



Development and Analysis of a Full Vehicle CFD Dataset for Rim Aerodynamics

Master's thesis in Applied Mechanics

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

www.chalmers.se

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Master's Thesis 2026
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Abstract

Rim geometry affects vehicle forces and flow around the wheels, but automotive computational fluid dynamics (CFD) datasets cover few rim designs. This thesis develops and analyses DrivAerRim to examine these effects and provide data for future geometric deep learning surrogates.

The dataset contains full vehicle simulations for all 904 three dimensional Deep-Wheel rims on a common DrivAer estateback. Vehicle geometry and numerical settings remain fixed, with zero yaw and a speed of 140 km h^{-1} . The simulations use steady Reynolds averaged Navier–Stokes equations with the realizable $k - \epsilon$ turbulence model. Moving reference frames represent rim rotation, while rotating wall conditions are applied to the tyres. Mesh sensitivity and wind tunnel comparisons of drag differences and surface pressure support this setup, although pressure errors vary by region. The drag coefficient range over the final 500 iterations is below 0.002 in all cases.

Vehicle drag spans approximately $C_D = 0.2334$ to 0.2549 , while total and axle lift also vary with rim geometry. The combined contribution of wheel assemblies, wheel supports and wheelhouses is concentrated near 29% of conventional vehicle drag. Accumulated drag shows that the largest differences develop around the front and rear wheels. Associations between wheel mass flow and local drag differ by component and axle. Selected high drag cases generally show broader total pressure deficits near the ground and altered connections between wheel wakes and the downstream wake.

The exported STL geometries, force coefficients, wheel region surface fields, global slices and local volumes are organised for open reuse. They support further aerodynamic analysis and surrogate training under the specified steady simulation conditions. Surrogate development and evaluation remain outside the scope of this thesis.

Keywords: automotive aerodynamics, rim geometry, CFD, rotating wheels, RANS, dataset generation.

Acknowledgements

I would like to thank Simone Sebben and Chao Xia for the opportunity to work on this project. I am particularly grateful to Chao Xia for his guidance during CFD dataset generation and analysis. I also thank the collaborators at Volvo Cars for the validation data and technical advice. The simulations were enabled by resources provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS).

Carl Lewerth. Gothenburg, September 2026

List of Acronyms

The acronyms used throughout this thesis are listed below.

AI	Artificial intelligence
AMG	Algebraic multigrid
BiCGStab	Stabilised biconjugate gradient method
CAD	Computer aided design
CFD	Computational fluid dynamics
CFL	Courant–Friedrichs–Lewy number
DDES	Delayed detached eddy simulation
FEA	Finite element analysis
FWD	Front wheel deflector
HPC	High performance computing
IDDES	Improved delayed detached eddy simulation
LagEB	Lag elliptic blending turbulence model
LES	Large eddy simulation
LIC	Line integral convolution
MRF	Moving reference frame
OR / CR	Open rim / closed rim
PVT	Volvo Cars aerodynamic wind tunnel
RANS	Reynolds averaged Navier–Stokes
RBM	Rigid body motion
RKE	Realizable $k - \epsilon$ turbulence model
SST	Shear stress transport $k - \omega$ model
SST_a1	SST variant with $a_1 = 1$ and realizability coefficient 1.2
STL	Stereolithography surface mesh format
TKE	Turbulent kinetic energy
VTK	Visualization Toolkit data format
WMLES	Wall modelled large eddy simulation

Nomenclature

The principal symbols used throughout this thesis are listed below.

A_{ref}	Reference frontal area, m^2
b	Wheelbase, m
C_D	Complete vehicle drag coefficient
$C_{D,V,i}$	Equivalent ventilation drag coefficient of wheel i
C_f	Skin friction coefficient
C_L	Complete vehicle lift coefficient
C_{LF}, C_{LR}	Front and rear axle lift coefficients
C_p	Surface pressure coefficient
$C_{p,\text{tot}}$	Total pressure coefficient, referenced to freestream static pressure
C_S	Side force coefficient
F_x, F_y, F_z	Cartesian force components, N
k	Turbulent kinetic energy, $\text{m}^2 \text{s}^{-2}$
k_{tot}	Exported total turbulent kinetic energy, $\text{m}^2 \text{s}^{-2}$
$\dot{m}_i$	Signed wheel plane mass flow rate, kg s^{-1}
M_y	Pitching or wheel axis moment, N m
p, p_∞	Local and freestream static pressure, Pa
q_∞	Freestream dynamic pressure, Pa
Q	Second invariant of the velocity gradient tensor, s^{-2}
r	Effective wheel radius, m
R_{CD}	Drag coefficient range in the averaging window
S_{ij}, W_{ij}	Mean strain rate and rotation rate tensors, s^{-1}
U_i, U_∞	Velocity component and freestream velocity, m s^{-1}
x, y, z	Streamwise, lateral, and vertical coordinates, m
y_w, y^+	Wall normal cell centre distance (m) and nondimensional wall distance
β	Yaw angle, degrees
ϵ	Turbulent kinetic energy dissipation rate, $\text{m}^2 \text{s}^{-3}$
μ, μ_t	Molecular and turbulent dynamic viscosity, Pa s
ρ	Air density, kg m^{-3}
τ_w	Wall shear stress, Pa
ω	Specific dissipation rate, s^{-1}
Ω	Wheel angular velocity vector, rad s^{-1}
ϕ	Lag parameter in the LagEB turbulence model

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1

Introduction

Reducing energy consumption and greenhouse gas emissions from passenger vehicles is part of the transition to low carbon transport. In the European Union, Regulation (EU) 2023/851 strengthened the CO₂ emission standards for new passenger cars. It set a fleet wide target for 2030 to 2034 that is 55% lower than the 2021 target [1]. Reducing aerodynamic drag improves energy efficiency by lowering fuel consumption and extending the range of electric vehicles. The wheels contribute to this drag through their own loading and their influence on the surrounding flow [2]. Previous studies examined rim configurations [3, 4, 5] and tyre tread patterns and profiles [2, 6], mainly within limited design families. These studies cover only part of the rim diversity found in current vehicles. Assessing more designs through computational fluid dynamics (CFD) and wind tunnel testing is costly and time consuming. Geometric deep learning surrogates can accelerate aerodynamic prediction and optimisation, but depend on diverse, high quality training data [7, 8]. Current automotive CFD datasets primarily vary vehicle dimensions and body features [9, 10, 11, 12]. They offer limited variation in local components such as rims, mirrors, and spoilers. This thesis develops DrivAerRim, a CFD dataset for 904 geometrically diverse DeepWheel rims [13]. Full vehicle simulations use a common DrivAer estateback and consistent numerical settings to compare rim effects on vehicle forces and wheel flow. The paired geometry and flow records are also intended for future geometric deep learning surrogates for aerodynamic prediction and optimisation.

1.1 Research objectives

The central question is how geometrically diverse rims change vehicle forces and the flow around the wheels under common operating conditions. Comparisons at both vehicle and component levels are needed to distinguish local force changes from effects on the surrounding body. The work has three objectives:

1. Develop a CFD dataset for all 904 DeepWheel rims on a fixed DrivAer estateback. Establish a consistent workflow, assess mesh sensitivity and experimental agreement, and check geometry, mesh, solution stability and exported records.
2. Analyse how rim geometry affects vehicle drag and lift and the forces on wheel assemblies, wheelhouses and wheel supports. Relate these responses to accumulated drag, signed wheel plane mass flow and local flow patterns, with ventilation resistance reported separately from conventional drag.

3. Organise and document the paired geometry and CFD records for open release. Include rim STL geometries, wheel region surface fields, global slices and local volumes to support future geometric deep learning surrogate training and evaluation.

1.2 Limitations

The dataset covers one vehicle at zero yaw and 140 km h^{-1} , with fixed tyres, ride height, closed cooling inlets, and identical rims at all four positions. Crosswinds, other bodies, and brake cooling are excluded.

Steady Reynolds averaged Navier–Stokes (RANS) simulations with moving reference frame (MRF) wheel regions do not resolve spoke passage or instantaneous turbulent structures. Validation covers selected configurations, not all 904 rims. Convergence checks establish iterative stability, not total prediction uncertainty. Surrogate training is future work.

1.3 Thesis outline

Chapter 2 reviews the background and research gap. Chapter 3 defines the physical models and aerodynamic quantities. Chapter 4 explains dataset generation and numerical settings. Chapter 5 presents validation, quality control, aerodynamic trends, and data records, including spatial fields. Chapter 6 summarises the conclusions and future work.

2

Background

This chapter reviews the environmental relevance of rim aerodynamics, previous wheel studies, CFD datasets, and synthetic rim collections. It then identifies the research gap addressed by this thesis.

2.1 Environmental aspects

Reducing transport energy use helps limit greenhouse gas emissions. Aerodynamic improvements reduce the power needed to propel a vehicle, especially at higher driving speeds. For fixed air density, frontal area, and drag coefficient, drag scales with speed squared and the associated propulsion power scales with speed cubed. Lower drag can therefore reduce fuel consumption and associated emissions in combustion engine vehicles. For battery electric vehicles, it can lower energy use per kilometre and extend driving range under comparable conditions.

Rim design offers one route to these improvements without changing the main vehicle body [4]. However, reducing conventional drag is only part of the aerodynamic objective. Aerodynamic torque also requires power to rotate the wheels, while rim openings influence air exchange around the brakes [3, 14]. Aerodynamic objectives must therefore be considered alongside brake cooling, structural strength, material use, and manufacturing requirements. This thesis evaluates aerodynamic responses and does not quantify fuel savings, emissions reductions, or the life cycle environmental performance of individual rims.

2.2 Wheel and rim aerodynamics

Wheel aerodynamics involves both conventional drag, the streamwise pressure and shear force, and ventilation resistance, the aerodynamic moment opposing wheel rotation [3, 14]. Rim geometry also affects flow around the wheelhouse, underbody, and vehicle base, so its influence extends beyond the wheel itself [4].

Using modular wheels, Vdovin et al. showed that spoke shape and radial coverage influence ventilation resistance [3]. Figures 2.1 and 2.2 show the tested configurations and their performance. Full coverage did not always give the lowest ventilation resistance. This ranking does not directly establish which rim gives the lowest conventional vehicle drag.

Their subsequent CFD study separated the ventilation moment into tyre, rim, and brake disc contributions [14]. The tyre and rim contributions depended on design and speed, while the brake disc contribution was small in the investigated cases.

2. Background

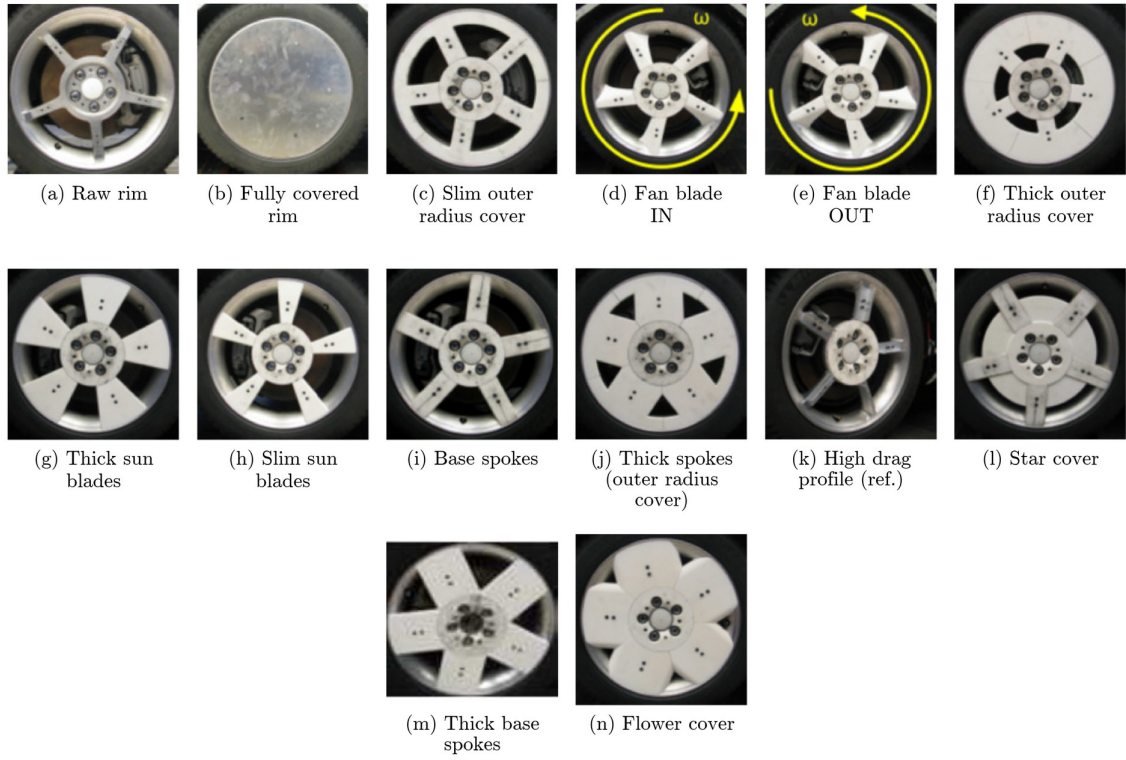


Figure 2.1: Fourteen configurations constructed from a common modular wheel. Photographs rearranged from Figure 10 of Vdovin et al. [3], with the original panel identifiers retained.

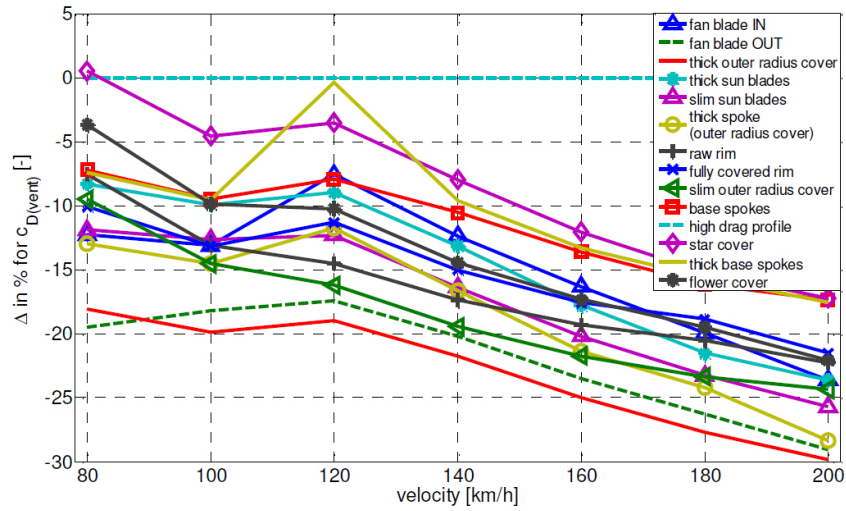


Figure 2.2: Percentage difference in ventilation resistance relative to the high drag reference in the modular wheel experiment. The image is extracted from Figure 11 of Vdovin et al. [3].

The equivalent ventilation force increased approximately with the square of speed, supporting its assessment alongside conventional drag.

Brandt et al. examined conventional vehicle drag using a parametric wind tunnel study of passenger car wheels [4]. Rim coverage had the strongest influence among the parameters tested, with increasing coverage reducing drag approximately linearly (Figure 2.3). Greater coverage reduced flow through the rim, weakened near ground jetting, and improved pressure recovery at the vehicle base. Front and rear rim changes produced different drag reductions, while rim angles and centre depth introduced secondary effects.

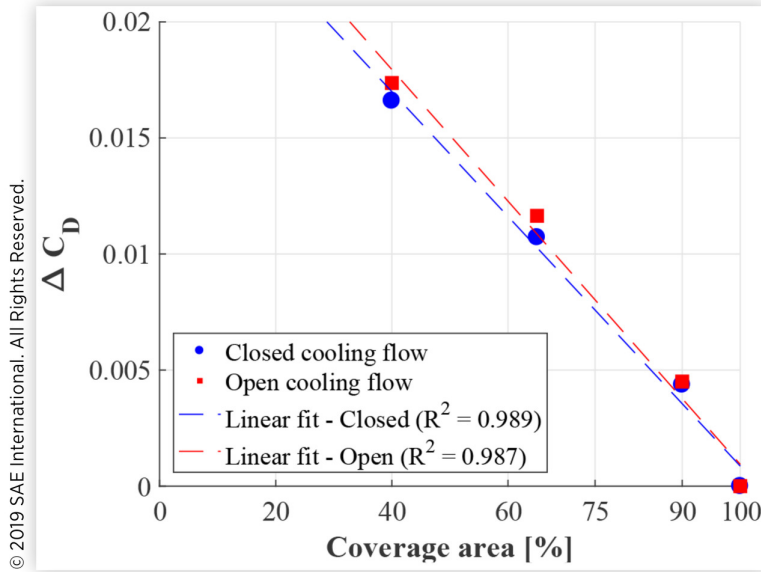


Figure 2.3: Effect of rim coverage on conventional vehicle drag with open and closed cooling flow. The fully covered wheel is the reference for ΔC_D , and the dashed lines are the original linear fits. Extracted from Figure 13 of Brandt et al. [4], SAE Paper 2019-01-0662.

Tyre geometry, ground systems, and wind tunnel surroundings further influence wheel flow and the measured drag differences [15, 16]. Altmann et al. compared numerical predictions for four production rims, emphasising consistent meshing and realistic, deformed tyre geometry [5]. Steady simulations using a moving reference frame (MRF) treatment captured the drag difference between the best and worst rims but remained sensitive to spoke orientation. Transient simulations resolving turbulent scales and actual rim motion reproduced the rankings and drag differences for all four rims in that comparison.

2.3 CFD datasets for data driven aerodynamics

Public CFD datasets cover increasingly varied geometries. AeroFlowData collects more than 500 high Reynolds number experimental and numerical flow conditions across aerospace and turbomachinery configurations [17]. HiLiftAeroML contributes

2. Background

1,800 wall modelled large eddy simulations for high lift aircraft, while BlendedNet provides 8,830 RANS cases for blended wing body variations [18, 19].

Automotive datasets cover both simplified bodies and realistic vehicles. AhmedML and WindsorML provide high fidelity data for simplified road vehicle bluff bodies [20, 21]. The latter contains 355 Windsor body variants computed using wall modelled large eddy simulation.

Figures 2.4 to 2.7 illustrate the geometry variation and multimodal records of four DrivAer based datasets. DrivAerNet contains 4,000 parametric fastback cases, with morphing regions distributed over the vehicle body [9].

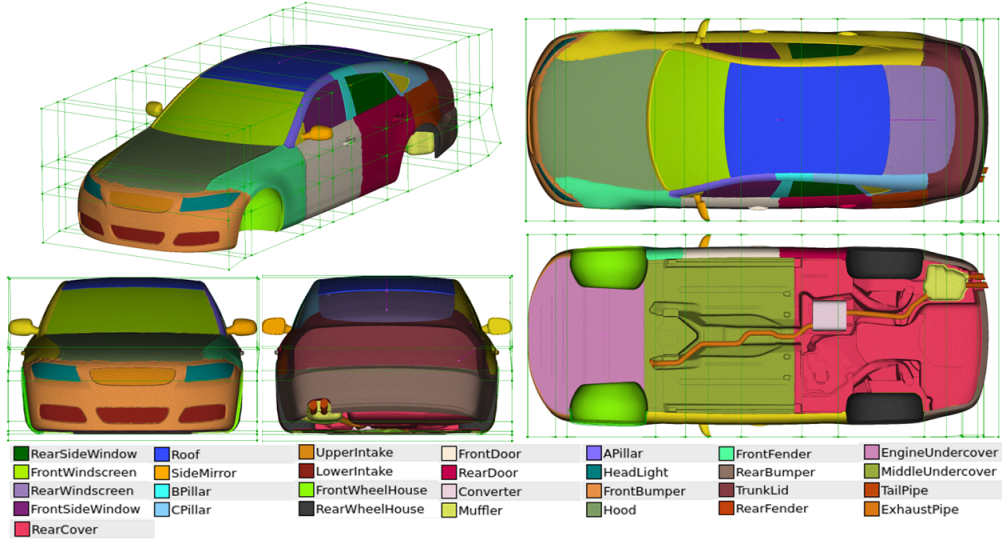


Figure 2.4: DrivAerNet parametric regions and morphing boxes on the detailed fastback. The complete graphic, including its legend, is reproduced from Figure 2 of the dataset publication [9].

DrivAerNet++ expands the design space to 8,000 fastback, notchback, and estate-back vehicles with multiple underbody and wheel options [10]. Its records include complementary geometric and CFD representations, as shown in Figure 2.5.

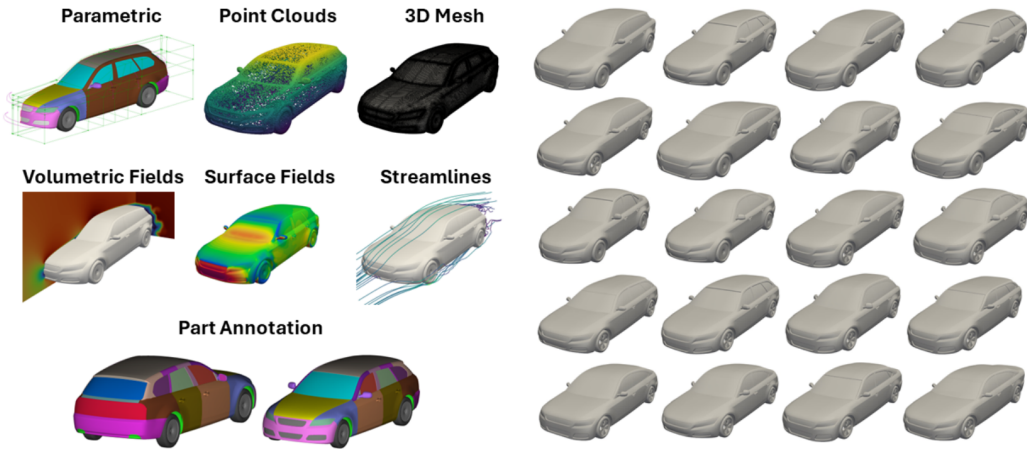


Figure 2.5: DrivAerNet++ multimodal records and representative shape variants. The image is cropped from the dataset publication [10].

DrivAerML supplies 500 high fidelity notchback cases [11]. Figure 2.6 shows the morphing boxes and sampled design parameters that define its vehicle geometry variations.

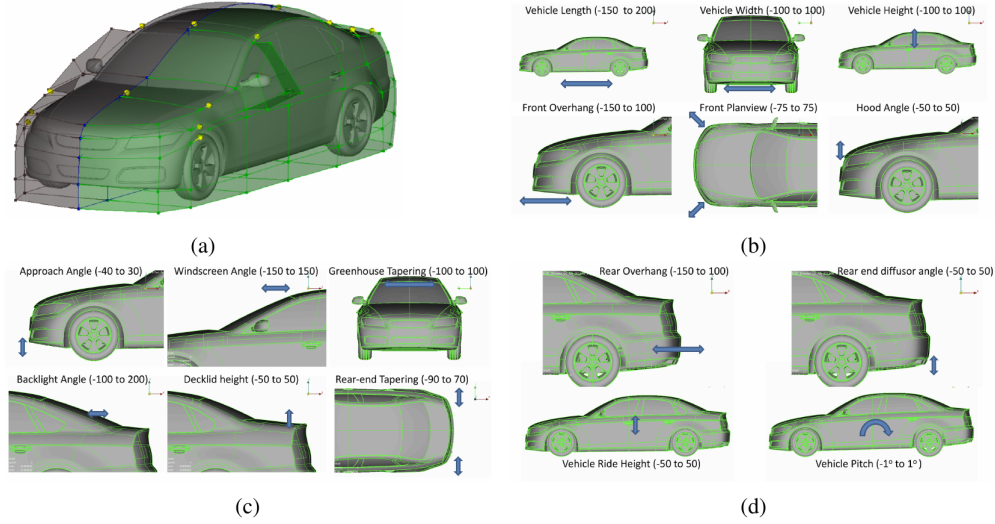


Figure 2.6: DrivAerML morphing boxes and the 16 sampled design parameters. The image is cropped from the dataset publication [11].

DrivAerStar provides 12,000 simulations with detailed vehicle components [12]. Its workflow connects geometric morphing, volume meshing, and the export of flow fields, illustrated in Figure 2.7.

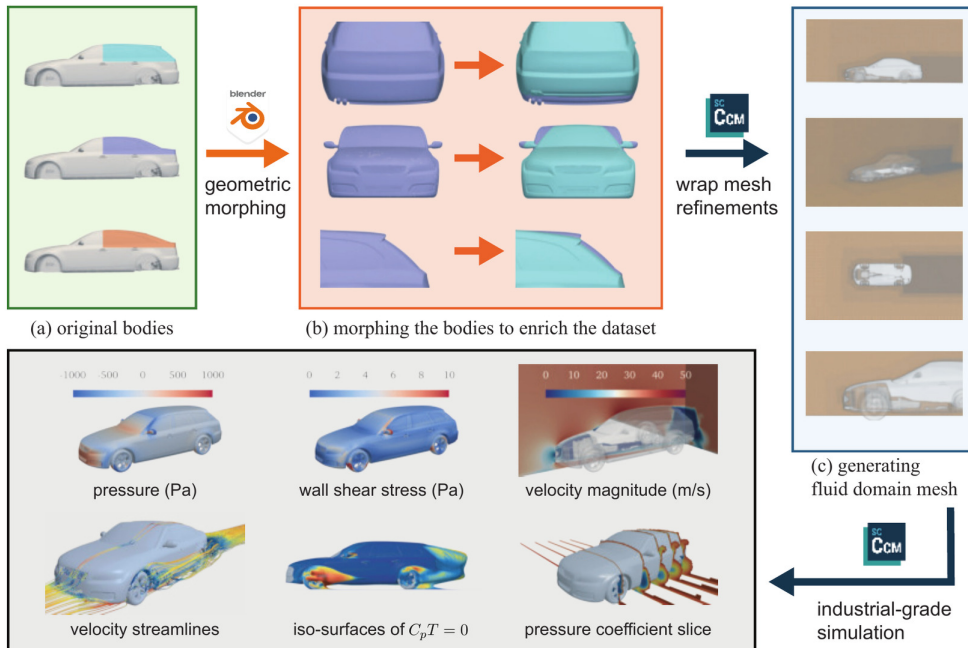


Figure 2.7: DrivAerStar geometric morphing, meshing, and exported CFD fields. The image is cropped from the dataset publication [12].

SHIFT-SUV contains 3,992 high fidelity simulations of full scale and quarter scale estateback and fastback sport utility vehicles [22].

2. Background

Table 2.1 summarises established automotive CFD datasets. Most vary the complete body or a set of global parameters. Wheel rotation, where included, is normally represented by rotating wall boundary conditions. Rim topology varies little under otherwise controlled conditions. CarBench identifies rotating wheels as a difficult region for neural surrogates because predictions are sensitive to small features, rotation, and local recirculation [8].

Table 2.1: Representative public automotive CFD datasets. Case counts and numerical methods follow the cited publications.

Dataset	Geometry	Cases	CFD method	Wheel treatment
AhmedML [20]	Ahmed body	500	DDES	No wheels
WindsorML [21]	Windsor body	355	WMLES	No wheels
DrivAerNet [9]	DrivAer fastback	4,000	RANS	Rotating wall
DrivAerNet++ [10]	Three DrivAer rear ends	8,000	RANS	Rotating wall
DrivAerML [11]	DrivAer notchback	500	DDES	Stationary wheels
DrivAerStar [12]	Three DrivAer rear ends	12,000	RANS	Rotating wall
SHIFT-SUV [22]	Two AeroSUV rear ends	3,992	DDES	Rotating wall

2.4 Synthetic wheel geometry datasets

Synthetic geometry collections extend design studies beyond small deformations of a baseline rim. DeepWheel combines generative image models, depth based 3D reconstruction, topology optimisation, and finite element assessment [13]. It contains 6,249 rendered designs and 904 reconstructed three dimensional rims that completed structural analysis.

Figure 2.8 shows variation in opening ratio, spoke thickness and count, surface depth, and topology. These geometries form the input design space for this thesis.

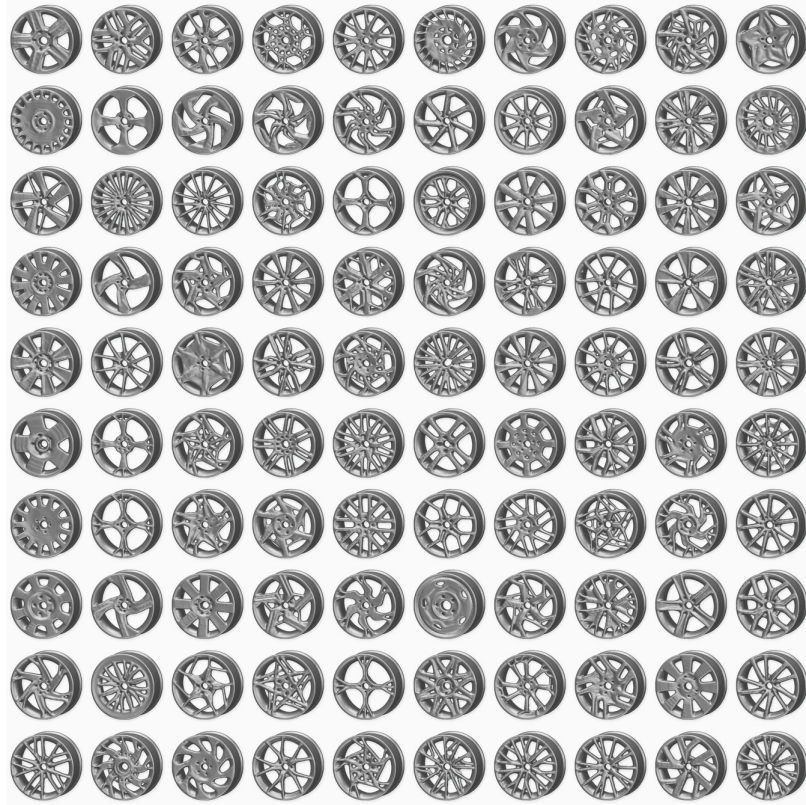


Figure 2.8: Representative DeepWheel rim geometries used in DrivAerRim. The renderings were prepared from the released STL geometries for this project. The source geometry dataset is described by Yoo and Kang [13].

2.5 Research gap

Automotive CFD datasets emphasise body shape variation, while rim studies generally cover only a few designs [4, 5, 9, 10]. DeepWheel supplies diverse rims without full vehicle aerodynamic fields [13]. A controlled dataset is needed to connect diverse rim geometries with whole vehicle and component forces. Paired surface fields, global slices, and local volumes would support physical analysis and future geometric deep learning surrogates.

3

Theory

This chapter presents the flow equations, four RANS turbulence models, and wheel rotation treatments considered in this work. It also defines the aerodynamic quantities used to analyse the dataset.

3.1 Reynolds averaged Navier–Stokes equations

Air is treated as an incompressible Newtonian fluid with constant density ρ and dynamic viscosity μ . The instantaneous velocity and pressure are decomposed into mean and fluctuating parts,

$$U_i = \overline{U}_i + u'_i, \quad p = \bar{p} + p', \quad \overline{u'_i} = 0. \quad (3.1)$$

An overbar denotes Reynolds averaging, and repeated Cartesian indices imply summation. Averaging the conservation equations gives

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0 \quad (3.2)$$

and

$$\rho \left(\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} \right) = -\frac{\partial \bar{p}}{\partial x_i} + \mu \frac{\partial^2 \overline{U}_i}{\partial x_j \partial x_j} - \rho \frac{\partial \overline{u'_i u'_j}}{\partial x_j}. \quad (3.3)$$

The Reynolds stresses, $-\rho \overline{u'_i u'_j}$, represent momentum transport by turbulent fluctuations. Turbulence models approximate these unresolved velocity correlations to close the equations. Steady RANS sets the mean flow time derivative to zero while modelling the effects of turbulence.

RANS does not resolve individual turbulent eddies. Its relatively low cost makes large geometry studies possible, but the stress approximation introduces uncertainty in separated and strongly curved flows. Fluctuations between solver iterations are numerical behaviour, not a physical time series.

3.2 Turbulence modelling

The closures considered here use an eddy viscosity framework, relating modelled stresses to the mean strain rate,

$$-\rho \overline{u'_i u'_j} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij}, \quad S_{ij} = \frac{1}{2} \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right). \quad (3.4)$$

Here, $k = \overline{u_i' u_i'}/2$ is turbulent kinetic energy, δ_{ij} is the Kronecker delta, and μ_t is turbulent viscosity. The models differ in how they determine μ_t , represent near wall behaviour, and respond to departures from local turbulence equilibrium.

3.2.1 Realizable $k - \epsilon$ model

The realizable $k - \epsilon$ model, abbreviated RKE, solves transport equations for k and its dissipation rate ϵ . Its eddy viscosity has the form

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon}. \quad (3.5)$$

Unlike the standard $k - \epsilon$ model, RKE uses a variable C_μ and a modified dissipation equation. The formulation incorporates constraints on normal stresses and shear stress correlations to improve realizability [23].

The two layer implementation combines an outer flow model with a near wall description. Its accuracy for rim induced force differences is assessed against experiments in Section 5.1.

3.2.2 Shear stress transport $k - \omega$ model

The shear stress transport $k - \omega$ model, abbreviated SST, solves for k and the specific dissipation rate ω . It blends a $k - \omega$ description near walls with a transformed $k - \epsilon$ formulation in the outer flow [24]. The blending limits sensitivity to freestream turbulence conditions while retaining the near wall behaviour of the $k - \omega$ model. SST also limits turbulent shear stress through its eddy viscosity relation. In the strain rate form of SST, this is written as

$$\mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, S F_2)}, \quad S = \sqrt{2 S_{ij} S_{ij}}, \quad (3.6)$$

where F_2 is a near wall blending function and the standard coefficient is $a_1 = 0.31$ [25]. The limiter affects the response to adverse pressure gradients and separation.

3.2.3 Modified SST model: SST_a1

The validation also considers an SST variant with $a_1 = 1$ and a realizability coefficient of 1.2, denoted SST_a1. These settings define the variant tested here, not a separately calibrated turbulence model.

Increasing a_1 changes the balance between the two branches of Eq. (3.6). Where the shear stress limiter is active, it permits a larger eddy viscosity for otherwise unchanged k , ω , and S . This may alter separation and wake mixing. The additional realizability setting also changes the closure constraints. The comparison therefore tests the combined variant, rather than isolating the effect of a_1 alone.

3.2.4 Lag elliptic blending model

The lag elliptic blending $k - \epsilon$ model, abbreviated LagEB, introduces a transported lag parameter ϕ alongside k and ϵ . An elliptic blending variable connects near

wall and outer flow behaviour [26]. Its underlying eddy viscosity relation can be expressed as

$$\mu_t = \rho C_\mu \phi \frac{k^2}{\epsilon}. \quad (3.7)$$

The lag parameter accounts for the effects of misalignment between stress and strain without solving a full Reynolds stress transport system. This can improve the response to nonequilibrium and separated flows.

The additional equations increase complexity relative to the two equation closures. Like the other RANS models, LagEB does not resolve the instantaneous wheel wake.

3.3 Wheel rotation modelling

Wheel rotation couples tyre motion, spoke geometry, the contact patch, and confined wheelhouse flow. Three common treatments differ in whether they prescribe wall velocity, rotate the reference frame, or physically move the rim mesh. Each treatment represents different flow features at a different computational cost.

3.3.1 Rotating wall boundary condition

A rotating wall condition prescribes the local tangential wall velocity associated with angular velocity $\boldsymbol{\Omega}$. For an axisymmetric surface centred at $\mathbf{x}_c$,

$$\mathbf{U}_w = \boldsymbol{\Omega} \times (\mathbf{x} - \mathbf{x}_c). \quad (3.8)$$

The mesh remains stationary, making this treatment inexpensive. It also preserves a fixed, deformed tyre and its ground contact geometry.

On nonaxisymmetric spokes, the prescribed motion may require projection onto the surface tangent plane. Some spoke faces can consequently receive little tangential motion, and no geometric passage of the spokes is resolved [5]. A rotating wall is therefore useful for tyres but is a limited description of the pumping action of a complex rim.

3.3.2 Moving reference frame

A moving reference frame (MRF) describes flow relative to a rotating coordinate system within a fixed mesh region. For constant angular velocity, the relative velocity is

$$\mathbf{U}_{\text{rel}} = \mathbf{U}_{\text{abs}} - \boldsymbol{\Omega} \times (\mathbf{x} - \mathbf{x}_c). \quad (3.9)$$

The momentum equation includes Coriolis and centrifugal terms, and interface fluxes connect the rotating and stationary regions.

MRF represents flow through the spoke passages while retaining a steady calculation. Its principal advantages are low cost and compatibility with automated meshing. However, the spoke orientation is frozen, and the result depends on the rotating region extent and its interfaces. Orientation sensitivity can affect small drag differences between rims [5].

3.3.3 Rigid body motion and sliding mesh

Rigid body motion (RBM) physically rotates the rim mesh through successive time steps. Sliding interfaces exchange fluxes between the rotating and stationary regions as their relative positions change. This approach represents spoke passage and its unsteady interaction with the wheelhouse. It can be combined with unsteady RANS or scale resolving turbulence modelling, depending on the required flow fidelity. RBM requires time step control, sampling over multiple revolutions, and time dependent interface calculations. This increases cost and complicates automated production. Rotating wall tyres can be combined with RBM rims to retain a fixed tyre deformation. Table 3.1 summarises the three treatments.

Table 3.1: Comparison of wheel rotation treatments.

Treatment	Main advantage	Main limitation
Rotating wall	Low cost, fixed tyre shape	No spoke passage
MRF	Steady rim passage flow	Frozen rim, interface sensitivity
RBM	Resolves unsteady spoke passage	Moving interfaces, high cost

3.4 Road vehicle aerodynamics

The coordinate system uses x downstream, y laterally, and z upwards. Positive lift acts upwards, and the left wheels lie at negative y . The force and moment definitions follow the DrivAerRim conventions.

3.4.1 Force coefficients and axle lift

Freestream dynamic pressure and the complete vehicle force coefficients are

$$q_\infty = \frac{1}{2}\rho U_\infty^2, \quad (3.10)$$

$$C_D = \frac{F_x}{q_\infty A_{\text{ref}}}, \quad C_L = \frac{F_z}{q_\infty A_{\text{ref}}}, \quad C_S = \frac{F_y}{q_\infty A_{\text{ref}}}. \quad (3.11)$$

The reference area A_{ref} is the projected vehicle frontal area. Component coefficients use this same area, not each component's area, so their signed contributions can be compared and summed. One drag count denotes 10^{-3} in C_D throughout this thesis. Front and rear axle lift are equivalent loads obtained from the total lift and pitching moment. Let $M_{y,R}$ and $M_{y,F}$ denote $+y$ moments about ground height reference points at the rear and front axles. With wheelbase b ,

$$C_{LF} = \frac{M_{y,R}}{q_\infty A_{\text{ref}} b}, \quad C_{LR} = -\frac{M_{y,F}}{q_\infty A_{\text{ref}} b}, \quad C_L = C_{LF} + C_{LR}. \quad (3.12)$$

These quantities describe axle loading, rather than separate integrals of vertical force over the front and rear halves of the body.

3.4.2 Pressure and skin friction coefficients

Conventional vehicle drag contains pressure and wall shear contributions. Their local nondimensional measures are

$$C_p = \frac{p - p_\infty}{q_\infty}, \quad C_f = \frac{|\boldsymbol{\tau}_w|}{q_\infty}, \quad (3.13)$$

where p_∞ is freestream static pressure and $\boldsymbol{\tau}_w$ is the wall shear stress vector. The nonnegative magnitude C_f does not retain the direction of viscous traction. Calculating its streamwise force contribution requires the vector components and surface integration.

Near wall mesh resolution is described by

$$y^+ = \frac{\rho u_\tau y_w}{\mu}, \quad u_\tau = \sqrt{\frac{|\boldsymbol{\tau}_w|}{\rho}}, \quad (3.14)$$

where y_w is the wall normal distance to the first cell centre. A mesh with low y^+ resolves the steep velocity gradient close to the wall.

3.4.3 Ventilation drag

Pressure and shear forces also produce an aerodynamic moment about each wheel axis. Following the dataset convention, the equivalent ventilation drag coefficient of wheel i is [14]

$$C_{D,V,i} = \frac{M_{y,i}^W}{q_\infty A_{\text{ref}} r_i}, \quad r_i = z_{c,i} - z_{\text{ground}}. \quad (3.15)$$

Here, $M_{y,i}^W$ is the signed $+y$ moment of the pressure and shear forces on the wheel surfaces. The effective radius is the wheel centre height above the road. For rolling motion, dividing a resisting moment by radius gives the equivalent force associated with its rotational power demand.

Ventilation drag and conventional streamwise drag are distinct quantities. Ventilation drag represents rotational power demand, not a streamwise surface force included in C_D , and is reported separately. A rim can change both quantities, as well as the loading of the surrounding wheelhouse and vehicle body.

3.4.4 Accumulated drag and wheel mass flow

The accumulated coefficient $C_D(x)$ integrates streamwise surface force over all vehicle surfaces upstream of a given position x ,

$$C_D(x) = \frac{1}{q_\infty A_{\text{ref}}} \int_{\mathcal{S}: x_s \leq x} dF_x. \quad (3.16)$$

Its downstream value approaches the complete vehicle coefficient. Differences between traces identify the locations where component loading changes. They do not directly measure local energy loss in the surrounding fluid.

The signed mass flow through a wheel plane intersection $\mathcal{A}_i$ with normal in $+y$ is

$$\dot{m}_i = \int_{\mathcal{A}_i} \rho \bar{U}_y dA = \rho \langle \bar{U}_y \rangle_{\mathcal{A}_i} A_i. \quad (3.17)$$

The angle brackets denote an area average over the intersection. The sign follows the global coordinate system and does not denote inflow or outflow at every wheel. Figure 3.1 illustrates the integration section at the front left wheel. The blue regions mark the fluid area visible through the rim openings.

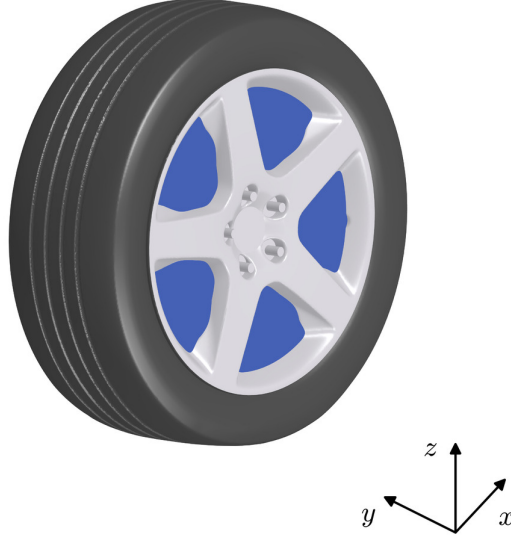


Figure 3.1: Front left wheel mass flow integration section. The blue regions mark the area used to integrate $\rho \overline{U}_y$ in Eq. (3.17). The coordinate triad indicates the global axes, with positive mass flow defined along $+y$.

3.4.5 Total pressure and vortical structures

The incompressible total pressure coefficient is referenced to freestream static pressure,

$$C_{p,\text{tot}} = \frac{p + \frac{1}{2}\rho U_i U_i - p_\infty}{q_\infty}. \quad (3.18)$$

It is approximately one in the freestream, so reduced values identify total pressure deficits. In the stored preview convention, the numerator uses mean pressure and the sum of the mean squared velocity components. This averaging order differs from squaring the mean velocity when iteration to iteration fluctuations remain.

Vortical regions can be visualised using the second invariant of the velocity gradient tensor [27],

$$Q = \frac{1}{2} (W_{ij}W_{ij} - S_{ij}S_{ij}), \quad W_{ij} = \frac{1}{2} \left(\frac{\partial \overline{U}_i}{\partial x_j} - \frac{\partial \overline{U}_j}{\partial x_i} \right). \quad (3.19)$$

Positive Q identifies regions where rotation exceeds strain. An isosurface depends on its chosen threshold and is not a direct measure of drag or vortex strength. For steady RANS, it describes structures of the mean flow rather than instantaneous turbulent eddies.

4

Methodology

This chapter describes the dataset design and generation workflow, vehicle and rim geometry, numerical settings, and mesh sensitivity. Validation and quality control results follow in Chapter 5.

4.1 Dataset design

DrivAerRim was constructed as a controlled computational experiment. Each of the 904 DeepWheel geometries defines one case, with the same rim design installed at all four wheel positions. The vehicle body, cooling state, underbody, tyres, ride height, and wheel locations remain fixed. Domain dimensions, boundary conditions, mesh controls, solver settings, iteration count, and export definitions are also common. Rim geometry is therefore the only intended design variable between cases. The dataset does not sample independent combinations of front and rear rims. Geometry, scalar labels, and spatial fields share a case identifier so that future surrogate studies can keep all records of one rim together.

4.2 Dataset generation workflow

Dataset generation followed three stages: rim preprocessing, automated batch CFD, and data export (Figure 4.1). Each case is identified by `RimXXXX`, with `XXXX` ranging from 0001 to 0904.

1. *Rim preprocessing.* ANSA was used to repair, align, and fit all source STL geometries to the fixed DrivAer wheel package. Watertightness and orientation checks produced consistently positioned inputs for automated meshing.
2. *Automated batch CFD.* A command line template was replicated into 904 working directories. Each CAD directory received its case specific rim, while shared templates and Java macros provided the common setup. A Python controller submitted consecutive batches to the HPC scheduler and monitored case status. Cases in an active batch ran in parallel, with the next batch submitted after completion. STAR-CCM+ macros prepared the geometry, generated the mesh, solved the RANS equations, and applied the quality checks. Failed cases returned for repair or rerun before acceptance.
3. *Data export.* Postprocessing generated `NumData`, `Surfaces`, `Slices`, `Volumes`, and `Pictures`. Force and accumulated drag summaries were consolidated for release, alongside STL geometry records. Spatial fields and previews remained

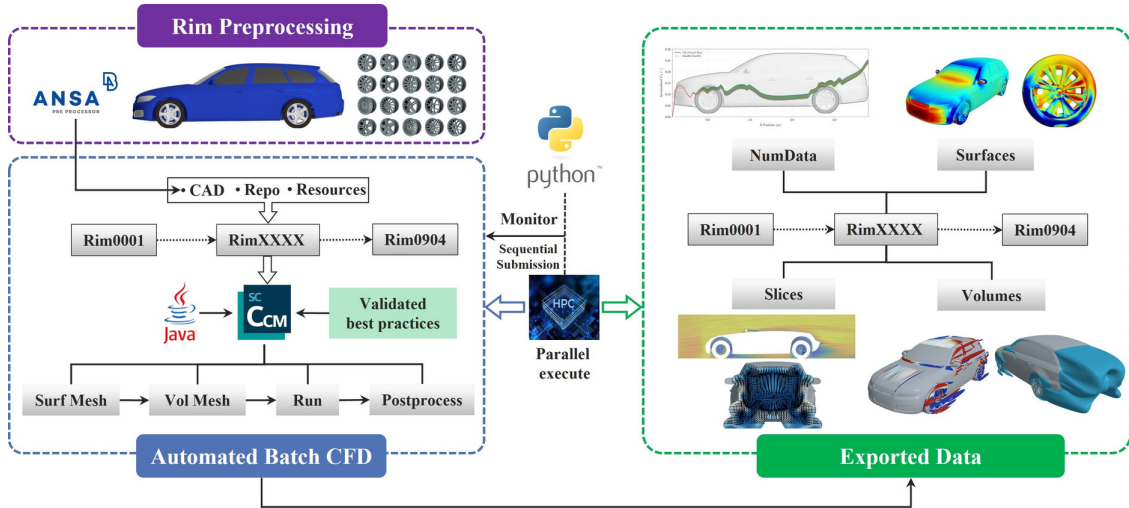


Figure 4.1: DrivAerRim production workflow from geometry preparation to quality controlled data records.

indexed by rim case. Section 5.5 documents the released file structure and variables.

A case entered the final dataset only after its geometry, mesh, coefficient history, force partition, and exports passed the checks in Section 5.2.

4.3 Geometry

4.3.1 Vehicle geometry

The common vehicle is the full scale DrivAer estateback introduced by Heft et al. [28]. Figure 4.2 shows its principal dimensions and the two underbody variants used in this work. The vehicle is 4613 mm long, 1820 mm wide, and 1420 mm high, with a 2786 mm wheelbase and 1524 mm track width. It includes exterior mirrors, an engine bay volume, rotating brake discs, deformed tyres, and detailed wheel installation components.

All 904 dataset cases use sealed cooling inlets and the smooth underbody in Figure 4.2c. This resembles the flat, enclosed floor of a battery electric vehicle and removes underbody detail unrelated to rim design. The detailed underbody in Figure 4.2d is used only for validation because it matches the physical model tested in the Volvo Cars aerodynamic wind tunnel (PVT). The restraint posts visible in panel (a) are likewise retained for the validation model and removed from the dataset cases.

The tyre uses the Rain (R) longitudinal tread investigated by Josefsson et al. [2]. Static deformation, the shoulder shape, grooves, and ground contact patch are retained. The wheel assembly consists of tyre, rim, and brake surfaces. Wheelhouses and wheel supports are separate component groups so that their drag and lift can be exported independently.

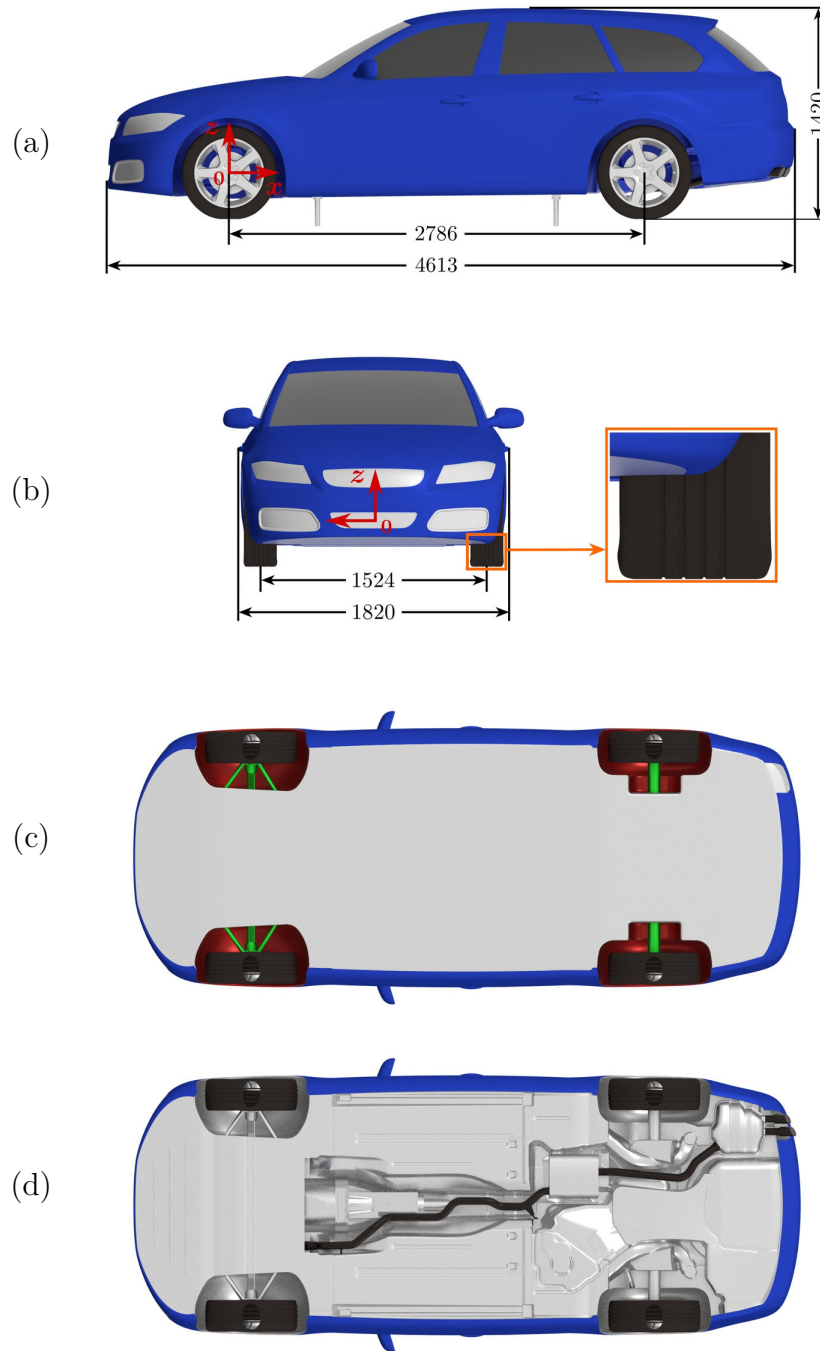


Figure 4.2: Full scale DrivAer estateback used in the study. (a) Side view showing dimensions, restraint posts, and coloured wheel components. (b) Front view showing the Rain tyre tread. (c) Smooth underbody used for dataset generation, with wheelhouses in red and wheel supports in green. (d) Detailed underbody used for wind tunnel validation. The rendering was prepared for this project from the DrivAer geometry [2, 28].

4.3.2 Rim geometry and preprocessing

The input comprises all 904 three dimensional rim surfaces in the DeepWheel structural analysis collection [13]. Their topology and local surface defects prevented reliable automated meshing without repair.

ANSA was used to batch repair open edges, duplicated facets, nonmanifold features, self intersections, and local defects that could prevent surface wrapping or volume meshing. Each repaired rim was scaled where necessary, oriented consistently, placed in the DrivAer wheel coordinate system, and checked for interference with the tyre and brake package. Geometry checks then verified watertightness, surface orientation, and the expected position. The front left and rear left wheel assemblies were exported for every case, with right side counterparts obtained by mirroring.

A compact cylindrical enclosure was generated around each rim for the MRF treatment described in Section 4.4.3. The outward gap between the rim face and MRF interface was kept below 5 mm for all cases. This construction was used because regions fitted between individual spokes could not be generated reliably for every geometry.

4.4 Numerical model

4.4.1 Numerical settings and turbulence model

The simulations were performed with Simcenter STAR-CCM+ 2506 using a finite volume discretisation of the three dimensional, steady, incompressible RANS equations. All production cases use the RKE two layer model with two layer all y^+ wall treatment. The validation matrix also contains LagEB, SST, and SST_a1, introduced in Section 3.2. SST_a1 uses a realizability coefficient of 1.2 and $a_1 = 1$. The validation results in Section 5.1 support the selection of RKE for production.

The dataset setup follows the Siemens external aerodynamics best practice guidance for version 2506 [29]. A coupled implicit solver was used for continuity and momentum. Flow equations and turbulence convection used second order spatial discretisation. Inviscid fluxes were calculated with Roe flux difference splitting without blending. Automatic CFL control adjusted the pseudo time step. Algebraic multigrid was used for both the flow and turbulence linear systems. The coupled flow equations used a V cycle with Gauss-Seidel smoothing and BiCGStab acceleration. The turbulence solver for the k and ϵ transport equations used a flexible multigrid cycle with Gauss-Seidel smoothing and no acceleration. Both multigrid solvers used at most 30 cycles and a linear convergence tolerance of 0.1 per solve.

Each production case ran for 3000 iterations. Residuals, complete vehicle and component coefficients, CFL number, maximum velocity magnitude, and maximum turbulent viscosity ratio were monitored. Means and convergence ranges were calculated over the final 500 iterations.

Each production case required approximately 0.5 h of wall clock time on 2880 CPU cores, corresponding to about 1440 CPU core hours. For all 904 cases, the estimated total was 1.30×10^6 CPU core hours, assuming one run per case and excluding validation runs and reruns.

4.4.2 Computational domain and boundary conditions

The production simulations use the open road domain in Figure 4.3a. Its length, width, and height are 15.2, 8.7, and 6.6 vehicle lengths, respectively. The inlet lies 4.3 vehicle lengths upstream of the vehicle, leaving 9.9 lengths between the vehicle and outlet. A uniform inlet speed of $U_\infty = 140 \text{ km h}^{-1}$ and turbulence intensity of 0.1% were prescribed. The outlet has zero gauge pressure, while the top and lateral boundaries are symmetry planes. The entire road is a no slip moving wall with speed U_∞ , which prevents an artificial boundary layer from forming over a stationary road. Validation used the five belt ground configuration in Figure 4.3b. The upstream light green region is a slip wall representing the PVT boundary layer suction system. A moving centre belt and four moving wheel drive unit belts reproduce the experimental ground system. Other domain boundaries match the production setup.

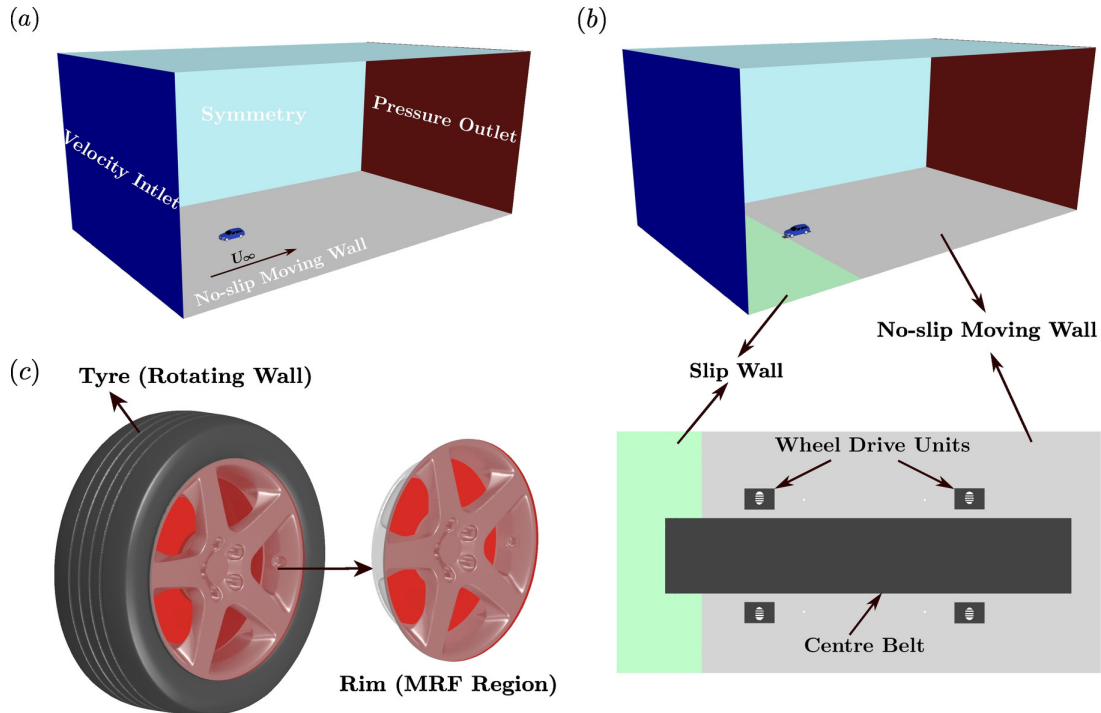


Figure 4.3: Computational configurations. (a) Open road domain used for all dataset cases. (b) Five belt wind tunnel ground representation used for validation. (c) Rotating wall tyres with compact cylindrical MRF rim regions.

4.4.3 Wheel rotation modelling

Each tyre is geometrically stationary but receives the tangential wall velocity associated with rolling at U_∞ . Each rim is enclosed by an MRF region rotating about its wheel axis at the corresponding angular speed. This preserves the deformed tyre and its contact patch. It also avoids zero tangential velocity on spoke side faces, which can occur with a rotating wall condition alone [5].

The steady MRF method retains one fixed spoke orientation and does not resolve the physical passage of spokes through the wheelhouse. It was selected to balance computational cost and flow fidelity. An unsteady RBM case is estimated to require

approximately 7.5 h on 2880 CPU cores, corresponding to 21,600 CPU core hours. This is about fifteen times the steady RANS cost reported in Section 4.4.1.

4.4.4 Reference quantities

The numerical values in Table 4.1 define the normalisation used for every case. Force, axle lift, pressure, skin friction, and ventilation coefficients use the definitions in Section 3.4. The same reference area is used for complete vehicle and component forces.

Table 4.1: Reference quantities common to all production cases.

Quantity	Symbol	Value
Air temperature	T	20 °C
Density	ρ	1.204 kg m ⁻³
Dynamic viscosity	μ	1.813 × 10 ⁻⁵ Pa s
Freestream speed	U_∞	140 km h ⁻¹
Frontal area	A_{ref}	2.16 m ²
Wheelbase	b	2.786 m
Yaw angle	β	0°

For the mass flow analysis, each left wheel region was intersected by the plane $y = -0.843$ m. The intersection area and area averaged lateral velocity define the signed flow rate in Eq. (3.17). This local plane is distinct from the fixed global slice layout distributed with the dataset.

4.5 Mesh and sensitivity

A trimmed, predominantly hexahedral volume mesh was generated automatically for each rim. Ten prism layers were placed on no slip surfaces, with 6 mm total thickness and 0.015 mm first cell height. The resulting near wall resolution is $y^+ < 1$ over the vehicle and wheel surfaces. External vehicle surface targets were 1 to 4 mm. Tyres, rim openings, wheelhouses, contact patches, and the case specific MRF volumes received 1 to 2 mm local targets. Figure 4.4 shows the wheelhouse refinement and the gradual coarsening away from the vehicle.

Three grid levels were assessed with the detailed validation vehicle in the five belt configuration. The coarse, baseline, and fine meshes contained 45.32, 97.88, and 180.43 million cells. Coarse and fine meshes were generated using approximate scaling factors of 1.5 and 0.75 for mesh controls outside the prism layers. Prism layer count, total thickness, first cell height, and wall treatment remained unchanged across the three grids. The streamwise accumulated drag difference relative to the baseline was

$$\Delta C_D^{\text{mesh}}(x) = C_D^{\text{mesh}}(x) - C_D^{\text{baseline}}(x). \quad (4.1)$$

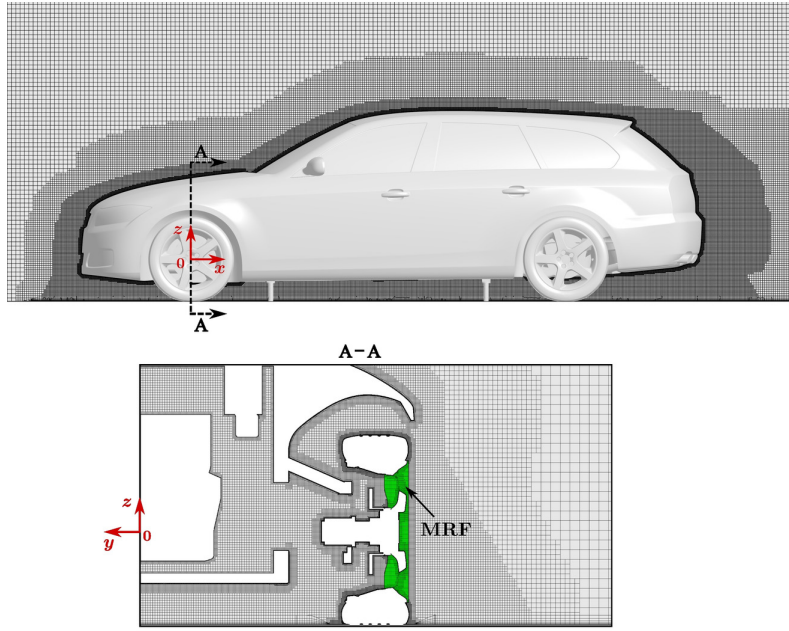


Figure 4.4: Baseline validation mesh. Section A-A shows the compact MRF region embedded in the refined wheelhouse mesh.

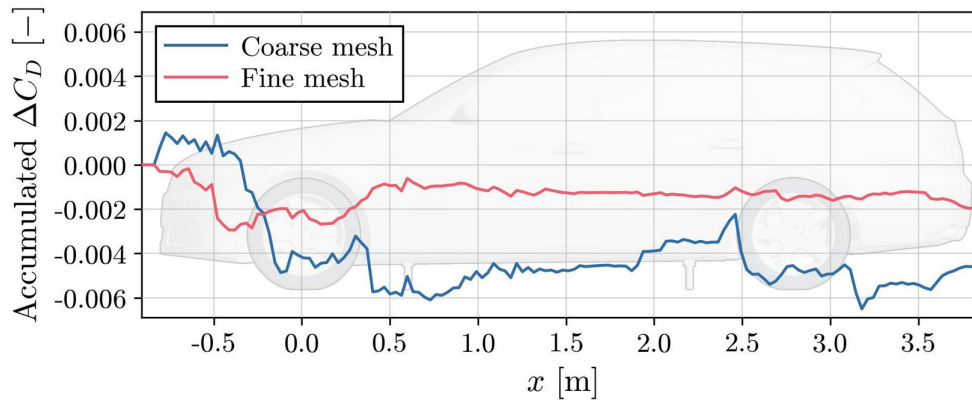


Figure 4.5: Streamwise accumulated drag difference for the coarse (45.32 million cells) and fine (180.43 million cells) grids relative to the baseline (97.88 million cells).

In Figure 4.5, the fine grid remains close to the baseline over most of the vehicle length. Coarsening produces larger departures around the front wheel, underbody, rear wheel, and base, where wheel wakes interact with other components.

Preserving the prism layer specification prevents a strict assessment of asymptotic grid convergence. Refinement changes accumulated drag much less than coarsening. The baseline was retained to limit mesh sensitivity at an affordable cost for 904 production cases.

5

Results

This chapter presents numerical validation, quality control, and the effects of rim geometry on vehicle and component forces. It then documents the data records and examines selected surface and flow fields.

5.1 Numerical validation

5.1.1 Validation configurations and metrics

Validation focused on drag differences because the dataset is intended to capture changes caused by rim geometry. The PVT data provide two complete vehicle drag comparisons. The first replaces an open rim (OR) with a closed rim (CR), shown in Figure 5.1. The second compares the vehicle without and with front wheel deflectors (Wo_FWD and W_FWD), shown in Figure 5.2. The differences are

$$\Delta C_D^{\text{OR-CR}} = C_D(\text{OR}) - C_D(\text{CR}), \quad (5.1)$$

$$\Delta C_D^{\text{Wo_FWD-W_FWD}} = C_D(\text{Wo_FWD}) - C_D(\text{W_FWD}). \quad (5.2)$$

A positive value denotes lower drag for the closed rim or the vehicle with deflectors.

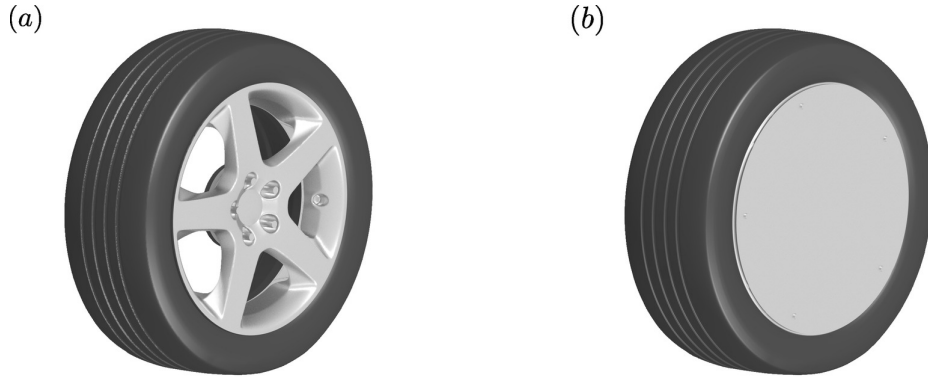


Figure 5.1: Rim configurations used for drag difference validation: (a) open rim (OR) and (b) closed rim (CR).

Experimental error bars use the PVT in test repeatability of ± 0.001 in C_D per configuration [16]. Combining the two repeatability values in quadrature without a covariance term gives $\pm \sqrt{2} \times 0.001$ for a measured difference. CFD variability was estimated from the full C_D ranges R_1 and R_2 over the last 500 iterations,

$$E_{\Delta C_D} = \sqrt{R_1^2 + R_2^2}. \quad (5.3)$$

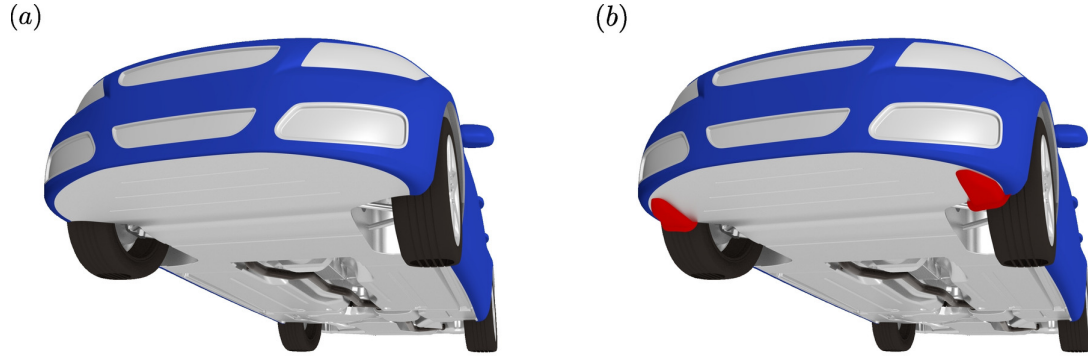


Figure 5.2: Front wheel deflector configurations used for drag difference validation: (a) without deflectors (Wo_FWD) and (b) with deflectors (W_FWD), highlighted in red.

This indicates variability between iterations, not a confidence interval or total numerical uncertainty.

5.1.2 Drag difference results

Figure 5.3 compares four steady RANS models with the two measured drag differences. For open versus closed rims, RKE and LagEB predict $\Delta C_D^{\text{OR}-\text{CR}}$ of approximately 0.006, close to the experiment. SST gives about 0.022 and therefore exaggerates the benefit of rim closure. SST_a1 reduces the prediction to approximately 0.014 but still overestimates the measured response by more than a factor of two. All four models predict the correct direction of the change, but only the two $k - \epsilon$ models closely reproduce its measured magnitude.

For the front wheel deflector comparison, every model predicts a drag reduction but overestimates its magnitude. The experimental difference is approximately 0.007. RKE gives approximately 0.010, SST_a1 0.011, SST 0.013, and LagEB 0.014. RKE has the smallest discrepancy. SST also shows the widest iteration based error bars in both comparisons, while LagEB shows substantial variation for rim closure. RKE gives the most consistent drag differences and iterative stability across the two comparisons.

5.1.3 Surface pressure results

Surface pressure validation supplemented the integrated forces. Six tap groups followed the upperbody and underbody centreline, the left side and base at $z = 150$ mm, and two circumferential rows in the front left wheelhouse at $y = -750$ and -600 mm. Their layout is shown in Figure 5.4 and follows the DrivAer instrumentation described by Hupertz et al. [30].

Figure 5.5 compares measured and predicted pressure at the six surface sections defined in Figure 5.4. On the upperbody, all four models reproduce the pressure rise at the windscreen base, suction at the roof leading edge, and recovery with nearly coincident curves. The left side profiles likewise show limited separation, although SST recovers slightly less pressure behind the front wheel opening.

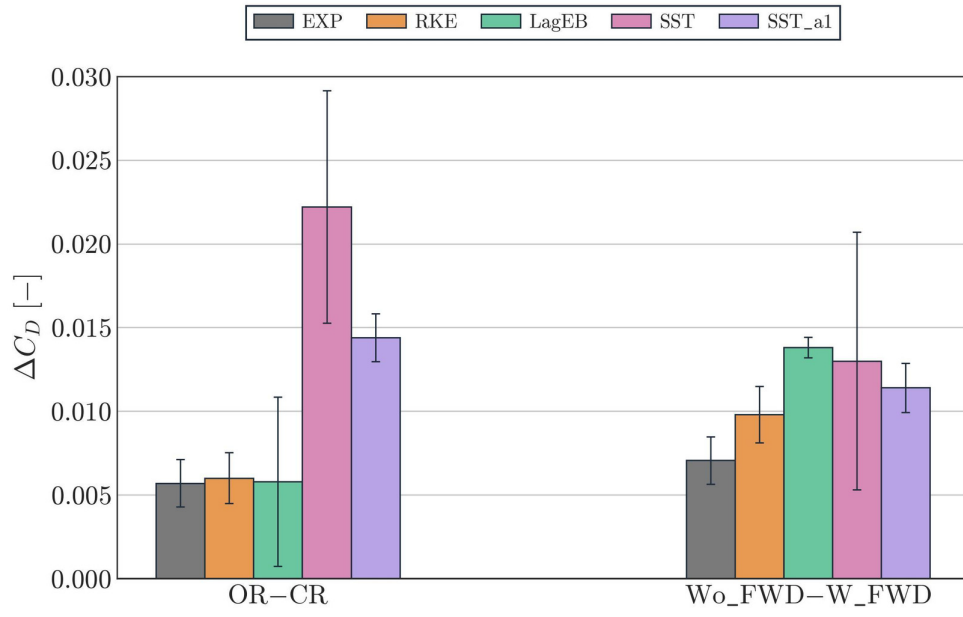


Figure 5.3: Measured and computed complete vehicle drag differences for open versus closed rims and without versus with front wheel deflectors. The experimental bars show repeatability, whereas the CFD bars show the combined final window iteration ranges.

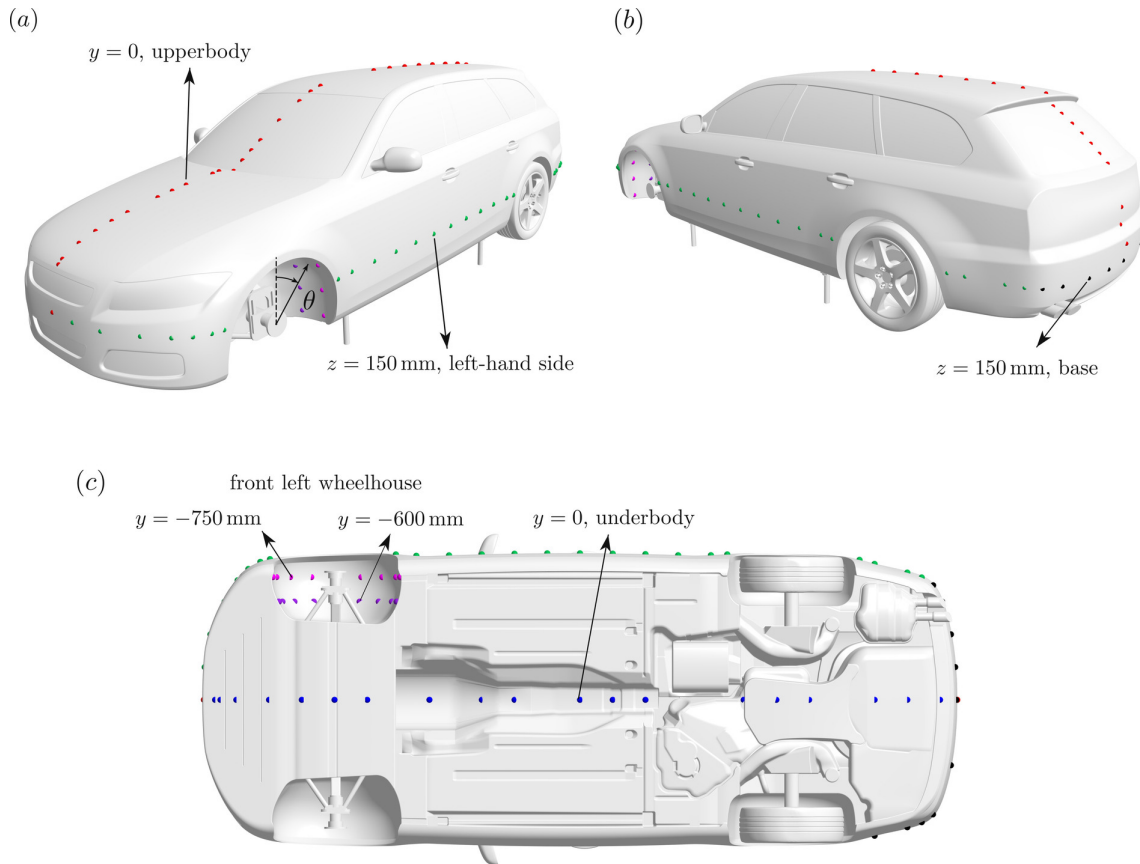


Figure 5.4: Pressure tap groups used for validation: upperbody and underbody centre-line, left side and base at $z = 150$ mm, and two front left wheelhouse rows.

The detailed underbody exposes larger discrepancies. All models reproduce the broad recovery towards $C_p \approx 0$ near $x = 1.8$ to 2.0 m but predict too much suction over part of the central floor. SST and SST_a1 are locally closer between $x = 0.8$ and 1.6 m, whereas RKE and LagEB better match the downstream level around $x = 2.6$ to 3.0 m. No model is uniformly closest.

At the base, the experiment shows stronger suction over much of the centre than RKE and LagEB predict. The SST variants are closer there, particularly on the side with negative y , but none reproduces the full measured distribution. This local advantage does not translate to a better prediction of the rim closure drag difference. The models differ most in the wheelhouse rows. At $y = -750$ mm, RKE most closely captures the measured pressure rise near $\theta = -90^\circ$. RKE and LagEB also avoid the excessive positive peaks produced by SST in parts of the two wheelhouse sections. Some angular ranges favour SST_a1, so performance varies by region.

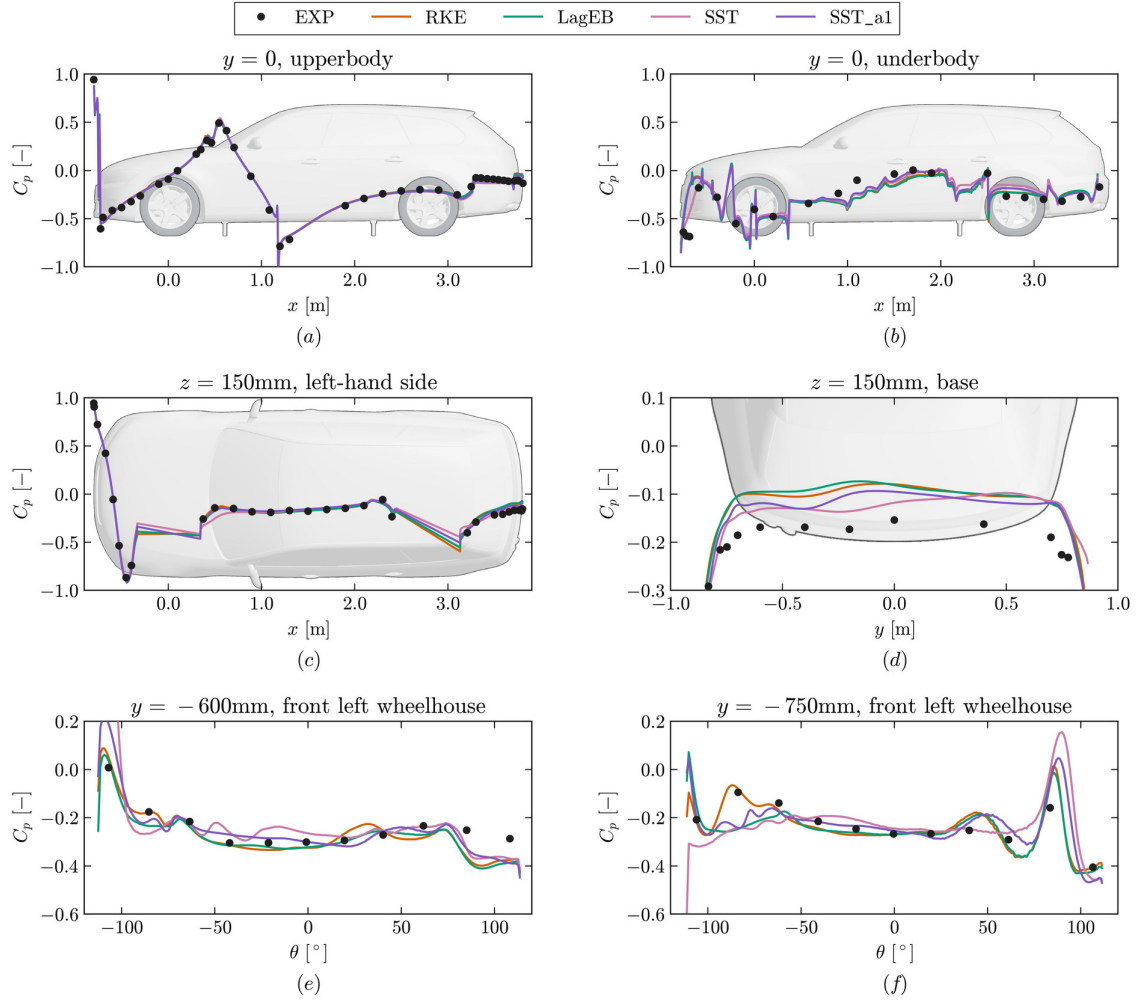


Figure 5.5: Surface pressure for the open rim validation vehicle: (a) upperbody, (b) underbody, (c) left side, (d) base, and (e,f) front left wheelhouse rows.

The pressure and drag comparisons support the use of RKE for this setup, although no model is most accurate everywhere. Agreement in total drag alone can conceal compensating regional errors.

Validation used the detailed underbody, restraint posts, and five belt ground needed to match the experiment. Production used the smooth underbody, no posts, and fully moving ground. This distinction limits direct transfer of the validation error to the 904 production configurations.

5.2 Dataset quality control

Quality control was applied at four levels:

Geometry: watertightness, orientation, scale, position, and intersections were checked after preprocessing.

Mesh: completion of prism layers, rim and contact patch refinement, and overall cell quality were checked for each case.

Solution: residuals, force histories, component partitions, maximum velocity, and turbulent viscosity ratio were monitored.

Export: required numerical, surface, slice, volume, and preview files were checked before a case was accepted.

Cells producing either $|\mathbf{U}|_{\max} > 4U_{\infty}$ or $(\mu_t/\mu)_{\max} > 10^4$ were identified and removed before the solution continued. These cells occurred mainly in the highly constrained region around the tyre contact patch.

Solution stability was evaluated over iterations 2501 to 3000. For each case,

$$R_{C_D} = \max(C_D) - \min(C_D) \quad (5.4)$$

was required to be below 0.002, or two drag counts. A case with an excessive range, abnormal force partition, geometry defect, or missing field export was reviewed, repaired, and rerun. The same window was used to calculate all reported mean coefficients.

All 904 rim configurations completed the production workflow and satisfied the final window criterion $R_{C_D} < 0.002$. Figure 5.6 shows the drag histories for the first 18 cases, with the final 500 iterations shaded. This interval defines both the mean and the convergence range. Equivalent plots were retained for every case.

The predominant cause of failed initial runs was a defect in the source or adapted rim surface rather than divergence of an otherwise valid case. Flagged rims were repaired, remeshed, and rerun. No rim geometries were omitted, and the case indices remain continuous from Rim0001 to Rim0904.

The acceptance range concerns complete vehicle drag only. It does not establish convergence of every local field, quantify turbulence model error, or provide a confidence interval for each force coefficient.

5.3 Dataset overview

5.3.1 Pairwise distributions of vehicle coefficients

The vehicle drag coefficient spans approximately 0.2334 to 0.2549, with a mean of 0.2427 over the 904 configurations. This range of about 21.5 drag counts arises from rim variation on an otherwise fixed vehicle.

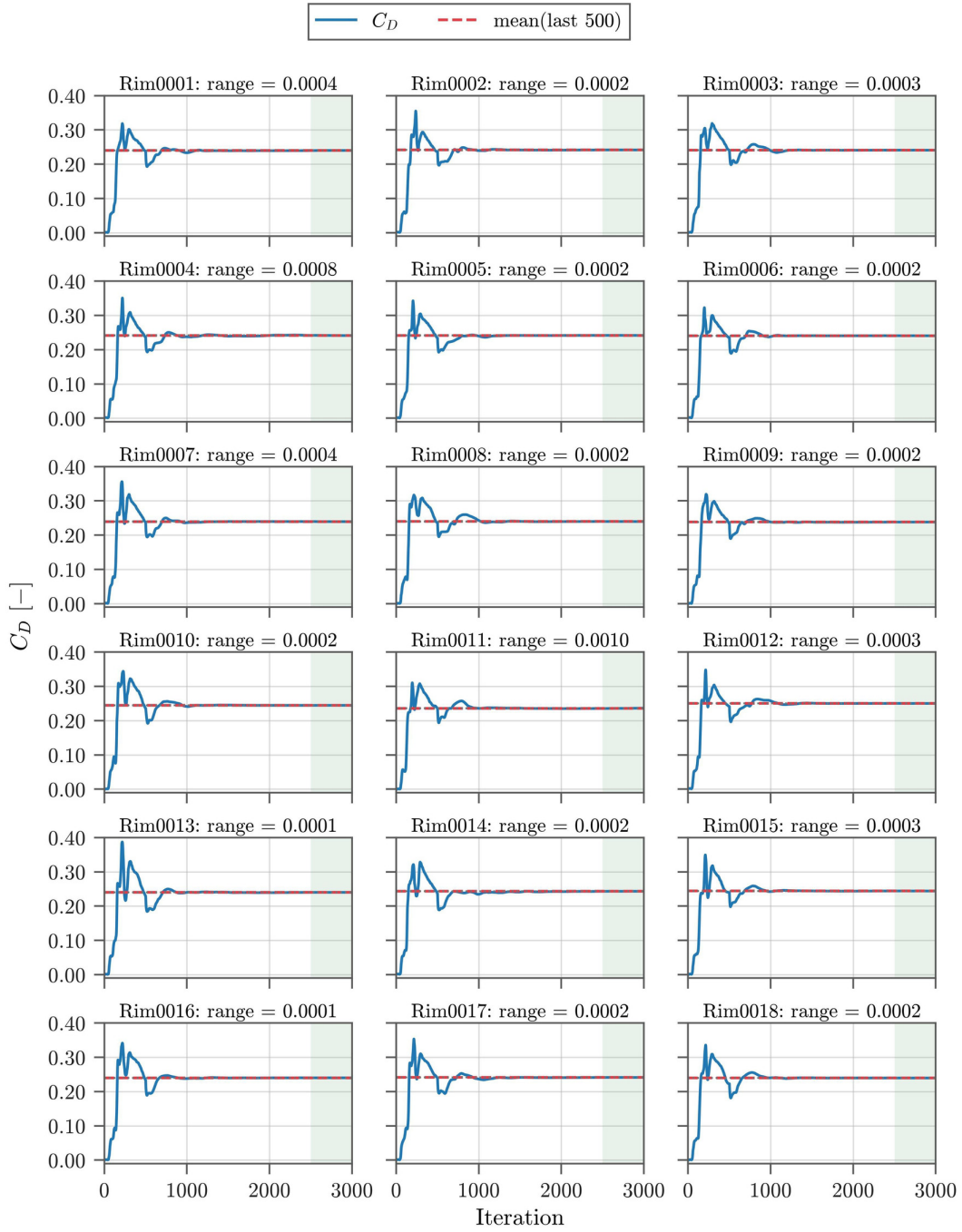


Figure 5.6: Complete vehicle C_D histories for Rim0001 to Rim0018. Shading indicates the final 500 iterations used for averaging and the range test.

Figure 5.7 compares the joint drag and lift distributions with the closed rim (CR) reference. CR lies within the main drag distribution but has more negative total and axle lift coefficients than the rim cases. It therefore produces greater downforce at both axes without achieving the lowest drag. Drag alone therefore does not describe changes in axle loading.

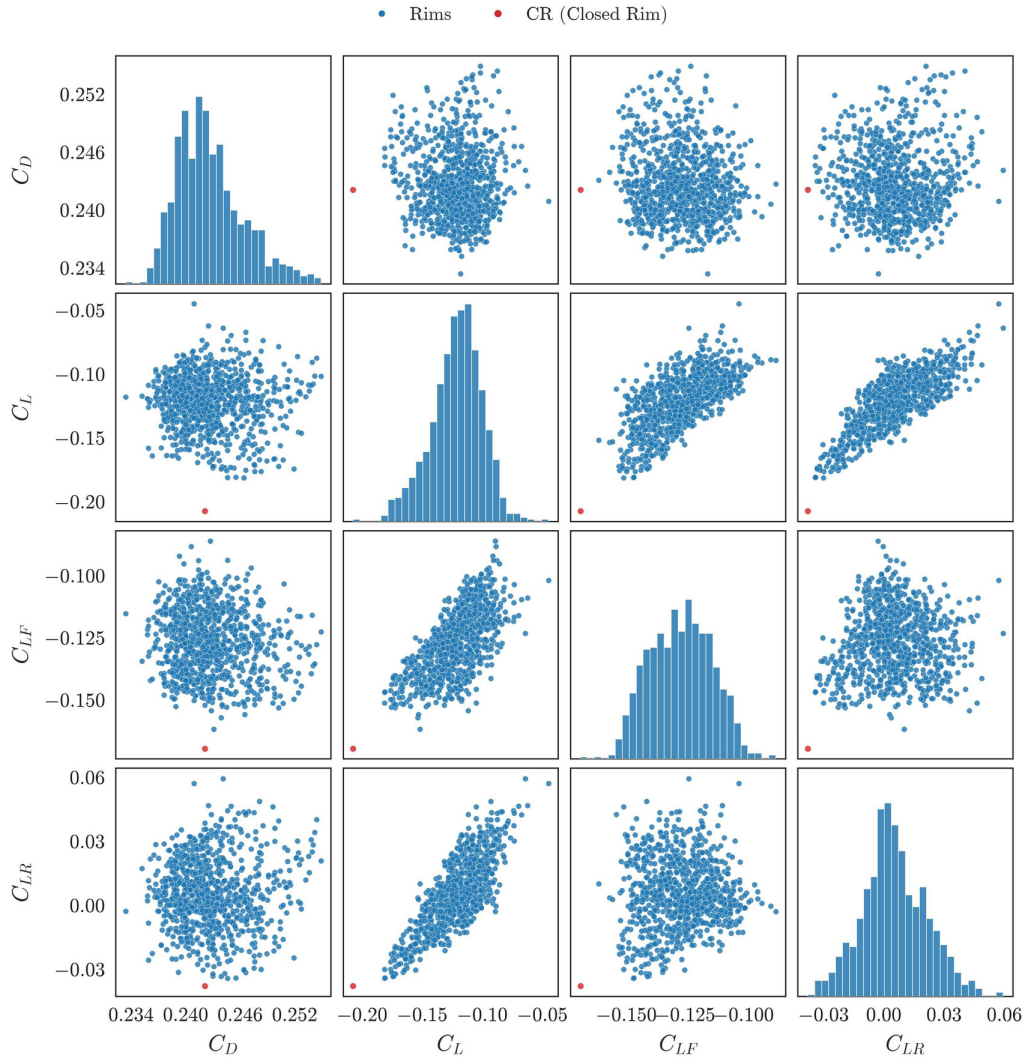


Figure 5.7: Pairwise distributions of complete vehicle drag and lift and the front and rear axle lift coefficients. Blue points show the 904 rim cases, and red points show the closed rim (CR) reference. Diagonal histograms show the rim case distributions.

5.3.2 Streamwise accumulation of drag

Figure 5.8 traces the accumulated drag coefficient $C_D(x)$ for all 904 rims and the closed rim (CR) reference. The envelope across cases spans 0.0012 at $x = -0.61$ m, upstream of the front wheel centre. It widens to 0.0191 at $x = 0.01$ m and 0.0223 at $x = 0.40$ m. The main differences first develop across the front wheel and wheelhouse.

Across much of the central underbody, approximately $x = 1.0$ to 2.4 m, the envelope remains near 0.021 to 0.023 and the curves are nearly parallel. The differences generated upstream therefore change little in this region. The spread grows again around the rear wheel and reaches its maximum of 0.0281 near $x = 3.11$ m. Downstream contributions partly compensate for this local maximum in the envelope. At $x = 3.80$ m, the 904 cases span $C_D = 0.2334$ to 0.2549. The mean is 0.2427, while the CR reference gives 0.2421, near the centre of the distribution.

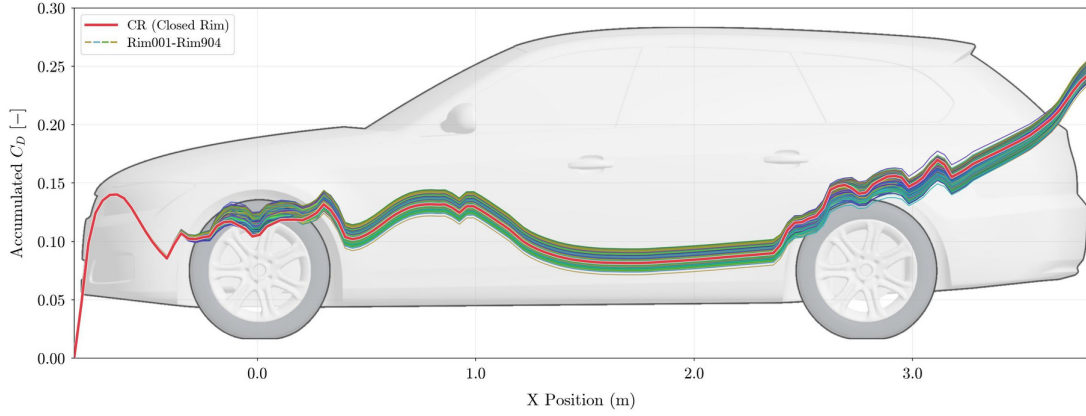


Figure 5.8: Streamwise accumulated drag coefficient for the 904 DrivAerRim cases. The red curve denotes the closed rim reference.

5.3.3 Wheel related drag contributions

Wheel contributions were grouped into wheel assemblies, wheel supports, and wheel-houses, with equivalent ventilation resistance reported separately. The summed conventional component contribution is

$$C_{D,W,\text{total}} = C_{D,W} + C_{D,WS} + C_{D,WH}, \quad (5.5)$$

where each term includes all four positions. Ventilation resistance is reported separately and is not added to this conventional force sum. Figure 5.9 reports $100C_{D,x}/C_D$ for each group.

The combined wheel, support, and wheelhouse ratio is concentrated near 29% of complete vehicle drag. Isolated cases extend from approximately 24% to 36%, while the individual component and ventilation ratios occupy narrower ranges. These values fall near the wheel related shares reported in earlier passenger vehicle studies, although component definitions and configurations differ [3, 4, 14].

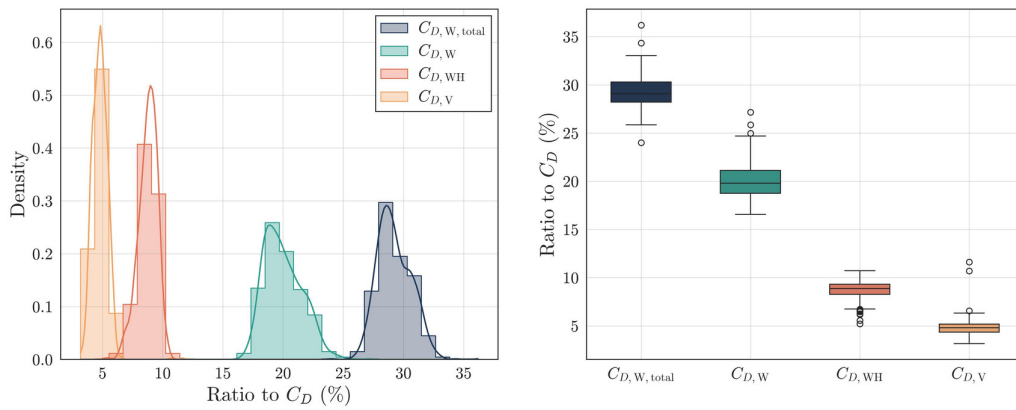


Figure 5.9: Wheel assembly, wheelhouse, ventilation, and combined wheel related contributions expressed as percentages of complete vehicle drag. Wheel support drag is included in the combined conventional contribution but is not plotted separately. Ventilation resistance is shown separately and is not included in that combined contribution.

5.4 Wheel mass flow and local drag

The signed wheel plane mass flow rate defined in Eq. (3.17) was compared with the local drag of the wheel assembly and wheelhouse. Figure 5.10 shows the front left (FL) results from matched mass flow and force records. FL wheel assembly drag is effectively uncorrelated with $\dot{m}_{\text{FL}}$ (Pearson $r = 0.012$, $R^2 < 0.001$). In contrast, FL wheelhouse drag has a strong negative association ($r = -0.825$, $R^2 = 0.681$): increasing the signed mass flow value corresponds to a lower $C_{D,\text{WH,FL}}$. The corresponding Spearman coefficients, 0.029 and -0.809 , show the same pattern.

For the rear left (RL) analysis, records with $A_{\text{RL}} > 0.12 \text{ m}^2$ were treated as cross sectional area outliers. Figure 5.11 shows that RL wheel assembly drag increases with the signed mass flow value ($r = 0.707$, $R^2 = 0.500$), whereas RL wheelhouse drag shows a weaker negative association ($r = -0.364$, $R^2 = 0.132$). The Spearman coefficients are 0.710 and -0.341 , respectively, consistent with the Pearson correlations.

Wheel mass flow alone does not describe drag consistently across components and axles. These correlations also do not establish causation. Rim geometry changes mass flow, pressure, and shear loading simultaneously, while the rear wheel receives the upstream vehicle wake. Explaining these relationships requires further analysis of the individual components.

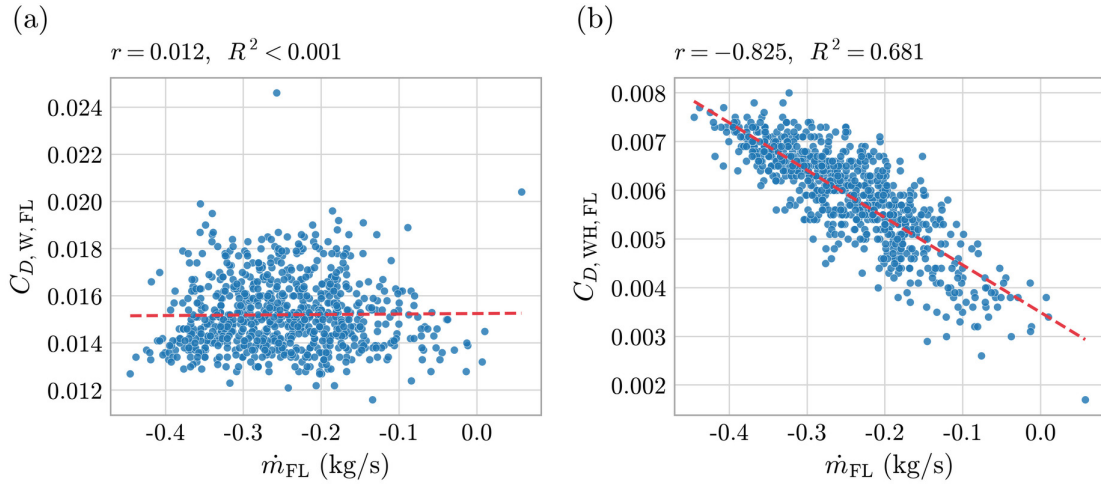


Figure 5.10: Front left component drag coefficients versus signed wheel plane mass flow rate. (a) Wheel assembly. (b) Wheelhouse.

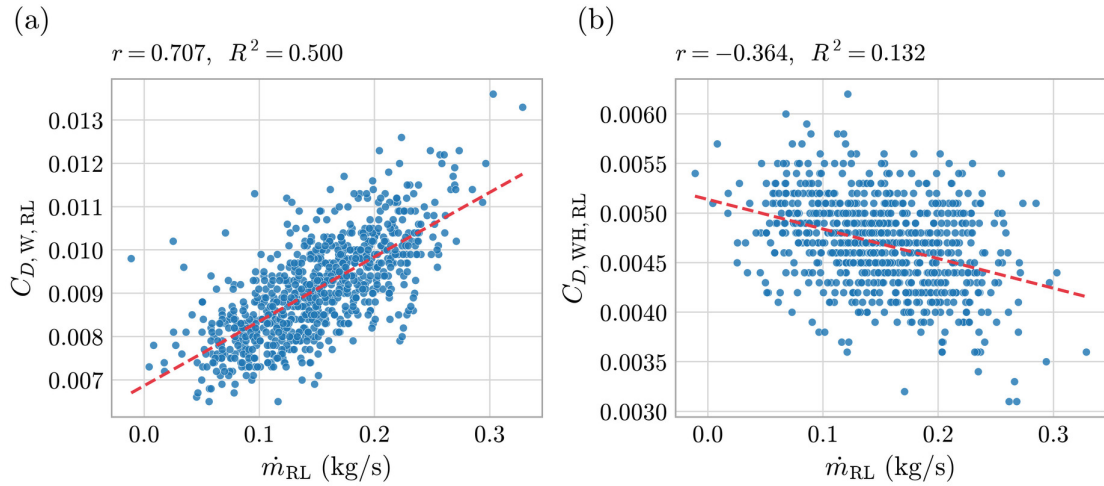


Figure 5.11: Rear left component drag coefficients versus signed wheel plane mass flow rate after applying the cross sectional area filter. (a) Wheel assembly. (b) Wheelhouse.

5.5 Data records

The release combines case geometries, scalar aerodynamic summaries, and spatial CFD fields. Tables 5.1 and 5.2 summarise their organisation and variables, following the DrivAerRim manuscript. File sizes are indicative and vary between rims. The local archive contains additional previews beyond the release specification.

The **Mean** prefix denotes averaging over the final 500 steady solver iterations, not a physical time average of instantaneous turbulent flow. Case identifiers use four digits in the release, so a local **Rim265** record corresponds to **Rim0265**. The suffixes **FL** and **RL** denote front left and rear left positions, while **wh**, **ws**, and **vent** denote wheelhouse, wheel support, and ventilation quantities.

Table 5.1: DrivAerRim file organisation, indicative sizes, and counts. Case level entries apply to each **RimXXXX**.

Root	Subdirectory	File or file pattern	Size	Count
NumData	None	ForceCoefficientsCombined.csv	127 KiB	1
	None	CdAccumulatedCombined.csv	2 MiB	1
Geometry	Wheel_FL	Wheel_FL_XXXX.stl	10 MiB	904
	Wheel_RL	Wheel_RL_XXXX.stl	10 MiB	904
	WheelHousing_FL	WheelHouse_FL.stl	2.4 MiB	1
	WheelHousing_RL	WheelHouse_RL.stl	2.4 MiB	1
	WheelSupport_FL	WheelSupport_FL.stl	6.0 MiB	1
	WheelSupport_RL	WheelSupport_RL.stl	2.9 MiB	1
RimXXXX	Surfaces/Wheel_FL	Wheel_FL_XXXX.vtp	37 MiB	1 per case
	Surfaces/Wheel_RL	Wheel_RL_XXXX.vtp	37 MiB	1 per case
	Surfaces/	WheelHouse_FL_XXXX.vtp	3.7 MiB	1 per case
	WheelHouse_FL			

Continued on the next page

Table 5.1: DrivAerRim file organisation, indicative sizes, and counts (continued).

Root	Subdirectory	File or file pattern	Size	Count
	Surfaces/ WheelHouse_RL	WheelHouse_RL_XXXX.vtp	3.6 MiB	1 per case
	Surfaces/ WheelSupport_FL	WheelSupport_FL_XXXX.vtp	2.4 MiB	1 per case
	Surfaces/ WheelSupport_RL	WheelSupport_RL_XXXX.vtp	1.2 MiB	1 per case
	Slices/X/X_ <position>	X_<position>_XXXX.vtp	184 MiB	80 per case
	Slices/Y/Y_ <position>	Y_<position>_XXXX.vtp	170 MiB	30 per case
	Slices/Z/Z_ <position>	Z_<position>_XXXX.vtp	179 MiB	18 per case
	Volumes/Wheel_FL_ Wheel_FL_region_XXXX.vtu region		134 MiB	1 per case
	Volumes/Wheel_FL_ Wheel_FL_volume_XXXX.vtu volume		983 MiB	1 per case
	Volumes/Wheel_RL_ Wheel_RL_region_XXXX.vtu region		132 MiB	1 per case
	Volumes/Wheel_RL_ Wheel_RL_volume_XXXX.vtu volume		952 MiB	1 per case
	Pictures	<preview_name>.webp	25 MiB	32 per case
	Pictures	Cd_steady_history.PNG	94 KiB	1 per case

Table 5.2: Variables provided in the DrivAerRim dataset files.

Field or quantity	Units	Symbol	Description
NumData/ForceCoefficientsCombined.csv			
Cd	—	C_D	Complete vehicle drag coefficient
Cl	—	C_L	Complete vehicle lift coefficient
Clf	—	C_{LF}	Front axle lift coefficient
Clr	—	C_{LR}	Rear axle lift coefficient
Cs	—	C_S	Complete vehicle side force coefficient
Cd_FL	—	$C_{D,W,FL}$	Front left wheel assembly drag coefficient
Cd_RL	—	$C_{D,W,RL}$	Rear left wheel assembly drag coefficient
Cd_vent_FL	—	$C_{D,V,FL}$	Front left ventilation drag coefficient
Cd_vent_RL	—	$C_{D,V,RL}$	Rear left ventilation drag coefficient
Cd_wh_FL	—	$C_{D,WH,FL}$	Front left wheelhouse drag coefficient
Cd_wh_RL	—	$C_{D,WH,RL}$	Rear left wheelhouse drag coefficient
Cd_ws_FL	—	$C_{D,WS,FL}$	Front left wheel support drag coefficient
Cd_ws_RL	—	$C_{D,WS,RL}$	Rear left wheel support drag coefficient
Cl_FL	—	$C_{L,W,FL}$	Front left wheel assembly lift coefficient

Continued on the next page

5. Results

Table 5.2: Variables provided in the DrivAerRim dataset files (continued).

Field or quantity	Units	Symbol	Description
C1_RL	–	$C_{L,W,RL}$	Rear left wheel assembly lift coefficient
C1_wh_FL	–	$C_{L,WH,FL}$	Front left wheelhouse lift coefficient
C1_wh_RL	–	$C_{L,WH,RL}$	Rear left wheelhouse lift coefficient
C1_ws_FL	–	$C_{L,WS,FL}$	Front left wheel support lift coefficient
C1_ws_RL	–	$C_{L,WS,RL}$	Rear left wheel support lift coefficient
Surfaces: VTK PolyData (.vtp)			
MeanPressure	Pa	$\bar{p}$	Static pressure
MeanWSS	Pa	$\bar{\tau}_{w,i}$	Wall shear stress vector
Slices: VTK PolyData (.vtp)			
MeanVelocity	m s^{-1}	$\bar{U}_i$	Velocity vector
MeanPressure	Pa	$\bar{p}$	Static pressure
MeanTotalTKE	$\text{m}^2 \text{s}^{-2}$	k_{tot}	Exported total turbulent kinetic energy
Volumes: VTK Unstructured Grid (.vtu)			
MeanVelocity	m s^{-1}	$\bar{U}_i$	Velocity vector
MeanPressure	Pa	$\bar{p}$	Static pressure
MeanTotalTKE	$\text{m}^2 \text{s}^{-2}$	k_{tot}	Exported total turbulent kinetic energy

The **Geometry** directory contains front left and rear left wheel assemblies, together with the corresponding wheelhouses and wheel supports. The four fixed wheelhouse and support geometries are each distributed once. Right side components are geometric mirrors, so the released spatial records focus on the two left wheel installations. The predicted flow is not constrained to be symmetric.

There are 128 fixed slices per case: 80 normal to x , 30 normal to y , and 18 normal to z , at nominally 0.1 m spacing. The four local volumes comprise the front left and rear left MRF regions and larger extraction boxes around those wheels. Figure 5.12 shows their spatial coverage. These volumes cover local regions, not the complete computational domain.

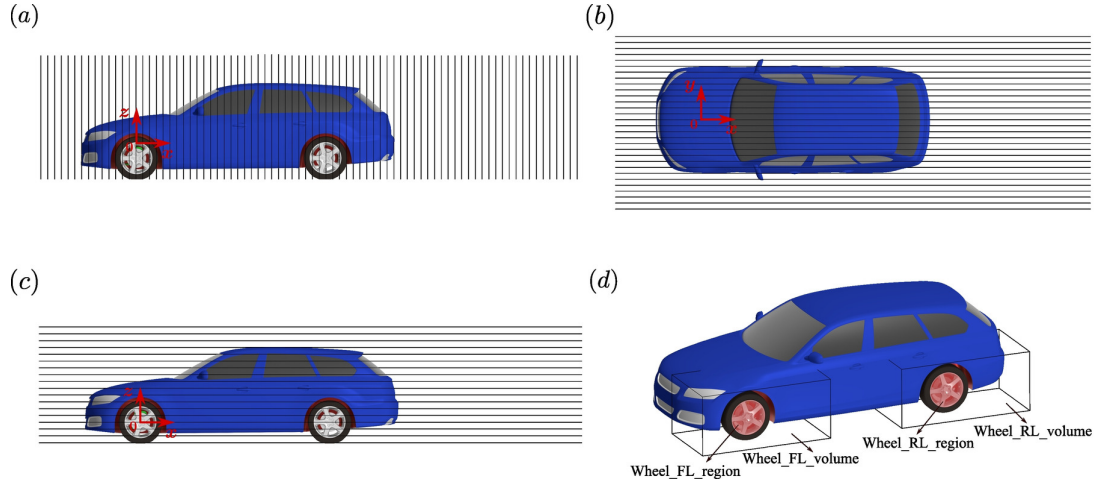


Figure 5.12: Spatial records showing planes normal to (a) x , (b) y , and (c) z . Panel (d) shows compact MRF regions and larger wheel centred volumes.

Total TKE combines modelled k with velocity moments averaged over solver iterations. In steady RANS, these moments do not represent resolved physical turbulence. Similarly, averaging wall shear magnitude differs from taking the magnitude of its averaged vector. Preview reuse must preserve these averaging definitions.

The DrivAerRim manuscript specifies the following dataset release address:

<https://huggingface.co/datasets/BeyondXia1212/DrivAerRim>.

Native STAR-CCM+ solutions are excluded, so the records do not support simulation restart. Files for one rim must share a training, validation, or test partition. Point correspondence between different cases cannot be assumed during data preparation. Any resampling and normalisation must therefore be documented for later reuse.

5.6 Surface and volume flow fields

The wheel montages and Rim0265 views illustrate the surface and flow records available in the dataset. Transverse sections and three dimensional isosurfaces then compare selected low and high drag cases, focusing on flow beside and downstream of the wheels.

5.6.1 Wheel pressure and skin friction

Figures 5.13 to 5.16 show the front left and rear left wheel fields for the 50 cases with the lowest C_D and the 50 with the highest C_D . Each figure contains ten rims per row. The first five rows show the low drag group and the last five show the high drag group. Within each group, complete vehicle C_D increases from left to right and then from top to bottom. The case arrangement is identical in all four figures.

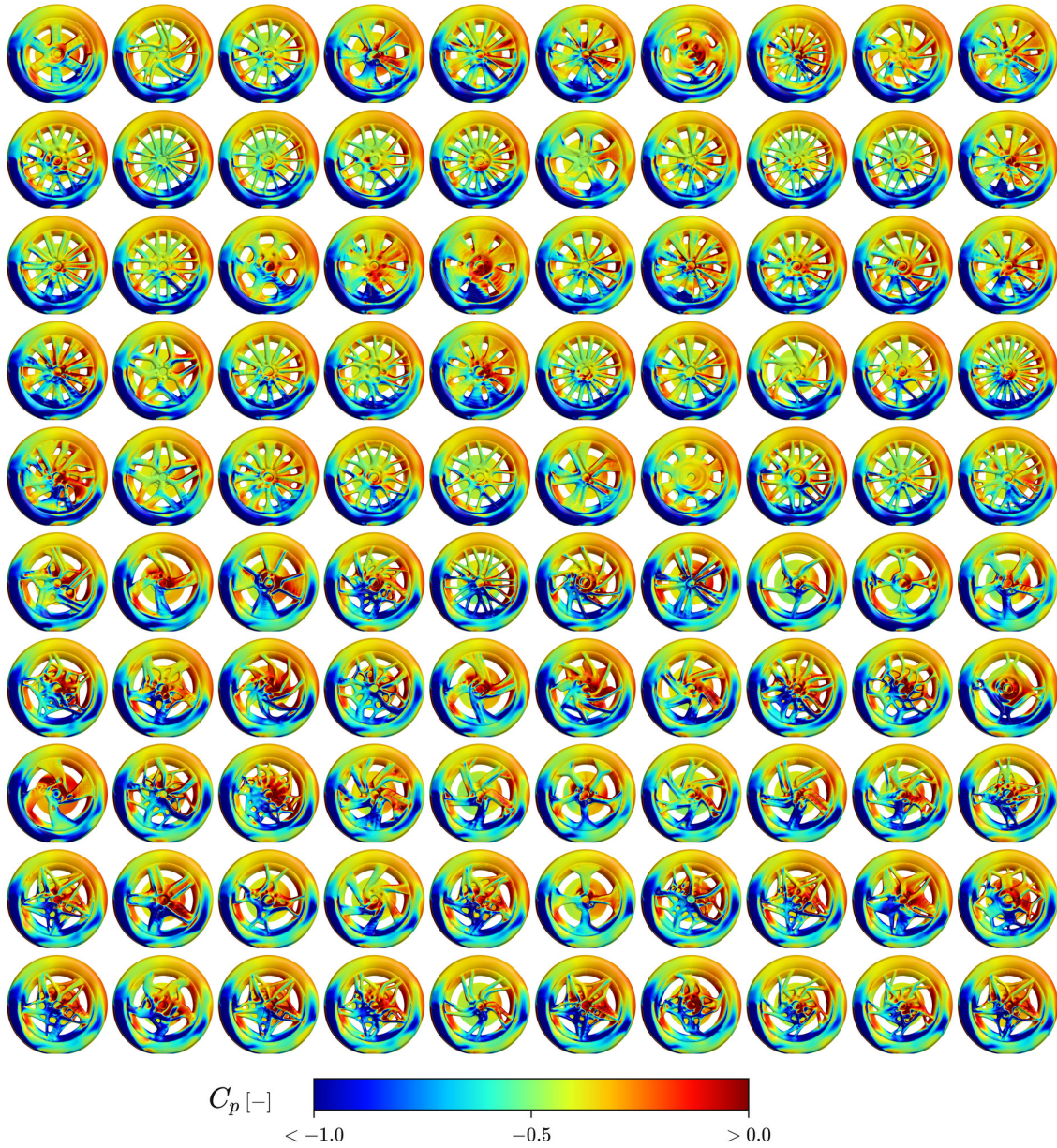


Figure 5.13: Mean pressure coefficient on the front left wheel. The upper five rows show the 50 lowest drag cases and the lower five show the 50 highest drag cases. Each group follows increasing C_D , row by row. The shared range is $-1 \leq C_p \leq 0$.

The front left pressure maps show local suction near the lower rim perimeter and around individual spoke openings (Figure 5.13). The size and position of these patches vary with the spoke layout. The corresponding C_f maps distinguish narrow regions of higher surface shear along edges from the lower values over much of the hub and spoke faces (Figure 5.14).

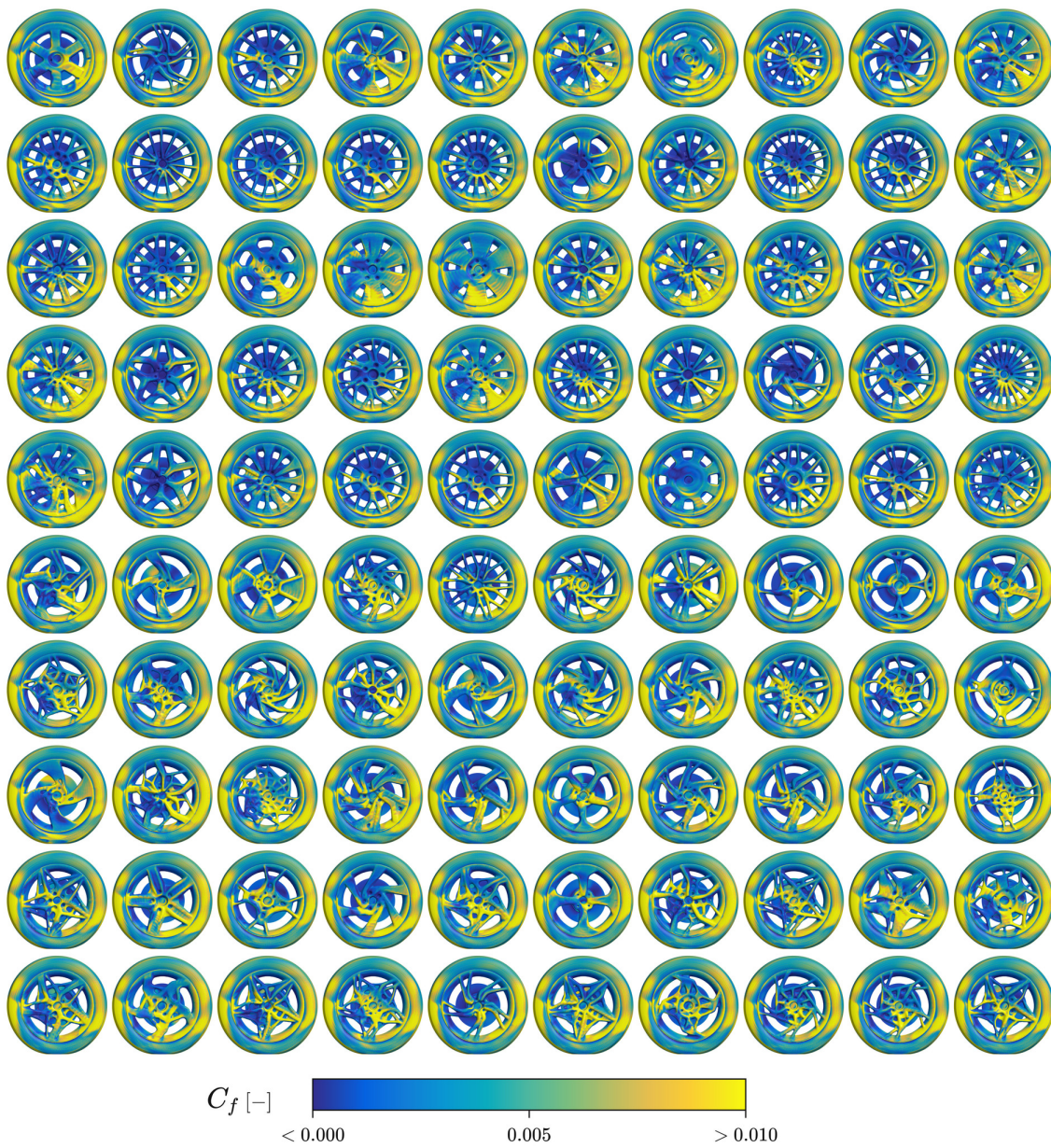


Figure 5.14: Mean skin friction coefficient on the front left wheel, with cases ordered as in Figure 5.13. The shared range is $0 \leq C_f \leq 0.010$.

On the rear left wheels (Figures 5.15 and 5.16), more of the visible surface lies near the upper end of the common pressure scale. Strong suction remains localised around parts of the rim perimeter and openings. The skin friction patterns also change between axles, even though the rim geometry is unchanged.

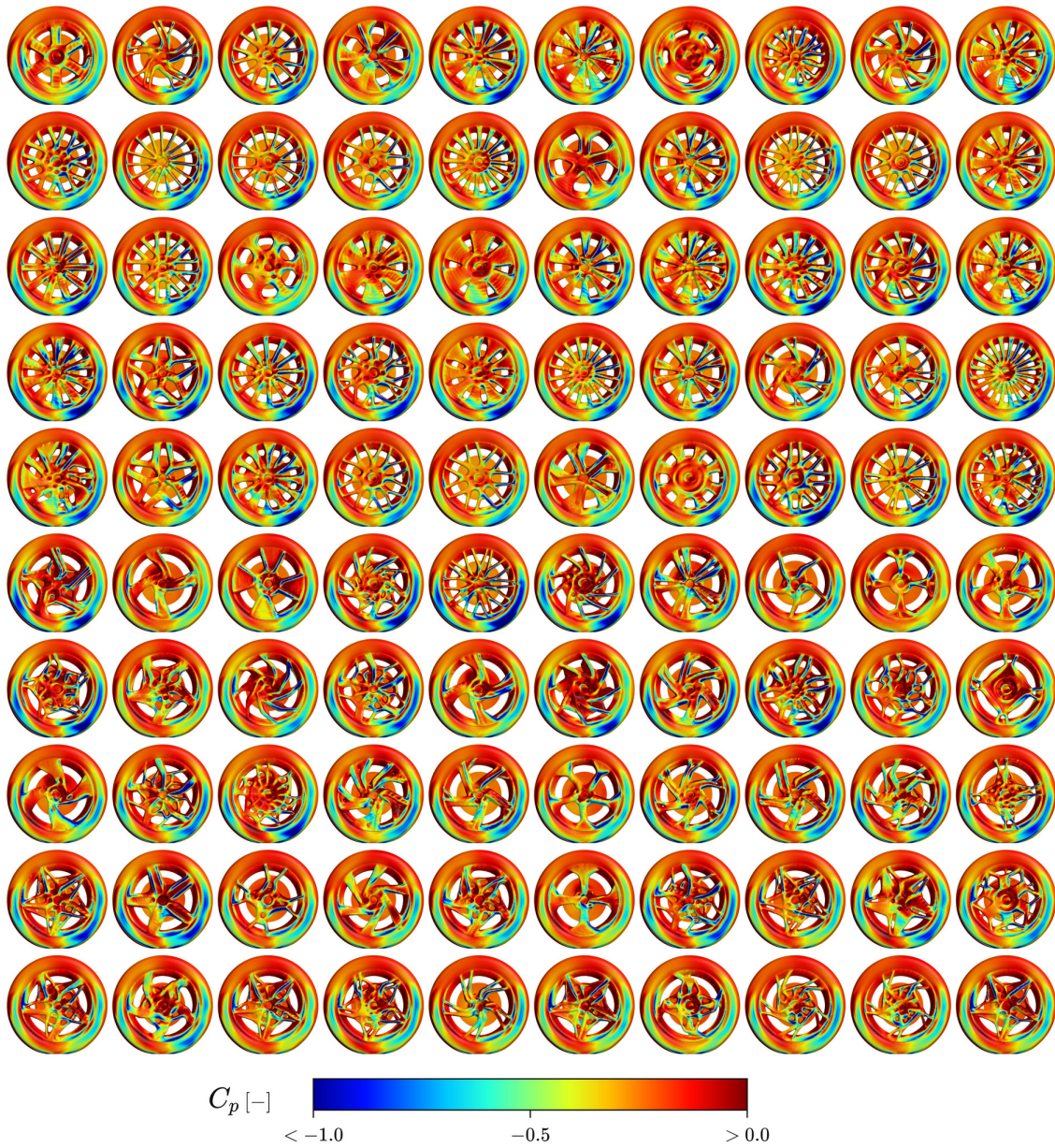


Figure 5.15: Mean pressure coefficient on the rear left wheel. Case order and colour scale match Figure 5.13.

Both drag groups contain varied surface patterns, so the montages do not visually identify a single favourable rim type. In addition, C_f describes wall shear magnitude, not its streamwise component. Wheel drag requires surface integration of pressure and shear forces.

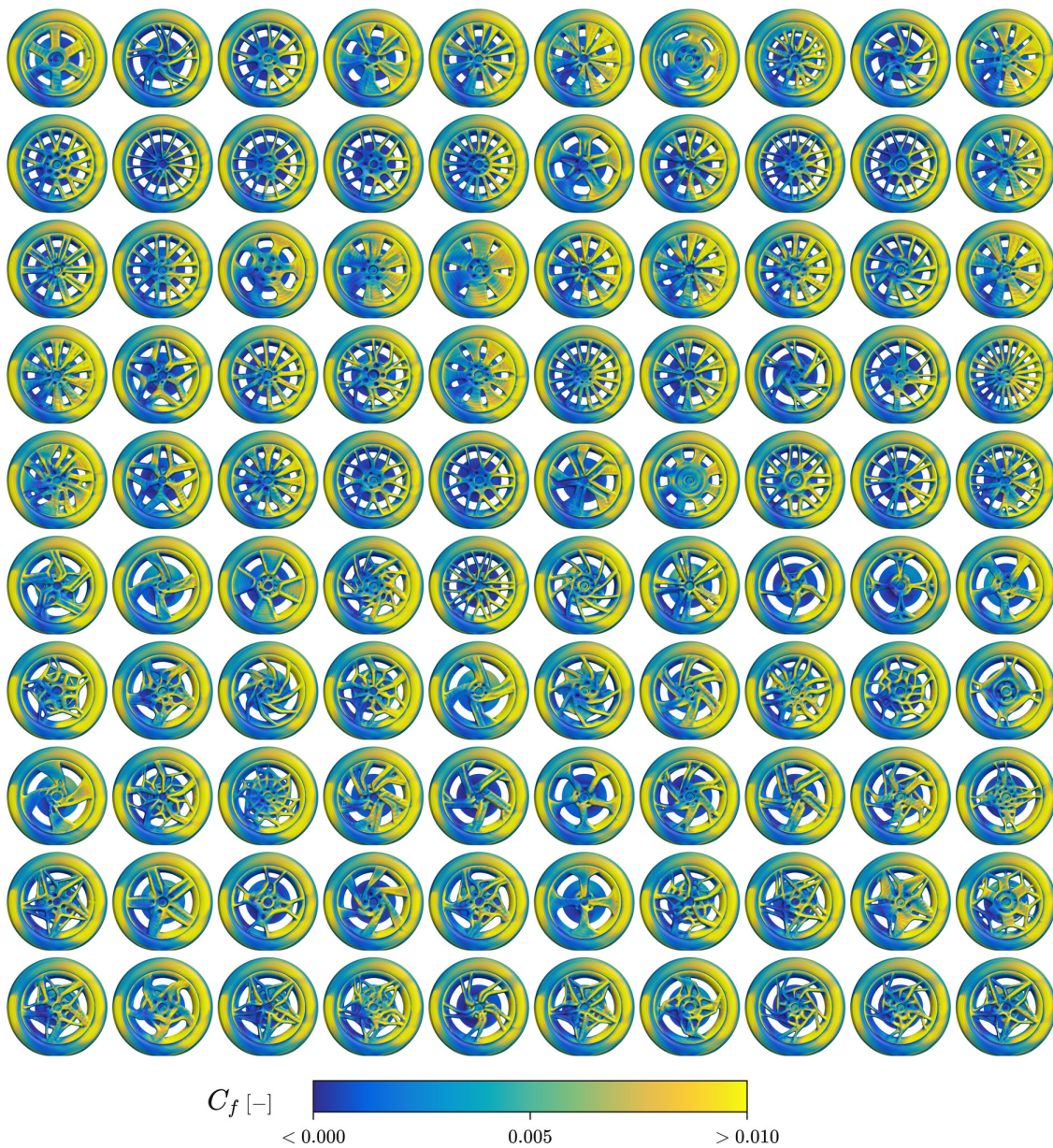


Figure 5.16: Mean skin friction coefficient on the rear left wheel. Case order and colour scale match Figure 5.14.

5.6.2 Exported fields for the lowest drag case

Rim0265 has the lowest complete vehicle drag in the production dataset, with $C_D = 0.2334$. Figures 5.17 to 5.19 illustrate its exported `Pictures` records. These include vehicle surface fields and transverse, longitudinal, and horizontal sections, averaged over the final 500 solver iterations.

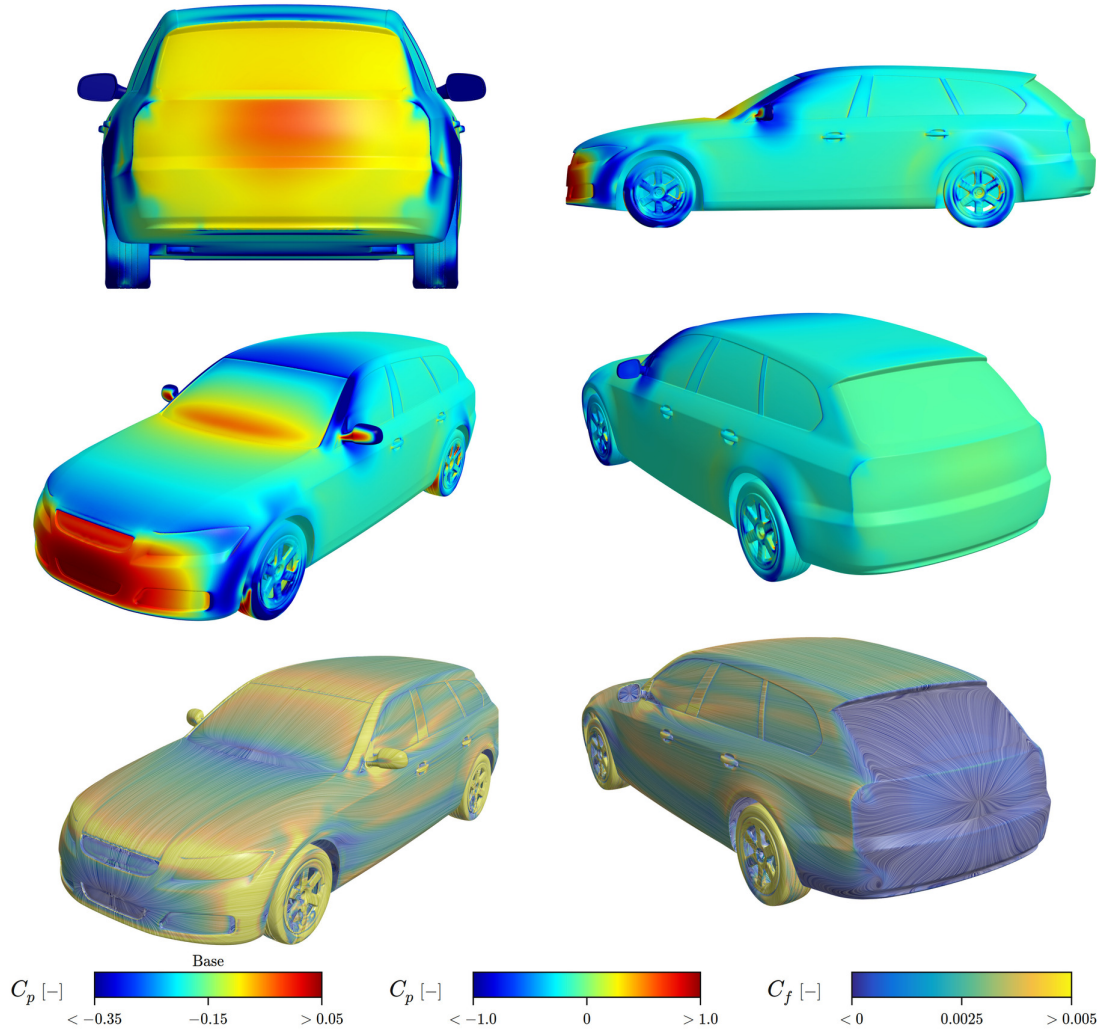


Figure 5.17: Surface fields for Rim0265. Top: base and left side pressure. Middle: front left and rear left pressure views. Bottom: skin friction with wall shear texture. Base pressure uses a separate colour scale.

Figure 5.17 shows high pressure on the front face, suction near the front corners, and lower pressure at the base. The narrower base pressure scale resolves variations over the rear facing surfaces. The skin friction views include texture aligned with the mean wall shear vector.

The velocity sections in Figure 5.18 show the magnitude of the mean velocity vector. Line integral convolution (LIC) texture indicates its direction within the plane. The sections intersect the wheel regions, vehicle side, centreline, and downstream wake.

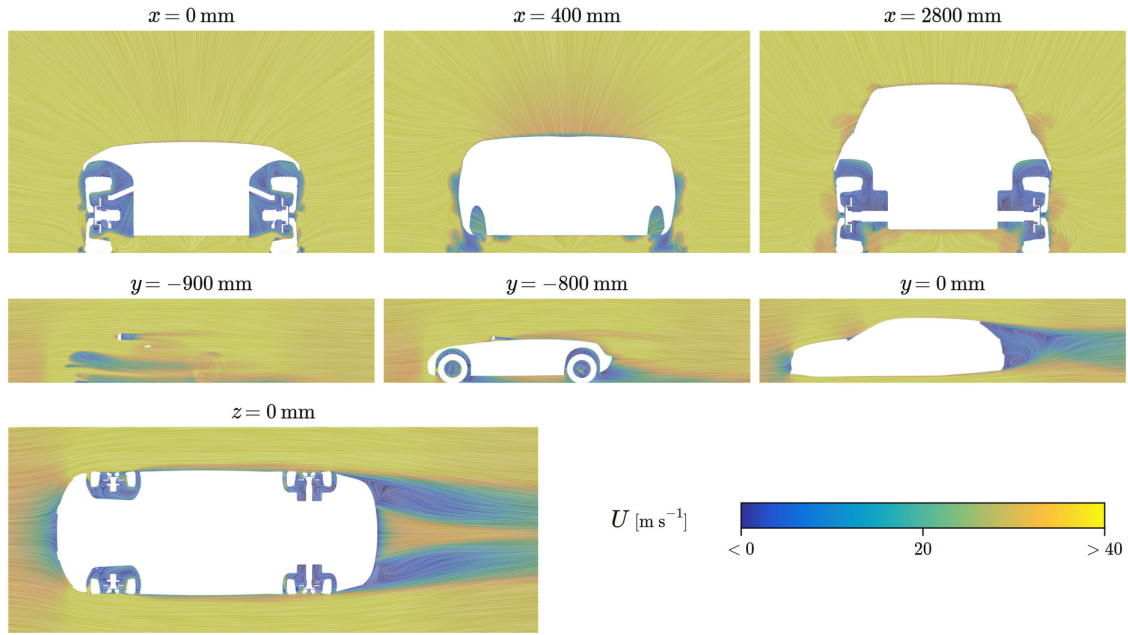


Figure 5.18: Mean velocity magnitude with LIC texture for Rim0265. Top: $x = 0, 0.4,$ and 2.8 m. Middle: $y = -0.9, -0.8,$ and 0 m. Bottom: $z = 0$ m.

Figure 5.19 shows total pressure on the same planes. Reduced $C_{p,\text{tot}}$ identifies disturbed flow around the wheels, beneath the body, and in the rear wake. The definition and averaging convention follow Eq. (3.18).

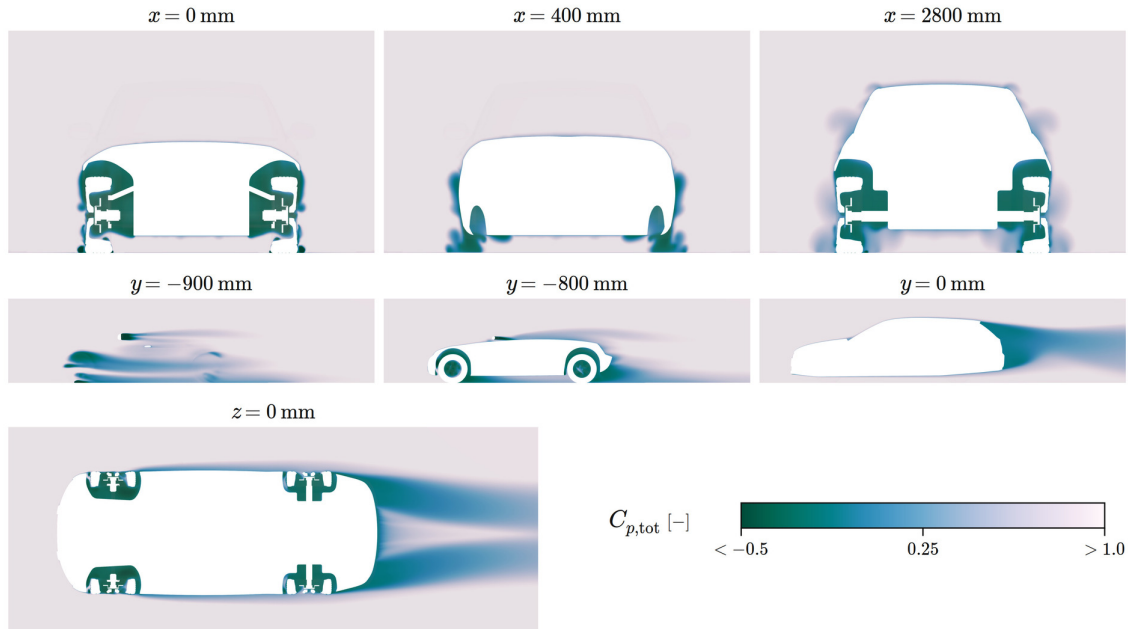


Figure 5.19: Mean total pressure coefficient for Rim0265, with planes and panel order as in Figure 5.18. The shared range is $-0.5 \leq C_{p,\text{tot}} \leq 1$.

5.6.3 Front wheel total pressure deficit

The transverse comparisons use the ten production cases with the lowest drag and the ten with the highest drag. Every plate has five columns and four rows. The first two rows contain the low drag cases and the last two contain the high drag cases. Within each group, C_D increases from left to right and then from top to bottom. All plates retain the same case order and the left half of the original transverse view. These cases represent the ends of the drag distribution, not the frequency of each flow pattern across all 904 rims.



Figure 5.20: Mean total pressure coefficient at the front wheel centre, $x = 0$. Upper two rows: ten lowest drag cases. Lower two rows: ten highest drag cases. Each group follows increasing C_D . The left half of the view is shown, with $-0.5 \leq C_{p, \text{tot}} \leq 1$.

The plane $x = 0$ passes through the front wheel centre (Figure 5.20). Both groups show strongly reduced total pressure within the wheel region and close to the lower wheel perimeter. The common tyre and wheelhouse geometry defines much of this pattern, while local differences remain near the exposed wheel and adjacent road. Much of the interior deficit reaches the lower limit of the colour scale, so its minimum values cannot be distinguished.



Figure 5.21: Mean total pressure coefficient downstream of the front wheel at $x = 0.4$ m. Case order, crop, and colour scale match Figure 5.20.

A clearer group difference appears at $x = 0.4$ m, downstream of the front wheel (Figure 5.21). The region of reduced total pressure outside the wheel track is generally more compact in the low drag cases. In the high drag group, this lower region spreads farther outboard along the road and occupies a broader area beside the

vehicle. The higher parts of the section remain comparatively similar. The main difference is the lateral extent of the lower wheel wake.

The differences extend beyond the rim openings into the surrounding wake. Patterns still vary within each group, so deficit extent does not rank all twenty cases exactly. The images locate the disturbed flow but do not quantify its contribution to drag.

5.6.4 Rear wheel crossflow

The rear wheel comparisons use $x = 2.8$ m, close to the rear wheel centre at $x = 2.786$ m, and $x = 3.4$ m, downstream of the rear wheel. The arrowed streamline views display the lateral and vertical mean velocity, with colour indicating $U_{yz} = (\overline{U}_y^2 + \overline{U}_z^2)^{1/2}$.



Figure 5.22: Mean crossflow at $x = 2.8$ m, ordered as in Figure 5.20. Arrows indicate direction, and colour gives U_{yz} from 0.05 to 8 m s⁻¹, within the $C_{p,\text{tot}} < 0.9$ mask.

The source field retains only $C_{p,\text{tot}} < 0.9$, and the display omits crossflow speeds below 0.05 m s^{-1} . Uncoloured regions therefore do not establish that crossflow is absent. The grey vehicle partly obscures the section.

At $x = 2.8 \text{ m}$, the high drag cases generally show a broader crossflow region near the ground outside the rear wheel (Figure 5.22). The low drag cases retain a more compact lower pattern. Features beside the upper body and roof are more alike across the groups.



Figure 5.23: Mean crossflow at $x = 3.4 \text{ m}$. Case order, crop, colour scale, and mask match Figure 5.22.

At $x = 3.4 \text{ m}$, the arrows form a curved lower pattern behind the rear wheel region (Figure 5.23). The high drag group shows a wider lateral spread near the road and a broader connection to the flow beneath the rear body. Arrow curvature and

position also change, but the clearest difference is the lateral extent. Peak U_{yz} is not uniformly higher for every high drag rim.

The crossflow display cannot separate changes in U_{yz} from changes in the area admitted by the total pressure mask. Its visible extent does not directly measure the magnitude of the total pressure deficit. Every case uses the same rim design at all four wheels. The rear wheel differences therefore include the influence of upstream flow as well as local rim geometry.

5.6.5 Three dimensional total pressure and vortical structures

The three dimensional views compare the three lowest drag rims (Rim0265, Rim0140, and Rim0011) with the three highest drag rims (Rim0736, Rim0792, and Rim0843). The first row contains the low drag cases and the second contains the high drag cases, ordered by increasing C_D within each row.

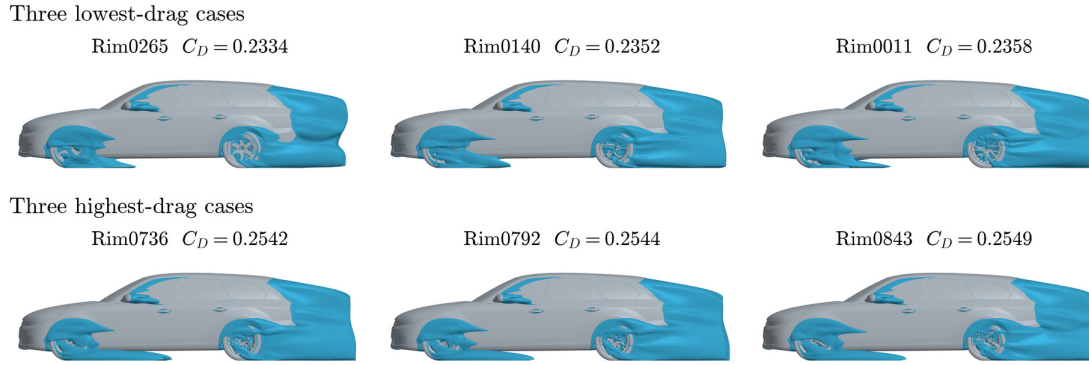


Figure 5.24: $C_{p,\text{tot}} = 0$ isosurfaces. Top: three lowest drag cases. Bottom: three highest drag cases. Each row follows increasing C_D . All panels use the same left side view and exclude points within 1 mm of walls.

Figure 5.24 shows the common $C_{p,\text{tot}} = 0$ surface. The high drag rims have a visibly longer envelope near the ground behind the front wheel. This lower lobe extends downstream from the exposed wheel region as a broad tongue along the road. For Rim0265, the lower envelope terminates closer to the wheel. The high drag cases also show more continuous coverage across parts of the lower rim face, linking the immediate wheel surroundings to this downstream lobe. This three dimensional view complements the broader front wheel total pressure deficit at $x = 0.4$ m.

The difference is not uniform around the wheel. Rim0140, despite belonging to the low drag group, has a prominent upper lobe behind the front wheel arch. The low and high drag distinction is therefore clearest in the lower envelope, not in the maximum downstream reach of every part of the isosurface.

At the rear wheel, the high drag cases show a broad lower connection between the wheel region surface and the base wake near the ground. More of the exposed spoke region is surrounded by the selected surface. Rim0265 leaves more of the rim face visible, with a clearer separation from the upper part of the base wake envelope. Rim0140 and Rim0011 also show connections to the downstream wake,

so connectivity is not unique to the high drag group. The groups differ mainly in the extent and shape of the lower coverage and in how the wheel region lobes merge into the rear wake.

Figure 5.25 shows the $Q = 2000 \text{ s}^{-2}$ isosurfaces. Features along the roof, window edges, and mirror remain broadly similar. Larger changes occur around the wheel openings and immediately downstream, where the isosurfaces differ in shape and connection. Colour gives the streamwise vorticity W_x on the selected Q surface.

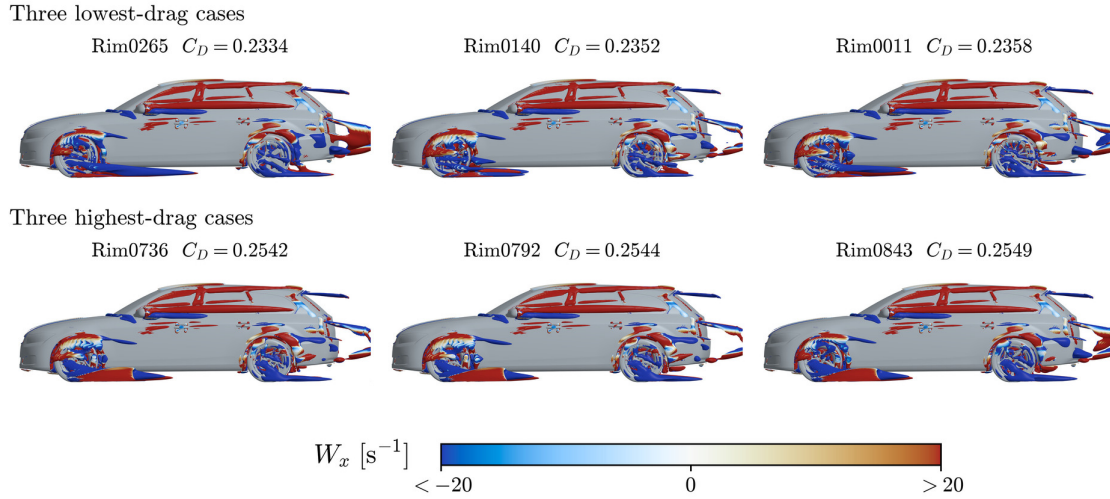


Figure 5.25: $Q = 2000 \text{ s}^{-2}$ isosurfaces, ordered as in Figure 5.24. Colour gives W_x from -20 to 20 s^{-1} . Points within 10 mm of walls are excluded.

Behind the front wheel, the high drag cases contain a broad red lobe close to the road, followed by a blue downstream tip. Rim0265 instead has a long, predominantly blue lower structure. Its Q isosurface extends farther downstream than those of the high drag cases. Rim0140 and Rim0011 show different mixtures of red and blue in the same region. Higher drag therefore does not correspond to a uniformly longer Q structure. Instead, the distribution of positive and negative W_x and the arrangement of the wheel wake structures change.

Around the rear wheel, the high drag cases show more connected patches across parts of the lower spoke region and pronounced lobes near the trailing wheelhouse edge. The openings, outer wheel flow, and near road structures are linked differently from those in Rim0265. Their proximity is consistent with interaction between the rim opening flow and the external wheel wake. The isosurfaces do not, however, trace individual fluid paths through the spokes.

These comparisons are qualitative associations under common viewing conditions. Projected isosurface coverage does not measure enclosed volume, integrated total pressure loss, or a component drag contribution.

6

Conclusion

This thesis developed and analysed DrivAerRim, a CFD dataset for 904 diverse DeepWheel rims on a common DrivAer estateback. Full vehicle simulations were used to examine rim effects on vehicle forces and wheel flow. The paired geometry and aerodynamic records were organised for open reuse.

Geometry repair, automated batch simulation and structured export produced the dataset under consistent numerical settings. Mesh sensitivity and wind tunnel comparisons supported the steady RKE setup with MRF rims and rotating wall tyres. RKE gave the most consistent predictions of the two measured drag differences among the four closures, although pressure errors varied by region. All cases satisfied $R_{C_D} < 0.002$ over the final 500 iterations, meeting the selected criterion for iterative stability.

Rim variation produced a vehicle drag range of approximately $C_D = 0.2334$ to 0.2549 and also changed total and axle lift. The combined contribution of wheel assemblies, wheel supports and wheelhouses was concentrated near 29% of conventional vehicle drag. Ventilation resistance was reported separately. The largest differences in accumulated drag developed around the front and rear wheels. Signed mass flow correlated strongly and negatively with drag on the front left wheelhouse, but positively with drag on the rear left wheel assembly. Its association with front left wheel assembly drag was negligible. The relationship therefore depends on both component and axle.

Selected high drag cases generally showed broader total pressure deficits near the ground and more extensive connections between the lower wheel regions and the downstream wake. Q isosurfaces showed changes in mean flow structure, but higher drag did not correspond to uniformly longer vortical features. The drag contributions of these local flow differences require further analysis.

The records pair STL wheel geometries and force coefficients with wheel region surface fields, 128 global slices and four local volumes per case. Common case identifiers link these records for future geometric deep learning surrogates of vehicle forces, component loading and flow fields.

6.1 Future Work

Further validation should assess the sensitivity of rim rankings to spoke orientation and the treatment of wheel rotation. Targeted RBM simulations should cover rims spanning drag, opening ratio, spoke layout and topology. Comparison with steady MRF predictions would identify geometries for which the rotation treatment changes rankings or local flow patterns. Wind tunnel measurements on selected rims would provide an independent check of these predictions.

Component analysis should test the relationships suggested by the force and flow comparisons. Matched pressure and shear integrals, wheel mass flow and local total pressure budgets could clarify how rim geometry redistributes aerodynamic loading. Varying yaw, tyre geometry and cooling state would test whether these relationships hold beyond the present setup.

Future surrogate benchmarks should keep all records of each rim within one training, validation or test partition. Initial tasks should predict vehicle drag, lift and rim ranking, before extending to component forces and spatial fields. Benchmarks could compare models based on point clouds, meshes, neural operators and transformers [7, 31, 32, 33, 34, 35, 36]. Comparisons against opening ratio and projected area baselines would test whether geometric models capture information beyond simple descriptors. Test sets with distinct geometries and external production rims are needed to assess generalisation beyond the synthetic collection.

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