boundary layer extends to approximately $z^* \cong 0.20$ at $|y^*| = 1.00$, and is gradually thickened towards the vehicle rear centre while merged with the vehicle wake. Even though the ground boundary far from the model has the same thickness at $|y^*| = 1.00$, it is halved at $|y^*| = 0.75$ and constant until reaching the outer rear wheels.

In summary, minor flow differences were expected since there are significant differences between the two vehicle geometries, each with singular influence on the surrounding flow; and differences on the flow conditions would expand those discrepancies (*e.g.* blockage, model scale, ground boundary layer). However, it can be seen that most of the time-averaged flow characteristics (*e.g.* (i) wake topology as a function of velocity magnitude, (ii) diffuser-rear coupled mechanism and (iii) position of vortex structure) from the race car data given by [27] were able to be reproduced by the CFD method adopted.

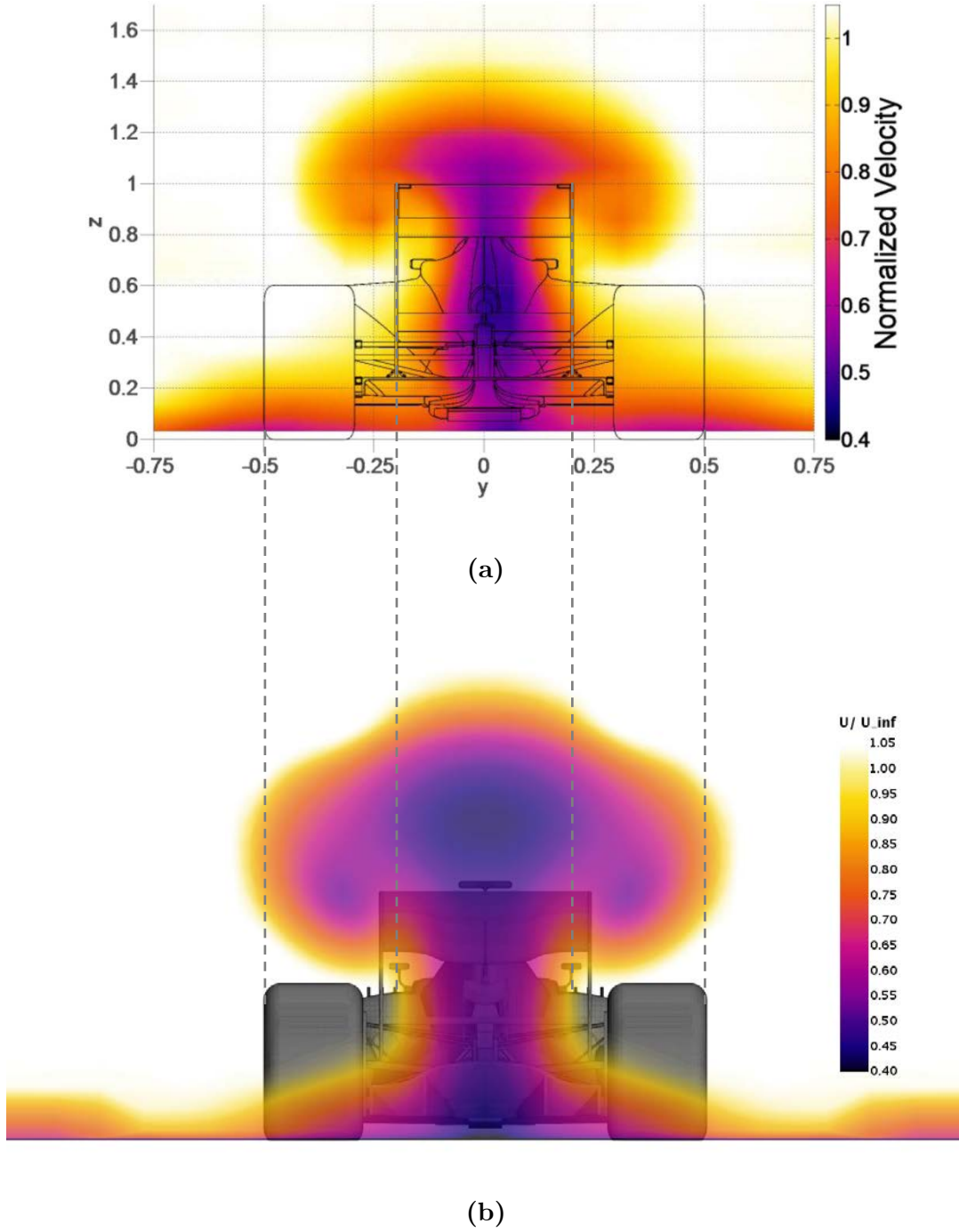
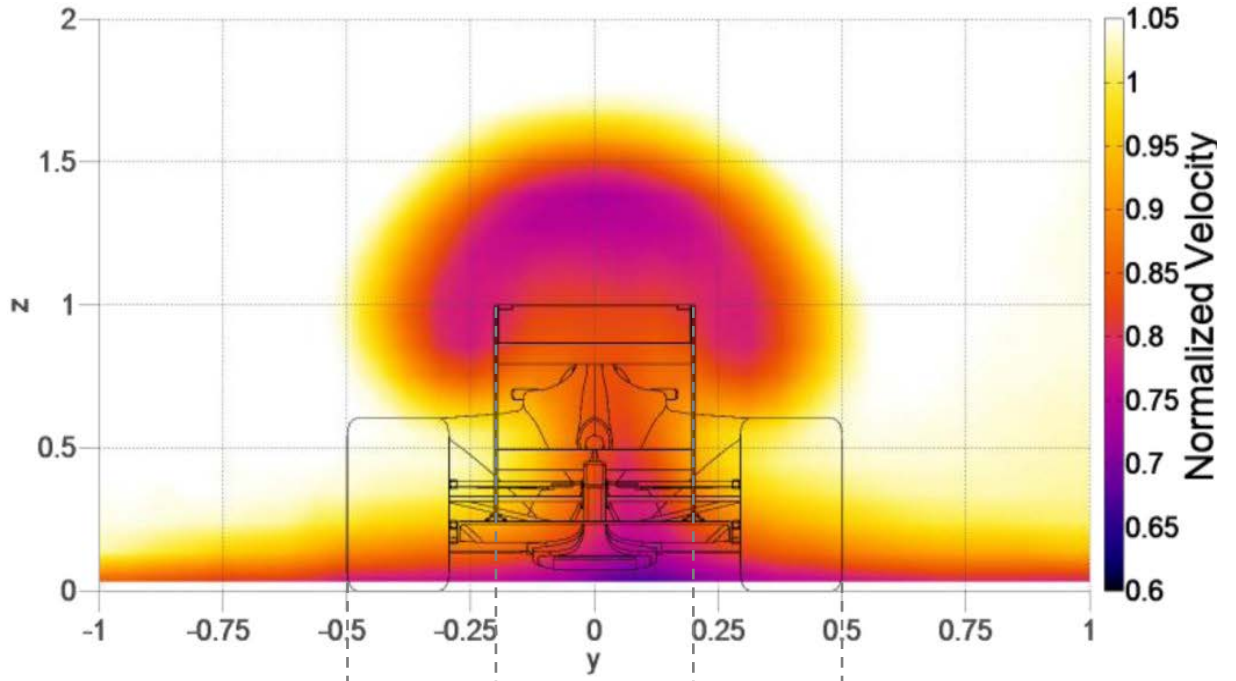
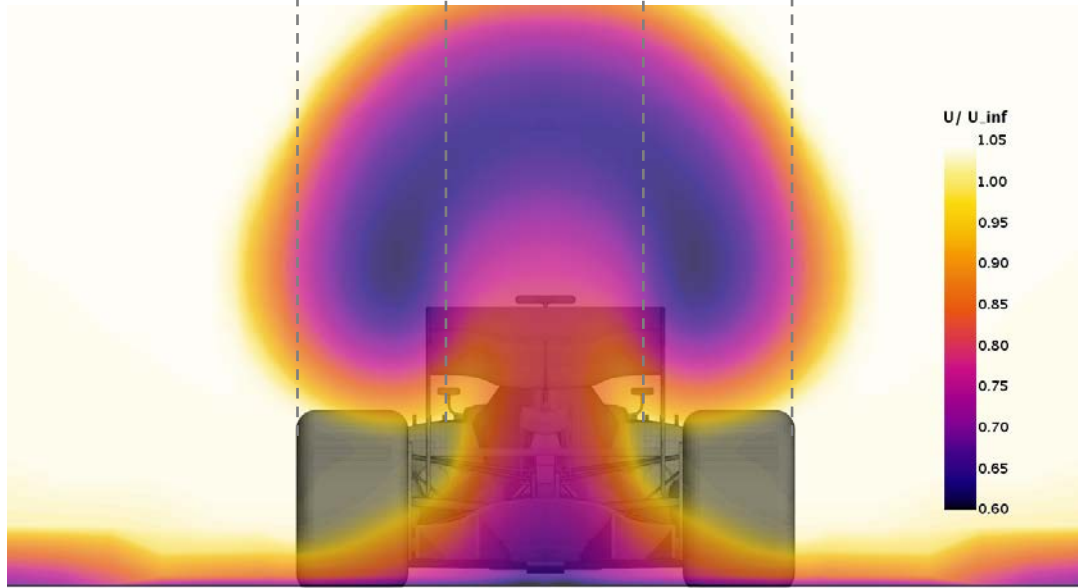


Figure 34. Wake development as a function of velocity magnitude. Comparison between (a) Watts *et al.* experiment [27] and (b) simulation (*woGS* case) in plane $x/L = 0.50$ downstream of the model. Reference scale limits and colorbar are reproduced in the simulation.



(a)



(b)

Figure 35. Wake development as a function of velocity magnitude. Comparison between (a) Watts *et al.* experiment [27] and (b) simulation (*woGS* case) in plane $x/L = 1.00$ downstream of the model. Reference scale limits and colorbar are reproduced in the simulation.

3.4.5 CASE II – Newbon *et al.* [28] simulation study, GSon: Wake Velocity Distribution

Results published by Newbon *et al.* [28] gives the opportunity to compare the wake prediction from the CFD simulation for a different condition (*i.e.* ground simulation, *GSon*). This adds to the reference case [28] the ground relative movement and proportional velocity field on the wheel’s surfaces. Unfortunately, more significant flow discrepancies may occur related to the differences between Newbon *et al.*’s geometry and the baseline adopted, particularly in relation to the rear wing. Considering the car width, W , as dimensional unit, the reference case geometry [28] compared to the baseline adopted has larger span (*e.g.* $0.54W$ vs $0.48W$) and shorter cord, while having lower height (*e.g.* $0.47W$ vs $0.56W$) and being at smaller angle of attack.

The wake characteristics are presented by Newbon *et al.* [28] in terms of axial velocity (*i.e.* downstream direction, U_x) in cross-flow planes between $x/L = 0$ to $x/L = 1$ in steps of $\Delta x/L = 0.25$. Figure 36 compares the refence study [28] to a simulation of the baseline geometry on ground simulation.

The nearest plane to the vehicle, $x/L = 0$, shows that the deficit in axial velocity is inherent to perpendicular vehicle surfaces in relation to the freestream direction. This is clearly exemplified by a rectangular velocity deficit trace from the chassis backlight; but also including rear wheels and rear wing central regions (Figure 36, *a*). For flow with axial velocity lower than $0.5U_\infty$, both results highlight two regions. The first is a projection of the rear wheel and chassis rear base, while the second is a mostly thin horizontal region above, and in proportional size, to the rear wing trailing edge. The second region shows the origin of a pair of counter-rotating, rear wing tip vortices located outboard of the endplates.

The axial velocity loss is significant at a quarter vehicle-length downstream, at $x/L = 0.25$. The reference study indicates that the wake topology is box-like with an inner, horizontal hyperbolic area with $U_x < 0.5U_\infty$ between the ground and the rear wing projection (Figure 36, *b*). In contrast, the simulation of the baseline model would provide similar topology, except by the effect of a likely inward flow next to the ground, which seems to be pushing the rear wheel wake inwards. Both cases exhibit a maximum velocity loss at the central rear projection; however, the baseline wake has a large change of wake topology earlier, revealed by the ‘mushroom-like’ trace, then resulting in a phase on the wake evolution between reference [28] and baseline cases on subsequent planes.

At $x/L = 0.50$ (Figure 36, *c*), the wake trace from the reference study model has morphed to the ‘mushroom-like’ shape. The chassis and diffuser traces are concentrated into a column on the symmetry plane, a region of high upwash flow. This feature bends and deflects the upper wake trace further, while it feeds the rear wingtip vortices structure. The baseline case also shows a column of velocity deficit but has a larger velocity recovery on the diffuser-projected region. The cores of each rear tip vortex are also recognisable in the wake trace, whereas they are formed outside the endplates due to a shorter rear wingspan in relation to the diffuser upwash width.

Figure 36, *d* shows that the wake trace topology (*i.e.* $U = 0.9U_\infty$) on both models is nearly doubled in height of the respective geometry by the plane $x/L = 0.75$. These wakes are mainly concentrated above the ground, near the rear wing height for the reference case [28]. A similar wake topology is found in the simulation of the baseline case, although the lower axial velocities are seen above the rear wing geometry.

The plane $x/L = 1.00$ shows minor changes of the axial velocity distribution in comparison to its antecedent plane (*i.e.* $x/L = 0.75$), indicating that velocity

gradients in the wake are reduced as a function of the distance (Figure 36, e). The ‘mushroom-like’ trace expands upwards while the region of minimum axial velocity in $x/L = 0.75$ is recovered by $\Delta U_x \approx 0.1U_\infty$ at $x/L = 1.00$.

Apart from differences over the entire chassis *per se*, the baseline geometry adopted has a larger gap clearance (*e.g.* $43.5mm$ vs $9mm$) and higher rear wing with shorter wingspan (*e.g.* $0.48W$ vs $0.54W$) and larger cord when compared to the geometry presented in [28]. The coupled effect of underbody-diffuser-rear wing design can be found on the intensity and position of the ‘mushroom-like’ topology denoted by Watts *et al.* [27].

In summary, both geometries exhibit similar trends in terms of wake evolution. The reference case [28] generated a wake delayed and more intense than the baseline model adopted; however, those differences seem to be strongly related to the respective geometry characteristics.

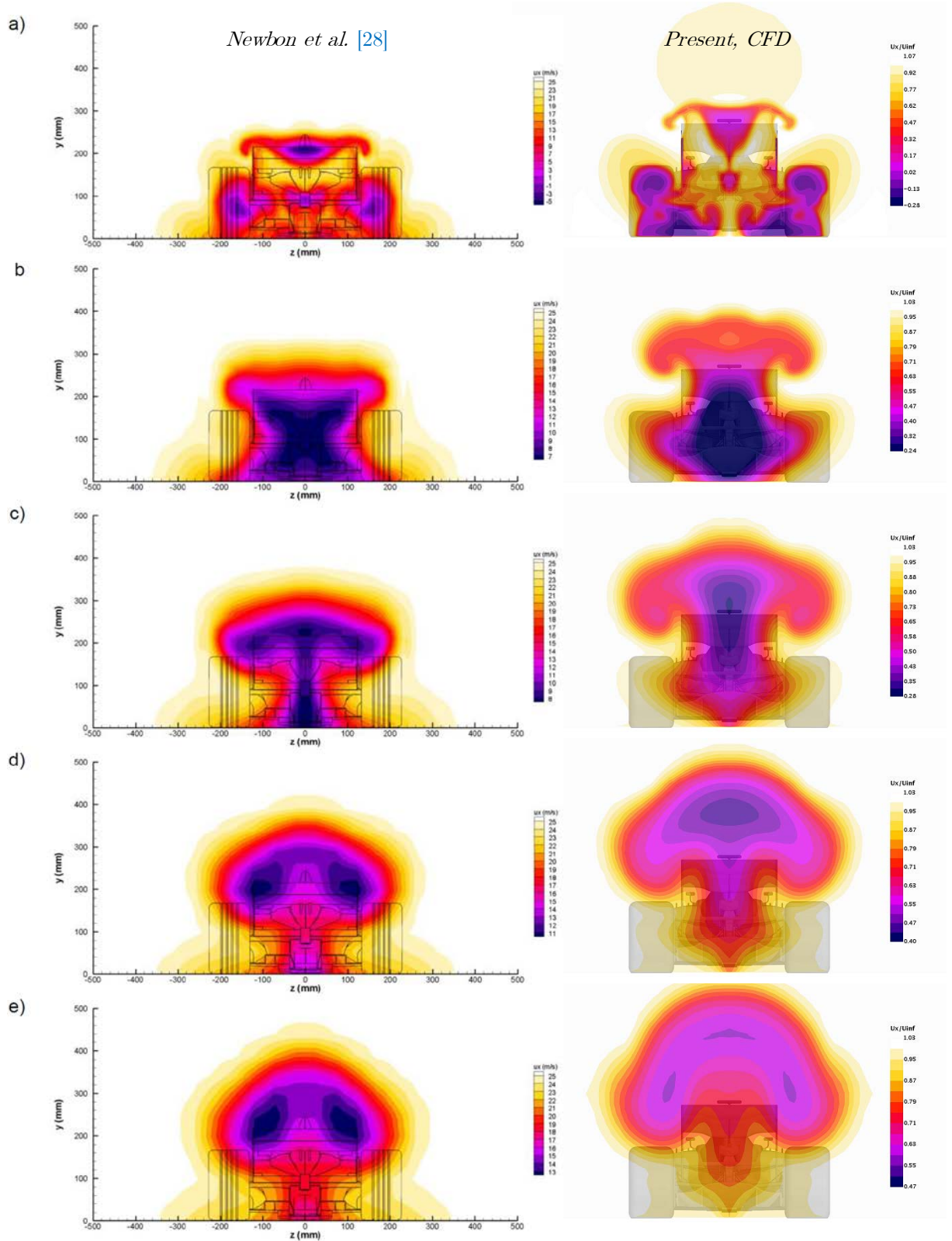


Figure 36. Wake development as a function of axial velocity. Comparison between (a) Newbon *et al.* [28] (left column) and baseline simulation (right column, *wGS* case). Cross-flow planes from (a) $x/L = 0$ to (e) $x/L = 1$ at $L/4$ steps. Reference scale limits and colorbar are reproduced in the simulation.

3.5 ON THE CONCLUSION AND LIMITATIONS OF THE CFD METHODOLOGY FOR VEHICLE WAKES

The cost-effective CFD approach based on RANS method has proved to be a reliable enough tool for the prediction of time-averaged, external aerodynamics of automotive applications.

In terms of passenger vehicle geometries, surface static pressure distributions have an acceptable correlation between experimental cases and respective virtual recreation by CFD, with an accuracy of $\overline{\Delta C_p} < 0.05$ to those references.

Surface oil-flow visualisation can be related to the numerical simulation; however, the analysis of the experimental reference [22] suggested that direct comparison to time-averaged CFD approach can be imprecise and/or inconclusive. Therefore, caution is recommended assuming that oil-flow experiments may be revealing a time-average flow condition; and time-average flow symmetry whenever the geometric conditions are accordingly.

In relation to the simulation of a high-performance vehicle, the CFD approach showed that the key features in the wake found on the experimental reference could be qualitatively reproduced with another similar geometry. A strong upwash combined with a pair of counter-rotating tip vortices were found on both references and on the geometry simulated.

Unfortunately, the validation for high-performance model was limited to qualitative evaluation due to the lack of a CAD geometry with respective experimental dataset [27] [28]. It highlighted the need for an open-source reference model for high-performance cars since they generate a unique category of ground vehicle aerodynamics.

To conclude, it was found that the time-averaged CFD approach adopted can provide acceptable results for the main features of the wake flow in automotive aerodynamics, yet with low-computational cost in comparison to other modelling alternatives.

Chapter 4.

EXPERIMENTAL ANALYSIS OF AUTOMOTIVE WAKES, Part I: a pressure-based analysis

This chapter presents the results of an investigation of the wake characteristics of the DrivAer automotive configurations using total pressure probes. This technique is an established method for characterising wake flows in terms of the variation in averaged total pressure in planes downstream of the vehicle base, using a multi-probe rake (Figure 37).

The objectives of this study are (i) to characterise the wake of automotive bodies as a function of total pressure and (ii) compile a wake dataset of the DrivAer model configurations, while (iii) assess the limitations of the technique.

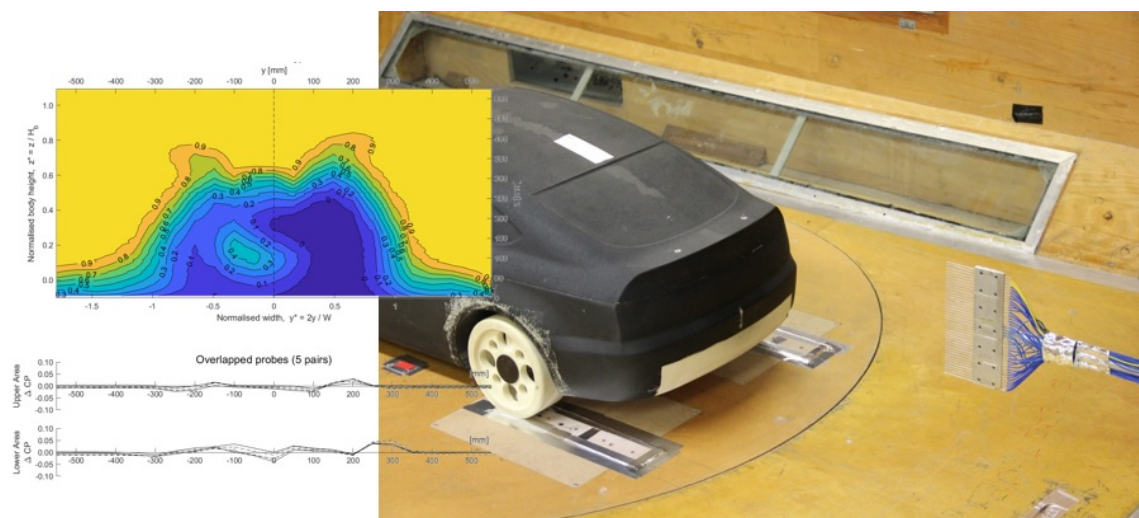


Figure 37. Total pressure rake being used for the wake analysis of a full-body, DrivAer Fastback model.

4.1 ON THE REFERENCE AUTOMOTIVE BODIES

4.1.1 Cranfield DrivAer model version

After earlier computational study using CFD, physical DrivAer models were manufactured for the experimental assessment of automotive wakes. Three modifications on the original DrivAer geometry were made: (i) wheel shape, (ii) wheel cavities, and (iii) underfloor surface.

[Figure 38](#) illustrates the wheel design manufactured and adopted for all experimental tests cited in this thesis. This design simplifies the original geometry for regular-based shape and is intended for ground fixing, non-rotating wheel cases. An inner cavity was added in order to host a metal structure that connects the wheel to the main body, while allowing fixing the body assembly on pins in the floor. Wheel cavities are simplified for a regular-based geometry. [Figure 39](#) highlights the changes over the original version [\[5\]](#), which simplifies both (i) manufacturing process for experiments and (ii) meshing process for CFD simulations.

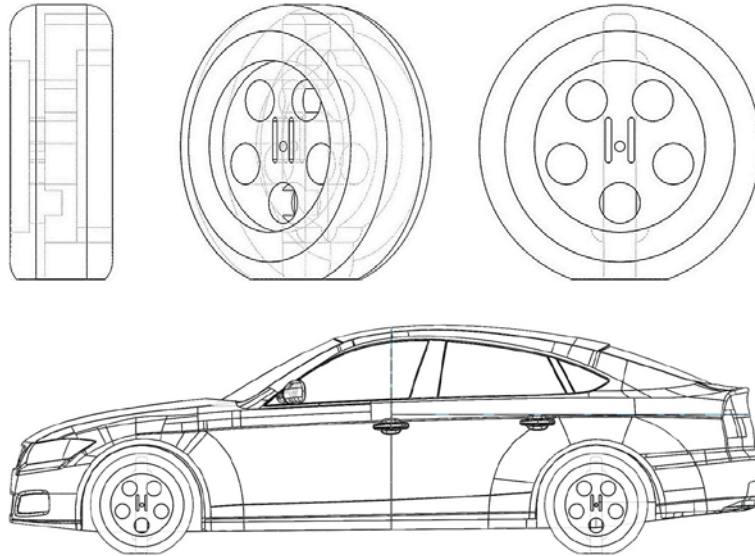


Figure 38. Cranfield DrivAer model: wheel geometry for non-rotating, ground fixed DrivAer model.

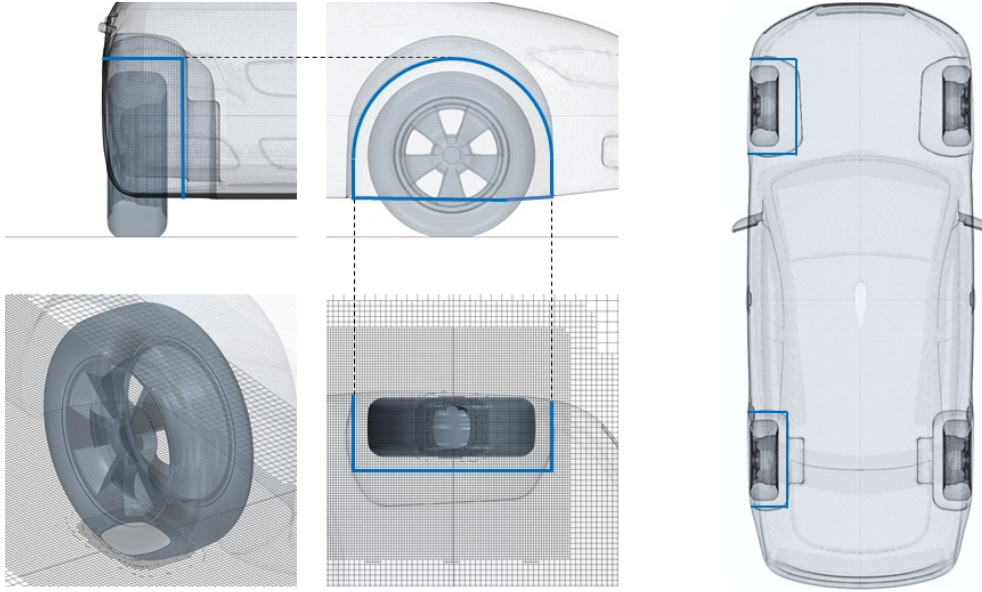


Figure 39. Cranfield DrivAer model: geometric simplification of wheel cavities (blue edges) highlighted over the original version [5].

The third significant change is on the underbody surface (Figure 40), where the larger planar surface is extended to match the projection of the rear wheel axle. The extended edge become a hinge for the diffuser plate, then allowing adjustment of the diffuser angle (*e.g.* [49]).

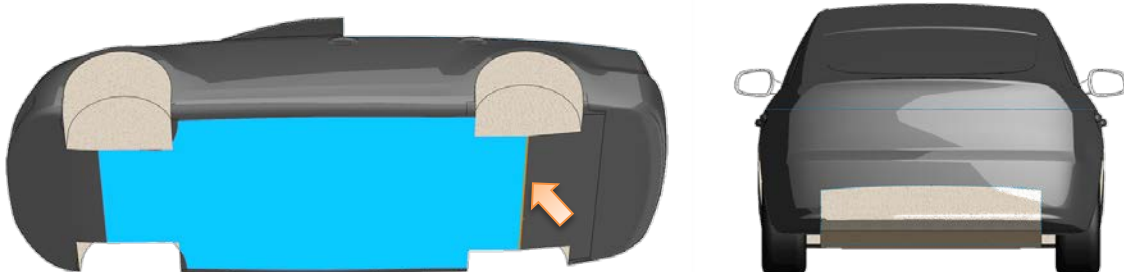


Figure 40. Cranfield DrivAer model: extended underfloor plate matching the rear axle x -coordinate.

Apart from those changes, the model has overall dimensions identical to the original geometry and still can be assembled with original parts, like the three rear-ends and side mirrors [5].

Table 16 summarises the dimensional definitions used in CAD and consequent physical dimensions the 35%-scale model built for experimental tests.

Table 16. Parametric dimensions for Cranfield DrivAer model version.

Parameter	Symbol	Definition	DrivAer Cranfield	
Car scale	CS	—	35 %	
Reference length	L	$4.6126 \times CS$	1.6144	m
Front end (x -position)	x_o	$-0.8075 \times CS$	[-0.283, 0, 0]	m
Front wheels axle position	x_F	0	[0, 0, 0]	m
Rear wheels axle position	x_R	$2.7861 \times CS$	0.9751	m
Gap clearance	h_c	$0.1272 \times CS$	0.0445	m
Reference height	H	$1.4182 \times CS$	0.4963	m
Reference width; Wheel track	W	$1.7529 \times CS$	0.6135	m
Wheel radius	wr	$0.3143 \times CS$	0.1100	m
Wheelbase	wb	$2.7862 \times CS$	0.9752	m
Reference area	A_{ref}	$2.1605 \times CS^2$ (full-car)	0.2647 (full-car)	m^2

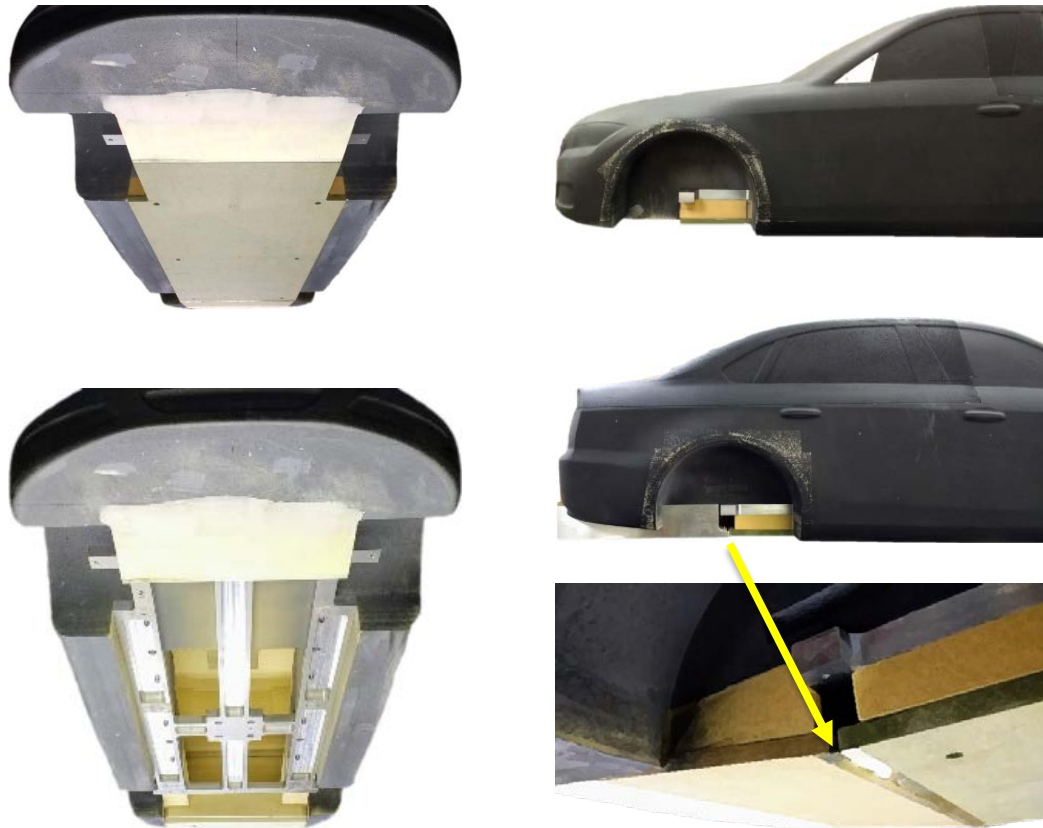


Figure 41. Details of the physical model, highlighting underbody and wheel cavities of the manufactured Cranfield DrivAer version.

For illustrative purposes, [Figure 41](#) shows the manufactured inner frame, underbody cover, wheel cavities and position of the underbody-diffuser edge. The CAD geometries of the main body, rear-end(s), and wheels are packs of the open-source ‘DrivAer-hp’ CAD collection, available online at:

Soares, Renan Francisco; Olives, Sergio Goñalons; Knowles, Andrew Paul; Garry, Kevin; Holt, Jenny (2018): *DrivAer hp-F: the CAD geometry pack*. Figshare. Collection. <https://doi.org/10.17862/cranfield.rd.c.3969120>.

DrivAer hp-F refers to the high-performance DrivAer model configuration developed and proposed as a benchmark for motorsport aerodynamics, then used for wake assessment during this research project as described in the next section.

4.1.2 Development of a High-performance Reference Model: a fourth, high-performance vehicle configuration of the DrivAer model

The earlier stages of the research project run into a relevant gap in the academic field of automotive aerodynamics: the lack of a benchmark model for high-performance vehicles.

While the DrivAer benchmark has supported the investigation of aerodynamics-related topics on passenger cars, high-performance vehicles have not been investigated to the same extent by the academic community.

A collection of (i) *experimental dataset* with respective (ii) report of *experimental conditions* and access to (iii) *CAD geometry* is of utmost importance for appropriate CFD validation, then reflecting on the quality of computational design. In experimental applications, the use of a reference model can assist to better compare and evaluate experimental findings across different facilities.

In order to fill this gap, a simplified but effective aerodynamic pack was developed to convert the well-adopted DrivAer model into a high-performance configuration (Figure 42). This outcome is based on a series of parametric assessment usually applied on race car aerodynamics, divided into four groups and assessed in independent studies:

- i. Forebody strakes (dive planes)
- ii. Front bumper splitter
- iii. Rear-end spoiler
- iv. Underbody diffuser

The influence of each add-on device on the performance of the baseline body was assessed individually in a range of ride heights over a moving belt.

The proposal of a fourth, high-performance vehicle configuration of the DrivAer model configuration (denotated in this thesis as ‘*hp*’ configuration) concluded this collaborative project (Figure 42), where [49] provide further details of the aerodynamic loading performance of this configuration as a function of ride height and Reynolds number.

In agreement with the open-access philosophy which the original DrivAer model was published, this proposed high-performance configuration has (i) CAD geometry and (ii) experimental data (*e.g.* aerodynamics loads with statistical analysis) available online for the international community to support independent studies (Figure 43).



Figure 42. ‘DrivAer-hp’ configuration [49]: development team.

All digital material related to the high-performance DrivAer configuration are available at:

Publication:

Soares, R., Knowles, A., Goñalons Olives, S., Garry, K. *et al.* “On the Aerodynamics of an Enclosed-Wheel Racing Car: An Assessment and Proposal of Add-On Devices for a Fourth, High-Performance Configuration of the DrivAer Model”. SAE Technical Paper 2018-01-0725, 2018, <https://doi.org/10.4271/2018-01-0725>.

CAD geometry packs:

Soares, Renan Francisco; Olives, Sergio Goñalons; Knowles, Andrew Paul; Garry, Kevin; Holt, Jenny (2018): *DrivAer hp-F: the CAD geometry pack*. Figshare. Collection. <https://doi.org/10.17862/cranfield.rd.c.3969120>.

Experimental database:

Soares, Renan Francisco; Garry, Kevin; Holt, Jenny (2018): *Dataset for SAE 2018-01-0725 “On the Aerodynamics of an Enclosed-Wheel Racing Car: an assessment and proposal of add-on devices for a fourth, high-performance configuration of the DrivAer model”*. Figshare. Fileset. <https://doi.org/10.17862/cranfield.rd.5833875>.

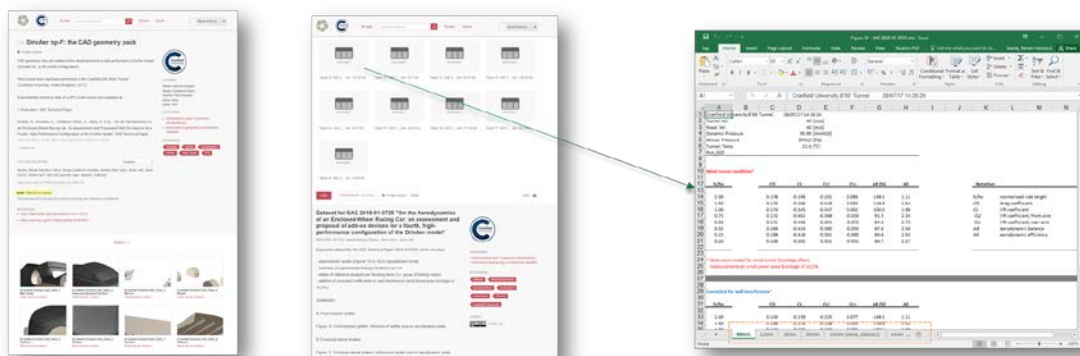


Figure 43. ‘DrivAer-hp’ configuration [49]: CAD geometry packs and wind tunnel database available at Cranfield Online Research Data (CORD).

4.2 ON THE EXPERIMENTAL METHODOLOGY

4.2.1 Wind Tunnel Test Section Configuration

The Cranfield 8x6 Wind Tunnel was fitted with stationary floor configuration for automotive testing, which consists of: (i) an elevated, main wooden floor plate holding the turntable and model mounting system, and (ii) two-stage, boundary layer control system.

The 1st-stage of the boundary layer control system (BLC1) is designed to remove most of the contraction wall boundary layer with a scoop intake. The boundary layer that subsequently forms downstream of the 1st-stage is removed by suction through a flush-mounted, perforated aluminium plate (*i.e.* 2nd-stage, BLC2). [Figure 44](#) highlights both boundary layer control system and the turntable, used for model mounting in the test section.

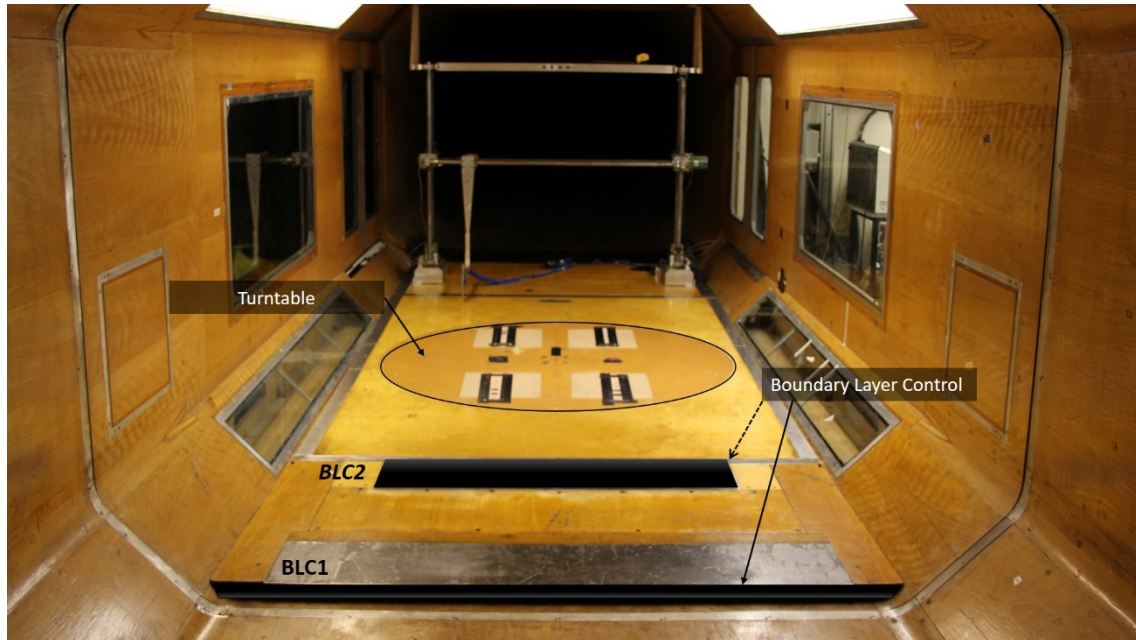


Figure 44. Cranfield 8x6 Wind tunnel turntable configuration for automotive application: turntable plate and two-stage control system for treatment of ground boundary layer.

4.2.1 Total Pressure Rake

The total pressure rake consisted of 40 total pressure probes assembled with the probe centrelines separated by $4.77 \pm 0.50\text{mm}$ (*i.e.* minor variance due to tubes misalignment).

The metallic tubes are held in place by an aerodynamic support and connected via plastic tubes to a transducer device (Figure 45).

The decision to maintain the Pitot rake frame fixed was made to mitigate vibrations in the support strut (*i.e.* even though the frame is based on metallic beams, the total pressure rake can be sensitive since the rake support is only attached to one of the transverse bars nearly 2m long).

Figure 46 illustrates the installation in the wind tunnel, where the standard acquisition plane is orthogonal to freestream and positioned at 1450mm upstream the working test section end.

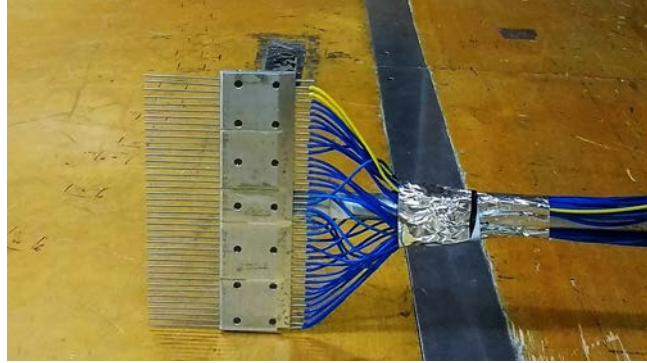


Figure 45. Total pressure rake: 190.8mm rake of 40 simple (single-hole) total pressure probes during an measurement of the ground floor boundary layer.

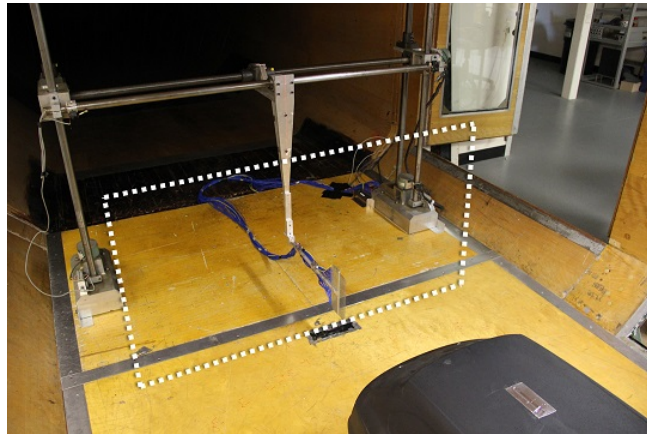


Figure 46. Experimental apparatus installed for experiments.

4.2.2 Degrees of Freedom

A stationary ground simulation was adopted as a compromise that allows assessing automotive wakes as a function of streamwise position and freestream yaw incidence angle.

Since the wake data acquisition plane position was kept constant (a result of fixing the total pressure rake frame position), the relative displacement between vehicle and the crossflow measurement was varied by displacing the model in the working section. With the model at the required streamwise position, any effective yaw angle can be set by rotating the turntable: a circular, wooden plate fitted flush to the floor of the working section.

The total pressure rake is mounted on a two-component automated transverse, which allows independently controlled adjustment of the vertical (z -axis) and lateral position (y -axis) of the rake. This provides the ability to cover planar sections of the wake of interest. [Figure 47](#) illustrates the variables used during experiments.

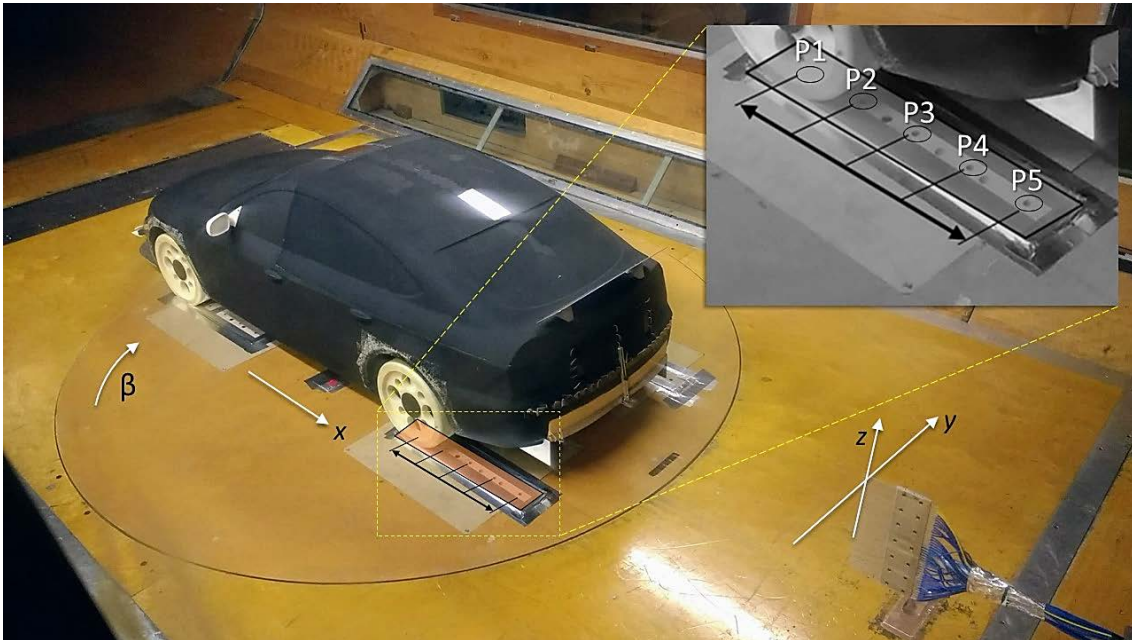


Figure 47. Illustration of spatial degrees of freedom used for measurements.

4.2.3 Experimental Setup

A class 1, laser sheet levelling tool was used to support the alignment of the vehicle models and total pressure rake at required, reference positions.

The levelling tool was positioned upstream of the test section in order to cast a vertical laser sheet downstream to match the reference wind tunnel centreline (Figure 48).

While axial displacement used predetermined positions, only the turntable rotation allowed alignment fine-tuning (*i.e.* definition of the nominal zero-yaw angle position). Small lateral displacement of $\sim 5\text{mm}$ was found between the model axial centreline and wind tunnel the reference laser plane, although it is negligible if compared to the distance to wind tunnel's lateral walls.

After the reference vehicle position was found (*i.e.* the definition of nominal zero-yaw angle), the Pitot rake had three degrees of freedom to be set: one rotational and two translational. The rake was rotated so that a vertical position was found and locked. The horizontal displacement at the model centreline plane defined the y -axis origin.

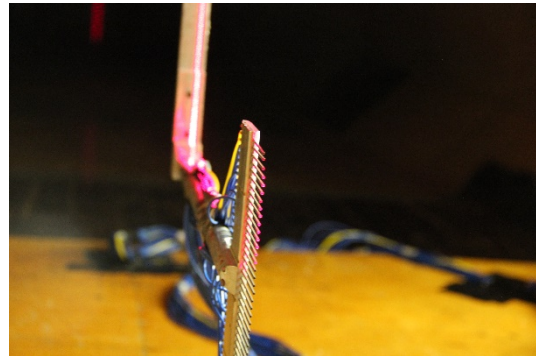
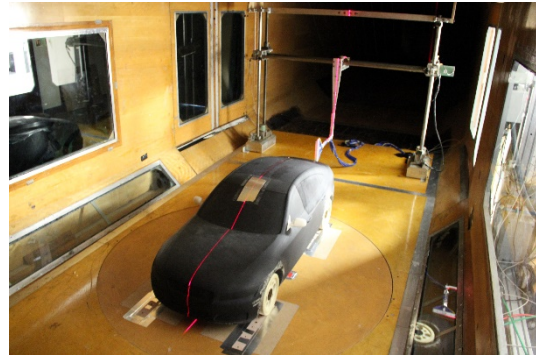


Figure 48. Alignment of both rake and vehicle model assisted by laser. Laser sheet is a useful tool for aligning of both model and probe.

Independently, the z -axis was the vertical coordinate with origin on the floor surface.

4.2.4 Data Acquisition Procedure

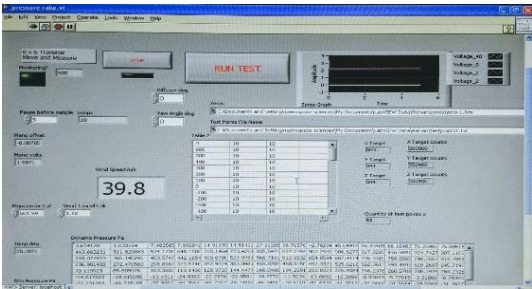


Figure 49. Software interface for pressure rake control.

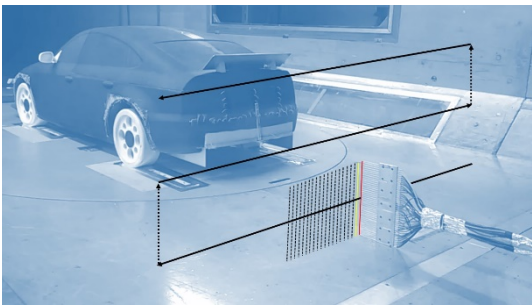


Figure 50. Rake path routine: direction and examples of subsequent rake positions during an acquisition routine.

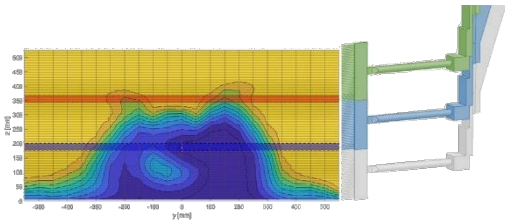


Figure 51. Construction of a data grid using multiple passes, with overlapping areas for statistical purposes.

Dedicated software developed in LabVIEW was used to operate the Pitot rake system for both data acquisition and positioning. The interface provided real-time readings of target rake position, reference voltage and freestream temperature (Figure 49), while the working section flow velocity was maintained in a separated system.

Total pressure contour maps were obtained by sweeping the rake through the plane of interest (Figure 50). For statistical purposes, two overlapping areas were created by matching five of the 40 probes between adjacent path pairs (Figure 51).

The probe was held stationary for 10s during data acquisition at all positions of interest; this ensured results for a steady-state condition and mitigated any potential for time-

dependent bias. To illustrate this point, if the acquisition routine were performed with a constant-moving rake, data relating to a specific position would be recorded over a small elapsed time – or respective number of samples. This would increase the potential noise or bias due to the fluctuations of a time-dependent flow, such as seen in the turbulent wakes of bluff-bodies.

Freestream temperature and ambient pressure were measured during each wind tunnel run; density was therefore calculated assuming the ideal gas law:

$$PV = nRT \quad (4.1)$$

where P denotes pressure, V is volume, n equal to the number of moles, R is universal gas constant, and T the fluid temperature – all in SI base units. The relation between V and n can be converted into molecular weight equivalent to air, M_w , and gives the air density, ρ , then defined as [Eq. \(4.2\)](#).

$$\rho = \frac{M_w P}{RT} \quad (4.2)$$

Dynamic viscosity is estimated using Sutherland's equation [\[50\]](#) as follows:

$$\mu = \mu_o \left(\frac{T_o + S}{T + S} \right) \left(\frac{T}{T_o} \right)^{3/2} \quad (4.3)$$

Constants used for density and viscosity estimations are defined and presented in [Table 17](#). The air properties of wind tunnel experiments, described in ‘*Results and Discussion, Part I and II*’ ([sections 4.3 and 4.4](#)), were measured at the beginning of each run and are summarised in [Table 18](#).

Table 17. Constants for air properties estimation [50].

Constant	Symbol	Value	Unit
Molecular Weight	M_w	28.96	$kg/kmol$
Universal Gas Constant	R	8314.4	$J/kgmol.K$
Sutherland Constant	S	110.4	K
Reference Temperature	T_o	273.15	K
Reference Viscosity	μ_o	1.716×10^{-5}	$Pa.s$

Table 18. Summary of air properties during the total pressure measurement campaign.

Air property	Symbol	Min	Max	Unit
Temperature	T	24.1 297.6	33.9 307.1	$^{\circ}C$ K
Pressure, Environmental, reference	P_{∞}	100 058	101 592	Pa
Density (estimated)	ρ	1.1435	1.1849	kg/m^3
Viscosity,				
Dynamic (estimated)	μ	1.8343×10^{-5}	1.8791×10^{-5}	$Pa.s$
Kinematic (estimated)	ν	1.5503×10^{-5}	1.6358×10^{-5}	m^2/s

4.3 RESULTS AND DISCUSSION, PART I: On the Assessment of Tool and Experimental Conditions

This section details the preliminary analysis of the experimental facility, in order to understand the flow conditions relevant to measurement campaigns using the total pressure rake.

4.3.1 On the sensitivity of Boundary Layer Control system (BLC)

The performance of the working section boundary layer control system was assessed in order to understand the experimental conditions and define a standard setup for the subsequent automotive application.

In an empty wind tunnel configuration (*i.e.* no model in the test section), the ground boundary layer the standard acquisition plane was measured as a function of control system arrangement. [Figure 52](#) illustrates this experimental investigation.

The flow on the working section floor was influenced by different combinations of the independent flow intakes (BL1 and BL2) as expected. In terms of variations in total pressure, all cases indicate that the gradient decay as a function of the height, and boundary velocity profile matches the freestream magnitude before 100mm . With both systems off, a larger area of total pressure loss is produced compared to a full-operational case with both BL intakes on. However, results also exhibit some non-intuitive characteristics in terms of relative performance and uniformity.

Compared to a passive case with both BL intakes off, the active BL first-stage (only BL1 on) yields only a residual reduction of the boundary layer area, while the total thickness is almost unaltered ([Figure 53](#)). Adding the second-stage (both

BL on) promotes a substantial performance gain, reducing both the total pressure loss and boundary layer thickness.

It can also be seen that the boundary layer profile (Figure 53) and distribution (Figure 54) vary at different locations along the y -axis for all cases. The time-averaged result would provide, in theory, a smooth and uniform boundary layer profile over the planar walls of the wind tunnel test section. However, all cases have a maximum total thickness variation of at least 10mm , while locations at $+ve$ y -axis tends to larger thickness than those with $-ve$.

In relation to these differences in the boundary layer thickness, the wooden plate where the acquisition was taken was assessed with a digital protractor, which showed that it was not perfectly flat along y -axis (Figure 45 and Figure 46). Relative height gap of nearly 5mm was found between path limits ($y = \pm 600\text{mm}$). This partially explains the bias between $+ve$ and $-ve$ measurements.

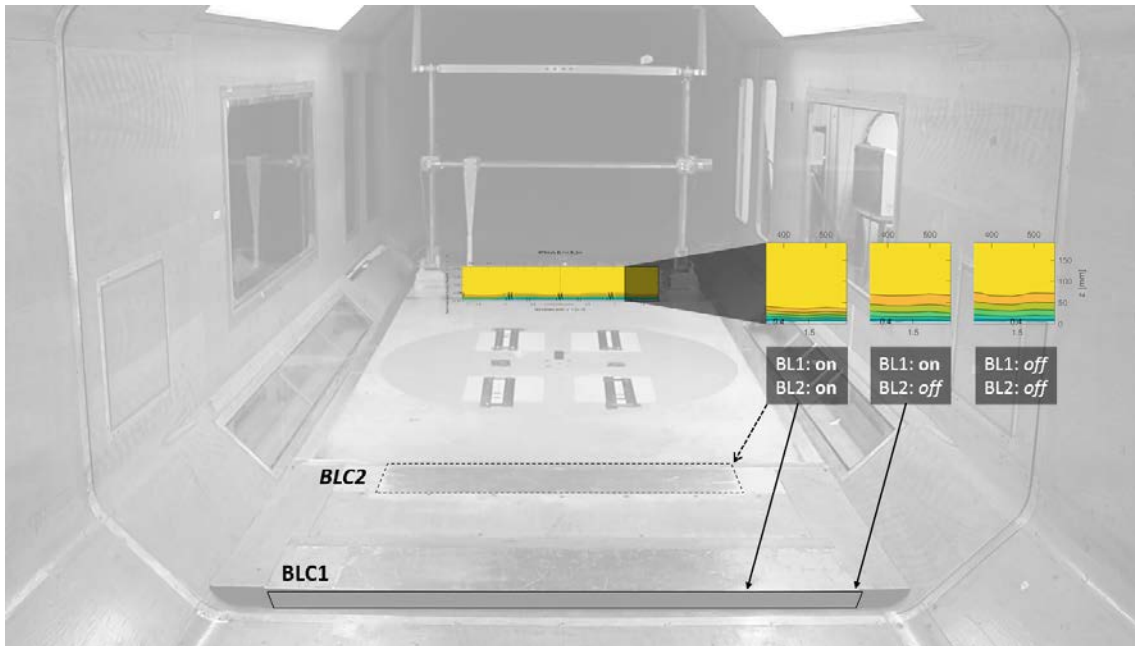


Figure 52. Boundary control system (BL1 and BL2) influence on an empty test section case.

The floor turntable surface was also inspected in an attempt to identify the cause of the boundary layer thickness non-uniformity. Minor gaps (2 to 5 mm) and steps (1 to 2 mm) around the wheel support pads may have perturbed the boundary layer growth, resulting in minor thickness increment in the region of $y = \pm 300\text{ mm}$.

Note that the porous suction surface that constitutes BL2 is not as wide as BL1, then the boundary layer outboard grows differently from that after BL2. This means that, at the y -axis extremes, the flow is exposed to the mixing from those two boundary layers. A minor trend of non-uniformity is identified at the y -axis extremes (*e.g.* between $|550 < y < 600| \text{ mm}$) and is considered sufficiently distant to not influence wake measurements at zero-yaw angle

In conclusion, the measurements support the decision to employ both BL1 and BL2 as a boundary layer control system. Their use does not eliminate possible influence of the ground boundary layer on the wake development, but this setup is the best option to significantly reduce its effects and can deliver a smoother ground boundary layer no thicker than 40 mm at the rake position.

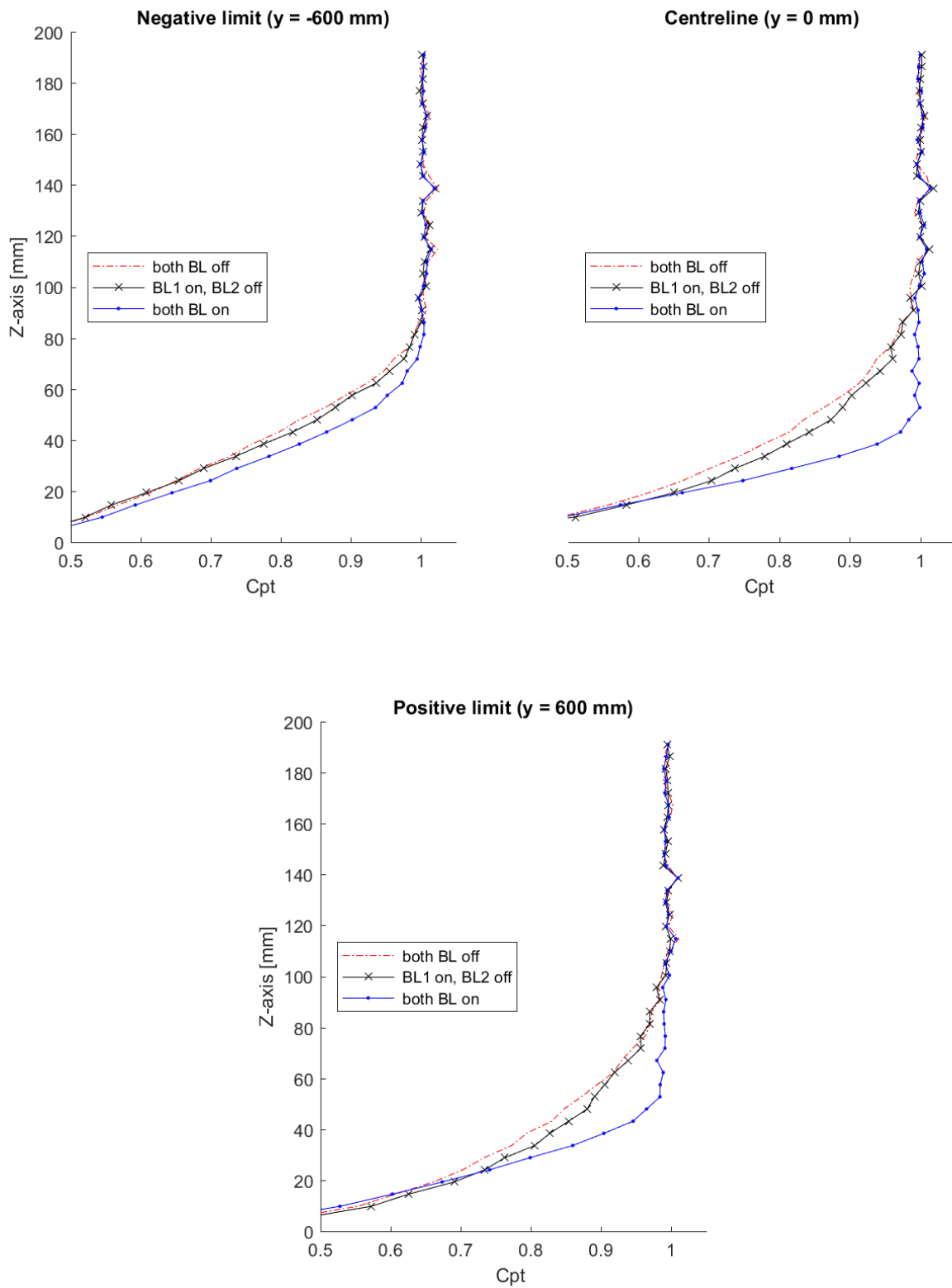
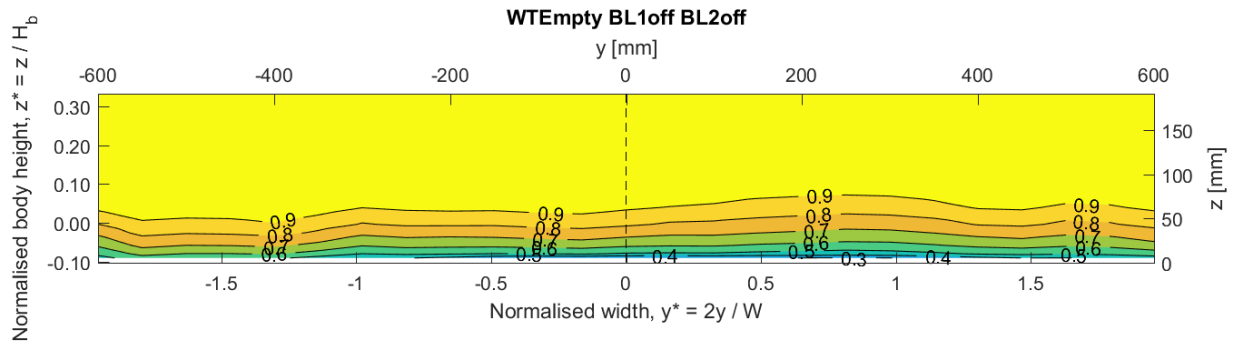
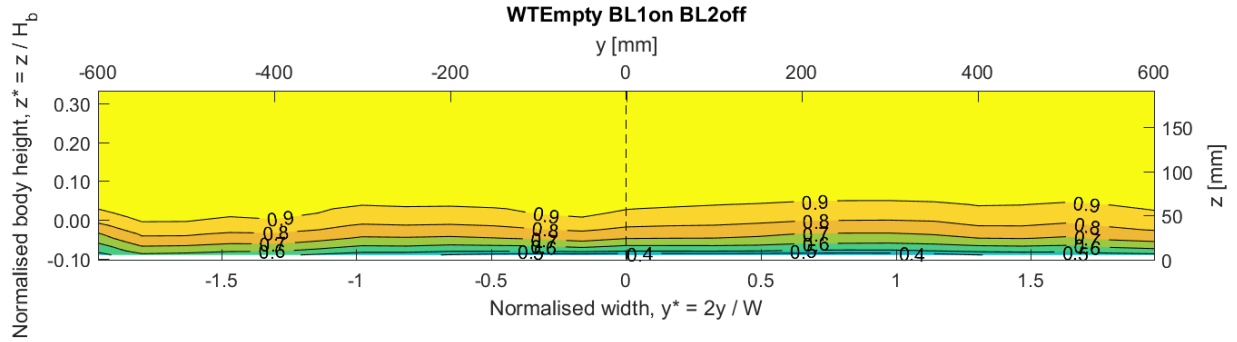


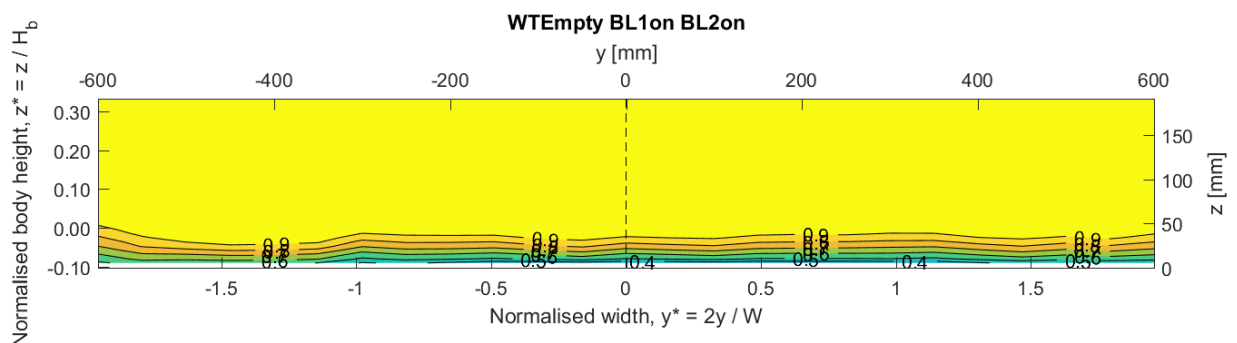
Figure 53. Total pressure rake as a function of BL control system. Measurements at 1450mm upstream of the working section end.



(a)



(b)



(c)

Figure 54. Total pressure surface as a function of the BL control system.
 (a) both turned off, (b) only the BL1 active, and (c) both turned on.

4.3.2 On the effects of Measurement Grid Resolution

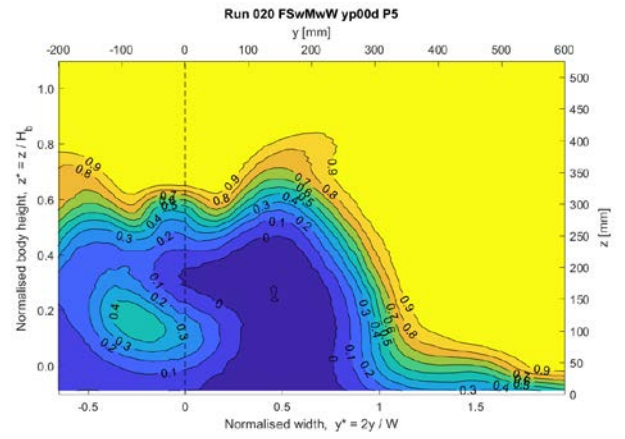
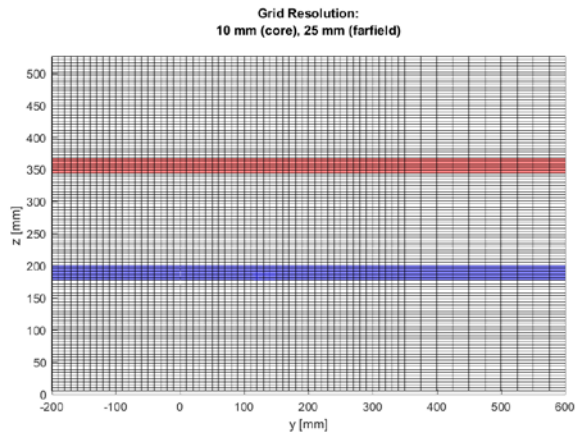
This section presents an assessment of measurement grid sensitivity as a function of grid resolution over the horizontal y -axis – the direction of successive displacement steps, forming a probe acquisition grid and respective total pressure map (Figure 50). Only y -axis resolution is variable and analysed in the range of 10 to 50 mm . Considering that the total pressure rake is set vertically, the z -axis acquisition resolution is equal to the constant rake pattern itself (*i.e.* $4.77 \pm 0.50 mm$), which is considered sufficient for the experiment.

Three grid resolutions were studied and summarised in Table 19. The DrivAer Fastback model (*FSwMwW*) was the benchmark configuration used under identical conditions to ensure appropriate evaluation of grid-sensitivity for the total pressure contour map.

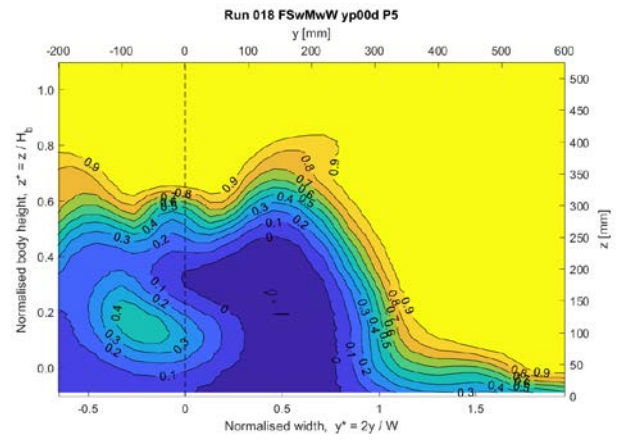
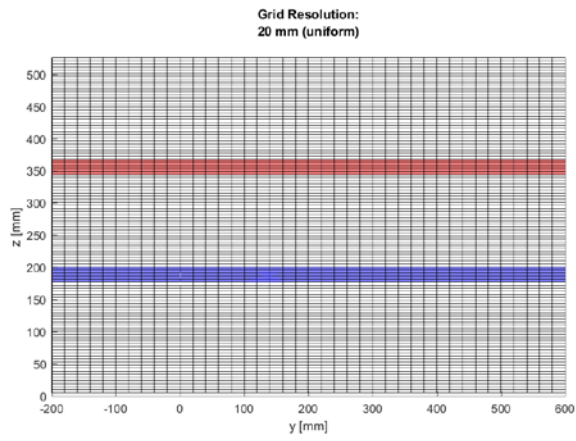
Table 19. Description of measurement grid-sensitivity cases.

Reference	Distribution	Spatial resolution	Total number of rake positions	Total time elapsed (<i>i.e.</i> one WT run)
Refined	Dual-zone, uniform	10 mm (core), 25 mm (outside)	198 (66 per pass)	~ 30 min
Medium	Uniform	20 mm	123 (41 per pass)	~ 23 min
Coarse	Uniform	50 mm	51 (17 per pass)	~ 17 min

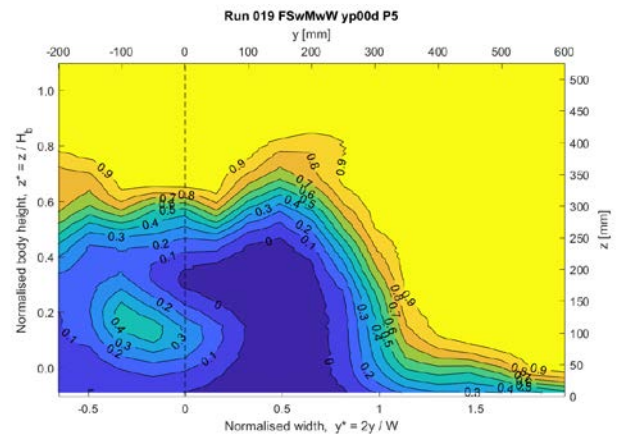
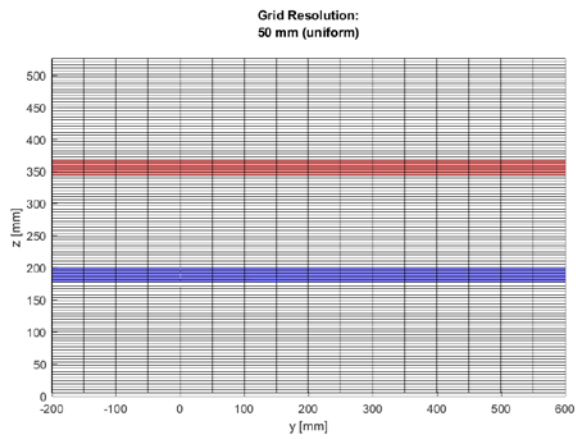
Qualitative analysis shows that all the grids tested can map the total pressure distribution within an automotive wake (*i.e.* after near-wake recirculation). A preliminary comparison in the region at the top of the wake (Figure 56) shows that only minor, local differences are noticeable as the grid resolution decreases. The complete set of grids are presented in Figure 55, as well as the corresponding total pressure surfaces generated using linear interpolation.



(a)



(b)



(c)

Figure 55. Total pressure surface as a function of grid resolution.
(a) Refined: 10mm core, 25mm outside; (b) Medium: 20mm uniform; (c) Coarse: 50mm uniform.

An alternative method of assessing the influence of grid resolution uses the total data for a given probe path. Figure 57 displays six linear-interpolated response curves as a function of the grid resolution, each acquired from the same probe (*i.e.* constant height) along a path segment.

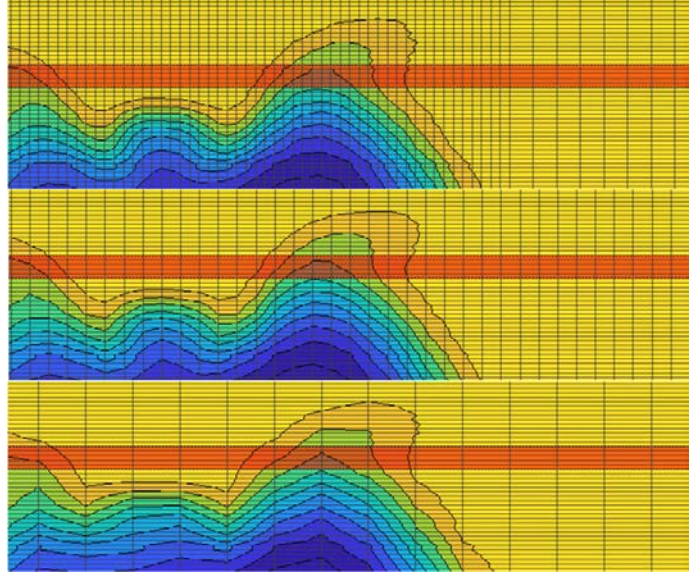


Figure 56. Illustration of the grid resolutions and respective total pressure contour map.

The refined grid delivered smooth, continuum-like curves over multiple pressure gradients presented in the model wake (*e.g.* Probe #50 and #60). In addition, the inner-refinement zone limited to $y < 350 \text{ mm}$ successfully captured the total pressure deficit in the wake. However, a test cycle based on this acquisition grid would require 198 rake iterations (66 per pass) and approximately 30min of wind tunnel time.

Although it has nominally twice the step size of the refined grid, the medium-resolution grid offered similar precision (Figure 57, red dash-dotted lines). The curves also captured the pressure gradients, albeit with minorly discontinuities (*e.g.* pressure peaks from probe #50 and #60). The total number of iterations was reduced to 123 rake positions (66 per pass) saving 7min per wind tunnel test cycle.

The coarser resolution (Figure 57, black dash lines) is suitable for measurement of the overall pressure distribution with low gradient under acceptable accuracy (*e.g.* Probe #10 and #20), but areas with high oscillations were poorly defined (*e.g.* Probe #30, #50 and #60). While a wind tunnel test cycle can be concluded

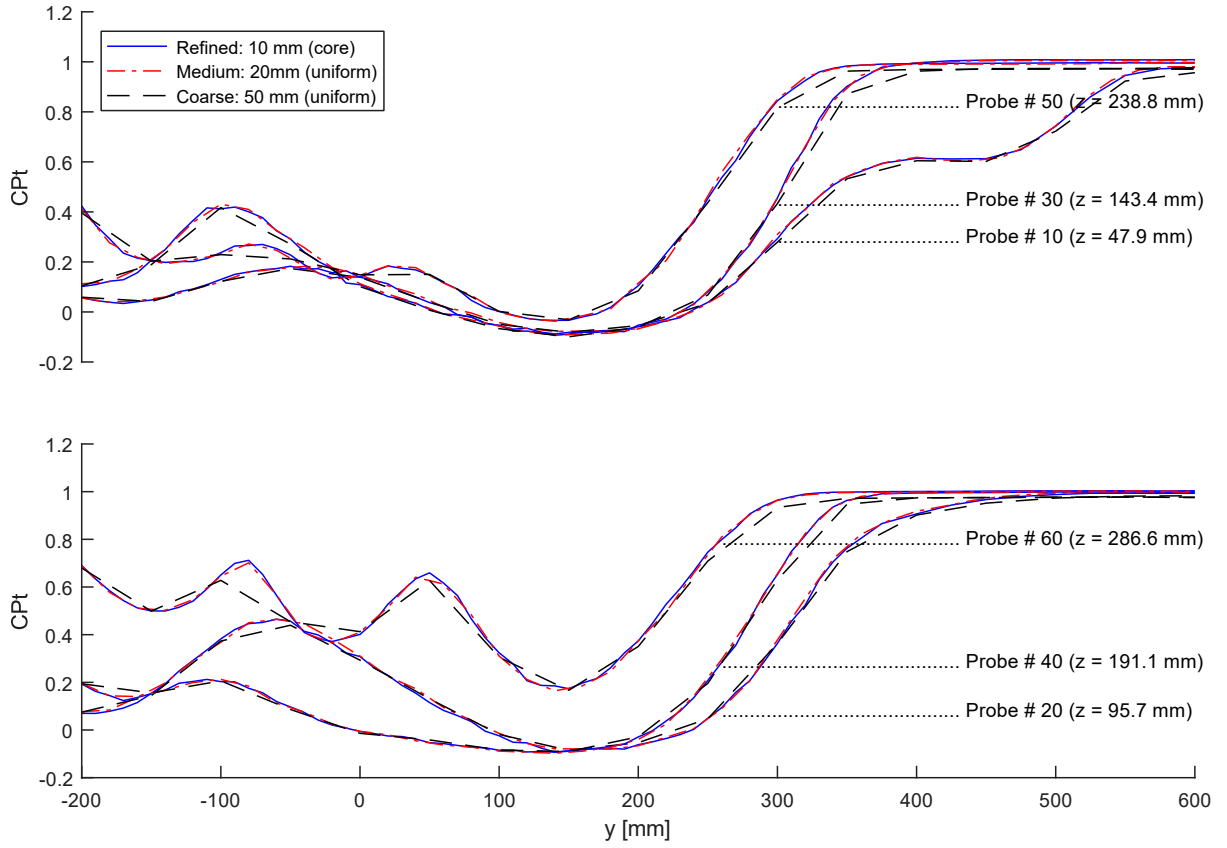


Figure 57. Comparison of grid resolution-sensitivity along the y -axis.

in approximately 17 *min* – corresponding to a time reduction more than 40% due to use of 51 rake iterations (17 per pass), the pressure oscillations are filtered by the resolution unit (*e.g.* Probe #60).

In summary, all measurement grids successfully mapped the total pressure planar distribution in an automotive wake. The decision for the resolution must be a compromise between the resolution required and the wind tunnel time available for the test. A resolution between 20 mm to 50 mm can be considered for wind tunnel cost-effectiveness, while resolutions no smaller than 10 mm are advised for well-defined results.

4.4 RESULTS AND DISCUSSION, PART II: On the Compilation of a Wake Database

This section reports on the provision of a wake database for automotive aerodynamics. The results of experimental tests using four automotive model configurations are presented and discussed in relation to three aspects:

- Group I: Wake characteristics as a function of distance downstream of vehicle base*
- Group II: On the sensitivity to changes in freestream Reynolds Number for full-body automotive wakes*
- Group III: Statistical Analysis*

Apart from the three rear-body configurations (F , N , and E) and high-performance kit (hp), all vehicle models shared a standard configuration: ‘ $S\mathcal{w}M\mathcal{w}W$ ’, which denotes smooth underfloor (S), external side mirrors ($\mathcal{w}M$), and generic wheels ($\mathcal{w}W$).

Note that the total pressure contours are presented with both dimensional and normalised axes, in order to better quantify the spatial dimension of the features and give adequate proportion to the vehicle models.

A normalisation of the z -axis, $z^* = z/H_b$, is proposed and used to simplify the reference to the vertical position of an aerodynamic feature to the DrivAer vehicle body height (H_b), independently of ride height variations. The tangential underbody plane corresponds to $z^* = 0$, while $z^* = 1$ is the tangential upper plane on the model. Therefore, the ride height is found at -ve direction, while $z^* = z/H_b$ is independent. The normalised y -axis, y^* , scales the axis relatively to the DrivAer

model width, where a unit represent the lateral position of the vehicle (*i.e.* $y^* = 1 = 2y/W$).

4.4.1 Wake characteristics as a function of distance downstream of vehicle base

Although total pressure mapping does not provide local flow direction explicitly, several aerodynamic phenomena can still be estimated from the data, as follows:

- (i) magnitude of total pressure loss [6].
- (ii) wake spatial size [6].
- (iii) free-surface stagnation point [21].
- (iv) location of the cores of strong, coherent vortex structures.

Wake development was analysed by measuring the flow in transverse planes downstream of each automotive configuration (Table 20, Figure 58). The displacement of the model in relation to the stationary apparatus resulted in five relative planes, equidistant into the range of $x/L = 0.176$ (*P5* plane) to $x/L = 0.362$ (*P1* plane) from the rearmost vehicle point. The wake evolution for each automotive category (*i.e.* *F*, *N*, *E*, *hpF*) are presented in Figures 59, 60, 61, 62.

Table 20. Relative planes description.

Plane	P5	P4	P3	P2	P1
Distance [mm]	284	359	434	509	584
x/L	0.176	0.222	0.269	0.315	0.362

A key observation is that at the nearest planes (*e.g.* *P5*, $x/L = 0.176$; and *P4*, $x/L = 0.222$) of all four vehicle wakes, there is a pressure recovery peak inside each region of total pressure loss. It is not so noticeable at the subsequent plane,

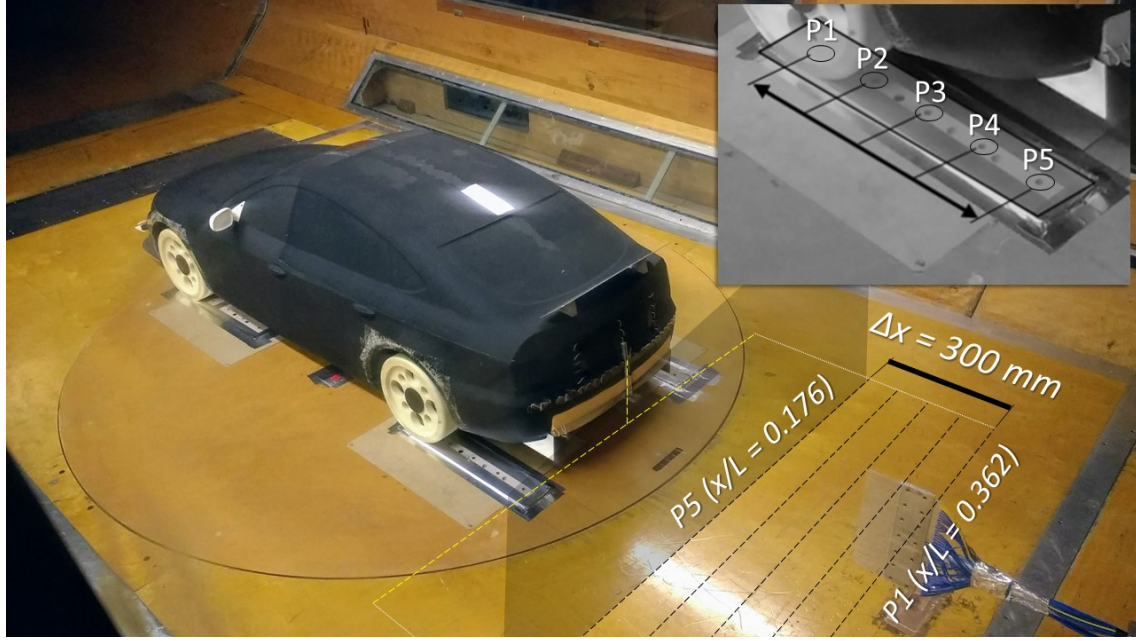


Figure 58. Illustration of relative planes resulted from model displacements.

almost vanished at the third crossflow plane. This feature in the total pressure distribution is believed to be a trace of the free-stagnation point in the 2D wake plane that occurred just upstream the first plane, then the pressure peak is diffused to the surrounding total pressure deficit during the wake evolution.

Another relevant indication is found at the far-end: an asymptotic behaviour on the wake distribution. The last two planes (*e.g.* $P2$, $x/L = 0.315$; and $P1$, $x/L = 0.362$) provided a minor gradient in comparison to the variations at wake formation upstream. The free-surface stagnation trace has been completely dissipated at the farthest plane for all models.

Assessment of these two features leads to the conclusion that the distance and number of planes were able to measure a relevant range of the wake evolution, which extend from just after the near-wake (*i.e.* nearest plane, $P5$) to the beginning of an asymptotic regime downstream (*i.e.* farthest plane, $P1$).

Comparing the wake evolution of the four automotive bodies, their wake characteristics as a function of vehicle distance can be classified into three types:

- Type I:*** Vortex-dominated wake with weak downwash
(DrivAer Fast- and Notchback wakes – [Figures 59 and 60](#))
- Type II:*** Bluff-body flow separation with horizontal inwash
(DrivAer Estateback wake – [Figure 62](#))
- Type III:*** Vortex-dominated wake with strong diffuser-spoiler upwash
(high-performance DrivAer Fastback wake – [Figure 61](#))

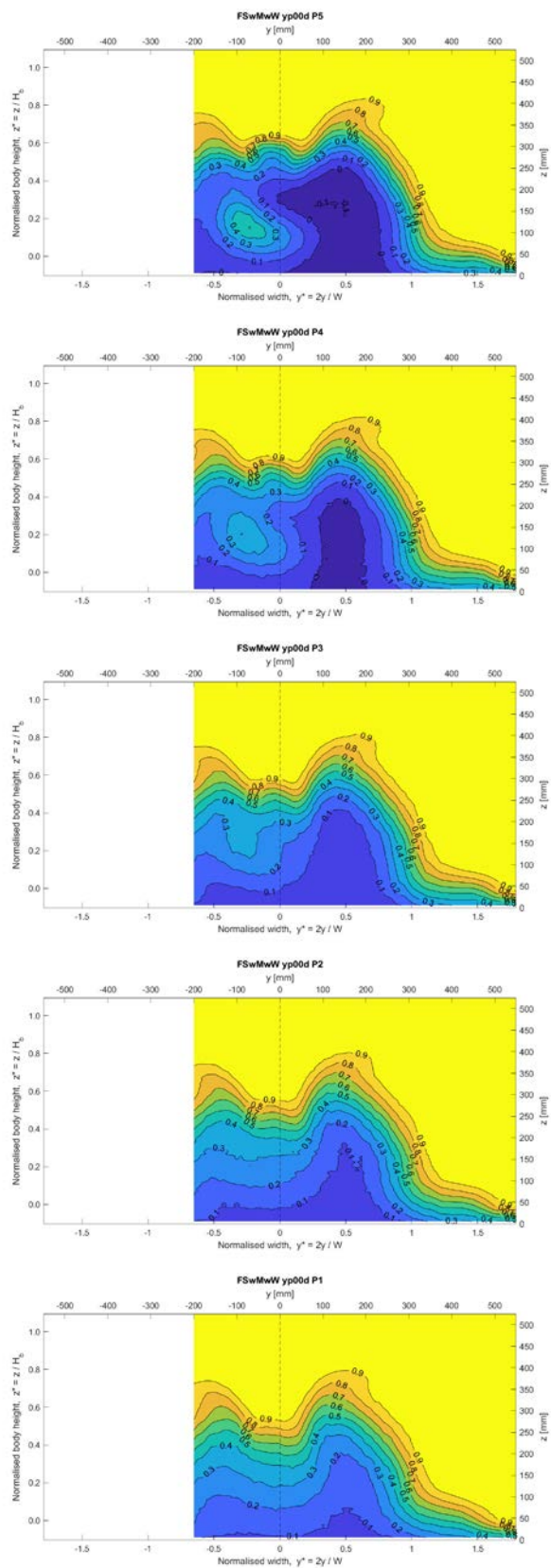


Figure 59. DrivAer Fastback
(*FSwMwW*).

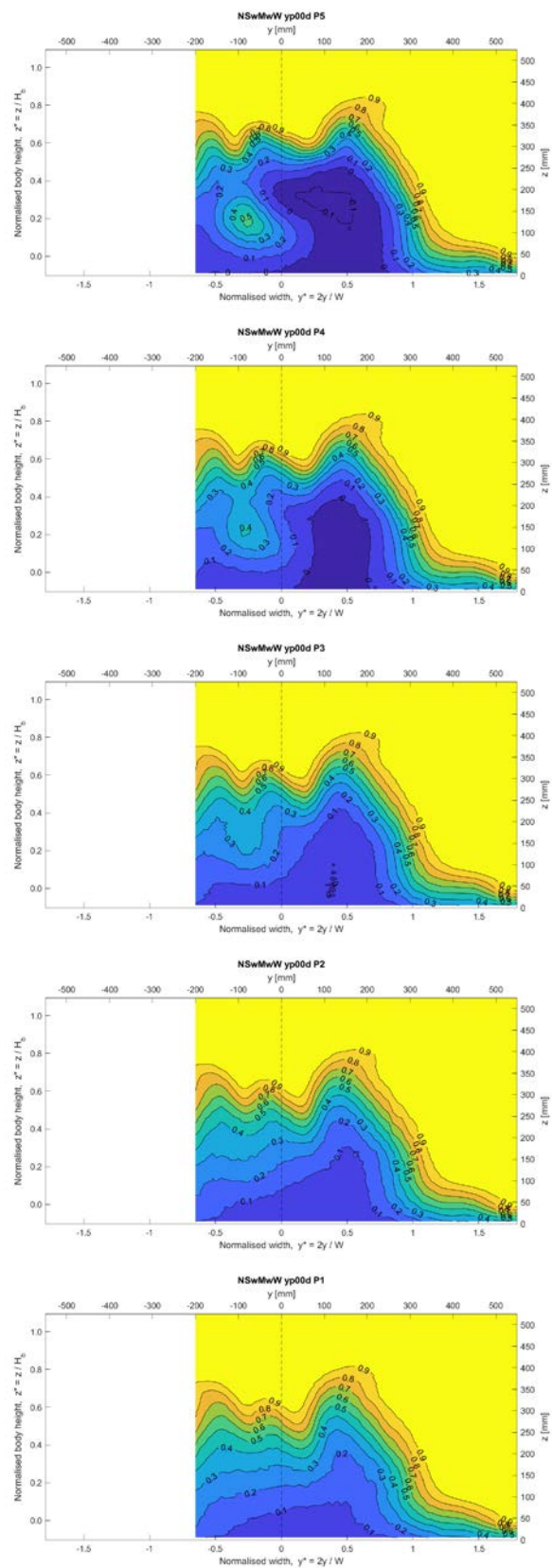


Figure 60. DrivAer Notchback
(*NSwMwW*).

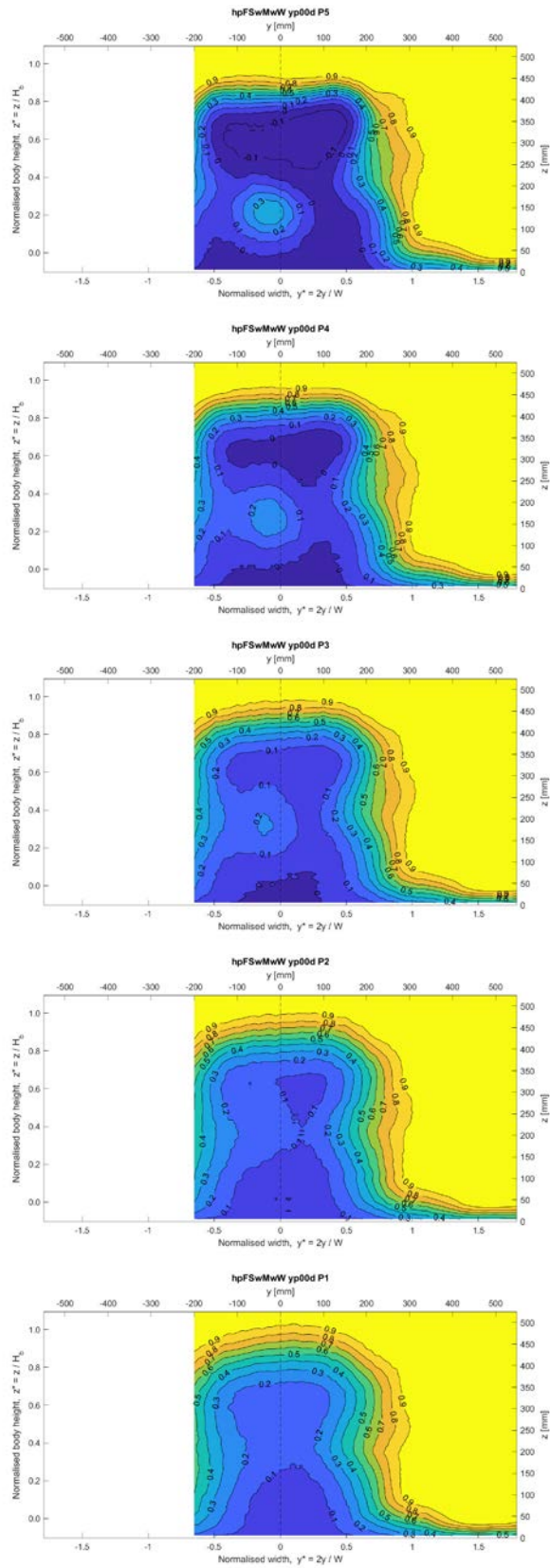


Figure 61. DrivAer high-performance Fastback ($hpFSwMwW$).

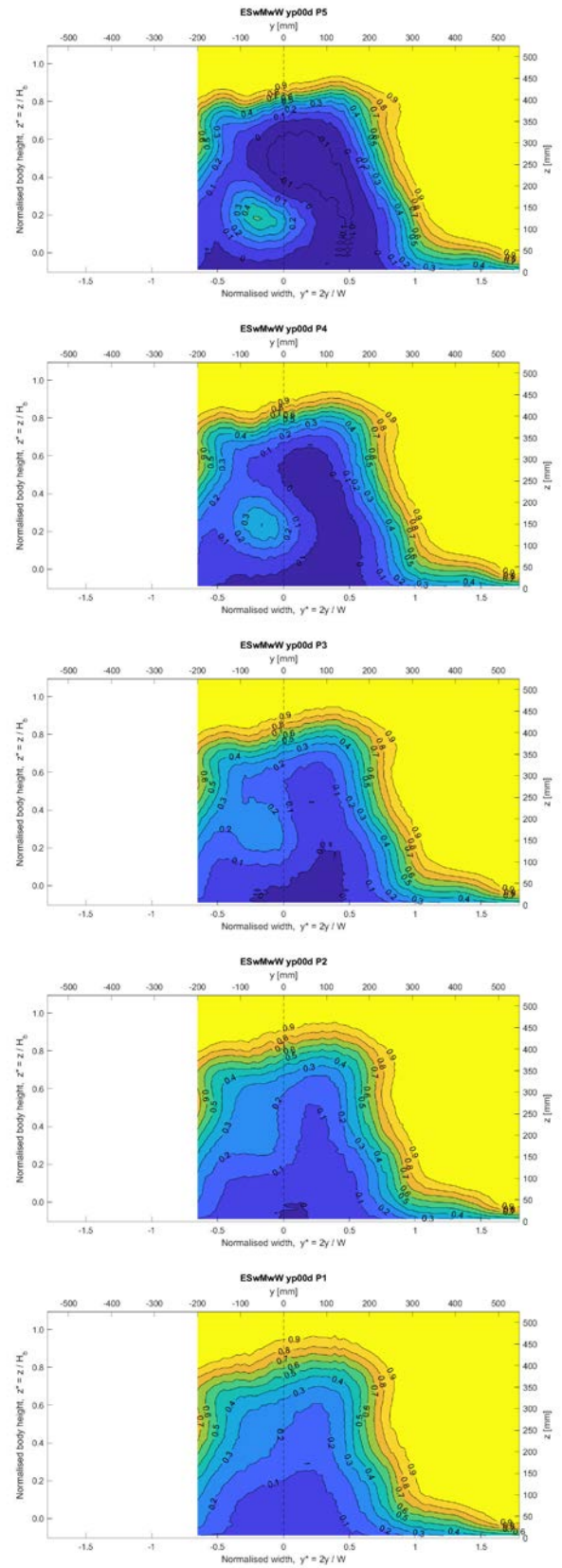


Figure 62. DrivAer Estateback ($ESwMwW$).

4.4.1.1 On the wake *Type I*: Vortex-dominated wake with weak downwash

The total pressure deficit from the Fastback and Notchback configurations is the smallest among the wake types investigated, and is classified here as *Type I* (see [Figures 59](#) and [60](#)). The smaller pressure deficit can be directly linked to the base pressure and lower drag. This wake structure is one of the reasons why these rear body shapes are generally more aerodynamically efficient³.

The 2D wake topology *Type I* resembles an extension of the rear base, with expansion near the ground, potentially associated with both: (i) wheel-related features and (ii) the ground boundary layer. The first is due to the total pressure decay in the turbulent flow into wheel cavities and the wheels themselves, then advected downstream and merged with the rear base wake. The second suggests a mutual influence of outer boundary layer growth on the floor. While the empty working section test showed that the ground plane boundary layer thickness at the acquisition plane is approximately $40mm$ (see [Figure 54](#)), it appears to have thickened due to the influence of the vehicle models. A boundary layer thickness of less than $50mm$ is only seen further from the model, for $y^* > 1.5$. The area of total pressure loss is gradually intensified from $y^* \cong 1.5$ to approximately the lateral-end of the vehicle ($y^* \cong 1.1$), observable at the vehicle lower heights ($z^* \cong 0.1$) (see [Figures 59](#) and [60](#)).

Another relevant feature is the symmetrical protuberances on the upper corners of the wake trace, which initially was believed to be due to the influence of each side mirror. Additional tests removing the side mirrors, (*i.e.* *woM* configuration) were performed to clarify this initial assumption, where the influence of external

³ The author is aware that the term ‘aerodynamic efficiency’ can be vague even technically. In the context presented, it implies the energy efficiency of the vehicle shape to overcome aerodynamic resistance (*e.g.* form and lift-induced drag).

side mirrors on the automotive wakes are highlighted in [Figure 63](#). The previous assumption is shown to be partially correct: the upper corners of the total pressure loss region are influenced by the side mirror, but its removal of this geometry only subtracts partially the feature found on the total pressure map.

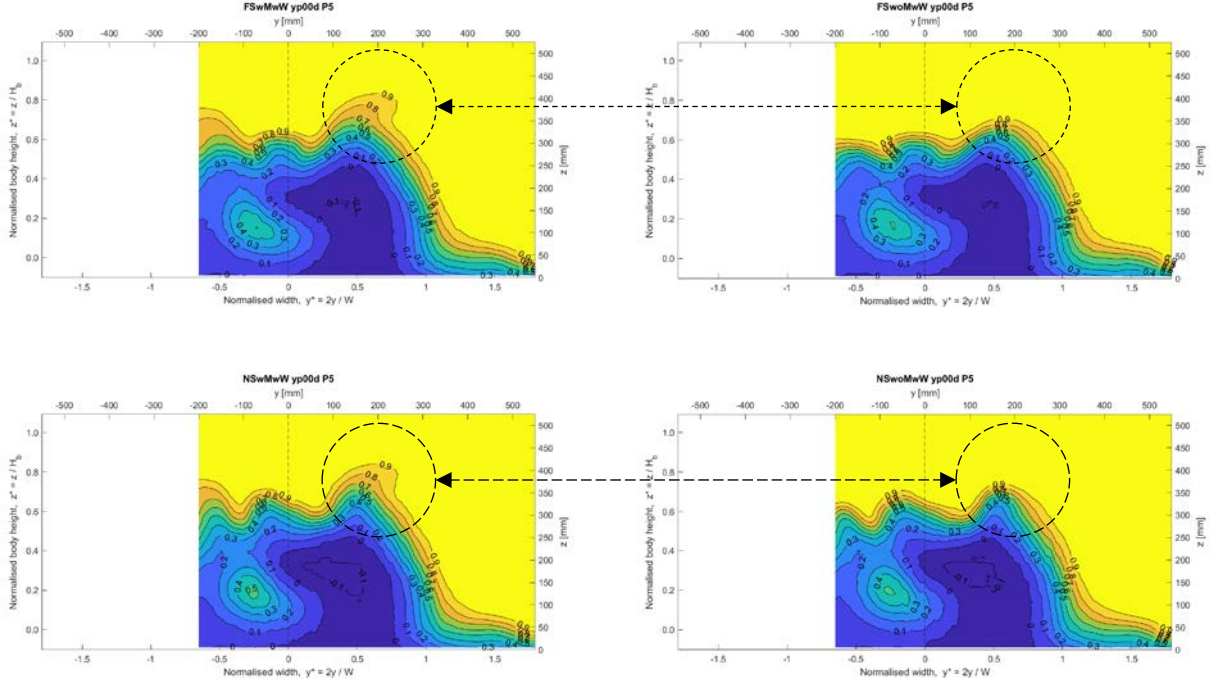


Figure 63. Mirror influence on Fastback (upper) and Notchback (lower) wake: total pressure mapping with mirrors (*SwMwW*, left-hand side) *vs* without mirrors (*SwoMwW*, right-hand side).

This leads to the conclusion that the upper protuberances are a combination of the wake from the side mirrors and the rear-base geometry. For both the Fastback and Notchback configurations, the wake from the side mirrors appears as a small total pressure loss positioned at $y^* \cong 0.65$ and $z^* \cong 0.75$ ([Figure 63](#)), which subsequently merge with the main wake. However, the removal of the side mirrors produces a slightly larger difference between the Notchback and Fastback wake profiles. They have a similar wake topology, but the Notchback model generates

larger central and upper protuberances, a feature that relates to the small difference on the rear-end surface (*e.g.* boot step geometry).

These automotive shapes produce comparable wakes to which a vortex-dominated mechanism can be attributed. The phenomenon is coupled with a trend for vertical motion of the wake flow from the upper body towards the ground (*i.e.* downwash), whereas the downwash is not completely clear alone ([Figure 59](#) and [Figure 60](#)). The formation of a pair of large, coherent vortex structures generated by the main downwash can be better evaluated if observed in terms of the edge of total pressure distribution (*i.e.* $C_{p_t} = 0.9$). The upper prominences of pressure loss migrate inwards while the lower regions appear to move outwards, as illustrated in [Figure 64](#).

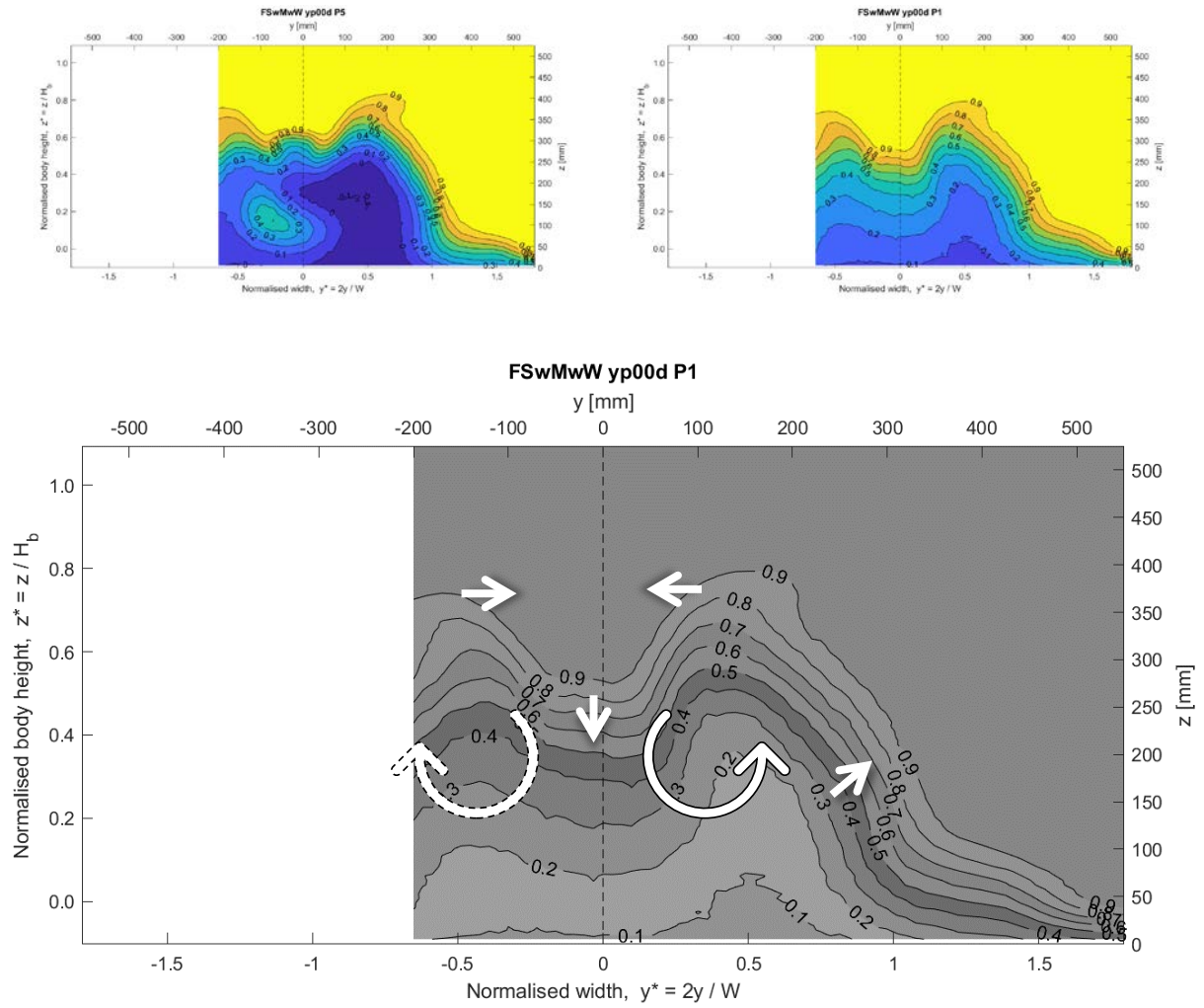


Figure 64. Wake *Type I*: illustration of the flow motion in the range measured showing the wake downwash and formation of a farfield wake vortex.

4.4.1.2 On the wake *Type II*: Bluff-body flow separation with horizontal inwash

Wakes similar to that seen for a regular bluff-body is classified here as wake *Type II*. The DrivAer Estateback is the automotive configuration that represents this wake category. [Figure 62](#) reports the total pressure rake surveys indicating that the wake resembles the edges and size of the vehicle projected area, with a trapezoid-like shape, although a few deviations can be noticed.

The Estateback wake height observed at the closest plane (*P5*), is approximately $z^* = 0.9$, which suggests that the separated flow has a small vertical inwash between the flow separation from the body surfaces and that acquisition plane. This confirms the behaviour of a bluff-body type wake flow that tends to migrate inwards the body's projected centreline, forming a near-wake recirculation zone. A similar horizontal inwash is present (*e.g.* $y^* = 0.9$ at the upper-end), but with specific distribution along the vertical axis.

As seen for the Fastback and Notchback configurations, the Estateback wake is similarly affected by the wake from the wheels and wheels cavities. Conversely, the gradual inwards expansion of the boundary layer is relocated inwards to $y^* = 1.0$ near the vehicle lower region. This means the wake width is reduced nominally by 10% of the vehicle width ($\Delta y^* = 0.1$) when compared to the wake *Type I*. The wake lateral edge (*i.e.* $C_{pt} = 0.9$) is a linear boundary until reaching $y^* = 0.9$ at $z^* = 0.9$, which differs from the smoothly rounded lateral delimitation of the wake *Type I* ([Figures 59 and 60](#)).

A significant characteristic of the wake evolution from the Estateback configuration is the horizontal inflow occupying the rear projection. It happens as the upper flow, then in a minor vertical inwash, seems to start a vertical outflow, while the horizontal inflow is sustained during the course of the wake evolution, as illustrated in [Figure 65](#).

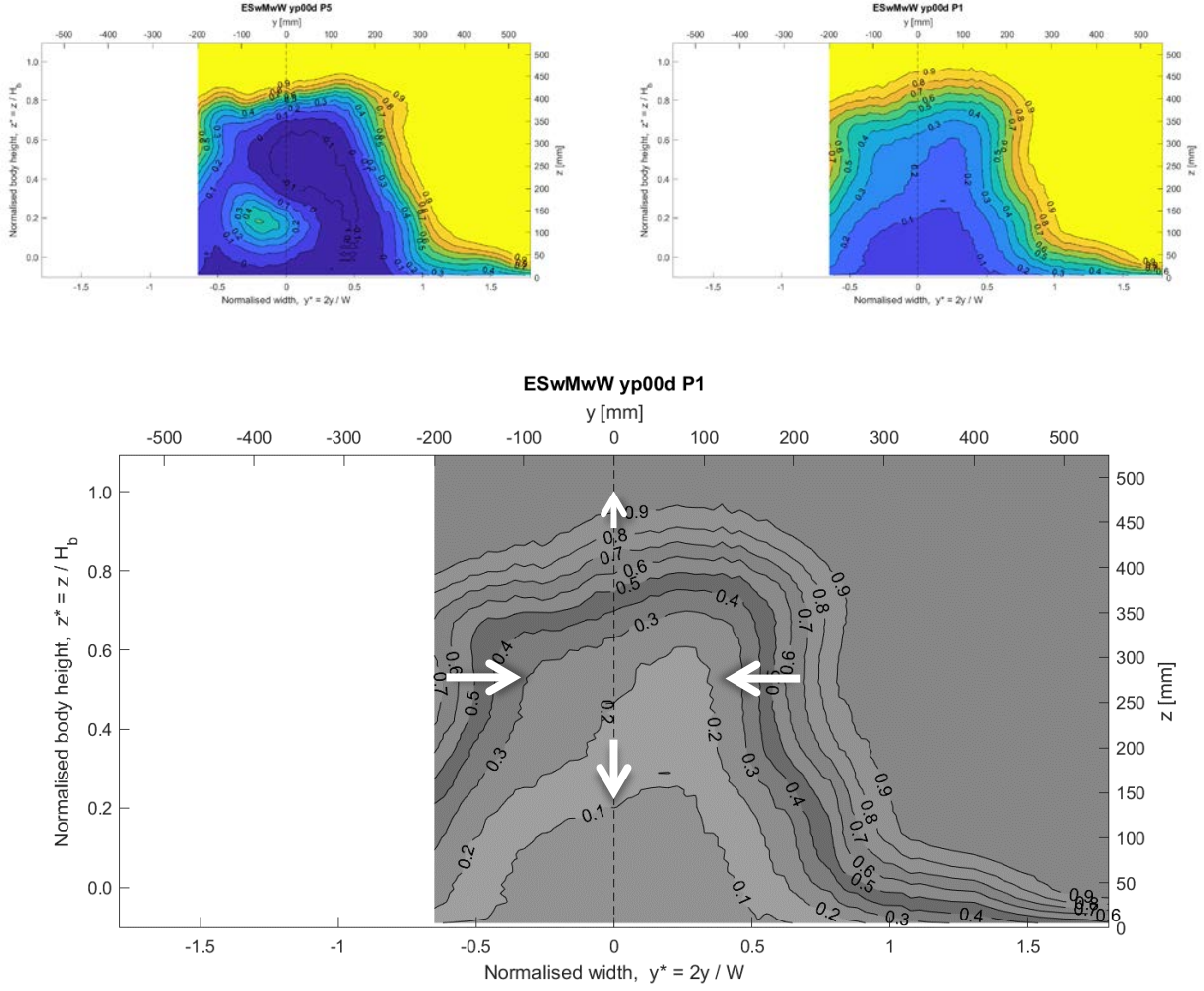


Figure 65. Wake *Type II*: illustration of the flow motion in the range measured showing the horizontal inwash and vertical expansion of the total pressure wake trace.

The wake evolution from the Estateback's side mirrors can also be identified, as seen in [Figure 66](#). The total pressure variation found for the side mirror wake is circa $\Delta C_{P_t} = -0.1$ at the first acquisition plane (*P5*). The deficit is almost completely diffused by the wake assessment range (*i.e.* $P5 \rightarrow P1$, or $x/L = 0.176 \rightarrow 0.362$), although it is believed to be much higher at its origin.

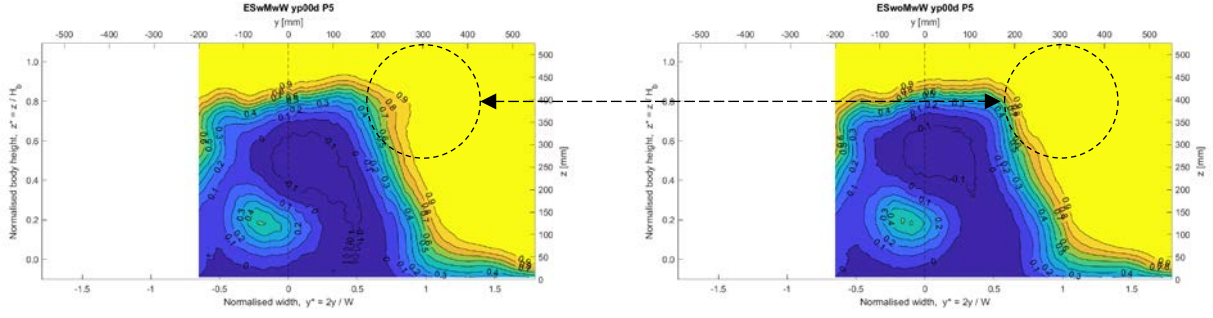


Figure 66. Mirror influence on Estateback: *ESwMwW* (left-hand side) vs *ESwoMwW* (right hand-side).

4.4.1.3 On the wake *Type III*: Vortex-dominated wake with strong diffuser-spoiler upwash

In the discussion that follows it should be remembered that both the standard (*F*) and high-performance (*hpF*) Fastback configurations are based on nominally the same base model. The only differences are the introduction of an underbody and addition of three small aerodynamic solutions (*e.g.* a splitter, strakes and spoiler), as presented in Figure 42, section 4.1.2.

These differences proved to be critical in terms of the wake characteristics, which are seen to be significantly different (Figure 67) and provide evidence of the complexity of automotive wakes even with similar base bodies.

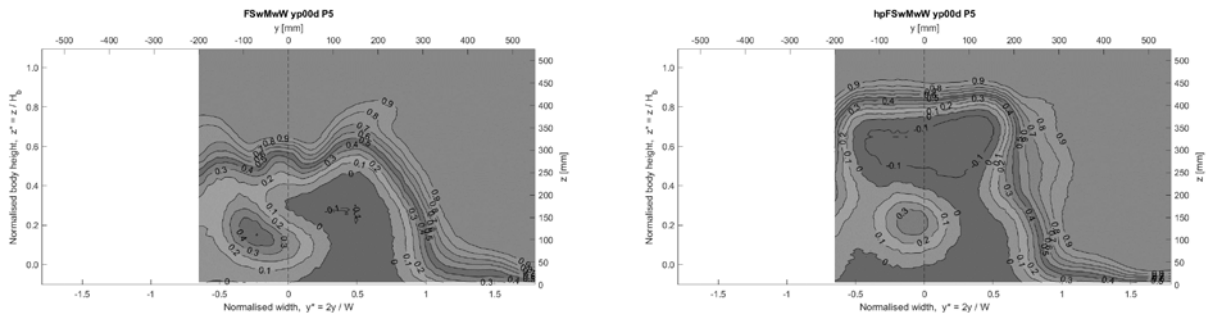


Figure 67. Comparison of wake *Type I* ('standard', at left-hand side) and *Type III* ('high-performance', at right-hand side) Fastback configurations.

In view of its relative complexity, the high-performance Fastback model wake (denotated as ‘hp-Fastback’ or *hpF*) is classified as wake *Type III*. It has features which could be associated with the previous wake types; it exhibits a shed vortex-based far-wake like *Type I*, and large wake topology like *Type II*. However, these features are combined and driven by a further aerodynamic mechanism: spoiler-diffuser coupled upwash.

A preliminary assessment of the hp-Fastback wake highlights the significant size and magnitude of total pressure loss. At the nearest plane (*P5*), the wake is ‘box-shaped’, $z^* = 0.9$ tall and $y^* \cong \pm 1.0$ wide. The ground boundary layer is not affected for $y^* < 1$, similarly to the other wake types.

Wake height difference between standard and high-performance Fastback bodies is mainly due to the rear-spoiler. While for Fast- and Notchback models (*i.e.* wake *Type I*, [Figures 59](#) and [60](#)) the upper flow separated from the rear-end surface with relatively little downwash, the results from hp-Fastback (*i.e.* wake *Type III*, [Figure 61](#)) shows that the presence of a rear spoiler pushes the upper flow higher in a large region between $-0.5 < y^* < 0.5$. The rounded lateral edges of the spoiler potentially introduce three-dimensional characteristics, where evidence of tip vortices can be seen in the total pressure contour at $y^* = \pm 0.5$ for $z^* \cong 0.7$.

In terms of the influence of side mirrors, the hp-Fastback configuration provides the clearest differences when assessing the wake with (*wM*) and without (*woM*) side mirrors, as shown in [Figure 68](#). The side mirror wakes were seen to be positioned next to the rear-spoiler, then merged in the resulting wake contour. Once the side mirrors are removed, the wake topology highlights other significant features associated with the rear-spoiler and frontal strakes. The total pressure loss from the former become a distinct region, then clearly delimited between $0.6 < z^* < 0.9$ for $|y^*| < 0.75$. The remaining outer protuberance at mid-height also became noticeable. This finding suggests the frontal strakes generate vortices

that are strong enough to still be evident in the nearest plane (*i.e.* $P5$, $x/L = 0.176$) behind the vehicle model.

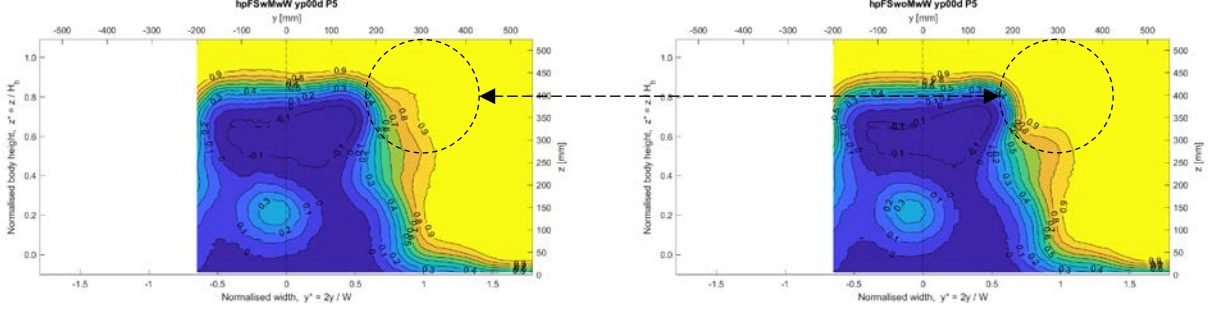


Figure 68. Mirror influence on high-performance Fastback: $hpFSwMwW$ (left-hand side) vs $hpFSwoMwW$ (right-hand side).

The wake evolution for this model configuration highlights the most significant phenomena in this wake type: a strong upwash flow (Figure 69). While the standard Fastback wake is based on a central downwash that drives a pair of counter-rotating longitudinal vortices near the ground, the high-performance Fastback has evidence of an upwash flow strong enough that the outer freestream is driven inwards to occupy the lower vehicle zone.

The upwash flow is a consequence of two key aerodynamic components: the rear spoiler and diffuser. Due to spoiler size and angle, it works as a physical barrier lifting the flow. Simultaneously, the flow underneath the vehicle reaches a gradual increase of free cross-section area (*e.g.* the diffuser), where the flow generates an upwash towards the vehicle mid-rear. The presence of the spoiler unbalances the flows (*e.g.* from upper, lateral, and lower surfaces) since the upper flow is deflected upwards, making the lower flow the dominant at the vehicle rear. Therefore, both spoiler and diffuser mutually contribute to creating a strong upwash flow that can be known as the *diffuser-spoiler coupled mechanism*.

Figure 69 illustrates the main flow motion. At the nearest plane, $x/L = 0.176$, wake height is $z^* \cong 0.95$ and mostly uniform due to the spoiler shape. At the

farthest plane, $x/L = 0.362$, the upper wake region is raised by the upwash reaching $z^* \cong 1.05$, but it has also been deformed by the outer freestream and the counter-rotating vortices from spoiler tips. In model dimensions, the wake centre rises 50mm ($\Delta z^* \cong 0.10$) in a distance of 300mm ($x/L = 0.186$), which suggest an inclination of $\sim 10\text{ deg}$ in the range of $0.176 < x/L < 0.362$.

While the wake expands vertically, the upwash creates a lateral inwash near the ground, which is in accordance with the principle of mass conservation. Wake width is $y^* \cong \pm 1.0$ in plane $x/L = 0.176$, but the inwash brings high total pressure flow and reduces the wake by $\Delta y^* \cong 0.30$, ($y^* \cong \pm 0.85$) in plane $x/L = 0.362$.

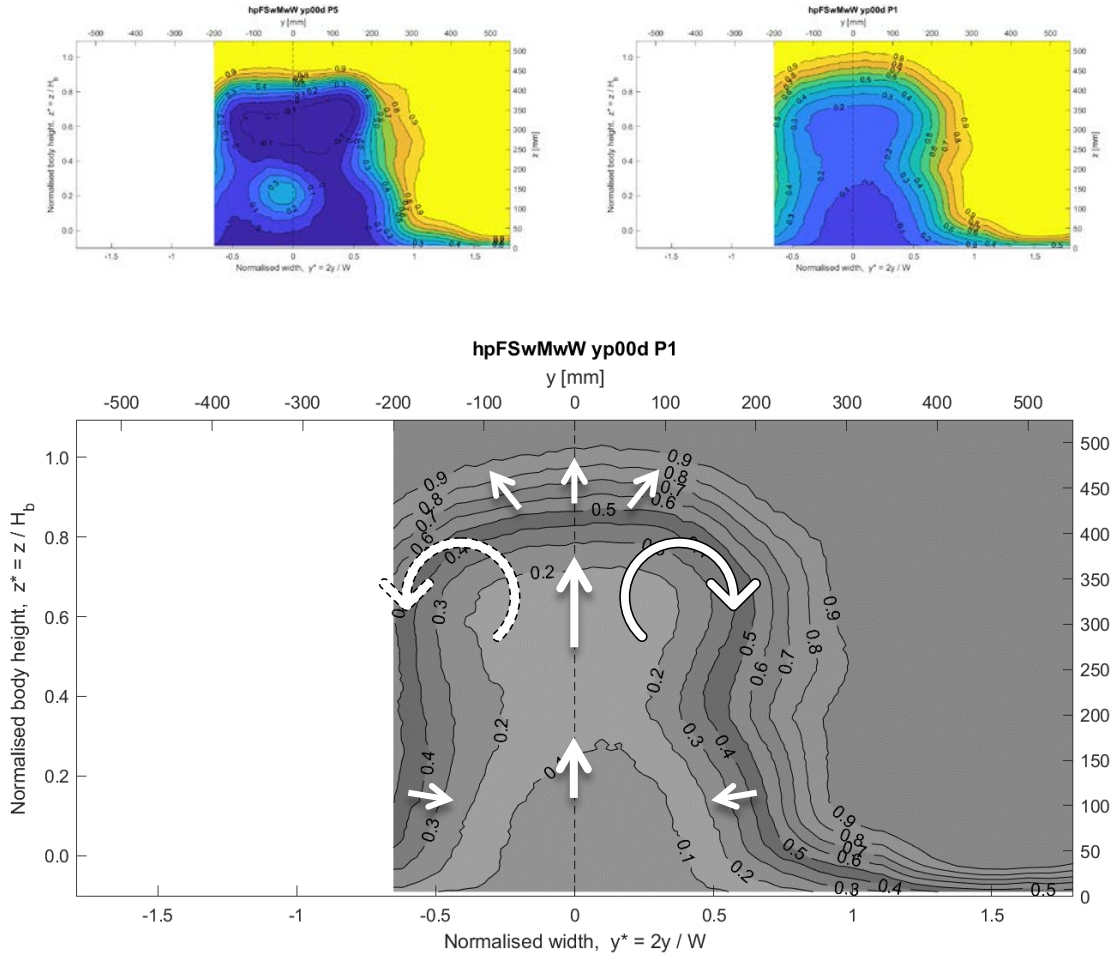


Figure 69. Wake *Type III*: illustration of flow motion, highlighting the (i) upper pair of counter-rotating vortices, (ii) intense upwash flow, and (iii) minor lateral inwash.

4.4.2 On the sensitivity to changes in freestream Reynolds Number for full-body automotive wakes

The effect of the Reynolds number on the wake characteristics is addressed by varying the freestream with predefined magnitudes: 20 m/s , 30 m/s and 40 m/s , corresponding to a nominal Re of 2.03×10^6 , 3.04×10^6 , and 4.05×10^6 , respectively, based on vehicle length.

The study is based on the nearest wake plane tested, $P5$ (*i.e.* $x/L = 0.176$), for all four models at ‘*SwMwW*’ configuration. Figures 70, 72, 74, and 76 present the wakes measured for freestream at 20, 30 and 40 m/s , while Figures 71, 73, 75, and 77 provide the incremental effect on the C_{p_t} distribution at wake plane $P5$.

Wake from the Fastback model (*i.e.* wake *Type I*) sustains the overall wake topology along the Re range tested; albeit a few effects can be noticed. For $U_\infty = 20 \rightarrow 30 m/s$ (Figure 71, *a*), the wake has a maximum fluctuation of $\Delta C_{p_t}|_{min} = -0.14$ to $\Delta C_{p_t}|_{max} = +0.09$. Despite the noise in the data on measurements at 20 m/s (*i.e.* low signal-to-noise ratio, Figure 70 *a*), the incremental result is coherent and nearly symmetric across the wake. While the upper wake trace protuberances are reduced by $\overline{\Delta C_{p_t}} = -0.06$, the adjacent inner valleys have an increase of $\overline{\Delta C_{p_t}} = 0.12$. Both changes elevate the wake and intensify those features (*e.g.* higher upper protuberances and even lower valleys), then highlighting the central protuberance from the upper rear-end edge. Likewise, the inner core peak rise while moving closer to the symmetry plane by $\overline{\Delta y^*} = 0.03$. There is also a minor total pressure recovery on the lateral edge of the wake trace suggesting a reduction in wake width.

For $U_\infty = 30 \rightarrow 40 m/s$, the Re sensitivity of Fastback wake is mostly residual (Figure 71, *b*) with maximum differences of $\Delta C_{p_t}|_{min} = -0.07$ and $\Delta C_{p_t}|_{max} = +0.08$. The negative peaks would contradict the previous found because suggests

enlargement of the wake width, but this pattern is inconsistent. Conversely, the inner core peak shows minor but clear displacement trend increasing the region by $\overline{\Delta z^*} = 0.06$ and its peak by $\overline{\Delta z^*} = 0.03$. A residual fluctuation of $\overline{\Delta C_{p_t}} = \pm 0.04$ is randomly spread over the rest of the domain analysed.

Re-sensitivity results for Notchback model confirms its similarity to the Fastback model. Large discrepancies are also found for $U_\infty = 20 \rightarrow 30 m/s$, where the maximum divergences are $\Delta C_{p_t}|_{min,max} = \pm 0.10$ (Figure 73, a). The overall trend found on the Fastback repeats for in the Notchback wake: (i) elevation of the upper wake protuberances, (ii) minor reduction of wake width, and (iii) inner core being elevated while moving towards the symmetry plane.

The only significant difference to the Fastback model is the upper, central protuberance that is larger and slightly uneven at $U_\infty = 20 m/s$, but better balanced at $U_\infty = 30 m/s$. The Notchback wake is equally *Re*-independent for $U_\infty = 30 \rightarrow 40 m/s$ (Figure 73, b) when neglecting a fluctuation level of $\overline{\Delta C_{p_t}} = \pm 0.04$, where the only clear exception is the inner core displacement continuing the rising trend with $\overline{\Delta z^*} = 0.07$ for the region but only $\overline{\Delta z^*} = 0.03$ for the inner peak.

Figure 74 presents *Re*-sensitivity results for the Estateback model (*i.e.* wake *Type II*). More considerable *Re*-sensitivity is noticed for increment at lower freestream magnitude, in agreement with previous models. For $U_\infty = 20 \rightarrow 30 m/s$, the discrepancies are larger and more intense, with $\Delta C_{p_t}|_{min} = -0.15$ and $\Delta C_{p_t}|_{max} = +0.13$ (Figure 75, a). The characteristics found are related to the ones found at Fast- and Notchback models. Both upper corners of the wake trace are pushed outwards and this enlarges the wake region. The inner core moves inwards by $\overline{\Delta y^*} = 0.08$ with minor height gain. There are two main differences to the other models. The first is the wake sensitivity in the upper region, which has the total pressure loss distribution intensified by $\overline{\Delta C_{p_t}} = -0.05$, with local regions within

the range of $-0.15 < \Delta C_{p_t} < 0.02$. The second is the clear reduction in the wake width with exception of the upper region.

For $U_\infty = 30 \rightarrow 40 \text{ m/s}$ (Figure 75, *b*), the Estateback wake has small regions of *Re*-sensitivity, although more intense than the previous models. These regions are: (i) inner core peak; (ii) lower, lateral edge; and (iii) central, upper edge. The first is in accordance with previous cases: the inner core migrates in the wake trace by $\overline{\Delta z^*} = 0.03$. The second reveals the wake width moves back and expands slightly in the lower half of the wake trace. The third region shows an incoherent pattern of vertical fluctuation in Figure 75(*b*), and it is believed to be an interference during measurement (*e.g.* local vibration of the rake frame in the wake).

The high-performance Fastback model, classified as wake *Type III*, is the most robust wake among the cases tested. For $U_\infty = 20 \rightarrow 30 \text{ m/s}$, total pressure distribution is reduced on the major part of the wake trace, while maximum differences can reach $\Delta C_{p_t}|_{min} = -0.10$ and $\Delta C_{p_t}|_{max} = +0.05$ (Figure 77, *a*). The upper corners have a loss of $\overline{\Delta C_{p_t}} = -0.07$, while the rest of the wake trace has a global, averaged decay of $\overline{\Delta C_{p_t}} = -0.03$. The only clear trend of total pressure recovery is found at the wake lateral edge, which reduces the wake width.

For $U_\infty = 30 \rightarrow 40 \text{ m/s}$ (Figure 77, *b*), the total pressure distribution remains constant over most of the domain when neglecting the random fluctuation of $|\overline{\Delta C_{p_t}}| < 0.04$. The upper edge of the wake trace is the only region still affected by the *Re* increment, resulting in a further averaged reduction of $\overline{\Delta C_{p_t}} = -0.04$, with distribution varying between $-0.09 < \Delta C_{p_t} < -0.01$. This wake *Type III* shows that even the wake distribution being mostly stable over the *Re* range tested, the wake height increased on both *Re* increments, $\overline{\Delta z^*} \approx 0.02$. Interestingly, it was the only case where the position of the inner peak into the wake is *Re*-independent.

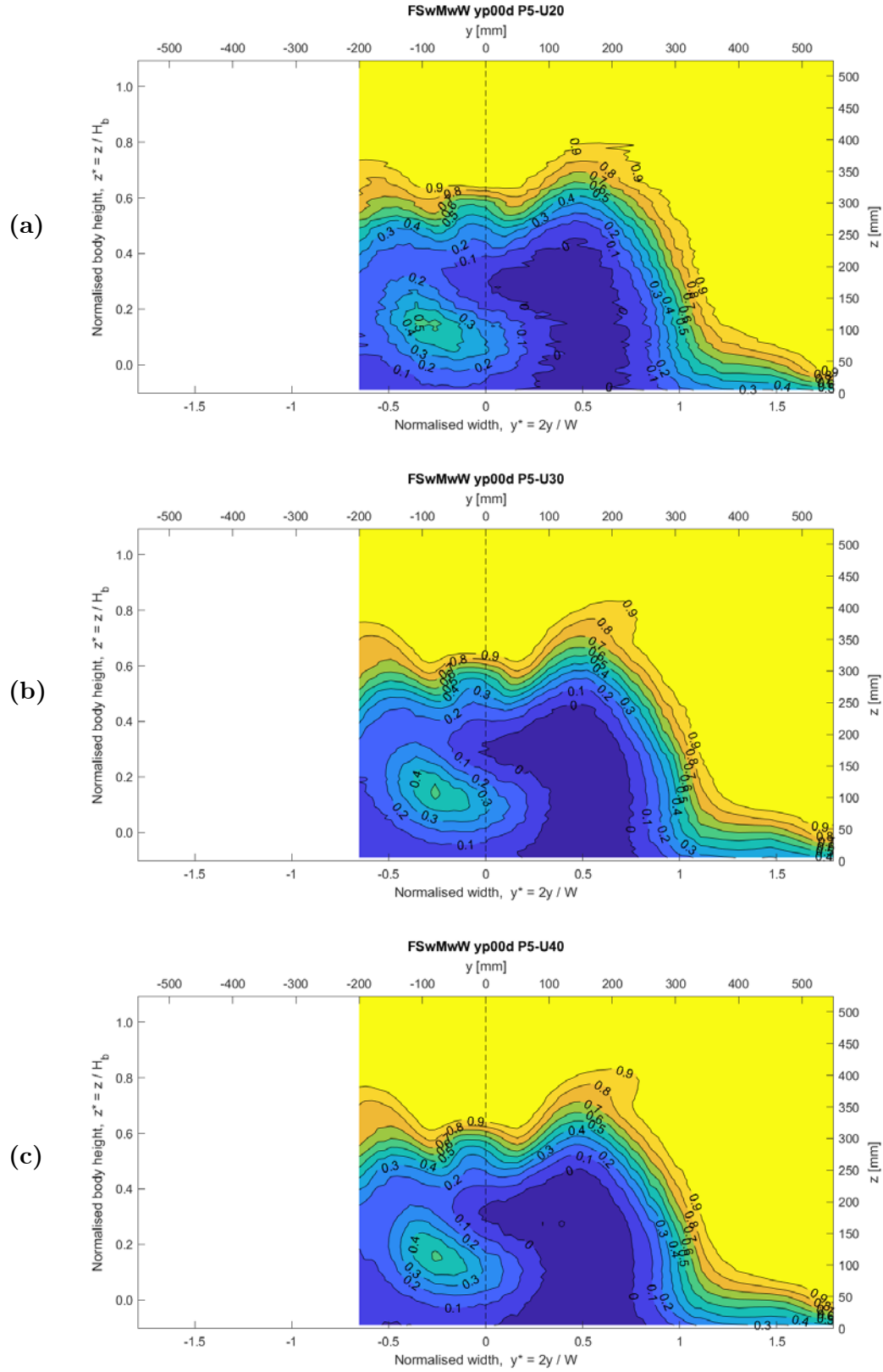


Figure 70. *Re-sensitivity* of DrivAer Fastback (*FSwMwW*), part I: C_{p_t} distribution at (a) 20 m/s, (b) 30 m/s, and (c) 40 m/s.

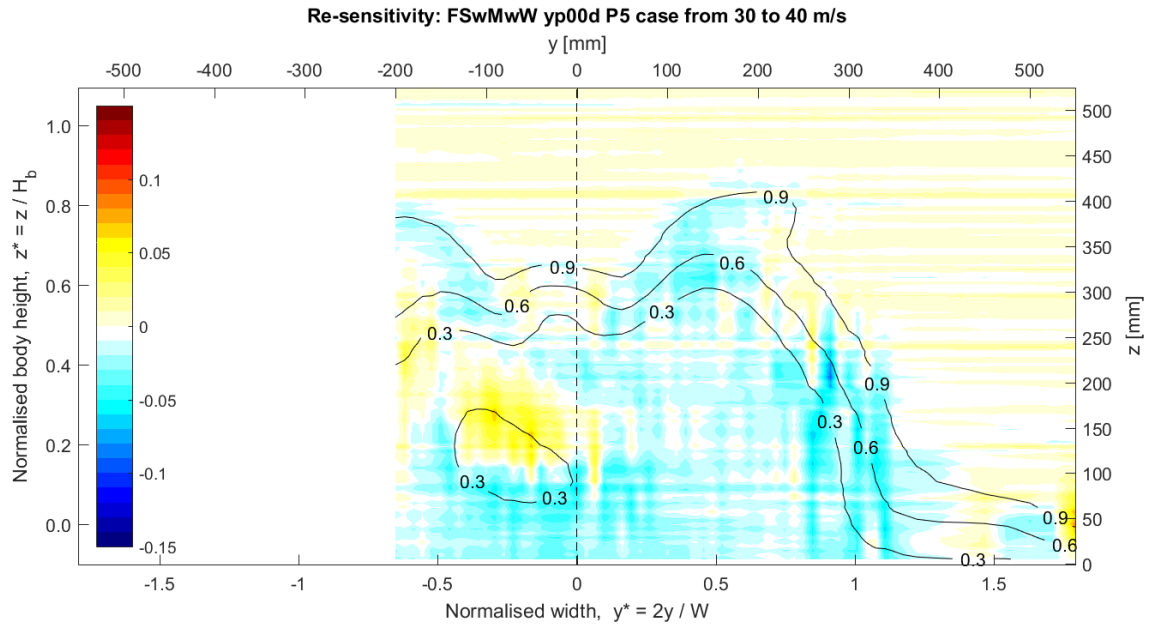
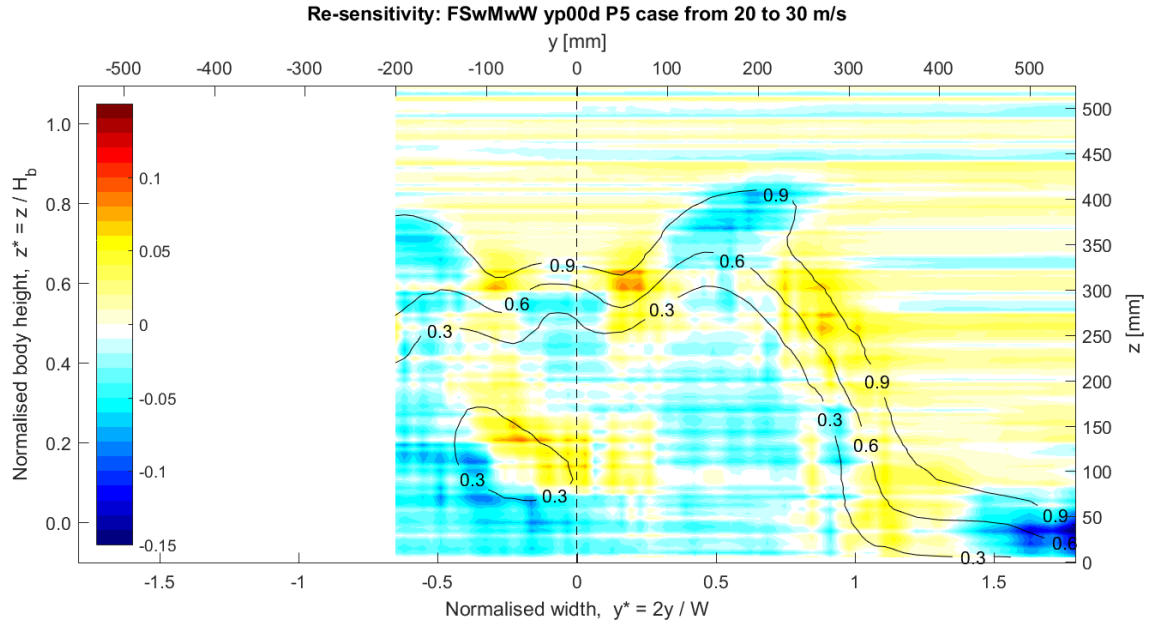


Figure 71. Re-sensitivity of DrivAer Fastback (*FSwMwW*), part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 m/s, and (b) 30 to 40 m/s.

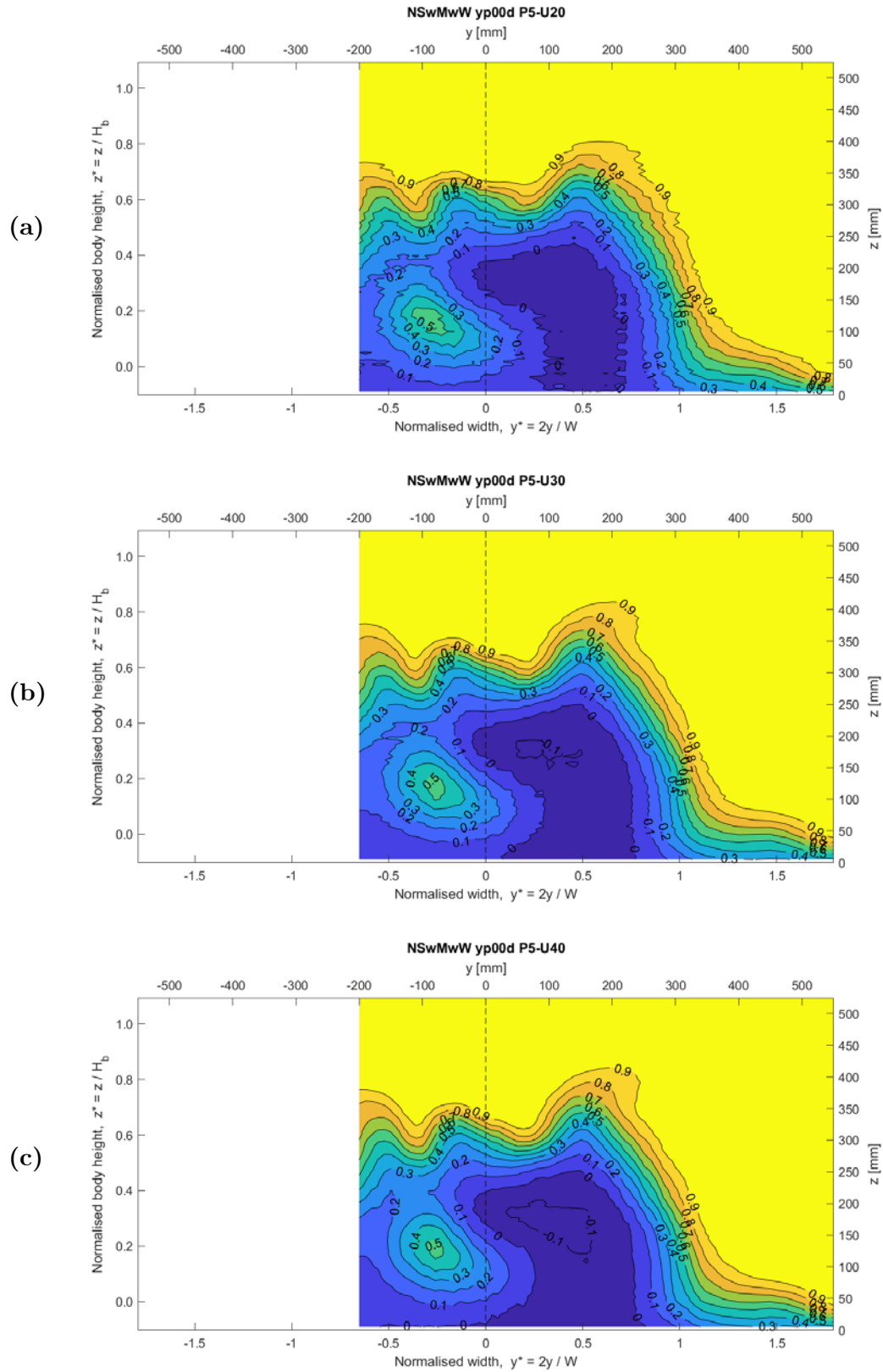


Figure 72. *Re-sensitivity of DrivAer Notchback (NSwMwW), part I: C_{p_t} distribution at (a) 20 m/s, (b) 30 m/s, and (c) 40 m/s.*

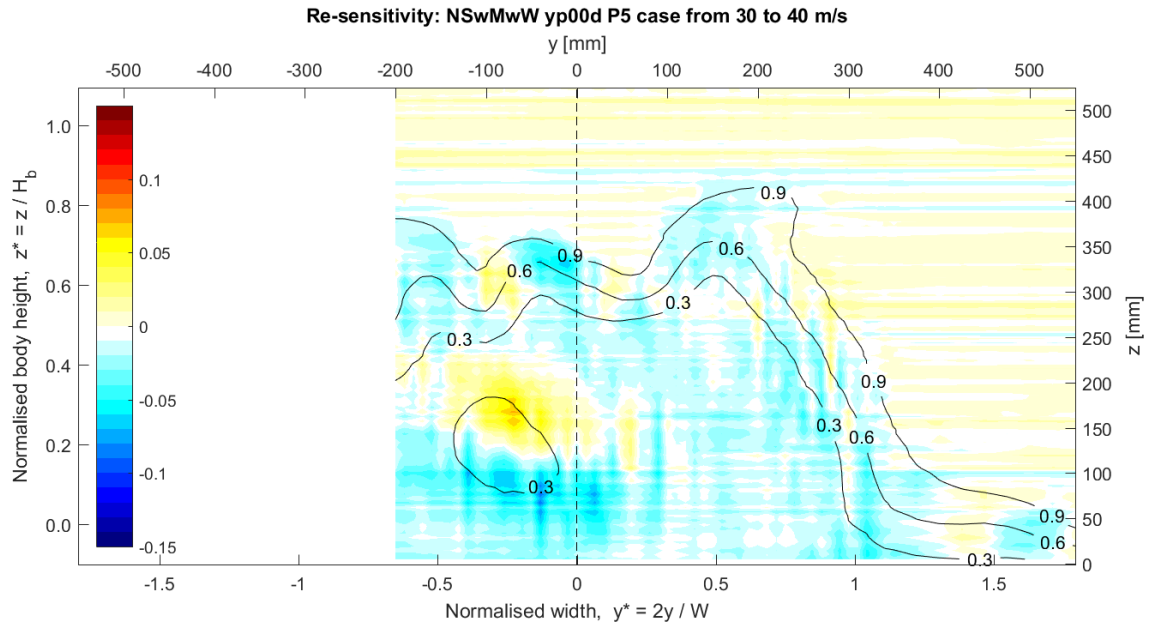
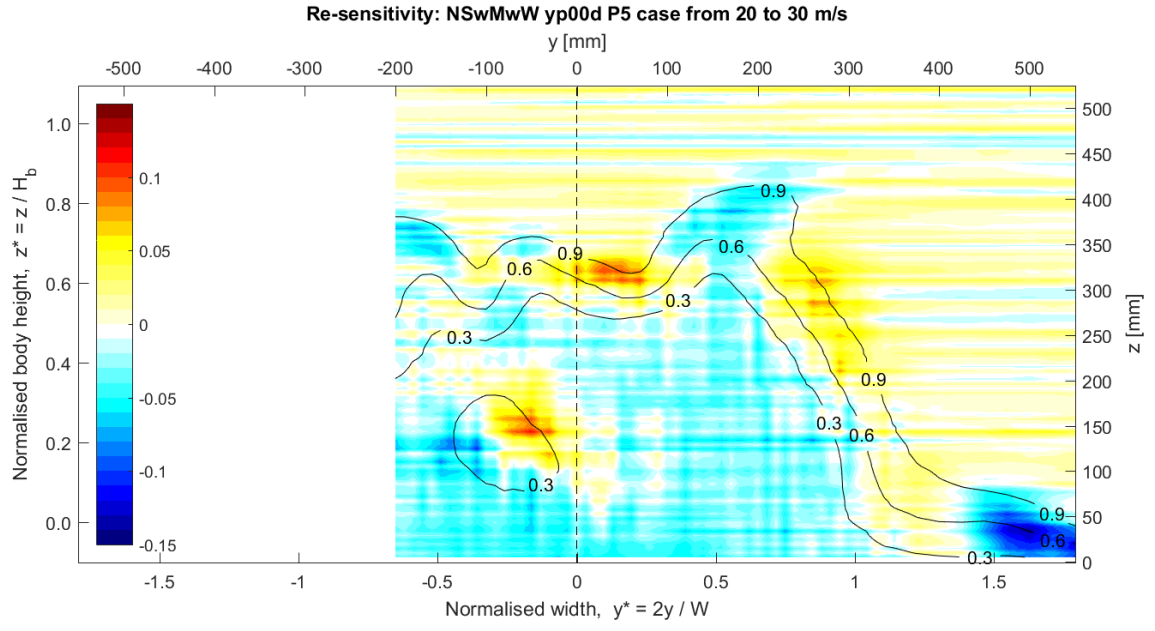


Figure 73. *Re-sensitivity* of DrivAer Notchback (*NSwMwW*), part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 *m/s*, and (b) 30 to 40 *m/s*.

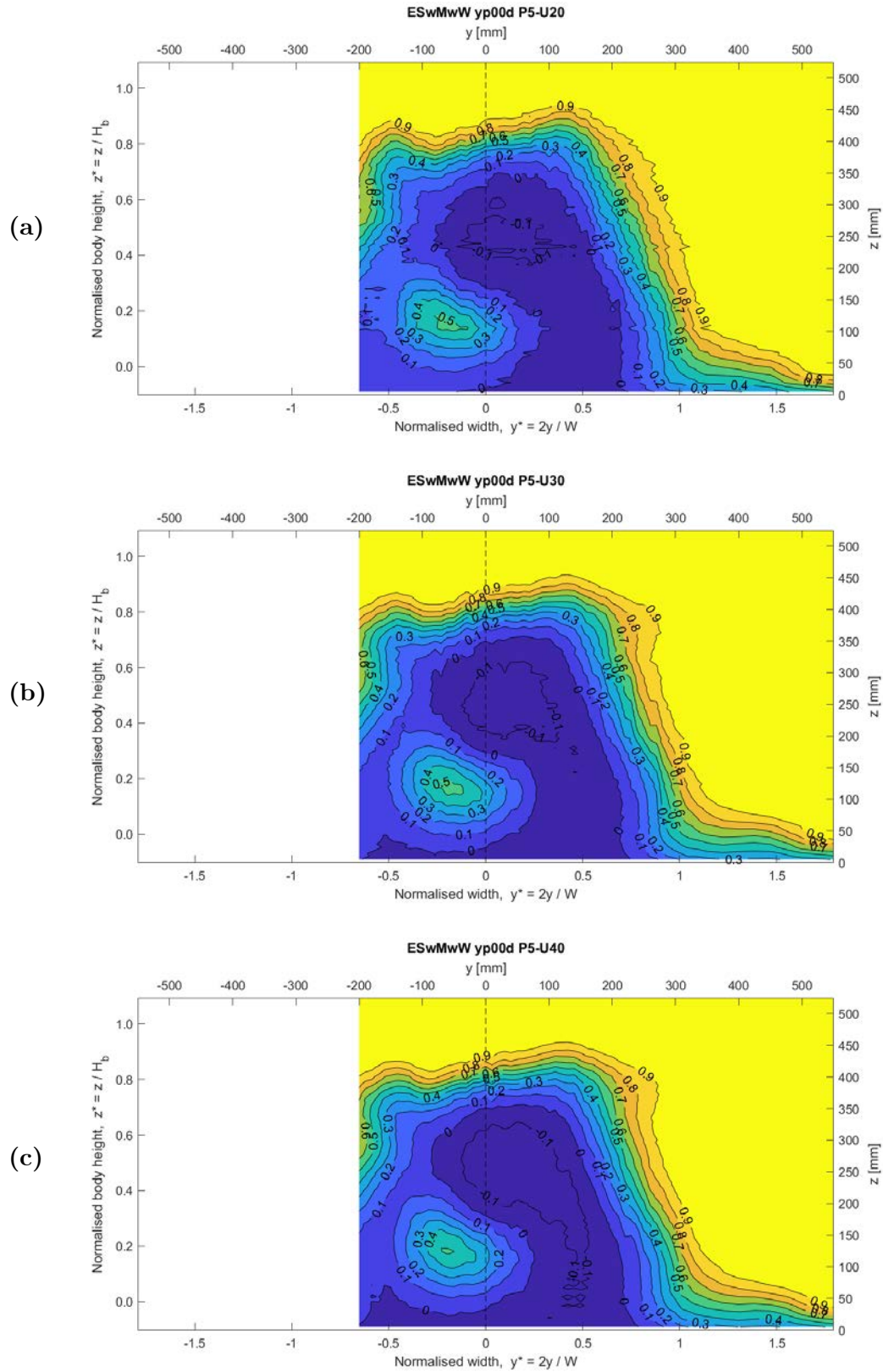


Figure 74. *Re-sensitivity of DrivAer Estateback (ESwMwW), part I: C_{p_t} distribution at (a) 20 m/s, (b) 30 m/s, and (c) 40 m/s.*

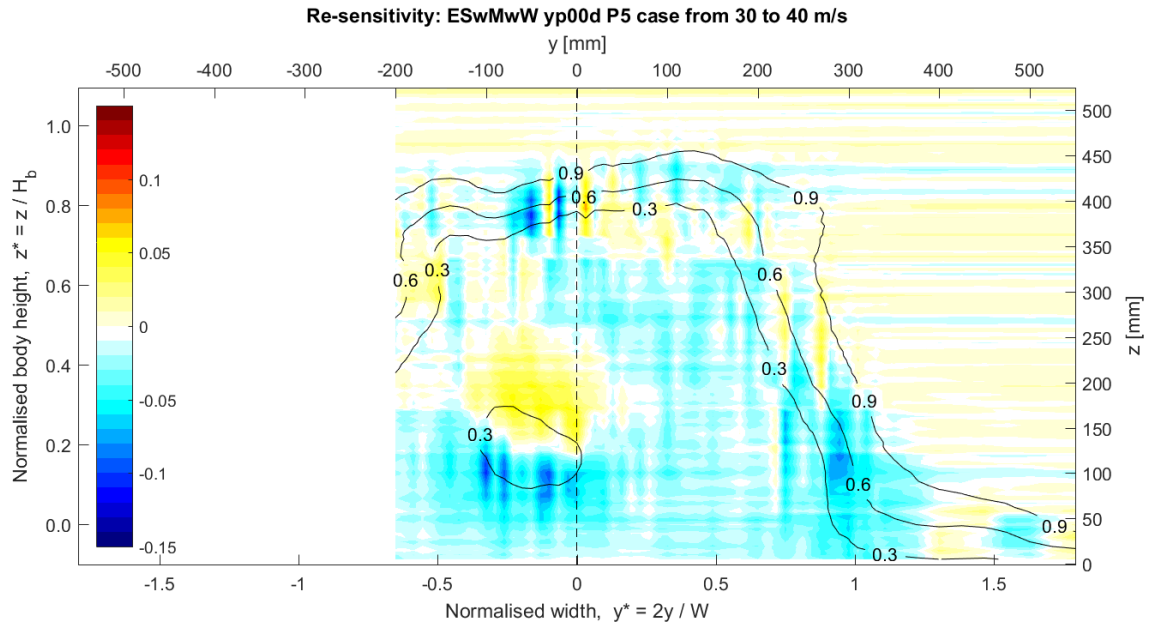
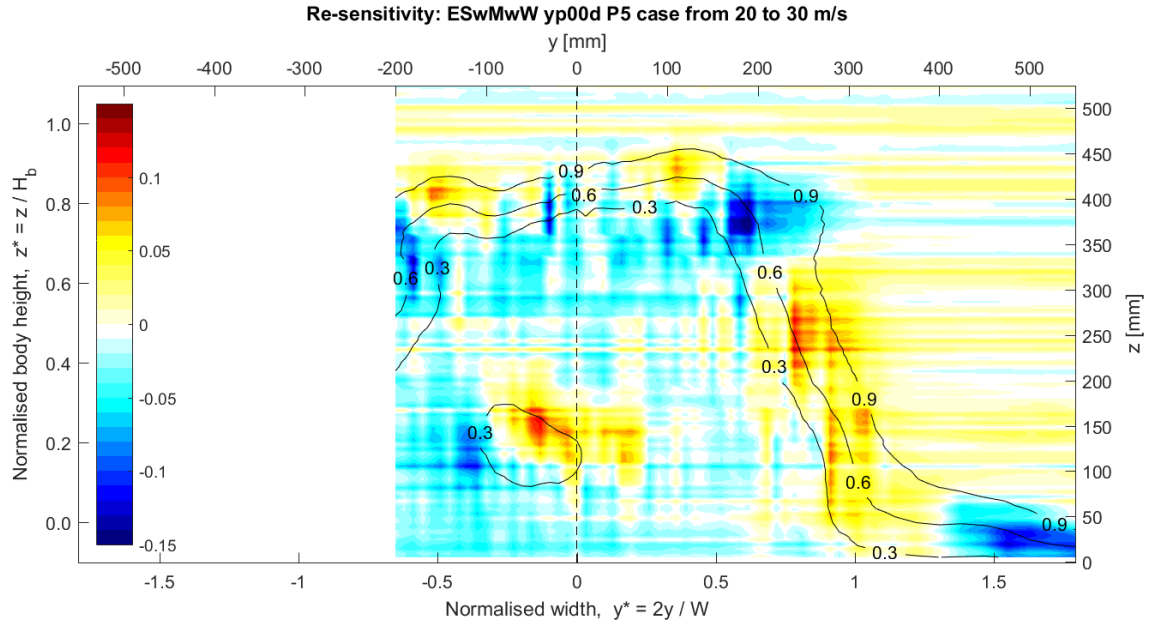


Figure 75. *Re-sensitivity* of DrivAer Estateback (*ESwMwW*), part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 m/s, and (b) 30 to 40 m/s.

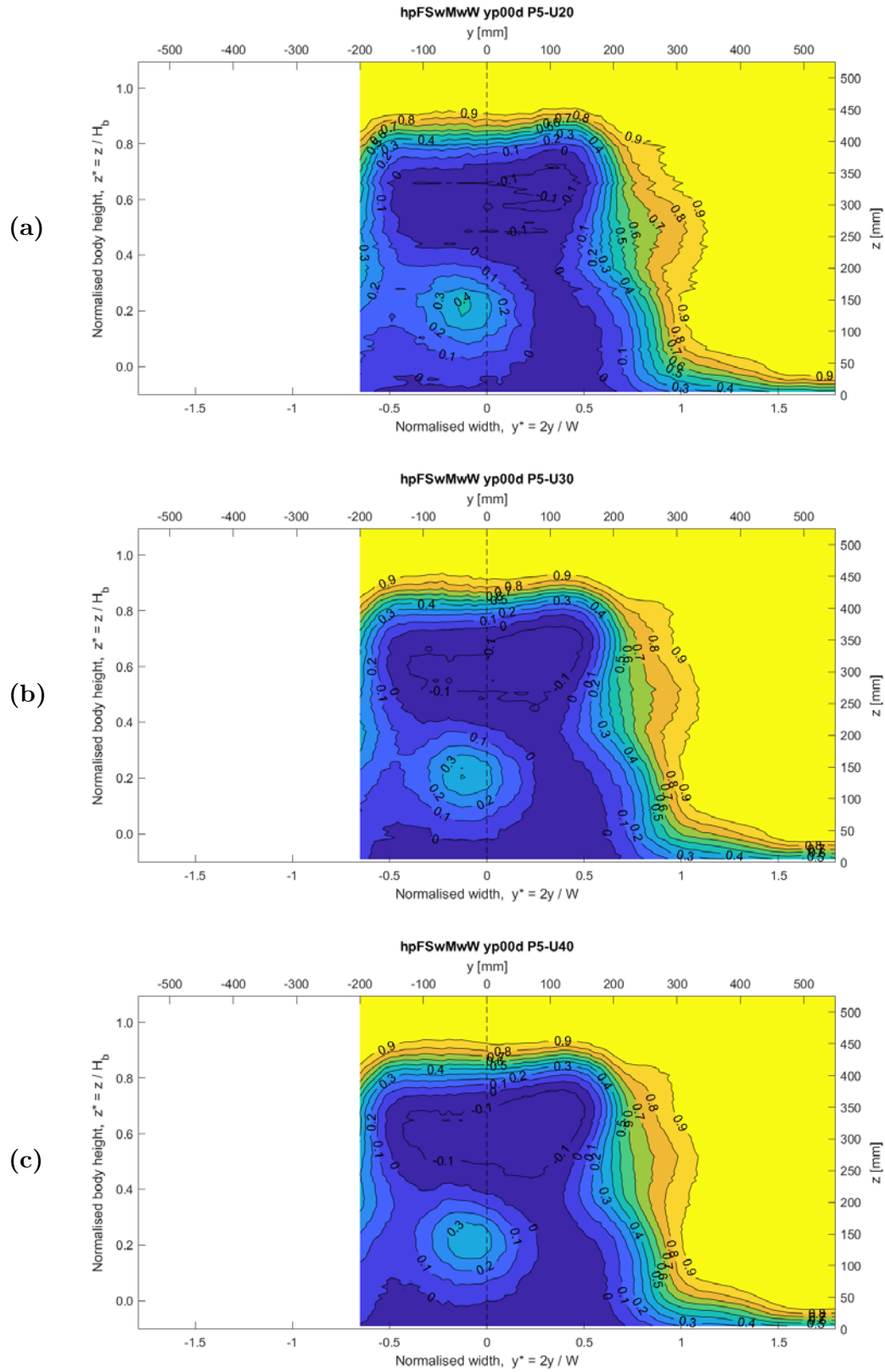


Figure 76. *Re-sensitivity of DrivAer high-performance Fastback (hpFSwMwW), part I: C_{p_t} distribution at (a) 20 m/s, (b) 30 m/s, (c) 40 m/s.*

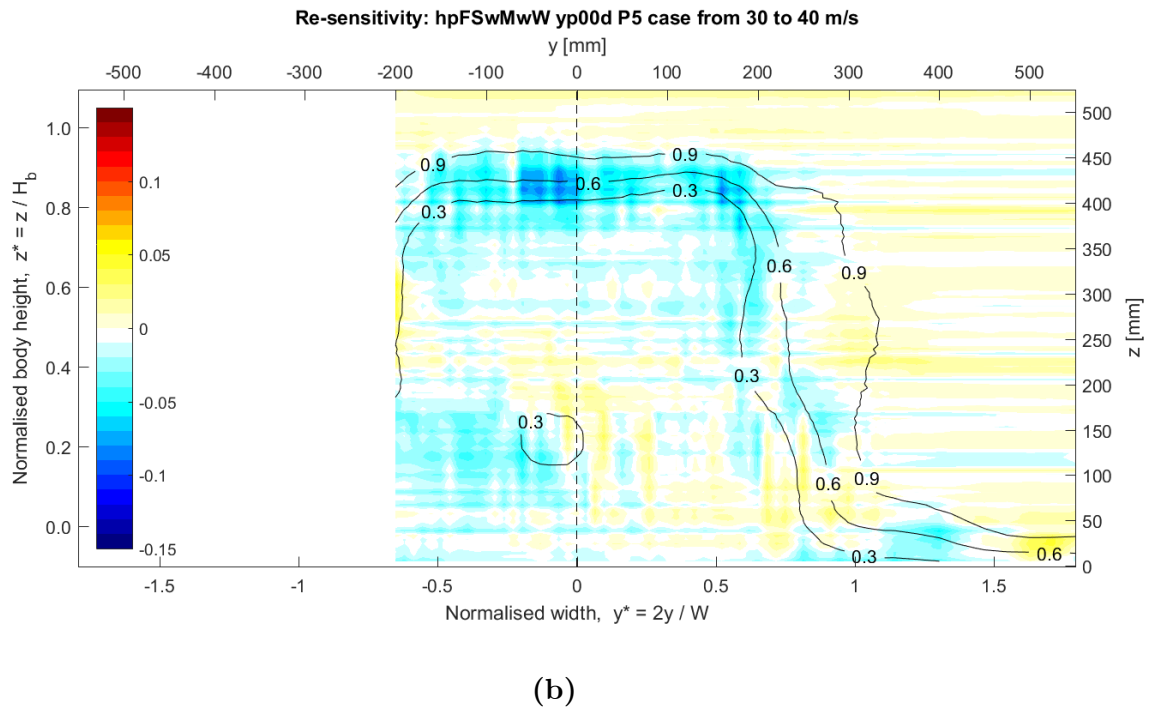
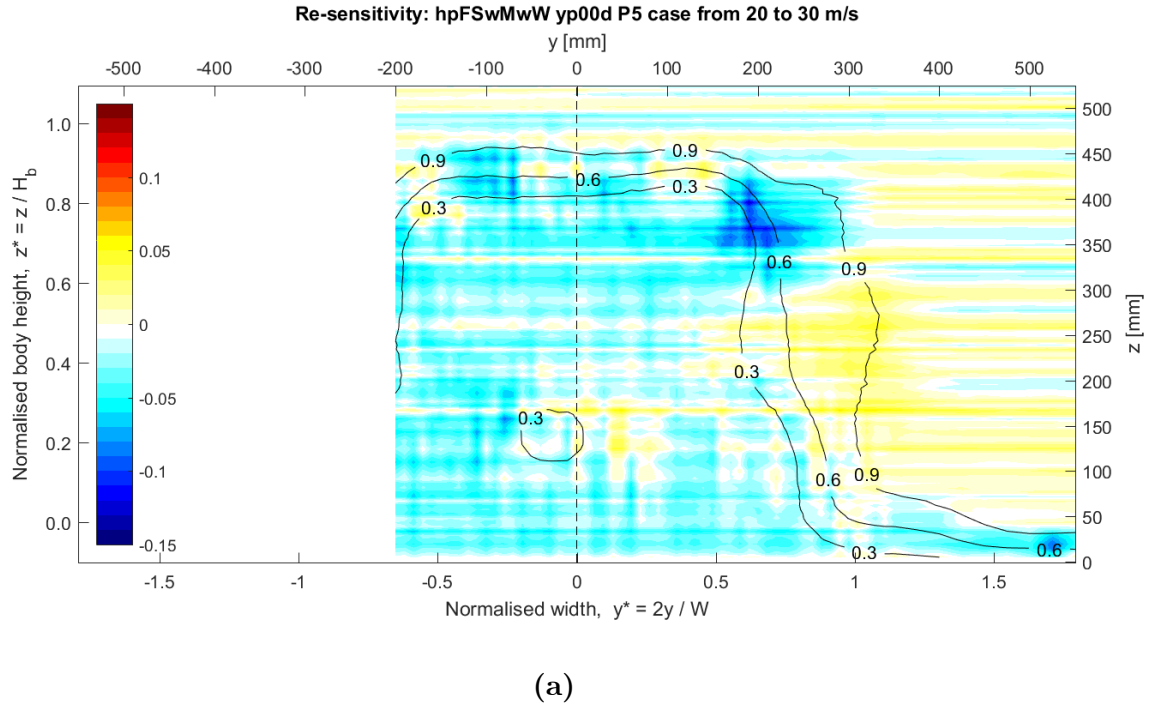


Figure 77. *Re-sensitivity* of DrivAer high-performance Fastback (*hpFSwMwW*), part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 m/s, and (b) 30 to 40 m/s.

4.5 STATISTICAL ANALYSIS

The statistical relevance of the experimental results corroborates the objective of providing a high-quality wake database to be used as an experimental reference for further investigations, mainly in the validation of computational simulations. Likewise, it quantifies the uncertainty level that findings and conclusions are grounded.

Five samples were acquired over an identical configuration: Fastback model (F) with smooth underbody, with mirrors (wM) and wheel-related features (wW), at nominal zero-yaw condition (denoted as ‘ $yp00d$ ’) at $x/L = 0.176$ (plane $P5$). These samples are shown in Figure 78.

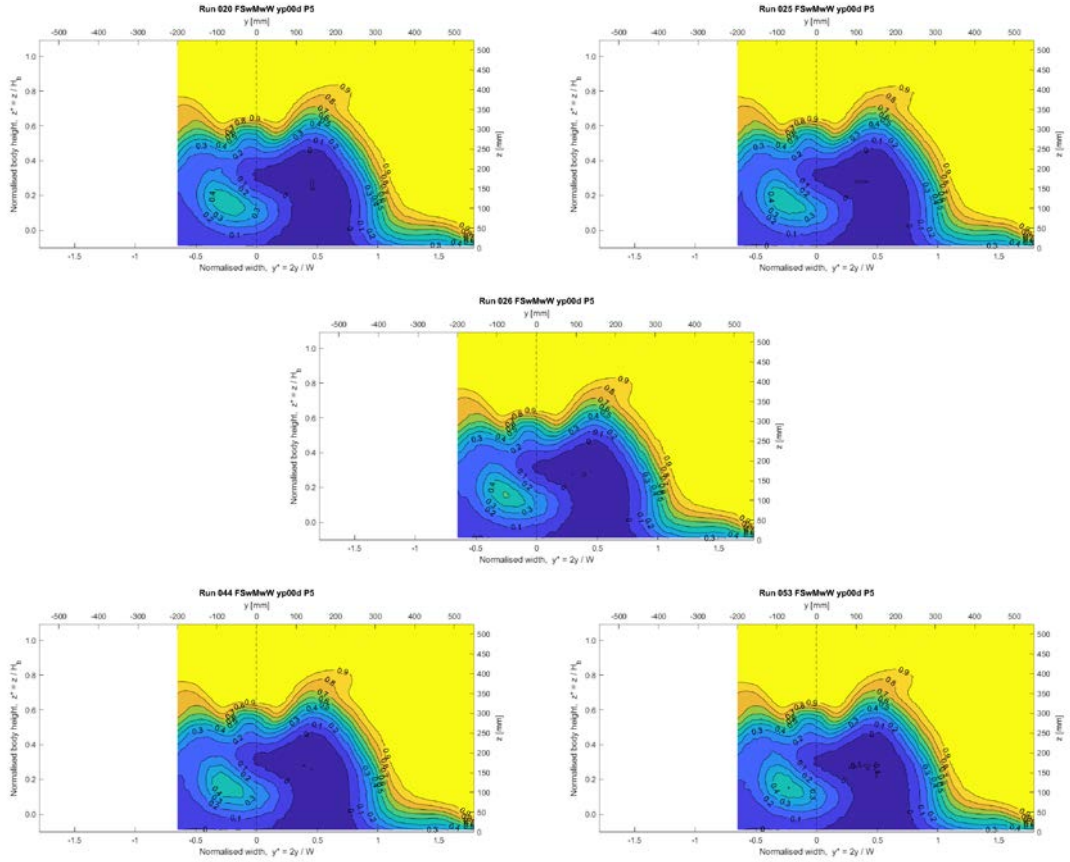


Figure 78. Repeatability samples of $FSwMwW$ $yp00d$ $P5$ case.

Note that the samples were non-sequential wind tunnel runs (*e.g.* Runs 020, 025 026, 044, and 053). It was intentionally planned with the purpose of including the maximum uncertainties associated with the experimental approach. To illustrate this point, this tactic allowed the coverage of more substantial variations on the facility (*e.g.* wind tunnel temperature and atmospheric pressure) as well as unquantifiable human factors (*e.g.* model rigging, misalignment and operational mistakes). These influences can be analysed as a resulting variance, which is the most relevant for applied engineering. Therefore, the goal in the statistical analysis is to estimate the overall uncertainty magnitude affecting the database.

4.5.1 Summary of mathematical background

Pressure measurement uncertainty is assumed as a Normal distribution: a zero-skewness distribution centred at the nominal value. Then, the margin of error (e) would be calculated by:

$$e = Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (4.4)$$

where $Z_{\alpha/2}$ is the standard score for a two-tail significance level of α , σ is standard deviation, and n the number of samples. However, both true mean (μ) and variance (σ^2) on experimental results are unknown.

In this scenario, the Student's t -distribution method can assist in the *estimation* of the confidence interval: a band of numerical values that can be accepted as the true mean. This confidence interval is also a function of the expected confidence level (*i.e.* also referred as confidence coefficient, $1 - \alpha$) and the number of samples analysed (*i.e.* degree of freedom, $df = n - 1$).

Therefore, the case is:

$$X_{measured} \sim N(\mu, \sigma^2), \text{ while } \mu \text{ and } \sigma^2 \text{ are unknowns} \quad (4.5)$$

Regarding that σ^2 is unknown and the number of samples are limited ($n \rightarrow \infty$ is unpractical in wind tunnel testing), the degree of freedom (df) becomes a relevant parameter because $t_{df} \neq Z \sim N(0,1)$.

Considering that:

$$N(0,1) \sim \frac{\bar{x} - \mu}{\frac{\sigma}{\sqrt{n}}} \quad (4.6)$$

$$\chi_{n-1}^2 \sim \frac{s^2(n-1)}{\sigma^2} \quad (4.7)$$

where $\bar{x}$ is the measured value and s^2 is the sample variance.

Considering that only sample properties can be known, further derivation of the Z-score distribution leads to the t -distribution factor, defined by:

$$t_{n-1} \sim \frac{\bar{x} - \mu}{\frac{s}{\sqrt{n}}} \quad (4.8)$$

Therefore, a two-tail maximum error of estimate for the pressure measurements can be calculated by:

$$e = \pm t_{df, \alpha/2} \sqrt{s^2/n} \quad (4.9)$$

Specific in this thesis, the attention is given to the entire range that must be accepted as ‘true values’, hereafter defined as the Confidence Interval, ΔCI :

$$\Delta CI = 2|e| = 2 \left| t_{(\alpha/2, df)} \sqrt{s^2/n} \right| \quad (4.10)$$

This parameter is mostly relevant whenever the experimental results will be compared to another data source, like CFD simulations. To highlight this point, there is the possibility of the ‘true value’ being the lowest limit of the confidence

interval ($X_{measured} - e$) while another experiment or simulation provides a result equal to the upper limit of the same confidence interval ($X_{measured} + e$). Therefore, they are not statistically different, even numerically differing by $\Delta CI \rightarrow 2|e|$.

4.5.2 On the Experimental Confidence Interval

The confidence level of 95% is adopted for this engineering purpose, which implies that the estimated confidence interval will not contain the ‘true mean’ in 1 out of 20 cases. The significance level corresponds to a two-tail distribution area since a ‘true value’ is equally probable to be below or above the respective measurement, each by a significance level of $\alpha/2 = 2.5\%$. This statistical analysis is based on five samples, resulting in $df = 4$.

The resulting confidence interval map is presented in Figure 79, where the spatial distribution of confidence interval (ΔCI) is calculated over $FSwMwW$ repeatability cases.

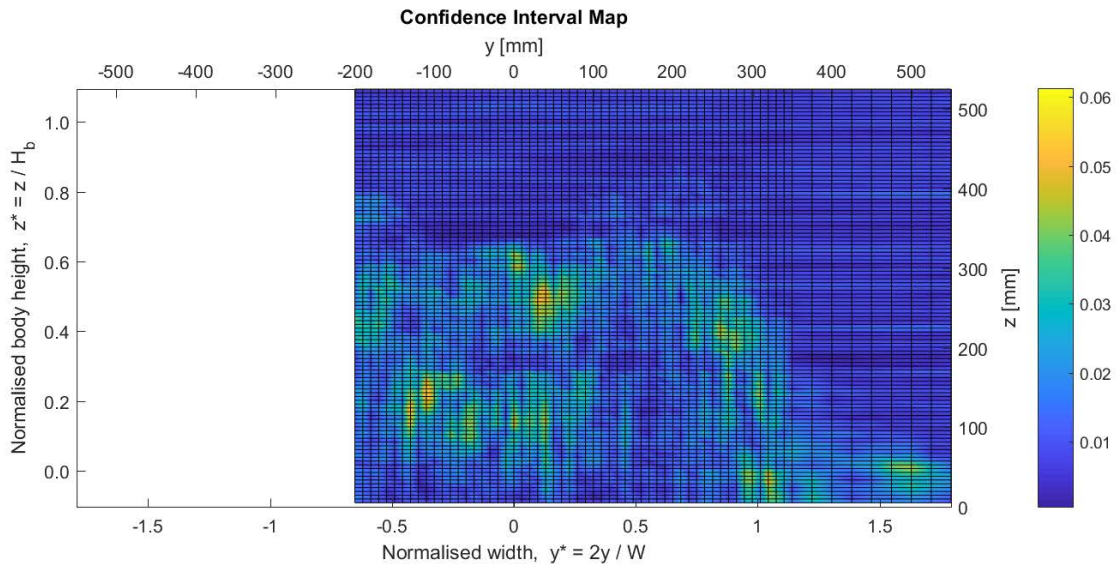


Figure 79. Analysis of confidence interval: planar distribution map (95% confidence level), DrivAer *FSwMwW* configuration.

A clear finding is the precision performance of the pressure rake. Total pressure measurements in the low-disturbed flow surrounding the wake core – then near to the freestream condition – indicated that total pressure measurements have a reliable precision: a maximum uncertainty of $\Delta CI < 0.01$.

Conversely, the wake zone is highlighted by higher uncertainty. The confidence interval range into the wake varies mostly between $\Delta CI = 0.02$ and $\Delta CI = 0.04$. Uncertainty peaks are found at (i) the wake edges and (ii) the central lower zone. The first is believed to be associate to the free shear layer between the inner-wake and the outer freestream. The second feature is a consequence of the free-stagnation point in the wake, which highlights its spatial- and time-dependency.

A quantitative analysis is done as a function of the accumulated frequency, presented in Figure 80. Another relevant conclusion is that the entire acquisition surface had a maximum uncertainty no more than $\Delta CI = 0.062$.

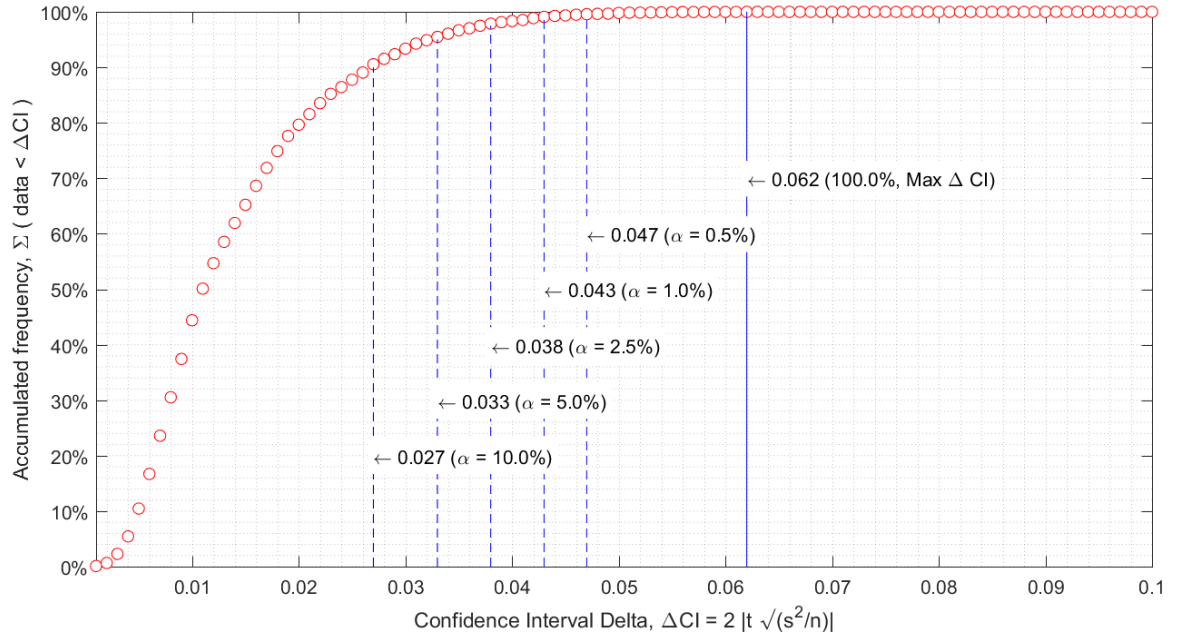


Figure 80. Analysis of confidence interval: accumulated frequency as a function of ΔCI range.

The accumulated frequency curve confirms the hypothesis that the pressure measurements tend to a Normal distribution. Even though the absolute maximum peak of $\Delta CI = 0.062$ is found, most of the confidence interval surface has lower magnitude. For 99.5% of the wake section (*i.e.* significance level of $\alpha = 0.5\%$), the maximum uncertainty is $\Delta CI = 0.047$; a peak reduction of approximately 25%. The maximum peak is nearly halved: $\Delta CI = 0.033$ for 95% if considering 95% of the wake section.

These findings lead to the conclusion that the wake acquisition can contain a maximum uncertainty of $\Delta CI = 0.062$, albeit most of the data are affected by a margin of error of ± 0.016 (*i.e.* $\Delta CI = 0.033$ over 95% of the acquisition surface).

4.6 ON THE LIMITATIONS OF THIS EXPERIMENTAL TECHNIQUE

Unfortunately, there is an inherent bias on single-hole pressure results that cannot be adequately identified in the data *per se*: the occurrence of excessively large cross flow angle and/or magnitude in relation to the probe orientation.

To illustrate this point, consider a fully reversed flow at the rake - the most critical scenario. Only the static pressure of this flow is measured correctly, while the dynamic pressure cannot be converted since the flow of interest would not fully deaccelerate to stagnation at the probe tube tip. The mentioned scenario yields larger discrepancies at the vicinity of crossflow occurrences, then the *acquired* total pressure (hereafter referred to as *nominal*) can differ from the ‘expected true’ – *theoretical* – total pressure value. This undetermined discrepancy is believed to be a function of crossflow magnitude and direction, which are both unknown flow properties from this method.

Therefore, the analysis of results must not be taken as unequivocal and categorical, unless the findings can be contrasted to data obtained from another technique.

In the matter of boundary conditions, the flow on the ground floor was a concern since it can affect the aerodynamic performance of the vehicle models, especially the high-performance benchmark (DrivAer hp-Fastback). The diffuser model has a smooth underbody, but the diffuser angle designed to near optimum in ground simulation can stall under the influence of the ground boundary layer, consequently influencing the wake development from the model.

4.7 CONCLUSIONS

An experimental campaign based on total pressure rake measurements proved a robust and effective method to assess the wake evolution of automotive bodies. A time-averaged, pressure-based wake database is developed, covering four automotive body types (DrivAer F , N , E , and hpF) as a function of downstream distance ($x/L=0.176, 0.222, 0.269, 0.315$, and 0.362). Additional cases evaluated the influence of Reynolds number (2.03×10^6 , 3.04×10^6 , and 4.05×10^6) and side mirror configurations (wM , woM).

Three types of wake evolution are identified when analysing the downstream development of total pressure coefficient (C_{p_t}) distributions. The Fast- and Notchback DrivAer models generate wakes denoted as *Type I*; a small, vortex-dominated wake with minor downwash. Wake *Type II* refers to a typical bluff-body flow wake with horizontal inwash, related to the Estateback DrivAer model. The high-performance model generates a wake classified as wake *Type III*: a vortex-dominated wake driven by a strong diffuser-spoiler upwash.

The influence of side mirrors on the wake is relatively small when compared to the wake core. Nevertheless, whilst the side mirrors are located at $\Delta x/L = 0.6$ upstream the vehicle base, the influence on the total pressure loss in the wake can be clearly identified in all downstream measurement planes, for on all models in woM configuration.

The sensitivity of the wake structure to changes in Re number is also assessed in terms of C_{p_t} distribution. Changes due to lower freestream speeds (*e.g.* $20 \rightarrow 30\text{m/s}$) proved more significant than at higher freestream speeds (*e.g.* $30 \rightarrow 40\text{m/s}$) for all vehicle cases. While wake *types I* and *II* (*e.g.* F , N , and E) have both positive and negative variation of C_{p_t} on the wake planes, wake *Type III* (*e.g.* hpF) has the unique tendency of an asymptotic C_{p_t} reduction. The available

results only allows confirmation that the wake structures have not reached the Re_{tr} in experiments at $30m/s$ (*e.g.* 3.04×10^6) since minor variations can found in comparison to a freestream at $40m/s$ (*e.g.* 4.05×10^6). Nevertheless, C_{p_t} gradients as a function of Re suggest that the wakes may have been at transcritical Reynolds number (Re_{tr} , [51]) for $Re > 4 \times 10^6$. Further Re assesment in intermediate levels between 3 to 4×10^6 is recommended for further studies.

The statistical analysis estimated the precision of the experimental tool for a 95% of confidence level. An averaged, nominal confidence interval range of $\Delta CI < 0.01$ (*i.e.* $\Delta C_{p_t} < \pm 0.005$) can be attributed for measurements at low-disturbed flow, such as the freestream. Measurements within the wake provided a maximum uncertainty of $\Delta CI < 0.062$ (*i.e.* $\Delta C_{p_t} < \pm 0.031$), but the distribution analysis of accumulated frequency of confidence interval indicated that it can be considered a spurious event. Therefore, it is concluded that wake measurements have a nominal precision of $\Delta C_{p_t} \approx \pm 0.02$ for 99% of each plane analysed.

Chapter 5.

EXPERIMENTAL ANALYSIS OF AUTOMOTIVE WAKES,
Part II: a SPIV-based analysis

This chapter presents the investigation of wake characteristics of automotive models using Stereoscopic Particle Image Velocimetry (SPIV). This image-based technique can characterise the 3D velocity field in a given plane, with high accuracy at the expense of some complexity in the execution of the experiments.

The objectives of this study are: (i) characterise the wake of automotive bodies in terms of the 3D velocity field, (ii) compile a wake dataset of the DrivAer model configurations, and (iii) assess the limitations of the simulation and experimental technique.

5.1 EXPERIMENTAL METHODOLOGY

This SPIV-based experiment has a similar methodology to the total pressure-based investigations, as a result only SPIV-related features are described in this section to avoid duplication. All other characteristics (*e.g.* wind tunnel test section, boundary layer control system, and model alignment) are as presented in [Chapter 4, section 4.2](#).

5.1.1 Laser light source

The light condition is a key-feature for image-based techniques. In most of PIV experiments, there is a requirement for a dark environment where only the

observation domain will be illuminated; the reason why laser⁴ devices are widely employed in this type of experiment.

This investigation required a planar, cross-flow laser sheet in order to replicate the acquisition surface used for the total pressure measurements ([Chapter 4](#), [Figure 51](#) and [Figure 50](#)).

The main components of a high-intensity laser device are the generator, also known as ‘laser head’, and its cooler. The cooler must maintain a fixed temperature because any variation will reflect in instabilities of the laser properties. [Figure 81](#) illustrates the laser head, power supply with the water cooler and articulated optical arm.

This experiment used a Class IV laser generator model NanoPIV, manufactured by Litron Lasers, using a power supply model LPU550-PIV. It has two independent laser sources based on Nd:YAG crystals capable of repetition rates up to 15 *Hz* and energy emission up to 200 *mJ*.

⁴ ‘Laser’ is usually associate to an intense, concentrated light sources. Technically, the name is an abbreviation for ‘Light Amplification by Stimulated Emission of Radiation’.

5.1.2 Laser optics

An articulated optic arm (Figure 81) was particularly useful in the transport of the laser between the laser head and the point of interest – an aperture on the wind tunnel test section roof. The final laser sheet is a result of a pair of lenses installed at the end of the articulated arm: (i) one spherical, for adequate control of the laser expansion, and (ii) one cylindrical, to expand the circular laser into a plane to cover the acquisition area of interest.

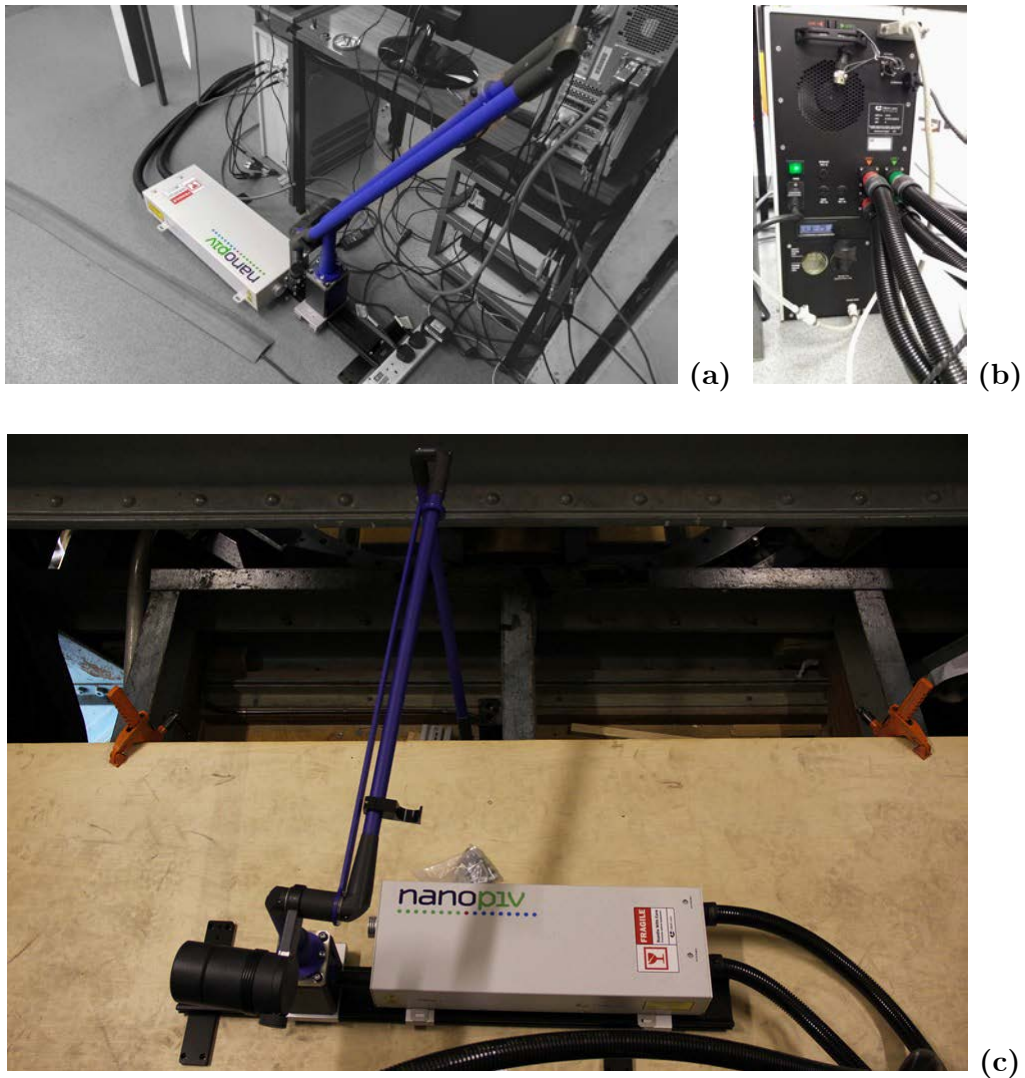


Figure 81. Illustration of (a) the laser generator (head) with articulated optic arm, (b) the power supply with water cooler, and (c) installation on the wind tunnel upper wall.

5.1.3 CCD cameras

Two identical CCD cameras (model VC-Imager LX 8M, GigaBit) were used for stereo perspective, operating at 12-bit with 8MB (3312 x 2488 pixels) with a Gigabit Ethernet interface. Each camera was set at 30 degrees to the normal direction of the acquisition area (*e.g.* freestream direction) and with an equidistant, focal distance of approximately $1.35m$ (see [Table 21. SPIV acquisition areas.](#)).

Nikon 50mm lenses with aperture F2.8 provided the best trade-off between light intensity and particle focus. In order to ensure constant focus over the acquisition plane, Scheimpflug adaptors (LaVision Scheimpflug mount v3) were connected between the camera and lenses, thus facilitating fine adjustment of the image focus during the calibration process.

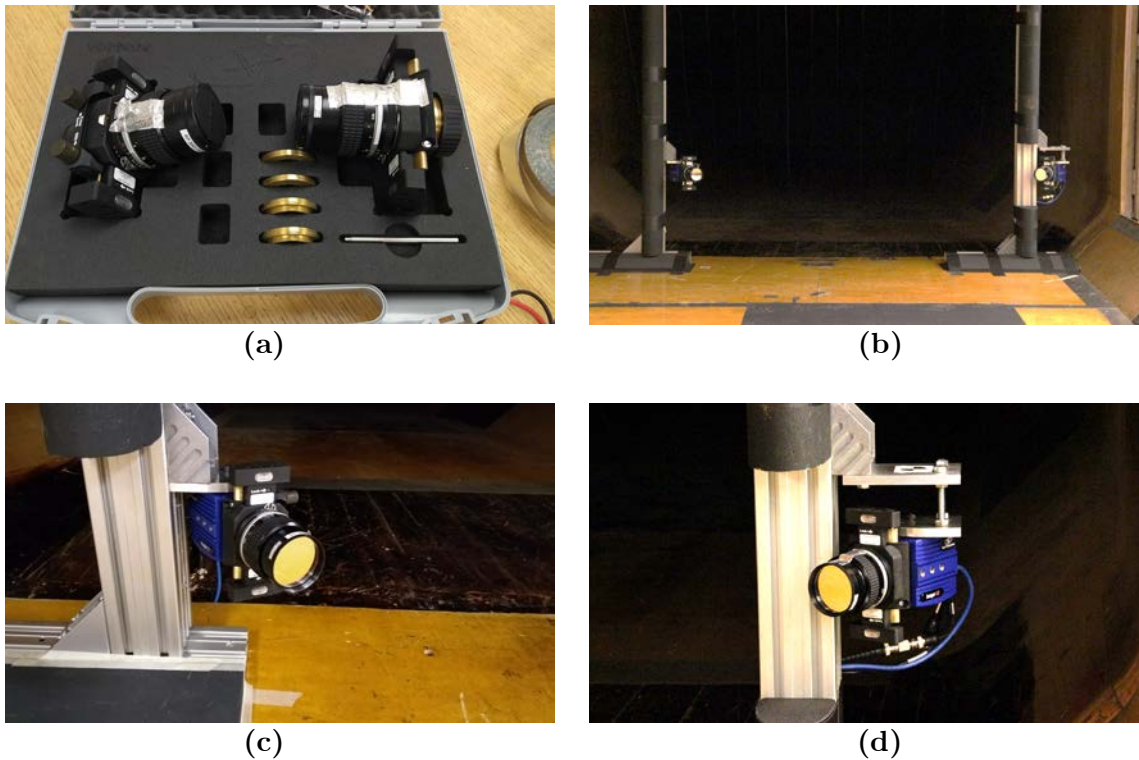


Figure 82. Camera setup. (a) Cameras kit with Scheimpflug adaptors; (b) equidistant, stereoscopic setup; (c) right- and (d) left-hand side cameras ready for use.

5.1.4 Seeding generation

Freestream flow seeding is achieved using a medium-sized device with 45 cascable nozzles, referred to by the manufacturer PIVTEC GmbH as ‘Aerosol Generator PIVPart45’, with a technique known as liquid atomisation.

Operating in an overpressure range of 1 to 3 *bar*, it generates a ‘seeding’ flow with pulverised liquid drops of 95%-concentrated Bis(2-ethylhexyl) sebacate, with 0.9 μ m nominal diameter size [52].

The level of flow seeding was checked before each acquisition run and manually adjusted by a solenoid valve on the seeding generator.

5.1.5 Laser-related Hazards

Safety procedures must be followed while using Class IV laser devices in order to protect users’ eyes and skin, as well as to prevent ignition of flammable materials.

Using optical lenses to alter the spatial laser density, represents significant risk of immediate and irreversible eye damage, requiring the use of laser safety goggles.

Laser devices emit light in wave frequency as a function of the material used as the light-exciting medium. The Nd:YAG crystal used emits light at wave frequency of 532 *nm* – a visible green light in the human perception spectrum.

Therefore, safety goggles suitable for 532 *nm* (and any half-frequency residual wave, 1064 *nm*) had always been used while the laser source was turned on, either for setup adjustment or measurement campaign.

Another safety system is the physical, external control of the laser system including (i) cooling pump, (ii) laser, (iii) shutter, and (iv) attenuators. In the event of a critical situation, one dedicated button can shut down the entire system.

5.1.6 Measurement strategy

The acquisition area and measurement resolution are conflicting parameters in any SPIV setup. In order to acquire data corresponding to the wake height (previously assessed using the total pressure surveys, [section 4.4.1](#)), the laser investigation had to perform measurement in several sub-areas to ensure minimum resolution. Subsequently data for each of these sub-areas is combined to form the wake planar section for each configuration.

Considering the wind tunnel time available and nominal zero-yaw condition, the test programme was optimised to acquire the most relevant data. Two acquisition areas are defined in critical regions for wake analysis, as described in [Table 21](#).

Table 21. SPIV acquisition areas.

Acquisition domain	Position (centroid)	Size (nominal)	Description
A1	[x , -200, 173] <i>mm</i>	300 x 300 <i>mm</i>	Projection of lower rear-end, and wheel related features.
A2	[x , -200, 343] <i>mm</i>	300 x 300 <i>mm</i>	Projection of upper rear-end and side mirrors.

5.1.7 Calibration

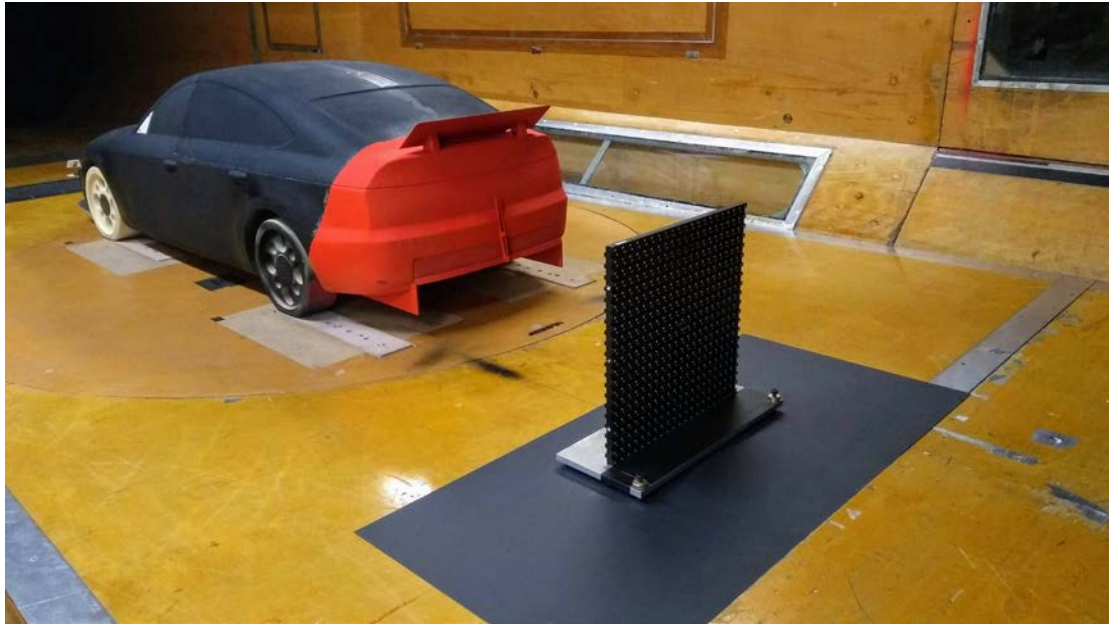
Calibration in a SPIV setup is a fundamental process; it generates the correlation between raw images and the spatial domain. For each area of interest, a preliminary calibration procedure must be carried out.

A 3D calibration board model 309-15, manufactured by the SPIV system supplier, was employed. It consists in a grid of dots in a pattern of 15mm over the entire board, where a sequence of intermittent horizontal grooves distributes all dots on two planes separated by 3mm (Figure 83, *a*). Using images from each camera, the Davis software can reconstruct the spatial domain tracking the dot pattern. Thus, a two-plane board and stereoscopic formation allow a three-dimensional reconstruction.

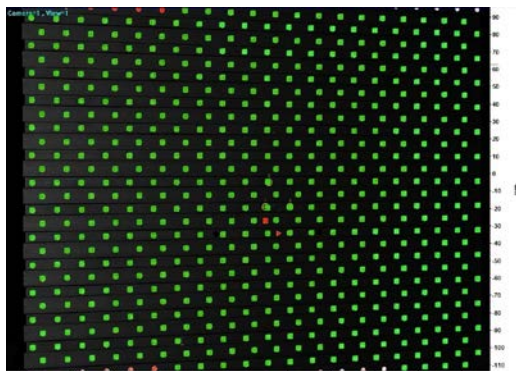
Accurate translational and rotational positioning of the calibration plate is of critical importance since all particle displacements, measured on the laser sheet plane, will be processed based on the calibration corrector.

Therefore, the calibration plate will directly impact the accuracy of SPIV results and must be placed precisely on the laser plane, ideally covering the entire area of measurement.

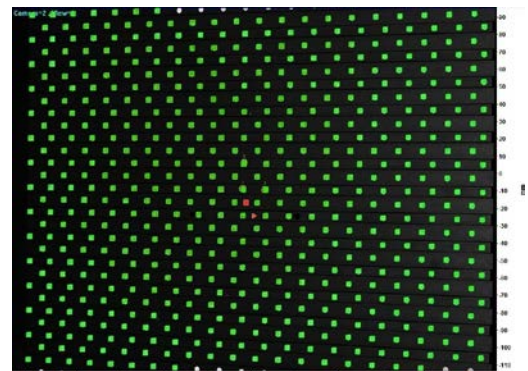
Figure 83 illustrates the calibration procedure, from the positioning of the calibration board (*a*), dots identification from each camera perspective (*b*, *c*) and software reconstruction of the spatial domain (*d*). A summary of the calibration processing properties is given in Table 22.



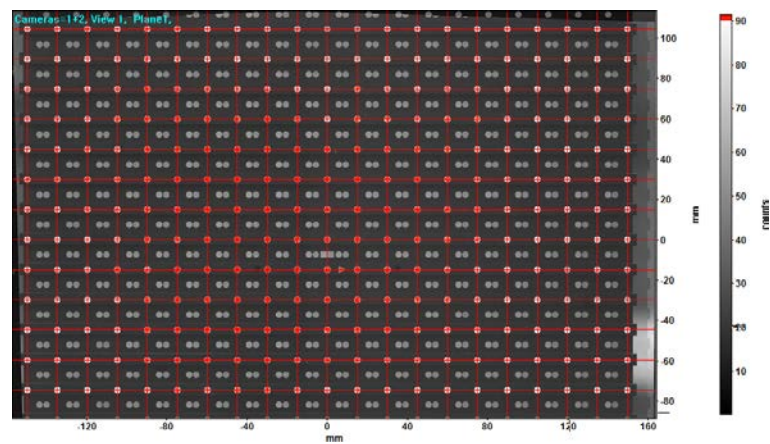
(a)



(b)



(c)



(d)

Figure 83. Calibration process: use of 3D calibration board for SPIV applications.

(a) 3D calibration board at the area of interest, identification of references dots by (b) camera 1 (left-hand side) and (c) camera 2 (right-hand side), and (d) planar reconstruction from stereoscopic camera formation.

Table 22. Report of a calibration process.

	Camera 1	Camera 2
<i>General</i>		
Fit Model	Pinhole	Pinhole
Handedness	Right-handed	Right-handed
RMS of fit	0.392 px	0.382 px
Size of dewarped image	3828 x 2477 px	3828 x 2477 px
<i>Camera configuration</i>		
Focal length f	77.05 mm	81.40 mm
Pixel size	0.0055 mm	0.0055 mm
Pixel aspect ratio	0.9671	0.9956
<i>Camera position relative to the calibration plate</i>		
Translation	[3.37, -10.13, 1186.34] mm	[-9.36, -4.92, 1248.31] mm
Rotation	[-0.212, -27.298, 0.345] deg	[0.234, 29.049, -0.530] deg
<i>Camera scale</i>		
Origin	[1949.56, 1299.66] px	[1949.56, 1299.66] px
Scale factor	11.84 px/mm	11.84 px/mm
<i>Image distortion</i>		
Principal point	[1752.69, 1239.92] px	[1691.94, 1302.14] px
Radial distortion	1 st order = -0.120355 2 nd order = -0.0257428	1 st order = -0.135482 2 nd order = -0.0224431

5.1.8 Image Processing

Each pair of ‘raw images’ of particle displacement was processed to obtain the 3D velocity vector field using the Davis 8.0 software. The computational processing was carried out on a workstation with Nvidia’s CUDA capability v6.1, GeForce GTX 1080. The total amount of global RAM memory is 8GB with 20 multiprocessors providing 2560 cores.

A total of 400 image pairs were acquired at 2.3Hz for each case using a constant resolution of 8 megapixels (3312 x 2488 pixels). Considering the interest of time-averaged flow pattern, this low-frequency acquisition was suitable since it randomised samples of flow structures over multiple flow structures, as demonstrated in [21] [53] [54].

After a preliminary processing setup investigation, it was concluded that the best vector calculation processing was based on a multi-passing search starting with two passes with an interrogation window size of 64 x 64 pixels with 50% overlap, then three passes of 32 x 32 pixels with 75% overlap. Figure 84 illustrates a typical outcome case from the adopted processing methodology.

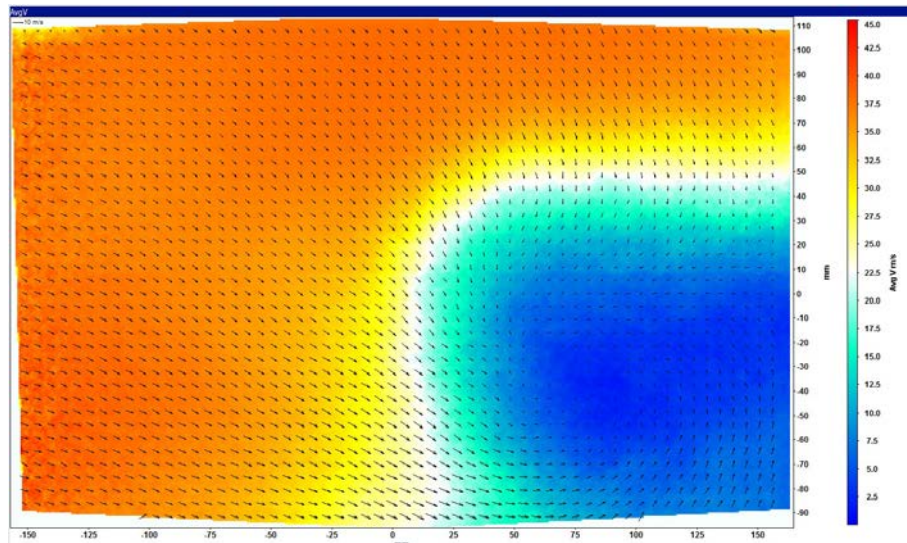


Figure 84. Sample of time-averaged in-plane vector component with velocity magnitude background. Case *hpFSwMwW*, plane *P5*, area *A2*.

5.2 EXPERIMENTAL PLAN

A SPIV wake database for the full-body DrivAer models has been generated for the vehicle configurations outlined in Table 23. This required a test matrix of 24 cases at the standard wind tunnel condition (Table 24).

Table 23. Experimental variables for the SPIV wake database.

	Levels	Description	Notation
<i>Geometry</i>			
DrivAer models	4	Fastback	F
		Notchback	N
		Estateback	E
		High-Performance Fastback	hpF
Mirrors	2	with external mirrors	wM
		without external mirrors	woM
<i>Wake</i>			
Planes	3	284 <i>mm</i> , $x/L = 0.176$	$P5$
		434 <i>mm</i> , $x/L = 0.269$	$P3$
		584 <i>mm</i> , $x/L = 0.362$	$P1$

Table 24. Summary of the standard experimental conditions.

Freestream	Model alignment	Ground treatment
40 m/s	zero-yaw	both BL on

Note that all acquisition planes are identical to the pressure-based surveys, where $P5$ corresponds to the cross-section nearest to the model ($x/L = 0.176$) while $P1$ is furthest downstream ($x/L = 0.362$). According to the earlier assessment

([section 4.4.1](#)), those planes are downstream of the near-wake recirculation zone for all the models tested.

[Table 25](#) summarises the main parameters of the SPIV experimental setup. In relation to wind tunnel time utilised, each run required between 23 and 28 minutes to conclude the following routine:

- i. Model setup (*e.g.* positioning, replacement, fixing).
- ii. Run-up wind tunnel to required freestream velocity.
- iii. Inspections of camera signals and seeding distribution.
- iv. Safety check before open laser shutter.
- v. Data acquisition.
- vi. Turn off laser signal and close shutter.
- vii. Data recording, simultaneously with wind tunnel run-down.

Table 25. Summary of SPIV experimental setup.

Feature	Description
PIV method	Stereo cross-correlation
Number of cameras	2
Lenses Aperture	F 2.8 (each camera)
Scheimpflug adaptors	Included and adjusted (each camera)
Laser (pair) Intensity	100% (each laser)
Pulse duration	20 μs
Acquisition frequency	2.3 Hz
Number of samples	400 samples
Wind tunnel time per run (total):	23 - 28 min
(i) Pre-acquisition:	10 - 15 min
(ii) Acquisition:	174 s
(iii) Post-acquisition:	10 min

Air properties like temperature and ambient pressure are measured before each wind tunnel run, which are used to calculate air density and dynamic viscosity assuming the ideal gas law (Eq. (4.2)) and Sutherland's equation (Eq. (4.3)), respectively. Table 26 summaries the freestream properties range for all the SPIV tests done.

Table 26. Summary of air properties during SPIV measurement campaign.

Air property	Symbol	Min	Max	Unit
Temperature	T	18.1 291.3	24.1 297.3	°C K
Pressure, Environmental, reference	P_∞	99 348	101 546	Pa
Density (estimated)	ρ	1.1614	1.2069	kg/m ³
Viscosity,				
Dynamic (estimated)	μ	1.8042×10^{-5}	1.8362×10^{-5}	Pa.s
Kinematic (estimated)	ν	1.5020×10^{-5}	1.5810×10^{-5}	m ² /s

5.3 RESULTS & DISCUSSION, PART I:

Corrections and Image Processing Issues

5.3.1 Processed, initial results

When analysing the SPIV processed data, specifically that outside of the wake core region, it has been found that the local velocity magnitude, for each acquisition area, are scaled differently to the expected freestream. This issue is seen to be constant for all cases when combining each of the acquisition areas to form the surface of interest (Figure 85).

Although each area position had different heights, the cameras were moved accordingly, and the camera perspective was maintained. Therefore, both acquisition areas were measured under identical experimental conditions and perspective.

As a result, it was decided to apply a factor, estimated comparing the SPIV results with CFD simulations. It was concluded that results from the lower area (*A1*) seem scaled by a factor of 0.931 while the upper area (*A2*) should be corrected by 1.04. Figure 86 shows both correction factors applied in respective areas.

5.3.2 Post-processed, final results

Post-processed SPIV results are presented from Figure 87 to Figure 98. Both physical and normalised geometric scales are presented in a format which corresponds with the total pressure data presented in Chapter 4, section 4.4.

To aid analysis, each SPIV dataset is shown in terms of (i) velocity magnitude contour plot (left-hand side) and (ii) in-plane velocity components ($\overrightarrow{U_y + U_z}$) as vector field (right-hand side).

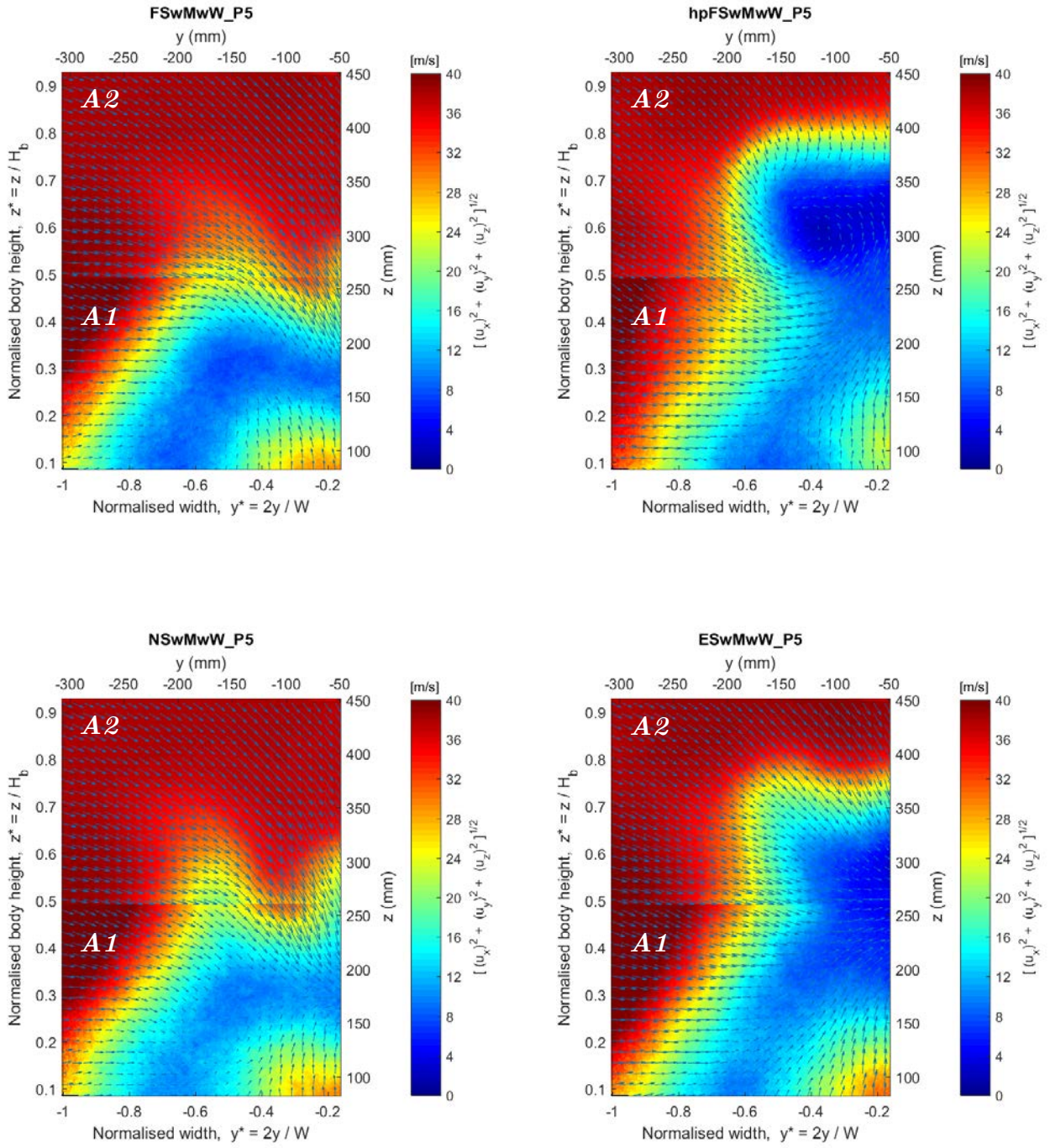


Figure 85. Merging acquisition areas: out-of-scale velocity fields.

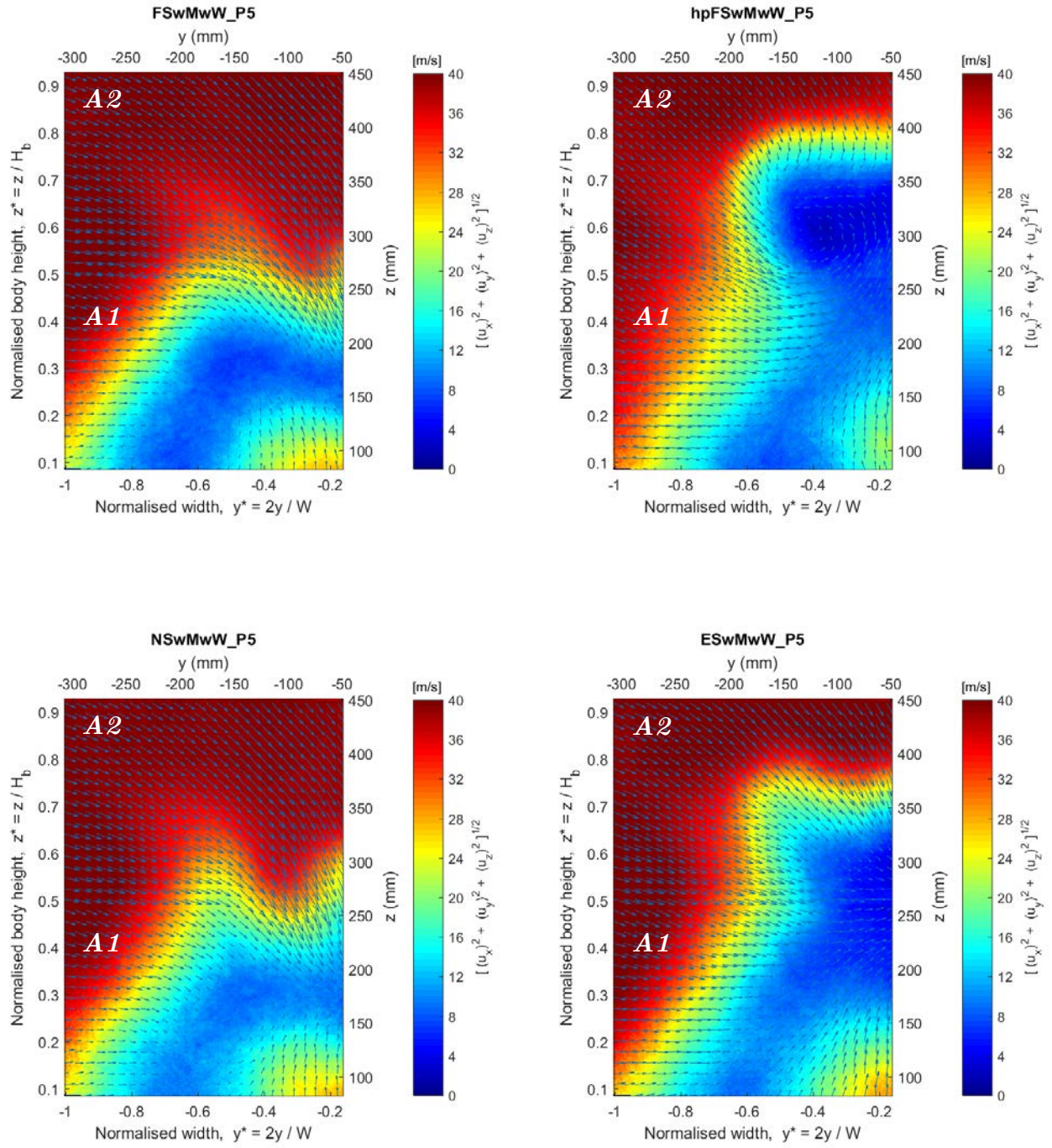


Figure 86. Merging acquisition areas: corrected velocity fields.

5.4 RESULTS & DISCUSSION, PART II:

On the Compilation of a SPIV-based Wake Database

This section addresses the analysis of results compared to the total pressure rake data since this can be linked to velocity magnitude by:

$$P_t = P_s + P_d = P_s + \frac{\rho U^2}{2} \quad (5.1)$$

Recognising that compressibility is negligible for $M < 0.15$ [55] [38], then:

$$P_t \propto U^2, \quad \text{for } P_s \rightarrow P_{sref} \quad (5.2)$$

For summary purposes, the present discussion avoids repetition of previous discussion and findings outlined in [Chapter 4](#). Reference to the ‘wake trace’ relates to the wake region with flow under $0.9 U_\infty$ contour for a given plane.

5.4.1 Wake characteristics as a function of vehicle distance

In terms of the local velocity magnitude, all SPIV results agree with the findings obtained using the total pressure-based assessment (see [section 4.4.1](#)), in particular to the classification of three the wake types.

Wake *Type I*, generated by the Fastback ([Figures 87, 88, 89](#)) and Notchback DrivAer models ([Figures 90, 91, 92](#)), has a nominally semi-circular area of velocity deficit diffused as the wake develops downstream. At the nearest plane (*P5*, [Figures 87 and 90](#)), the wake trace height is nominally $z^* = 0.7$. The main portion of the wake trace corresponds to a time-averaged flow less than $0.3 U_\infty$ distributed in a nominally semi-circular band: $|0.4| < y^* < |0.8|$ at $z^* = 0.1$, while $0.2 < z^* < 0.4$ at $y^* = |0.15|$.

In the subsequent plane ($P3$, Figures 88 and 91), the wake trace is slightly reduced while a central downwash occurs, and the velocity deficit has been mitigated. Nearly half of the wake trace has a flow speed higher than $0.5 U_\infty$. Even though the wake changes are reduced towards the furthest plane ($P1$, Figures 89 and 92), it sustains the trend from $P5 \rightarrow P3$ and at least 75% of the wake has a time-averaged velocity of $0.5 U_\infty$.

An advantage of the SPIV technique is that the results expose the individual velocity components. The in-plane velocity $\overrightarrow{U_y + U_z}$ shows that the wake *Type I* is dominated by a horizontal cross-flow inward towards the wake core, while a strong downwash from the model upper surface is coupled with a upwash from the diffuser. Since the upper surface downwash dominates the diffuser upwash, the wake trace is seen to move downwards at the rear-centre. This downwash, combined with the lateral inflow, initiates a large vortex structure that rotates and dissipates the velocity deficit into the wake.

Wake *Type II*, produced by the DrivAer Estateback model, exhibits a bluff-body wake type with large velocity deficit at its central region and no dominant vortex structure (Figures 93, 94, 95). SPIV results show that, at the nearest plane ($P5$, Figure 93), the wake trace extends in a trapezoidal pattern over an area at least $y^* = |0.75|$ wide and $z^* = 0.8$ tall. The large velocity deficit can be found at the central region between $y^* < |0.4|$ and $0.3 < z^* < 0.6$ for $0.2 U_\infty$. When clipping the wake velocity up to $0.3 U_\infty$, it exposes the wake trace from the wheels which moves inwards and diagonally connects to the central, large velocity deficit region.

This wake type also has a large difference between the first and mid-plane tested (*i.e.* $P5 \rightarrow P3$). Although the wake trace maintains a nominally trapezoidal shape, the underbody flow reduces its velocity magnitude. The wake trace associated with the wheels also cannot be identified at $P3$ (Figure 94), which suggest a significant flow mixing. Approximately 50% of the wake trace has a flow

magnitude higher than $0.5 U_\infty$. The farthest plane measured (*P1*, [Figure 95](#)), shows that the high velocity deficit zone has moved nearer to the ground while its intensity has been mitigated: only $\sim 5\%$ of the wake trace has flow velocity magnitude below $0.4 U_\infty$. Along the range of three planes, $\Delta x/L = 0.186$, wake height had a minor reduction from $z^* = 0.80$ to $z^* = 0.75$.

In terms of the velocity vector field, it is found that the reduction of wake height is not dominated by a downwash from the upper car surface, in contrast to Fastback-like models. The first plane (*P5*, [Figure 93](#)) reveals that the outer flow migrates inwards to the wake core from all directions almost uniformly, with exception of the low-speed flow downstream the wheels. The diffuser upwash is comparable with the downwash from the upper surface, reaching an averaged equilibrium at $z^* = 0.50$. At this height, the time-averaged flow has migrated horizontally across the wake trace and pushed the vertical balanced flow towards the vehicle axial centreline. The second plane ([Figure 94](#)) shows that the overall vector directions persist, whereas the in-plane magnitude has been reduced, and the vertical inflow equilibrium moved $\Delta z^* = -0.05$. By the most downstream measurement plane (*P1*, [Figure 95](#)), velocity vectors have nearly the same magnitude, but the upwash flow found on the diffuser projection has almost disappeared and vertical inflow equilibrium drops ($z^* < 0.50$). This leads to the dominance of the horizontal inflow over most of the wake region investigated.

Finally, wake *Type III* has been assessed using SPIV. Previously seen to be produced by the DrivAer high-performance Fastback configuration ([Chapter 4](#)), this wake type is driven by a strong upwash, which creates the largest wake trace of all the models tested. SPIV results ([Figures 96, 97, 98](#)) confirm the total pressure survey assessment and expose the intensity of the momentum loss with this class of automotive configuration.

Local velocity for plane *P5* (Figure 96) shows similarities to wake *Type II* (*i.e.* Estateback-like models), but with some important differences: (i) the trapezoid wake trace is even larger, at least $y^* = |0.8|$ wide and $z^* \cong 0.85$ tall; (ii) the wake trace related to the wheels is displaced inwards, and (iii) the inner velocity deficit zone is offset above the trace centre. Approximately 70% of the wake trace assessed has a velocity deficit higher $0.5 U_\infty$, which illustrates the intensity of the flow momentum into this wake.

The region of high velocity loss is diffused in plane *P3* (Figure 97), similarly the velocity peak due to the diffuser flow. At this position, $0.5 U_\infty$ is the velocity magnitude threshold for circa 50% of the wake. While the wake trace width remains mostly identical, its height increases as the upper edge bends upwards in comparison to previous plane (*P5*). At the furthest plane (*P1*, Figure 98), the wake trace reduction shows signs of width reduction, whereas the vertical development continues and reaches $z^* \cong 0.90$.

The velocity vector field reveals that the rear spoiler generates strong, coherent vortex structures with cores at $y^* = |0.43|$, $z^* = 0.59$ in plane *P5*. This feature occurs because of the flow differences surrounding the spoiler tip, which are supplemented by the upwash flow only counterbalance at $z^* \cong 0.70$ (see Figure 96). The lower area features the outer flow moving inwards horizontally while the diffuser has a strong vertical flow leaving the diffuser. A small area of high velocity deficit can be found near the bottom of the data acquisition plane (*i.e.* $|0.50| < y^* < |0.65|$, $0.1 < z^* < 0.2$), evidence of the wheel wake being deflected inwards.

The magnitude of the in-plane velocity components ($\overline{U_y + U_z}$) are generally reduced in plane *P3* (Figure 97) particularly in the lower acquisition area (*A1*). The upper vortex structure is still present, although not as defined as in the previous plane (*P5*), and it has moved inwards to $y^* = |0.35|$, and raised to $z^* = 0.65$. By the furthest plane (*P1*, Figure 98), a residual of the vortex structure can

be found surrounded by the major rotational motion of the flow, creating the ‘mushroom’ type flow formation [27].

5.4.2 Influence of side mirrors

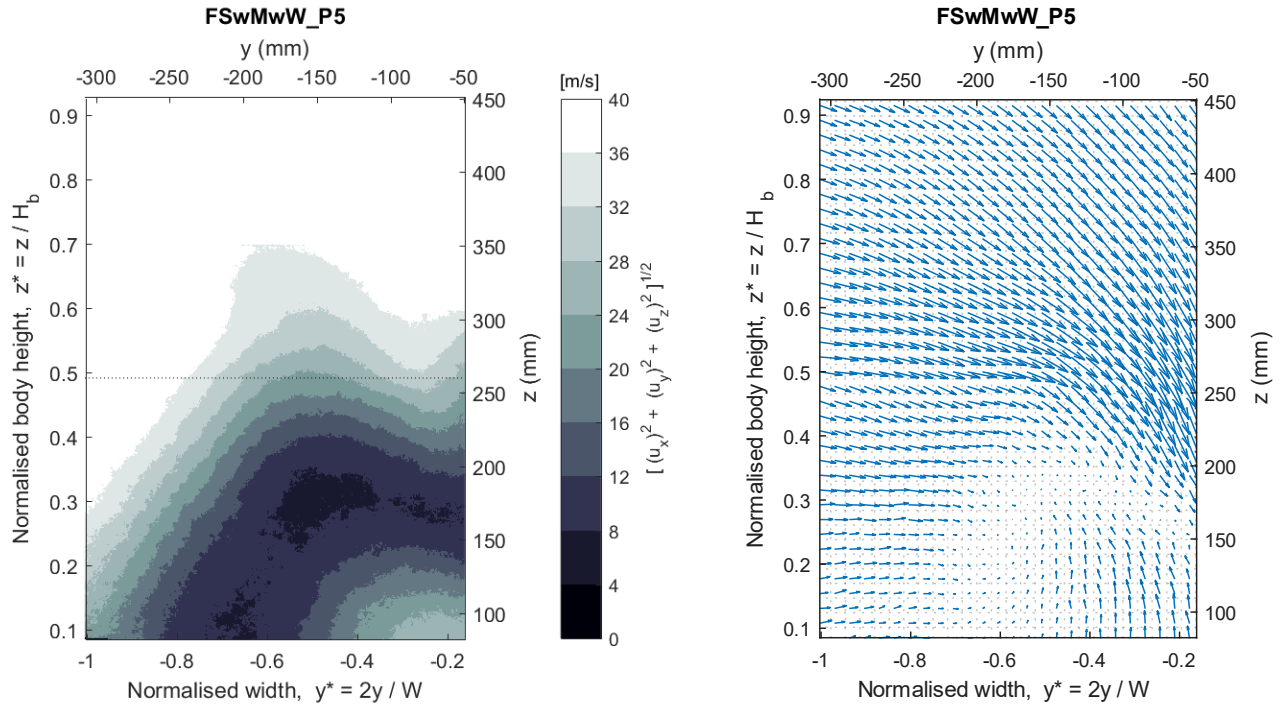
The influence of side mirrors on the flow field is evident by a region of velocity magnitude deficit, mainly on the nearest wake plane, for all vehicle types; where this is consistent with the total pressure measurements. In terms of the time-averaged in-plane velocity field, extend and position of the region effected varies according to the vehicle configuration.

The SPIV technique reveals that the High-performance Fastback model wake is the less sensitive to side mirrors (Figures 96). This is found only as a small region of velocity magnitude deficit is found next to the region, corresponding to the rear spoiler wake, while no significant difference is seen on in-plane vector field over all wake planes assessed.

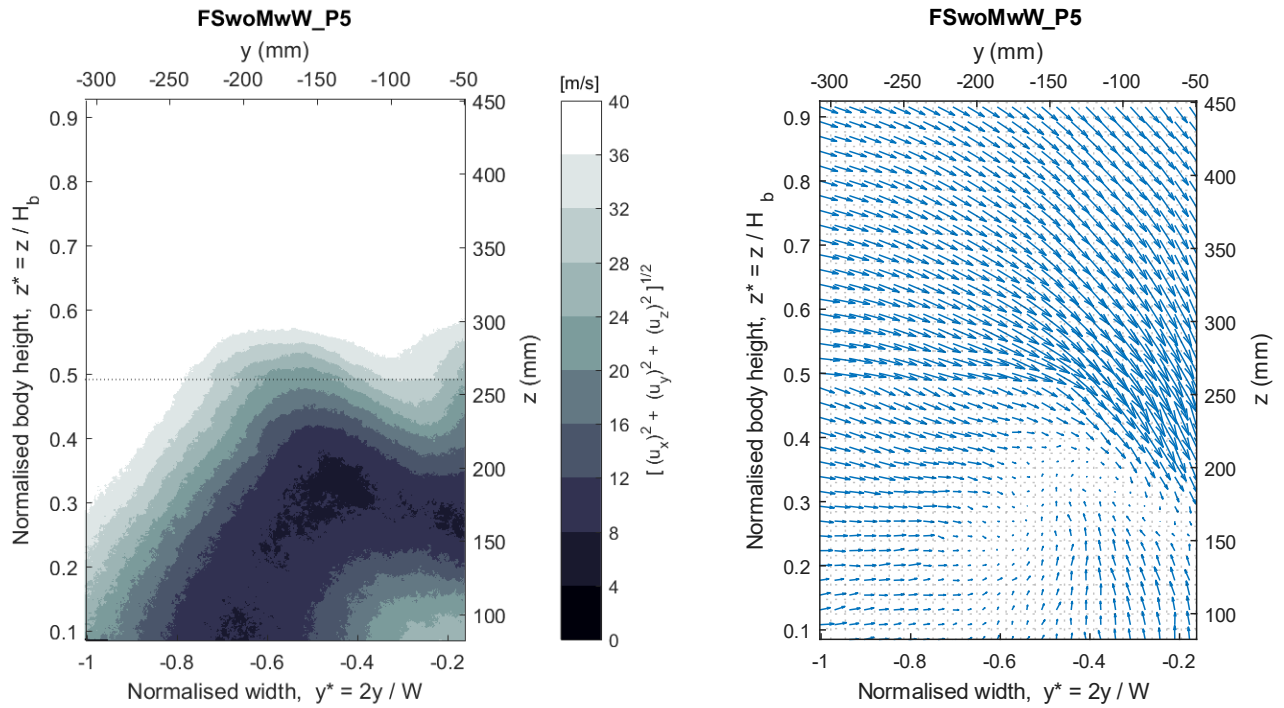
When fitting side mirrors on both the Fastback and Notchback models, the side mirror wake is found as a small region with velocity deficit of $\overline{\Delta U/U_\infty} = 0.1$ in comparison to *w0M* configurations. In the nearest plane (*P5*), a velocity deficit region from side mirrors can be found at $y^* = |0.60|$, $z^* = 0.65$ for the Fastback (Figure 87) and $y^* = |0.55|$, $z^* = 0.63$ for the Notchback (Figure 90). These regions are upper protuberances on the respective car wake. In relation to the in-plane velocity vector field $(\overline{U_y + U_z})$, side mirrors weaken the dominant recirculation vortex on both vehicle types.

Wakes generated by the Estateback model are more sensitive to the side mirrors only at the nearest plane (*P5*, Figure 93). Adding mirrors mitigates a small vortex structure near to the vehicle side surface at mid-height (*i.e.* $y^* = |0.4|$, $z^* = 0.6$) and moves the horizontal inwards flow from $z^* = 0.6$ to $z^* = 0.5$. The vortex structure found on *ESw0MwW* case is revealed to be weak and mostly dissipated

by the intermediary plane ($P3$). Both $w0M$ and wM configurations have the respective horizontal inflow deflected downwards by $\Delta z^* \cong 0.07$. In the plane $P1$, $x/L = 0.362$, no significant difference can be identified.

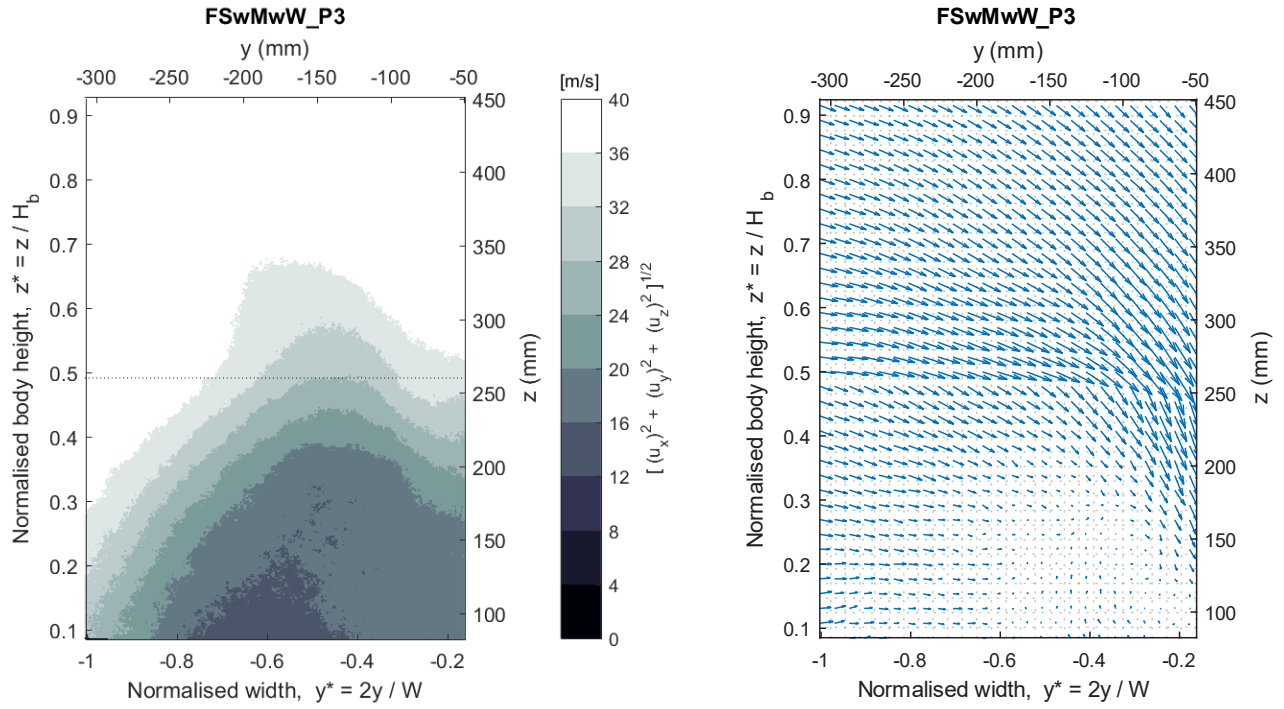


(a) with external mirrors (*FSwMwW*).

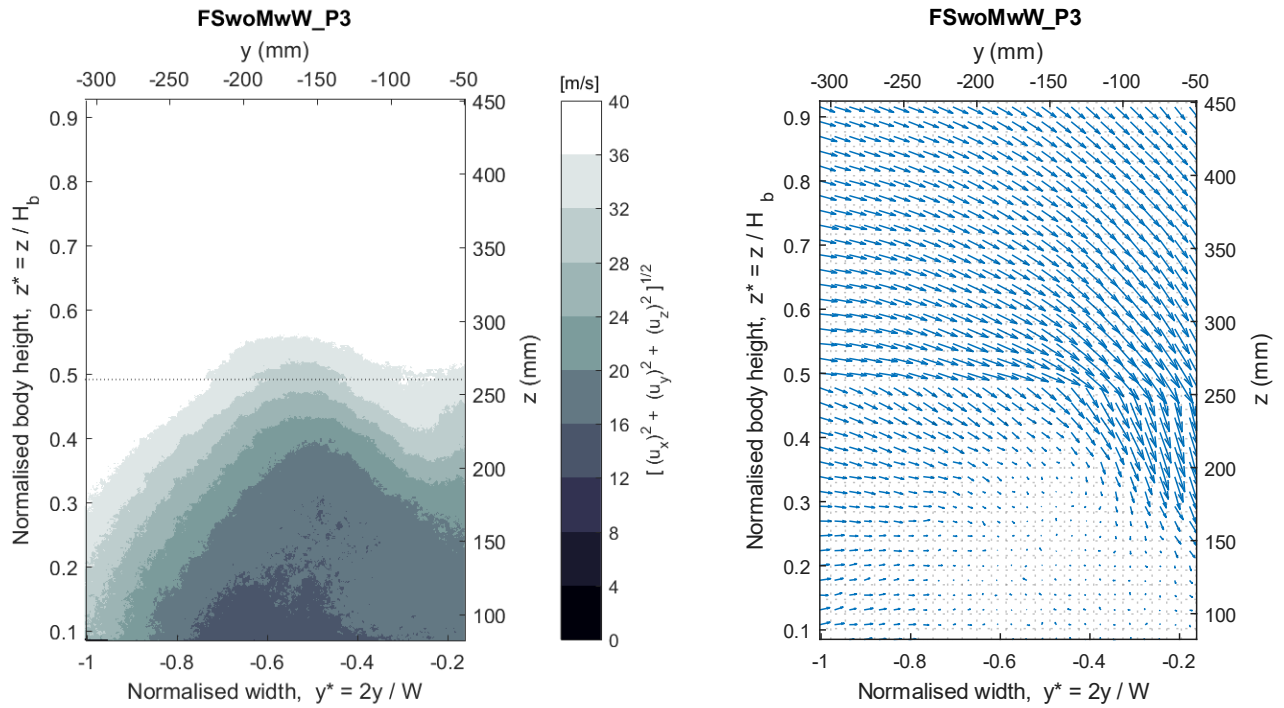


(a) without external mirrors (*FSwoMwW*).

Figure 87. DrivAer Fastback configurations, plane *P5*.

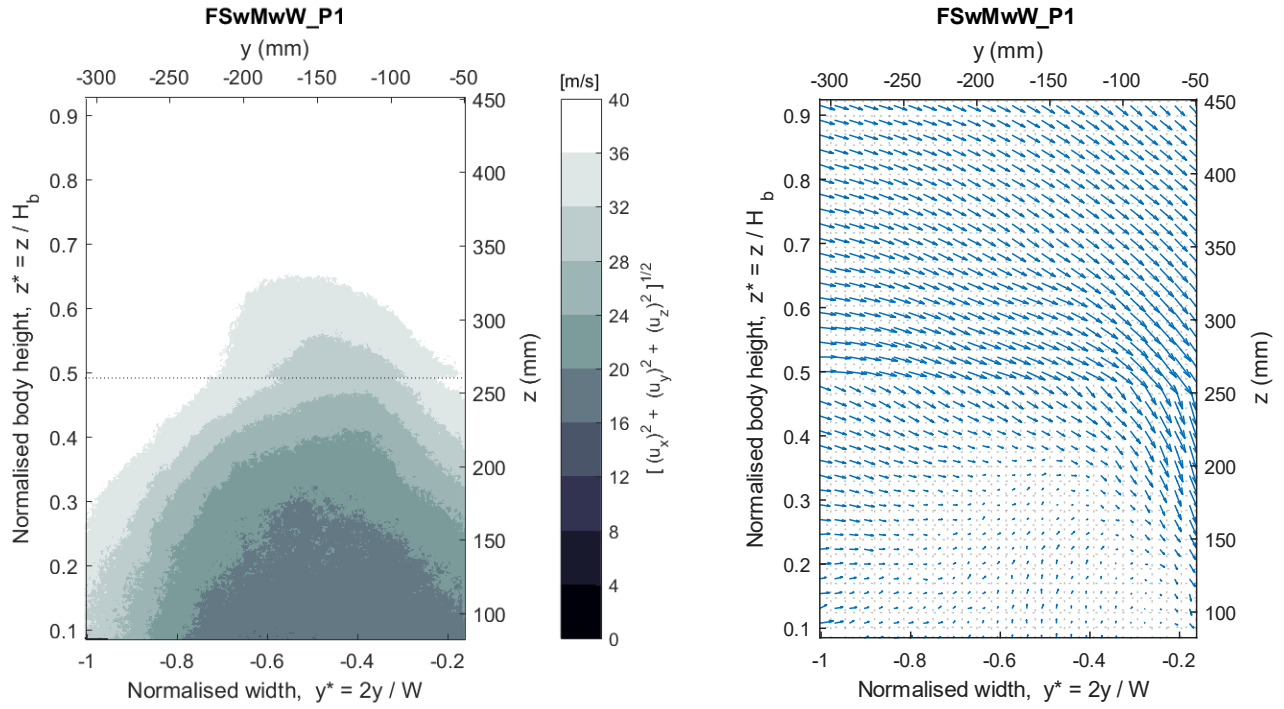


(a) with external mirrors (*FSwMwW*).

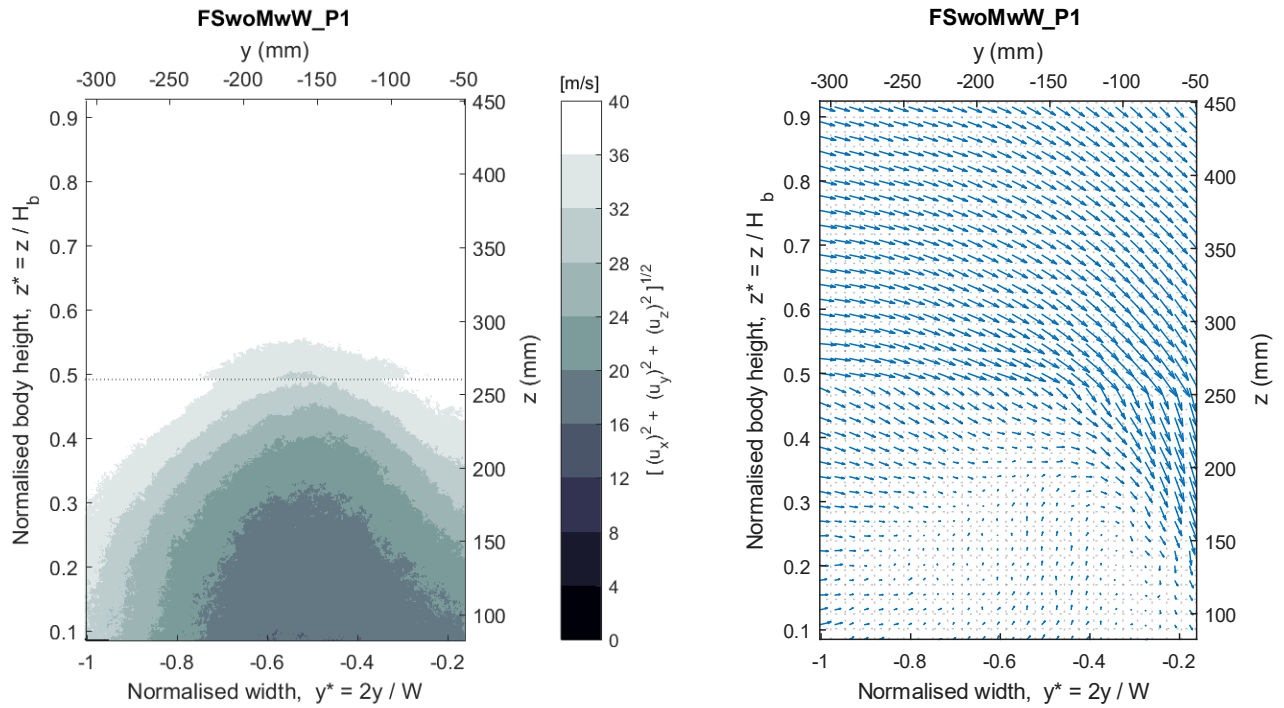


(a) without external mirrors (*FSwoMwW*).

Figure 88. DrivAer Fastback configurations, plane *P3*.

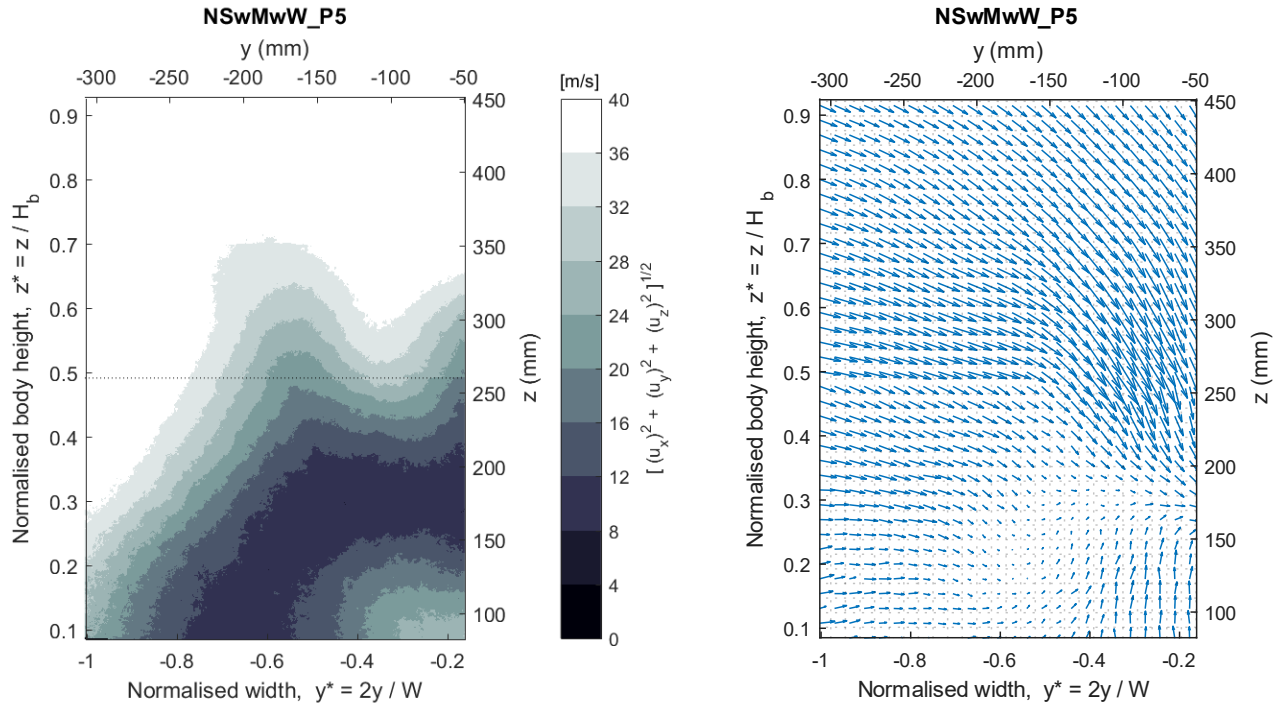


(a) with external mirrors (*FSwMwW*).

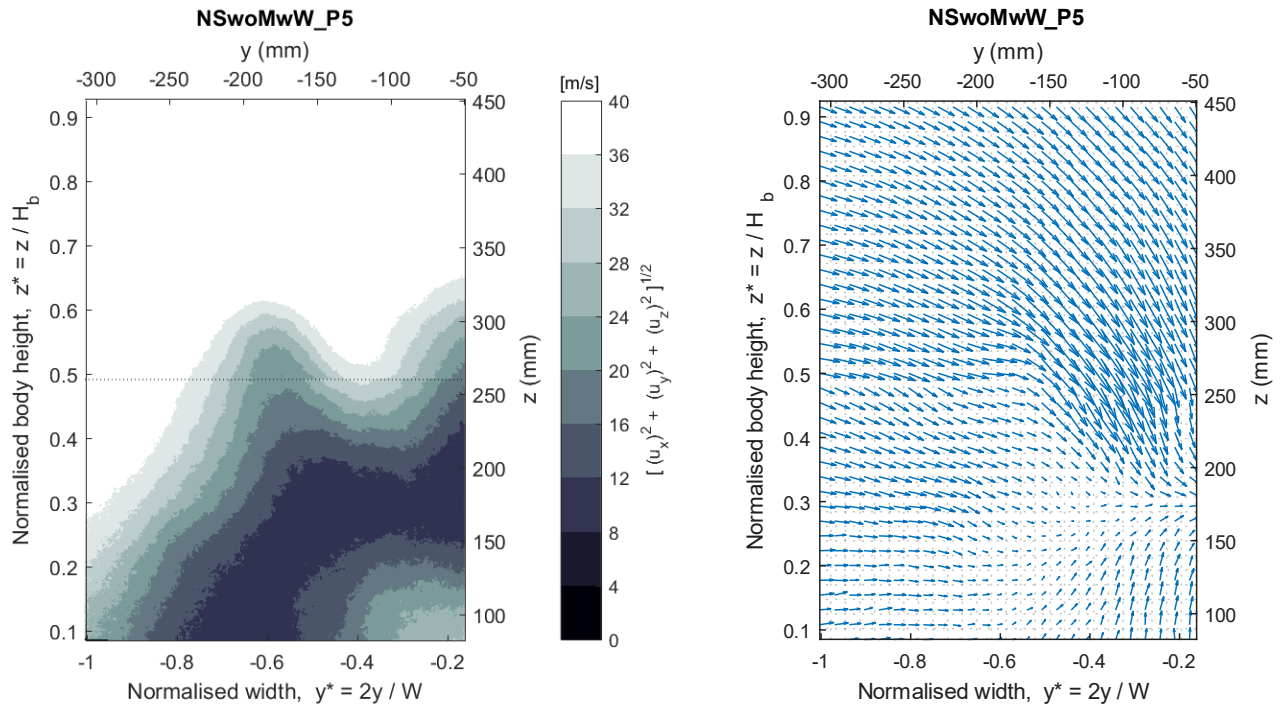


(a) without external mirrors (*FSwoMwW*).

Figure 89. DrivAer Fastback configurations, plane *P1*.

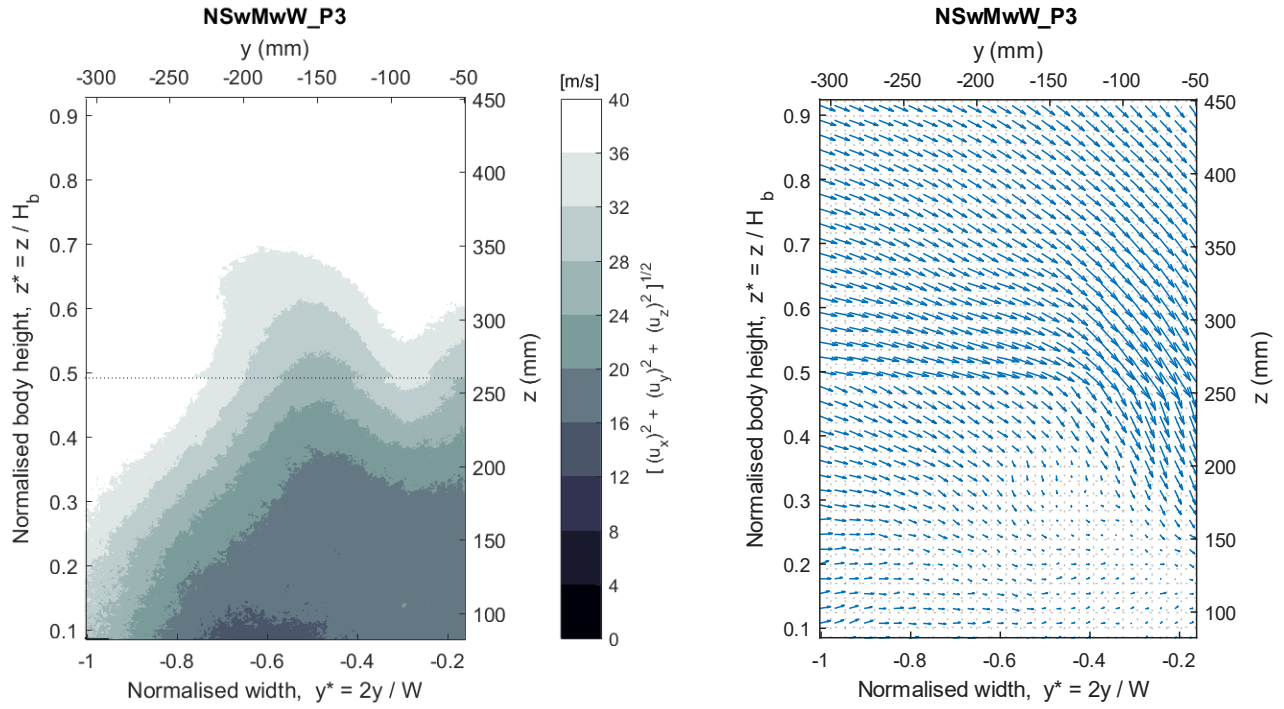


(a) with external mirrors (*NSwMwW*).

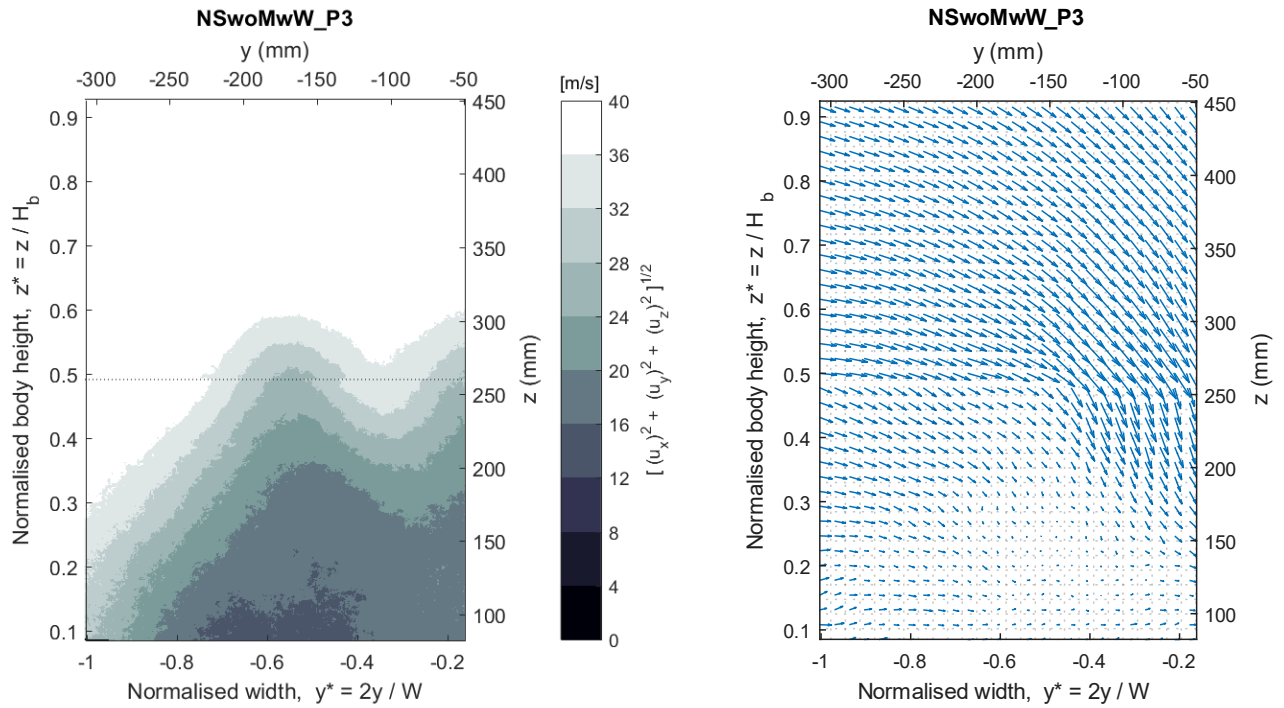


(a) without external mirrors (*NSwoMwW*).

Figure 90. DrivAer Notchback configurations, plane *P5*.

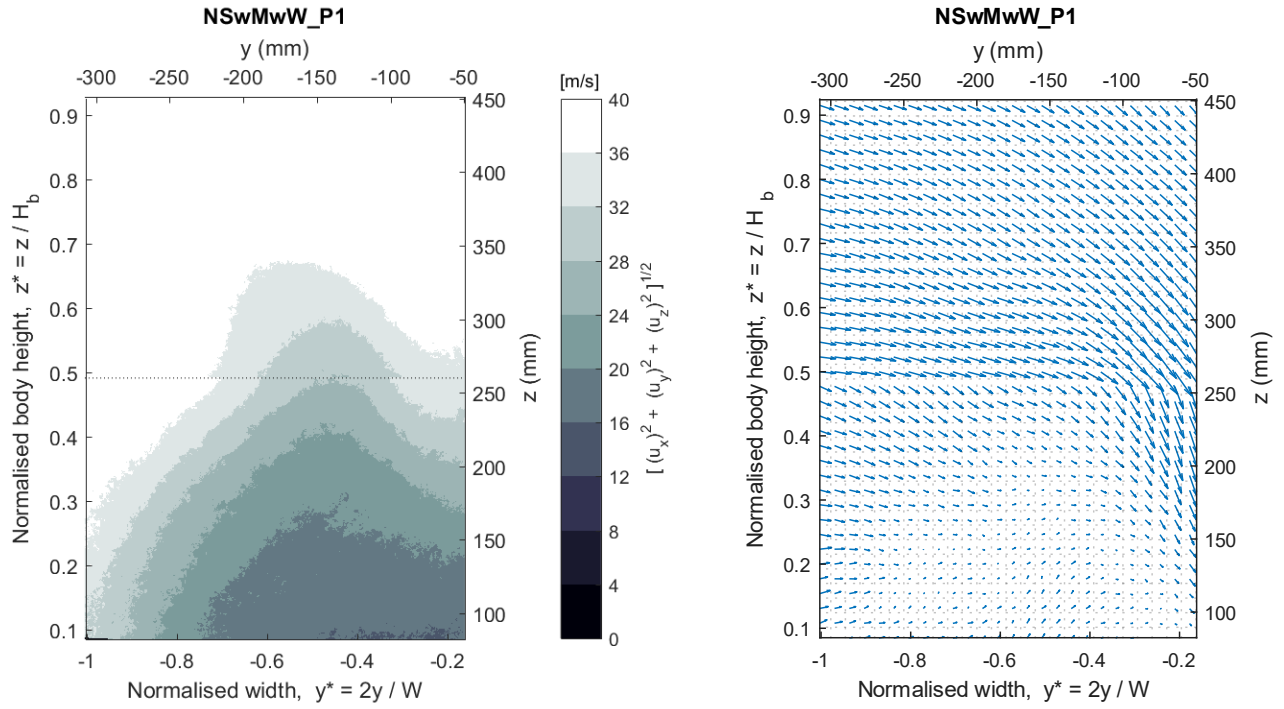


(a) with external mirrors (*NSwMwW*).

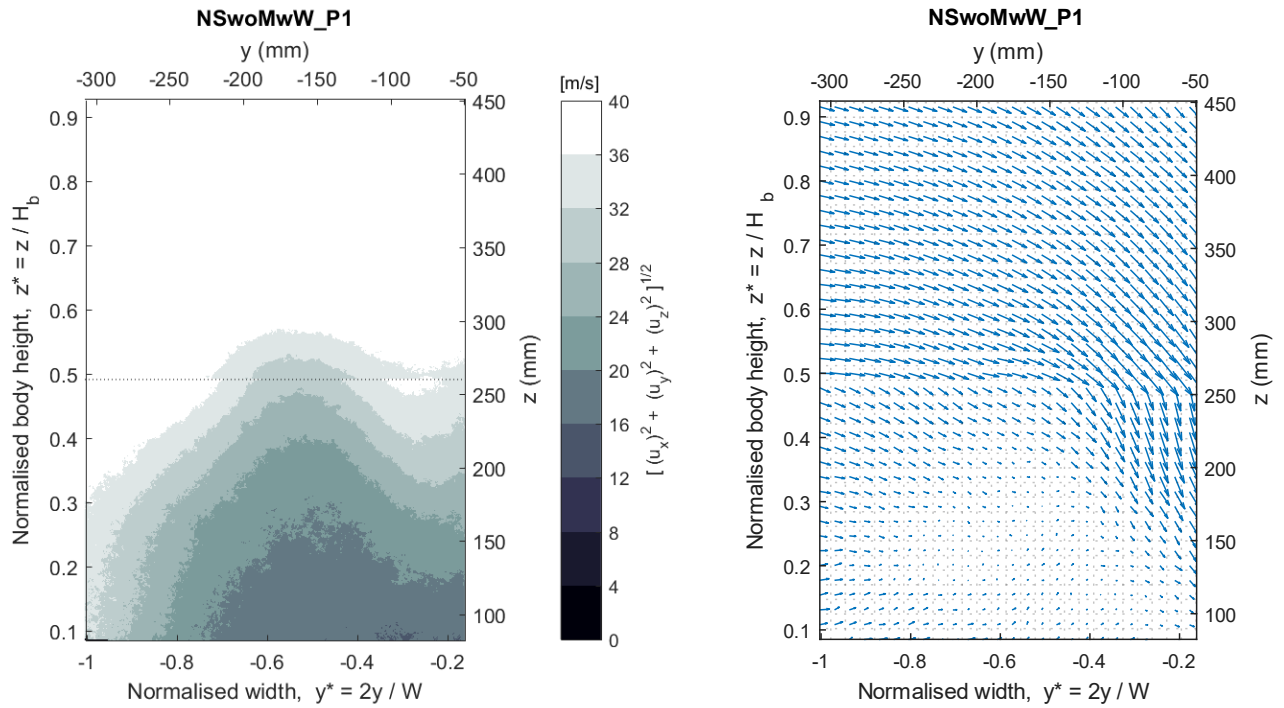


(a) without external mirrors (*NSwoMwW*).

Figure 91. DrivAer Notchback configurations, plane *P3*.

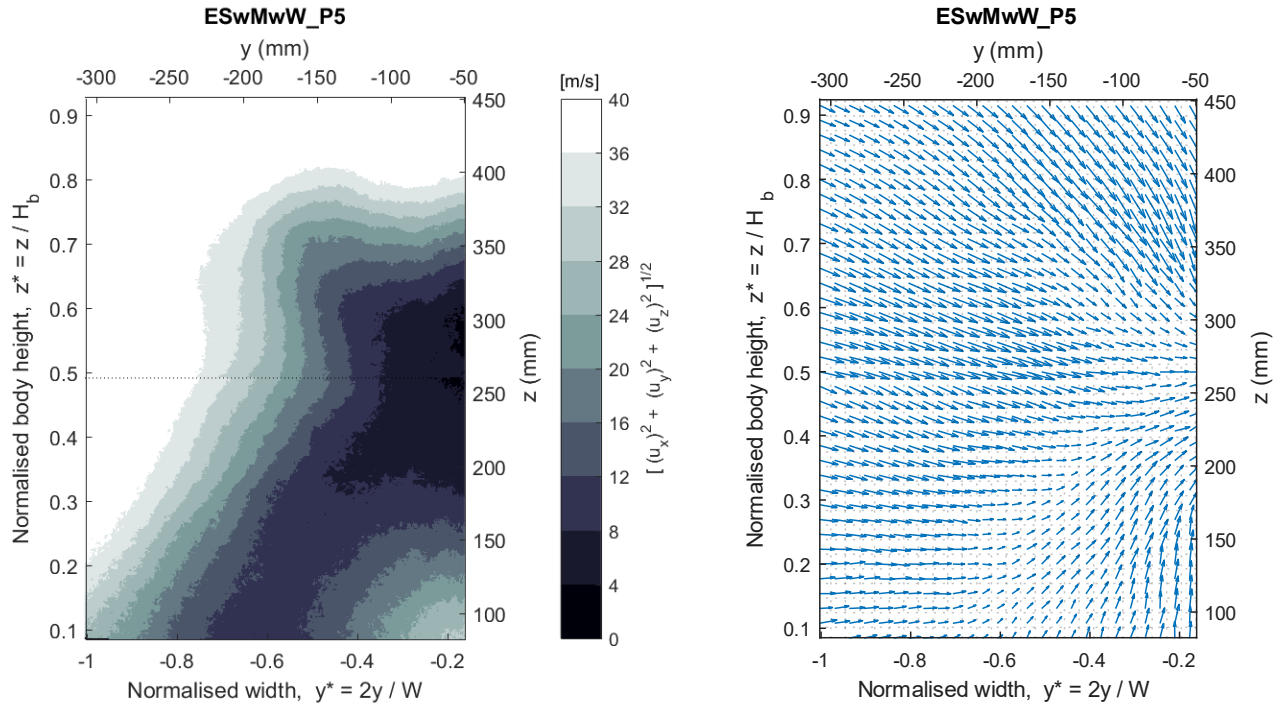


(a) with external mirrors (*NSwMwW*).

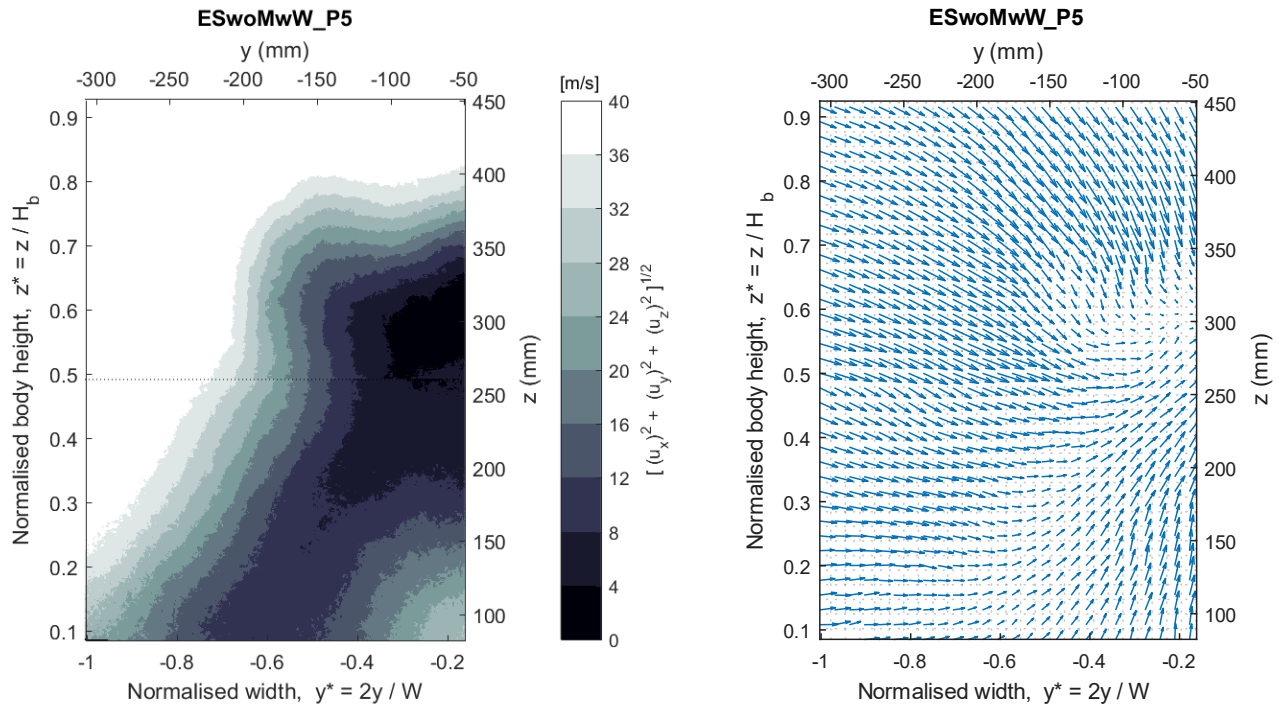


(a) without external mirrors (*NSwoMwW*).

Figure 92. DrivAer Notchback configurations, plane *P1*.

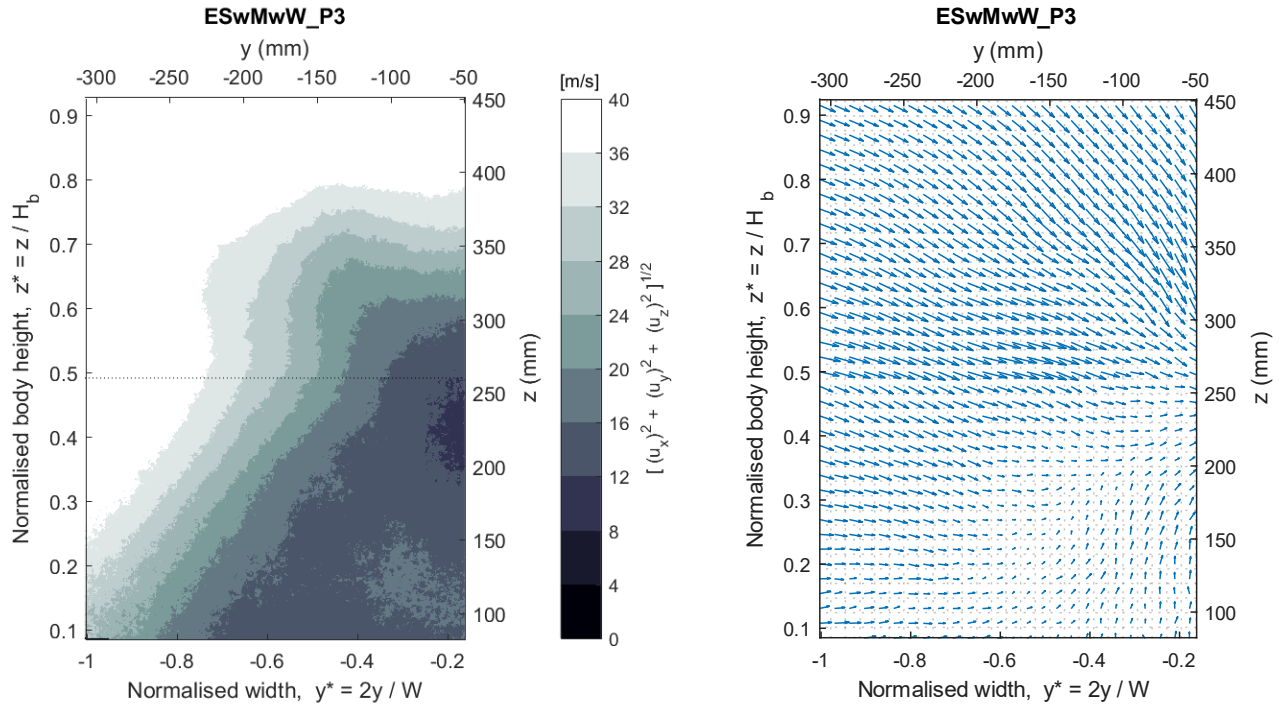


(a) with external mirrors (*ESWMwW*).

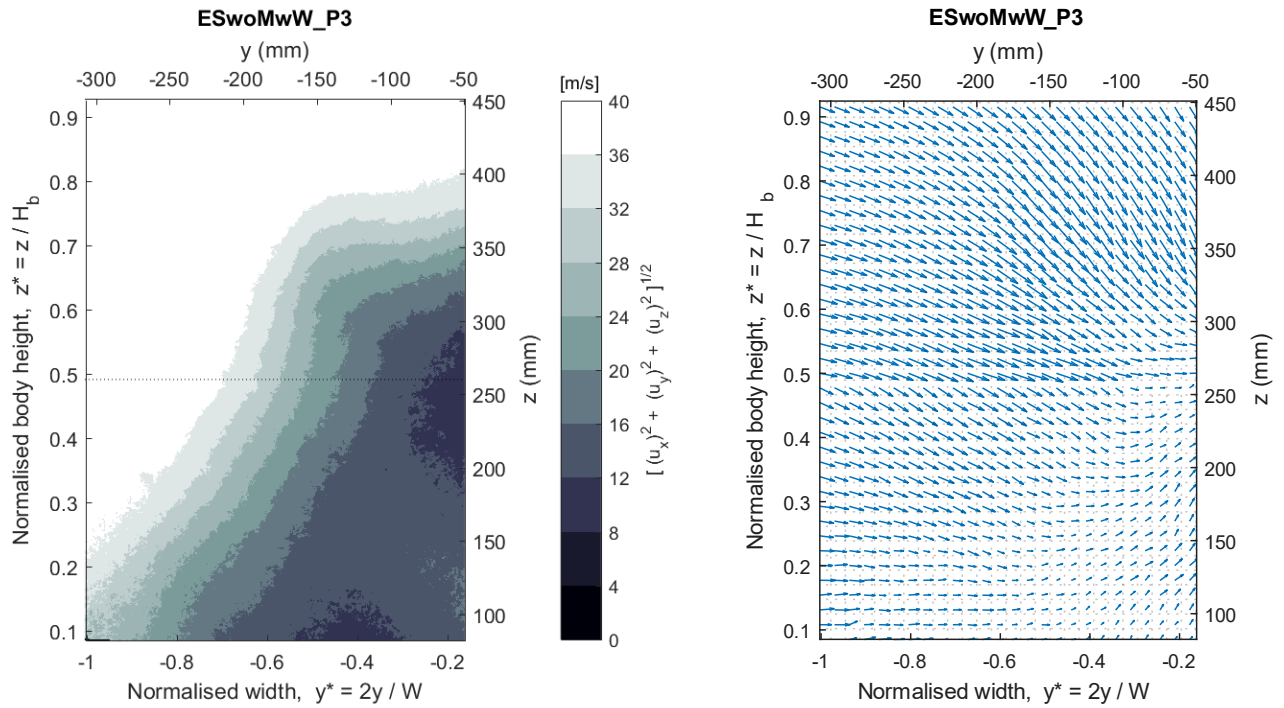


(a) without external mirrors (*ESwoMwW*).

Figure 93. DrivAer Estateback configurations, plane *P5*.

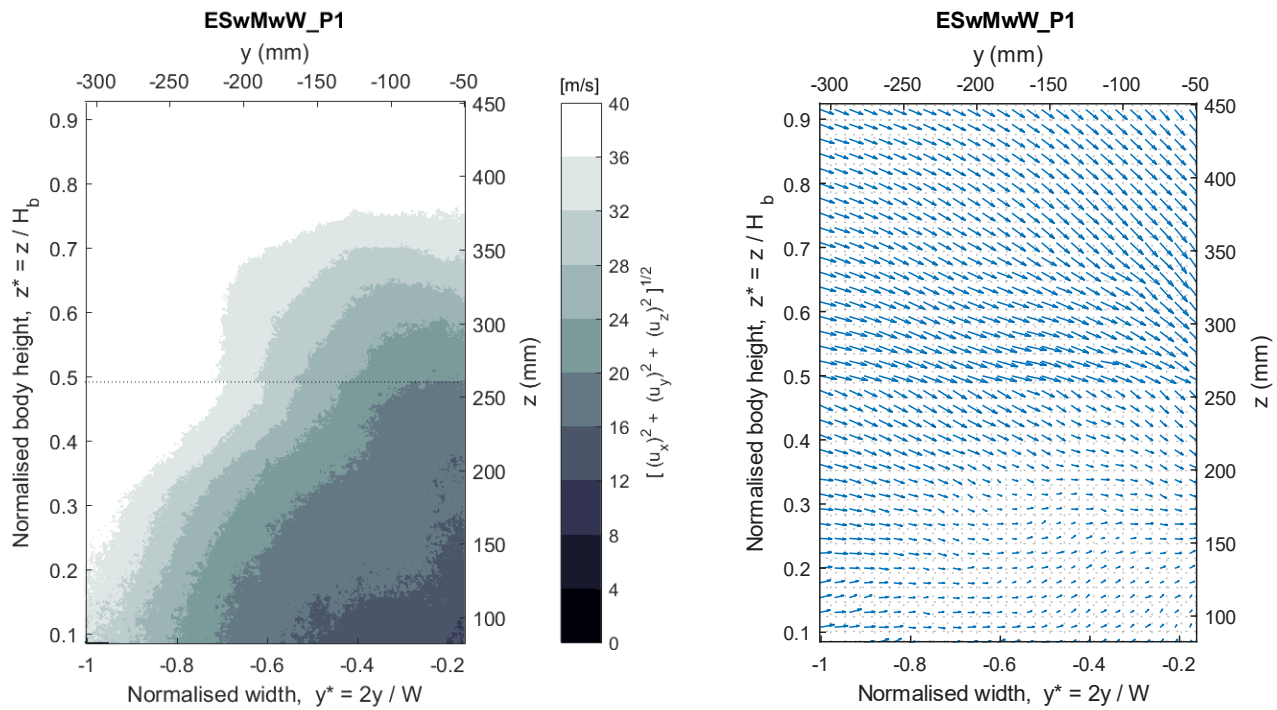


(a) with external mirrors (*ESWMwW*).

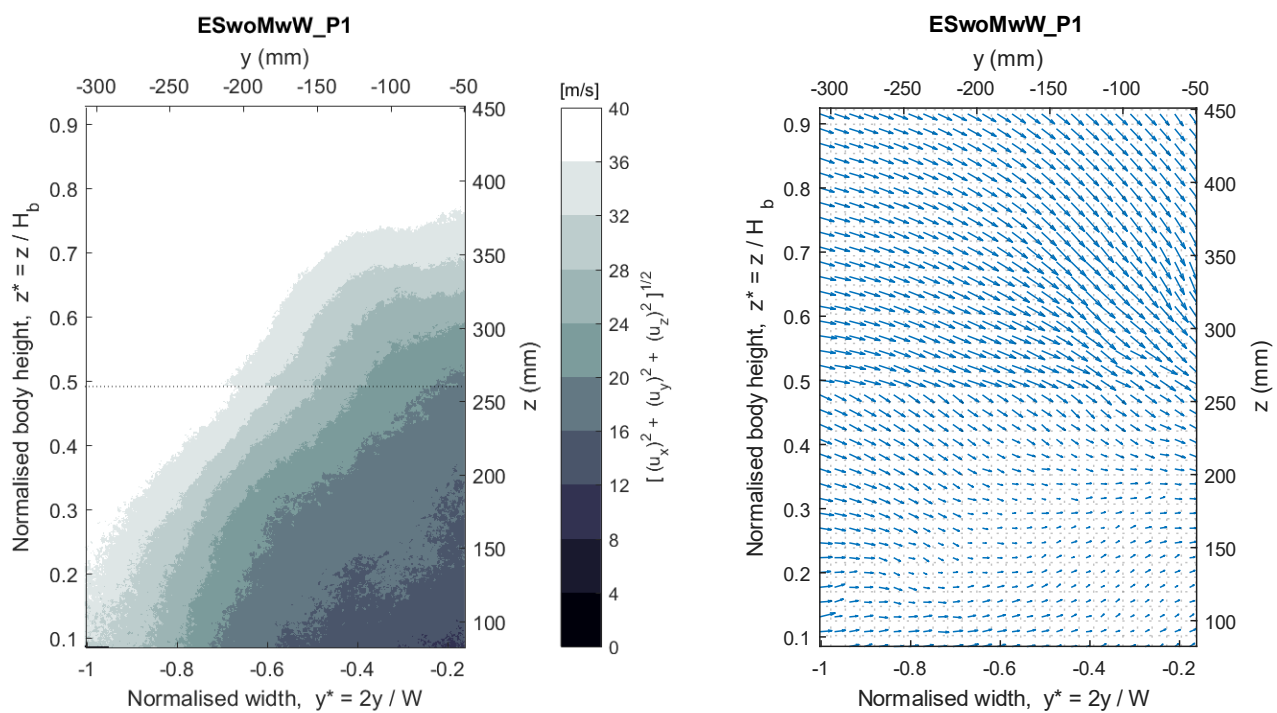


(a) without external mirrors (*ESwoMwW*).

Figure 94. DrivAer Estateback configurations, plane *P3*.

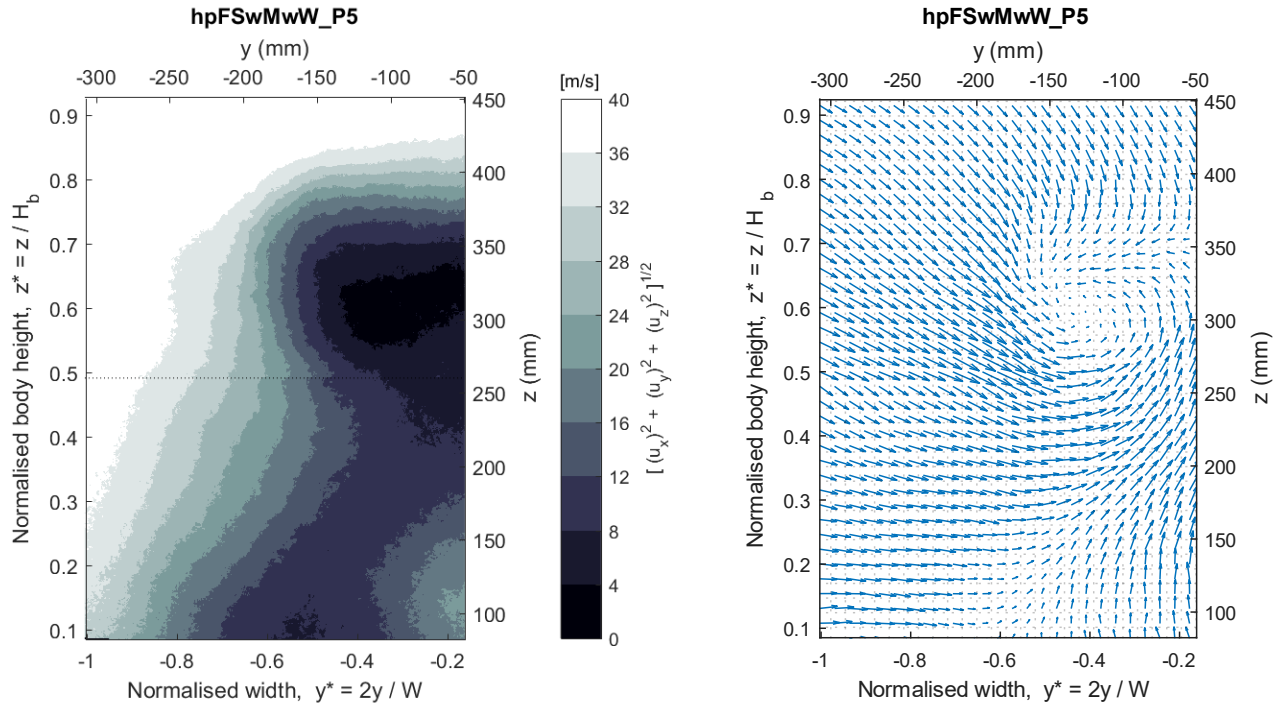


(a) with external mirrors (*ESWMwW*).

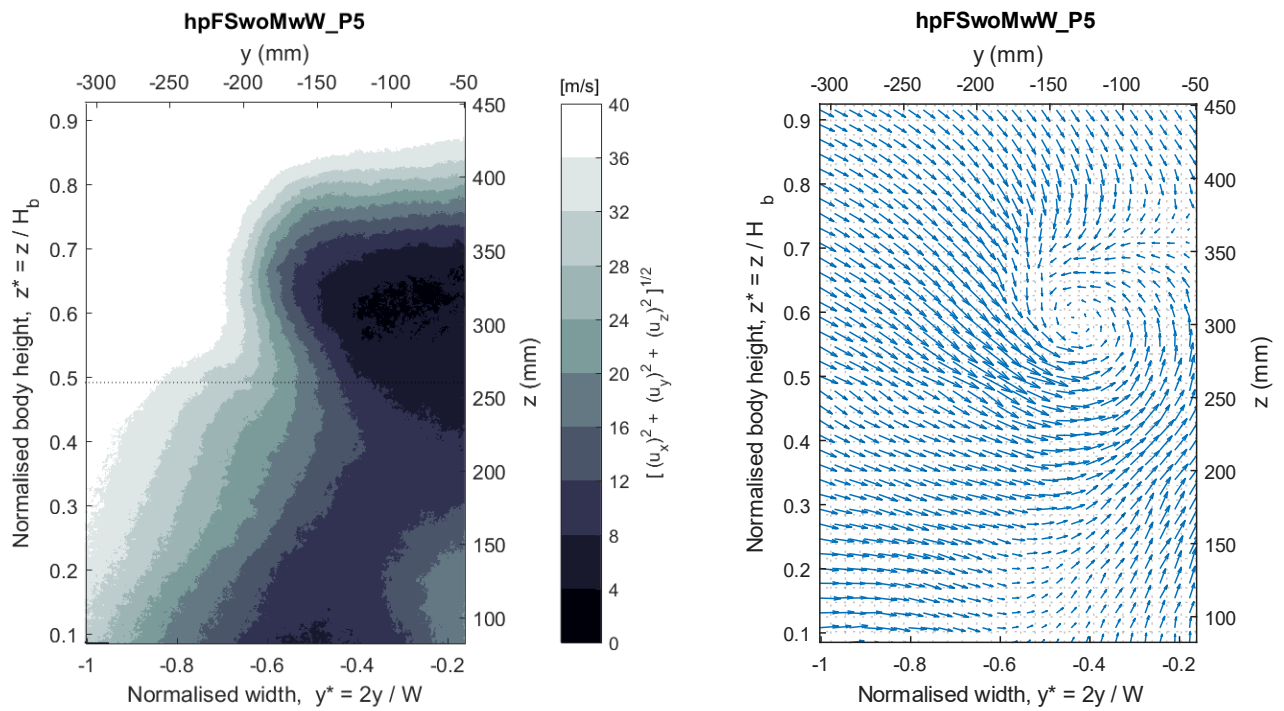


(a) without external mirrors (*ESwoMwW*).

Figure 95. DrivAer Estateback configurations, plane *P1*.

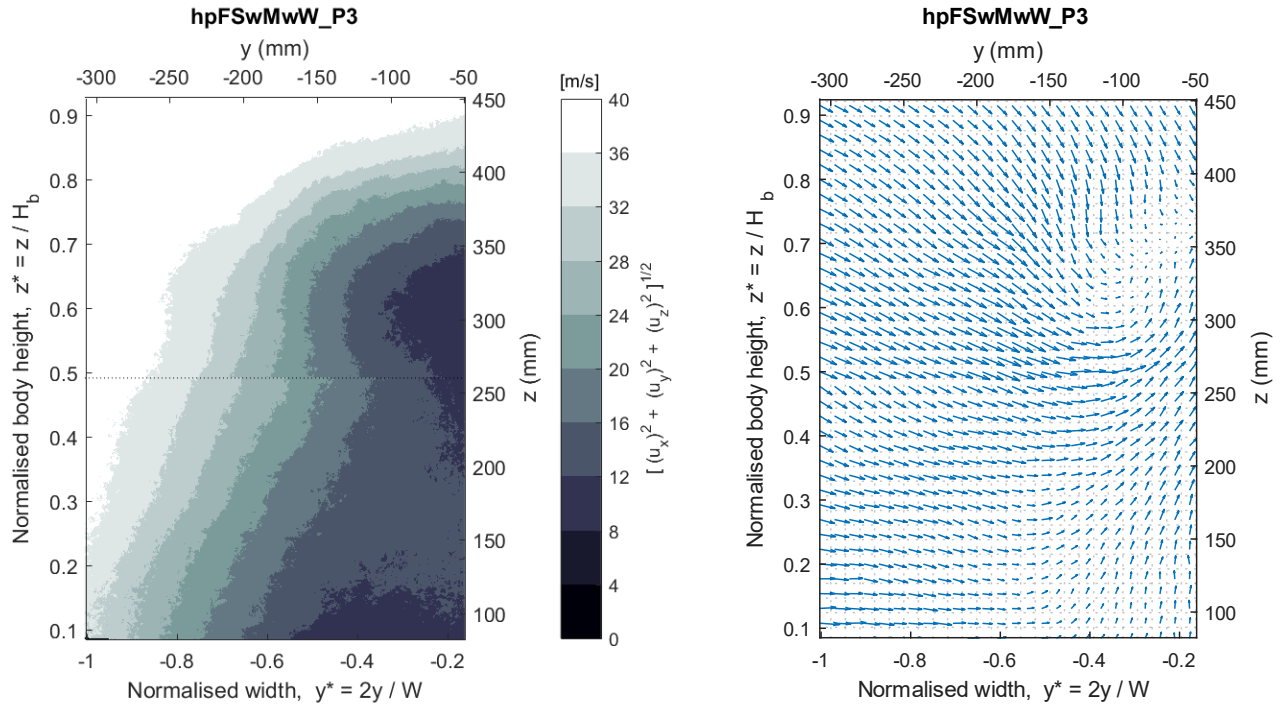


(a) with external mirrors (*hpFSwMwW*).

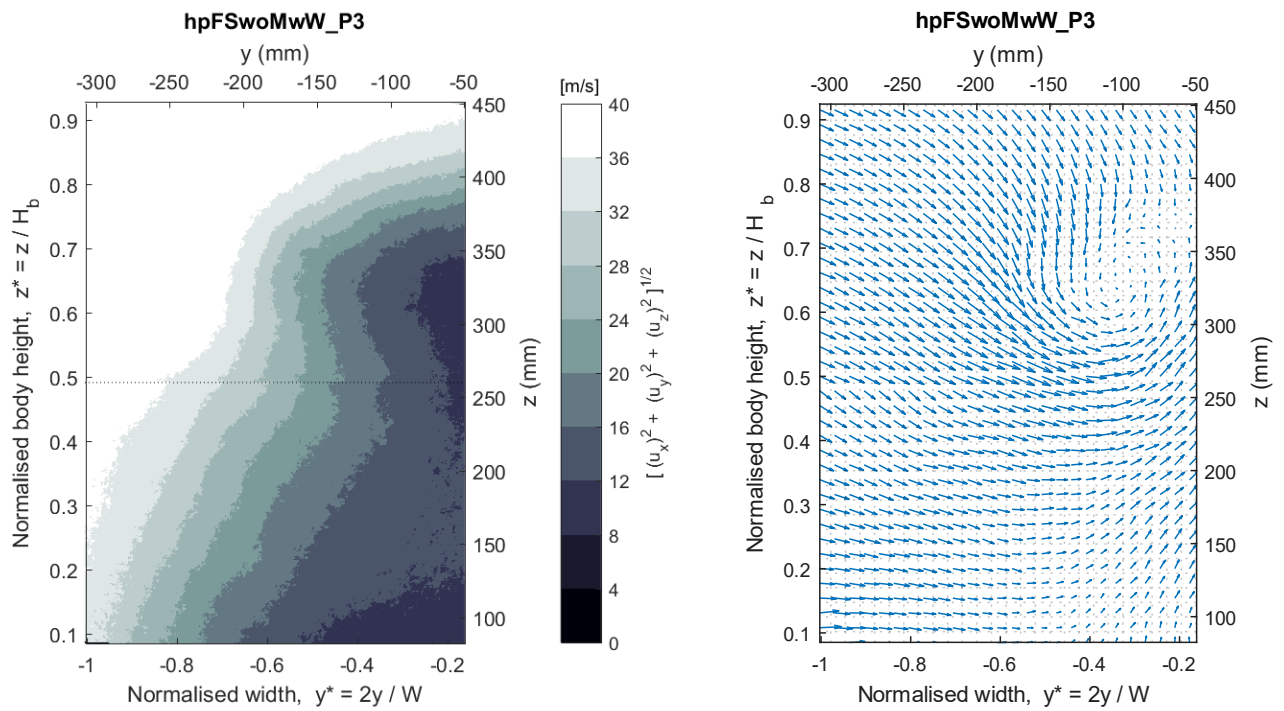


(a) without external mirrors (*hpFSwoMwW*).

Figure 96. DrivAer high-performance Fastback configurations, plane *P5*.

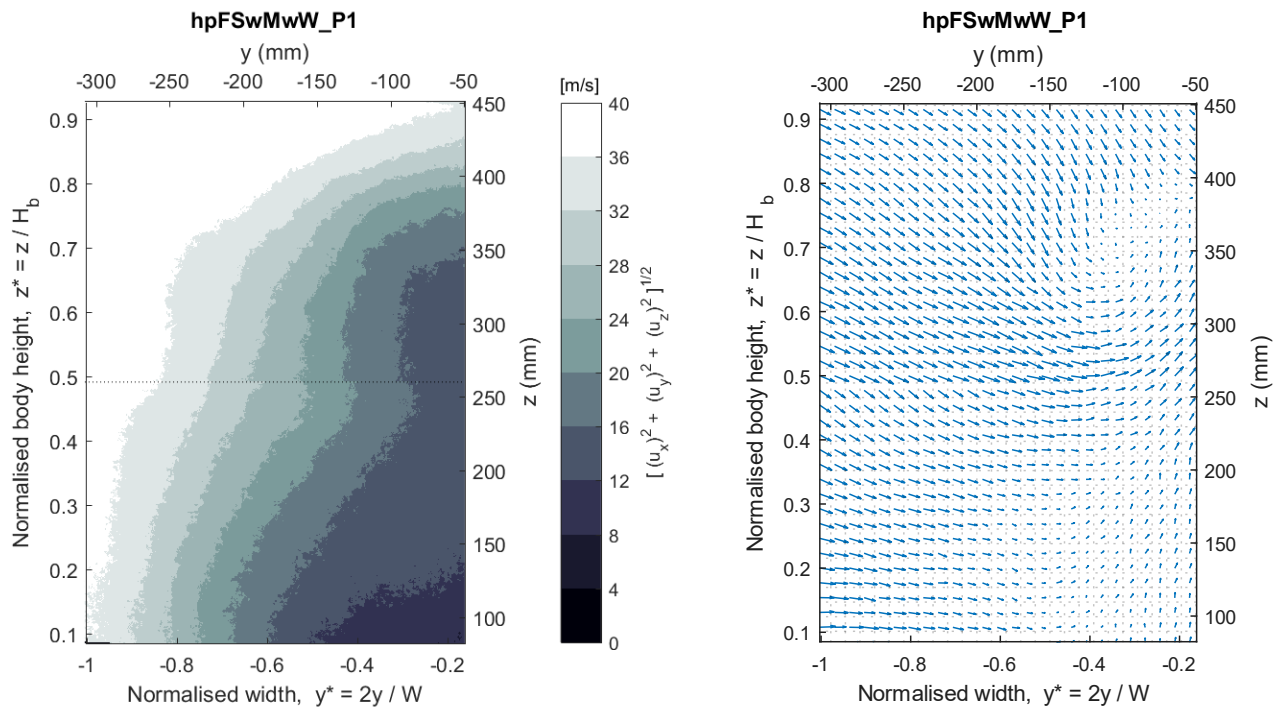


(a) with external mirrors (*hpFSwMwW*).

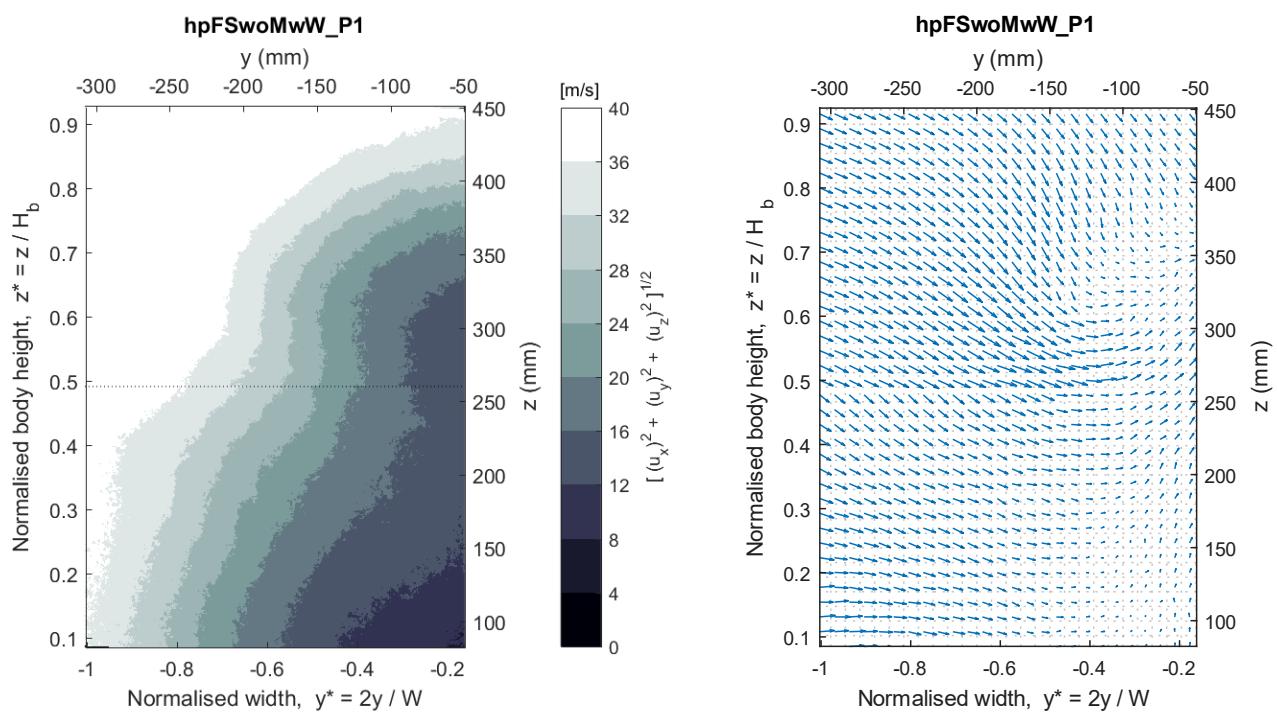


(a) without external mirrors (*hpFSwoMwW*).

Figure 97. DrivAer high-performance Fastback configurations, plane *P3*.



(a) with external mirrors (*hpFSwMwW*).



(a) without external mirrors (*hpFSwoMwW*).

Figure 98. DrivAer high-performance Fastback configurations, plane *P1*.

5.5 ADDITIONAL WAKE-SENSITIVITY STUDIES

Additional wind tunnel runs were included for the analysis of automotive wake sensitivity to wind tunnel conditions. The goal is estimating the sensitivity of SPIV wake results as a function of:

- i. Reynolds-number level
- ii. Ground boundary layer condition

The first is evaluated in three levels by altering the test section freestream, while the second can be investigated by deploying or suppressing the boundary layer control system, which reduces the layer thickness on the floor (see [section 4.3.1 – ‘On the sensitivity of Boundary Layer Control system \(BLC\)’](#)).

The Fastback configuration proved to cast the smoothest wake investigated (*i.e.* wake *Type I*), while the high-performance vehicle model (*i.e.* wake *Type III*) generates the largest wake size combined with higher momentum loss. Then, these two extreme model configurations were selected in order to contrast different automotive flow conditions, then expanding the applicability of potential findings.

Table 27. Cases for wake sensitivity analysis as a function of Reynolds number and ground configuration.

	Model configuration	Plane	Freestream	BLC condition
Case I	Fastback (<i>FSwoMwW</i>)	$x/L = 0.176$ (<i>P5</i>)	20 <i>m/s</i>	both BL ON
			30 <i>m/s</i>	both BL ON
			40 <i>m/s</i>	both BL ON
			40 <i>m/s</i>	both BL OFF
Case II	High- Performance Fastback (<i>hpFSwoMwW</i>)	$x/L = 0.362$ (<i>PI</i>)	20 <i>m/s</i>	both BL ON
			30 <i>m/s</i>	both BL ON
			40 <i>m/s</i>	both BL ON
			40 <i>m/s</i>	both BL OFF

With the purpose of improving the spatial range of this analysis, one extreme plane position was designed for each configuration. *FSwoMwW* wake is analysed on the nearest plane, *P5*, while the furthest plane, *P1*, is used when evaluating *hpFSwoMwW*. [Table 27](#) summaries the additional eight runs used exclusively for wake sensitivity analysis.

The wake *Type I* at nearest plane represents a smooth wake evolution but assessed at a cross-section with high turbulence intensity. Results show it sustains the overall wake characteristics while increasing the Reynolds number, including wake trace shape and downwash dominance from the upper surface; however, significant changes are found.

Wake trace size – defined as $0.9U_\infty$ for velocity-based analysis – reduces in both height and width dimensions as the freestream increases. To illustrate this point, the maximum height of the wake trace was $z^* = 0.60$ at $U_\infty = 20m/s$, then reduced to $z^* = 0.57$ at $U_\infty = 40m/s$. When measuring the width along $z^* = 0.50$ (*i.e.* a horizontal reference line), the wake width reduces from $y^* = |0.88|$ to $|0.79|$ when increasing $U_\infty = 20m/s$ in 50%, then reduced to $y^* = |0.78|$ at $U_\infty = 40m/s$. In terms of wake trace area, it contracts in 4.5% for $U_\infty = 20 \rightarrow 30m/s$, and another 4.4% drop for $U_\infty = 30 \rightarrow 40m/s$.

Even though the total acquisition provided by the SPIV measurements did not capture the entire wake trace, the area ratio of those results can expose the influence of both Reynolds number and BL control on the wake momentum distribution.

When computing the area of wake regions using different velocity threshold, they can be normalised with the wake trace measured into the acquisition domain. These area ratios can express the changes into the wake quantitatively while removing the bias of variation of wake size. [Table 28](#) reports the comparison among four cases by means of area ratios as a function of wake regions below flow

magnitude of 0.2 , 0.3 , and $0.5U_\infty$. Note that flow magnitude under $0.2U_\infty$ also means a flow with at least 80% of momentum loss when comparing to freestream.

Table 28. Wake sensitivity for wake *Type I*, nearest plane: comparison of wake area ratio as a function of normalised velocity threshold.

Case	$(< 0.2 / 0.9) U_\infty$	$(< 0.3 / 0.9) U_\infty$	$(< 0.5 / 0.9) U_\infty$
Freestream at 20 m/s	22%	42%	65%
Freestream at 30 m/s	13%	37%	62%
Freestream at 40 m/s	6%	34%	60%
Freestream at 40 m/s , No BL control	-	23%	54%

For flow regions under $0.5U_\infty$, the case with lowest Reynold number have the largest momentum deficit, a total of 65% of the wake trace. Increasing the freestream to 30 m/s , the region under $0.5U_\infty$ is reduced by 3%; then reaching 60% at the highest Reynolds number case. Therefore, there is a tendency of larger velocity deficit as the Reynolds number reduces.

The wake trace for momentum loss higher than 70% (*i.e.* flow regions under $0.3U_\infty$), a similar behaviour is found. At 20 m/s , the area ratio is 42%, reducing 5% when increasing the freestream to 30 m/s , then another 3% drop if increasing to 40 m/s .

For wake region with momentum loss higher than 80% (*i.e.* flow regions under $0.2U_\infty$), it confirms that the vehicle model at lower Reynolds number generates not only the largest wake as a function of velocity-averaged magnitude, but also the one with highest momentum deficit. At 20 m/s , around 1/5 (22%) of the wake trace is under $0.2U_\infty$, while it represents only 1/8 (13%) at 30 m/s , and 1/14 (7%)

at $40m/s$. Therefore, it is found that averaged momentum loss into the wake is mitigated as the Reynolds number increases, mainly into the wake core.

On the influence of boundary layer control system ('BLC', which consists of two subsystems: 'BL1' and 'BL2') on wake measurements, it was found that the wake trace is almost the same size and topology. However, the suppression of flow control induces a slight reduction of the wake height, while the diffuser flow has, surprisingly, higher velocity magnitude with larger upwash.

When turning on the boundary layer control (BLC ON), it widens areas of velocity deficit. For flow regions under $0.5U_\infty$, it represents 60% of the wake trace for BLC ON, in contrast to 54% if BLC is turned off. The wake trace for momentum loss higher than 70% (*i.e.* flow regions under $0.3U_\infty$) amplifies the gap; 34% of the wake trace for BLC ON, with a reduction of 11% when not deploying the system.

Higher averaged velocity over the wake section under no BLC deployment can be seen in a glance when observing that not deploying BLC resulted in a wake with no regions of velocity average lower than $0.2U_\infty$, while using the system generates respective regions summing circa 6% of the wake trace.

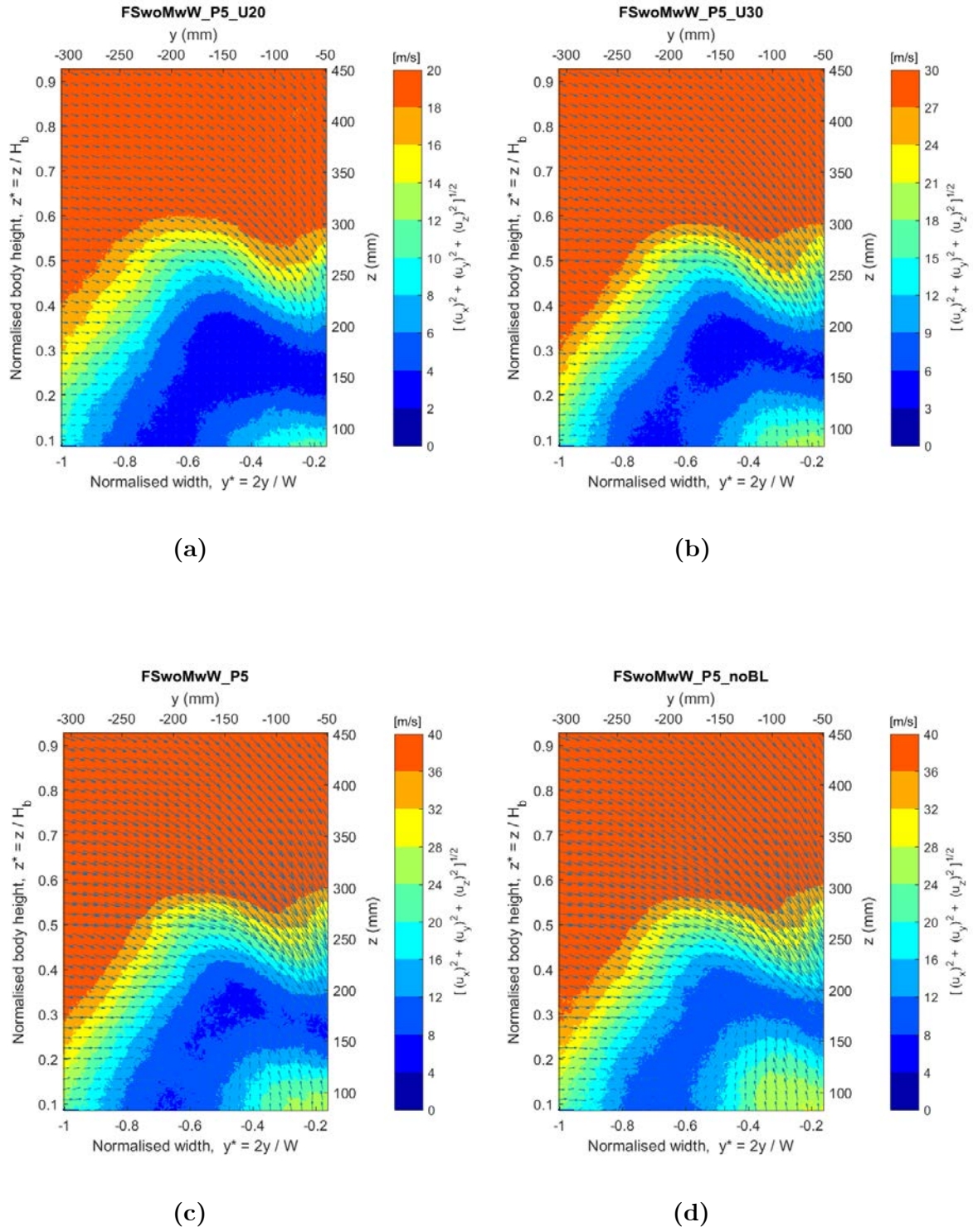


Figure 99. Wake sensitivity for Reynold number and ground condition: *FSwoMwW*, plane *P5*.

(a) 20 m/s, (b) 30 m/s, and (c) 40 m/s; (d) 40 m/s with no boudary layer control.

Table 29. Wake sensitivity for wake *Type III*, furthest plane: comparison of wake area ratio as a function of normalised velocity threshold.

Case	$(< 0.2 / 0.9) U_{\infty}$	$(< 0.3 / 0.9) U_{\infty}$	$(< 0.5 / 0.9) U_{\infty}$
Freestream at 20 <i>m/s</i>	<1%	11%	47%
Freestream at 30 <i>m/s</i>	<1%	10%	45%
Freestream at 40 <i>m/s</i>	<1%	5%	41%
Freestream at 40 <i>m/s</i> , No BL control	<1%	7%	41%

The second case for sensitivity study, wake *Type III* at the furthest plane (*hpFSwoMwW*, *P1*), represents a wake of large proportions among automotive categories, but investigated at a crossflow plane where turbulence level may have significantly reduced in comparison to the intensity at its genesis.

Results corroborate the earlier finding on the effect of Reynolds number on the wake size: the wake trace reduces as Reynolds number increases. Wake trace area reduces in 4.1% for $U_{\infty} = 20 \rightarrow 30 \text{ m/s}$, but growths 0.8% drop for $U_{\infty} = 30 \rightarrow 40 \text{ m/s}$. Wake width contraction can be measured along $z^* = 0.50$ (*i.e.* a horizontal reference line), where it corresponds to $y^* = |0.89|$ for $U_{\infty} = 20 \text{ m/s}$, reduces to $y^* = |0.80|$ for $U_{\infty} = 30 \text{ m/s}$, then reduced to $y^* = |0.78|$ at $U_{\infty} = 40 \text{ m/s}$. Again, there is a larger delta found for $U_{\infty} = 20 \rightarrow 30 \text{ m/s}$ ($\Delta y^* = -0.09$) than $U_{\infty} = 30 \rightarrow 40 \text{ m/s}$ ($\Delta y^* = -0.02$).

However, this evidence is valid only for width since a small wake height increase is detected. Wake height corresponds to $z^* = 0.89$ for $U_{\infty} = 20 \text{ m/s}$, increasing $\Delta z^* = 0.04$ at $U_{\infty} = 30 \text{ m/s}$, then $\Delta z^* = 0.01$ when reaching $U_{\infty} = 40 \text{ m/s}$.

With reference to velocity distribution, data presented in [Table 29](#) leads to conclude that averaged velocity into the wake increases as Reynolds number does

so. Velocity loss larger than $0.5U_\infty$ responds to 47% of wake trace measured at $U_\infty = 20m/s$, which shrinks by 2% to $U_\infty = 30m/s$, then another 4% when at highest freestream.

This trend persists when analysing higher momentum deficit threshold like 70%. The sum of flow regions under $0.3U_\infty$ reduces linearly from 11% to 5% between $U_\infty = 20 \rightarrow 40m/s$. Due to the distance of the plane analysed to the model, the wake has an overall velocity recovery, a reason for averaged velocity below $0.2U_\infty$ being residual into the wake.

There is a contradiction on the effect of the ground BL control on the wake when comparing to the findings from the previous case. The wake from the second case proved to be less sensitive and with higher momentum loss if suppressing ground flow treatment. Overall wake topology only has a residual difference of 1% in area if activating the system. The momentum loss distribution into the wake seems virtually independent to ground flow condition, since the flow area under $0.5U_\infty$ is constant at 41% for either BL status, but with minor higher loss when deploying the control system: increment of 2% of the flow region below $0.3U_\infty$.

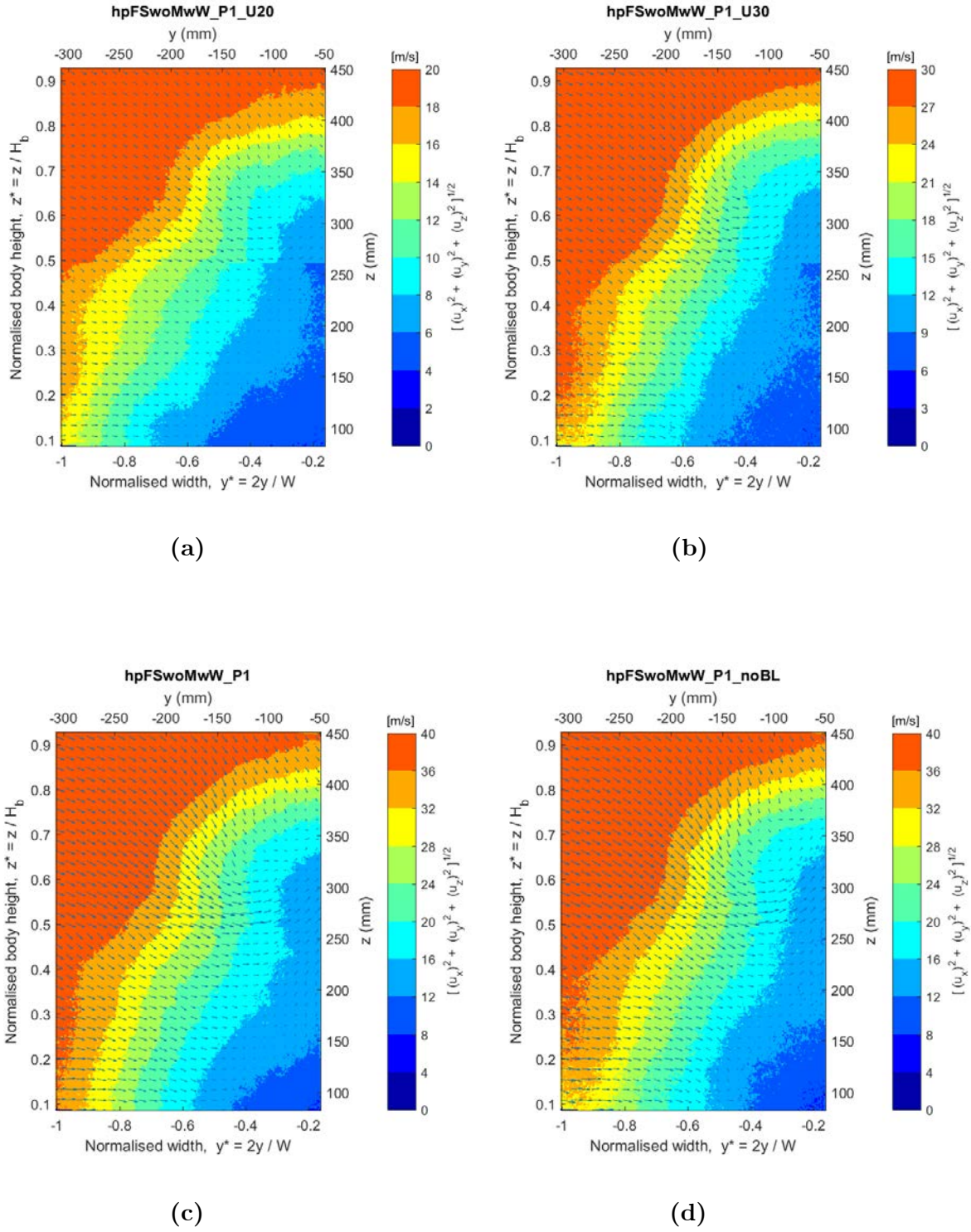


Figure 100. Wake sensitivity for Reynold number and ground condition: *hpFSwoMwW*, plane *P1*.

(a) 20 m/s, (b) 30 m/s, and (c) 40 m/s; (d) 40 m/s with no boudary layer control.

5.6 STATISTICAL ANALYSIS

In similarity to any other experimental campaign, results are subject to inherent systematic and random errors acting simultaneously from accumulative causes (*e.g.* methodology, operation, instruments, just to cite a few). Even though effort were made during the execution of wind tunnel tests to ensure stability of experimental conditions and measurement, residual discrepancies between cases accumulated with unknown factors building up a global range of uncertainty over the results.

Therefore, this subtopic aims to infer the confidence interval over SPIV results presented in this chapter. It assists in improving the robustness of findings based on those results. The mathematical approach described in [Chapter 4, section 4.5 ‘Statistical Analysis’](#) is reapplied on this analysis.

Two groups of repeatability tests infer the confidence interval in which the SPIV data may be biased. Identical case configurations (*e.g.* *FSwoMwW*, *P5*; *hpFSwoMw*, *P1*) analysed at [section 5.5](#) are adopted again for multiple sampling in order to directly match and enrich the analysis around those cases.

The first case study – wake *Type I* at nearest cross-plane ([Figure 101, a](#)) – reports that the confidence interval (*i.e.* $\Delta CI = 2|e| = 2 \left| t_{(\alpha/2, df)} \sqrt{s^2/n} \right|$) has a good level of precision. The upper acquisition area (*A2*) has a averaged confidence interval of $\overline{\Delta CI} < 0.01U_\infty$ (*e.g.* $\overline{\Delta U/U_\infty} < \pm 0.005$), while the lower acquisition area (*A1*) has $\overline{\Delta CI} = 0.032U_\infty$ (*e.g.* $\overline{\Delta U/U_\infty} = \pm 0.016$).

Two clusters of higher ΔCI (*i.e.* > 0.04) are found at area *A1*. The first is located between the upper protuberance of wake trace and the central downwash from upper rear-end, while the second is a dispersed cluster at the diffuser projection.

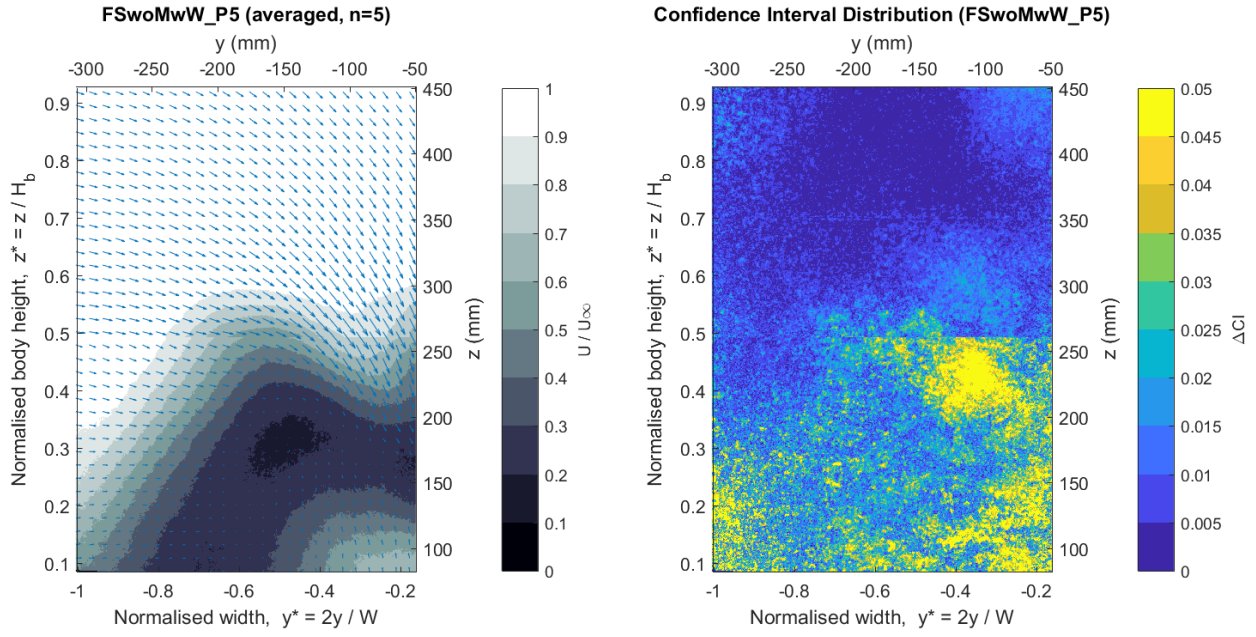
Wake *Type III* analysed at farthest cross-plane (Figure 101, *b*) has an averaged amplification compared to the previous case but restricted within the wake trace. Results highlight the data quality acquired at the lower area, *A1*, where nearly half of the respective domain has $\Delta CI > 0.04U_\infty$ – in contrast to approx. 20% found on the previous wake case. The diffuse area also generates the cluster of high ΔCI , however, the rest of the area *A1* has averaged increment in data uncertainty.

The upper area has better performance since the portion of the wake trace into area *A2* has a confidence interval of $\overline{\Delta CI} = 0.25U_\infty$, while the rest of the acquisition area shows the outer flow sustaining a stable flow condition with $\overline{\Delta CI} < 0.05U_\infty$.

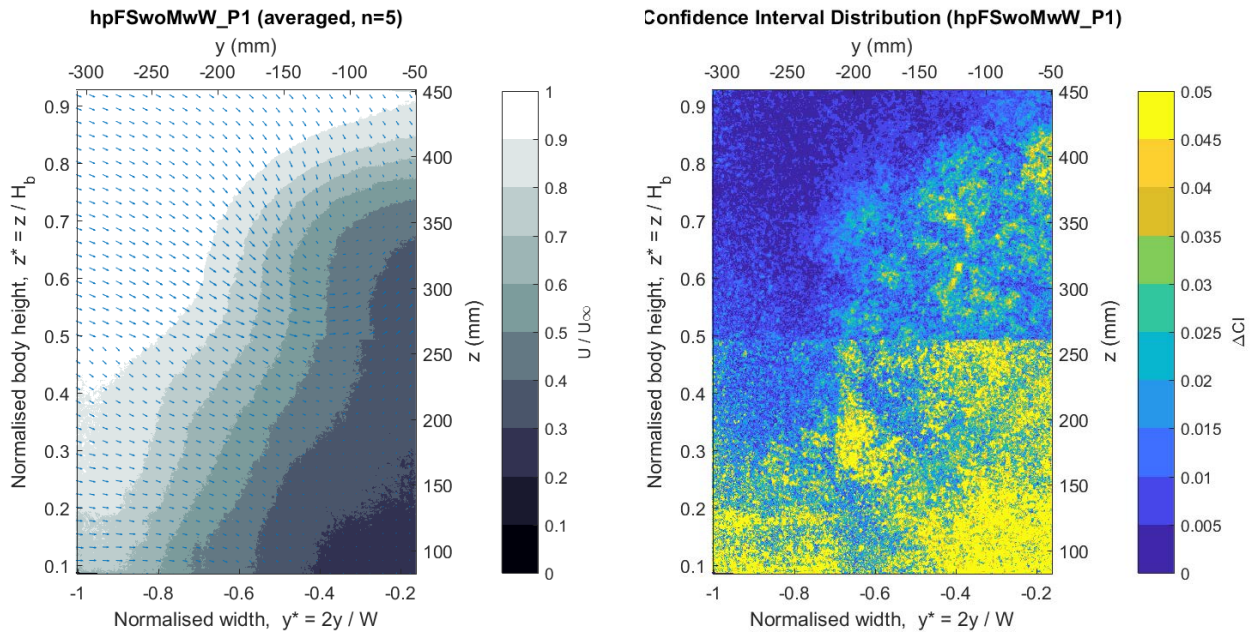
For the perspective of experimental acquisition, it can be concluded that the flow from the diffuser is less precise than the rest of the wake; likewise, the lower area compared to the upper area.

A few sharp discontinuities on the ΔCI distribution expose that the acquisition quality from the lower area had been influenced by a larger random error, then reflecting into a large uncertainty band when compared to the upper area. However, the velocity field reveals a systematic error difference present in all cases: a minor discontinuity of in-plane, vector orientation between *A1* and *A2*.

The indirect light reflection on the models is believed to be a relevant source of uncertainty. Rear base and bumper surfaces produced reflections normal to the cameras, which might have compromised the quality of stereo-reconstruction in specific regions. Even though the quality of the particle identification was not ideal, the effect was minimised by post-processing setup that was carefully programmed to identify and exclude potential spurious vectors. It has resulted in an uncertainty band over the acquisition domain no more than $\pm 3\%$ of the freestream intensity (*e.g.* $\Delta CI < 0.06U_\infty$) on both cases analysed.



(a)



(b)

Figure 101. Confidence interval of SPIV wake results between extreme cases. Average over independent samples (left-hand side) and confidence interval map (right-hand side). (a) Fastback model, nearest plane (*P5*), and (b) high-performance Fastback mode, furthest plane (*P1*).

5.7 CONCLUSIONS

In terms of the SPIV technique, it is concluded that the combination of spatial resolution, number of samples and light intensity provides a good setup balance for a cost-effective SPIV methodology for wind tunnel tests. The experimental methodology can assess the wake of automotive models in planar sections of a time-averaged, 3D velocity field.

Three wake development types were identified among the models tested, which can be directly correlated to the total pressure-based tests and findings presented in [Chapter 4](#). SPIV results confirm that (i) Fast- and Notchback DrivAer models generate a wake dominated by a central, upper downwash (*i.e.* wake *Type I*), while (ii) the high-performance model has a wake driven by an intense upwash flow with coherent vortex structure (*i.e.* wake *Type III*). This evidence supports the hypothesis of a diffuser-spoiler coupled flow mechanism as a key feature in the wake of performance cars wakes.

The most significant divergence between SPIV and total pressure rake tests is found for the Estateback model (*i.e.* wake *Type III*), where it was revealed that the wake upper region has both a vertical and horizontal inflow of similar magnitude.

In terms of in-plane vector components ($\overrightarrow{U_y + U_z}$), side mirrors have a minor impact and were only observable in a few cases. Wakes are more sensitive to changes in Re while results indicate that the transcritical level, Re_{tr} [\[51\]](#), for the respective wakes were almost reached experimentally. Both side mirror and Re influence on wake are better observed by 3D velocity magnitude contours for all cases.

The statistical analysis shows that the data have uncertainty peaks of $\pm 3\% U_\infty$ into the wake, mainly on the diffuser projected area. For flow regions outside the

wake region, the uncertainty is reduced to less than $\pm 0.5\% U_\infty$; the nominal precision uncertainty estimated for the SPIV setup.

The use of multiple acquisition areas assists in covering a domain of interest with better flow resolution; however, minor discontinuities were identified when connecting them. Time-averaged results are not significantly compromised since the post-processing investigation can estimate corrections to mitigate these effects. Further investigation on the SPIV setup is required when considering this multi-acquisition experimental setup for analysis of time-solved flows.

Chapter 6.

ON THE DEVELOPMENT OF A WAKE EMULATOR FOR AUTOMOTIVE APPLICATIONS

This chapter reports the development and proposal of a wake generator concept for automotive-related investigations ([Figure 102](#)). A CFD-based design process is divided into a (i) proof-of-concept, (ii) conceptual body topology, and (iii) geometry optimisation of an adaptable, multi-wake generator body.

The goal is to propose a wake generator design that can be adaptable to emulate a representative wake for each of the four DrivAer model configurations (*e.g.* F , N , E , hpF), investigated earlier as full-body models ([Chapter 4](#)). The shapes of the best design are assessed experimentally in [Chapter 7](#).

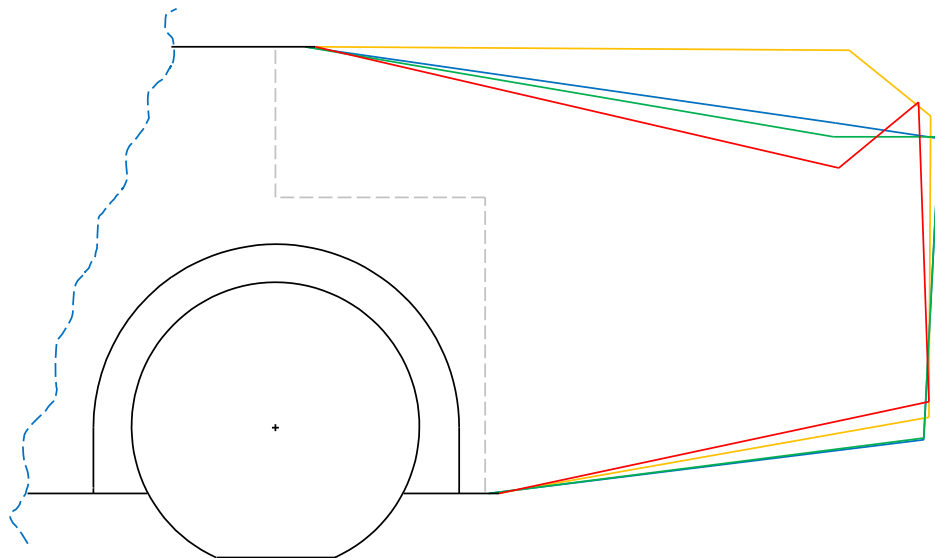


Figure 102. Idealised concept for multi-wake generator design based using movable surfaces.

6.1 ON THE PROCESS DEVELOPMENT OF A WAKE GENERATOR

The design development of an automotive, multi-wake generator is divided into three phases:

- Phase I:* Proof-of-Concept for Simplified, Bluff-Body Generation of Automotive Wakes
- Phase II:* Investigation of Baseline Concepts
- Phase III:* Investigation of an Adaptable, Multi-Wake Generator

The wake generator design was developed in a virtual environment, a combination of CAD and CFD simulations. All the CAD-related designs used SolidWorks 2017, while the aerodynamic characteristics were assessed with STAR-CCM+. Design decisions considered the analysis of wake topology as a function of:

- i. Pressure:
 - Zero- C_p isosurface.
 - Crossflow section (yz -plane) C_{p_t} distribution.
- ii. Velocity vector field:
 - Crossflow section (yz -plane).
 - Vertical, downstream zx -plane.
- iii. Vortex identification:
 - Vortex core path⁵.
 - Q-criterion [56].

⁵ Vortex core identification is a feature included in STAR-CCM+. Steve Portal, the software user library, claims that the implementation followed the works of [106], [107], [110] and [111].

6.2 DESIGN PROCESS – PHASE I:

Proof-of-Concept for Simplified, Bluff-Body Generation of Automotive Wakes

The first challenge was to prove that automotive wakes, generated from full-body models like the DrivAer *F* and *hpF* configurations, can be successfully emulated with a shorter, simplified configuration of the respective models.

Only the rearmost third of each vehicle geometry are preserved (*e.g.* rear wheels and rear body), while the forward two-thirds are removed and replaced by a common rounded forebody. In order to generate a smooth geometric transition to the rear body features, edges of windows and roof are extended gradually to the nose leading point. [Figure 103](#) illustrates the bluff-body simplification of both vehicles to be assessed in CFD simulations.

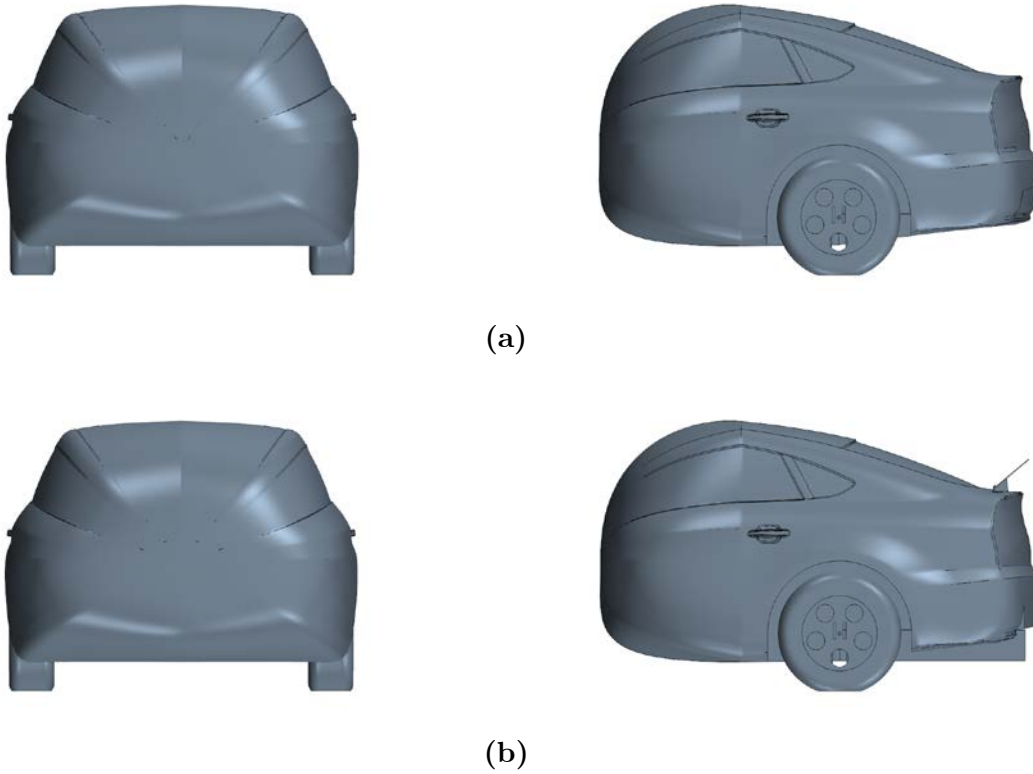


Figure 103. Wake generator, proof-of-concept: bluff-body simplification of DrivAer (a) Fastback, and (b) high-performance Fastback models.

Computational results in [Figure 104](#) (*F*) and [Figure 105](#) (*hpF*) indicate that a bluff-body simplification can successfully represent the main wake features of full-body models.

The forebody design exceeds earlier expectation when considering the limitations of bluff-body simplification presented in [\[24\]](#). Not only the velocity field but also pressure distribution is correlated to the respective properties from full-body models.

On the DrivAer Fastback model simplification, the zero- C_p isosurface ([Figure 104, b](#)) suggests the wake topology remains almost identical to the full-body geometry, except with the wheel wake expanded outwards. Orthogonal C_{p_t} planes in the wake expose minor discrepancies ([Figure 104, c](#)), like the suppression of the side mirror trace and a reduced total pressure loss, combined with lower wake height. This smaller wake height is also observable in the velocity field ([Figure 104, a](#)), which demonstrates that the attached upper flow is associated with stronger downwash flow when compared to the full-body model.

On the DrivAer high-performance model simplification, the wake topology, as a function of the zero- C_p isosurface, is similar to the respective full-body ([Figure 105, b](#)). The wake core on the upper region is generated almost exactly, while the wakes from the rear wheels are both laterally larger and at the same distance to the symmetry plane. These findings are confirmed with orthogonal C_{p_t} planes ([Figure 105, c](#)), while highlighting the suppression of the wake trace from the forebody strakes. The upwash flow from this model, a key feature in this type of wake, has a velocity vector field similar to the original model ([Figure 105, a](#)).

The forebody design intended to divert less flow underneath the body than over the rest of the geometry by using a smaller radius on the lower curvature. However, both simplified bodies have a greater underbody flow than the original model, since (i) there is less boundary layer loss from a shorter geometry and (ii)

the forebody accelerates more flow underneath the body than the full-body geometry. This appears to be the reason for the wheel wakes being pushed outwards by this amplified underbody flow, identifiable by the high momentum from velocity field and high C_{p_t} in wake planes.

Apart for those minor discrepancies, the proof-of-concept can be considered a successful approach for reduction of automotive bodies since the resultant simplified bodies have only 47% of the respective full-body model length (*i.e.* forebody of $0.15L$, original rear body of $0.32L$).

Considering the goal of designing a simplified but effective wake emulator device, it is concluded that further attention must be given to (i) the forebody, mainly on the accelerated underbody flow, (ii) wheel representation, and (iii) the flow balance from upper and lower surfaces.

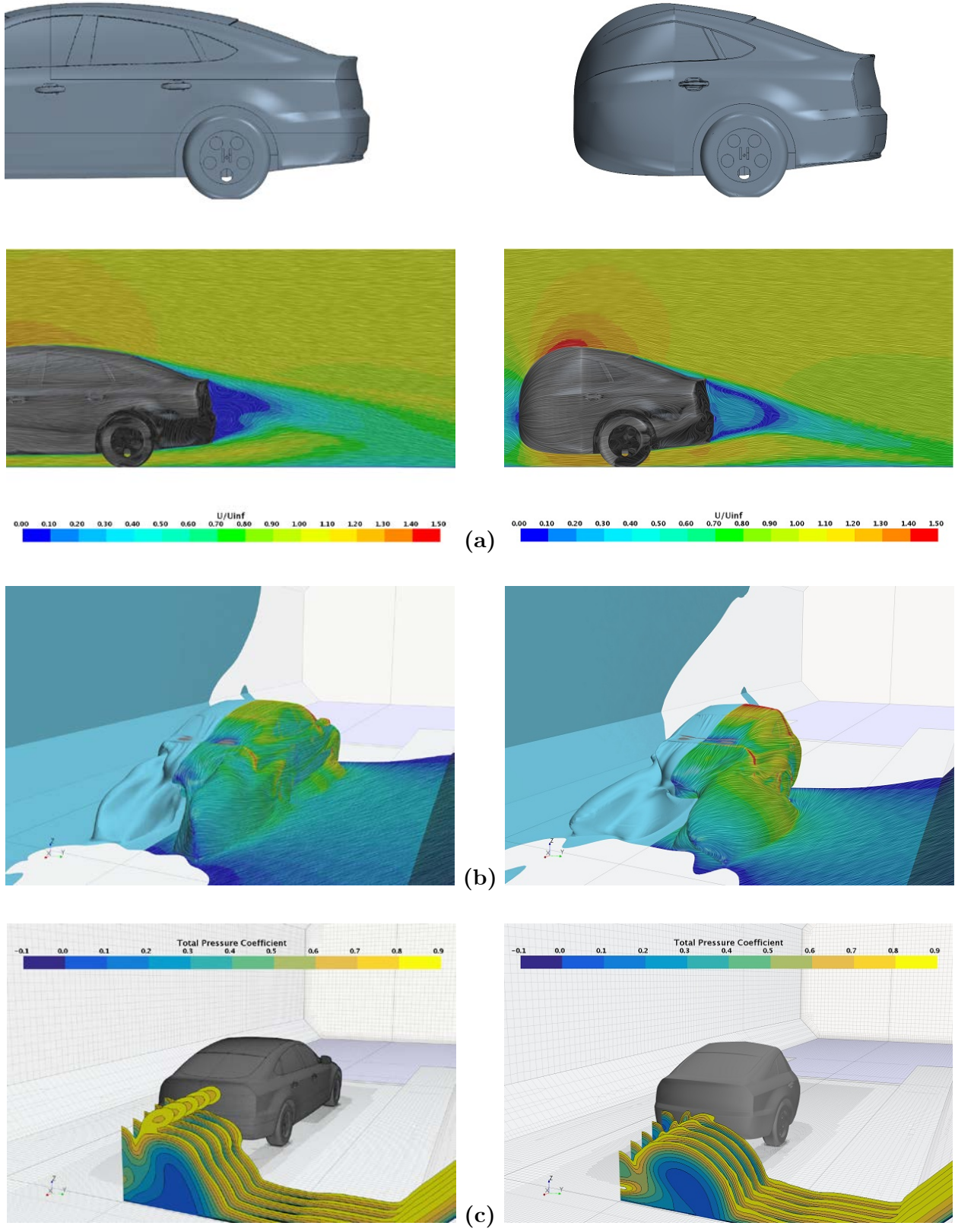


Figure 104. Wake generator, proof-of-concept for the DrivAer Fastback (*FSwoMwW*). Full-body (left column) and simplified body (right column).

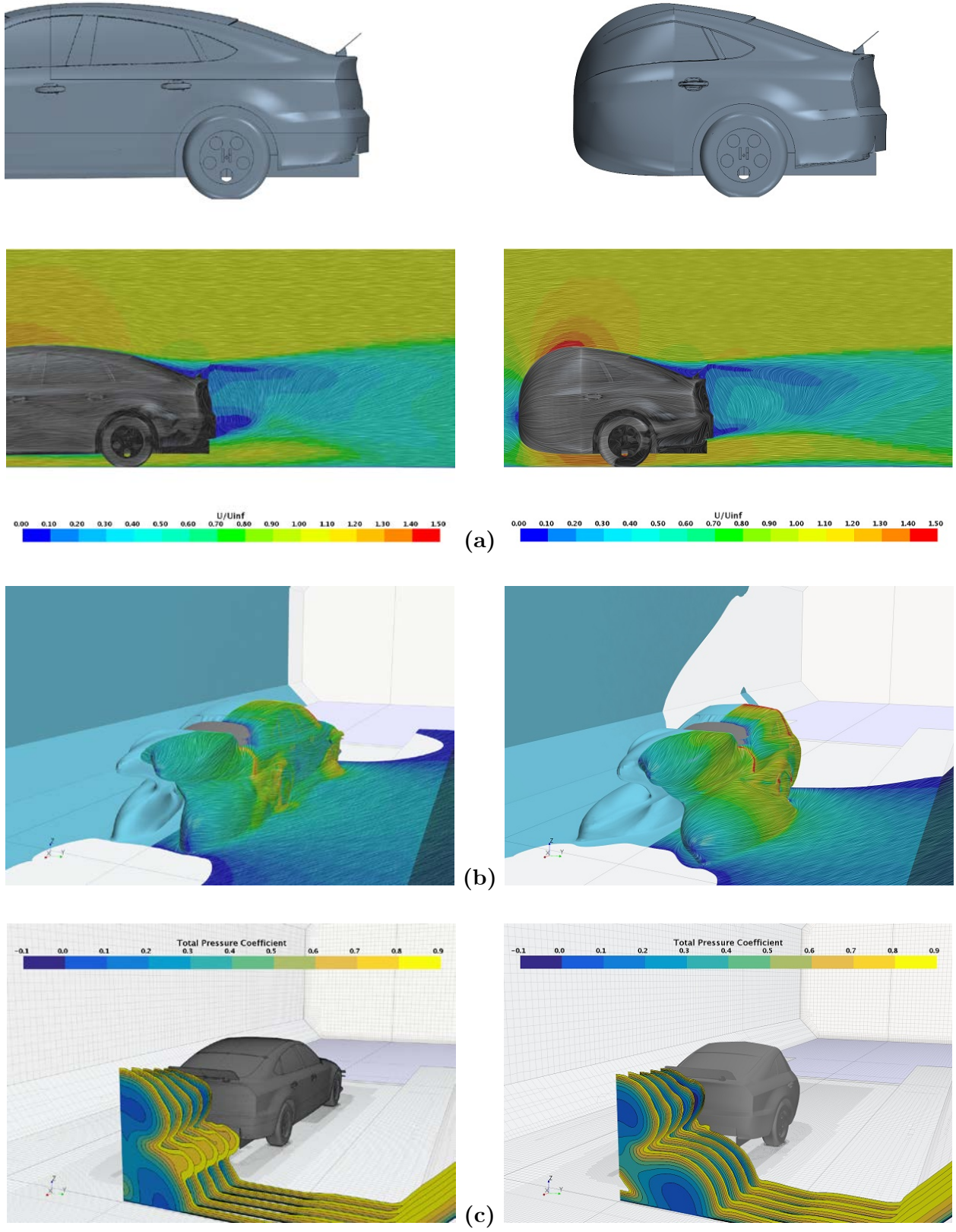


Figure 105. Wake generator, proof-of-concept for the high-performance Fastback (*hpFSwoMwW*). Full-body (left) and simplified body (right).

6.3 DESIGN PROCESS – PHASE II:

Investigation of Baseline Concepts

This section reports a collection of generic, bluff-body wake generators to represent the Fast- and Notchback DrivAer models (*i.e.* wake *Type I*). The design process evaluates simultaneously (i) the performance of detail-oriented solutions and (ii) different body concepts. Dimensional drawings of the bodies are presented in [Appendix E](#) (Figure E-1 to 8).

6.3.1 Wake Generator, Concept 1

6.3.1.1 Concept 1a

The experimental results of full-body models (*i.e.* DrivAer model family) highlighted the relevance of critical features such as wheels, upper and lower rear slants (*i.e.* top rear-end and diffuser), while the *wM* configuration added the side

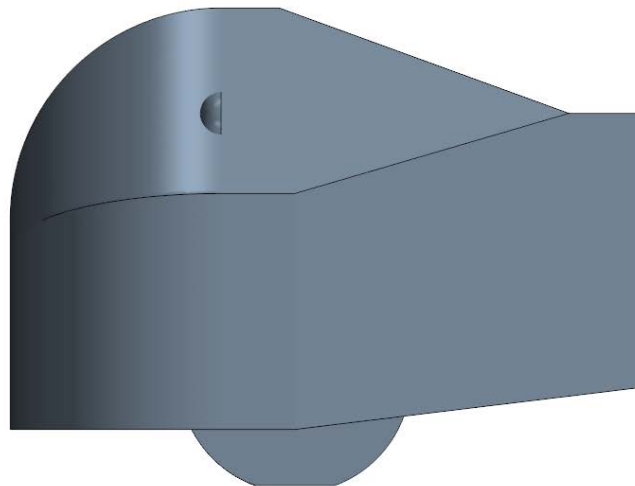


Figure 106. Wake generator, Concept 1a.
Design scope: initial bluff-body for Notchback vehicle type.

mirror wake. This evidence led to Concept *1a*, opening the iterative design process to emulate the full-body wake using a simplified geometry.

This bluff-body generates the primary flow features of an automotive wake (even using a simplified body), such as the near-wake from rear and energy loss from the wheels. This first conclusion can be checked by observation of the zero- C_p isosurface, velocity and total pressure distributions (Figure 107; *b,c,d*) downstream of this initial conceptual design; however, there were critical differences to be either addressed or at least mitigated.

Analysis of the underbody cylindrical protuberances from the bluff-body (*i.e.* body representation of vehicle wheels, see Figure 106) helped to emulate a wake topology comparable to a Notchback vehicle model, as well as the upper slant with a rearmost horizontal step. The lateral protuberances recreate a representative wake for side mirrors.

The side mirror flow features are considerably reduced before reaching the rearmost body position (Figure 107; *b,e,f*). The wake from wheel-like bodies are too wide, and the velocity field in the crossflow plane reveals it as a vortex-dominated wake moving outwards. This flow enhances that in the central downwash region from the upper surface and results in an elongated wake attached to the ground.

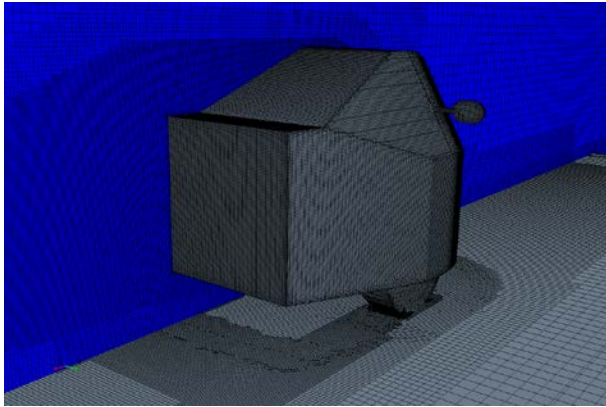
The free-surface stagnation point, found in Figure 107(*d*) confirms that the averaged near-wake is longer than the reference wakes for the full-body Fast- and Notchback DrivAer models. The crossflow planar area of total pressure supports the conclusion of a wide near-wake. The furthest plane section shows that the total pressure (Figure 107, *c*) loss is mitigated, but there are clearly two main regions with different trends. The central part of the wake (*i.e.* downstream the near-wake) is deflected downwards, while the portion associated with the wheel-like geometry maintains its position. It results in a change of the overall shape,

where a semi-circular total pressure zone is compressed as the wake develops downstream.

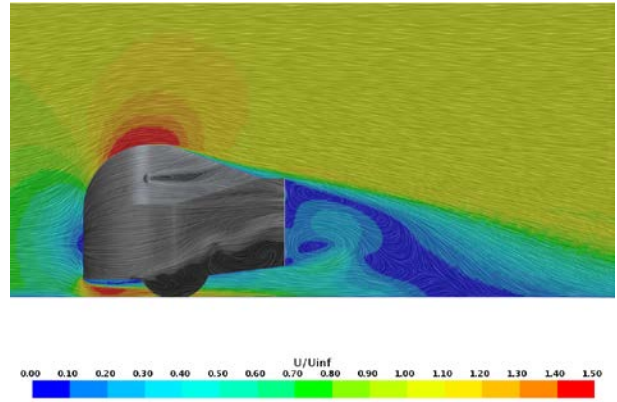
The ‘oil-surface’ visualisation⁶ (Figure 107, *d*) highlights that the side mirror wake is deflected upwards but reaches the rear slant edge by its midpoint, equivalent to the respective DrivAer model. In contrast, the behaviour of the lateral flow is a poorly representation. A recirculation zone starts from the lower edge, by the end of the forebody, and grows up to half of the rear edge.

The underfloor flow is another area that requires improvement. It is unclear how the flow is impacting the near-wake. A recirculation zone is found at the underbody leading edge, which accelerates the flow up to $1.5U_\infty$. This high velocity flow is nominally half of the ride height gap and is attached to the ground surface. The diffuser stall and respective total pressure loss is believed to be partially a consequence of this poorly emulated flow, apart from the diffuser design itself.

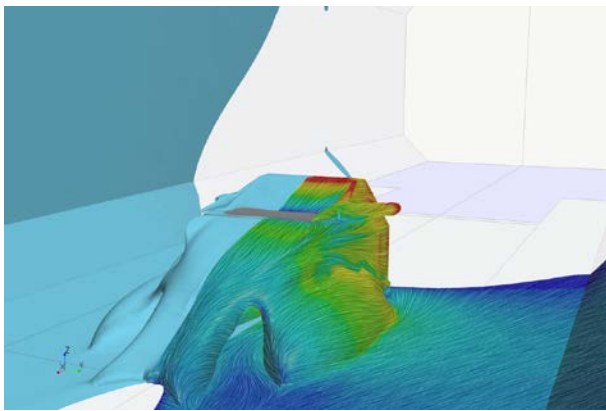
⁶ This computational emulation of the experimental oil-flow technique is based on flow lines (known as line integral convolution - LIC) calculated by the shear stress vector field on the body surface.



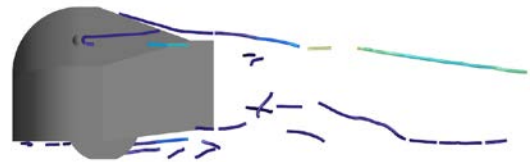
(a)



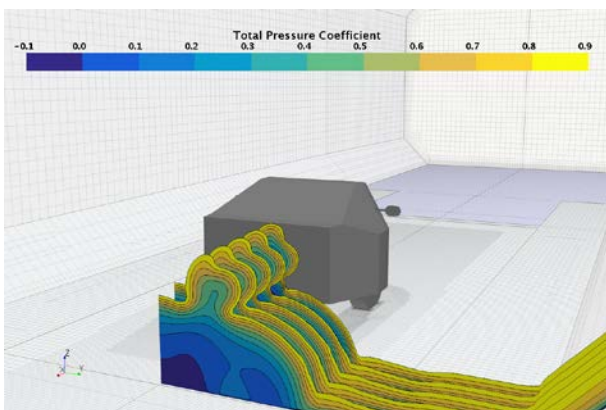
(d)



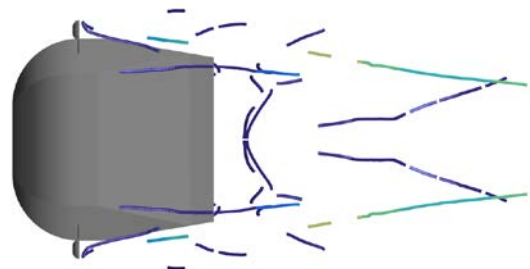
(b)



(e)



(c)



(f)

Figure 107. Flow visualisation of the wake generator, Concept 1a.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.1.2 Concept 1b

A solution considered for the underbody flow involves the use of a frontal splitter on the Concept *1a*, which is a rectangular plate attached under the leading edge of the forebody flush with the underbody surface. The installation of the splitter changes the underbody flow, resulting in $U_{max} = 1.3U_{\infty}$, a reduction of nearly $0.2U_{\infty}$ in the velocity peak compared to Concept *1a*.

Not only the underbody flow is modified, but also the wake topology. The downwash is weakened, and the zero- C_p isosurface shows the wake more like the reference full-body wakes (Figure 108, *b*). In this case, the wheel-related wake is less distant from the main near-wake trace.

However, the splitter has an inherent flow flaw: tip vortex generation. This undesired feature can be seen in the total pressure planes as a wake trace twice as large as the ride height (Figure 108, *c*). When observing the velocity field

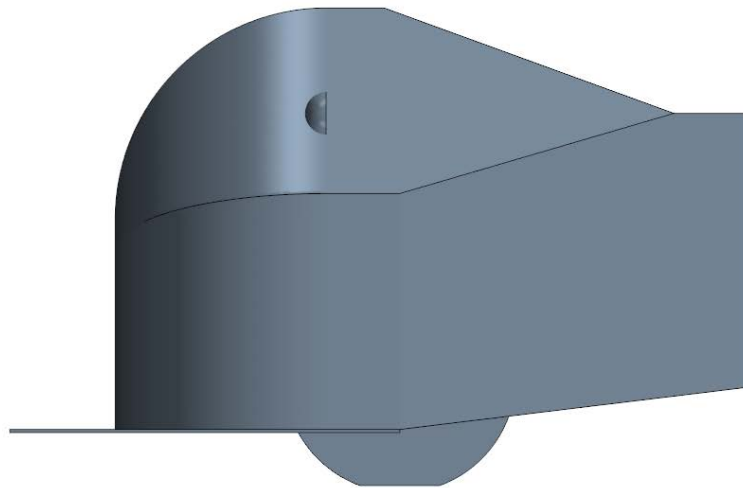
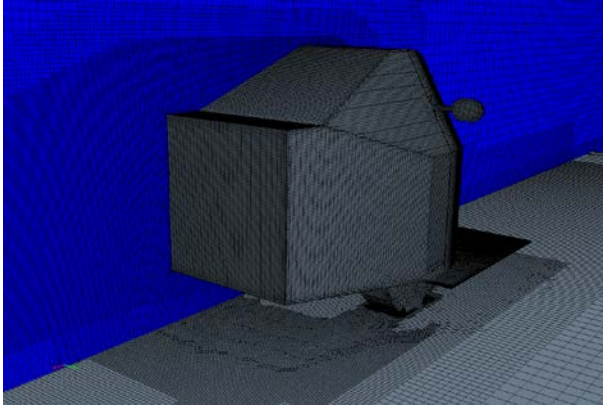


Figure 108. Wake generator, Concept 1b.
Design scope: underflow control solution.

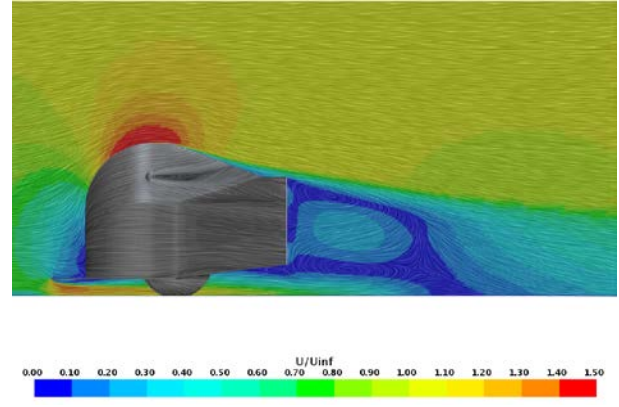
(Figure 108, *d*), it can be seen that the total pressure loss trace is a result of a vortex pair. It is believed that one is generated from the splitter tip edge starting from the leading corner (*i.e.* tip vortex), while the second is a result of a recirculation flow along the edge between the splitter and frontal surface (*i.e.* root vortex).

Apart from the upper and lower slants (*e.g.* notchback-like rear end and diffuser surface), the Concept *1a* and *1b* are based on a rear body with lateral tapering (seen in Figure 108, *f*). Although oversimplified, this design intends to be equivalent to the tapering found on realistic vehicle geometries.

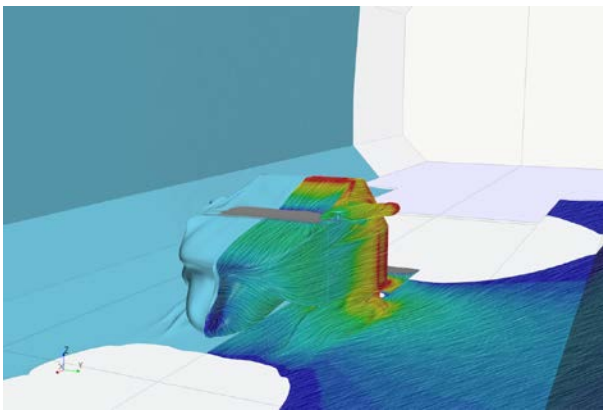
The splitter assists in the emulation of a more realistic automotive wake; unfortunately, there are side effects from this solution. The combined tapering may be triggering a partial diffuser stall, where a separation over half of the diffuser surface is present.



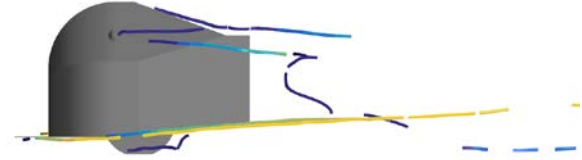
(a)



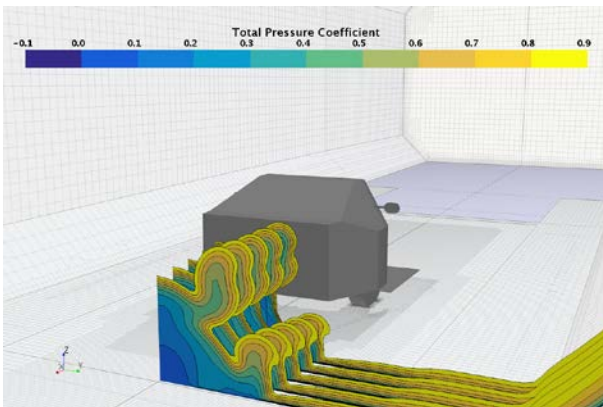
(d)



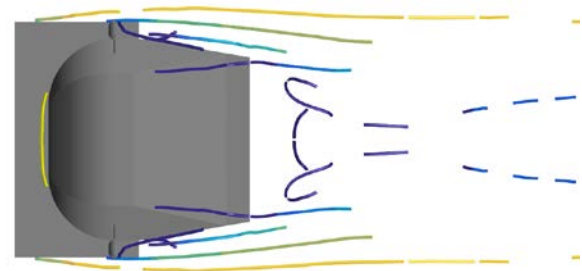
(b)



(e)



(c)



(f)

Figure 109. Flow visualisation of the wake generator, Concept 1b.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.2 Wake Generator, Concept 2

Iterative steps led to Concept 2, where the goal was investigating another body simplification that may allow a more straightforward body modification inspired by the modular DrivAer rear-end.

The outcome is a simplified body with narrow forebody and regular rear base with a diffuser slant. Tapered surfaces are present only on the upper part of the body, intended to be a case-specific rear-end separated body sharing a base body. In the case presented in [Figure 110](#), the upper part is a reference to Notchback design for comparison to Concept 1.

[Figure 111](#) shows the CFD simulation, where the wake central downwash, a feature of the Notchback models, is confirmed by both the total pressure distribution and velocity field. Orthogonal C_{p_t} planes ([Figure 111, c](#)) reveal that the wake has become wider than with the previous design, a consequence of the

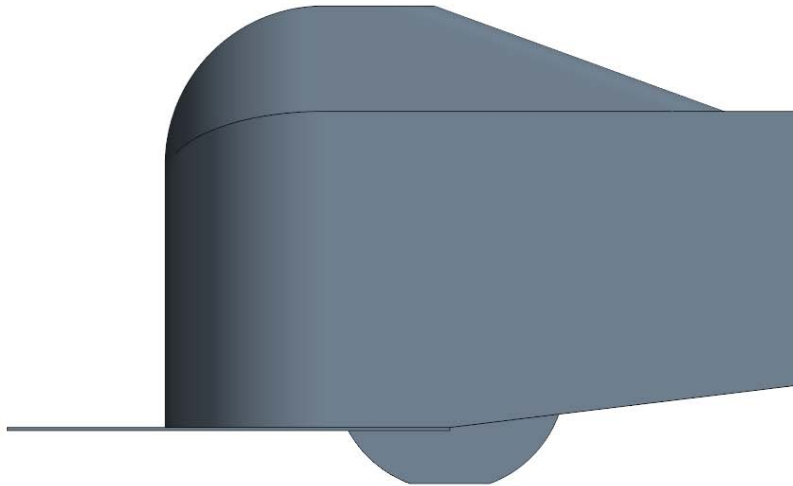


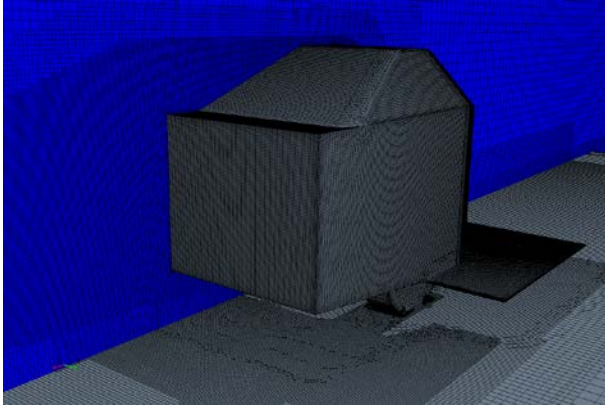
Figure 110. Wake generator, Concept 2.
Design scope: alternative simplification of body features.

non-tampered side that would reduce the rear base area. The velocity field ([Figure 111, d](#)) displays a better topology of the near-wake, where the upper downwash and the underbody flow is well-balanced, although elongated.

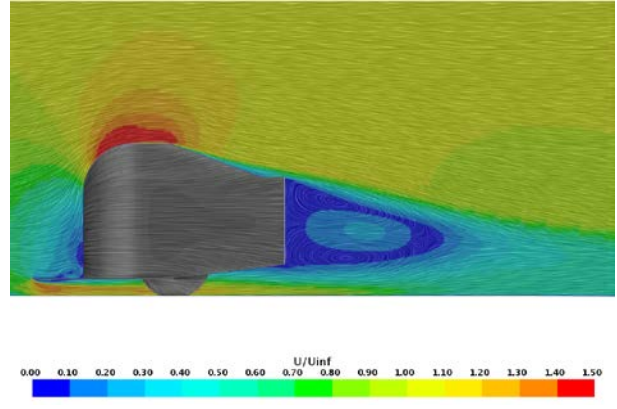
Issues with splitter design were addressed by using a wider plate which was expected to displace the influence of the tip edges. While the tip vortex is not fully mitigated, the intensity of pressure loss is significantly reduced. It also improves the underbody flow, which combined with a smoother diffuser angle has separation flow on the diffuser surface avoided.

However, there is a flaw identified in this design: the cross-velocity vector field shows that the wake is not compatible with the coherent-vortex found in the experimental tests (*i.e.* [4.4.1.1: Wake Type I](#)). Instead of a dominant vortex structure on each side, the body generated a pair of counter-rotating vortices on each side that generates an outward flow at mid-height of the rear base.

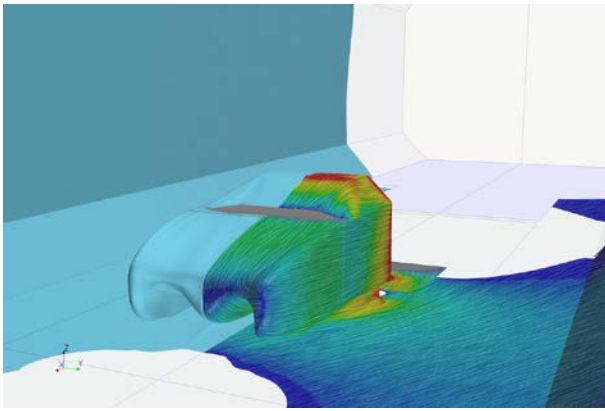
In conclusion, this rear base geometry results in a wake that is incompatible with the target automotive wake assessed in [Chapter 4](#) and [Chapter 5](#).



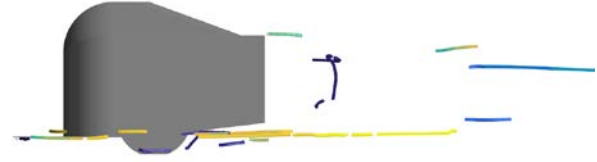
(a)



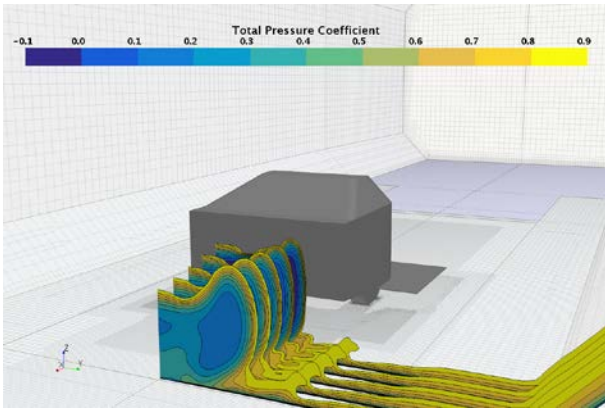
(d)



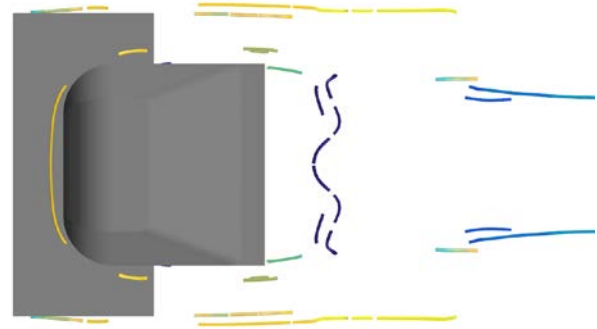
(b)



(e)



(c)



(f)

Figure 111. Flow visualisation of the wake generator, Concept 2.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.3 Wake Generator, Concept 3

Concept 3 shares a similar forebody design with previous versions (Concept 1a, 1b), but the semi-conical rear body shape is the main feature investigated. Figure 112 shows that the wide upper 45°-chamfers silhouette the body from forebody to the rear base, forming planar faces with rounded edges. Sharp edges are only found on the rear base and diffuser surfaces.

Only the position and size of the wheel-like bodies are maintained. The nose profile has been enlarged to create a conical rear body with plane rear base, which is smaller than previous versions (Figure 113).

Overall, the body resembles features of a Fastback vehicle rear. Side mirrors and frontal splitter are included. The latter is extended laterally to ensure sufficient distance between splitter tip edge and nose surface.



Figure 112. Wake generator, Concept 3.
Design scope: simple, conical fastback body.

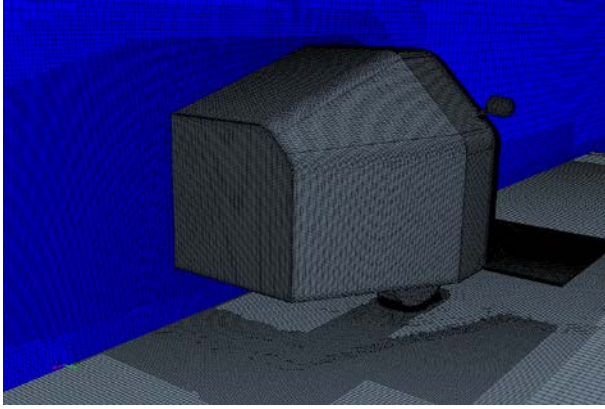
Results shown in [Figure 113](#) confirm that this shape generates the shortest near-wake of all the concepts tested. An inspection of the zero- C_p isosurface ([Figure 113, b](#)) corroborates with the velocity field. The wake downwash is well-represented, as well as the underbody flow that expands without detachments or recirculation on the diffuser slant.

Even though previous concepts used chamfered forebody edges, this version features continuously chamfered faces with rounded edges, while the body profile reduces linearly between the forebody and rear base. It is seen to be determinant to the reduction of the near-wake recirculation zone.

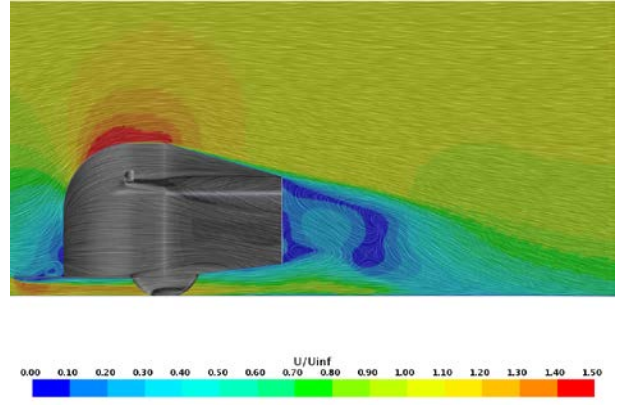
Total pressure cross-planes ([Figure 113, c](#)) also supports the statements above. The energy loss is the lowest among the wake generator bodies, and the near-wake and wheel wake zones are easily identifiable. At the nearest observation plane, the wake topology is closest to the full-body DrivAer Fastback wake, whereas the downwash is found to be too strong and compresses the wake trace against the ground surface.

The velocity field ([Figure 113, d](#)) indicates the presence of a large recirculation structure on each side, but closer analysis reveals that the effect is a combination of vortices rotating with the same orientation, moving in parallel downstream within the wake development.

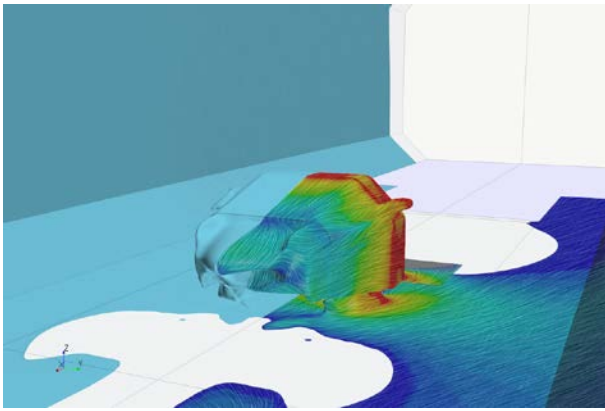
In conclusion, the wake structure is satisfactory for the purpose of wake emulation, but the body dimensions become too large for the purpose of a compact device, particularly the splitter plate.



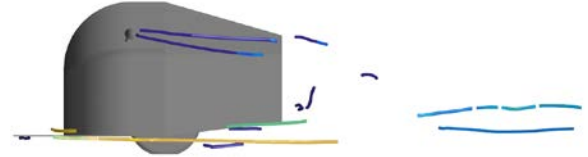
(a)



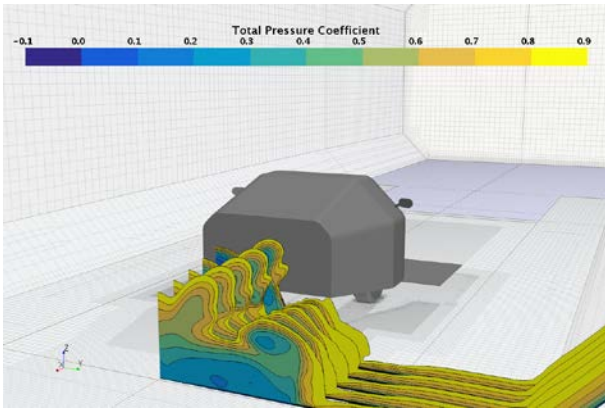
(d)



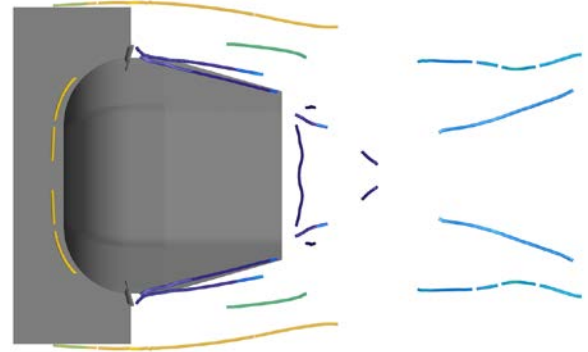
(b)



(e)



(c)



(f)

Figure 113. Flow visualisation of the wake generator, Concept 3.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.4 Wake Generator, Concept 4

The previous concepts used a splitter plate as a passive tool to control the underbody flow, respectively the wake topology. Another option considered for the underbody flow are rounded lower edges at the forebody. Concept 4 is expected to reveal is the new feature will be an acceptable substitute for the splitter plate.

Secondly, a new rear base design is also tested which uses a vertically-chamfered rear base (Figure 114, Figure E-5). The goal is quantifying the influence of those small rear base inclinations on the near-wake topology.

Observation of the velocity field indicates that there are considerable changes as a result of using rounded edges instead of a splitter plate (Figure 115, *d*). Even a small radius prevents the flow separation seen on Concept 1; however, it

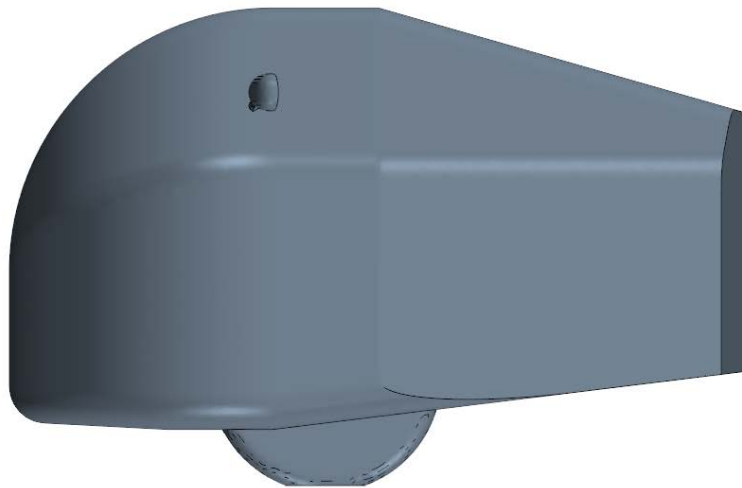


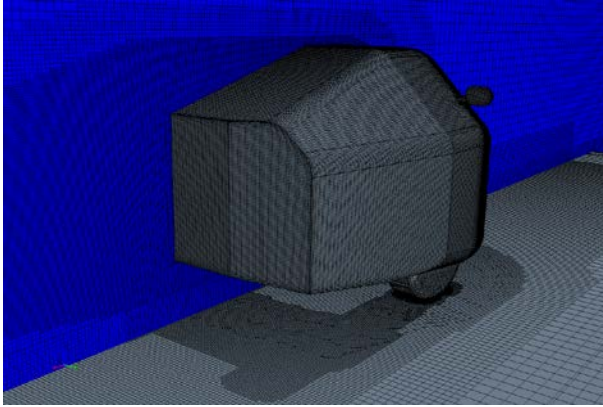
Figure 114. Wake generator, Concept 4.
Design scope: assess wake-sensitivity for a vertically tapered rear base.

accelerates the flow resulting in a large area of $U_{max} < 1.5U_{\infty}$. This is compatible with performance cars, but unusual for passenger vehicles.

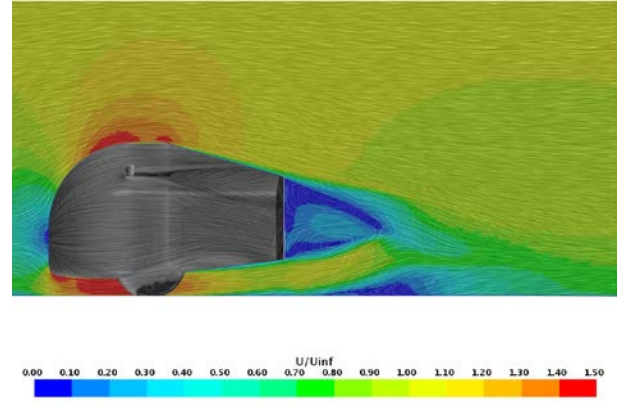
Other evidence confirms the extra mass flow under the vehicle compared to previous cases. The first indication is the ‘oil-flow’ visualisation (*i.e.* line integral convolution of wall shear stress vectors), specifically on the wheel surfaces. The well-known ‘horse-shoe’ vortex structure is larger than the same feature from Concept 3. Considering that both concepts have identical wheel geometries, it is believed that the increment in vortex intensity and expansion is due to a higher speed of the surrounding flow. Another sign is the reduction of the velocity peak above the leading edge of the nose, which is found connected to an increase of the underbody flow speed.

In terms of the near-wake, Concept 4 becomes the wake generator body with the second nearest free-surface stagnation point. Interestingly, the zero- C_p isosurface exhibits the smallest near-wake volume of all the concepts investigated so far in this work (Figure 115, *b*). Total pressure cross-planes (Figure 115, *c*) correlate with previous findings since the total pressure loss is greatly mitigated compared to the first wake generator, Concept 1. The accelerated underbody flow has elevated the free-surface stagnation point (Figure 115, *d*), which seems associated with a reduction on the total pressure losses (Figure 115, *e*).

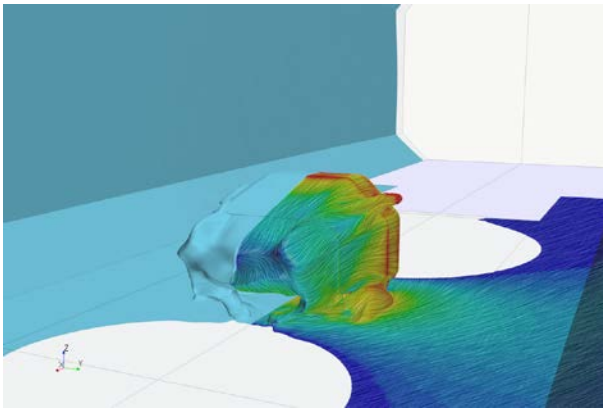
To conclude, Concept 4 is found incompatible with the purpose of wake emulation of current automotive models. Nevertheless, this shape demonstrated to be a basis for further investigation of energy-efficiency shapes for the automotive industry.



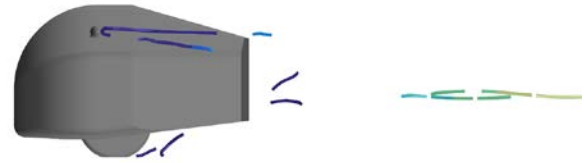
(a)



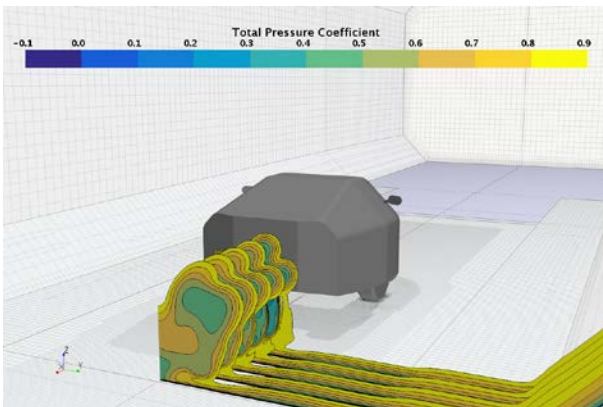
(d)



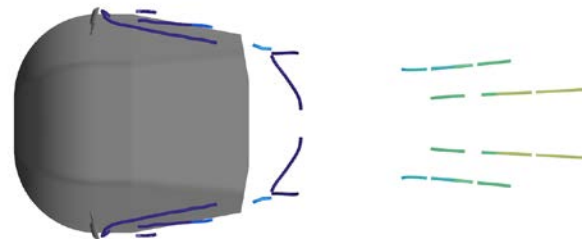
(b)



(e)



(c)



(f)

Figure 115. Flow visualisation of the wake generator, Concept 4.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.5 Wake Generator, Concept 5

This Concept, illustrated in [Figure 116](#), still focusses on a Fastback-like wake generation and adopts the lateral rear tapering and side mirrors-like geometries employed in Concept 4.

However, Concept 5 is significantly changed by adopting (i) wheel cavities, (ii) a separated wheel body, and (iii) rear bumper representation. While the width is reduced, the wheel-related features are displaced downstream to the plane where the lateral tapering starts, as used in Concept 3. The goal is assessing these new features for different forebody flow control (*e.g.* Concepts 5a, 5b, and 5c).

6.3.5.1 Concept 5a

[Figure 117](#) reports the aerodynamic simulation from Concept 5a, where C_{p_t} distribution planes ([Figure 117, c](#)) suggest the wake generated as the most similar

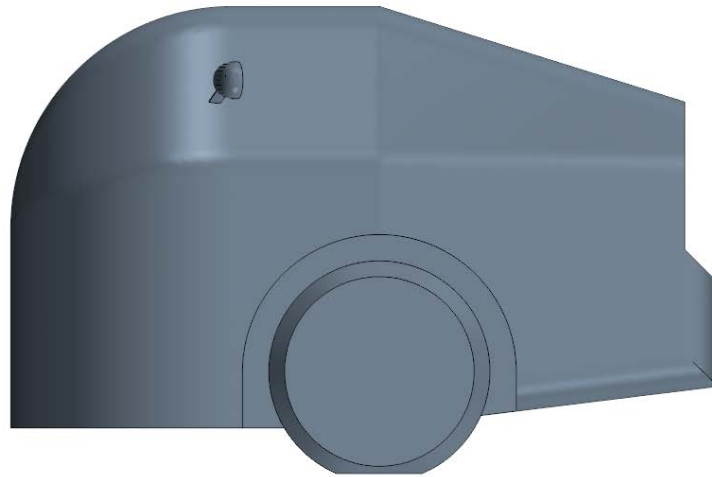


Figure 116. Wake generator, Concept 5a.
Design scope: back-end flow sensitivity for wheels and rear bumper features.

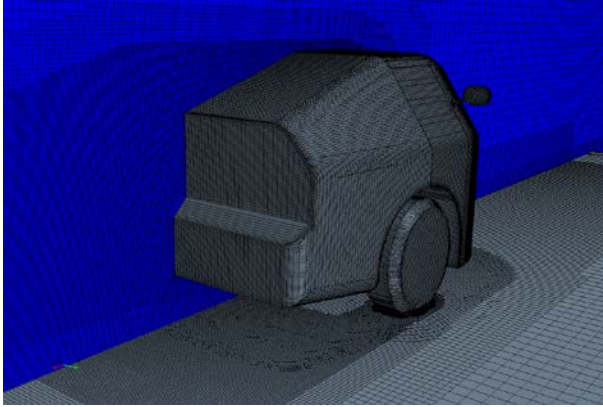
to the full-body DrivAer Fastback of all the concepts assessed. The inclusion of wheels and cavities contributes to a more realistic automotive wake.

The C_{p_t} wake trace caused by the side mirrors appears to merge quickly with the main wake, indicating the presence of a large, downstream-oriented vortex structure (Figure 117, *c*). This wake pattern was previously identified in the experiments of Fast- and Notchback models (*i.e.* wake *Type I*), where results suggested that an upper downwash assisted in the formation of this structure. Since the C_{p_t} distribution seems to almost split the wake into two sections, it demonstrates the occurrence of a strong downwash from the upper rear-end, albeit of greater intensity than the full-body cases.

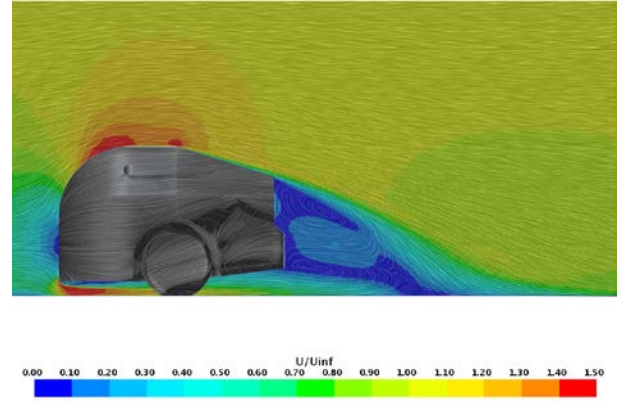
The zero- C_p isosurface (Figure 117, *b*) shows that the downwash flow from the upper surface moves the wake core downwards in comparison to the full-body reference, while the rear bumper corners seem to guide the lateral wake topology downstream. The side mirror wake is found over the ‘C-pillar’-like edge, which merges into the main wake topology.

The velocity field in the symmetry plane (Figure 117, *d*) displays the sharp, lower nose edge creating a recirculation flow as observed with Concept *1a*. As a result, the effective flow cross-section is reduced and accelerates the flow to a local peak with $U_{max} < 1.5U_\infty$. The strong downwash from the upper surface is also detected on the velocity field, which is not well-balanced with the underbody flow.

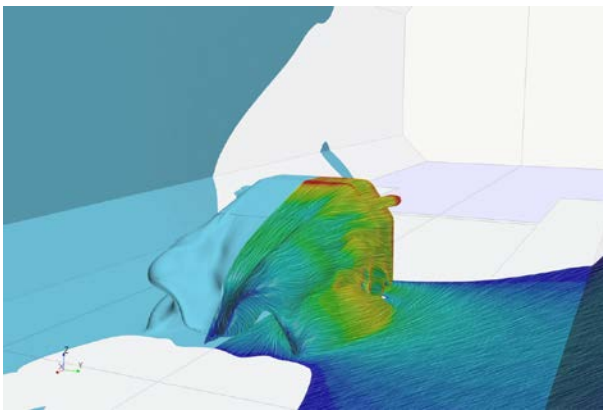
In terms of the pressure distribution, Concept *5a* generates a wake which is very similar to the full-body. Evidence suggests that the underbody flow is a key feature to be enhanced. Since the use of a front splitter proved to be a satisfactory solution in this respect, it is assessed in the subsequent design as Concept *5b*.



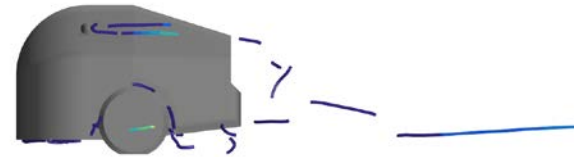
(a)



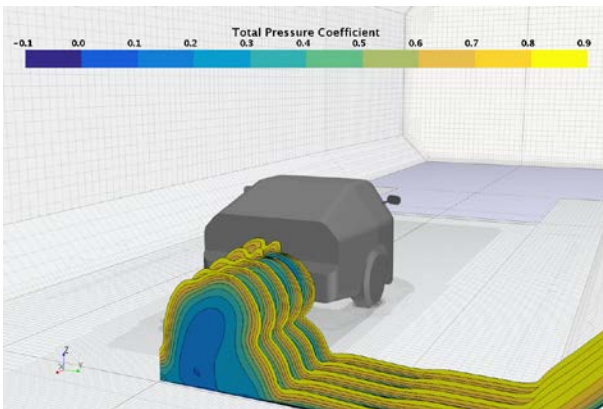
(d)



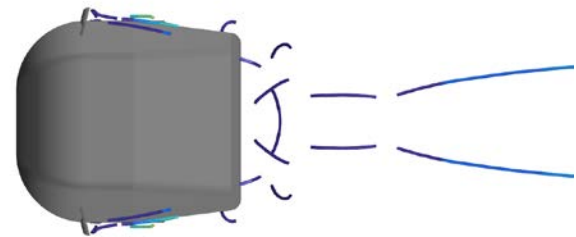
(b)



(e)



(c)



(f)

Figure 117. Flow visualisation of the wake generator, Concept 5a.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.5.2 Concept 5b

Although the splitter plate seems to assist in the representation of the underbody flow (*e.g.* Concepts 1b, 2, and 3), regular shapes generated a side effect: tip vortex structures.

Concept 5b (Figure 118) evaluates the performance of a single front nose splitter in the 5a version, Figure 119 present the simulation results from this design. Rather than a regular splitter shape, this version explores a new design with rounded corners (see Figure 119, f) in order to mitigate tip vortex formation.

The velocity field in the symmetry plane shows that there is a residual recirculation under the splitter, that is smaller in size and intensity when compared to the baseline case (Concept 5a). This reflects in the underbody flow, which recovers most of the effective flow cross-section and reduces the velocity peak to $U_{max} = 1.4U_{\infty}$.

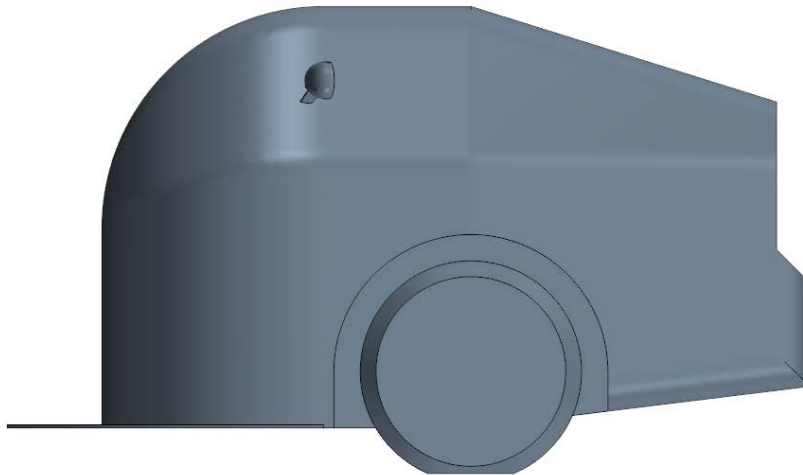


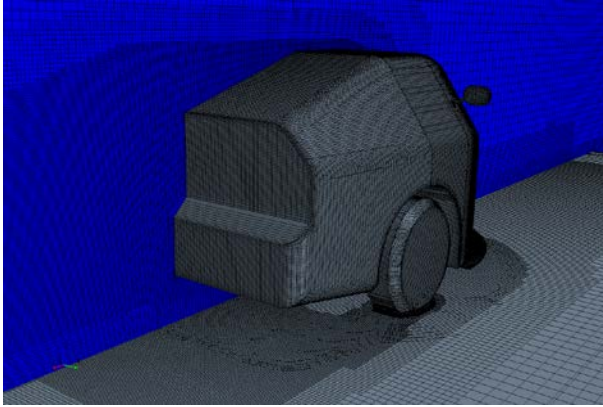
Figure 118. Wake generator, Concept 5b.
Design scope: underbody flow control using a frontal splitter.

The new splitter version used in Concept *5b* succeeds in mitigating the tip vortex propagation. There is no clear trace of C_{p_t} loss in the wake that can be associated with a vortex structure (Figure 119, *c*), while the vortex path shows that a residual structure generated by the splitter rounded edges decays near the wheels (Figure 119, *e, f*).

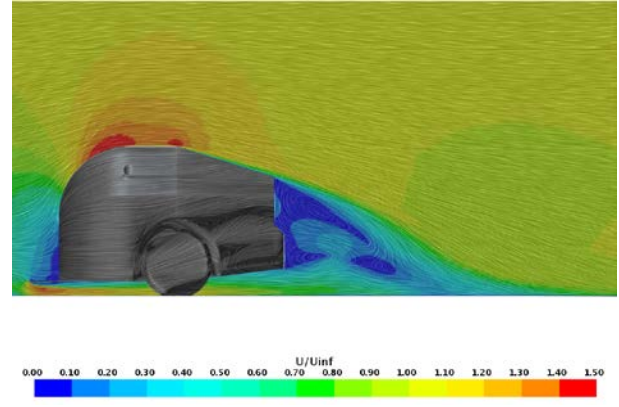
This tip vortex decay contrasts with the features generated by Concepts *1b*, *2*, and *3*. A clear trace of C_{p_t} loss (*i.e.* a vortex core effect) can be found on orthogonal planes in the wake (Figures 109, 111, 113; *c*), while vortex path identification (*idem*; *e, f*) showing a coherent structure of, at least, $2L$ in length downstream each of respective body.

The wake topology, when characterised by zero- C_p isosurface, remains mostly unaffected when adding the splitter (Figure 119, *b*). The only exceptions are (i) a reduction of the gap between each wheel wake, and (ii) a slightly shorter global wake. Orthogonal C_{p_t} planes suggest that despite the similar wake topology, the splitter promotes a minor total pressure recovery in the wake.

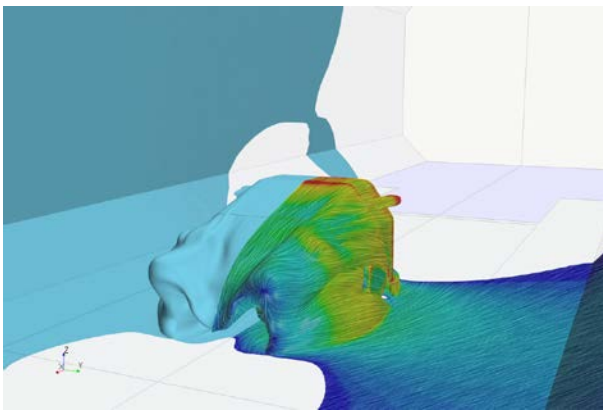
In the view of the velocity field (Figure 119, *d*), it is seen that the underbody flow is better balanced to the upper downwash than the baseline. The wake recirculation zone is marginally reduced in size, whilst the average-velocity magnitude increases. The latter can be related to the total pressure recovery in the wake (Figure 119, *c*).



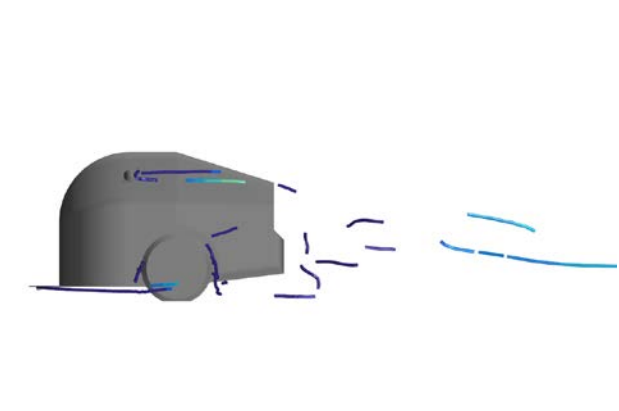
(a)



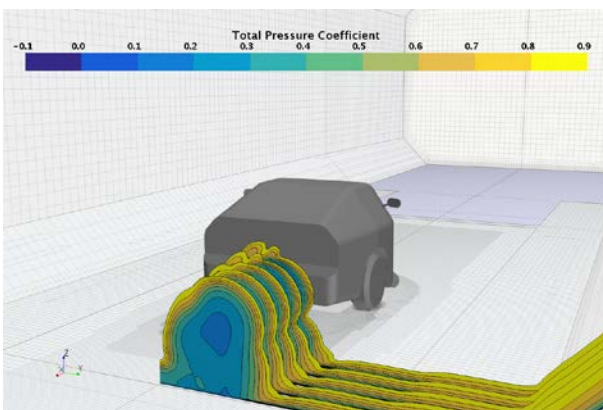
(d)



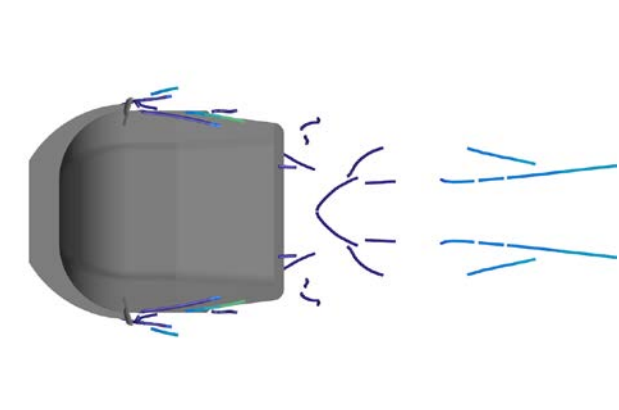
(b)



(e)



(c)



(f)

Figure 119. Flow visualisation of the wake generator, Concept 5b.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.3.5.3 Concept 5c

Concept *5c* evaluates the performance of a dual splitter plate to control the underbody flow while diverting flow sideways. This case is used to confirm if a reduction in the upper downwash can be achieved with lateral flow diversion on the forebody. This design explores the flow control on the forebody, by placing a second splitter plate 70mm above the first plate, as illustrated in [Figure 120](#).

When comparing to Concept *5b*, the zero- C_p isosurface indicates that the wake topology maintains the overall shape with minor changes ([Figure 121, b](#)). There is a small trend of wake size reduction, and a separation bubble on the upper wheel cavity.

The velocity field in the symmetry plane ([Figure 121, d](#)) shows minor wake-sensitivity to the dual splitter configuration. The upper flow has a minor reduction in the velocity magnitude, which reflects in a proportional reduction of the upper downwash. Consequently, the point where the upper flow reaches the ground is

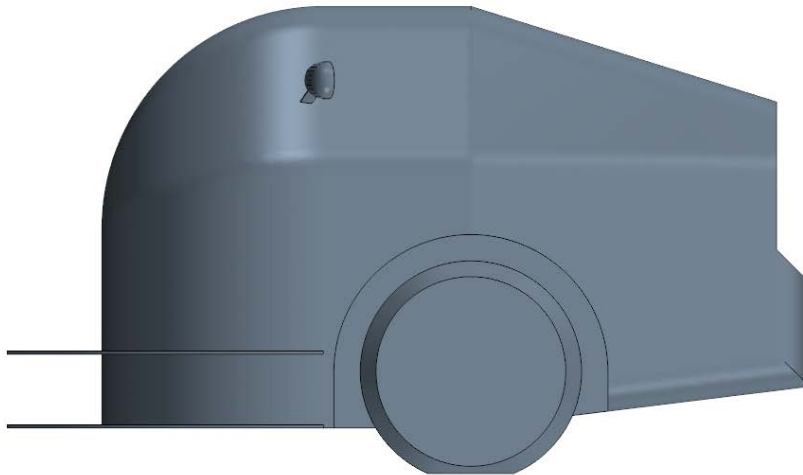
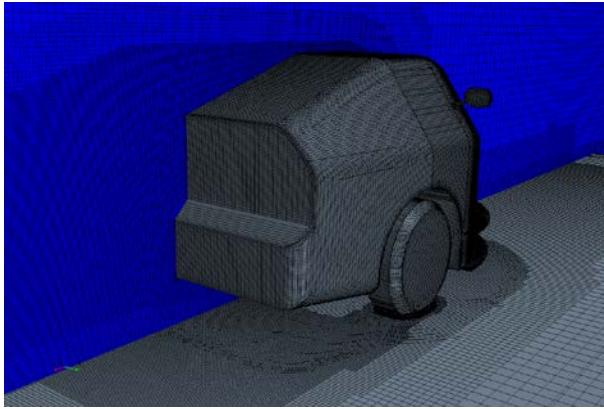


Figure 120. Wake generator, Concept *5c*.
Design scope: frontal flow control using a double-plate splitter.

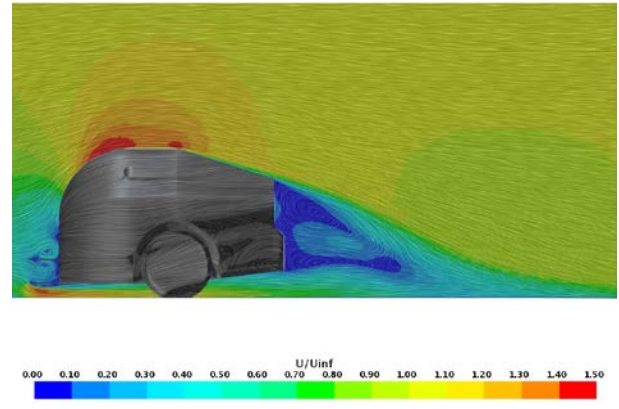
moved further downstream. The free-surface stagnation point from the wake suggests a minor rising tendency. Orthogonal C_{pt} planes (Figure 121, *c*) confirms that the wake has raised but with little impact in the wake topology.

Although the second splitter influenced the upper/lateral flow ‘balance’, it generated a side effect: a pair of root vortex structures. The root edge on each side of the upper plate generates two coherent vortices rotating in opposite direction (Figure 121, *d*).

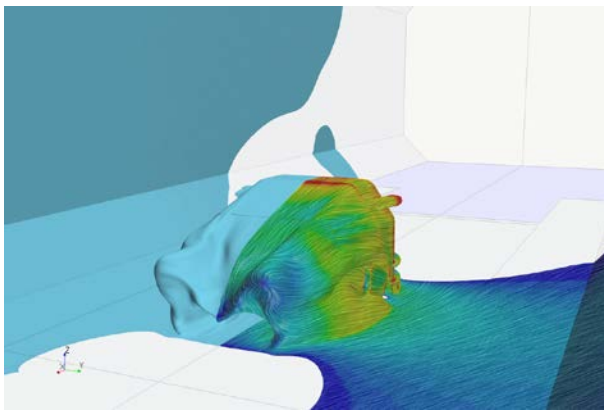
Vortex path identification (Figure 121, *e, f*) shows that the upper vortex structure is dominant since the lower vortex structure decays earlier, near the body end. This flow feature is advected downstream next to the rear wake, where a respective trace of C_{pt} loss can be identified (Figure 121, *c*).



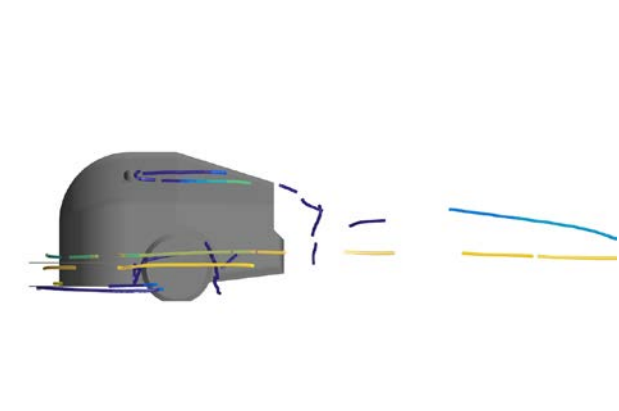
(a)



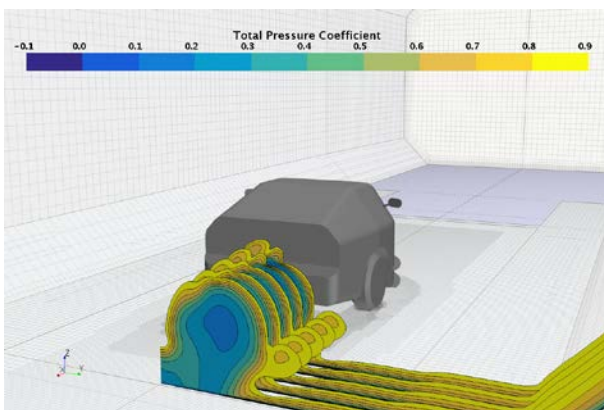
(d)



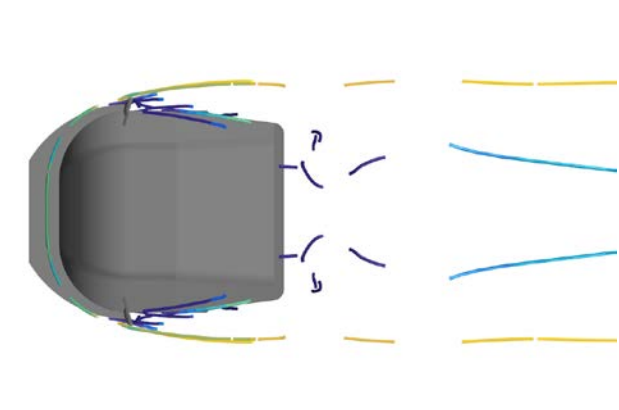
(b)



(e)



(c)



(f)

Figure 121. Flow visualisation of the wake generator, Concept 5c.

(a) Meshing illustration, (b) zero- C_p isosurface, (c) orthogonal C_{p_t} planes, (d) normalised velocity field, (e) side and (f) top views of vortex path identification.

6.4 DESIGN PROCESS – PHASE III:

Investigation of an Adaptable, Multi-Wake Generator Body

This third phase intended to compromise in a single compact body the capability of wake emulation for four automotive types covered in *Chapter 4* (e.g. Fastback, Notchback, Estateback, and hp-Fastback). The key wake characteristics to be emulated are:

- 1) Wake *Type I*: Fastback geometry:
 - a) small wake with minor downwash.
 - b) vertically balanced wake.
- 2) Wake *Type I*: Notchback geometry:
 - a) similar to Fastback, with differences as:
 - i) downwash attenuated.
 - ii) increasing total pressure loss.
- 3) Wake *Type II*: Estateback geometry:
 - a) large, full detached flow.
 - b) wake size proportion of the rear base.
 - c) lateral inwash.
- 4) Wake *Type III*: High-performance fastback geometry
 - a) strong upwash.
 - b) generation of coherent, counter-rotating vortices.

The previous design campaign found that Concept *5b* can represent a wake *Type I* (e.g. Fast- and Notchback models). However, this solution is considered in conflict with the initial objective of ‘geometric simplicity and cost-efficiency’ of

6.4.1 Multi-Wake Generator, Design 1

A few features were found relevant to the purpose of automotive wake generation using simplified bodies, exemplified by the rounded forebody, single splitter plate, and representation of wheels and wheel cavities.

Even though side mirrors had a relevant past on external automotive aerodynamics, it has been discussed that the replacement of external side mirrors for small cameras with aerodynamic struts. Then, these cameras would have a negligible impact in the wakes compared with general side mirror geometries.

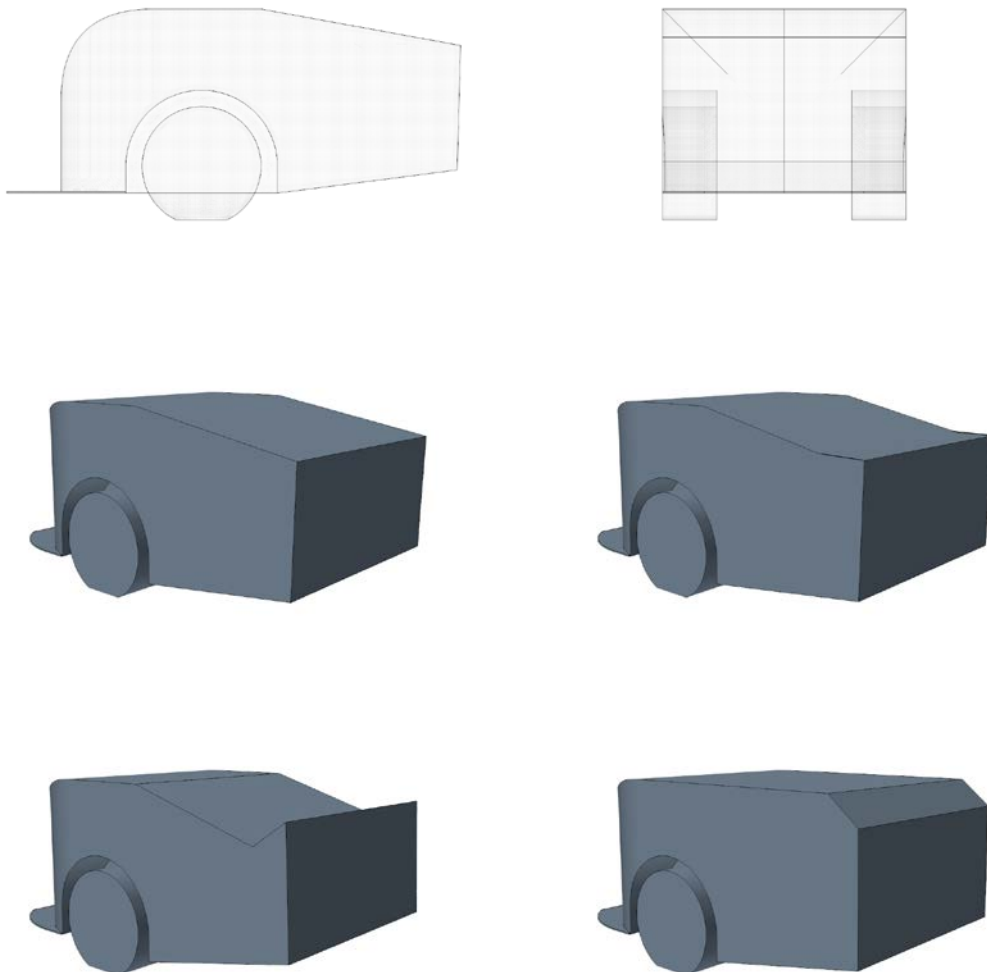


Figure 123. Adaptable, multi-wake generator configurations - Design 1.

Considering this tendency on the automotive industry, side mirrors are removed from the wake generator design for both geometry simplification and to generate a wake more coherent with future vehicle configurations.

Front splitter and wheel-related features are incorporated into the first formulated concept of the novel approach (Figure 123) as fixed features, while the body rear is adjusted to four profiles. All geometric adjustment, which involves the positioning of the four plates of the body rear, is successfully reduced to a single degree of freedom (*e.g.* linear actuator, piston or adjustable arm; solid line in Figure 122).

The overall shape is simplified to a regular base shape, allowing the intended degree of freedom idealised for the wake generator. From a manufacturing point of view, parallel plates sliding on each other can seal the transverse hollow, providing the closed bodies of the profiles illustrated above.

Figure 124 reports the performance of the four wake generator states in terms of orthogonal C_{p_t} planes. Even though the outcome from this first design is unsatisfactory when compared to the full-body DrivAer wakes adopted as references, the geometries show preliminary agreement with the wakes intended. It confirms the potential of the approach for further development in the goal of an adaptable, multi wake generator.

The wakes *Type I* generated (Figure 124, *a*, *b*) have roughly adequate proportional size, but the wake topology must be improved in further designs. The Notchback geometry casts a wake under-performing the upper downwash, a feature that is over-performing on the Fastback case (Figure 124, *a*). The topology of the wheel wake trace is fairly represented on both configurations.

The wake *Type II* from the Estateback-like configuration has a height decay in the range presented (Figure 124, *d*), with negligible reduction in width, while the wake trace from the wheels is similar to the previous cases.

The high-performance configuration generated the best representation among the cases, where the upwash is comparative with the detailed, full-body experiment. A robust upper recirculation downstream the model dominates the wheel wakes, bringing this feature inwards (Figure 124, *c*).

There is a trace of tip vortex from the splitter plate observable on all cases, but with insignificant intensity and dominated by the wakes within one body length.

Although the outcome of a this first design is unsatisfactory when compared to the full-body DrivAer wakes adopted as references in Chapter 4 and Chapter 5, the geometries show preliminary agreement with the wakes intended, suggesting that further development may achieve the goal of automotive wake emulation.

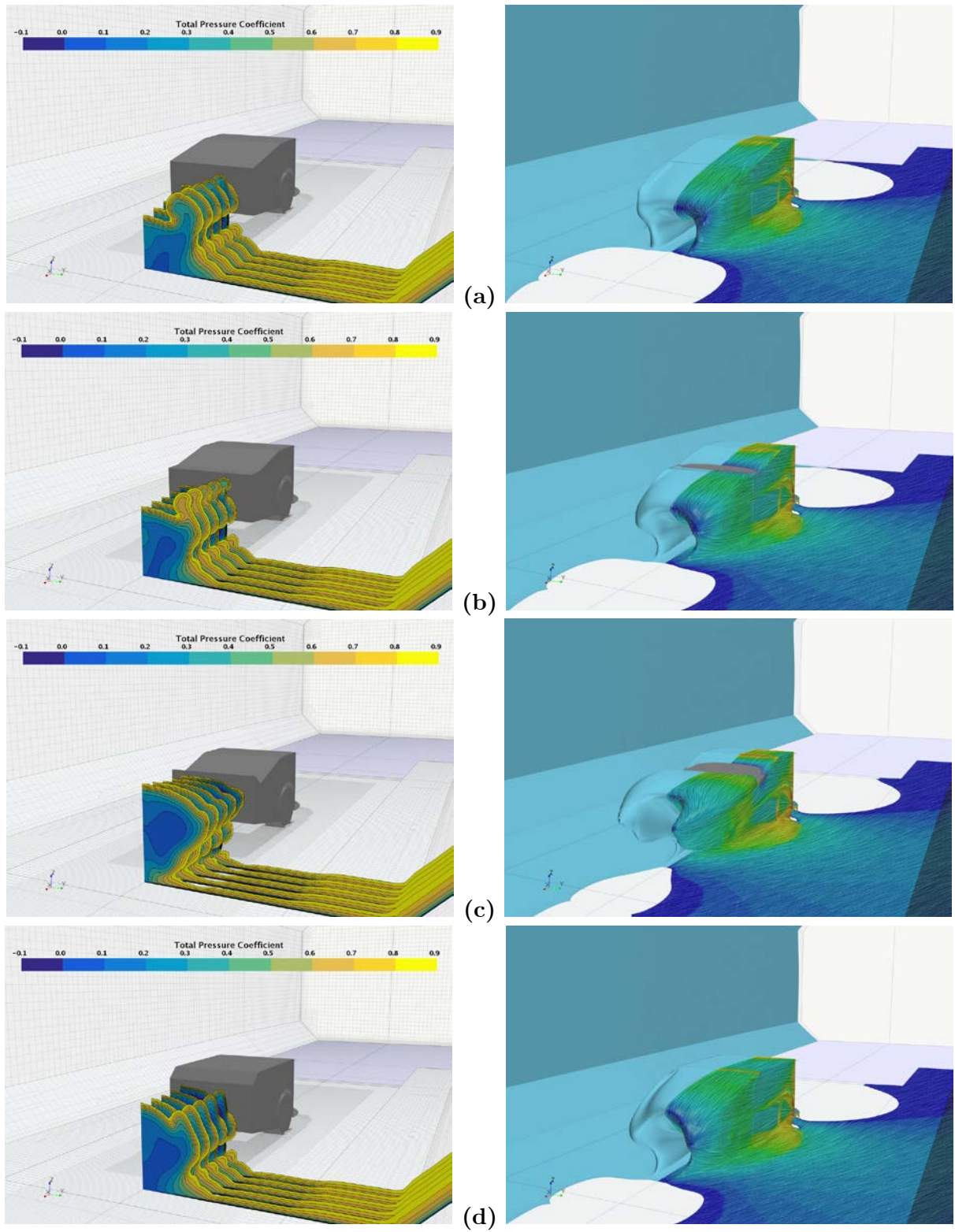


Figure 124. Flow visualisation of the multi-wake generator, design 1. Orthogonal C_{p_t} planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

6.4.2 Multi-Wake Generator, Design 2

This design involves minor changes in the dimensions and evaluated the use of rounded edges on the sides of the diffuser plate (Figure 125). For the Fastback case only, rounded edges are also applied on the lateral edges of the upper rear-end, in order to evaluate the sensitivity of the wake to rounded edges.

The wheel radius is maintained while the width is reduced to create (i) a small step between the body surface and the wheel, and (ii) an inner gap into the wheel

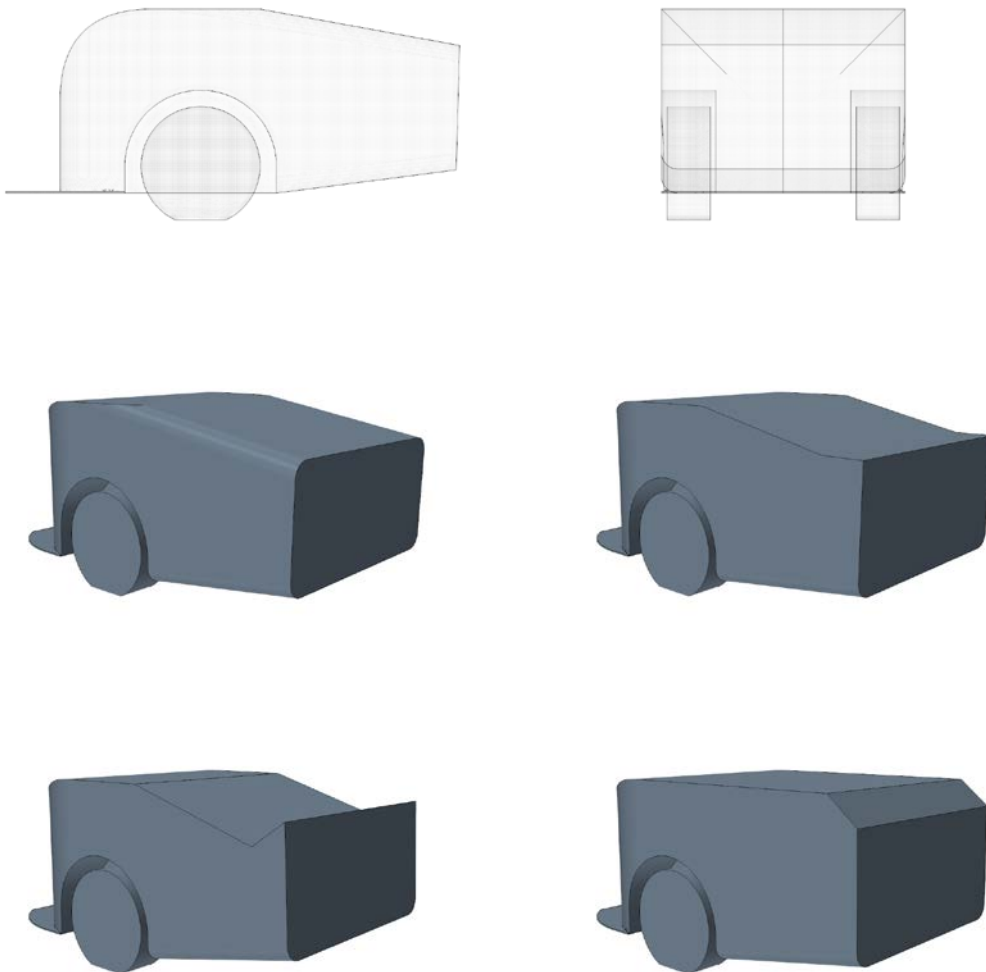


Figure 125. Adaptable, multi-wake generator configurations - Design 2.

cavity. These changes intend to improve the wake topology from the wheel-related features while using regular shapes.

The total pressure in the wake of the Notchback configuration (Figure 126, *b*) is more uniform than the previous design. The wake trace from the wheel is closer to the main wake region, while the upper wake protuberance is widened. The latter is directly associated with the wheel step created, then generating the recirculation bubble usually found on the upper edge of realistic wheel cavities.

The flow characteristics from the high-performance configuration are also improved, where the upper recirculation is intensified (Figure 126, *c*) and well-identified in the wake. The overall wake topology becomes more uniform and with an increase of height downstream of the body. Flow features like the tip vortex and the rear wheel recirculation are dominated and merged into the wake, confirming the higher intensity of the upwash mechanism.

The inner wake C_{pt} distribution from the Estateback configuration is mostly constant (Figure 126, *d*), with minor changes linked to the rear wheel recirculation (expanding the upper wake width) and lower edge (contracting the lower wake width). There is a mild increment in the wake height, potentially resultant from the lower lateral inflow that moves the wheel wake inwards.

Not only the lower but also the upper edges (equivalent to ‘C-pillars’) are rounded on the Fastback configuration evaluated. This feature is included for wake sensitivity analysis only, but is considered physically unfeasible with the upper moving parts using regular geometry (Figure 126, *a*). It is found that the upper downwash from the Fastback-like geometry is considerably intensified, which reduces the trend of lower flow inward from on the other shapes (Figure 126, *b, c, d*).

To summarise, the inner flow in the wheel cavities seems to enhance the wake representation, where the C_{p_t} distribution becomes near to topology found on experimental references (*Chapters 4* and *5*). The lower rounded edge does not provide convergent conclusions among all cases to support an increase of geometric complexity, therefore the feature is not adopted in further design.

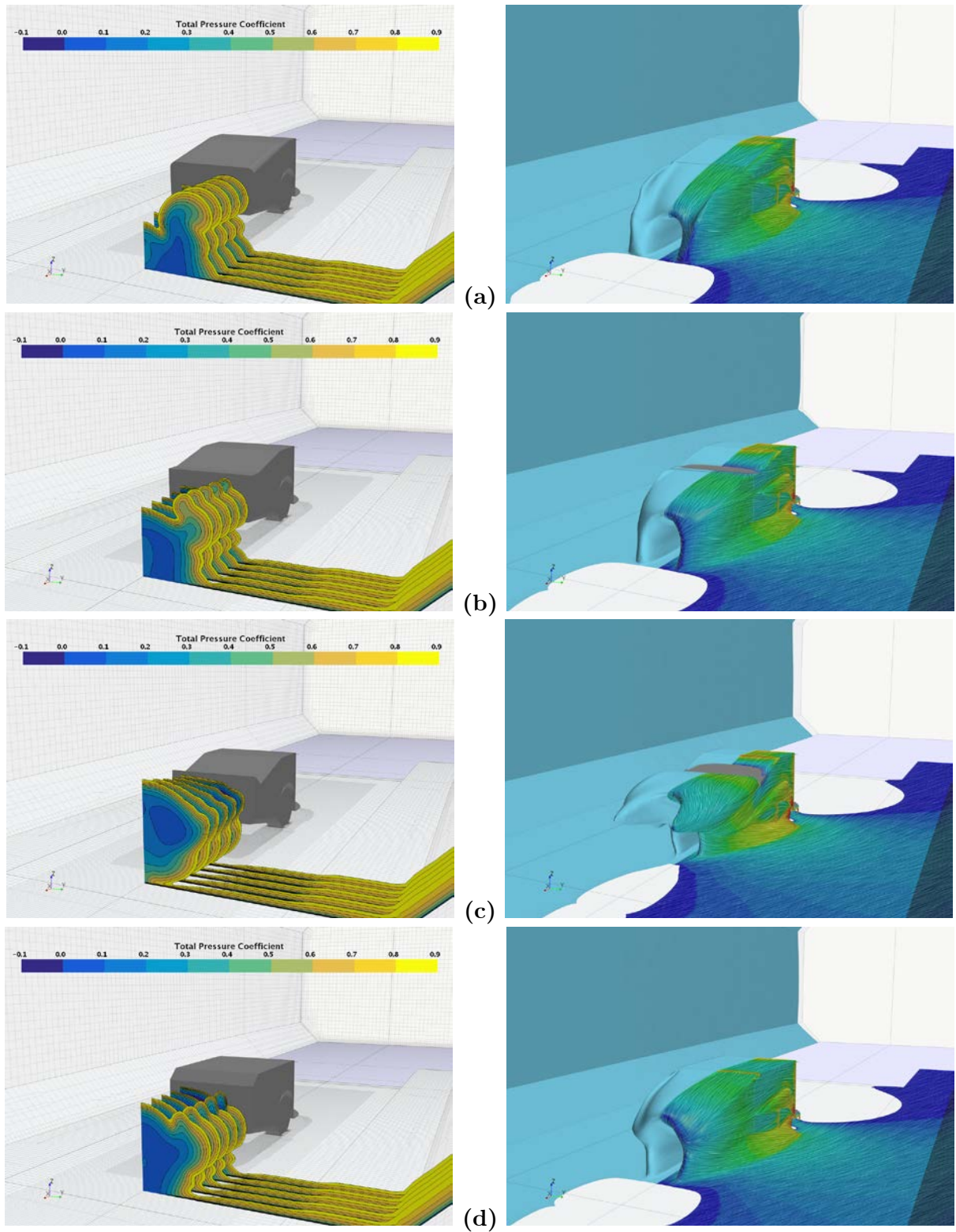


Figure 126. Flow visualisation of the multi-wake generator, design 2. Orthogonal C_{p_t} planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

6.4.3 Multi-Wake Generator, Design 3

This design evaluates the impact of a rear bumper representation on the wake of all four configurations, in contrast to the single analysis done for a Fastback-like body in the design process, phase II (*6.3.5 Wake Generator, Concept 5*). The goal is to identify if the rear bumper can be used to affect the balance between (i) upper and lower flows and (ii) the inner wake recirculation.

For direct comparison, this design adopts the body evaluated in design 2, but suppress the lower rounded edges on the diffuser surface and adds a regular

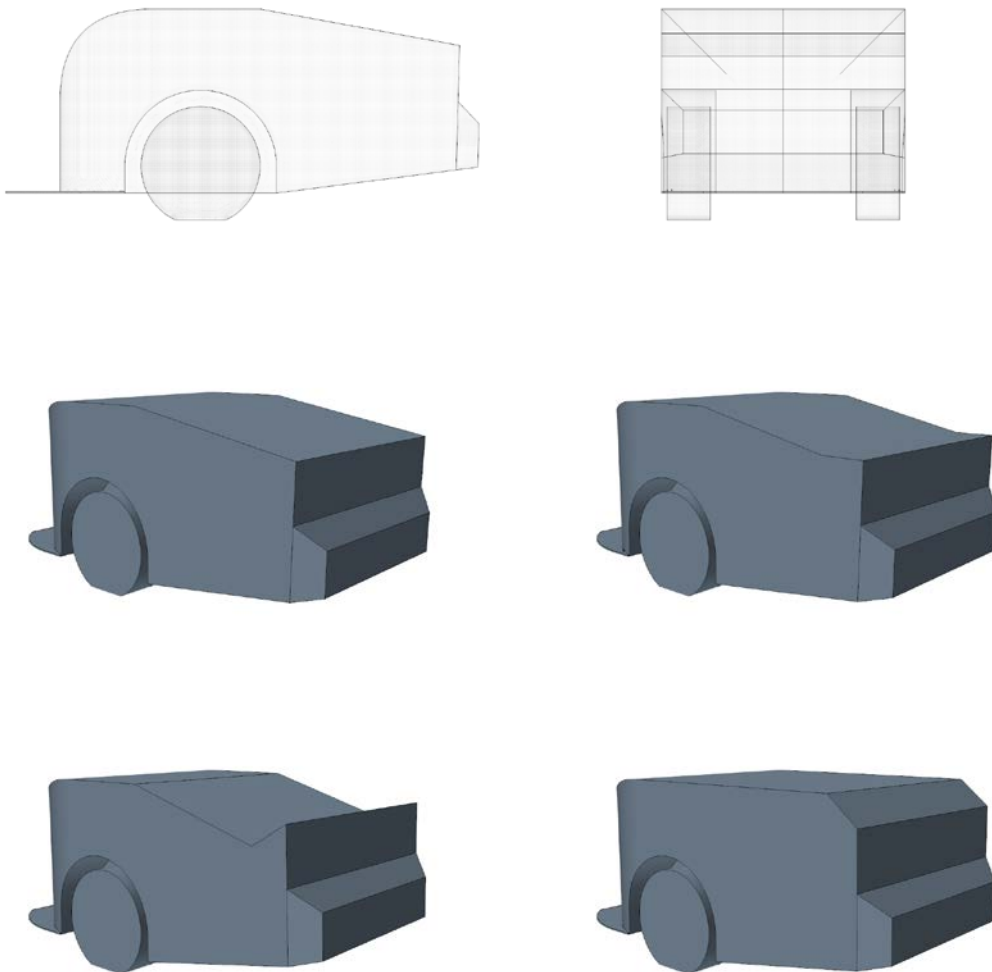


Figure 127. Adaptable, multi-wake generator configurations - Design 3.

protuberance at the rear base. It has a lower surface flushed with the diffuser plate, while the other surfaces are chamfered at 45 degrees (Figure 127). Results presented in Figure 128 shows the aerodynamic performance of the four wake generator configurations, design 3.

The zero- C_p isosurface on both Fast- and Notchback configurations indicate the main effect on the rear body protuberance on the wake topology (Figure 128, *a*, *b*). The Coandă effect [57] may be present on lateral chamfer surface generates, which generates an inflow at lower wake height. In comparison to the previous design, the wakes topologies are closer to the full-body DrivAer references. Orthogonal C_{p_t} planes of both cases suggest that both wakes increase the wake trace vertically, while the C_{p_t} distributions exhibits a minor energy recovery.

For the high-performance shape (Figure 128, *c*), the wake topology is mostly unchanged in terms of zero- C_p isosurface. Only the total pressure distribution reveals a minor downwards displacement of the central wake region, while the lateral traces have slightly gained in height. This suggests that the added geometry can reduce the diffuser-spoiler upwards mechanism⁷.

The Estateback shape has the less sensitive wake among the four configurations. Both wake topology and C_{p_t} distribution sections are roughly the same; except by a minor influence of the lateral inflow found on the latter (Figure 128, *d*).

It is concluded that the protuberance on the rear base, like a rear bumper geometry, can interfere on the wake topology, but with minor impact.

⁷ In the view of applied aerodynamics, the investigated geometry would result in a downforce reduction since it can be associated to the upwash intensity from diffuser-spoiler ([1] [49], illustrated in Figure 35 and Figure 36).

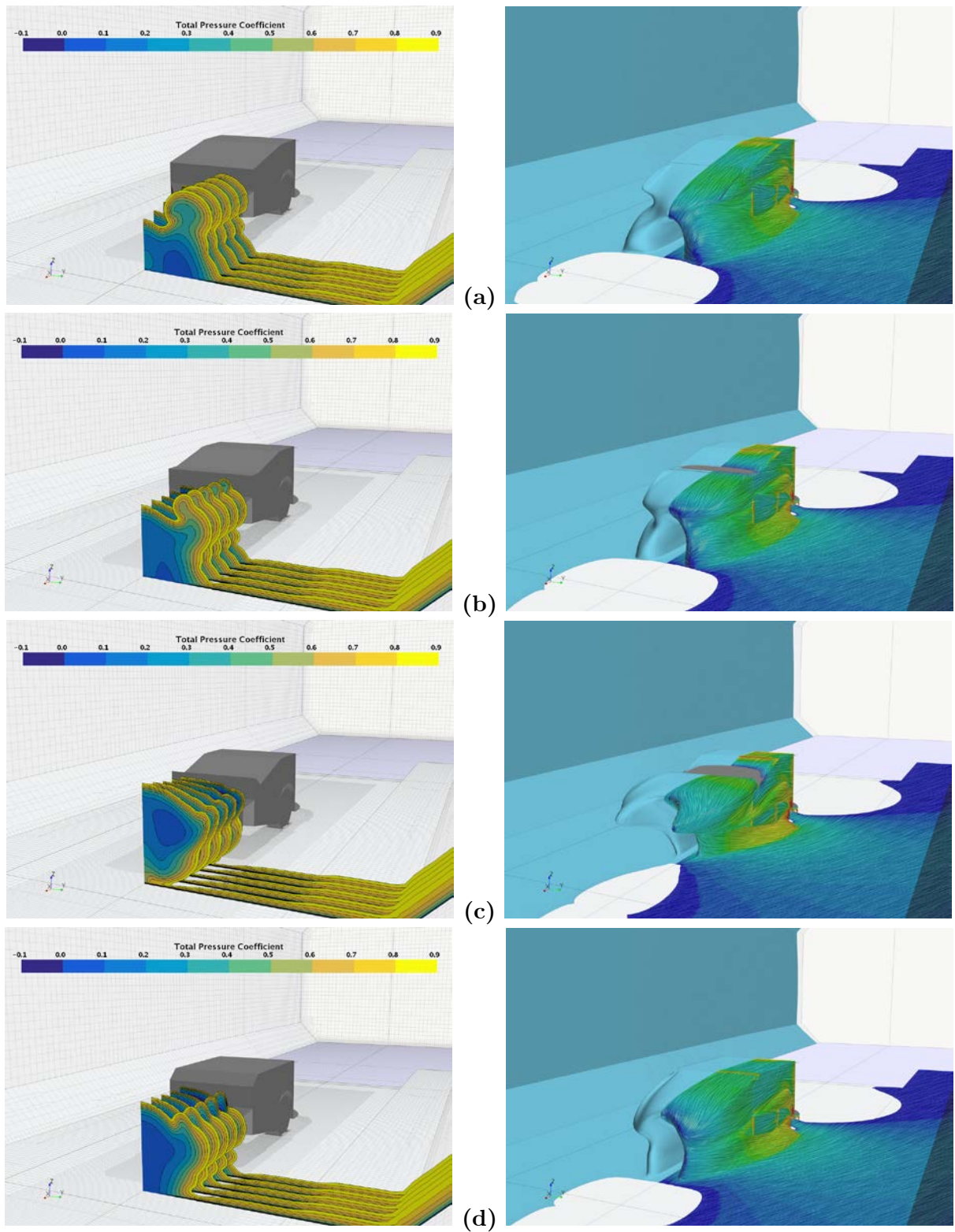


Figure 128. Flow visualisation of the multi-wake generator, design 3. Orthogonal C_{p_t} planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

6.4.4 Multi-Wake Generator, Design 4

This design version intends to improve C_{p_t} distributions of the design 3 wakes by changes in the incidence angle of both upper and lower flows in the wake. The only geometry modifications are (i) the articulation point and (ii) length of the upper slant surface, and (iii) minor reduction of the diffuser angle from 7.34° to 7.09° ($\alpha = -0.25^\circ$). The change on the upper plate impacts the upper slant angle, which represent a change from 10.35° to 8.15° ($\alpha = -2.20^\circ$) on the Fastback shape (Figure 129).

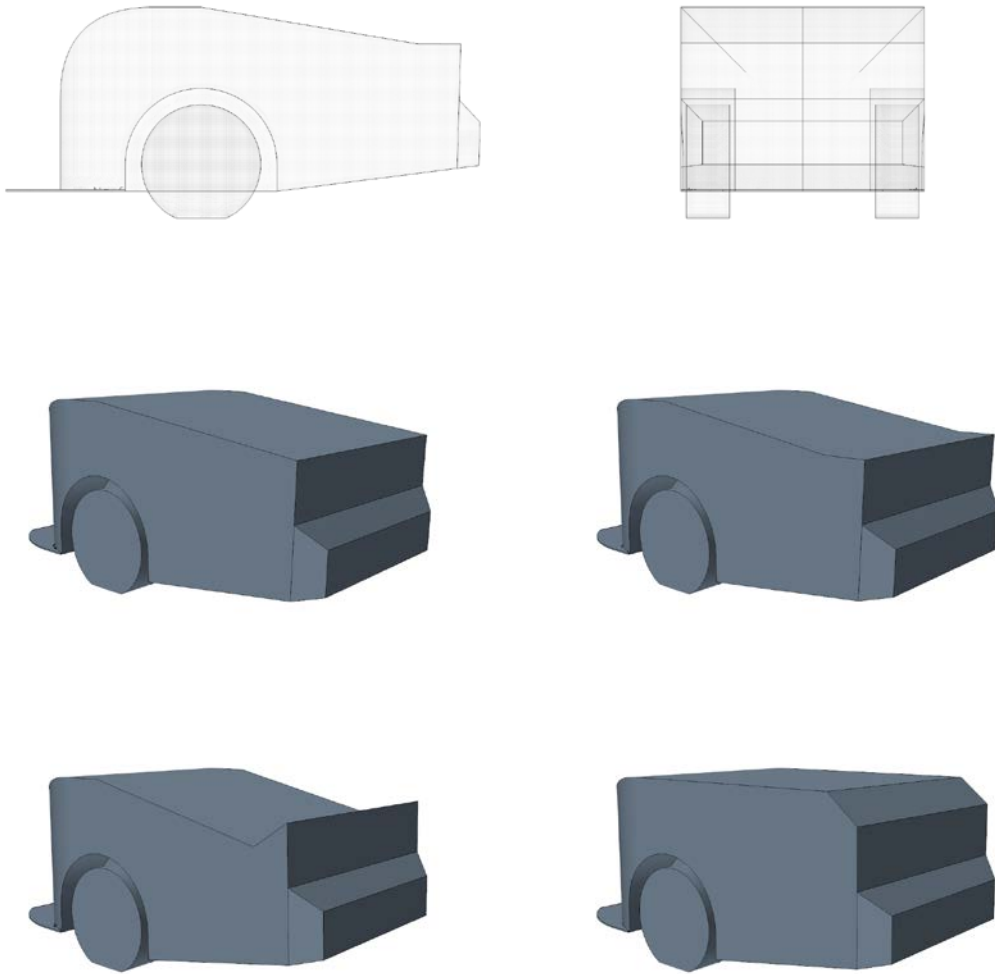


Figure 129. Adaptable, multi-wake generator configurations - Design 4.

There are evidence that the Fastback wake configuration (Figure 130, *a*) has the upper surface downwash reduced proportionally to the slant angle of the upper rear surface, which improves the correlation to the experimental wake reference. In terms of wake topology as a function of the zero- C_p isosurface, the wake core rises while the wake region from the wheels is slightly moved inwards. Orthogonal C_{p_t} planes display that the wake cross-area is significantly increased and reduce the discrepancy to the Notchback wake configuration, then corresponding to a better representation of the wake *Type I* previous design.

The Notchback configuration has the less sensitive wake in relation to the geometric changes adopted in design 4 (Figure 130, *b*). There are no significant changes found on the wake topology, while C_{p_t} distribution suggest a minor increase of the wake size due to the reduction of the upper flow incidence.

Figure 130(*c*) confirms that the geometric changes also improve the wake representation for the high-performance case. The low-incidence flow from the upper surface has a stronger interaction with the spoiler-like protuberance, which generates more intense tip vortices. The upwash wake mechanism is also better represented than the previous design, potentially a result of the minor change in the diffuser angle.

The Estateback configuration has identical results to design 3 since the alignment of the upper surfaces (*e.g.* nose top surface and adjacent pivoting rear body part) generates identical shapes (see Figure 127 and Figure 129).

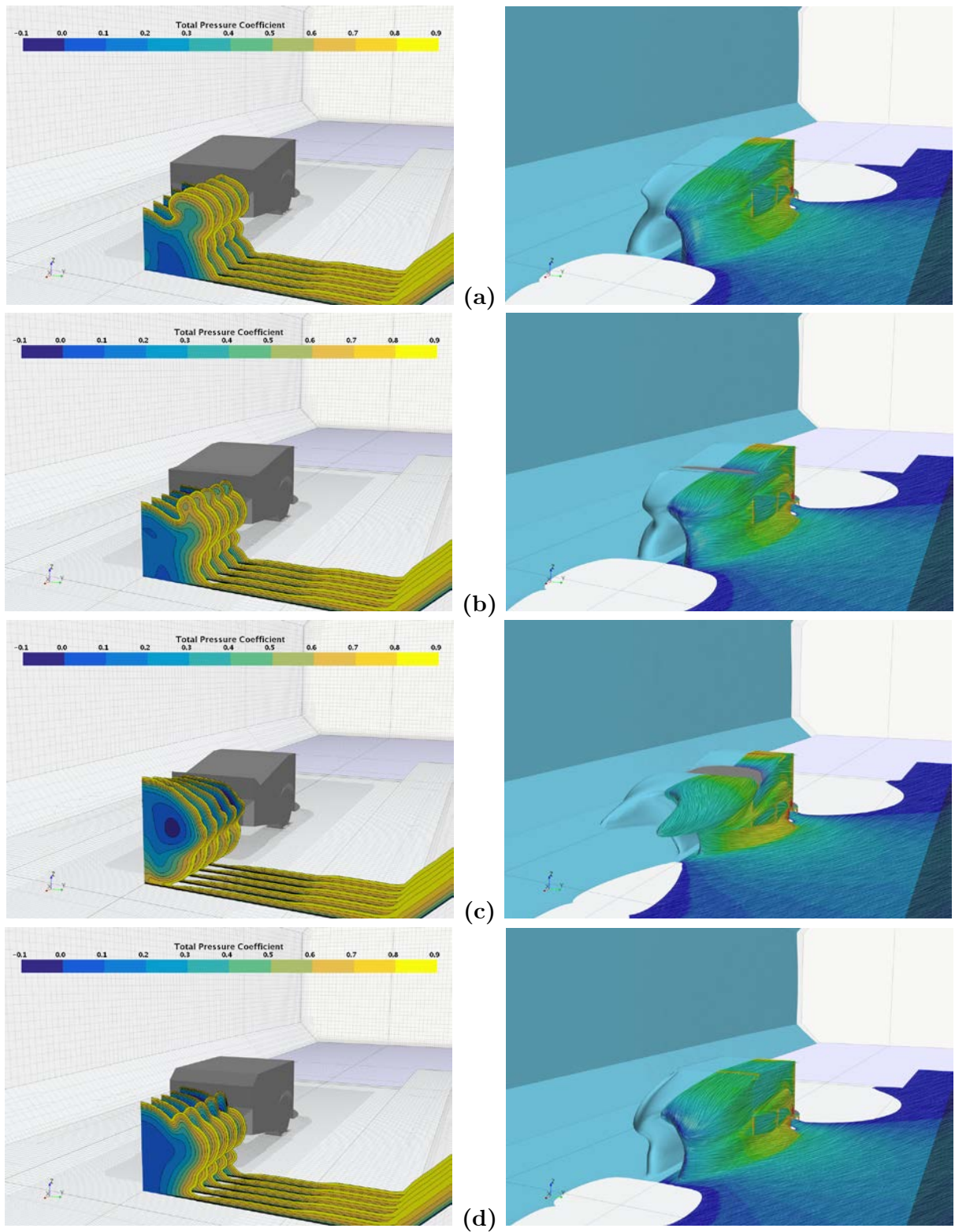


Figure 130. Flow visualisation of the multi-wake generator, design 4. Orthogonal C_{p_t} planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

6.4.5 Multi-Wake Generator, Design 5

Design 5 (Figure 131) focusses on body simplification and better representation of the C_{p_t} distributions to the respective vehicle types. The main geometric changes are (i) the forebody extension equal to $20mm$, while (ii) wheels-related features sustain the same distance to the nose (*i.e.* moves $20mm$ forwards), and (iii) rear bumper suppression. The effect of the rear base protuberance is not significant on the wake evolution from the previous design shapes. The presented

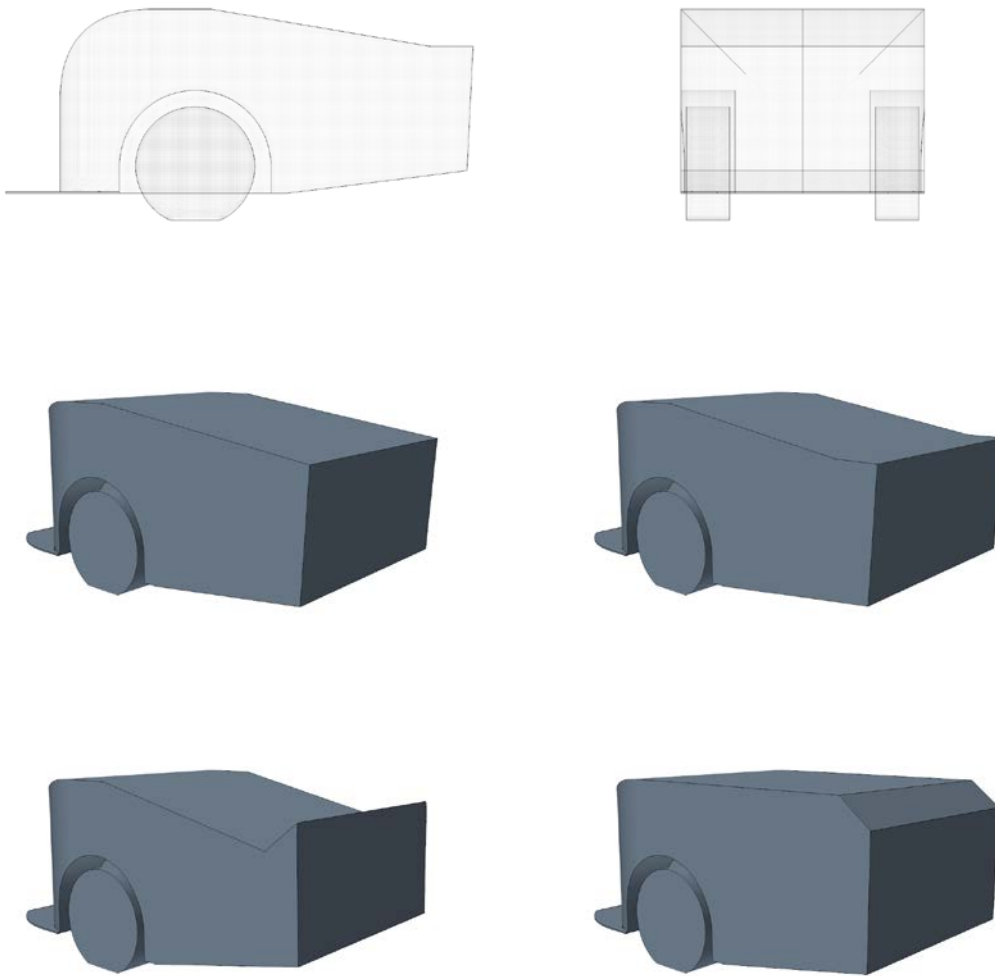


Figure 131. Adaptable, multi-wake generator configurations - Design 5.

design then evaluates if removing the rear bumper is a good compromise for body simplification.

The design changes impacted both Fastback and Notchback (Figure 132, *a*, *b*) configurations similarly. The C_{p_t} planes reveal that the total pressure loss is more similar to measurements of the full-body DrivAer model. The suppression of the rear bumper geometry reduced the lateral inflow, and the upper downwash become slightly more intense. There is a minor horizontal expansion of the upper wake, which is believed to be linked to suppression of the lateral inflow; while the analysis of the zero- C_p isosurface support this conclusion.

However, the Notchback configuration (Figure 132, *b*) provides a wake (i) with more C_{p_t} loss and (ii) with central protuberance higher than the Fastback, both in accordance with experimental references.

The high-performance shape (Figure 132, *c*) is also improved. The C_{p_t} planes show that the total pressure loss is more comparable to the experimental reference, while the a more intense upwash flow expand the wake trace.

There are no significant changes on the Estateback wake, apart from the effects from the rear bumper suppression described above (*e.g.* mitigation of the inflow from the rear bumper lateral edge). Overall, the wake topology and C_{p_t} distribution found in the wake is considered a satisfactory representation for the Estateback vehicle type.

Considering the goal of multiple wake generation from a compact device, the current design provides a good compromise between body dimensions and representation of four vehicle types (*e.g.* Fastback, Notchback, Estateback, and high-performance models), as well as the three automotive wake types classified in Chapter 4, section 4.4.1. Therefore, this wake generator device is proposed for automotive studies and selected for manufacturing and experimental assessment.

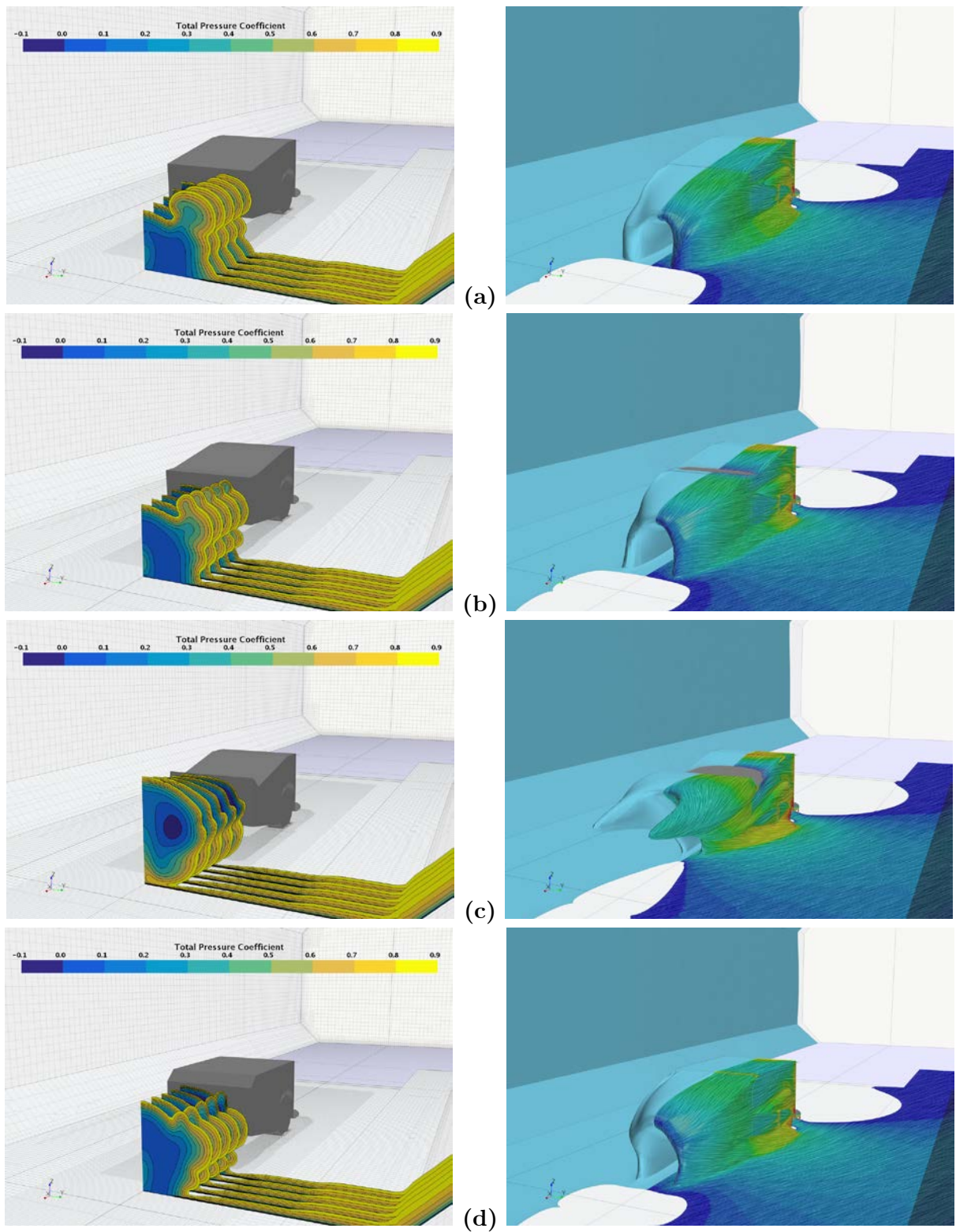


Figure 132. Flow visualisation of the multi-wake generator, design 5. Orthogonal C_{p_t} planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

6.5 CONCLUSIONS

The development of a wake generator device was divided into three design phases. Phase *I* evaluated the possibility of wake emulation using a compact bluff-body based on two DrivAer models (*e.g.* ‘standard’ (*F*) and ‘high-performance’ (*hpF*) Fastback configurations).

These ‘proof-of-concept’ cases themselves can be considered a successful approach to the use of more compact automotive bodies since the resultant bodies have only 47% of the respective vehicle model length.

Phase *II* of the design process explored shape concepts in order to understand the influence of the geometry of a bluff-body on the wake characteristics and then identify the relevant geometric features required for a wake generator body. A front splitter plate demonstrated effective performance in terms of the control of the underbody flow, while a compact, rounded forebody is suitable to expand the flow for the rear body wake generation. The addition of the wheel-related features (*e.g.* wheel body and cavity) improves the representation of the rear wheel wake, compared to the main wake generation.

It is concluded that the representation of side mirrors has low impact on the resultant wake generation with compact bodies. Recent trends in the automotive industry suggest a desire to replace external side mirrors with small cameras in the near future. Therefore, any attempt to represent the side mirror wake in a wake generator is considered negligible and could become obsolete for future applications.

Design Phase *III* focused on the optimisation of four rear body shapes (*i.e.* configurations of an adaptable wake generator geometry). Even though the representation of both velocity field and pressure is a challenge task (see sample in [Figure 12](#), [24]), it was found that the body can assume forms that generate

wakes related to each of the reference DrivAer models, then representing the automotive wake *Types I, II, and III*, defined in [section 4.4.1](#).

An additional design assessment targeting a further implementation of the wake generator as an adaptable, active device is presented in [Appendix D](#).

Chapter 7.

EXPERIMENTAL ANALYSIS OF THE PROPOSED WAKE GENERATOR SHAPES

This chapter reports the experimental tests of the configuration shapes of the wake generator (*Multi-Wake Generator, Design 5*). This experimental campaign employs the same total pressure rake and wind tunnel conditions as full-body models, presented in *Chapter 4*. The experimental validation model of the wake generator shapes also illustrates an alternative approach for wind tunnel implementation: modular components.

The goal is to provide an experimental wake database of the wake generator shapes as a function of total pressure, which can support future studies and development in either CFD or experimental applications.

7.1 WIND TUNNEL MODEL

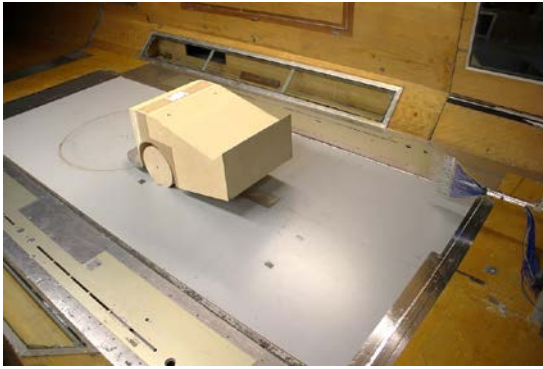
Regarding the interest in wake characteristics only, it was decided to compromise the device manufacturing to solid bodies (*Figure 134*), where modular rear parts can represent the four shapes intended by an active control.

This approach is adopted for two reasons: First, experimental interferences during the aerodynamic evaluation, like body vibrations and deviation of movable parts positioning, are expected to be suppressed. Second, a design with modular parts provides a simpler, more robust and cheaper alternative for implementation and use of the proposed multi-wake generator.

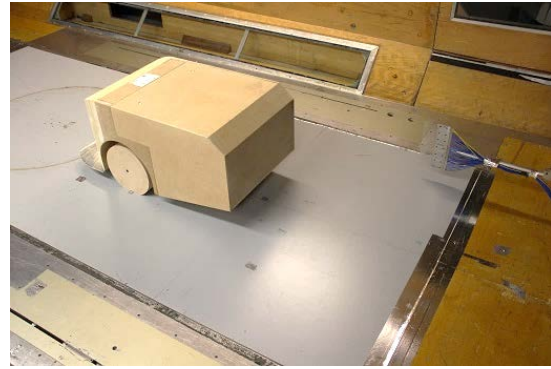
The dimensional body design is in line with the reference 35%-scaled DrivAer model, used as design reference in earlier full-body experiments. *Figure 135* shows

the sketch highlights the forebody components common for all bodies, while [Figure 136](#) presents the four rear ends.

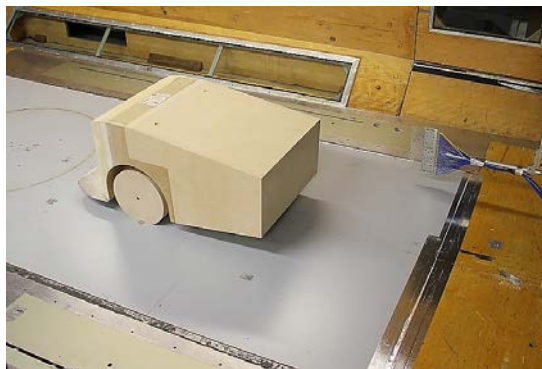
The forebody is a solid wood part with a front splitter made of metallic plate. Wheels are shell bodies made of wooden plates, connected to the main body using a metallic rod as the axle. Each of the four interchangeable rear-body is also shell component built with wooden plates, which can be positioned on the sharable forebody by horizontal pins and fixed by vertical screws ([Figure 133, 134](#)).



(a)

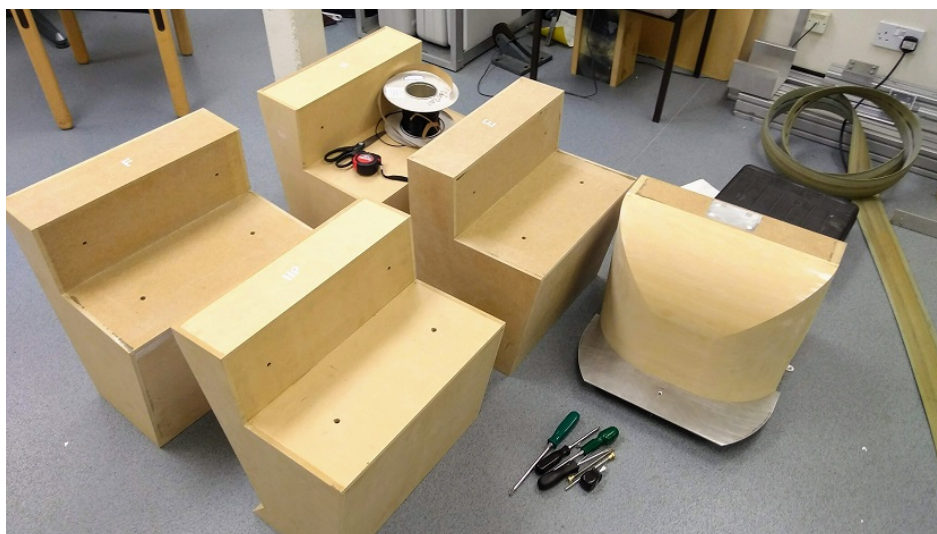


(b)

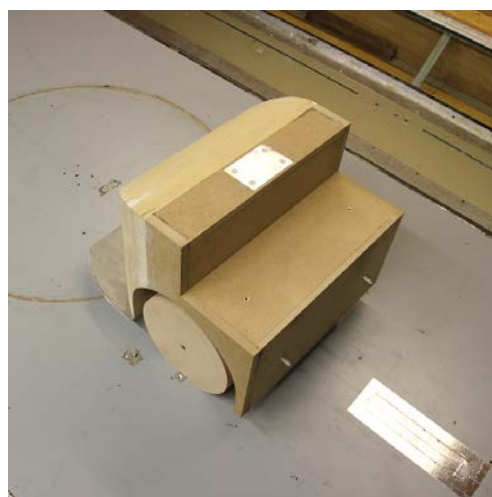
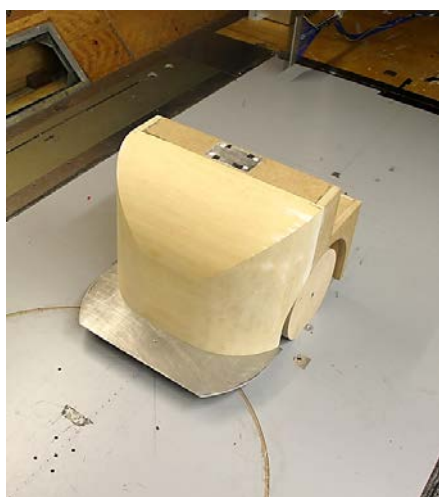


(c)

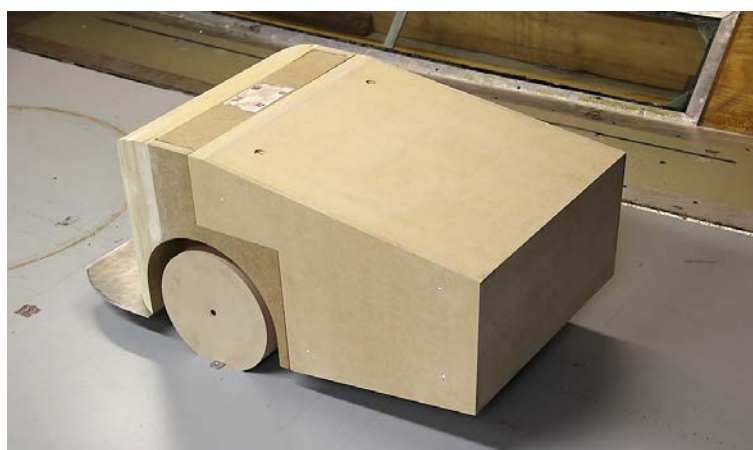
Figure 133. Three relative distance between model and data acquisition plane. (a) *P1*, furthest plane; (b) *P3*, mid-plane; (c) *P5*, nearest plane.



(a) Modular components.



(b) Fixed, forebody part.



(c) 'Fastback' configuration assembled for experiment.

Figure 134. Manufactured components for experimental assesement of the wake generator shapes.

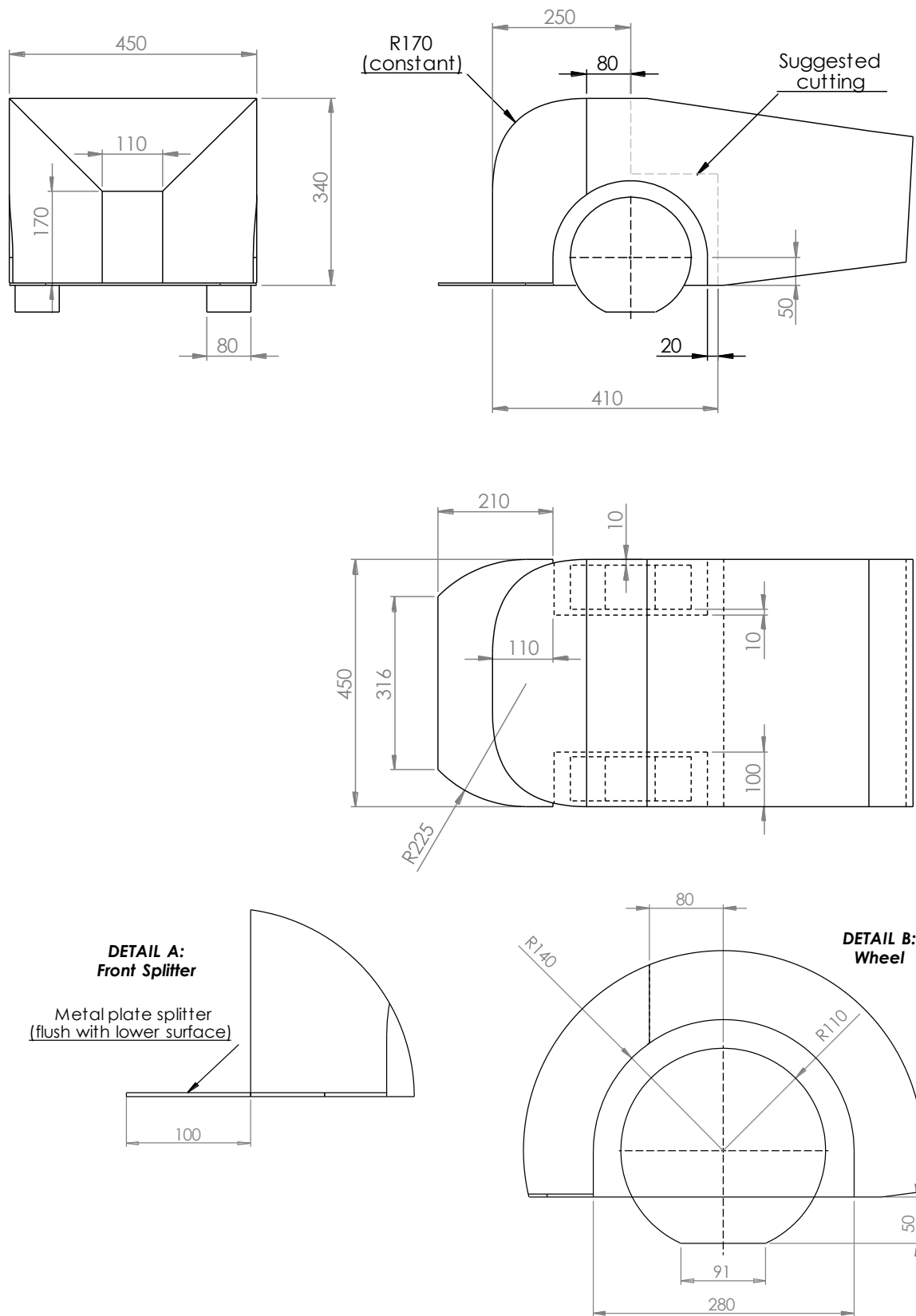


Figure 135. Wind tunnel model: forebody details.

7.2 EXPERIMENTAL METHODOLOGY

This experimental campaign employs similar wind tunnel configuration and conditions of the full-body DrivAer models tests. Details of the experimental methodology and acquisition tool not described in this section are presented in [Chapter 4](#).

The wind tunnel testing plan included 29 experiments covering (i) wake development at standard wind tunnel conditions ([Table 31](#)), (ii) *Re*-sensitivity cases, and (iii) samples for statistical analysis. The first corresponds to a test matrix of 12 cases, summarised in [Table 30](#).

The nomenclature of the DrivAer models is applied on the wake generator configurations for a simpler association to wakes of full-body DrivAer models. [Figure 133](#) illustrates the relative positions in the working test section.

Table 30. Test matrix for cases at standard wind tunnel condition.

	Levels	Description	Notation
<i>Geometry</i>			
Wake generator shapes	4	‘fastback’	<i>F</i>
		‘notchback’	<i>N</i>
		‘estateback’	<i>E</i>
		‘high-performance’	<i>hp</i>
<i>Wake</i>			
Planes	3	300 <i>mm</i>	<i>P5</i>
		450 <i>mm</i>	<i>P3</i>
		600 <i>mm</i>	<i>P1</i>

In terms of the total pressure rake, the only difference is the grid resolution adopted for all wind tunnel tests. The *y*-axis resolution is set equal to 25*mm* in

the range of $-450 < y < 450 \text{ mm}$, which is concluded as best cost-effective use of the wind tunnel time available after analysing the results of an earlier experimental campaign (see [section 4.3.2 ‘On the effects of Measurement Grid Resolution’](#)).

Due to the considerable reduction in the length of the body of interest, a reference to a nominal Reynolds number would contradict the fact that the wind tunnel freestream conditions used are identical to the tests of full-body models, both in terms of air properties and geometric blockage scale.

Therefore, references to the freestream condition are done by velocity magnitude, where the standard freestream condition, U_∞ , is sustained at 40 m/s . Reynold number sensitivity of the wakes are analysed on a same body configuration with additional test at $0.50U_\infty$ and $0.75U_\infty$.

The model alignment followed the procedure used for the DrivAer model tests, and the nominal zero-yaw alignment is set for all cases ([Figure 133](#) and [Figure 137](#)). [Table 31](#) summaries the standard experimental setup.

Table 31. Summary of the standard experimental setup.

Freestream	Position	Ground treatment	Grid resolution
40 m/s	zero-yaw	both BL on	25 mm

7.3 RESULTS AND DISCUSSION, PART I:

On the Assessment of Experimental Conditions

The only exception to the previous discussion in *section 4.2 ‘On the Experimental Methodology’* is the use of a new ground floor is adopted in this experiment. It allows installing the model using screws attached next to the wheels and a small strut underneath the front splitter (see [Figure 137](#)). An analysis of the boundary layer generated from this new surface in an empty wind tunnel was done to evaluate the aerodynamic performance in relation to the floor used for full-body models.

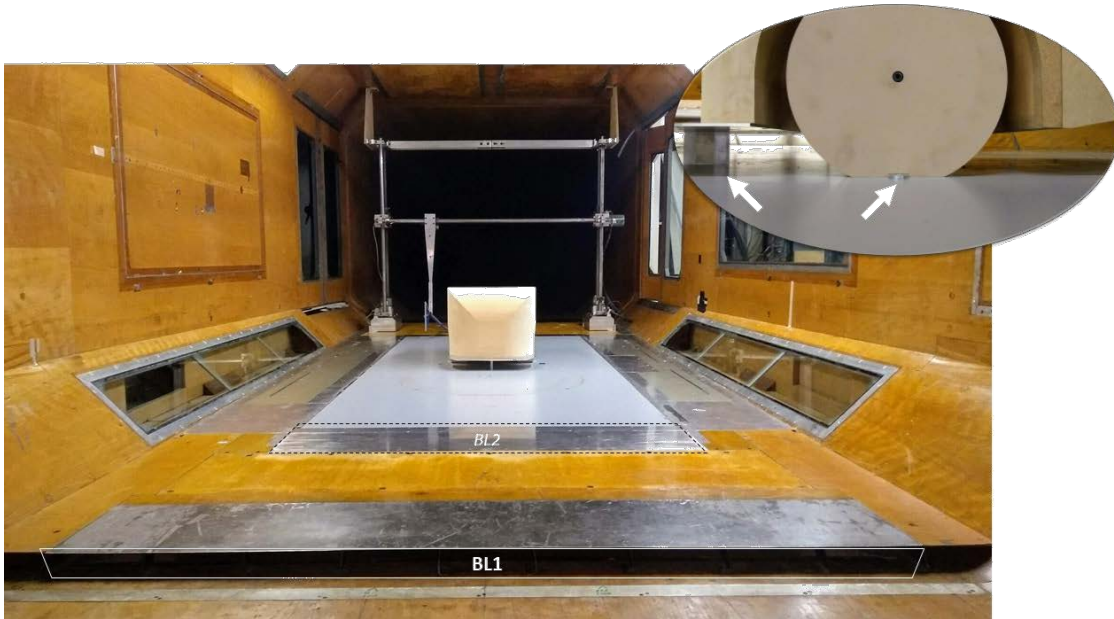


Figure 137. New floor surface used on experiments, highlighting the model connections to the floor and boundary layer control system (BL1 and BL2).

The results lead to the same findings on the previous case presented in *section 4.3.1 ‘On the sensitivity of Boundary Layer Control system (BLC)’*. [Figure 139](#) and [Figure 138](#) report the vertical C_{p_t} profile and distribution, respectively, of the ground boundary layer. The nominal thickness reduces from $85mm$ to $40mm$ when deploying both BL1 and BL2 control systems.

It corroborates the decision to use them during experiments, in order to the lessen the influence of the boundary layer on the wake results. The relation between boundary layer thickness and model gap clearance becomes similar to the full-body cases.

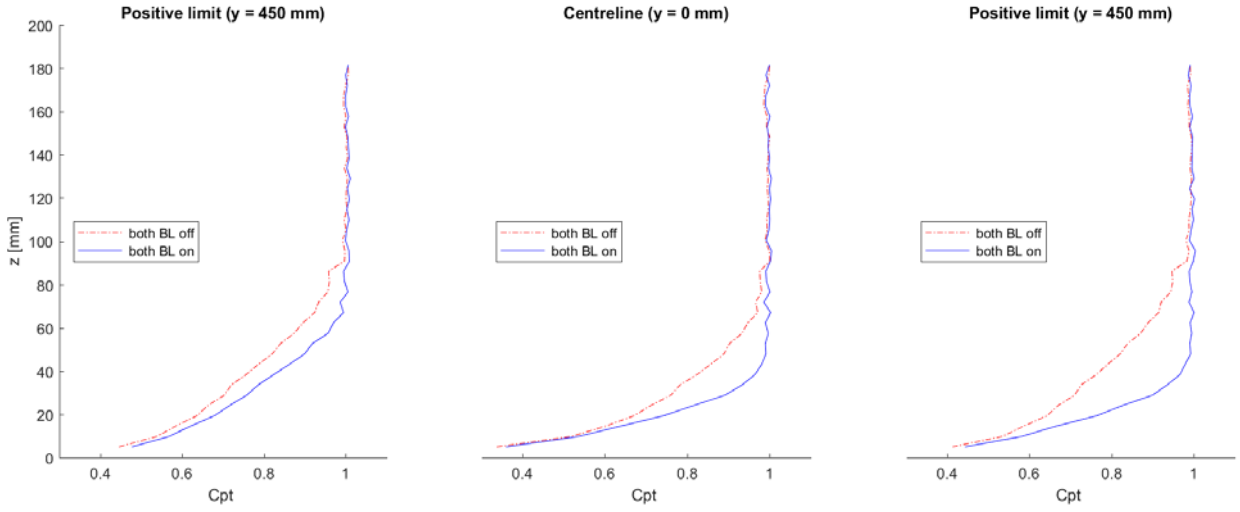


Figure 138. Vertical Cp_t profile as a function of the BL control system.

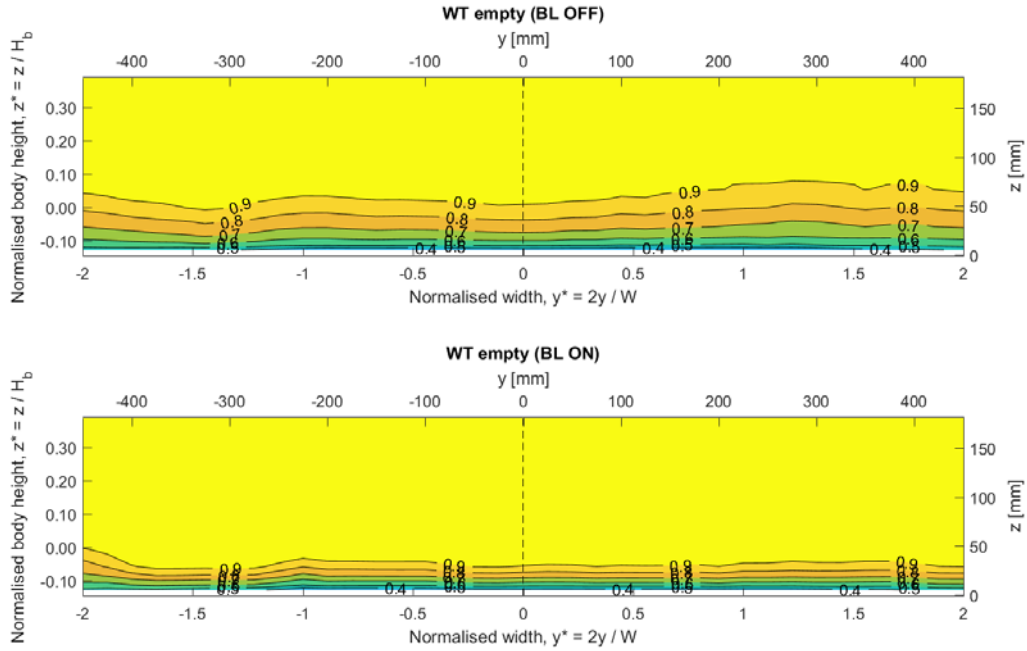


Figure 139. Planar Cp_t distribution as a function of the BL control system.

7.4 RESULTS AND DISCUSSION, PART II:

On the Analysis of the Wake Generator

The analysis of wake generator is divided into three groups:

Group I: Wake characteristics as a function of Vehicle Distance

Group II: On the sensitivity to changes in freestream Reynolds Number for emulated wakes

Group III: On the Statistical Significance of Results

A normalisation of the z -axis, z^* , adopts the body height (H_b). It means that $z^* = z/H_b$ considers the underbody plane as $z^* = 0$, while $z^* = 1$ correspond to the upper body height; therefore z^* is assumed independent to ride height. The normalised y -axis, y^* , scales the axis relatively to the body width, where a unit represents the lateral position of the vehicle (*i.e.* $y^* = 1 = 2y/W$).

Note that the configuration of the adaptable wake generator concept, experimentally evaluated their shapes, are named after the full-body DrivAer reference models: ‘fastback’, ‘notchback’, ‘estateback’, and ‘high-performance’ (Figure 136). The experimental analysis focusses on the wake region delimited by $C_{p_t} = 0.9$, neglecting the small region on the floor, since it is related to C_{p_t} loss due to the ground boundary layer.

7.4.1 Wake characteristics as a function of Vehicle Distance

Three planar sections are assessed by displacing each of the four models in relation to the stationary rake apparatus (Figure 133). The plane nomenclature follows the same use as in full-body analysis (Figure 58), where *P5* corresponds to the cross-section nearest to the model while *P1* is the farthest plane assessed.

Regarding the definition of normalised x -axis (*i.e.* downstream coordinate), the use of the wake generator length ($L = 0.750m$) can mislead an adequate comparison to the full-body models. Therefore, three reference length are proposed: (i) the length of a 35%-scaled DrivAer model ($L_D = 1.614m$) (ii) reference width (*i.e.* $W = 0.450m$), and (iii) the square root of the model reference area (*i.e.* body projection excluding wheels, $\sqrt{A} = 0.391m$) [51].

Table 32 reports the plane distances in terms of model dimension and normalised by relevant reference length (*e.g.* L_D , L , W , and $\sqrt{A}$). For easier association with the full-body DrivAer wakes (Chapter 4), x/L_D is considered for discussion; for further studies, $x/\sqrt{A}$ is recommended.

Table 32. Physical and normalized plane positions.

Plane	P5	P3	P1
Distance [mm]	300	450	600
x/L_D	0.186	0.279	0.372
x/L	0.400	0.600	0.800
x/W	0.666	1.000	1.333
$x/\sqrt{A}$	0.767	1.150	1.534

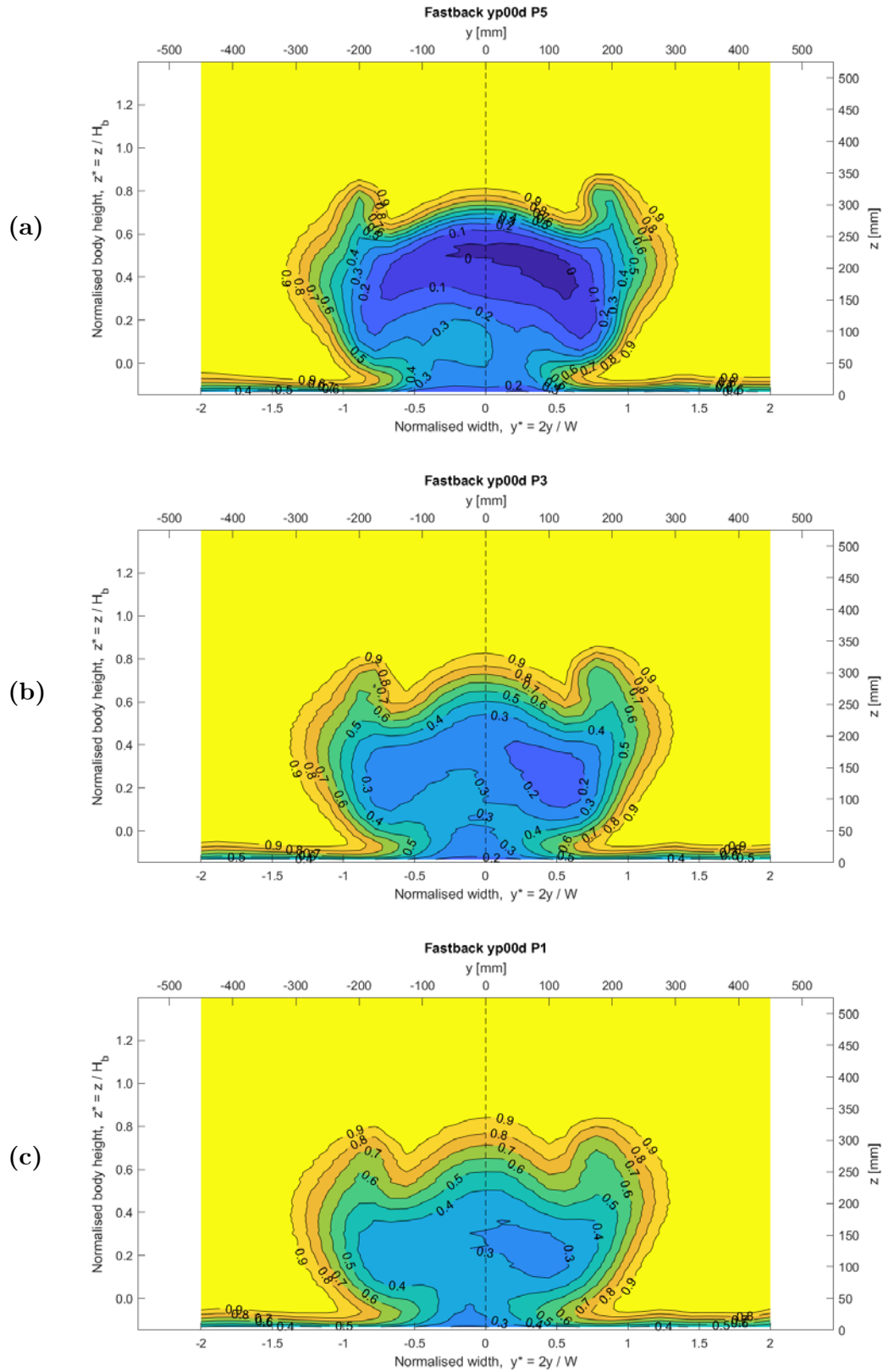


Figure 140. Adaptive wake generator, ‘Fastback’ configuration.
(a) 300mm (*P5*), (b) 450mm (*P3*), (c) 600mm (*P1*).

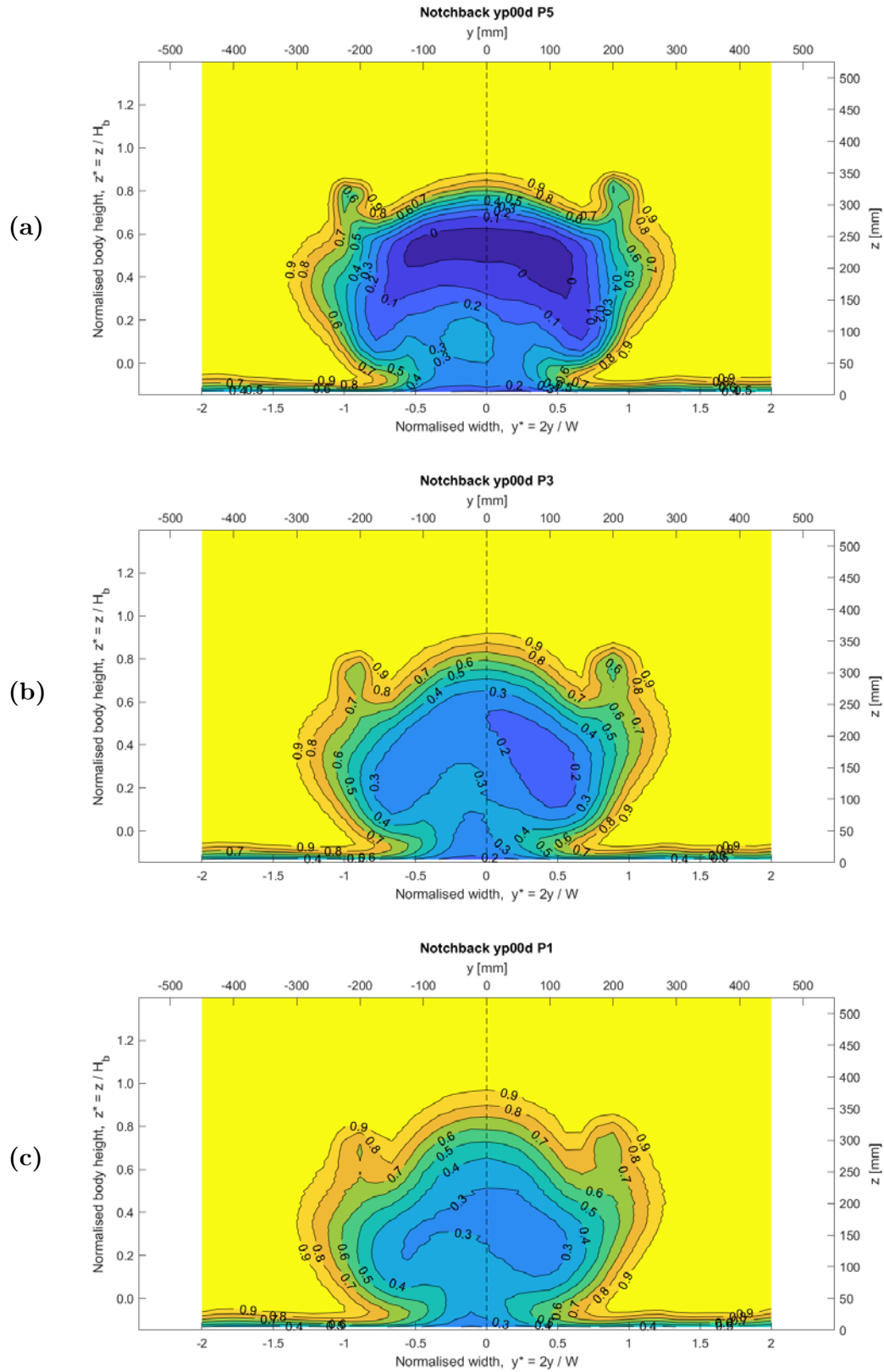


Figure 141. Adaptive wake generator, ‘Notchback’ configuration.
(a) 300mm (*P5*), (b) 450mm (*P3*), (c) 600mm (*P1*).

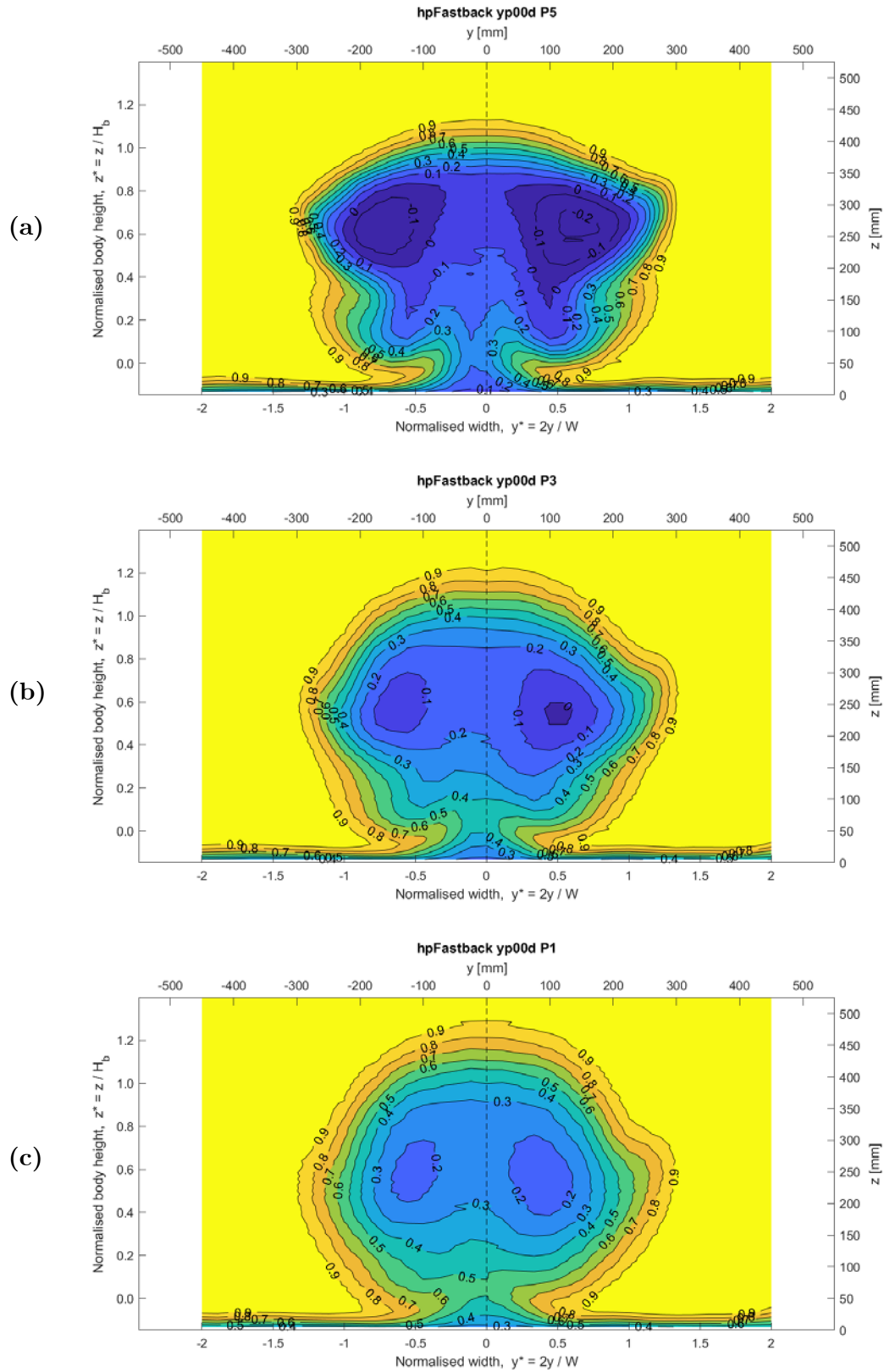


Figure 142. Adaptive wake generator, ‘high-performance’ configuration. (a) 300mm (P5), (b) 450mm (P3), (c) 600mm (P1).

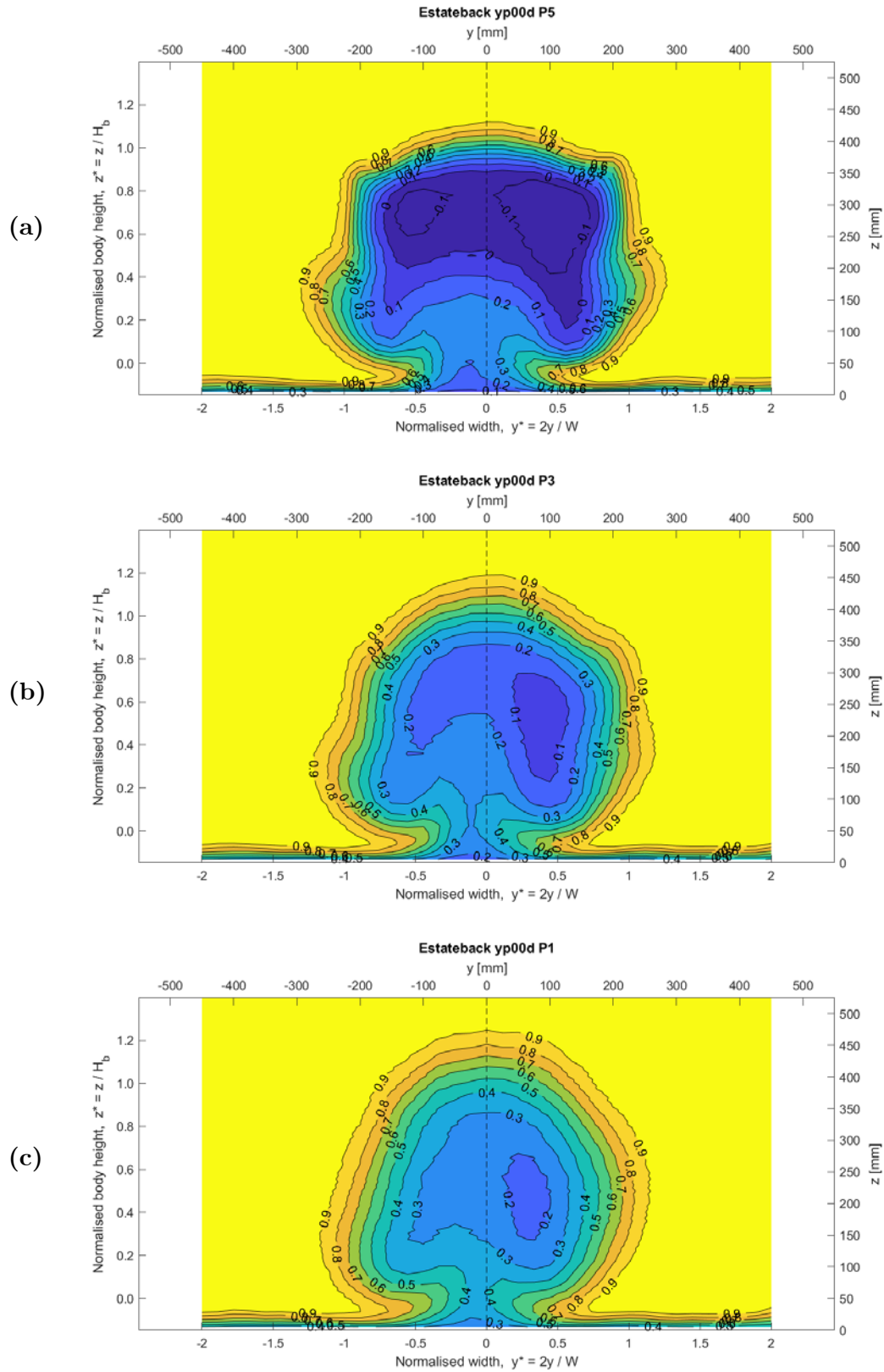


Figure 143. Adaptive wake generator, ‘Estateback’ configuration.
(a) 300mm (*P5*), (b) 450mm (*P3*), (c) 600mm (*P1*).

7.4.1.1 On the ‘fastback’ configuration

Figure 140 presents C_{p_t} contours of the emulated wake corresponding to Fastback-like vehicle models, earlier classified as wake *Type I* (section 4.4.1).

At the closest orthogonal plane $P5$ (*i.e.* $x = 0.186L_D = 0.767\sqrt{A}$), the area of high total pressure loss ($C_{p_t} \leq 0.3$) is found approximately into $-0.9 < y^* < 0.9$ and $0.2 < y^* < 0.6$; a region corresponding to the core of the rear base. Figure 140(a) also shows that the upper region of the wake trace ($C_{p_t} \leq 0.9$) has two lateral protuberances, indicating that the fastback configuration generates vortex structures similar to the ‘C-pillars’ flow produced on realistic automotive bodies, as illustrated in Figure 144. The rear body geometry allows to estimate these ‘C-pillar’ structures as a pair of counter-rotating vortices carrying high- C_{p_t} flow into the wake, which is also identified in CFD simulation (Figure 145).

The wake trace is found to be wider than the geometry base, nearly $|y^*| \cong 1.3$ at $z^* = 0.4$. These lateral regions of C_{p_t} loss are believed to be a consequence of flow structures originated at the wheel cavity (Figure 145), where a separation bubble usually occurs on realistic automotive bodies (illustrated in [34]).

Figure 140(b) presents results at the plane $P3$ (*i.e.* $x = 0.279L_D = 1.15\sqrt{A}$). The upper protuberances, associated to ‘C-pillar’ vortices, become more diffuse and are advected inwards the wake. Simultaneously, the area of high total pressure loss is displaced downwards. The wake region of high- C_{p_t} loss has recovered around $\Delta\overline{C_{p_t}} = 0.20$, and is found lower than in the previous plane ($P5$).

Figure 140(c) shows the C_{p_t} distribution at the furthest plane $P1$ (*i.e.* $x = 0.372L_D = 1.534\sqrt{A}$). It is found that the C_{p_t} gradient decays along the downstream direction, where the wake C_{p_t} distribution changes more significantly between $P5 \rightarrow P3$ (Figure 140, a,b) than the range $P3 \rightarrow P1$ (Figure 140, b,c); a comparable characteristic to the wake of realistic, full-body DrivAer models. Even though the

wake area is similar to the previous planar section ($P3$), the wake core continues the decay process and its C_{pt} distribution is incremented by $\overline{\Delta C_{pt}} \cong 0.15$.

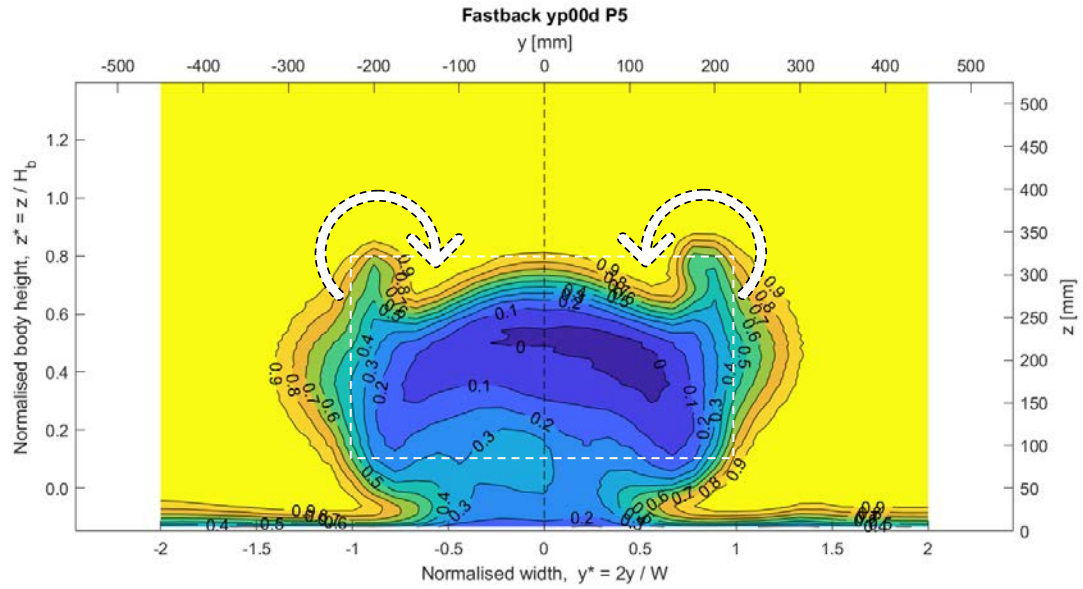


Figure 144. Wake section of the ‘fastback’ configuration at 300mm ($P5$), highlighting the rear base edges and the ‘C-pillar’-like structures.

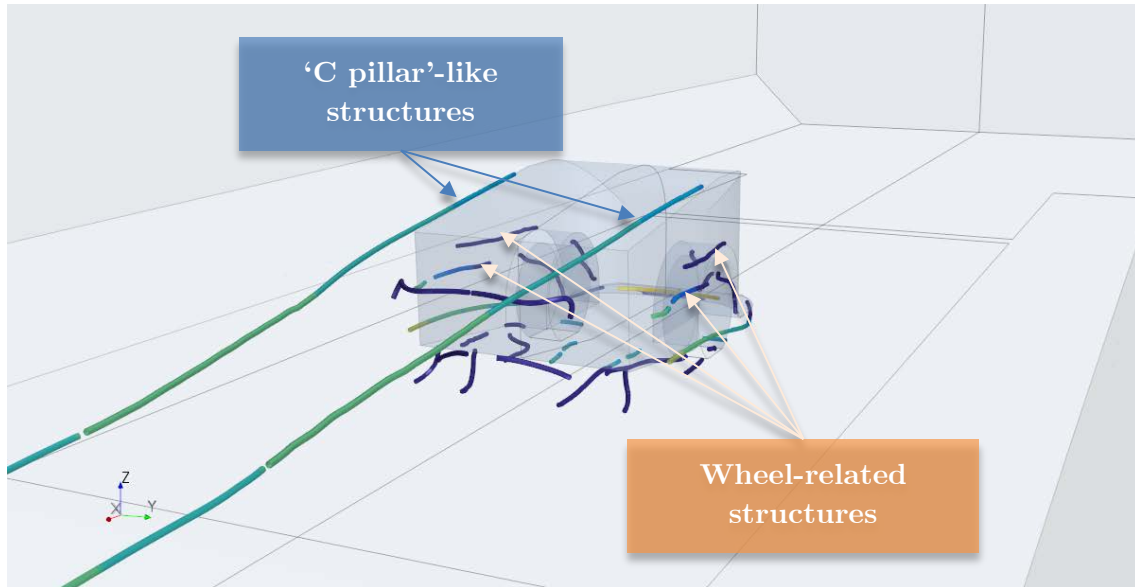


Figure 145. Supplementary CFD result: Vortex path identification related to the ‘C-pillar’-like vortices and wheel representation structures.

7.4.1.2 On the ‘notchback’ configuration

Figure 141 reports the experimental results of the wake generator at notchback configuration. The wake topology does not have critical changes in the overall topology when compared to the fastback configuration, which is in agreement with the proposed definition of wake types (*i.e.* *Type I*, section 4.4.1). The goal of this configuration is provide an additional option for representation of wake *Type I*, where Notchback-like automotive models have a more extensive total pressure loss mostly due to the flows instabilities on the rear window and more intense ‘C-pillar’ structures ([22] [45] [53] [37], illustrated in Figure 26).

The nearest plane to the wake generator, *P5*, shows that the lower half of wake is similar to the fastback configuration, while the upper half is affected by the geometric changes (Figure 141 vs 140; *a*). The upper region is extended vertically by $\Delta\bar{z}^* = 0.072$ when comparing to the fastback wake, where the additional C_{pt} loss area is linked to the larger slant angle of the Notchback rear-end.

The wake in plane *P3* (Figure 141, *b*) has decayed similarly to the fastback wake; however, the $C_{pt} \leq 0.9$ contours suggest that there is a trend of a vertical wake expansion (*e.g.* $\Delta\bar{z}^* = 0.042$ for *P5*→*P3*), which is a characteristic not intended during this configuration design. In plane *P1* (Figure 141, *c*), the wake still sustains a vertical expansion, which results in a total height increment of $\Delta\bar{z}^* = 0.079$ along the range *P5*→*P1*. The increase of wake height is linked with a small reduction in width, approximately equal to 3% when compared to the fastback wake width at the furthest plane (*i.e.* *P1*, Figure 141 vs 140; *c*).

Regarding the representation of the ‘C-pillars’ vortices, the C_{pt} distribution shows two deficit peaks almost separated from the main wake region along the range *P5*→*P1*. Their core are estimated to be higher and outwards of those found on the fastback configuration (Figure 141 vs 140; *a*). While these structures seem to be moved downwards along the fastback wake (Figure 140; *a, b, c*), the notchback

configuration has these flow structures moved diagonally (both inwards and downwards) along the same downstream distance (Figure 141, *a,b,c*).

Figure 146 provides supplementary CFD results on the ‘notchback’ configuration, which suggested that the upper wake has a small downwash. Therefore, it is unclear if the trend of wake height increment, in terms of C_{pt} , is a just a ‘diffusive’ effect or if there is a relevant advective flow mechanism.

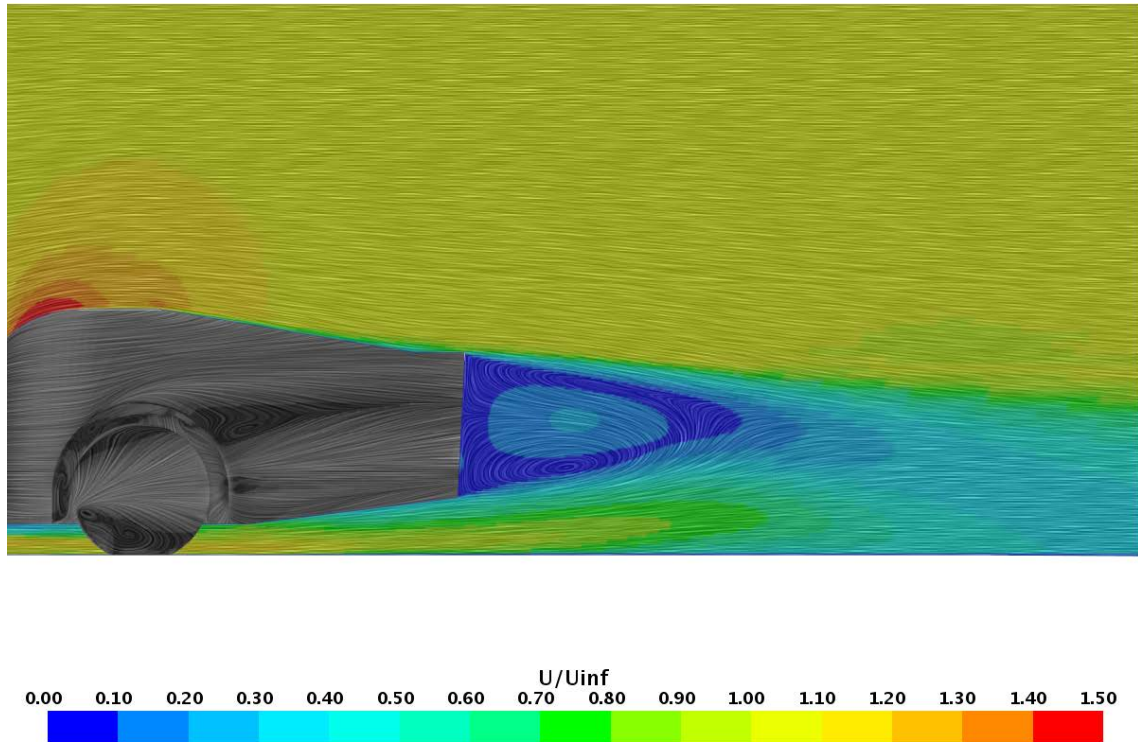
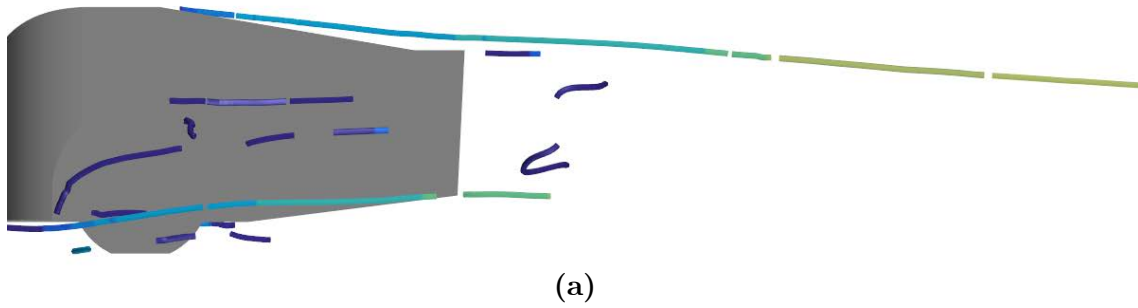


Figure 146. Supplementary CFD results: (a) vortex path identification and (b) LIC velocity field at symmetry plane.

7.4.1.3 On the ‘estateback’ configuration

A representation of a wake *Type II* ([section 4.4.1](#)) is intended with the wake generator at ‘estateback’ configuration, where the body shape is experimentally assessed and presented in [Figure 143](#).

The wake size is more significant than the previous shapes in plane *P5* ([Figure 143, a](#)), where the dimension of the wake trace ($C_{pt} \leq 0.9$) overpass the body height ($z^* \cong 1.11$) with $|y^*| > 1.0$ for the entire projection of the rear base surface. Roughly half of this rear base projection area has $C_{pt} < 0$. It is believed that the probes were not able to measure the flow in this specific wake area potentially due to local of reverse flow in relation to the rake orientation.

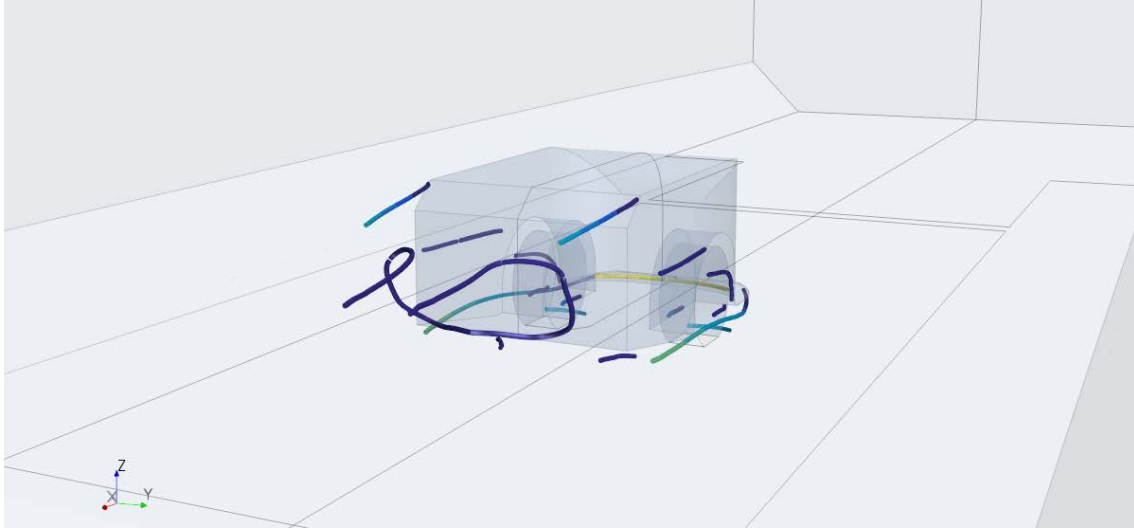
At the adjacent plane downstream the wake, (*i.e.* *P3*, [Figure 143, b](#)), the evidence of probable wake recirculation is not present anymore ($C_{pt} > 0$), therefore the near-wake recirculation limit may be found between *P5* and *P3* ($0.186 < x/L_D < 0.248$; or $0.767 < x/\sqrt{A} < 1.150$). The averaged total pressure recovery in range *P5*→*P3* is $\Delta \overline{C_{pt}} \approx 0.25$. There is a tendency of reduction in wake width, which is balanced by an expansion of the wake height ($\Delta \overline{z^*} = 0.046$).

[Figure 143\(c\)](#) presents the wake section at the furthest plane, *P1*. The wake continues the tendency of horizontal inwards displacement of the C_{pt} distribution, while it expands vertically. The wake is nominally the same in area, but the wake core has a recovery of the total pressure distribution by approximately $\Delta \overline{C_{pt}} \approx 0.20$, with no minimum local.

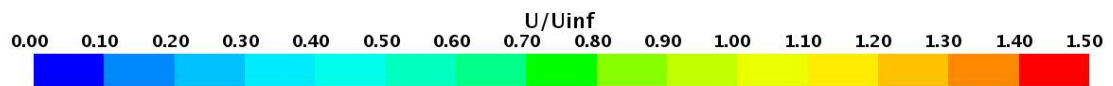
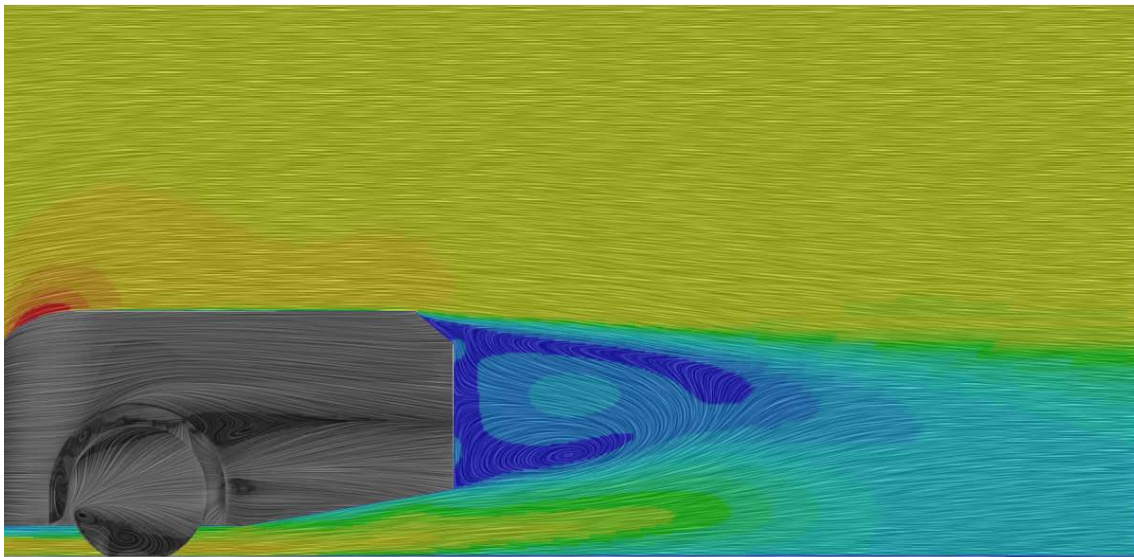
Overall, results suggest that the device can generate a wake *Type II*, which is driven by a full bluff-body flow separation, which characteristics of large C_{pt} decay and horizontal inwards displacement of the C_{pt} distribution.

A CFD simulation of the wake generator at ‘estateback’ configuration is presented in [Figure 147](#). It is found that robust flow structures decay within 1 *W* downstream

the body, confirming the characteristic of a bluff-body wake similar the one found on assessment of the full-body DrivAer Estateback model (*Chapter 4, section 4.4.1.2*).



(a)



(b)

Figure 147. Supplementary CFD results: (a) vortex path identification and (b) LIC velocity field at symmetry plane.

7.4.1.4 On the ‘high-performance’ configuration

Figure 142 presents C_{p_t} contours of the wake associate to high-performance vehicles, earlier defined as wake *Type III* (section 4.4.1). The main wake characteristics is the strong upwash mechanism, usually a coupled production from the diffuser and rear wing/spoiler. This flow characteristic can be found in the wake of either closed-wheel or single-seater open-wheel (Figures 34 to 36, Figure B-2 to 7) race cars.

The wake section in plane $P5$ (Figure 142, *a*) indicates that it corresponds to the largest and strongest wake emulated among the proposed four wake generator configurations. In plane $P5$, the wake trace ($C_{p_t} \leq 0.9$) reaches $z^* \cong 1.13$, with maximum width of $|y^*| \approx 1.34$; therefore, larger than the body dimensions itself. The large wake width is linked to the presence of two regions of high- C_{p_t} deficit with cores at located $|y^*| \approx 0.63$, $z^* \cong 0.64$. They suggest a pair of counter-rotating vortices in the wake (see Figure 148), which are designed to represent the tip vortices of rear wing/spoiler of realistic race cars.

At the subsequent plane $P3$ (Figure 142, *b*), the wake height is $z^* \cong 1.20$, an increment of $\Delta z^* = 0.092$ for $P5 \rightarrow P3$, while the width is reduced and the wake topology tend to assume a ‘circular’-like shape. The vortex structures are revealed as strong, coherent features in the wake since they sustain a difference of $\overline{\Delta C_{p_t}} \approx -0.20$ to the surrounding wake core.

The axial C_{p_t} gradient in the wake is significantly reduced when observing the $P3 \rightarrow P1$ planes (Figure 142, *b,c*). The wake expands vertically even further, reaching $z^* \cong 1.29$ ($\Delta z^* = 0.077$ for $P3 \rightarrow P1$), and the wake topology becomes even more a rounded area. A total pressure recovery of $\overline{\Delta C_{p_t}} \approx -0.10$ is found in the wake core for $P3 \rightarrow P1$.

A supplementary CFD simulation confirms the presence of a pair of vortex structures in the wake, where the vortex path area highlighted in [Figure 149](#).

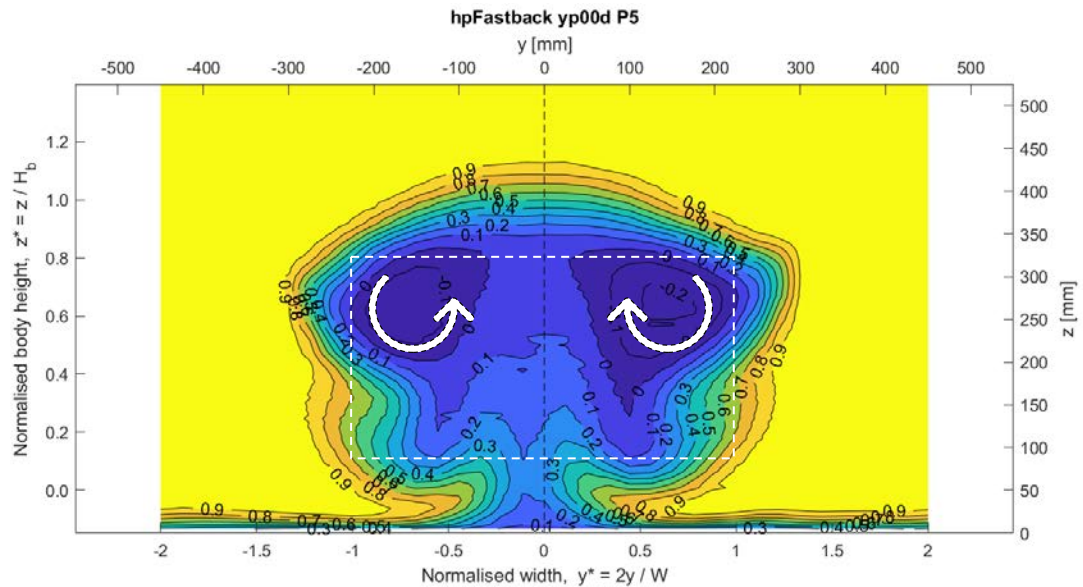


Figure 148. Wake section of the ‘high-performance’ configuration at 300mm (P5), highlighting the rear base edges and the ‘tip-vortex’-like structures.

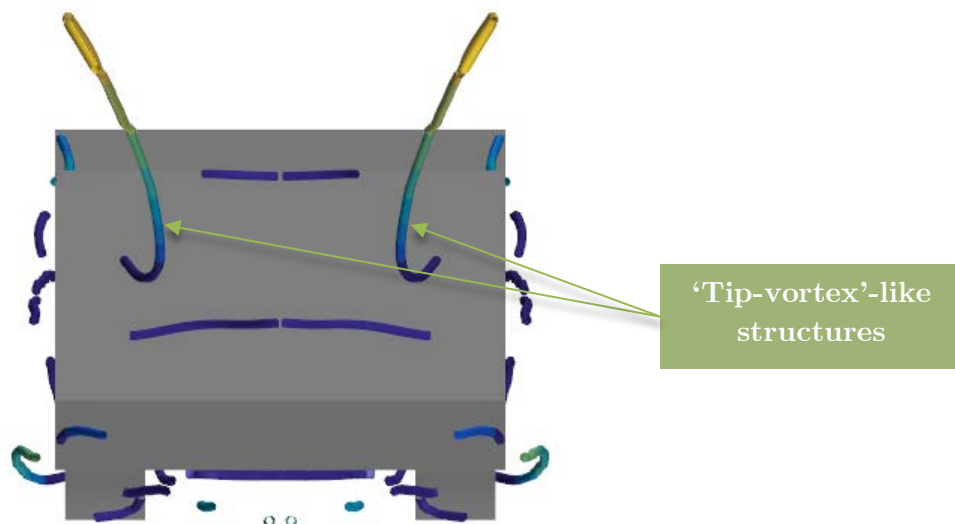


Figure 149. Supplementary CFD result: Vortex path identification highlighting a pair of vortex structures in the wake, representing the tip vortex from rear wing/spoiler from realistic race cars.

7.4.2 On the sensitivity to changes in freestream Reynolds Number for emulated wakes

In line to the discussion regarding length normalisation, the usual reference to Reynolds number as a function of the body length ($L = 0.750m$) could mislead the fact that the standard flow condition is similar to the tests of full-body models, in both air properties and geometric scale.

Therefore, references to the flow condition are undertaken by velocity magnitude, where the standard level is sustained identically at 40 m/s to full-body experiments, which correspond to $Re_L = 1.882 \times 10^6$, $Re_W = 1.129 \times 10^6$, or $Re_{\sqrt{A}} = 2.596 \times 10^5$. Note that identical flow condition is exposed when using the DrivAer model length ($L_D = 1.614m$): $Re_{L_D} = 4.05 \times 10^6$.

For simpler notation, the effect of the Reynolds number on the wake characteristics is quantified by the freestream speeds: 20 m/s , 30 m/s and 40 m/s ; corresponding to a nominal Re_{L_D} equal to 2.03×10^6 , 3.04×10^6 , and 4.05×10^6 , respectively. The Re -sensitivity analysis covers two opposing wake types emulated by the proposed device at different plane positions.

The wake from the ‘fastback’ configuration is assessed at the nearest plane, *P5*, and represents a wake *Type I* (. The furthest plane, *P1*, is used when evaluating the ‘high-performance’ configuration wake, which represents a wake *Type III*. Experimental wake measurements are presented, as a function of total pressure (C_{p_t}), for freestream at 20, 30 and 40 m/s (Figure 150 and 152), while the relative C_{p_t} increment is presented in (Figure 151 and 153).

Measurements at 20 m/s (Figure 150, 152; *a*) are affected by a significant noise ($\widetilde{C_{p_t}} < 0.05$), potentially due to a low signal-to-noise ratio, leading to a respective on the analysis of relative C_{p_t} increments (Figure 151, 153; *a*). Therefore, the analysis focus on fluctuations larger than $\pm 0.02C_{p_t}$, which removes both the noise

and the precision uncertainty of the experiment (*section 7.4.3 ‘On the Statistical Significance of Results’*).

Regarding the ‘fastback’ configuration, there is no significant fluctuation of the planar C_{p_t} distribution for $U_\infty = 20 \rightarrow 30 m/s$ (*Figure 151, a*). There is only one relevant area with a small total pressure decay, found at the upper wake region, corresponding to $\overline{\Delta C_{p_t}} = -0.039$. However, regions of the ground boundary layer demonstrated to be more Re -sensitive than the wake itself.

For $U_\infty = 30 \rightarrow 40 m/s$, the upper wake region has another small decay of $\overline{\Delta C_{p_t}} = -0.034$ (*Figure 151, b*). Overall, the wake topology and the C_{p_t} distribution at 30 and 40 m/s are nearly identical (*Figure 150, b,c*).

The most intense wake of the proposed device is generated by the ‘high-performance’ configuration. Despite the noisy data at lowest Re , *Figure 153(a)* shows that most of the upper wake region tends to reduce the total pressure distribution by $\overline{\Delta C_{p_t}} = -0.042$ for $U_\infty = 20 \rightarrow 30 m/s$. At the lower half of the wake, the region at +ve y -axis quadrant (right-hand side) has an averaged decay of $\overline{\Delta C_{p_t}} = -0.032$, while the portion at -ve direction (left-hand side) has a positive increment of $\overline{\Delta C_{p_t}} = +0.029$.

Figure 153(b) presents the changes in C_{p_t} distribution for $U_\infty = 30 \rightarrow 40 m/s$. The previous trends are reversed, since there is a total pressure recovery at the upper region of $\overline{\Delta C_{p_t}} = +0.036$, while the lower wake region has a total pressure drop of $\overline{\Delta C_{p_t}} = +0.030$, mostly at -ve direction (left-hand side). The overall wake topology is constant, indicating that the variations in C_{p_t} are negligible.

In summary, the Re -sensitivity evaluation of the wake as a function of C_{p_t} only shows small variations ($\overline{\Delta C_{p_t}} < \pm 0.05$). This fact suggests wakes are nominally Re -independent at the standard condition tested ($U_\infty = 40 m/s$), where the Re_{tr} is believed to within the range of $Re_{\sqrt{A}} = 1.947 \rightarrow 2.596 [\times 10^5]$.

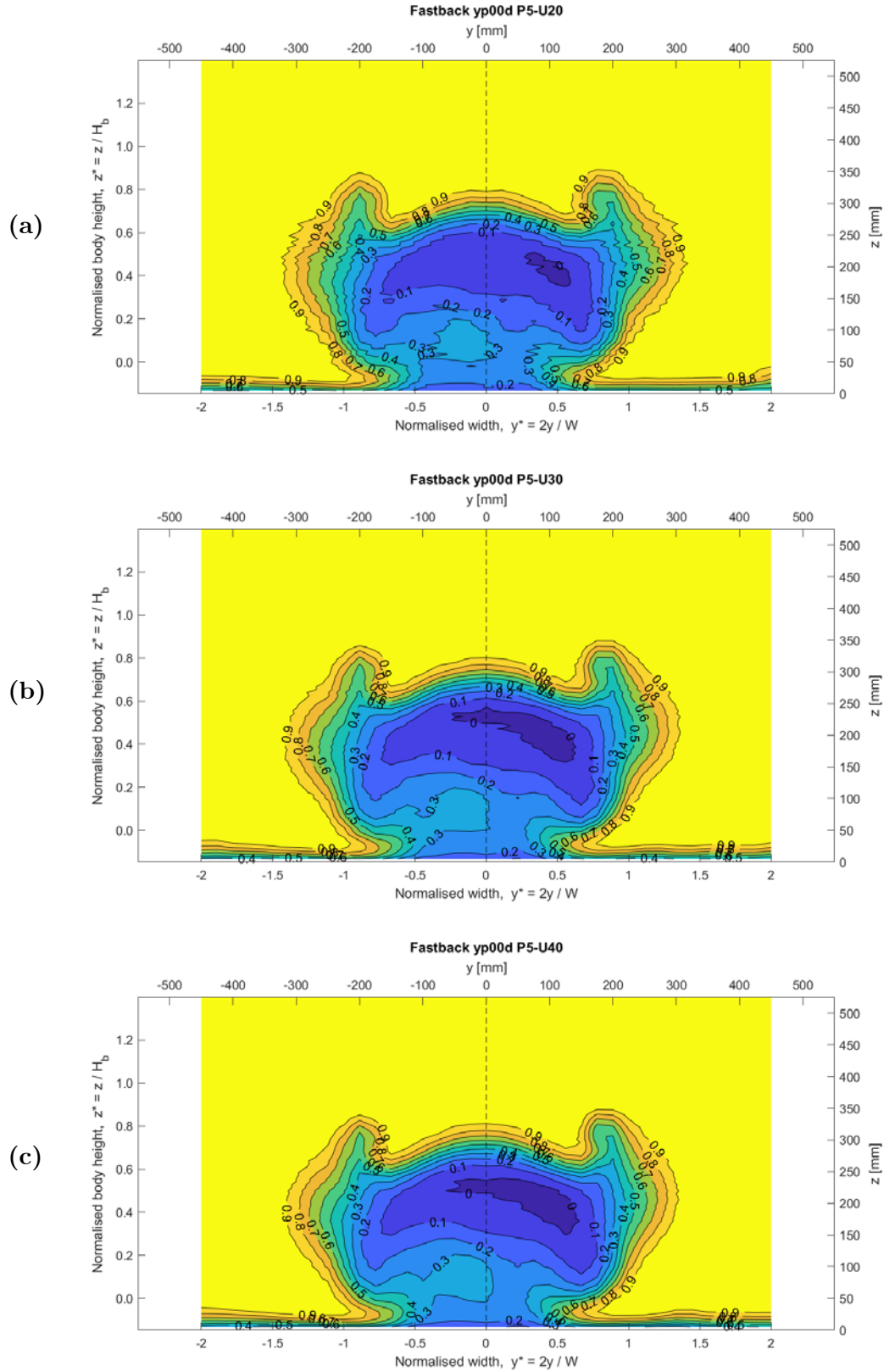


Figure 150. *Re*-sensitivity of ‘fastback’ configuration wake, part I: Cp_t distribution at (a) 20 m/s, (b) 30 m/s, (c) 40 m/s.

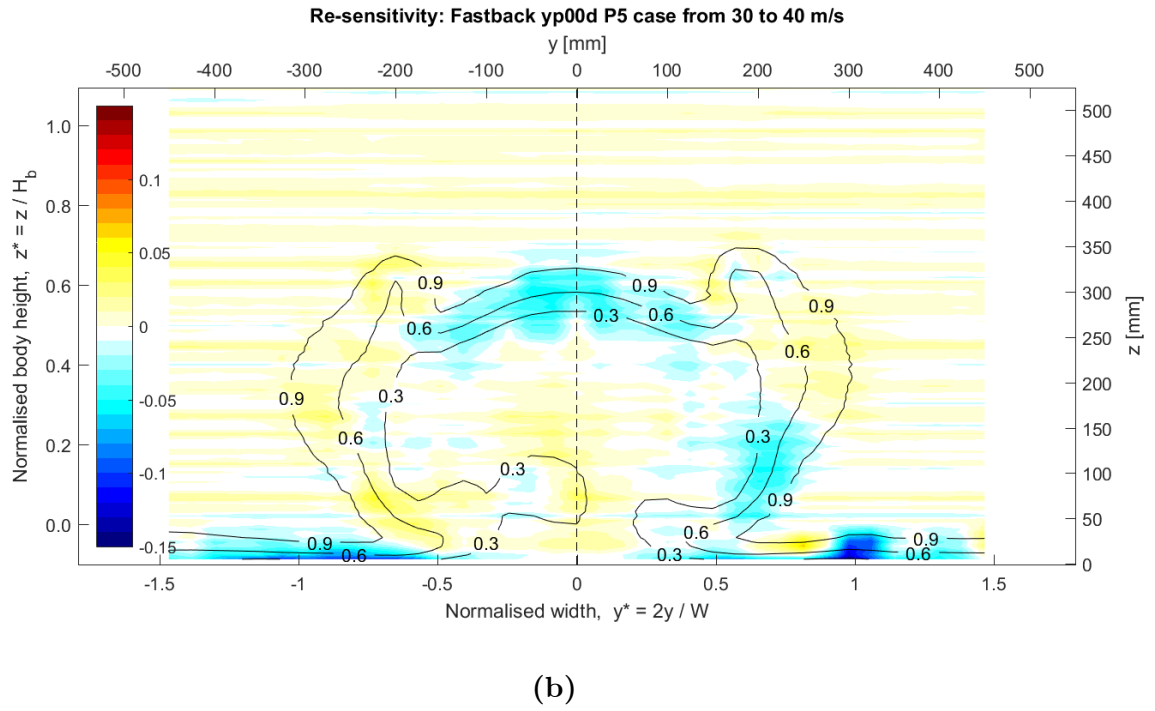
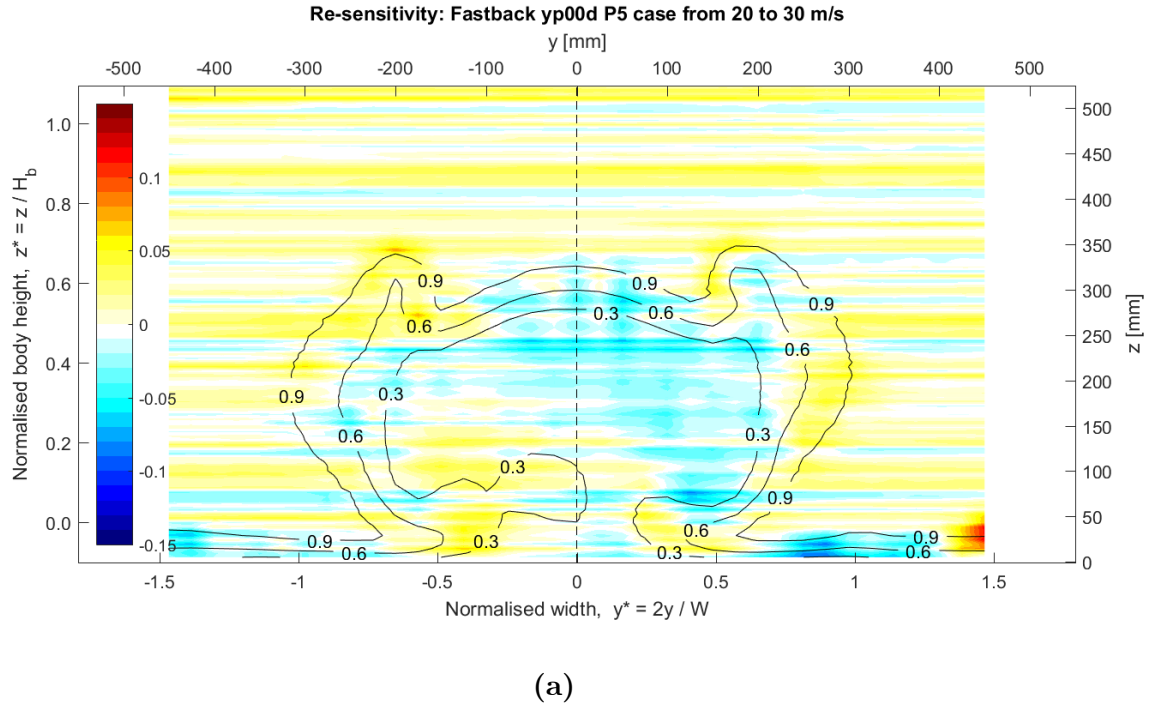


Figure 151. *Re-sensitivity* of ‘fastback’ configuration wake, part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 *m/s*, and (b) 30 to 40 *m/s*.

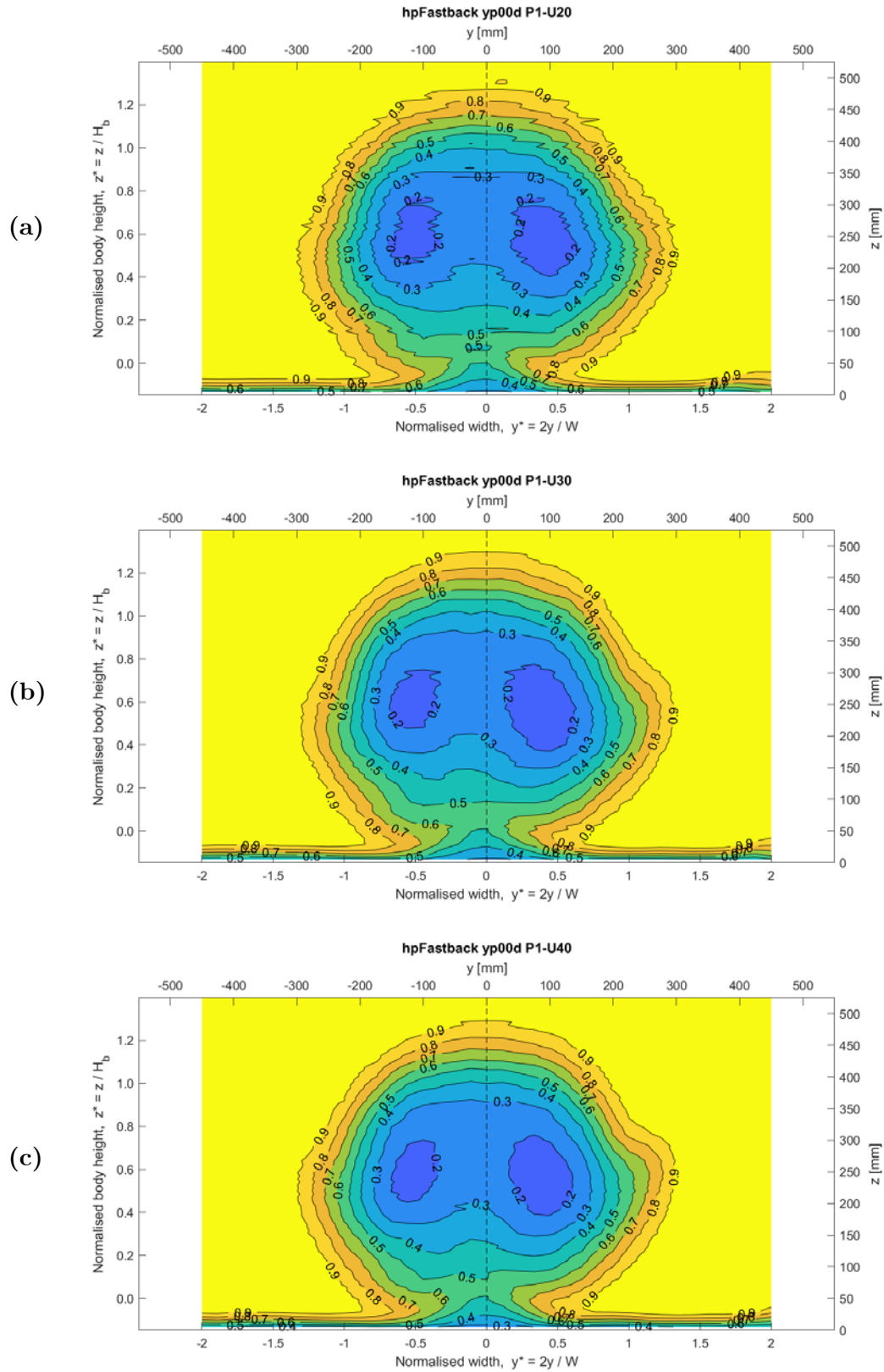


Figure 152. *Re-sensitivity* of ‘high-performance’ configuration wake, part I: C_{p_t} distribution at (a) 20 m/s, (b) 30 m/s, (c) 40 m/s.

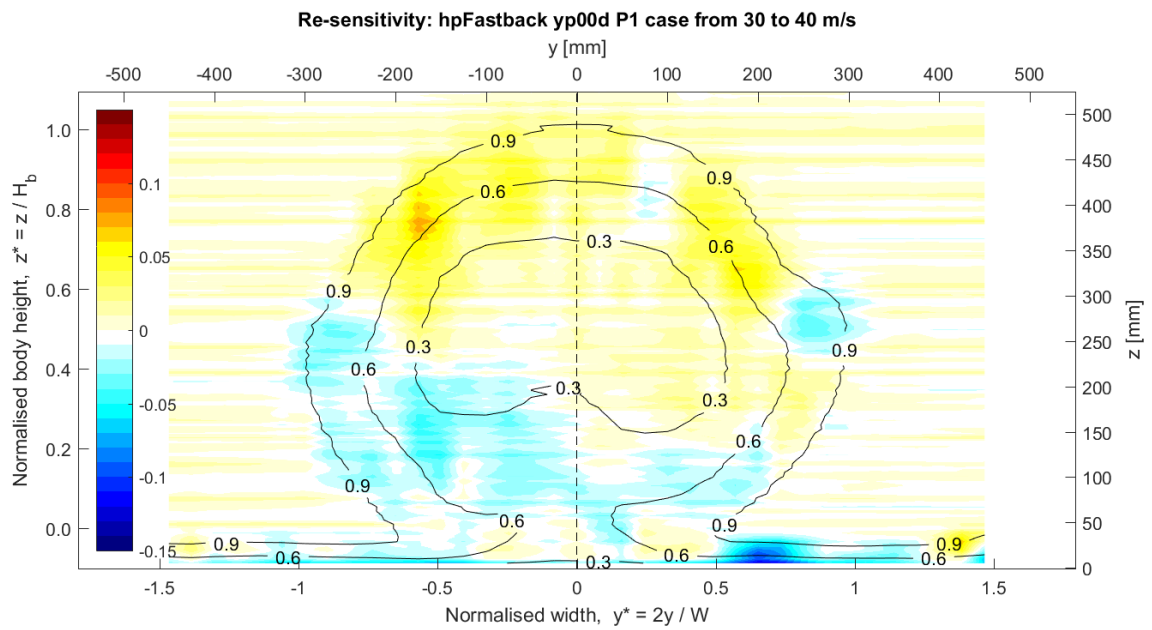
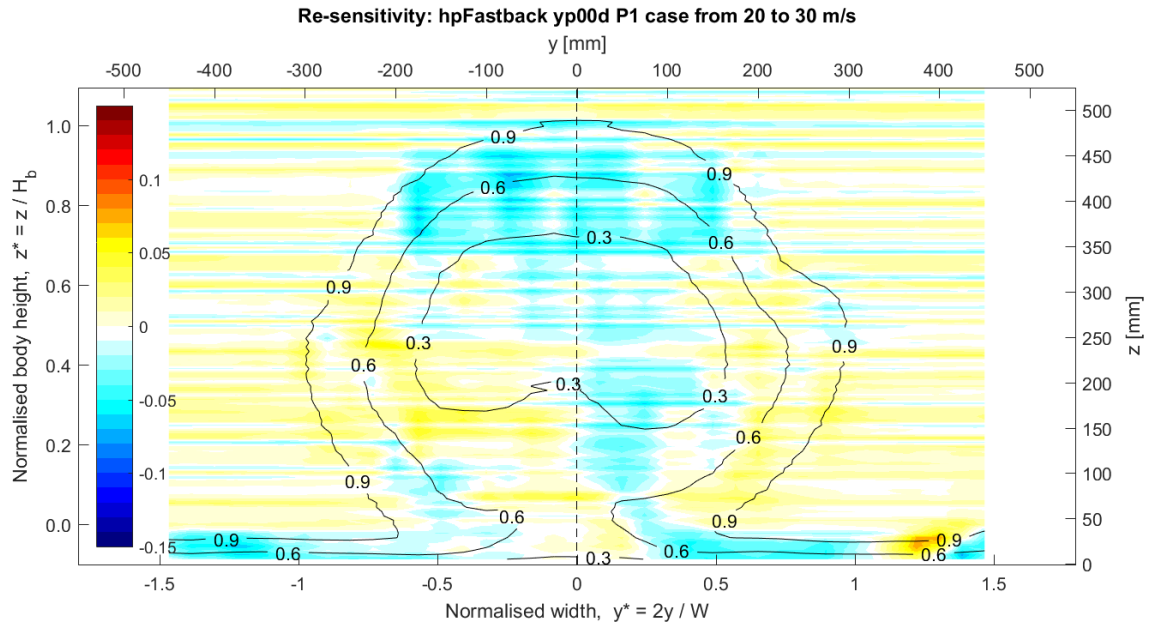


Figure 153. *Re*-sensitivity of ‘high-performance’ configuration wake, part II: ΔC_{p_t} increment for freestream variation between (a) 20 to 30 m/s, and (b) 30 to 40 m/s.

7.4.3 On the Statistical Significance of Results

The wake generator for the Fastback configuration is adopted as a baseline for this analysis, which reapplies the methodology used for full-body models (*Chapter 4, section 4.5 ‘Statistical Analysis’*). Therefore, the analysis presented is for a confidence level of 95%, considering a two-tail significance level of $\alpha/2 = 2.5\%$.

Figure 154 displays the resulted confidence interval map where the confidence interval (*i.e.* $\Delta CI = 2|e| = 2 \left| t_{(\alpha/2, df)} \sqrt{s^2/n} \right|$) are calculated using eight wake samples (*i.e.* $df = 7$) measured at the nearest plane, *P5*.

The precision of total pressure measurements is reaffirmed as satisfactory in the experimental campaign of the wake generator. For the region outside the wake trace (*i.e.* $z^* > 0.8$), the averaged uncertainty band is $\overline{\Delta CI} \cong 0.005$, with maximum peaks of $\Delta CI = 0.010$. It can be state that time-averaged probe precision is $\overline{\Delta C_{pt}} = \pm 0.003$ at steady flow with minor disturbances (*i.e.* $C_{pt} \approx 1$).

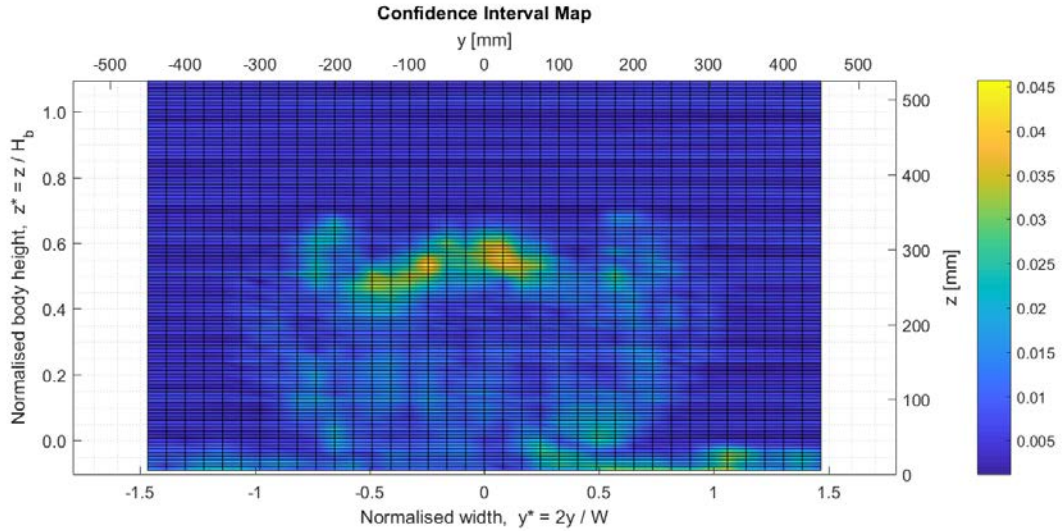


Figure 154. Analysis of confidence interval: planar distribution map (95% confidence level), ‘fastback’ configuration.

Any disturbance on the flow leads to a clear increment in the uncertainty band. To illustrate this matter, the trace of significant confidence interval above the random error (*i.e.* $\overline{\Delta CI} > 0.005$) is analogous to the wake trace of $C_{pt} < 0.9$. This evidence shows that the presence of turbulent flow in a region increases the confidence interval range of the respective point, albeit not proportionally.

Two regions of high uncertainty are found in the upper wake region, (*i.e.* $z^* \approx 0.55$), where the maximum peak found is $\Delta CI = 0.046$. Although the regions are almost symmetric, likewise the rest of the data, there is an evidence that the nominal yaw angle may have a systematic deviation. The nominal y -axis coordinates of the uncertainty peaks are $y^* = -0.25$ and $y^* = 0.08$.

Figure 155 expands the analysis addressing the confidence interval distribution. Although the uncertainty peak is $\Delta CI = 0.046$, it is found that that 95% of the total acquisition region has a confidence interval range of $\Delta CI < 0.021$, which means a time-averaged probe precision of $\overline{\Delta C_{pt}} \approx \pm 0.01$. For 99% of the data, the precision is $\overline{\Delta C_{pt}} \approx \pm 0.016$.

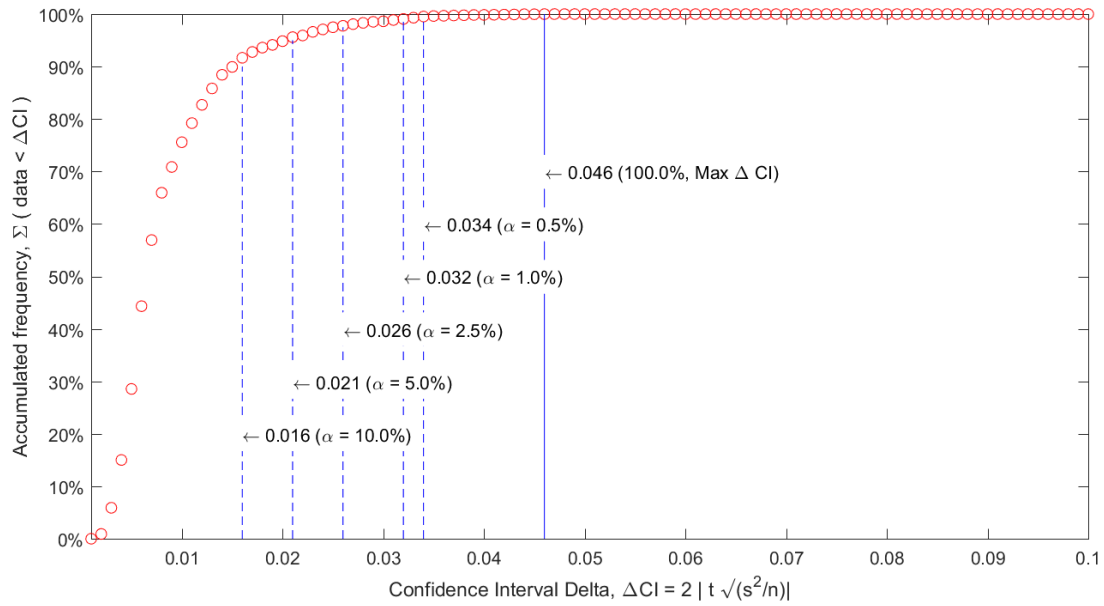


Figure 155. Analysis of confidence interval: accumulated frequency as a function of ΔCI range.

The confidence interval distribution only in the wake can be assessed if ignoring the region within the background uncertainty, assuming the previous finding that low-disturbance flow ($C_{p_t} > 0.9$) has $\Delta CI < 0.010$. It results in a subset of 991 measurements among 4070 of the entire acquisition domain. This subset has 210 points (21.2%) with $\Delta CI > 0.02$, in contrast to 56 points (5.7%) with $\Delta CI > 0.03$, and only 6 occurrences (0.7%) for $\Delta CI > 0.04$.

It is concluded that the maximum, local peak of $\Delta CI = 0.046$ is a spurious measurement during the acquisition procedure, which is nearly twice the uncertainty found on 95% of the acquisition domain (*e.g.* $\Delta CI < 0.021$). For 99% of the wake region delimited by $C_{p_t} < 0.9$, the averaged-confidence interval is $\overline{\Delta CI} \approx 0.04$ ($\overline{\Delta C_{p_t}} \approx \pm 0.02$) confidence level of 95%.

7.5 CONCLUSIONS

A modular version of the wake generator was built for the purpose of experimental validation, and it was assessed in the Cranfield 8x6 Wind Tunnel. This version represents the four configurations using solid, closed elements replacing the rear body section part; in line with the modular concept adopted in earlier reference models [5] [6] [7]. For the purpose of wind tunnel validation, this approach was effective and reliable.

Due to the use of an alternative ground board, an assessment of the ground boundary layer was carried out in the empty wind tunnel working section, similarly to the experimental campaign for full-body DrivAer models ([section 4.3](#)). Boundary layer velocity profiles confirm the previous conclusion: the use of the boundary control system is necessary since it reduces the boundary layer profile to nominally 40mm at the data acquisition plane (*i.e.* 1450mm upstream the working section end).

After ensuring comparable wind tunnel conditions, the wakes from each of the proposed device configurations were measured in terms of the total pressure coefficient (C_{pt}) distribution in a given plane within the wake. Experimental results demonstrated an overall correlation to the preliminary CFD simulations for all cases, both in terms of wake characteristics and dimensions. Minor differences can be found, which is believed to be due to both (i) compromising level adopted in the RANS approach and (ii) limitations of the experimental technique, as discussed in [section 3.5](#).

Both the ‘fastback’ and ‘notchback’ configurations seem to be able to generate representative wakes *Type I*, although use of the ‘fastback’ case is recommended for this wake category. The wake generated by the ‘estateback’ shape is confirmed as a wake *Type II*, while the results from the ‘high-performance’ version suggest

a large wake with the occurrence of a strong upwash and associated pair of vortex structures.

There is evidence of a small systematic deviation on the yaw angle in all the wake measurements at -ve z -axis direction, which is believed to be a consequence of model misalignment during the definition of the datum ‘zero-yaw’ position. A CFD investigation of the experimental conditions suggests that a constant yaw deviation of 0.7° occurred on all experimental campaigns presented in this research project (see [Appendix C](#), Figure C-1).

An investigation of the wake sensitivity to changes in Re number, using C_{pt} distribution data, suggests that the wakes presented are nominally Re -independent at the standard condition tested (*i.e.* $U_\infty = 40m/s$; $Re_{\sqrt{A}} = 2.596 \times 10^5$). The Re_{tr} is expected to be found in the range of $Re_{\sqrt{A}} = 1.947 \rightarrow 2.596 [\times 10^5]$, which are equivalent to between $30m/s$ and $40m/s$ at the wind tunnel conditions used. In comparison to the realistic, full-body DrivAer models, the wakes are less Re -sensitive, therefore can provide more reliability in experimental applications.

A statistical analysis of the total pressure confirmed that data can be acquired with averaged precision of $\overline{\Delta C_{pt}} = \pm 0.003$ in flows with low-disturbance (*i.e.* $C_{pt} > 0.9$). In the wake region, vibrations of the total pressure occur, and the maximum uncertainty reached $\Delta CI = 0.046$; however, it was found that uncertainty peaks are spurious occurrences. All planar C_{pt} distribution presented in this Chapter were estimated to have an uncertainty of $\overline{\Delta C_{pt}} \approx \pm 0.02$, assuming a confidence level of 95%.

Chapter 8.

FINAL COMMENTS

The synergy between a cost-effective CFD methodology and a range of wind tunnel measurement techniques for applied aerodynamics has been used to support the development of an aerodynamic wake emulator for automotive applications. It is believed that the outcome, in terms of the specification for a wake emulator geometry, will be valuable to the scientific community concerned with aerodynamics optimisation of vehicles operating in close proximity.

The ‘prediction accuracy’/‘computational cost’ ratio of the CFD methodology has permitted the efficient design of time-averaged wake-related cases. With further evolution of CFD methods (*e.g.* machine-learning techniques), this processing ‘low-cost’ approach can be a relevant option to be implemented in fully automated computational design.

The development of a 4th configuration of the DrivAer model intends to fulfil a current gap in automotive aerodynamics: a generic model for high-performance applications. Vehicles with aerodynamic characteristics akin to sport and race cars have only been addressed by specific organisations with their own unique reference models. The proposal of this high-performance configuration, based on a well-accepted DrivAer model, aims to create a shared, further development on the topic, with an open-source CAD and wind tunnel database.

Two wake databases have been built for the four DrivAer configurations (F , N , E , hpF). The first provides a total pressure-based wake data using a total pressure rake, while a second experimental campaign, based on SPIV, identifies the wake characteristics as a function of the local velocity field. A Re -sensitivity study and

statistical analysis are also provided for each experimental campaign. These experimental databases are expected to support (i) computational studies, as an experimental reference for validation; and (ii) other experimental studies, as projected wake characteristics to prepare experiments and for direct correlation of wind tunnel facilities and conditions.

Regarding the final outcome, the wake emulator is envisioned mainly for use on vehicle-to-vehicle proximity studies, which will gradually become more relevant with advances in the automotive industry. An experimental validation of the wake generator shapes is offered as a wake database, similarly to the full-body DrivAer model. This experimental campaign suggests an alternative option for wind tunnel implementation (*i.e.* modular approach).

For efficiency-driven applications, it is recommended that the concept of an active body control is adopted. Therefore, the aerodynamic performance of a vehicle model, exposed to several wake types, can be assessed without need of wind tunnel run-up and run-down for each configuration.

To conclude, platooning-related investigations are recommended for future studies, including: (a) performance of the wake generator in a wind tunnel's ground simulation, (b) on the measurement error due to intrusive experimental techniques, (c) improvement of CFD and experimental methodologies for the aerodynamics of platoon formations.

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Appendix A

Wake Vortex Pathline: [Chapter 3](#), Validation Cases

This appendix section presents the position of wakes generated from models investigated in [Chapter 3](#), divided into:

- *Wake Vortex Pathline from DrivAer Models*
- *Wake Vortex Pathline from a Race car Model*

Wake position is characterised as a function of the time-averaged, dominant vortex pathline extracted from the velocity vector field.

A.1 Wake Vortex Pathline from DrivAer Models

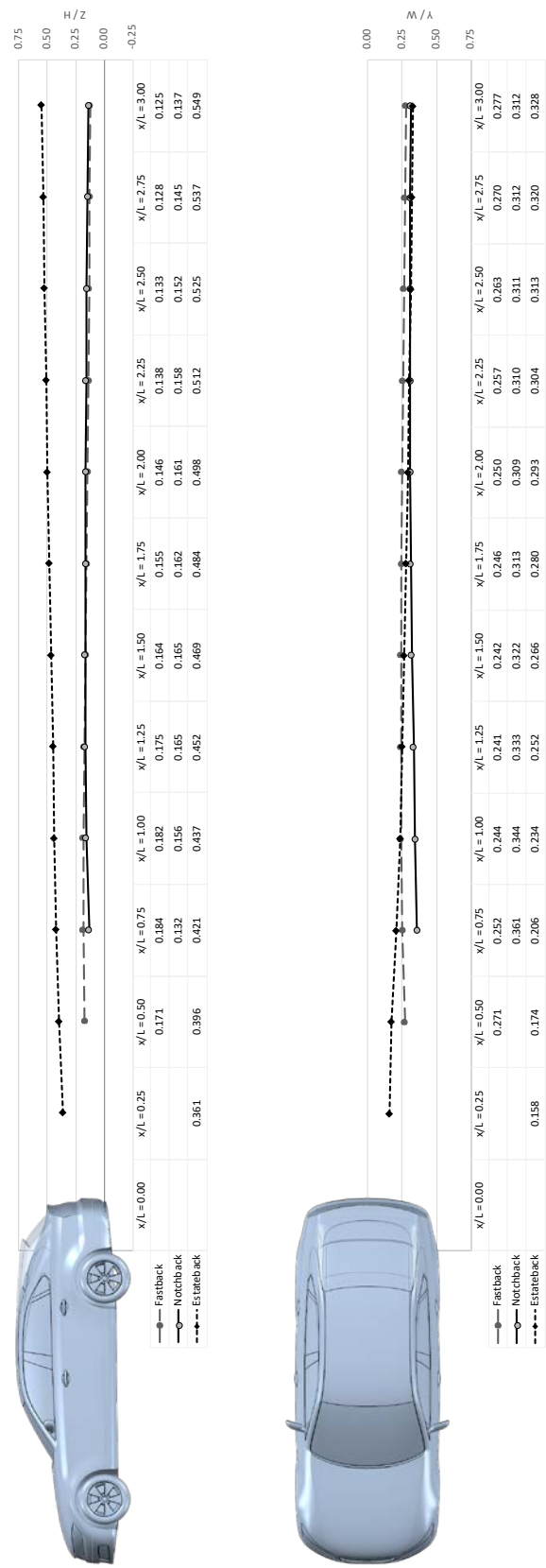


Figure A-1. Wake development from passenger car models: pathline of the main vortex core into the respective wake of the three DrivAer rear-end configurations.

A.2 Wake Vortex Pathline from a Race car Model

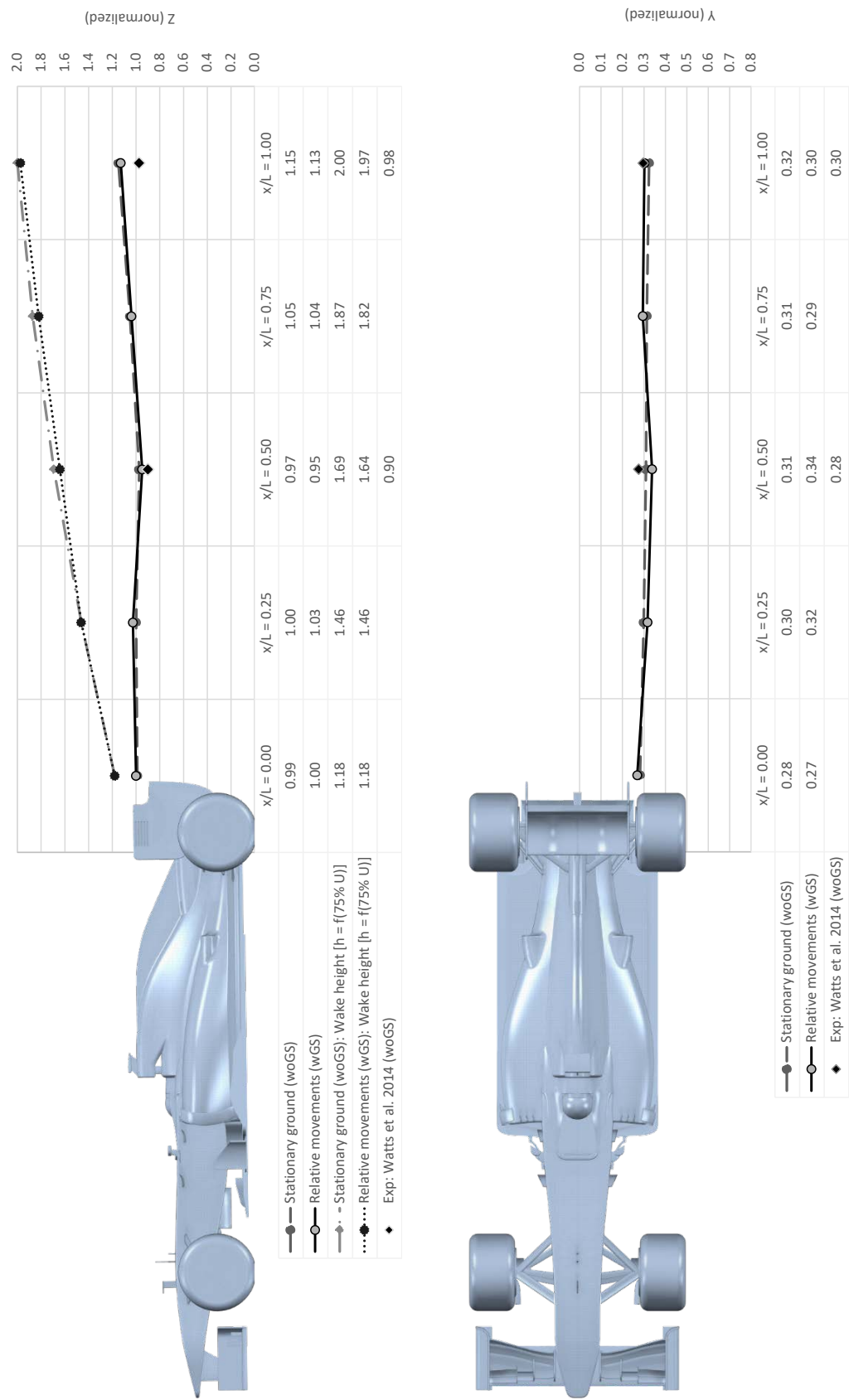


Figure A-2. Wake development from a race car model: pathline of the rear wingtip vortex in different ground conditions. Rear wing geometry of Watts *et al.* is 15% shorter (in *y*-direction) than the geometry presented.

Appendix B

Wake Development from a Single-seater Race car

The pictures presented in this appendix section are related to a numerical study on the wake development in two conditions:

- a) Stationary ground and wheel surfaces (*i.e.* *woGS* case, upper figures).
- b) Relative movement of the ground and wheel surfaces (*i.e.* *wGS* case, lower figures).

Velocity magnitude range between 0 and $0.75U_{\infty}$ (*e.g.* 9 m/s), in the perpendicular planes downstream to the rear wake into the range of $0 \leq x/L \leq 1$, in steps of $0.25x/L$ (Figure B-2 to Figure B-7).

Additional surface flow visualisation is included as a function of wall shear stress lines on the car surface (Figure B-8 to Figure B-10).

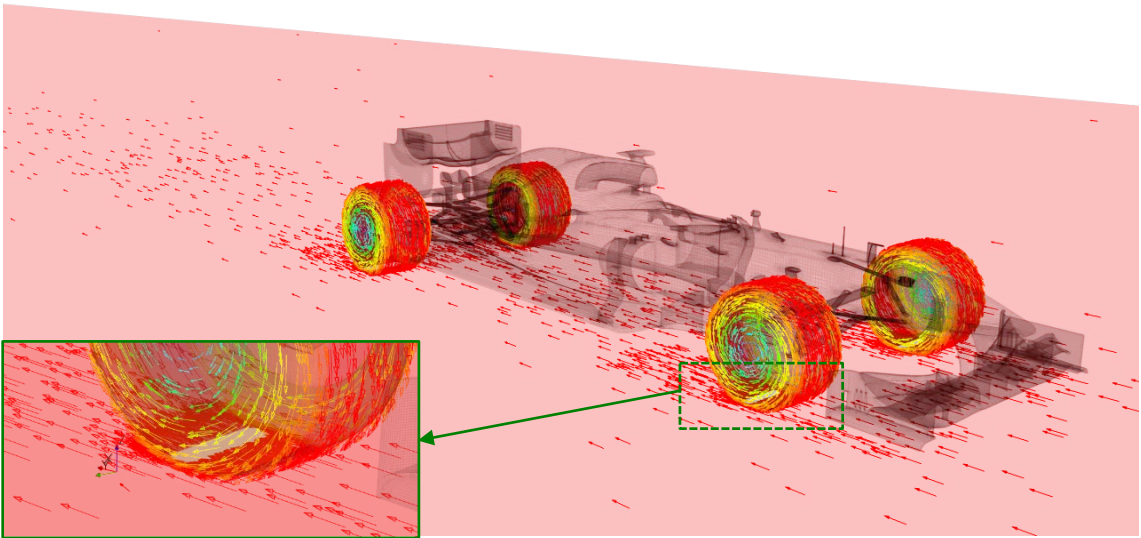
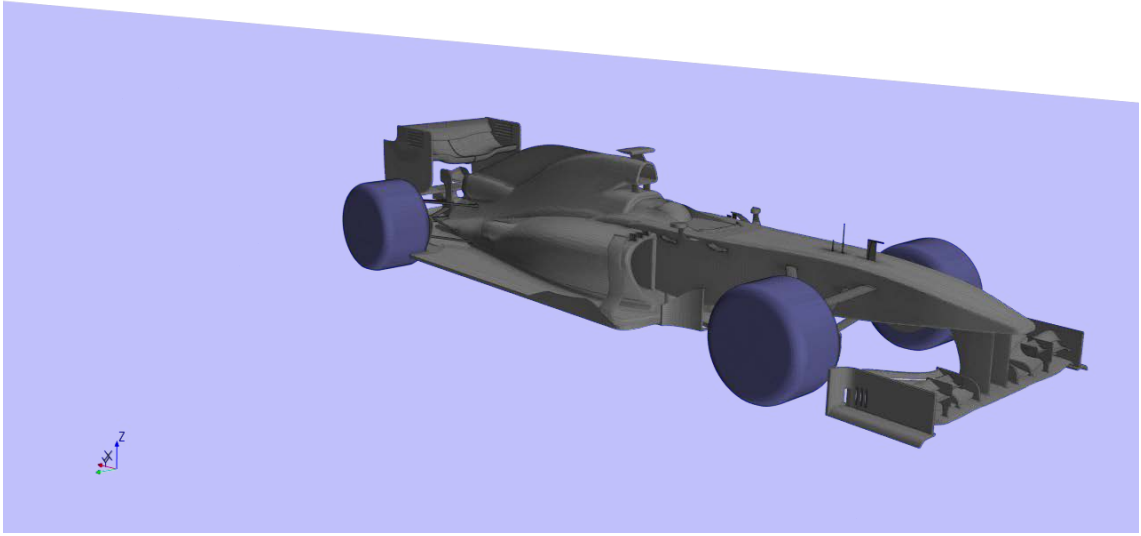


Figure B-1. Ground simulation approach on the ground and wheels boundaries. *woGS* (upper) and *wGS* (lower). $U_{\infty} = 12 \text{ m/s}$, closed model.

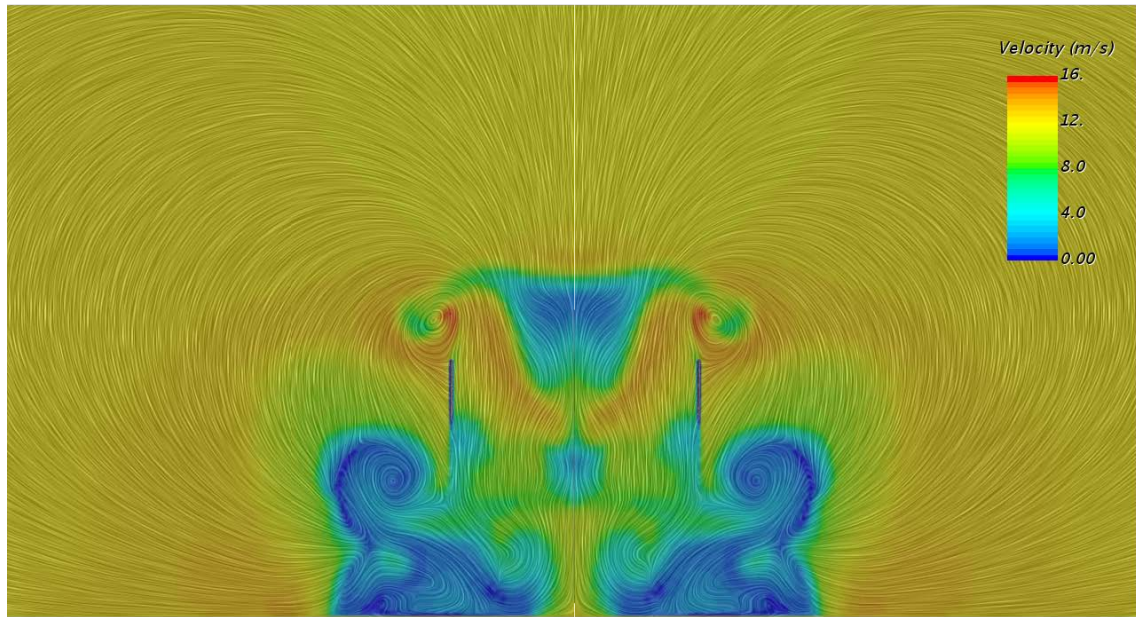
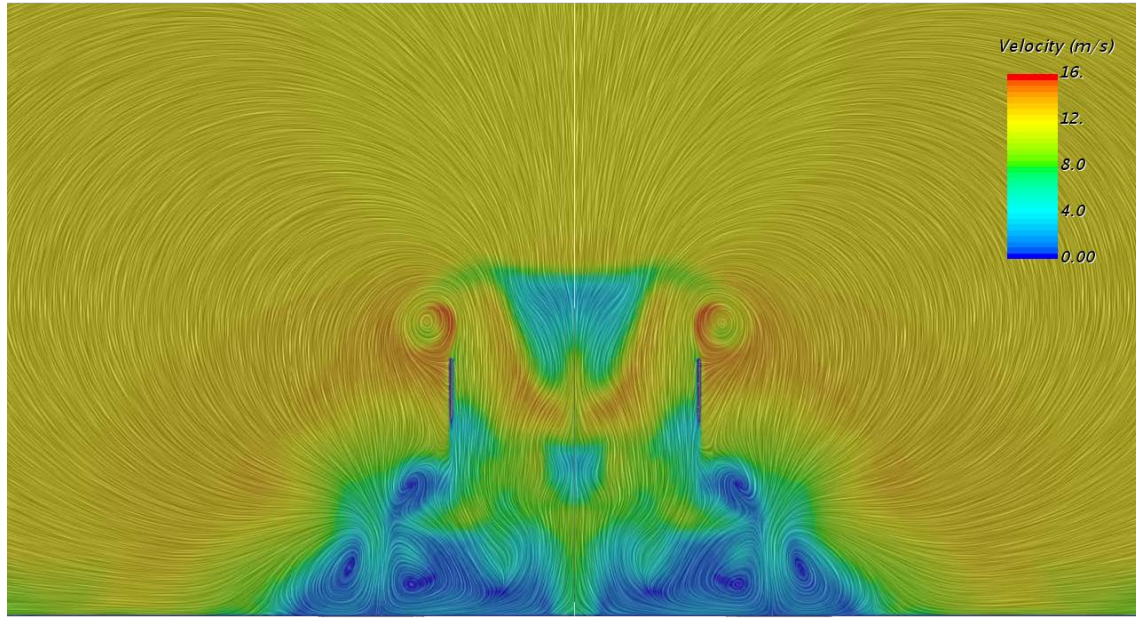


Figure B-2. Velocity distribution at $x/L = 0.00$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and 16 m/s ($1.33 U_\infty$).

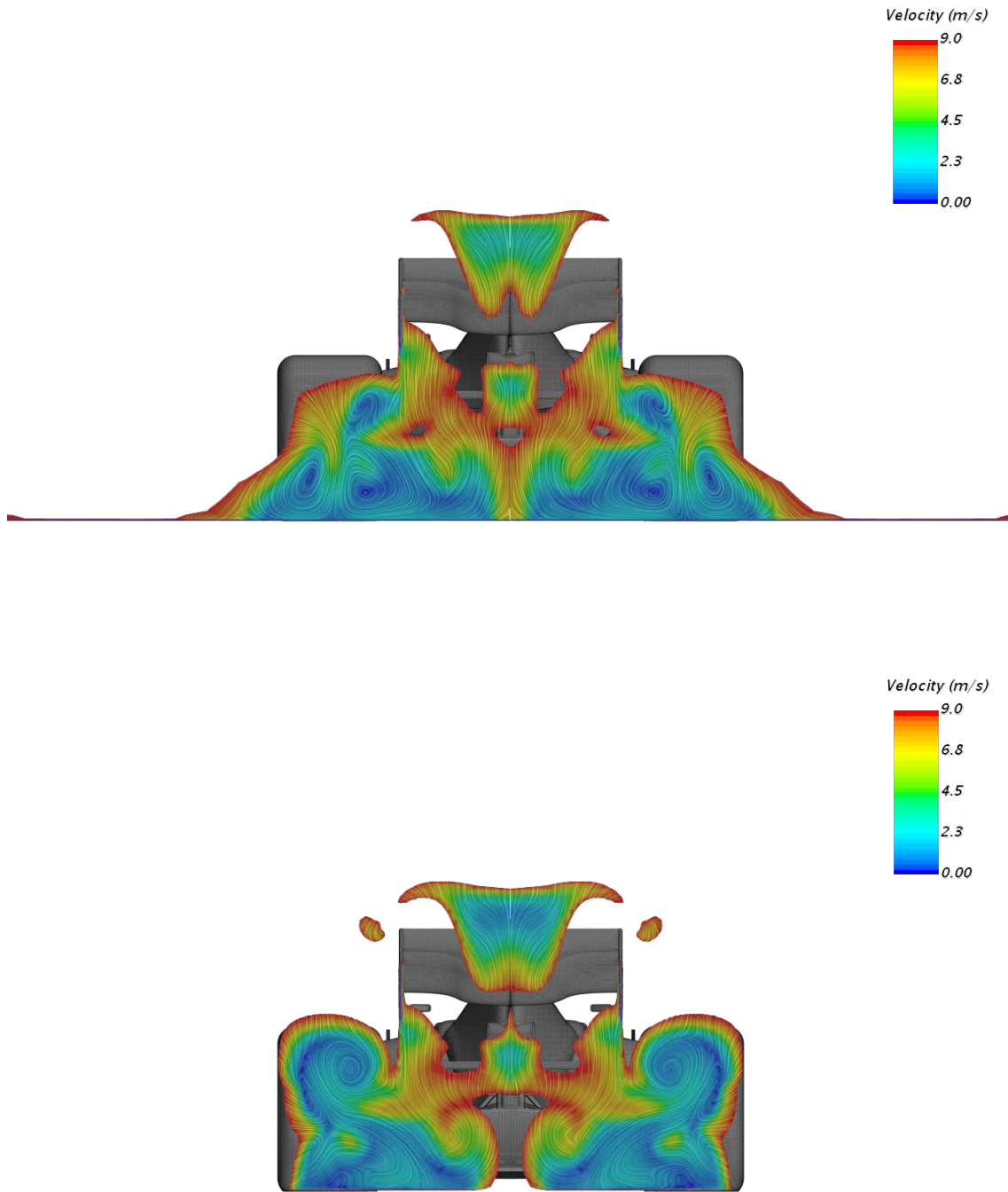


Figure B-3. Velocity distribution at $x/L = 0.00$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and $0.75 U_\infty$.

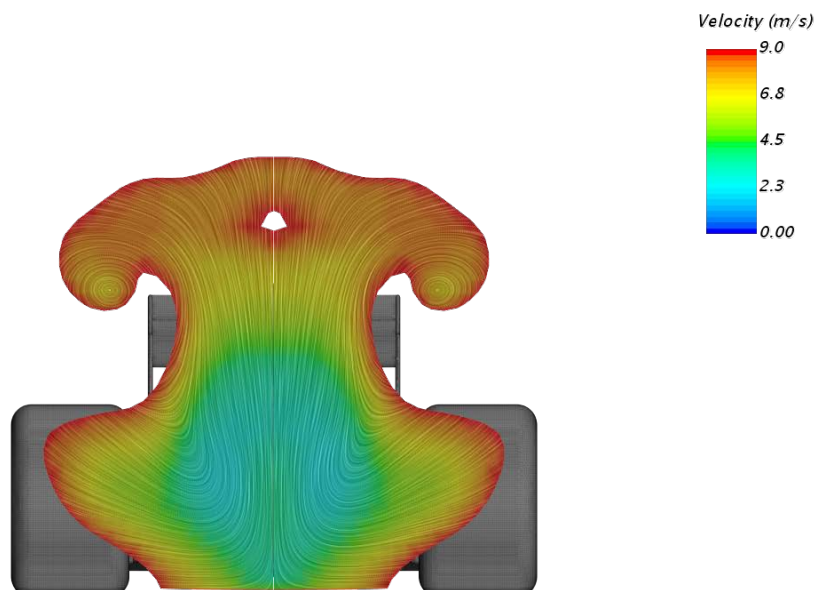
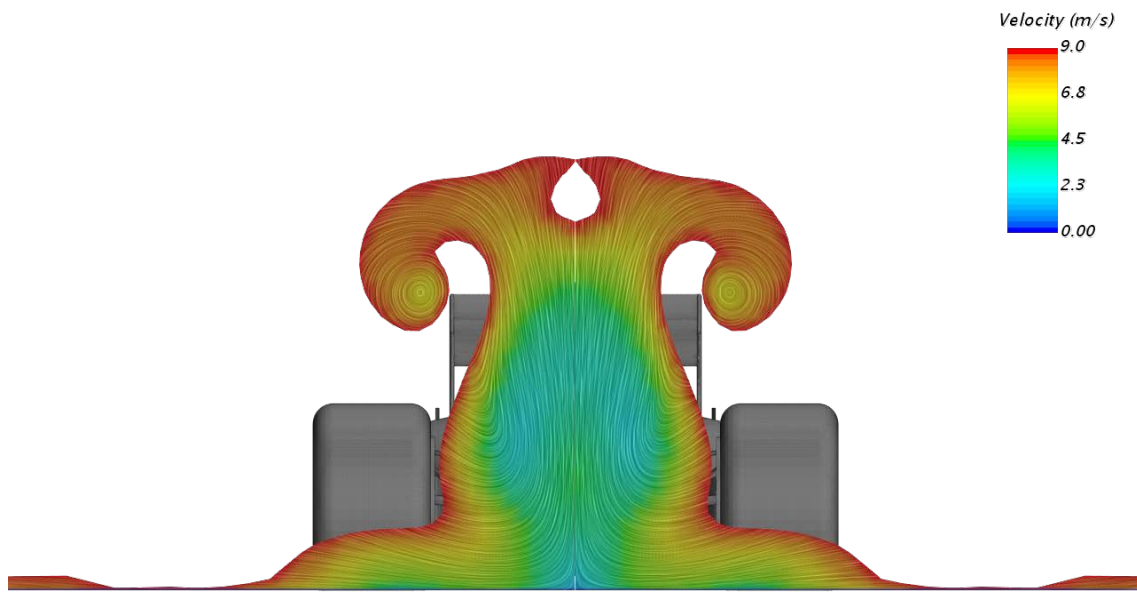


Figure B-4. Velocity distribution at $x/L = 0.25$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and $0.75 U_\infty$.

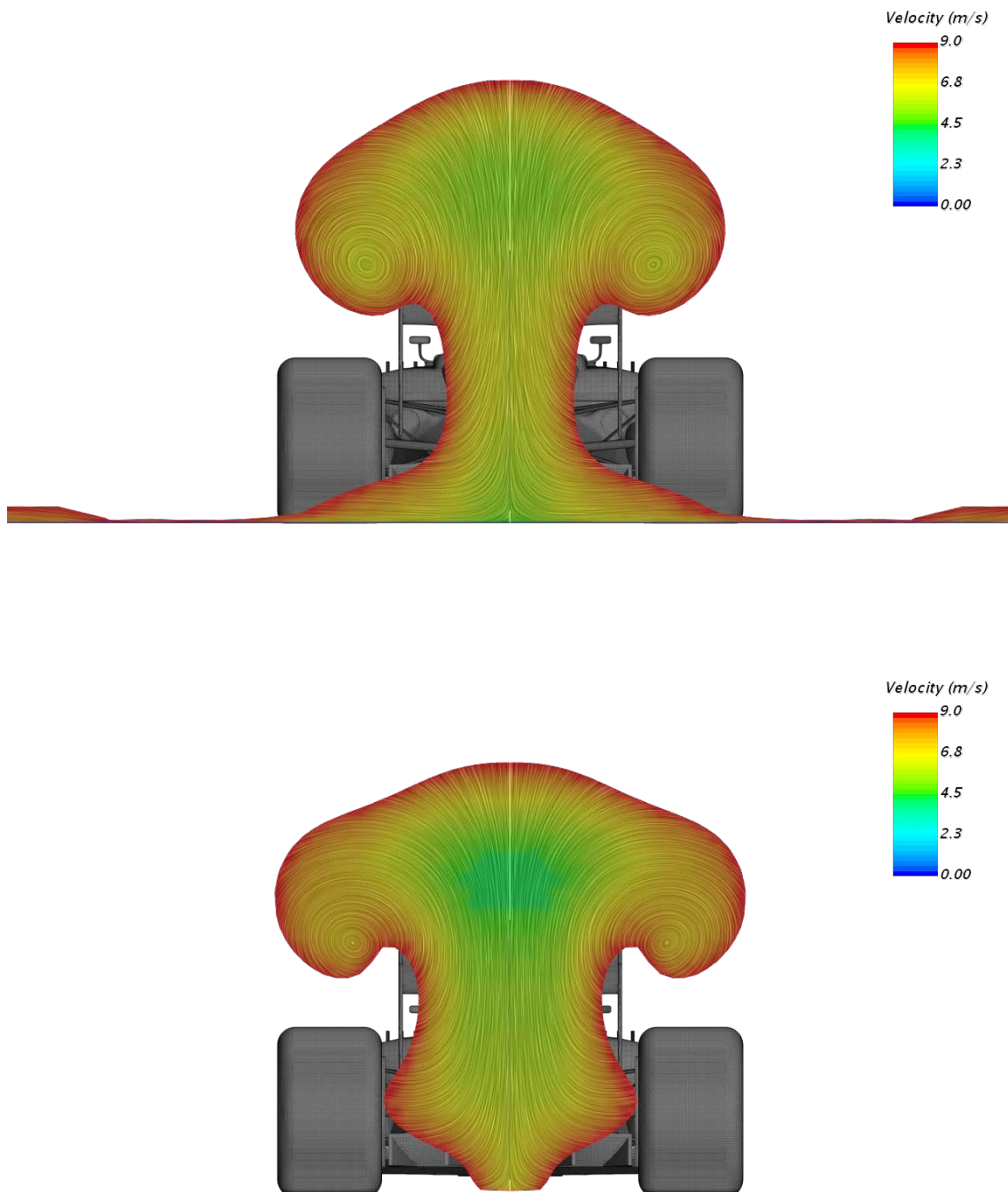


Figure B-5. Velocity distribution at $x/L = 0.50$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and $0.75 U_\infty$.

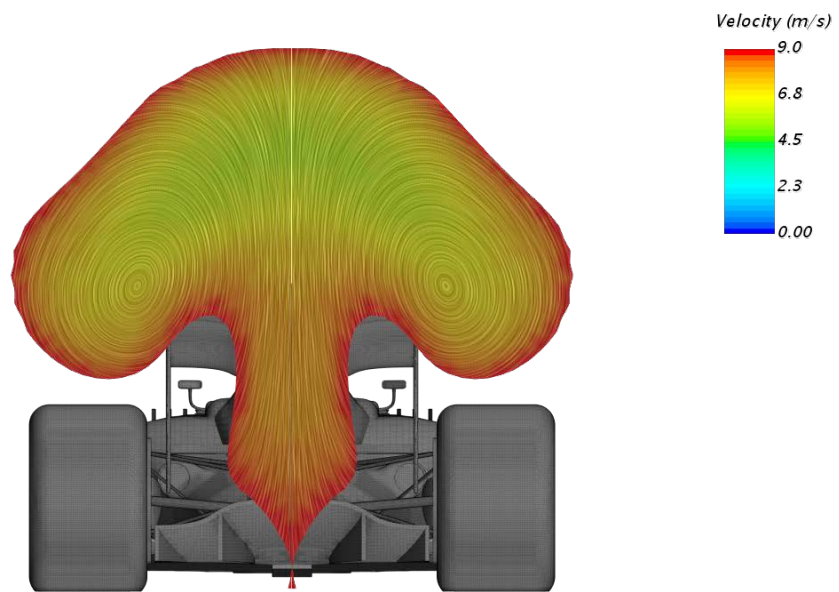
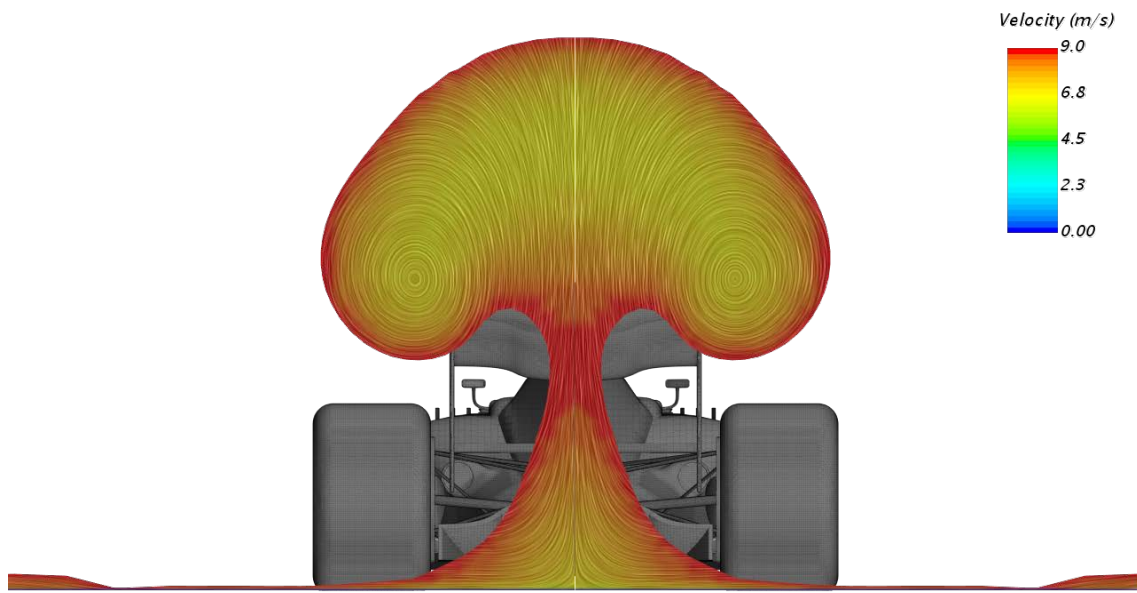


Figure B-6. Velocity distribution at $x/L = 0.75$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and $0.75 U_\infty$.

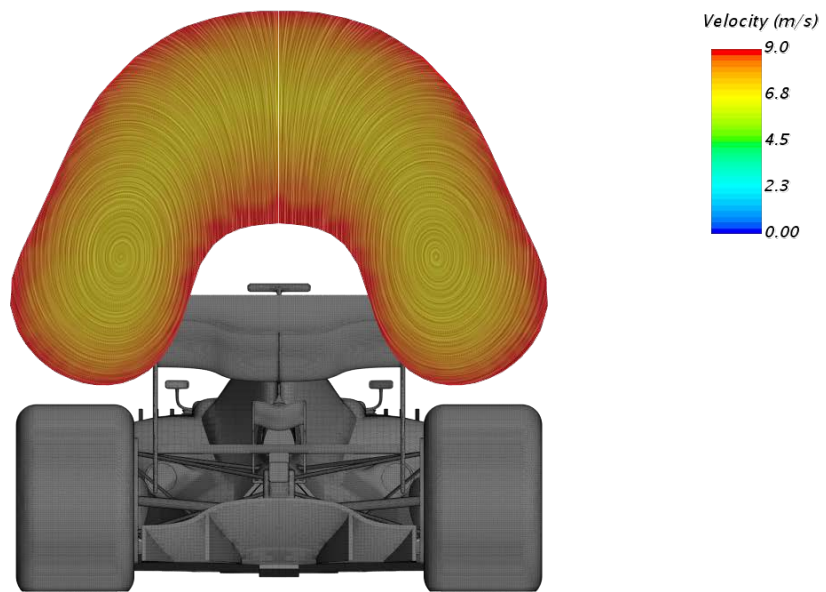
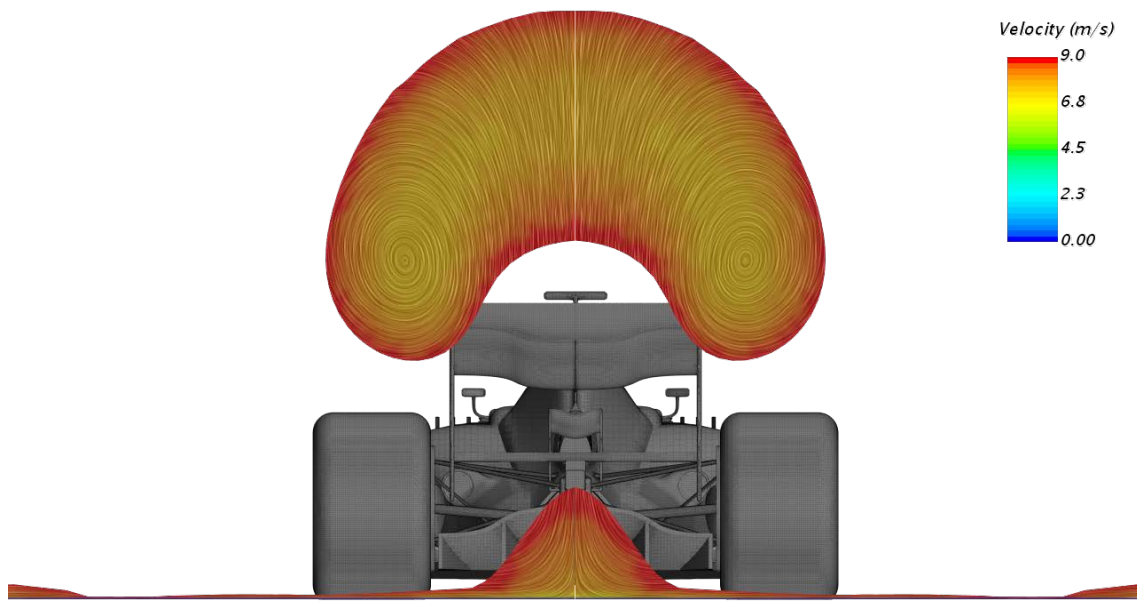


Figure B-7. Velocity distribution at $x/L = 1.00$ plane downstream in the wake of a race car: *woGS* (upper) and *wGS* (lower) ground simulation. $U_\infty = 12 \text{ m/s}$, closed model. Scale range between 0 and $0.75 U_\infty$.

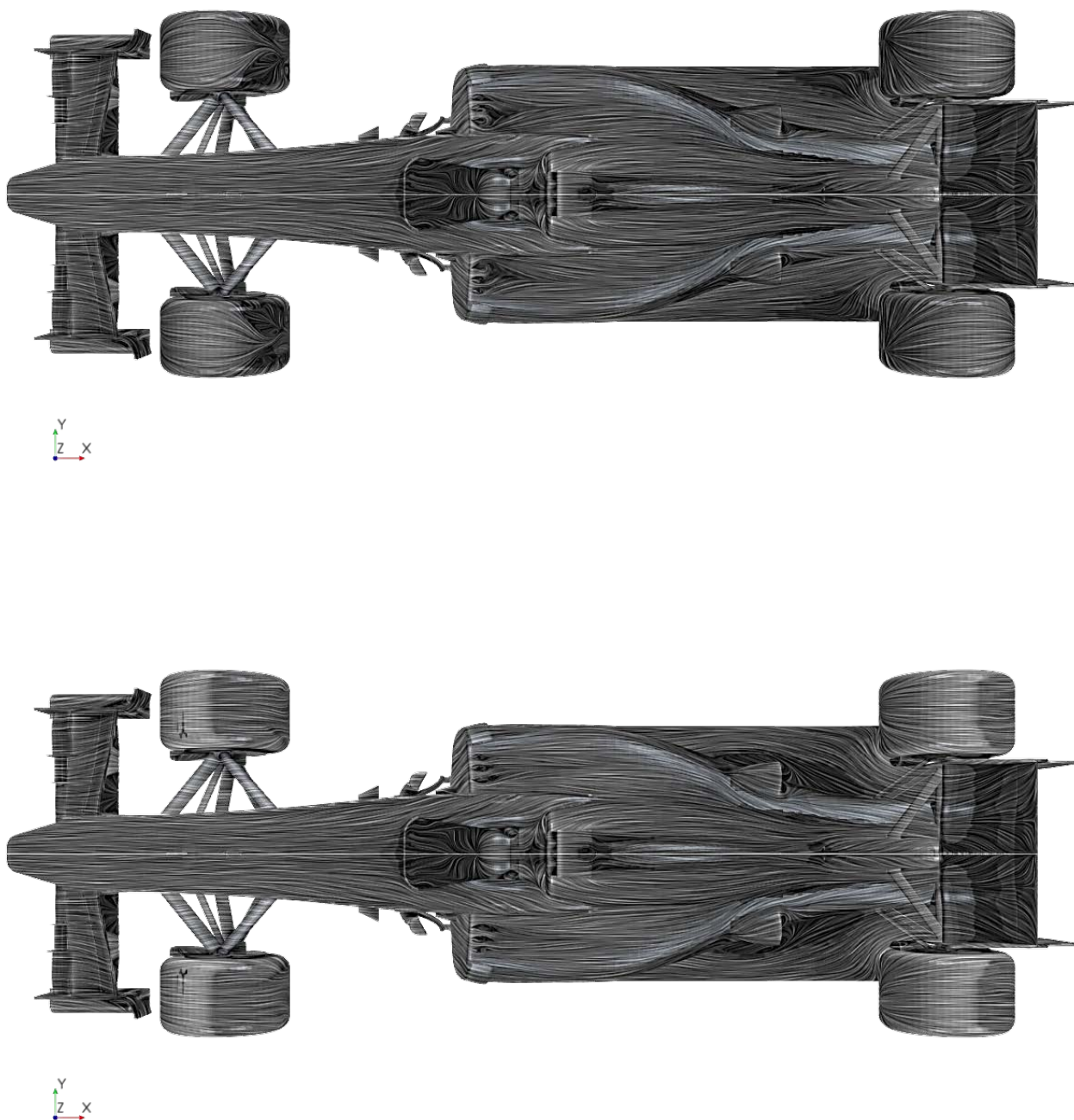


Figure B-8. Wall shear stress lines, top view: *woGS* (upper) and *wGS* (lower) ground simulation cases.

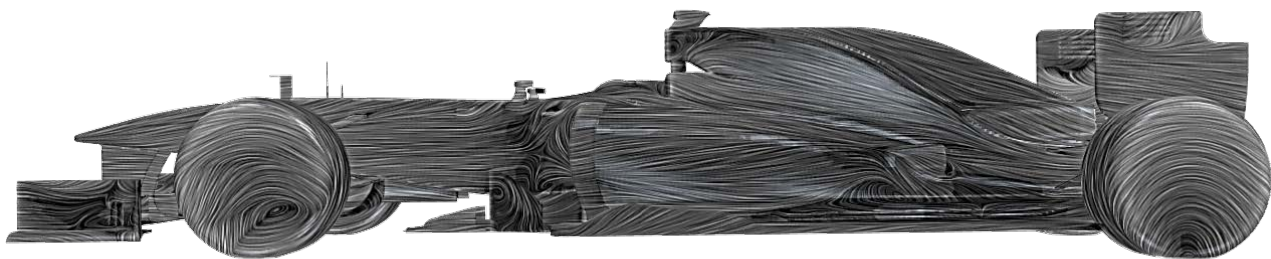
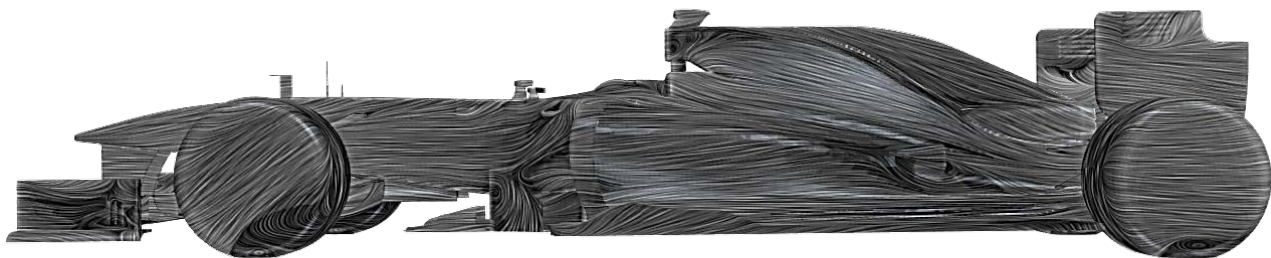


Figure B-9. Wall shear stress lines, side view: *woGS* (upper) and *wGS* (lower) ground simulation cases.

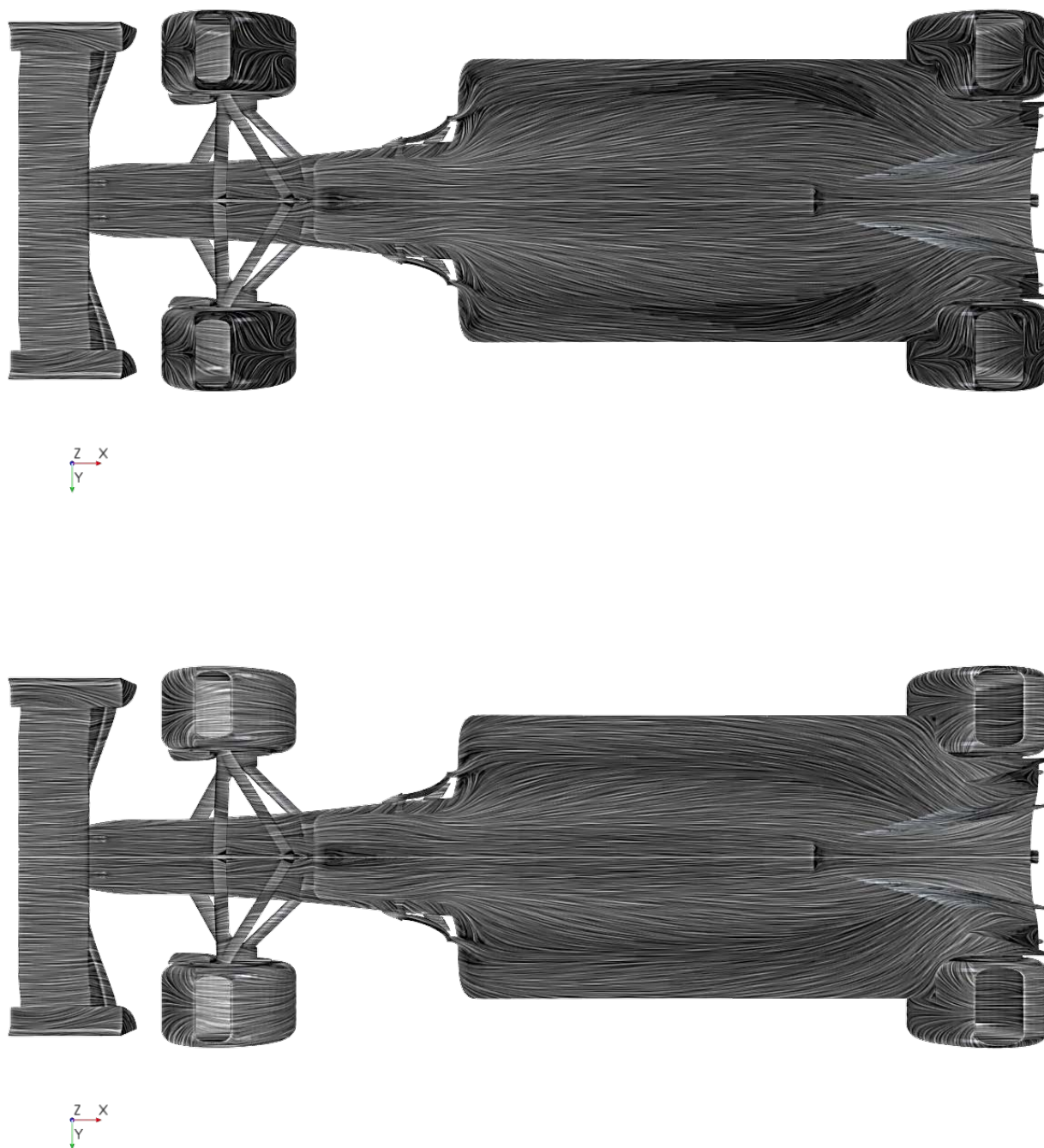


Figure B-10. Wall shear stress lines, bottom view: woGS (upper) and wGS (lower) ground simulation cases.

Appendix C

CFD analysis of Experimental Conditions

This appendix section summarises CFD investigations on (i) the experimental condition and (ii) aerodynamic performance of the apparatus employed on total pressure measurements.

CFD study I:

- *Analysis of Model Misalignment on Experimental Cases*

CFD study II:

- *Frame Optimisation for the Total Pressure Rake*

C.1 Analysis of Model Misalignment on Experimental Cases

A CFD study of the experimental condition has been undertaken due to a small but intriguing systematic asymmetry on the experimental wake topology. Considering that C_{pt} data is a result of 10s-averaged acquisition at 300Hz, all wakes were expected to be nearly symmetric (with minor random, not systematic error) due to likewise experimental condition (*e.g.* model geometry and freestream).

Numerical results led to conclude that the experimental models might have been misaligned by 0.7° to wind tunnel freestream (see Figure C-1); therefore, it is recommended to consider all references to yaw angles within this thesis as:

$$Yaw|_{Nominal(Experiment)} = 0^\circ \leftrightarrow Yaw|_{True(ideal\ condition)} \approx -0.7^\circ$$

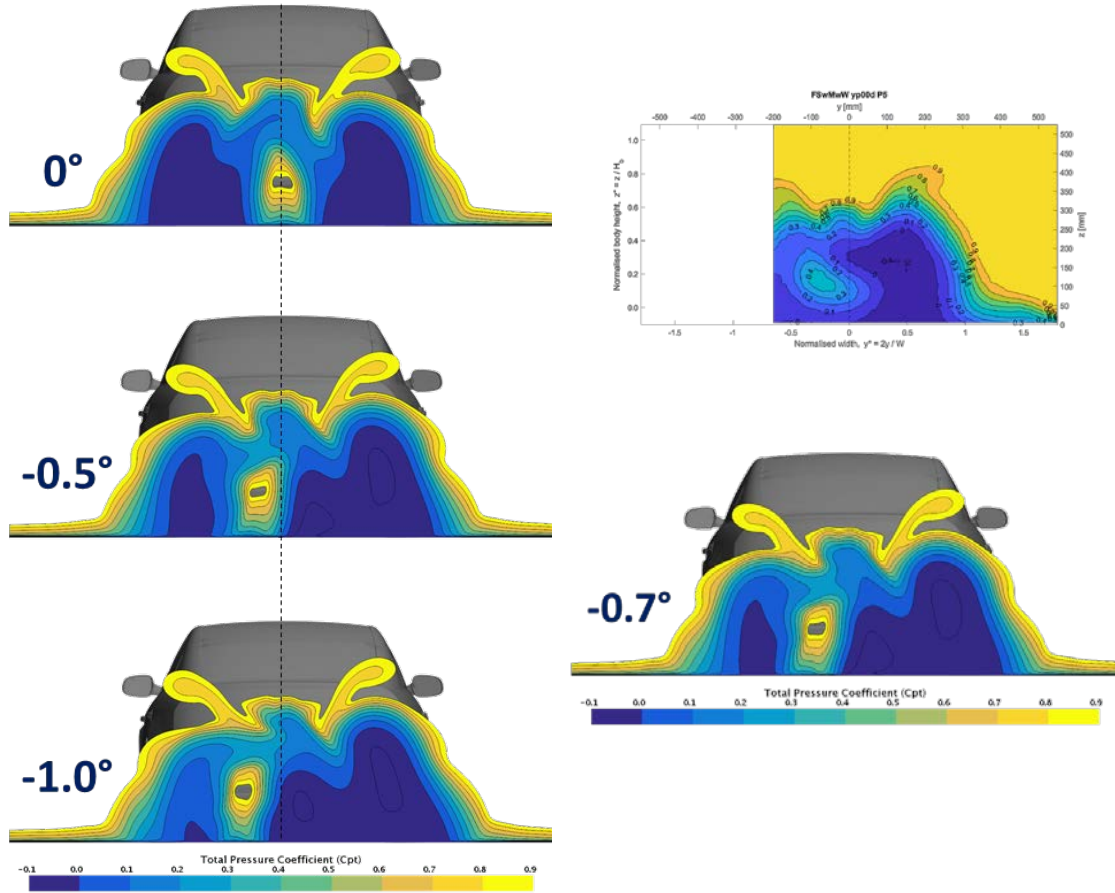


Figure C-1. CFD investigation on the experimental model misalignment.

C.2 Frame Optimisation for the Total Pressure Rake

Experimental cases reported in [Chapter 4](#) where recreated in CFD, and rake structure was found with more drag than the automotive model itself ([Figure C-3](#)). It could imply a bias on the experimental campaign, and a high energy consumption of the wind tunnel fan to sustain the freestream constant.

A simple, low-cost but effective solution was found on subsequent simulations investigating add-on parts to the current structure. The design proposed has a significant performance improvement, which returns the aerodynamic protagonism to the experimental body of interest ([Figure C-4](#)).

It is recommended to manufacture the add-on bodies (*e.g.* leading feet and upper bar) with solid foam, which is a cheaper material that provides enough stiffness at low body weight. For the add-on body for the moving frame holding the rake, 3D-printed shell (filled with honeycomb-like structure) is advised for minimum weight.

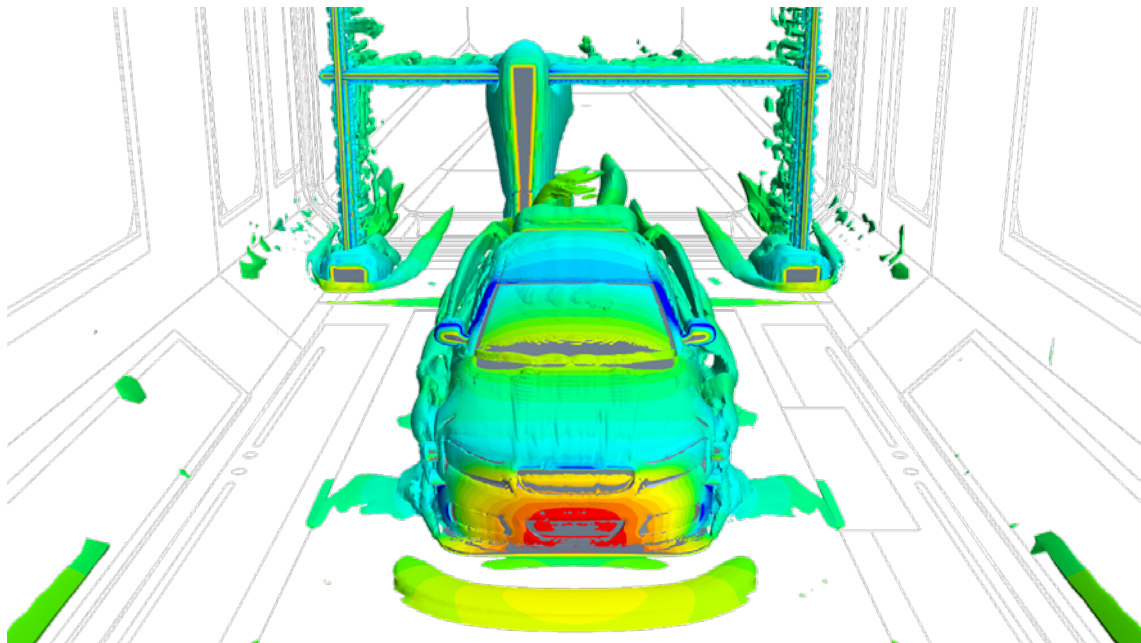


Figure C-2. Identifying the aerodynamic performance of the current total pressure rake as ‘in-operation’ state at 8x6 Cranfield wind tunnel.

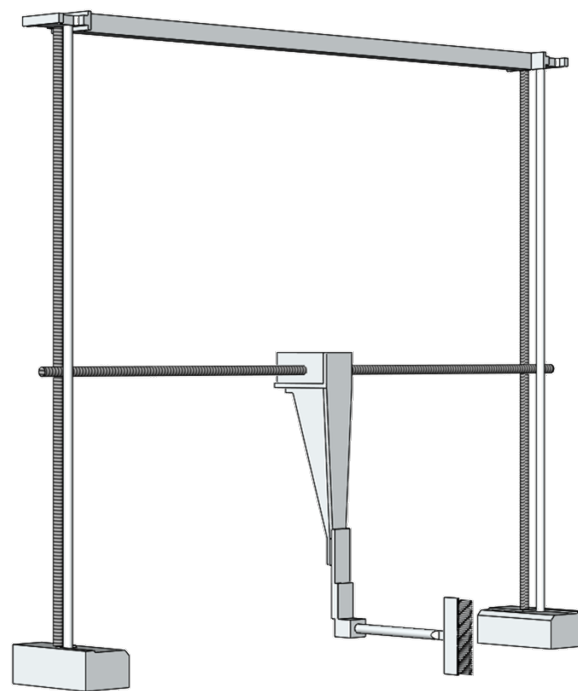
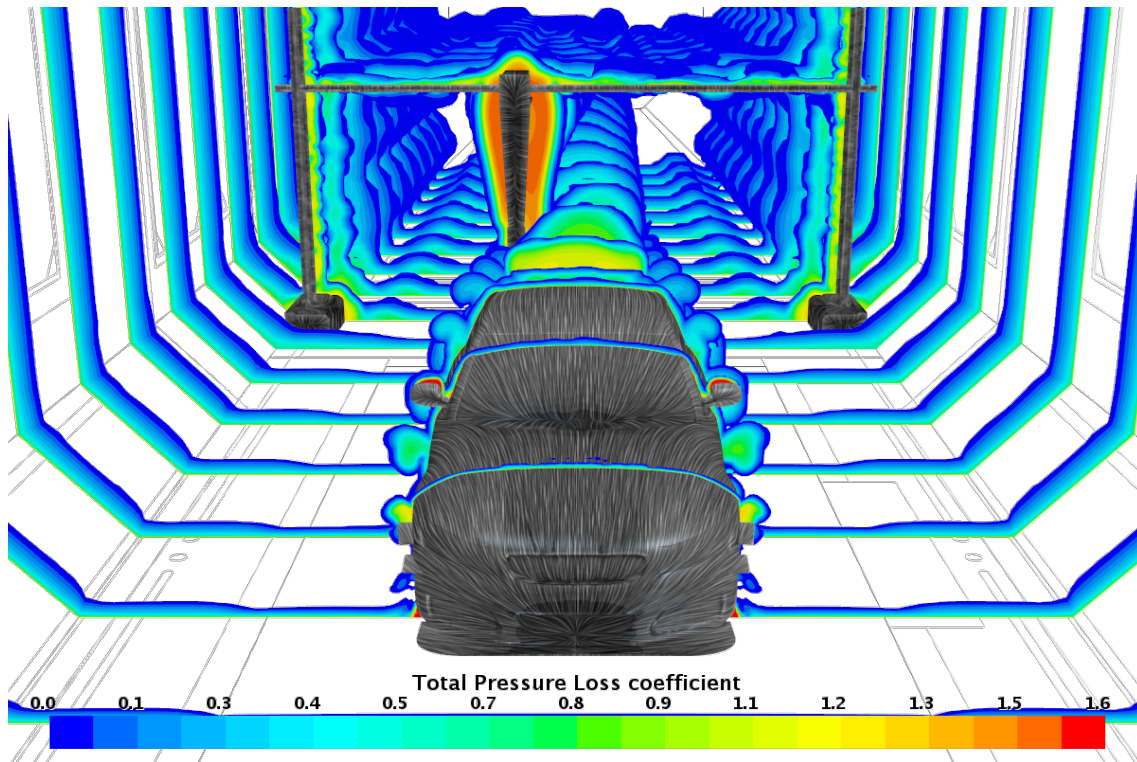


Figure C-3. Representation of the current frame (lower) and CFD investigation of experimental performance at 8x6 Cranfield wind tunnel (upper).

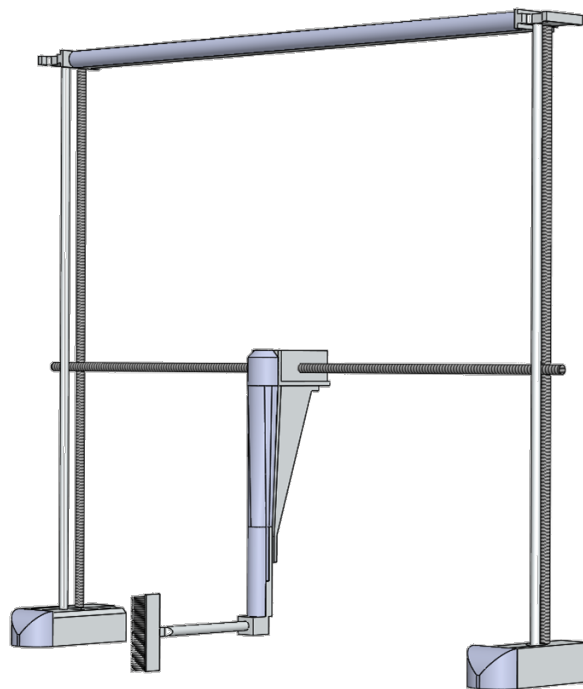
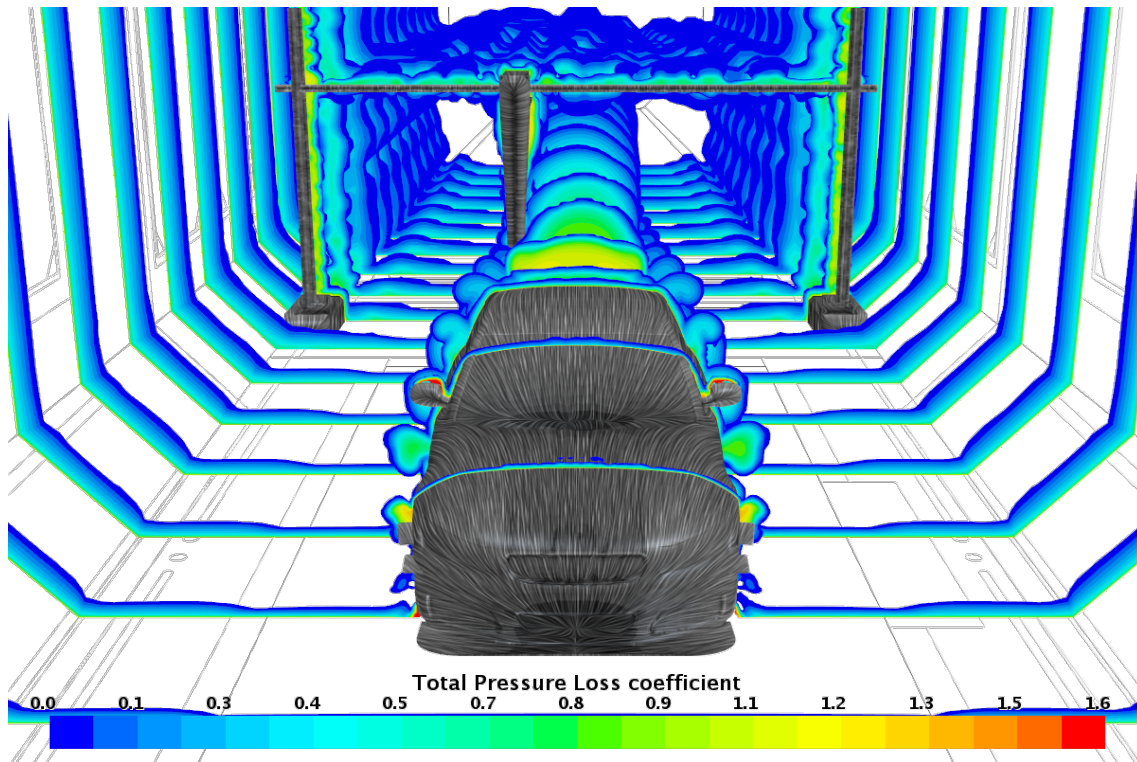


Figure C-4. Proposed aerodynamic add-on's to the current frame (lower) and CFD investigation of experimental performance at 8x6 Cranfield wind tunnel (upper).

Appendix D

On the Simplification of the Multi-Wake Generator Device for Wind Tunnel Implementation

This appendix reports an additional CFD analysis that investigated a potential simplification for the proposed multi-wake generator (Design 5, [Figure 132](#)). A ‘hollow’-based rear body is evaluated, as illustrated in [Figure D-1](#). The rear body is idealised as four thin, solid plates connected by hinges, which could be adjusted

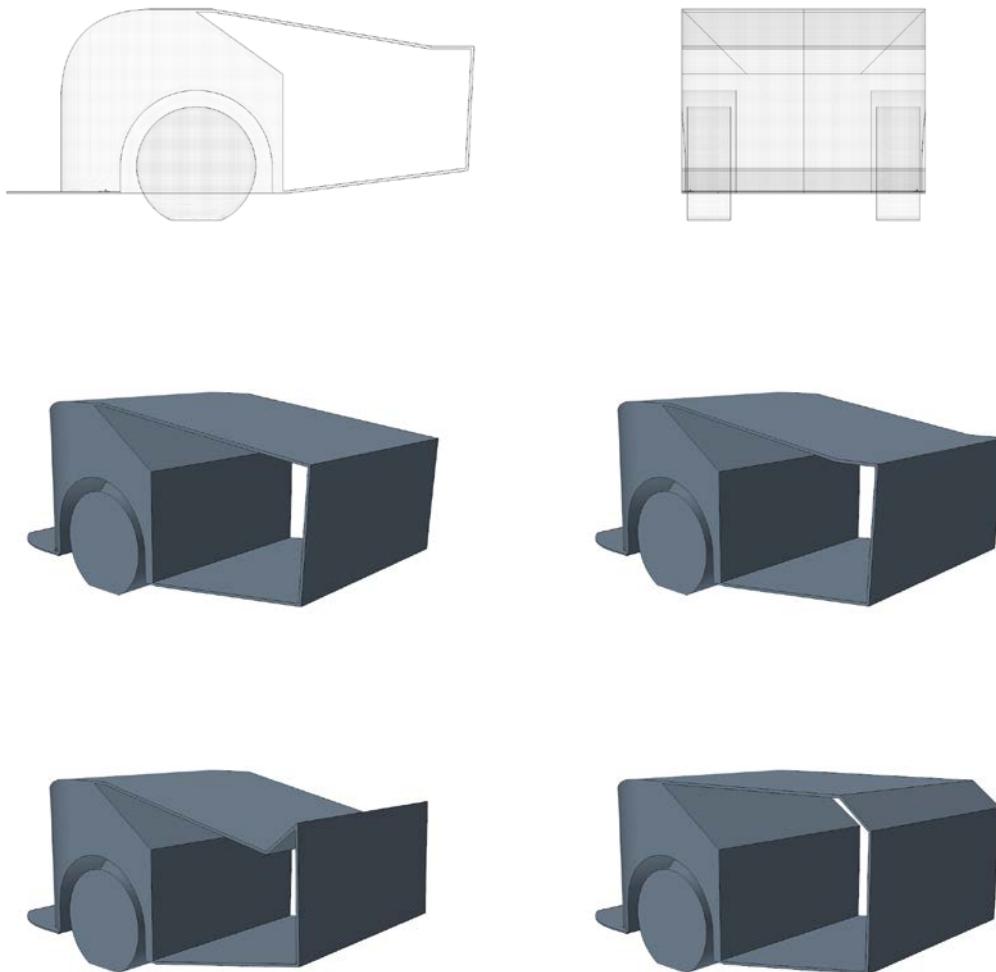


Figure D-1. Adaptable, multi-wake generator shapes, ‘hollow’ version .

by an inner piston (Figure 122) and reshape the rear body for the intended body forms.

However, note that this simplification considers the use of the device for *zero-yaw condition only*. For any other yaw positioning, it is expected a flow crossing the inner cavity, which may strongly compromise the intended wake representation.

The aerodynamic performance at zero-yaw condition is presented in Figure D-2, likewise the Design 5 (Figure 132) in terms of (i) orthogonal C_{p_t} planes and (ii) zero- C_p isosurface.

When observing C_{p_t} distribution, both estateback and high-performance configurations seems more affected than fast- and notchback versions. The core of the Estateback still have similar C_{p_t} distribution to the solid body version, but the lateral portion of the wake, mainly the upper region, has a increment on C_{p_t} decay, leading to a large wake trace delimited by $C_{p_t} = 0.9$. The high-performance wake is only affected on the upper corner, with more intense C_{p_t} decay in the vortex core. The both fast- and notchback configurations are less affected, showing only a small trend of C_{p_t} drop in the wake upper corner.

Zero- C_p isosurface of each configuration confirms that the overall wake topology is mostly sustained. It is found that all wakes have a small increase in width, mainly the Estateback. This occurs since the lateral flow separates in the forebody end, then adding flow instabilities downstream the region.

In summary, the wake topology between ‘hollow’ and solid rear body designs are mostly sustained for all four body configurations. For experimental studies regarding *zero-yaw condition only*, the ‘hollow’ design is a relevant option for future development.

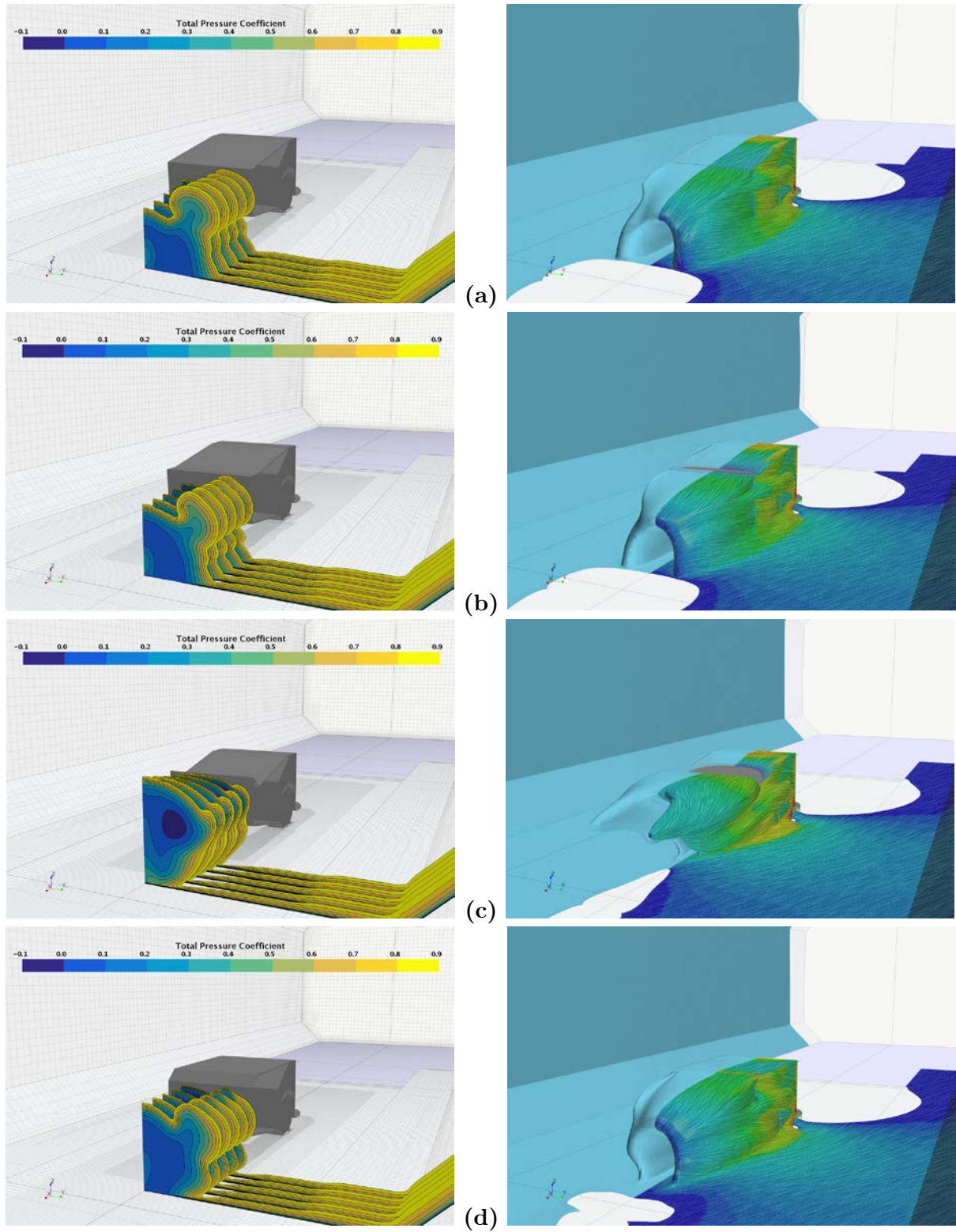


Figure D-2. Flow visualisation of the multi-wake generator, 'hollow' version. Orthogonal C_p planes (left column) and zero- C_p isosurface (right column). (a) Fastback, (b) Notchback, (c) high-performance, and (d) Estateback configurations.

Appendix E

Dimensional Drawings of the Wake Generator Development.

This appendix presents the drawings of the two versions of the wake generator device as follows:

Design Phase II:

Baseline concepts:

- [Figure E-1](#): Concept *1a*
- [Figure E-2](#): Concept *1b*
- [Figure E-3](#): Concept *2*
- [Figure E-4](#): Concept *3*
- [Figure E-5](#): Concept *4*
- [Figure E-6](#): Concept *5a*
- [Figure E-7](#): Concept *5b*
- [Figure E-8](#): Concept *5c*

Design Phase III:

Modular concept:

- [Figure E-9](#): Standard forebody
- [Figure E-10](#): ‘High-performance’ rear body

- [Figure E-11](#): ‘Fastback’ rear body
- [Figure E-12](#): ‘Notchback’ rear body
- [Figure E-13](#): ‘Estateback’ rear body

Adaptable concept:

- [Figure E-14](#): ‘High-performance’ rear body
- [Figure E-15](#): ‘Fastback’ rear body
- [Figure E-16](#): ‘Notchback’ rear body
- [Figure E-17](#): ‘Estateback’ rear body

Further implementation:

- [Figure E-18](#): Suggestion for future work: potential body design for yaw-variant applications.

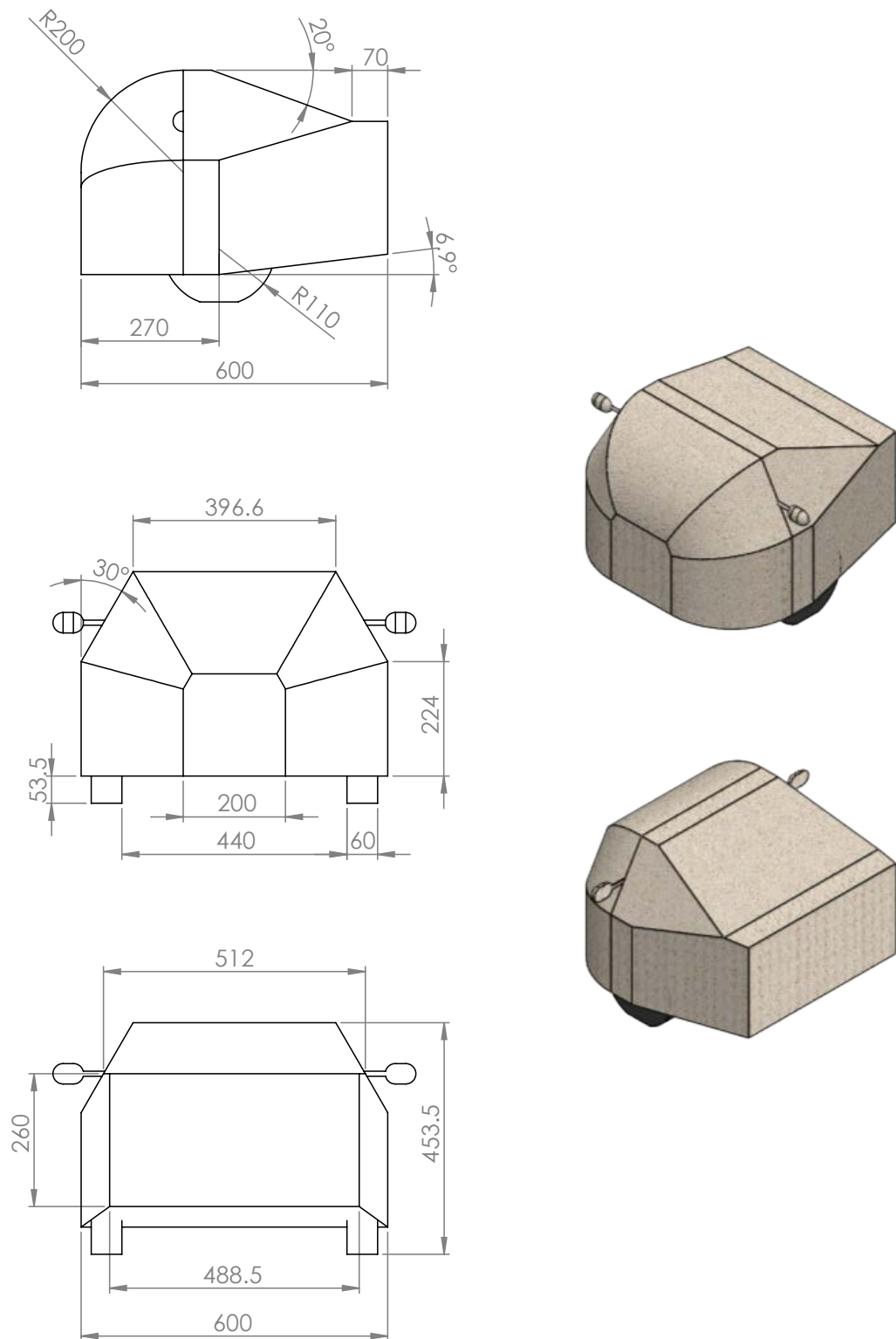


Figure E-1. Wake generator, Concept 1a.

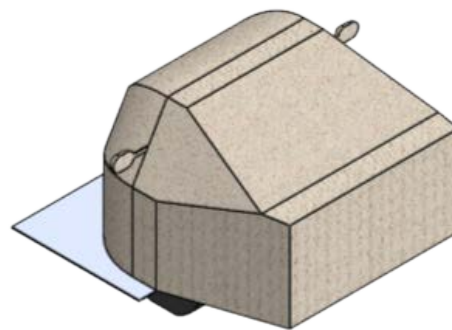
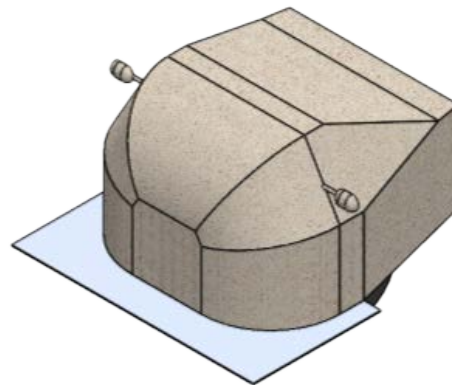
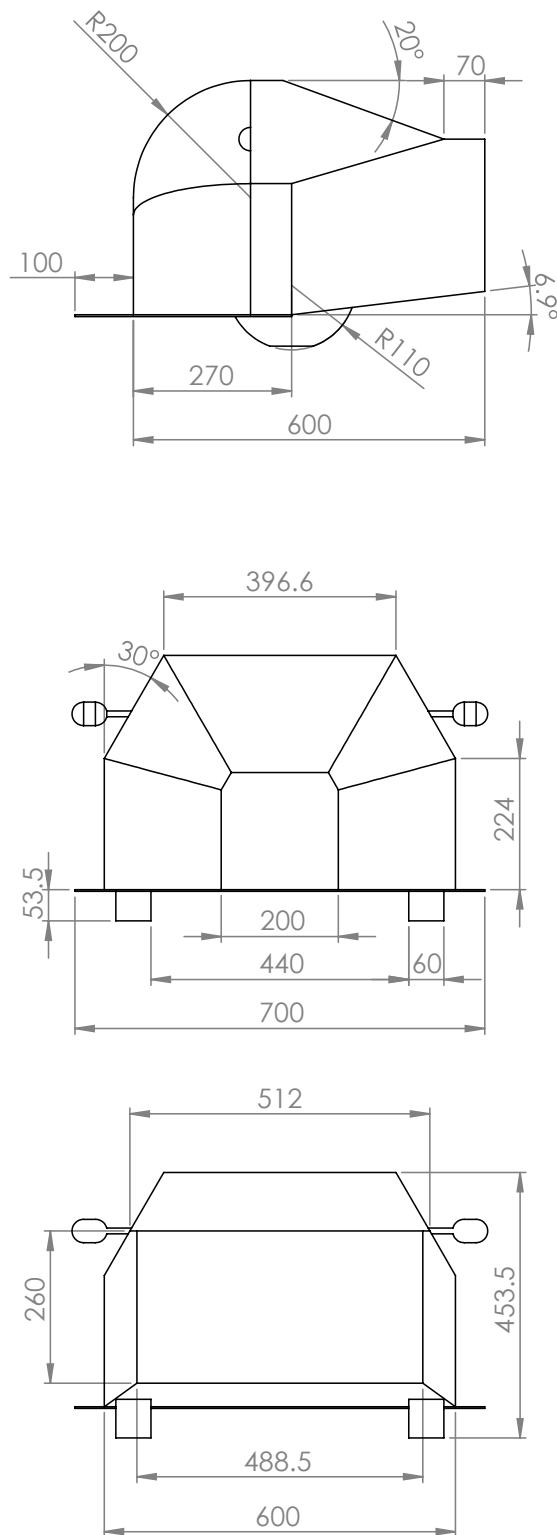


Figure E-2. Wake generator, Concept 1b.

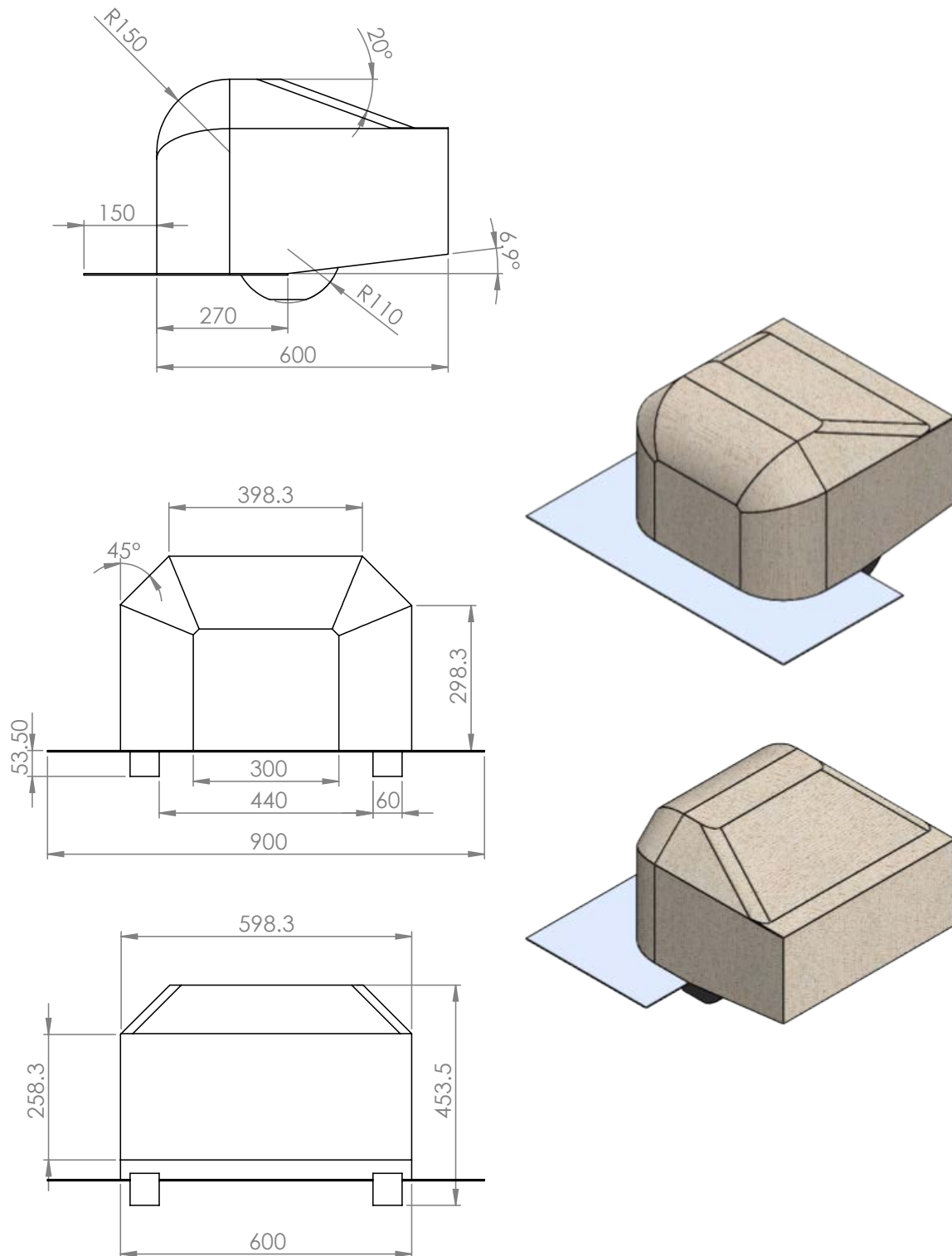


Figure E-3. Wake generator, Concept 2.

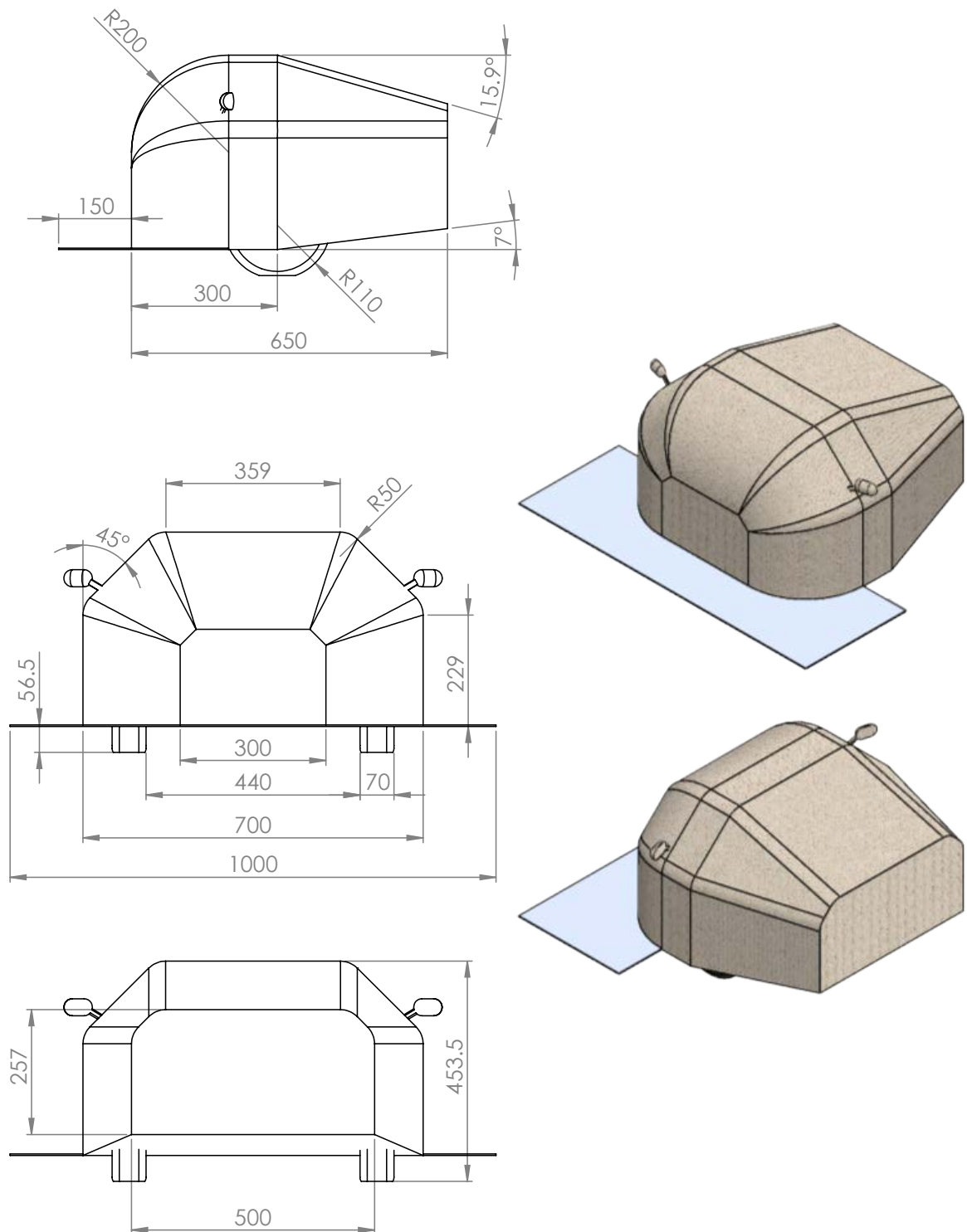


Figure E-4. Wake generator, Concept 3.

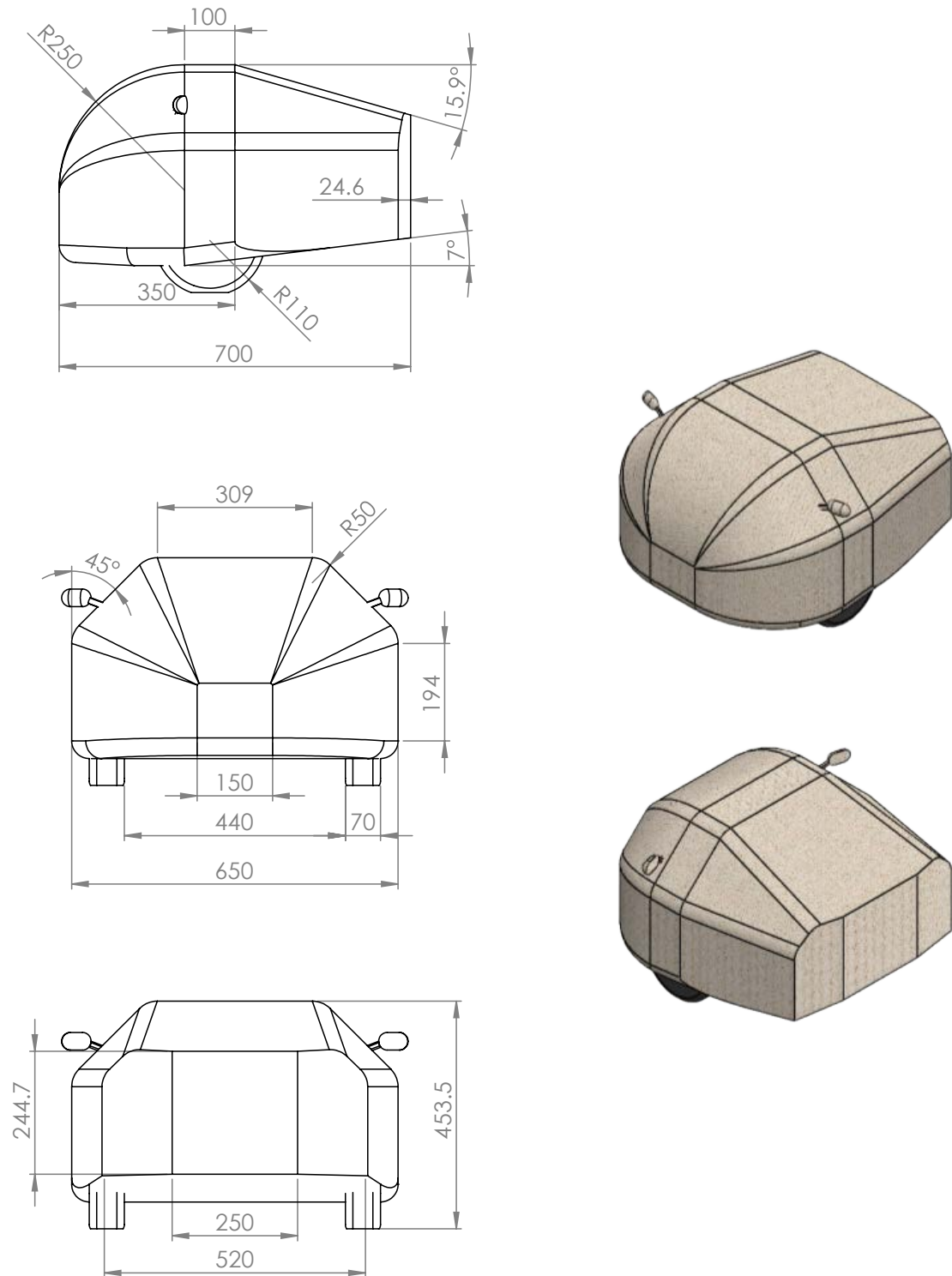


Figure E-5. Wake generator, Concept 4.

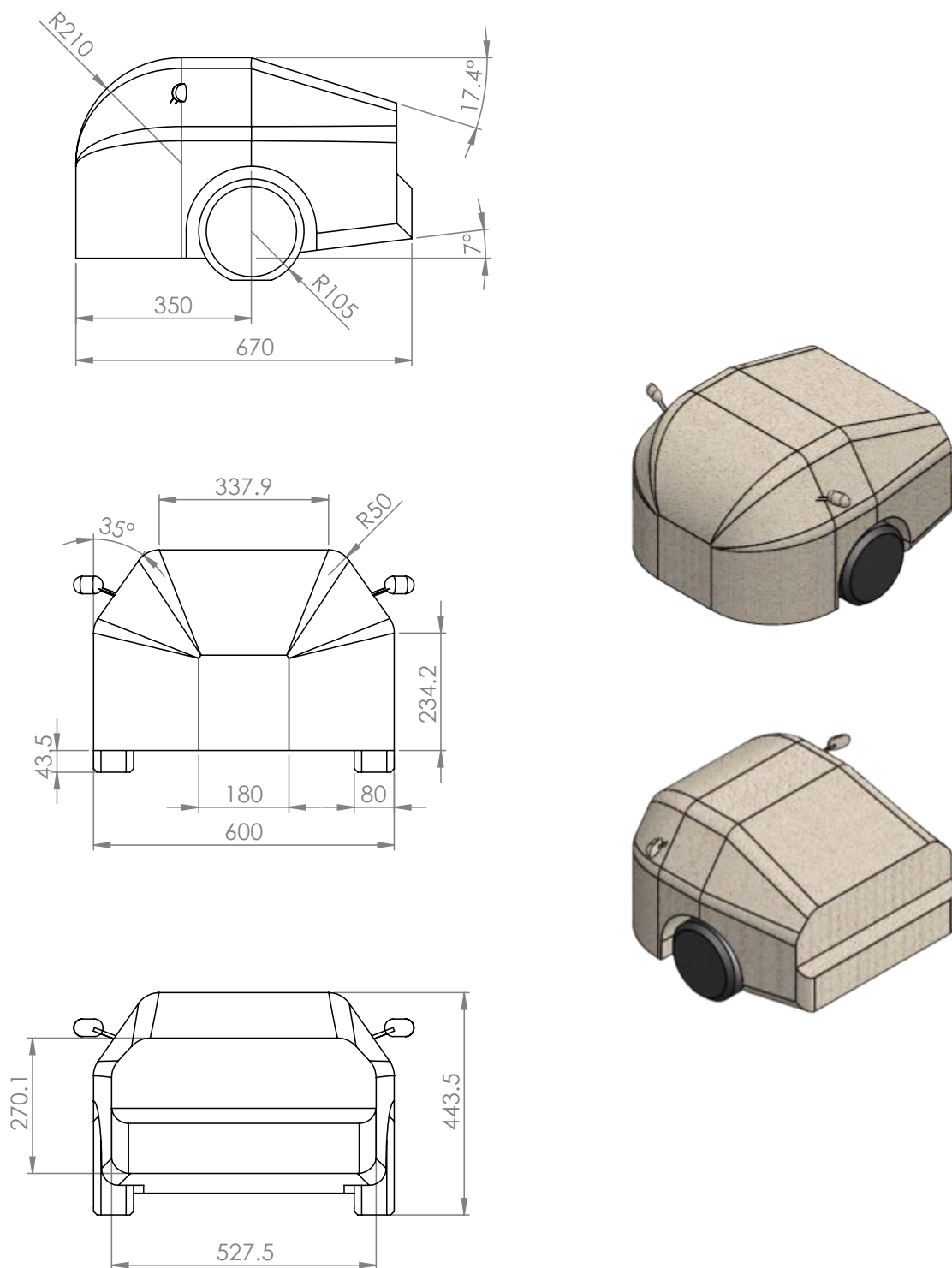


Figure E-6. Wake generator, Concept 5a.

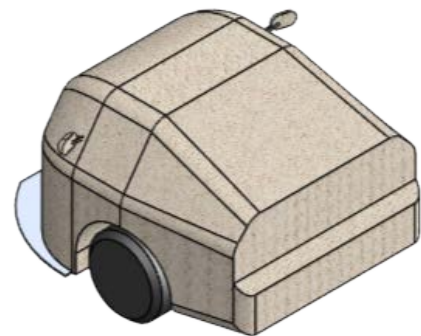
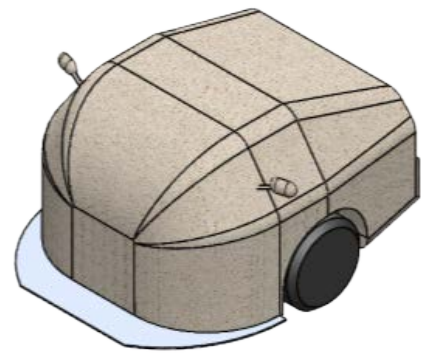
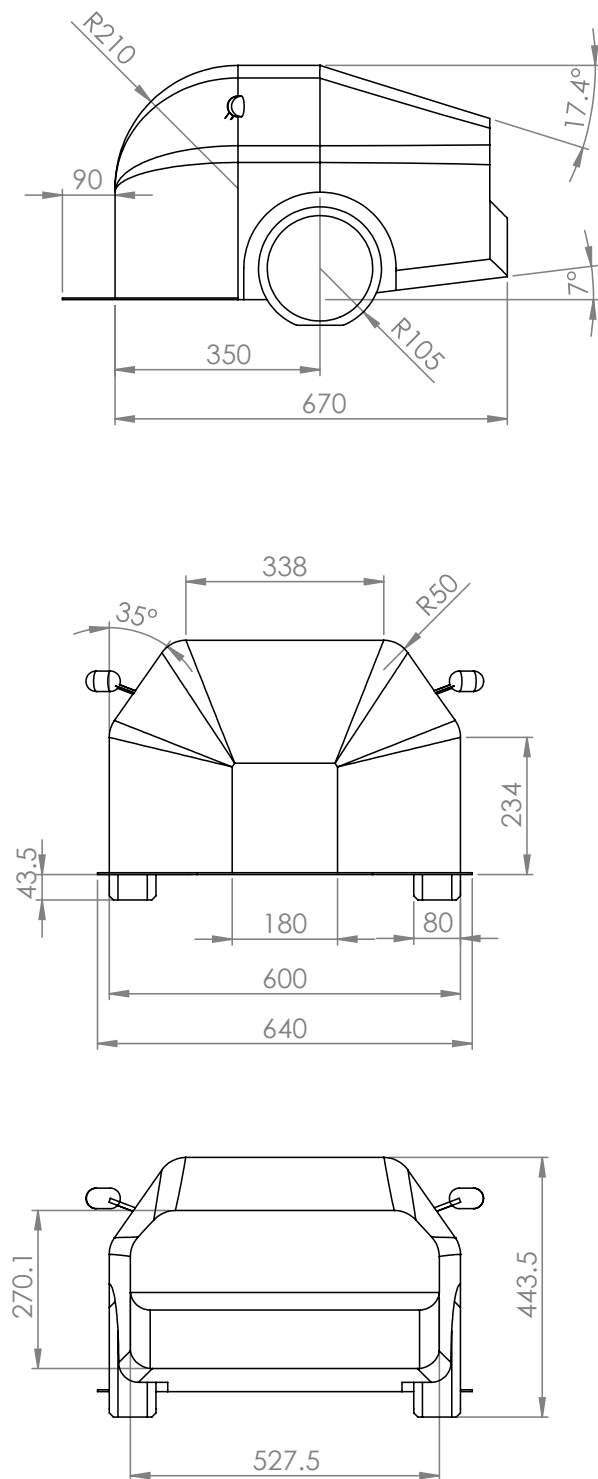


Figure E-7. Wake generator, Concept 5b.

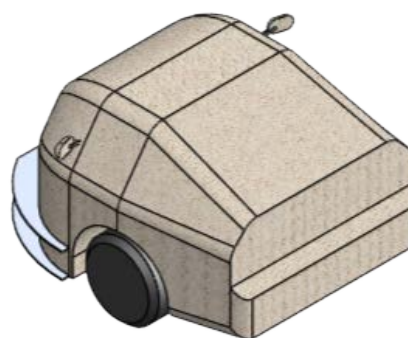
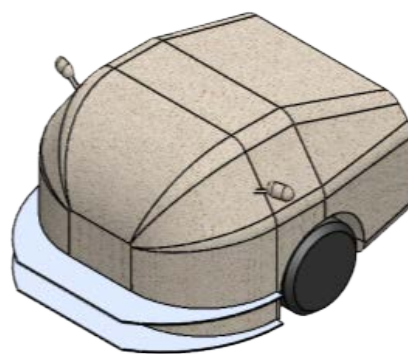
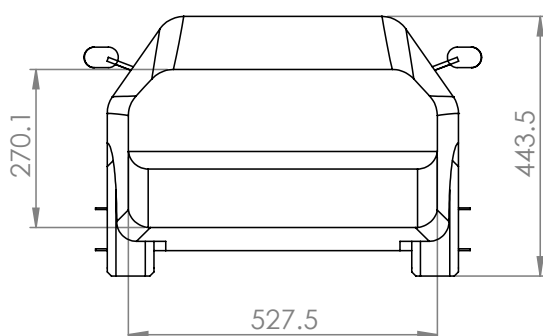
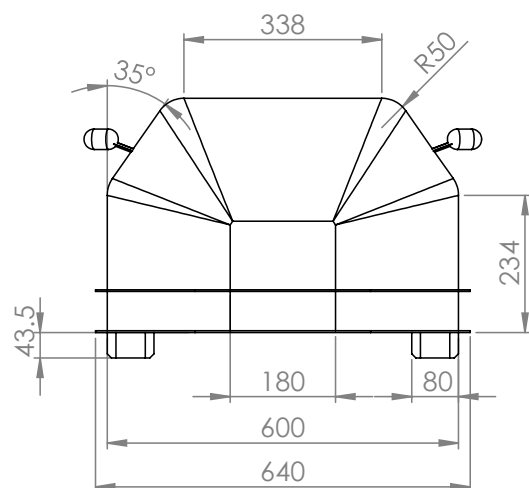
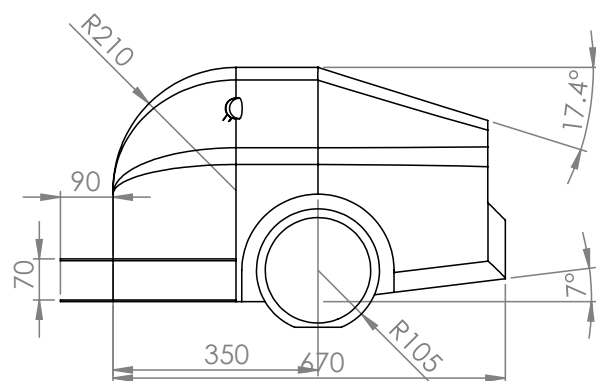


Figure E-8. Wake generator, Concept 5c.

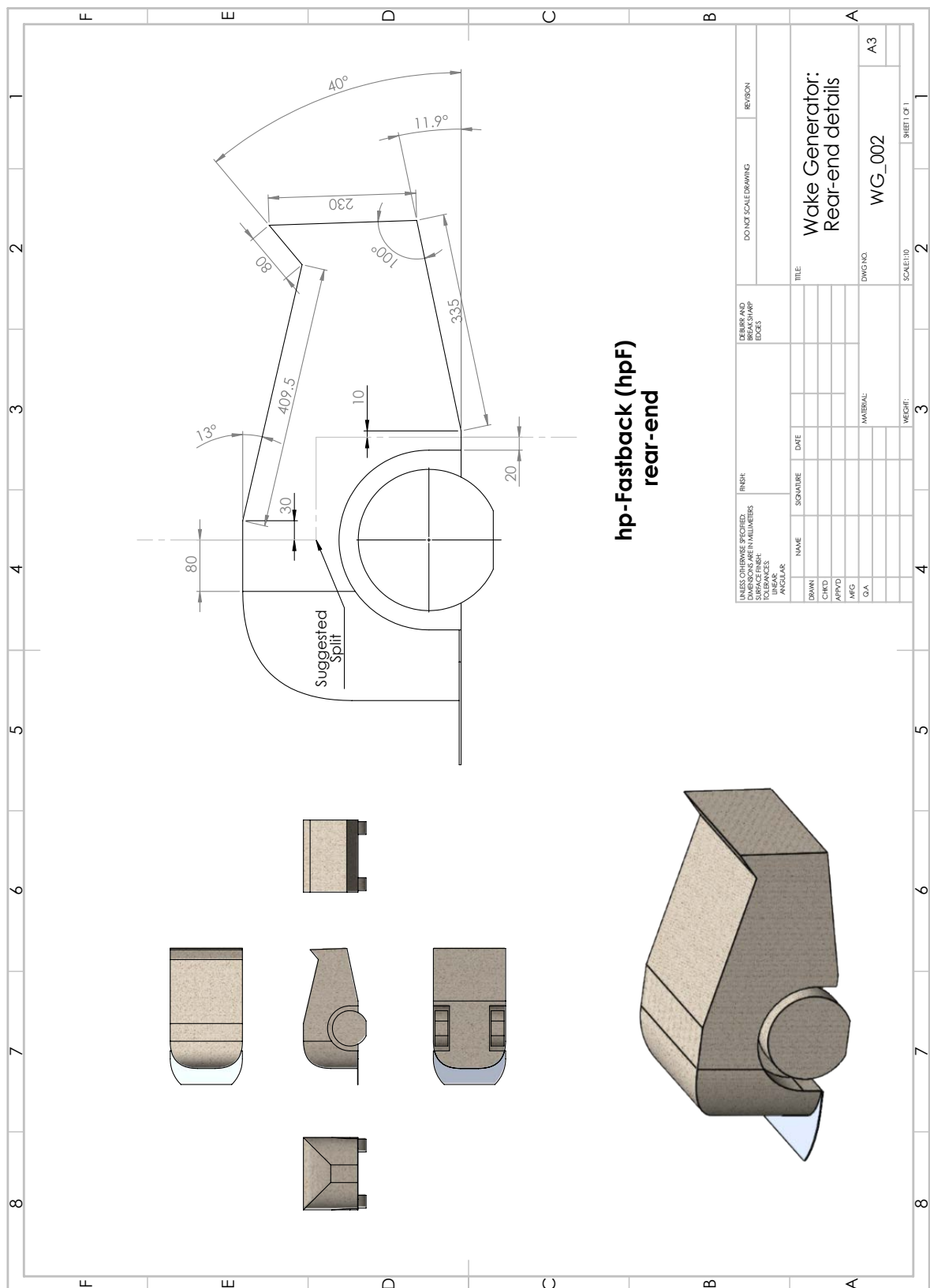


Figure E-10. Multi-wake generator, wind tunnel validation body. ‘High-performance’ rear body.

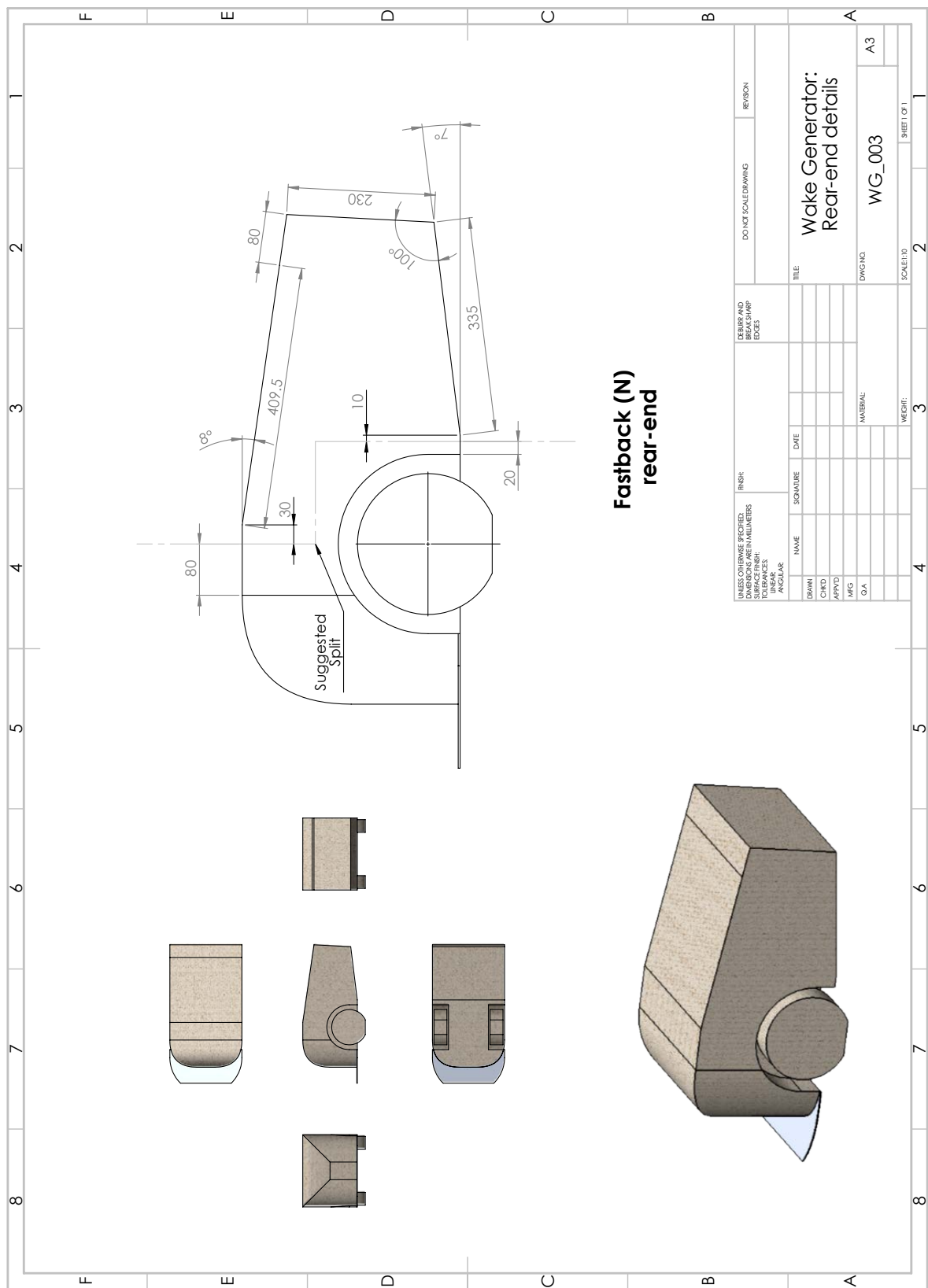


Figure E-11. Multi-wake generator, wind tunnel validation body. ‘Fastback’ configuration.

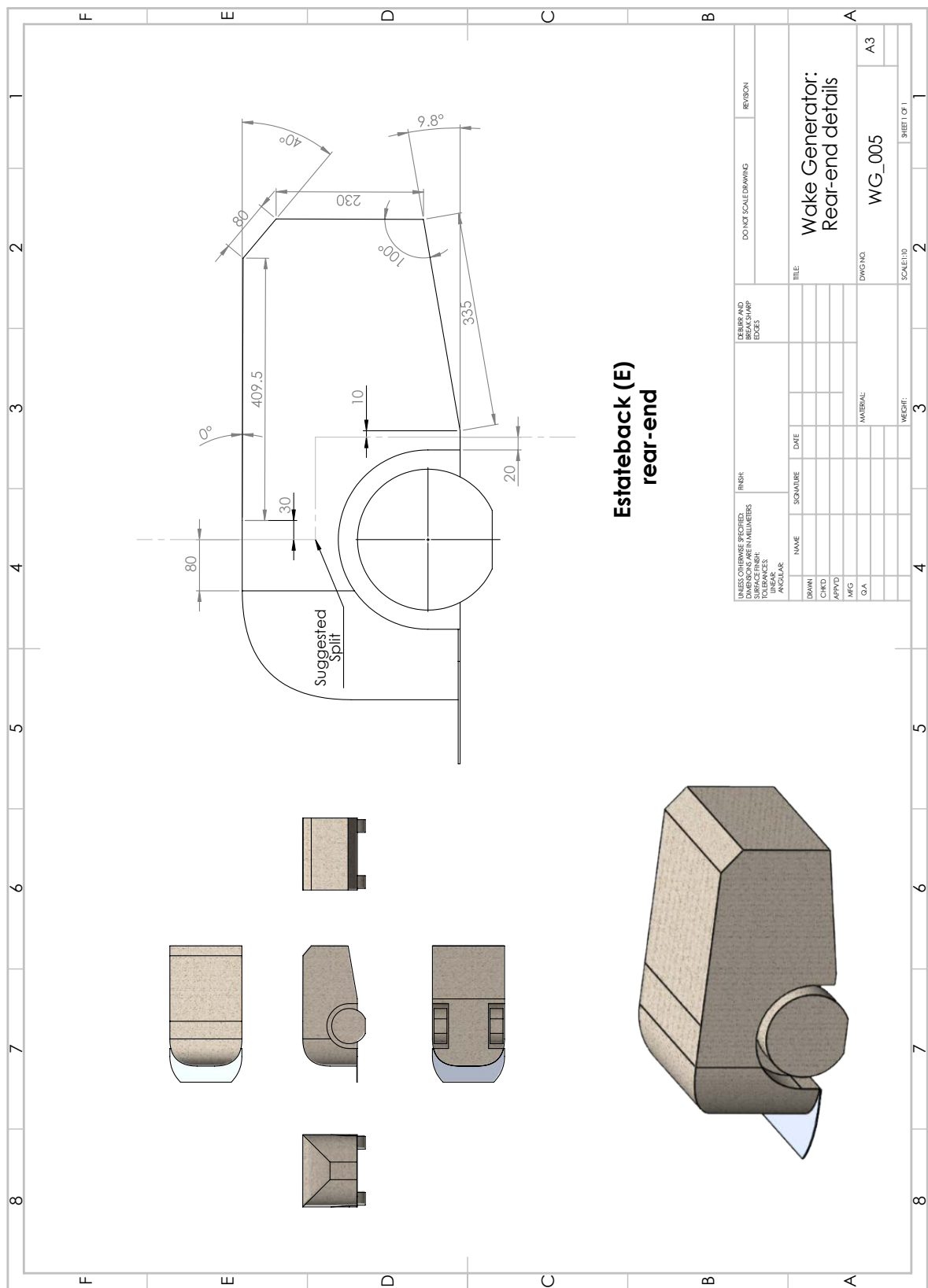


Figure E-13. Multi-wake generator, wind tunnel validation body. ‘Estateback’ configuration.

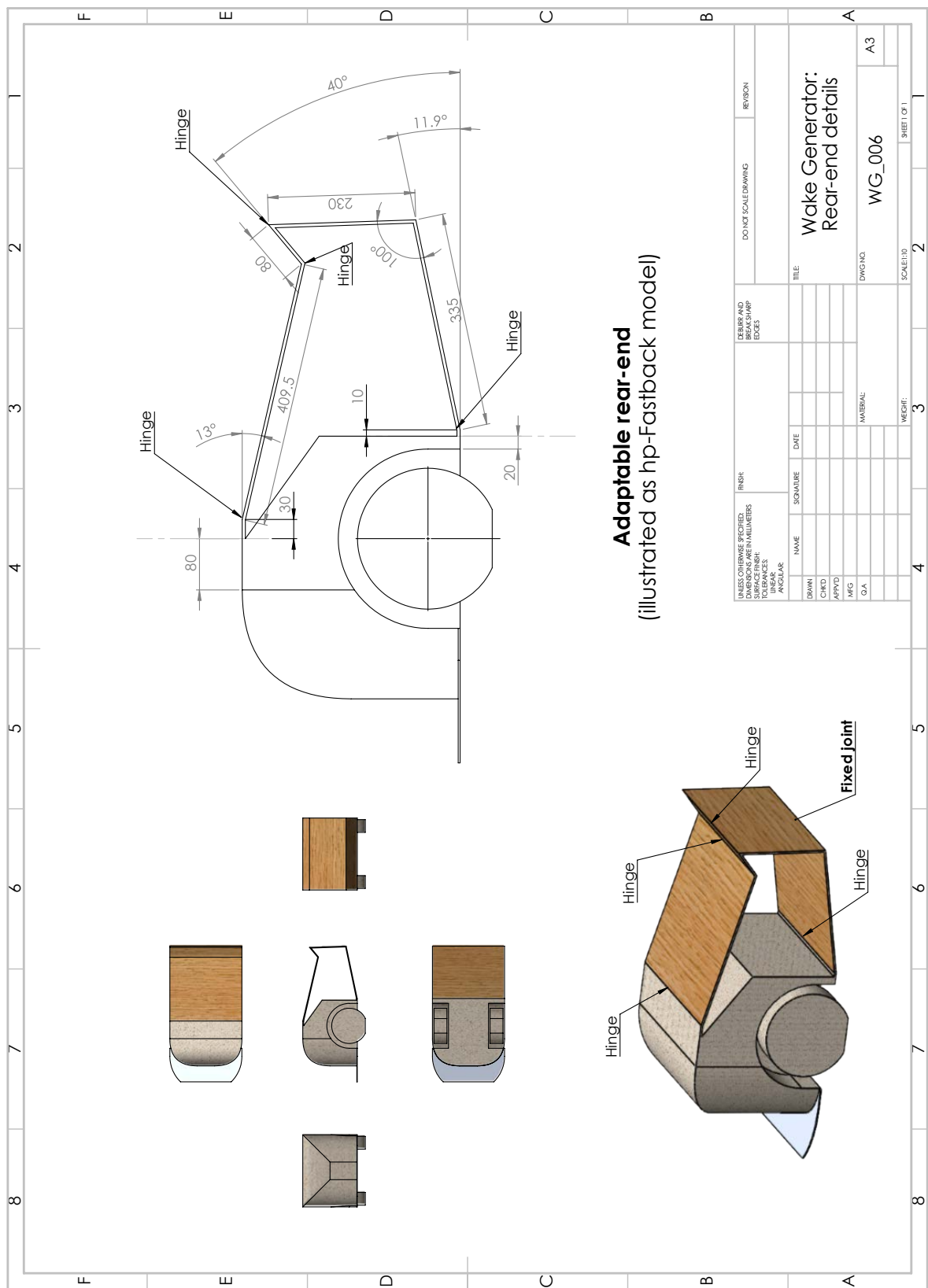


Figure E-14. Multi-wake generator, ‘thin-walled’ rear body version. ‘High-performance’ configuration.

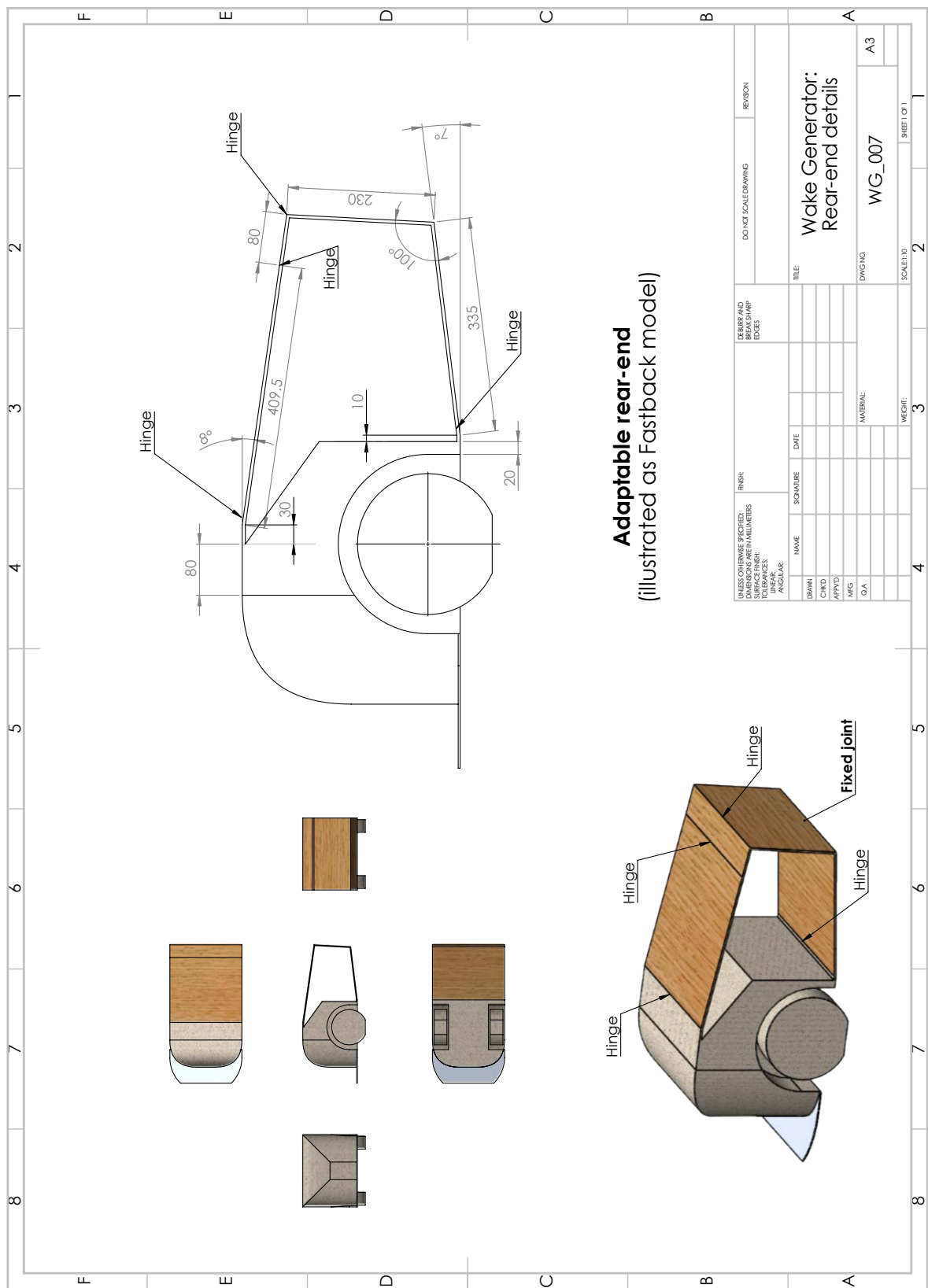


Figure E-15. Multi-wake generator, 'thin-walled' rear body version. 'Fastback' configuration.

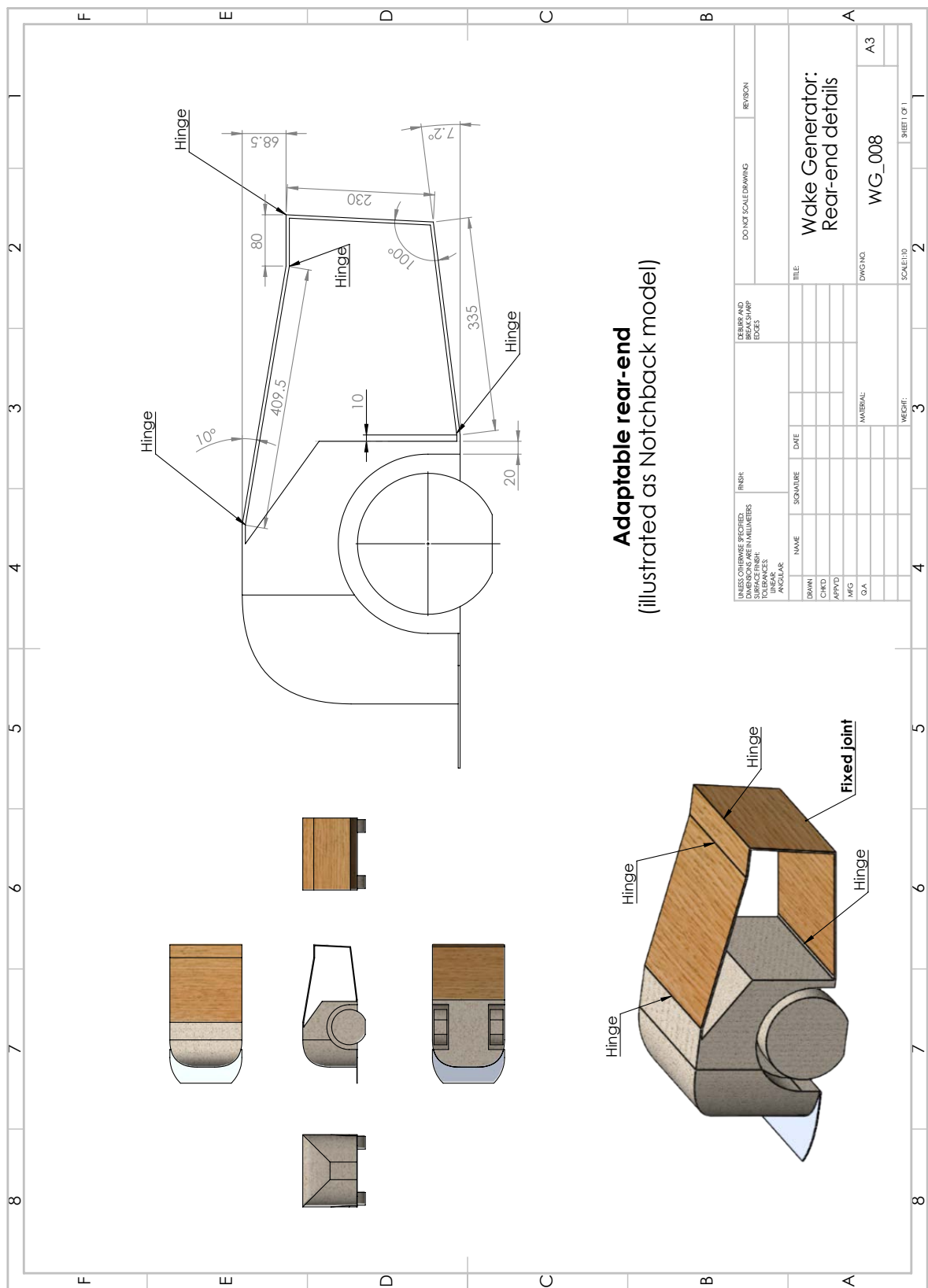


Figure E-16. Multi-wake generator, 'thin-walled' rear body version. 'Notchback' configuration.

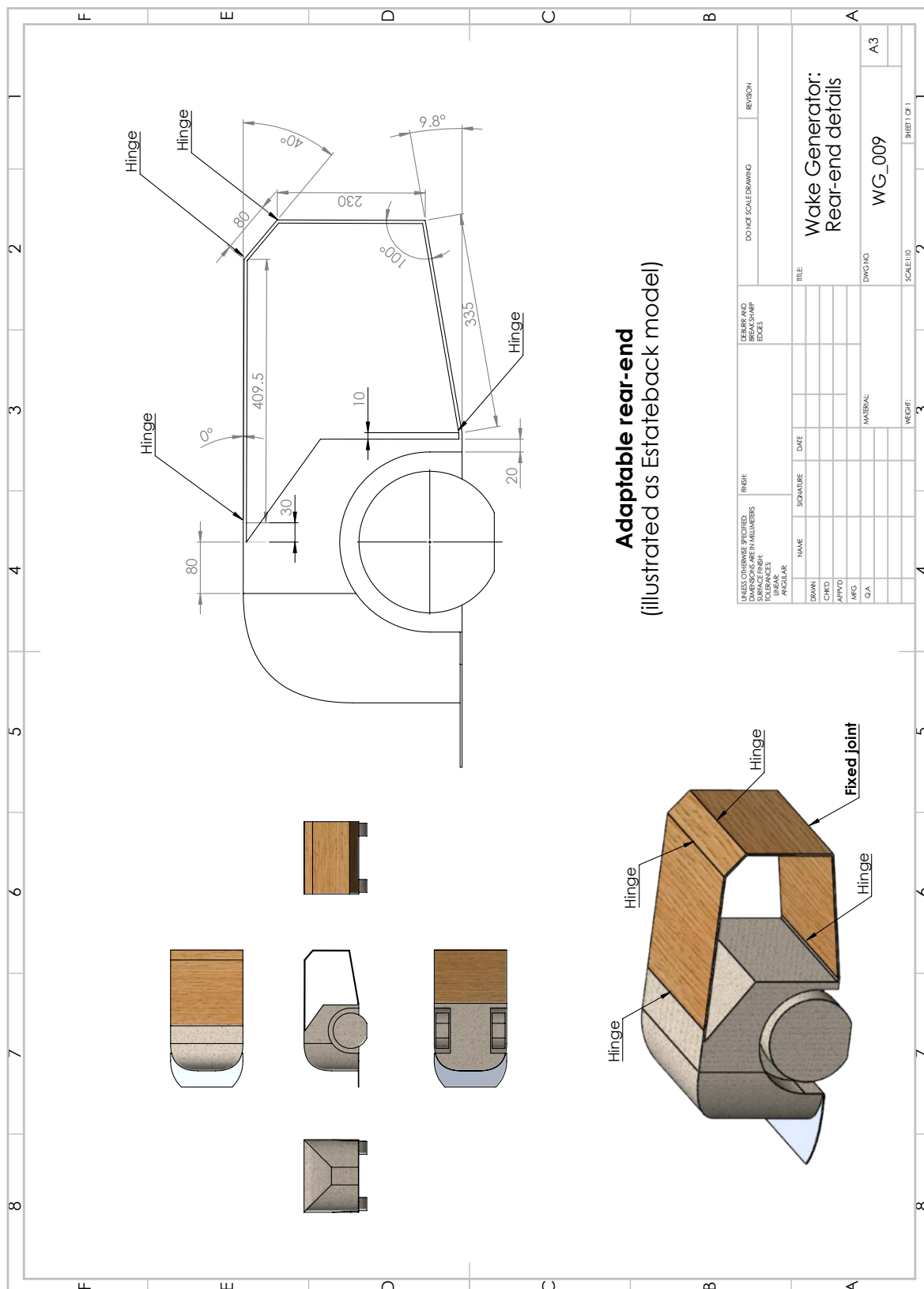


Figure E-17. Multi-wake generator, 'thin-walled' rear body version. 'Estateback' configuration.

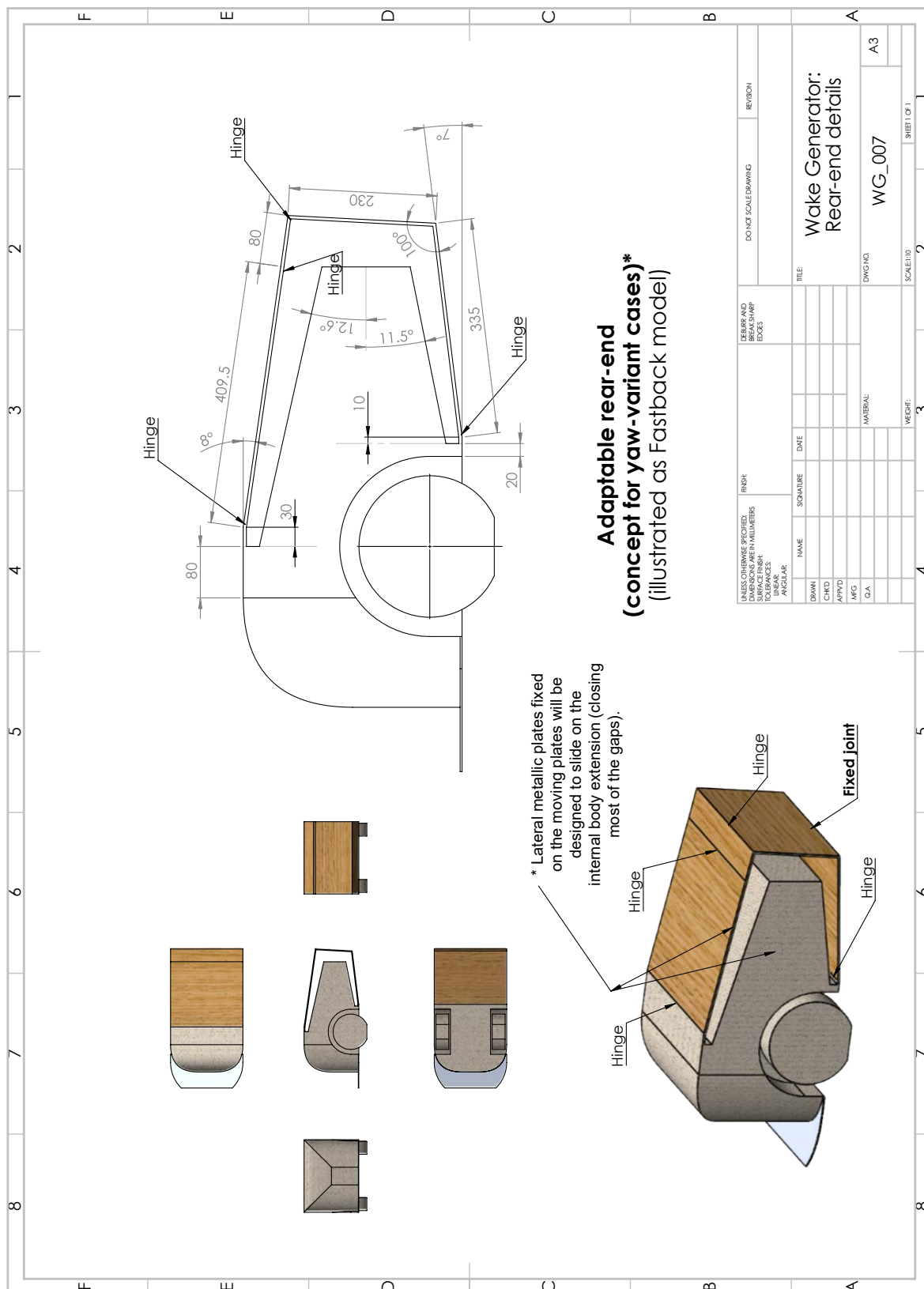


Figure E-18. Multi-wake generator, ‘thin-walled’ Potential body design for yaw-variant applications (suggestion for future work and implementation).