

Upstream Disturbance effects on Self-Similarity in the Wake of a DrivAer model

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Abstract

This study aims to provide an understanding of self-similarity in the turbulent wake generated by a Fastback DrivAer automotive model and assess the impact of upstream disturbances on the wake. The disturbances are generated using a circular cylinder placed five cylinder diameters upstream. Multiple ‘cylinder-model’ positions were tested by offsetting the lateral positioning of the cylinder with respect to the centreline of the model. Data was obtained at cross-planes in the wake going from 25% to 100% car length. Wind tunnel data has been obtained using a total pressure probe rake and a four-hole cobra probe. Data has also been obtained using RANS based simulations with $k-\epsilon$ realisable turbulence model. Mean axial-component velocity profiles were analysed with momentum thickness (θ) and vorticity thickness (δ_ω) used as the scaling parameters. It was seen that self-similarity marginally exists in the wake depending on the upstream conditions and the scaling parameter. Overall, vorticity thickness was seen to be better. Downstream, the mean profiles show a simpler collapse compared to the near wake. Understanding how deficit decay takes effect in the wake is useful to improve the aerodynamic performance of an automobile/motor car/ground vehicle. Therefore, establishing the similarity parameters presented in the work is an early step towards an analytical description of a turbulent wake model.

Introduction

The analysis of a turbulent wake structure in terms of understanding how deficit decay takes effect in a towed wake is one of the many useful ways to understand and improve aerodynamic performance. Self-similarity is an asymptotic state in the wake of a body wherein, the variation of particular parameters (such as mean velocity) downstream can be made geometrically congruent with the help of simple scaling factors depending on a few variables. Therefore, establishing self-similarity in the wake of a body simplifies the development of both analytical models and test campaigns.

Extensive literature is available for self-similar solutions of simple bodies, such as cylinders, discs, and flat plates. The wakes generated by these are known to have analytical solutions based on initial conditions and a few assumptions. For a complex body, however, the wakes are expected to be more convoluted and different to simple bodies. This project studies the self-similarity in one such turbulent

wake generated by a complex geometric body and assesses the impact of upstream disturbances on the self-similarity.

One of the DrivAer automotive model configurations [1] has been used as a complex wake generator with different upstream disturbances. Concepts of self-preservation and the similarity scales obtained from simple geometric body wakes will be applied to the complex bodies. This knowledge is aimed at improving the understanding of a turbulent wake behaviour for these automotive shapes as well as for the aspect of applications, through which experimental costs and required time can be substantially reduced. This preliminary study focuses on a limited number of specific locations within the wake that were considered to be of interest. It is recognised that a more extensive dataset would be required to facilitate a complete description.

Significant mathematical conclusions for self-similarity are presented, most notably by Tennekes and Lumley [2], and Townsend [3]. They postulate that an asymptotic, self-similar state is reached sufficiently downstream of the body and a moving equilibrium is established where the initial conditions of the flow are irrelevant, and the mean flow depends on a few simple parameters. The mean velocity profiles and second order components can be shown to be independent of streamwise coordinate when normalised by appropriate scaling parameters. These observations are subject to some assumptions; particularly relevant for the paper, the ambient turbulence intensity which is considered by these theories to be isotropic and homogeneous in the free-stream.

George [4] argues that such simplified theories are a result of the restrictive nature of experimentation and a more generalised self-preservation analysis concludes that there exists a range of self-similar states for a particular flow determined by the initial conditions. Flows can be fully, partially or locally self-preserving based on the scales at which it is applicable. George and Gibson [5] presented a then new theory in 1992, showing that homogeneous shear flows may achieve asymptotic states which are both self-preserving and determined by the initial conditions and concluding that the experimental evidence was generally consistent with the theory.

In recent years, with use of numerical simulations and hot-wire anemometry, Dairay T., Obligado, M., and Vassilicos, J. C., [6] used revised scaling laws for axisymmetric turbulent wakes relying on the mean streamwise momentum and turbulent kinetic energy (TKE) equations to establish self-similarity of the mean flow. Cafiero, G. and Vassilicos [7] studied the self-similarity and dissipation scaling of a turbulent planar jet and the theoretically implied mean flow

scaling. The Townsend [2] – George and Gibson [5] theory was applied to turbulent planar jets. Wei [8] investigated the self-similarity properties in the far downstream of high Reynolds number turbulent wake flow. Rai [9] explored the possibility of obtaining self-similarity in the near wake of a flat plate with a circular trailing edge via direct numerical simulations. Evidently there have been many studies related to simple body wake and the theories of self-similarity presented by [2], [3] and [5] have been applied and revised to achieve numerous scaling laws for wakes generated by simple bodies depending on their ambient conditions.

To study the effects of upstream disturbance on the wake, literature pertaining to analogous studies were referred. Khabbouchi et al. [10] studies the effects of freestream turbulence and Reynolds number on the separated shear layer of a circular cylinder. It was found that the shear layer evolved downstream approximately as a plane mixing layer for $TI \leq 2.2\%$. Increasing turbulence intensity ($TI \geq 3.4\%$) suppress self-similarity at certain locations downstream. Rind and Castro [11] investigated the effect of free-stream turbulence on the axisymmetric wake behind a disc. The disc and its wake were introduced to various turbulent streams having various levels of turbulence intensity and length scales. It has been shown that such levels of turbulence, if it is of sufficient strength, changes the far wake's decay rate and destroys any possibility of self-similarity in the far wake.

In summary, a similar method of investigation to [4] can be utilised for wakes generated by complex bodies, by focusing on the levels at which self-similarity might exist. Literature pertaining to particular parts of the objectives were chosen to simplify the project problem and handle each task separately.

The following sections discuss the methodology used for the study in terms of wind tunnel testing and numerical simulations. Then, key results obtained from both the numerical and experimental studies are presented and followed by an analysis of self-similarity in the wake. Lastly, conclusions and suggestions for future work are made.

Methodology

Wind Tunnel testing and numerical simulations were employed to achieve the objectives of the project. The experimental measurements were undertaken using a sub-scale model in the 8x6 closed working section, closed return Wind Tunnel, at Cranfield University [12]. Numerical simulations were setup and conducted using Ansys Fluent via the university HPC. The following sections provide description of the wake generator used in both and the instrumentation used for experiments.

DrivAer model

The Cranfield University DrivAer models are 35% scaled models of the original DrivAer model packages proposed in [1]. The CAD models used have been acquired from the Cranfield Online Research Database [13]. This CAD geometry package consists of separate models for the main body (which is common throughout all the variations Notchback, Fastback and Estateback), rear end, wheels, underbody and other add-ons. The configuration shown in Figure 1 was assembled and used, as denoted by -

Fastback Smooth underbody without Mirrors, with Wheels (FSwoMwW).

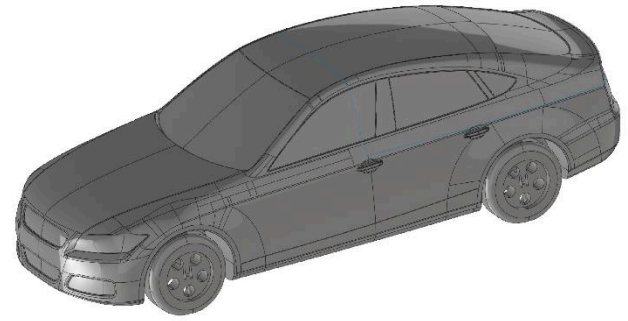


Figure 1. CAD model – DrivAer Fastback Smooth underbody w/o mirrors with wheels.

In order to simplify the wake categorisation in this preliminary phase of the study, a simplified version of the DrivAer fastback was adopted with a smooth underbody, non-rotating wheels (above a fixed ground plane) and side mounted mirrors removed. The dimensional properties of the model are shown in Table 1.

Table 1. Dimensional parameters for the Cranfield DrivAer Fastback model compared with the original DrivAer Fastback model as given by [1]

Parameters	DrivAer Cranfield definition	DrivAer TUM, DrivAer Audi
Car scale (CS)	35%	40%
Reference length (CL)	1.6144 m	1.8450 m
Reference width (W)	0.6135 m	0.7012 m
Reference height (H)	0.4963 m	0.5673 m
Reference area (A_{ref})	0.1323 m ²	0.1728 m ²
Wheel diameter	0.2223 m	0.2544 m
Front end position (X-coordinate)	-0.2826	-0.3230
Rear end position (X-coordinate)	0.9751	1.1145

Model and Instrumentation Setup

A two-dimensional probe traverse was fixed at the downstream end of the test section with the ability to move in the vertical (Z-axis) and lateral (Y-axis) directions. Both the total pressure rake and 4-hole cobra probe, were positioned within the wake using this traverse system, shown in Figure 2.



Traverse and probe support

Figure 2. DrivAer model setup in the Cranfield 8x6 Wind Tunnel – Fastback model with cylinder in front and a 2-D traverse at the end of test section for pressure data acquisition.

Total Pressure Probe Rake

A 40-tube total pressure rake was used to measure the mean total pressure in the wake. The probe centrelines are separated by 4.77 ± 0.50 mm and are connected via pneumatic tubing to a differential pressure transducer. This rake is mounted to the traverse via an aerodynamic support structure, and traversed laterally in 50mm steps. Synchronous sampling of the 40 pressure transducers, at a rate of 1kHz for a period of 10 seconds, ensured acceptable time-averaged data without prolonging the experimental run-time. Data obtained from the pressure rake was then used to identify regions of interest in the wake. These areas were later studied with the use of 4-hole cobra probe

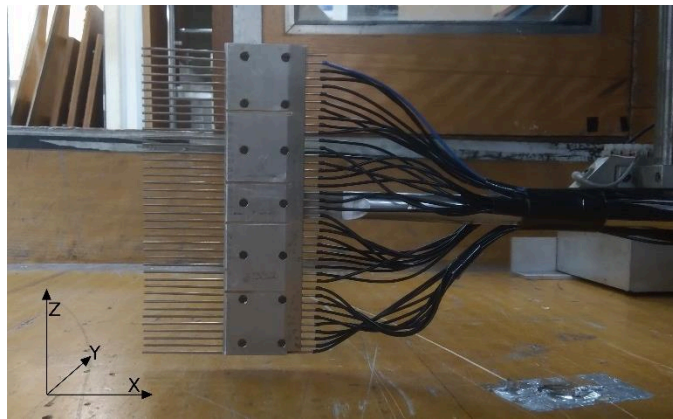


Figure 3. Wind tunnel and instrumentation axis system; total pressure probe rake mounted on an aerodynamic support structure.

4-Hole Cobra Probe

In order to supplement the time-averaged total pressure data obtained from the total pressure rake, the 4-hole cobra probe was used to obtain local velocity component data. It is a multi-hole pressure probe that provides dynamic, 3-component velocity and local static pressure measurements in real-time. The probe is capable of a linear frequency response up to 2 kHz and is valid in velocity ranges between 2 m/s and 100 m/s with an ability to measure flow angles in a $\pm 45^\circ$ cone [15].

Numerical Simulation Methodology

The numerical simulation strategy recognised constraints on computational resources. Consequently, RANS turbulence modelling was used within Ansys Fluent together with Ansys Design Modeler to support geometry management. To minimise usage of computational resources and time, a half geometry was used with assumed symmetry along the XZ plane splitting the DrivAer assembly. Although it should be noted that such a simplification would pose a major constraint on the characteristics of the wake.

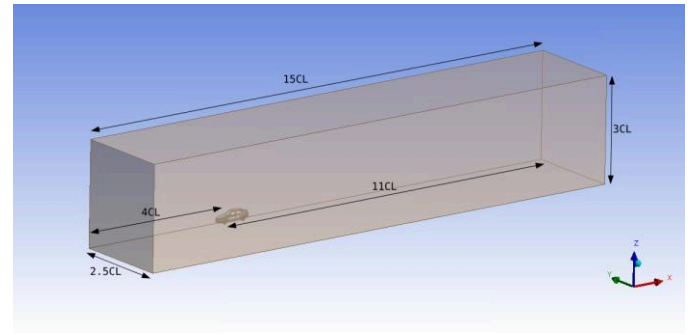


Figure 4. Dimensions of fluid domain used for CFD simulations; the bounding box sizes are given in terms of car lengths (CL).

Meshing Parameters

A computational fluid domain was constructed as shown in Figure 4, one of the faces of the rectangular domain has been used as a symmetry plane. All dimensions are shown in terms of one car length (CL). Refinement zones were added in the wake and near wake of the DrivAer model. Local sizing was used for different parts of the geometry to have better control over the cell sizes in critical regions. Table 2 shows the sizing parameters used for meshing. Polyhedral volume cells were chosen as global cell type as a cost-effective condition to use less computational time. To capture boundary layer effects over the model surfaces accurately, prism layer cells were generated targeting a $y^+ < 1$ and to specifically avoid the buffer layer zones ($5 < y^+ < 30$) over the no-slip condition surfaces, considering that only RANS methods were being used for solving and a y^+ between 5-30 would be solved poorly. Table 3 shows the prism layer cell generation setting used and the free-stream conditions, boundary conditions are shown in Table 4. The mesh sizing and solution controls were set as suggested by [14], [16]. It was concluded in [14,16], that using the settings shown in Table 2, with RANS based solver was a cost-effective simulation. Mesh independence studies were conducted to ensure appropriate mesh sizing was used, resulting in a cell count of approximately $4.34E+6$. Figure A.x shows the mesh independence.

Table 2. Meshing parameters for the DrivAer half body simulation geometry

Features and description		Feature definition
DrivAer body surface	Face	0.02 m
	Edge	0.0025 m
Wheels surface (and cylinder when in use)	Face	0.01 m
	Edge	0.0025 m
Local volume sizing	Outer Domain	0.6 m
	Inner Domain	0.2 m
	Near wake Domain	0.025 m
Growth rate	Global	1.2
Surface and proximity	Scoped to faces and edges	18° ; 5 cells per gap

Table 3. Prism layer sizing parameters and settings

DrivAer body (Prism layers)	Number of layers	20
	First layer thickness	1.74e-5 m
Wheels (Prism layers)	Number of layers	20
	First layer thickness	1.47e-5 m
Floor (Prism layers, Uniform method)	Number of layers	5
	First layer thickness	1.00e-3 m
Offset method	(for DrivAer body and Wheels only)	Last ratio method
Transition ratio	(for DrivAer body and Wheels only)	0.272

Solution Controls

For the solution methods and controls, 1st order upwind discretisation was used for turbulent kinetic energy (TKE) and dissipation (ϵ). 2nd order upwind was used for spatial, pressure and momentum terms. Rhie Chow distance-based flux type was set with a least-squares cell-based gradient. Pseudo-transient CFL number was set to be able to adapt steps easily. The free-stream and boundary conditions were set such that the solutions would be comparable with relevant literature [1], [15], [16] in terms of drag coefficient monitors.

Table 4. Numerical boundary conditions

Boundary	Condition	Definition
Inlet	Velocity-inlet	$U_{\infty} = 44.2 \text{ m/s}$; $Tl = 0.5\%$; $\mu_r/\mu = 2$
Outlet	Pressure-outlet	$P_{\infty} = 0 \text{ Pa}$; $P_{abs} = 101325 \text{ Pa}$
DrivAer body	wall	No slip
Sym wall	symmetry	
Far walls	symmetry	
Floor	wall	No slip; no ground simulation
Wheels	wall	No slip; no wheel rotation

Wind Tunnel Model Wake Data Acquisition Planes

Five planes perpendicular to flow (YZ plane) were considered for data acquisition ranging from 25% to 100% CL relative to the ‘trailing edge’ of the model. The lateral position of the total pressure probe rake extends 450mm either side of the model axial centre line (900 mm total, $\sim 1.5W$). Figure 5 shows the CAD representation of the data acquisition planes, Table 5 shows the axial locations of these acquisition planes.

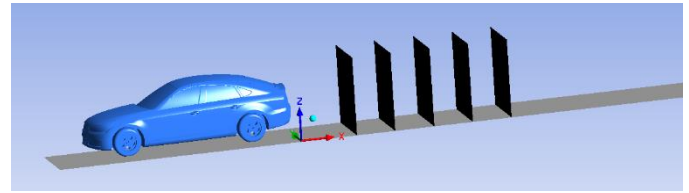


Figure 5. CAD representation of data acquisition planes in the wake of DrivAer model, 5 YZ planes from 25%CL to 100%CL from the ‘trailing edge’ of the model.

Table 5. Data acquisition plane axial location relative to ‘trailing edge’ of DrivAer model

Plane	X* (Normalised coordinate with 1 CL)	X (From rear end of the model), m
P5	0.250	0.4036
P4	0.437	0.7055
P3	0.625	1.0090
P2	0.812	1.3109
P1	1.000	1.6144

DrivAer Model Wake

The data obtained from the total pressure rake was used to identify locations of interest for further investigation using the 4-hole cobra probe. Figure 6 shows an example of average velocity contour at one of the acquisition planes (P1), the configuration - model with the cylinder at $Y = -0.155 \text{ m}$ is shown. Such contours were used qualitatively to determine the regions of interest.

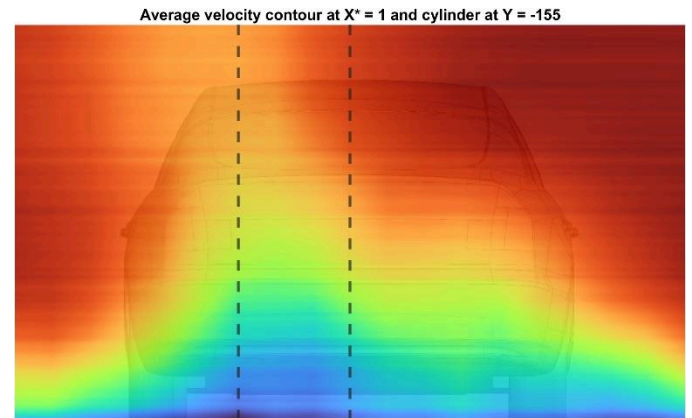


Figure 6. Average velocity contour P1 with upstream cylinder at $Y = -0.155 \text{ m}$; Dashed lines show the identified locations of interest

The vertical centreline $Y = 0$ has been considered as the baseline and vertical line at $Y = -0.155 \text{ m}$, where the C-pillar vortex is seen to be dominant, was considered as another location of interest (shown in dashed lines at $Y = 0$ and $Y = -0.155 \text{ m}$) and are henceforth referred as ‘centreline’ and ‘span-line’ respectively. Measurements were made with the two ‘model-cylinder’ positions and at the two locations in the wake, as shown in Table 6

Table 6. Notation for 'model-cylinder' setup (location of acquisition, position of cylinder)

configuration	Notation
Axial Centreline, no cylinder	CnC
Axial Centreline, cylinder at Y = -0.155 m	CC
Span-line (Y = -0.155 m), no cylinder	SnC
Span-line (Y = -0.155 m), cylinder at Y = -0.155 m	SC

Measurements were taken along vertical lines at P1, P3, P5 (see Table 5) and at the locations shown in Table 6 with a resolution of 18 points along the Z-axis.

Figure 7 shows an example of velocity profiles obtained in the wake of the DrivAer Fastback model. Since measurements were made with pressure based instruments unable to determine reversed flows, the recirculation regions in the wake could not be identified. The wake can then crudely be categorised into two separate zones, one in the immediate vicinity behind the model ($X^* = 0.25CL$) and another outside this zone ($X^* > 0.25CL$). The velocity profiles at 25%CL shown in Figure 7 are close to the rear end of the model and clearly show deficit affected by the proximity to the 'trailing edge'.

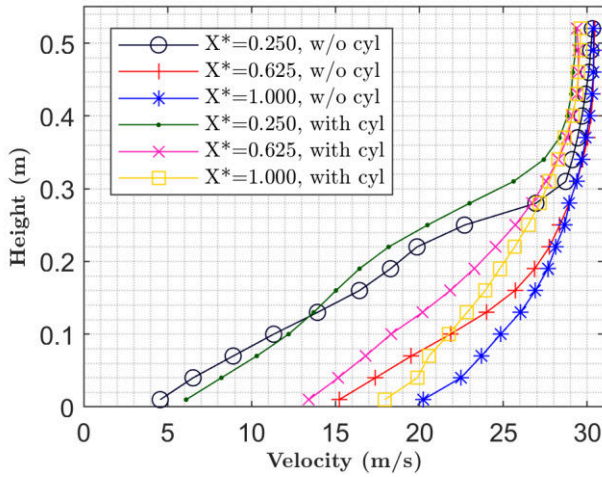


Figure 7. Mean U velocity profiles locations P1, P3, P5 (see Table 6); Obtained from 4-hole cobra probe data.; Profiles shown are both with and w/o the upstream cylinder measured along the model centreline (Y = 0).

Similar trends are observed from the numerical solutions, as shown in Figure 8. Difference between the wind tunnel data and the simulation results is seen in terms of wake recovery and turbulent mixing in the wake. The mean velocity profiles at the same 0.25CL location between CFD and WT data are completely different. The nature of profiles at $X^* = 0.625$ are comparable to the profiles at $X^* = 0.25$ in the wind tunnel data. The CFD fluid domain is larger, this causes the inlet turbulence to dissipate to low levels before the flow reaches the DrivAer model near upstream regions. The turbulence intensity values seen at the immediate upstream location of the DrivAer model were around the order of $10^{-4}\%$. The simulations appear to be predicting slower mixing between the underbody flow and the 'body

wake', this is not evident in the experimental data. Due to this the numerical solutions show a decreased wake recovery. This characteristic could be solver or mesh driven and could have an impact on correlation when $X^* < 0.625$. Domain size can have many other effects which could be numerical and physical.

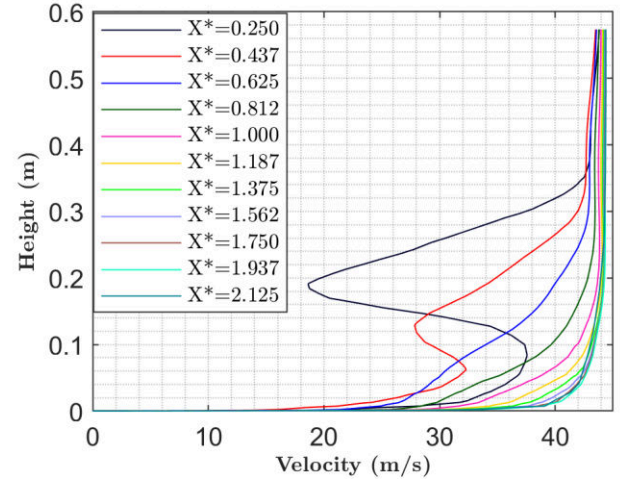


Figure 8. Mean U velocity profiles at locations ranging from 25% to 200%CL; Obtained from simulation data; Data points taken at the model centreline w/o upstream cylinder.

Scaling Parameters for Self-Similarity

The scaling parameters used for normalisation of the Z-axis were considered based on the nature of the profiles and the parameters required for calculation. Momentum thickness, θ , calculated over the entire height of the profiles, and vorticity thickness, δ_ω , calculated based on the shear values along the height have been used. Other parameters such as displacement thickness and half width were considered, but the outputs were similar to that of momentum thickness. The parameters used were calculated as shown in equations 1 and 2.

$$\theta = \int_0^\infty \frac{u}{u_\infty} \left(1 - \frac{u}{u_\infty}\right) dz \quad (1)$$

$$\delta_\omega = \frac{u_\infty}{\max(\partial u / \partial z)} \quad (2)$$

The 'X-axis' was normalised in terms of velocity deficit Δu shown in equation 3. The velocity deficit is normalised by the maximum velocity deficit ($\Delta u / \Delta u_{max}$) shown in equation 4.

$$\Delta u = u_{max} - u \quad (3)$$

$$\Delta u / \Delta u_{max} = \Delta u / (u_{max} - u_{min}) \quad (4)$$

Figures 9 to 12 show the comparison of velocity profiles and normalised profiles with the different setups mentioned in Table 6. Figure 9 displays absolute and normalised mean velocity data obtained using the 4-hole probe obtained at axial locations P1, P3, and P5, as defined in Table 5.

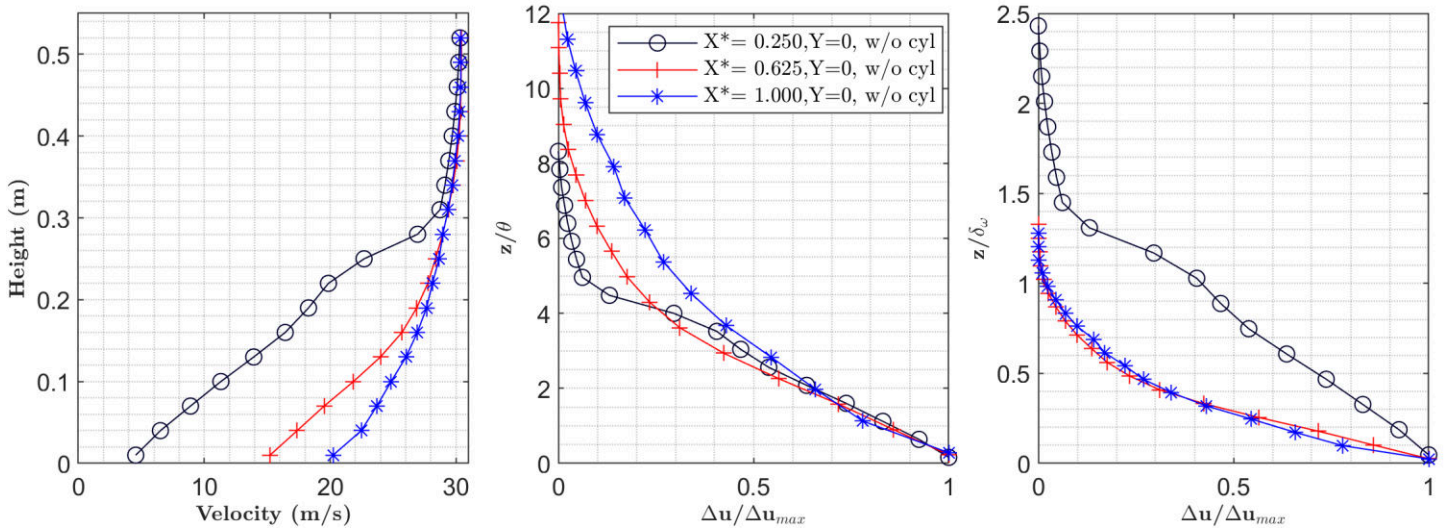


Figure 9. Velocity profiles obtained with 4-hole cobra probe at locations P1, P3 and P5 (CnC setup). Left – absolute velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (o – 0.25CL, + – 0.625CL, * – 1.00CL)

Both scaling parameters are length scales representative of flow properties. Momentum thickness θ is derived using information of momentum loss (velocity deficit) in the wake. Whereas, δ_ω is a length scale related to the size and strength of the vortex/eddy structures present in the flow.

On comparing the general trends in terms of the normalised profiles obtained by using momentum thickness and vorticity thickness, there are clear differences based on the model setup. In general, θ is seen to have marginal effects in the collapse of the velocity profiles. As the normalised height increases when moving along the ‘y-axis’, the collapse between the profiles starts spreading. Whereas, using δ_ω , results in a much closer collapse between the profiles at axial locations $X^* > 0.25CL$. The profile at 0.25CL is seen to be completely excluded. This trend is seen, across all combinations of setups (Figures 9 to 13).

Figure 10 shows the effect of the presence of the cylinder (CC setup), which results in a decreased velocity deficit. Thus, the non-normalised velocity profiles are closer together when compared with the CnC setup. The data collapse using θ is still marginal. Although δ_ω still produces a better result, the overlap between the different profiles is negatively affected by the presence of the cylinder. The δ_ω normalised profiles in Figure 10 are closer than the ones in Figure 9 but the collapse between profiles $>0.25CL$ is not as strict.

Figure 11 shows the profiles without the cylinder, at the vortex dominant span-line (SnC setup). The vortex causes a decrease in the velocity deficit (similar to the ‘with cylinder’ cases) and the mean velocity profiles are closer, but the presence of the vortex influences the 0.25CL profile strongly causing heavy skewness near the core region. θ is seen to be unaffected.

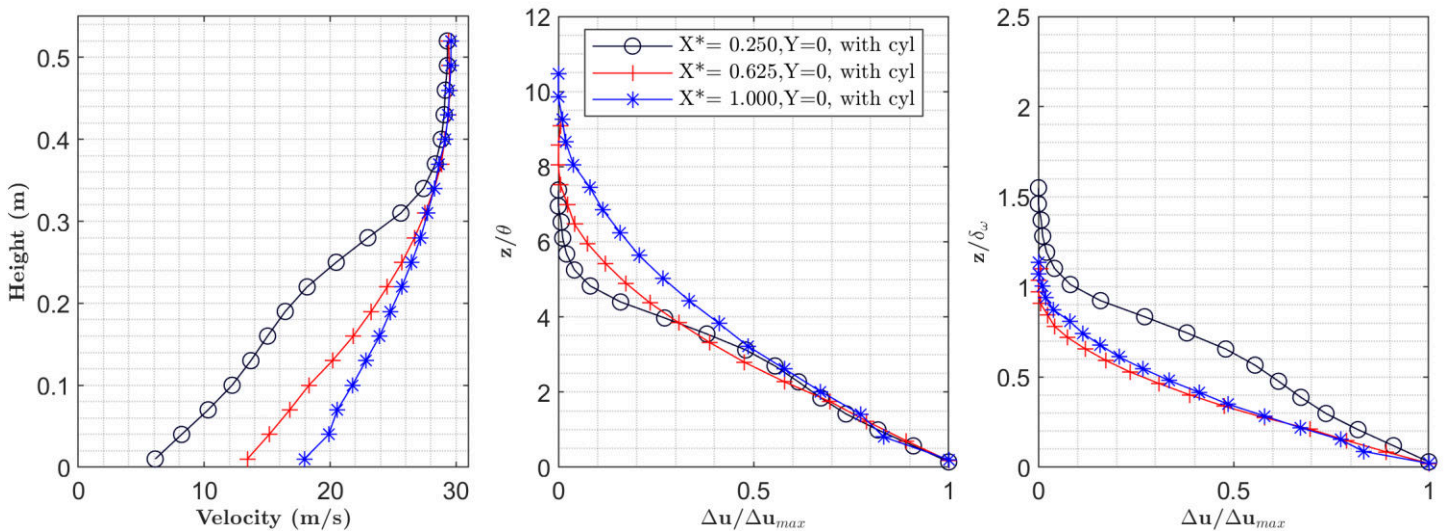


Figure 10. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup CC; Obtained from 4-hole cobra probe data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (o – 0.25CL, + – 0.625CL, * – 1.00CL)

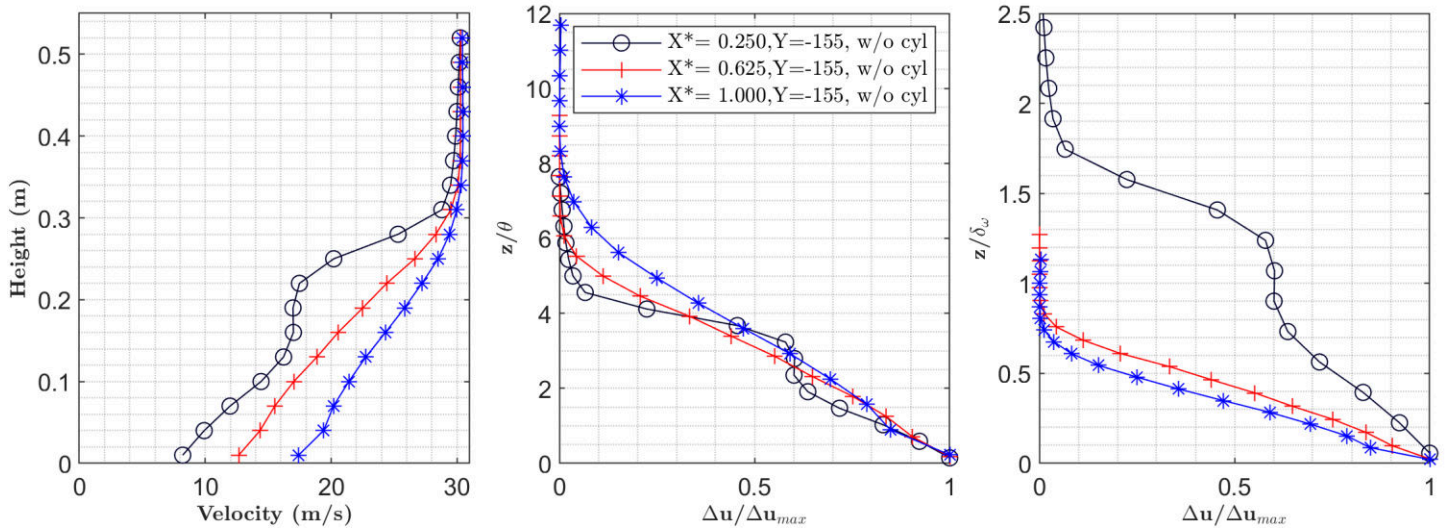


Figure 11. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup SnC; Obtained from 4-hole cobra probe data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (o – 0.25CL, + – 0.625CL, * – 1.00CL)

An opposite effect is seen with δ_ω wherein, the difference between the 0.25CL and the other two profiles is much larger than all the previous cases and the collapse between $>0.25CL$ profiles has improved.

Lastly, looking into the profiles in Figure 12, the model setup with the cylinder and observations at the span-line (SC setup). The cylinder and vortex wake has effectively decreased the maximum attainable velocity in the span-line location, with the topmost points only being able to reach ≈ 28 m/s instead of the 30m/s free-stream. θ is seen to be mostly unaffected as before, whereas δ_ω is affected the most in this set. The collapse between the profiles is no longer present, although the non-normalised profiles across all locations are closer than the previous cases.

As for the numerical solutions, both normalising parameters (θ and δ_ω) show similar effects compared to the wind tunnel data. The major

advantage here is that in the far wake of the DrivAer model ($>100\%CL$), the collapse of the profiles is much closer. Comparison of profiles with CC setup are shown in Figure 13. For the other setup cases (shown in Appendix, Figures A.1,A.2,A.3) similar trends in the mean velocity profiles are seen as before and θ shows similar effects. The use of δ_ω here is completely different, they do not match the trends observed in the wind tunnel data analysis. The velocity profiles here show an unexpected behaviour when moving from the wake of the DrivAer model towards the wake of the cylinder (going from floor to topmost point). The profiles do not seem to reach free-stream speed values in a manner similar to the wind tunnel data. This could be due to poorly resolved cylinder wake and vortex structures, because of conflicting shear values when moving from the wake of the DrivAer model to the wake of the cylinder. Similar results are observed with SnC, SC setups shown in Figures A.2,A.3 in the Appendix.

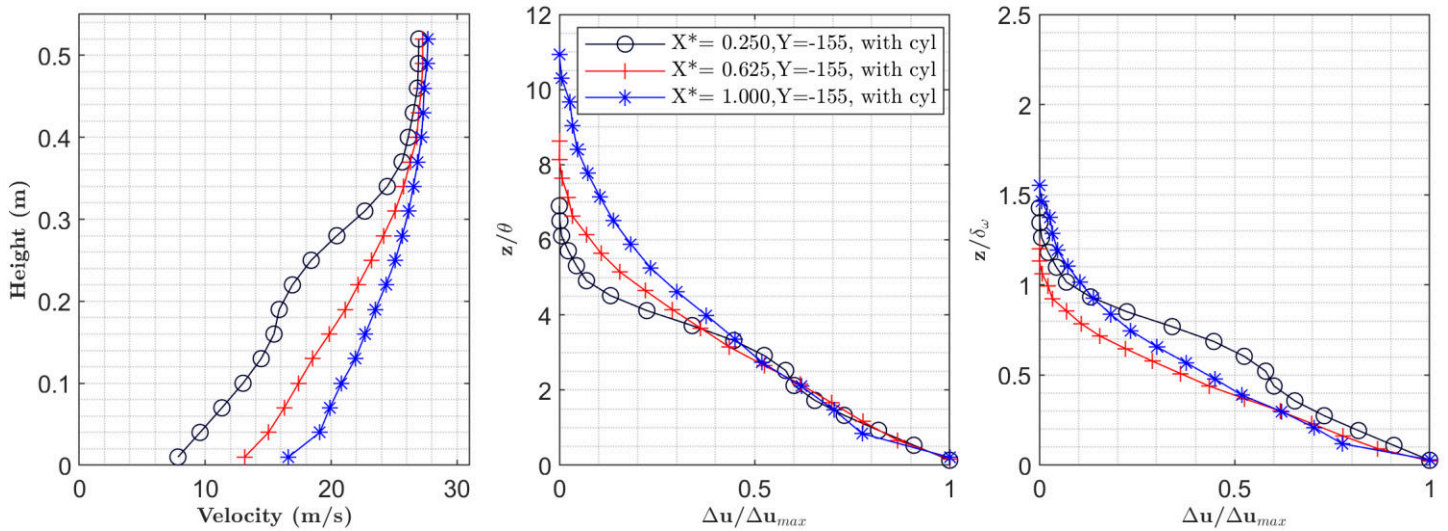


Figure 12. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup SC; Obtained from 4-hole cobra probe data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (o – 0.25CL, + – 0.625CL, * – 1.00CL)

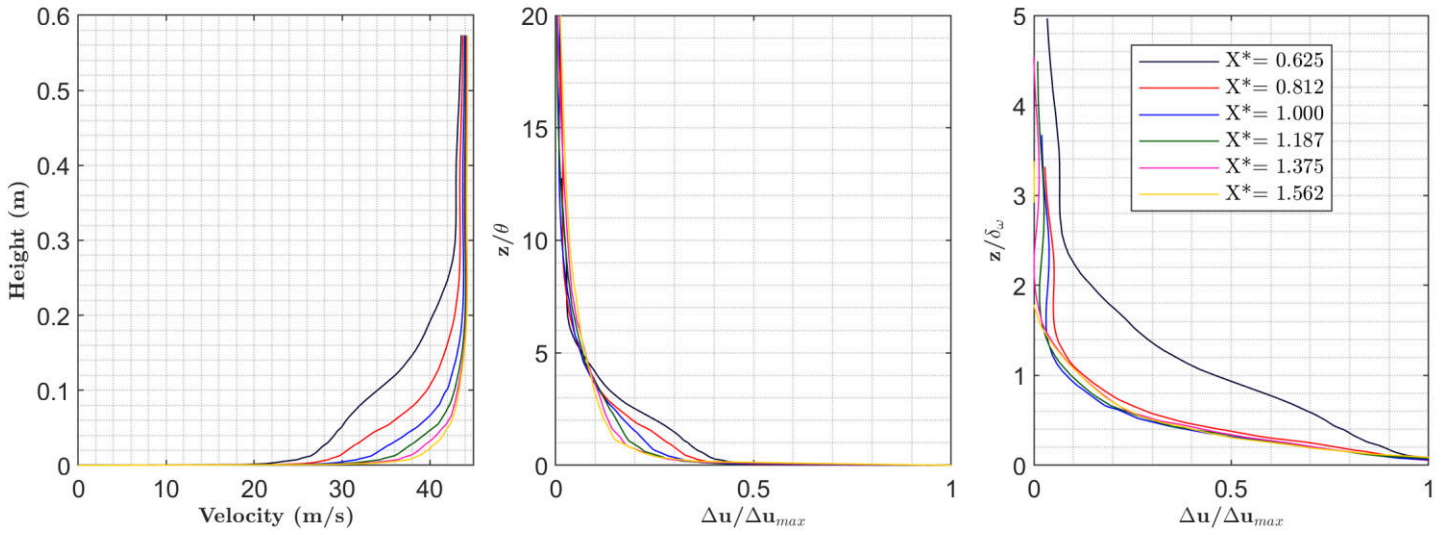


Figure 13. Comparison of velocity profiles with normalised profiles at locations with setup CnC; Obtained from numerical simulation data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (Profiles ranging from 0.625CL to ~1.5CL)

Comparison of Scaling Parameters

Figures 14 and 15 show the comparison of the scaling parameters, θ and δ_ω , across the different methods of measurements with CnC setup case only. There is a general trend for both parameters across all three. θ is seen to decrease downstream, thus, there is a decrease in loss of momentum (relative to free-stream). This is due to a decrease in velocity deficit downstream. δ_ω is seen to increase downstream, thus, the size of the vortex is increasing. This is evident from the fact that shear values ($\partial u / \partial z$) are decreasing downstream resulting in a decrease in the vortex strength which in turn results in the vortex spreading. Figures 16 and 17 show the comparison of the scaling parameters, θ and δ_ω , across all the setup cases, but only from the 4-hole probe data. The values of θ have the same trends across all combinations, they are all strictly decreasing irrespective of whether the measurements have been done at the centreline/span-line with/without the cylinder. The magnitudes increase when going from the setups CnC to SC.

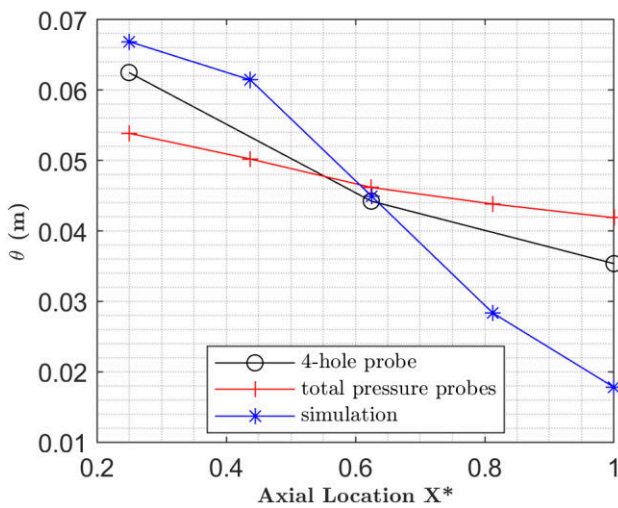


Figure 14. Comparison of momentum thickness across all instrumentations; (o – 4-hole probe, + – total pressure probes, * – k-ε realisable).

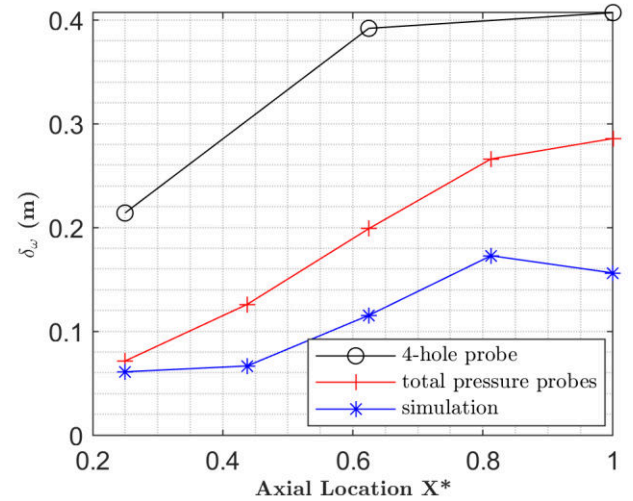


Figure 15. Comparison of vorticity thickness across all instrumentations; (o – 4-hole probe, + – total pressure probes, * – k-ε realisable).

δ_ω shows slightly different variations depending on the setup case. An increasing trend similar to θ is seen across the setup cases (CnC to SC) at the first axial location P5 (0.25CL). But downstream, for the setup case SC, δ_ω does not increase in the same trend as the other cases. The values at each axial location are seen to be close. This results in a bad collapse of the normalised profiles. Since for this setup case the wake contains a mixture of both the cylinder wake and the DrivAer model wake, the interaction of the two wakes results in stronger turbulent mixing. This causes issues with the self-similarity by removing the ‘trends’ in the mean velocity profiles and introducing skewness. Although θ is not affected by this, δ_ω does not contain information from the entire profile (since it is only dependant on the maximum shear values). This coupled with the skewness of the mean velocity profiles result in a bad quality of collapse.

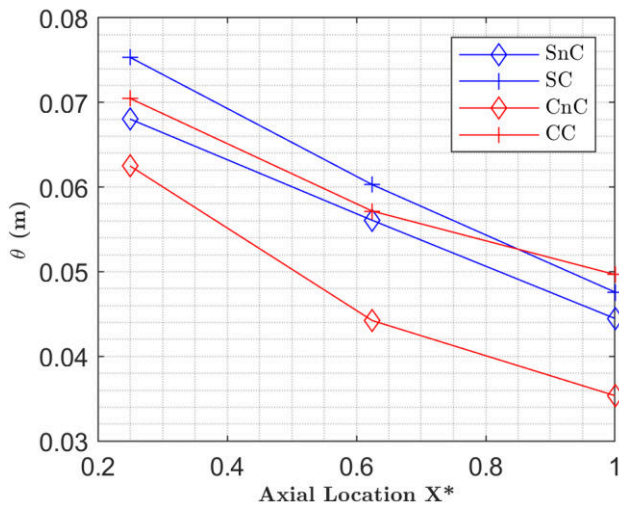


Figure 16. Comparison of momentum thickness across setups; 4-hole probe data only; (blue $\diamond$ – SnC, blue + – SC, red $\diamond$ – CnC, red + – CC).

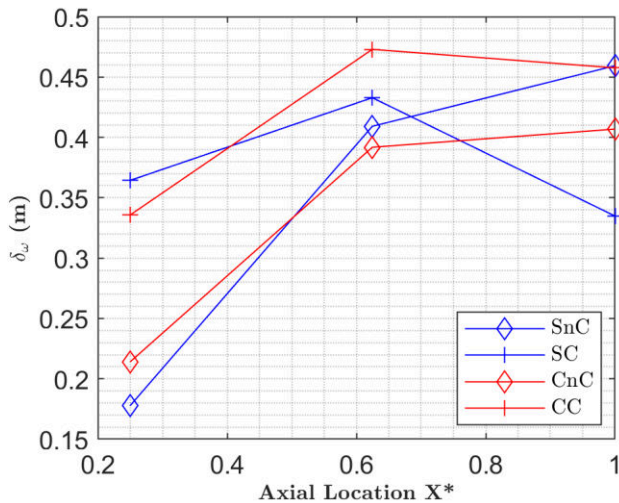


Figure 17. Comparison of vorticity thickness across setups; 4-hole probe data only; (blue $\diamond$ – SnC, blue + – SC, red $\diamond$ – CnC, red + – CC).

Summary/Conclusions

In this work, theories and concepts from analysis of self-similarity in simple wakes were applied to wake generated by the DrivAer body. The effect of upstream turbulence was analysed by relating the literature that studied the effects of free-stream and initial conditions on the wake of a body.

It was seen that the near wake ($X^* = 0.25CL$) proves to be a highly turbulent and difficult region to be analysed for trends. The presence of the C-pillar vortex also poses a number of issues for the scaling parameters. But, in general, the vorticity thickness (δ_ω) was seen to be a better scaling parameter than momentum thickness (θ) when not under the influence of adverse gradients. The presence of the cylinder causes significant changes to the velocity deficit which affect the

effectiveness of the scaling parameters by influencing the turbulent mixing in the wake.

This is in-line with previous works [10,11] where the effect of upstream turbulence makes it difficult for self-similarity to exist. θ only works marginally in specific zones of the profiles. The presence of the cylinder and vortex is seen to have minimal effect on its effectiveness as a scaling parameter. δ_ω showed varied effects based on the configuration setup. The presence of upstream disturbance and of vortex dominant regions significantly affect the effectiveness of δ_ω as a scaling parameter. The observations in the far wake show a better feasibility in self-similarity owing to smaller deficit values (as seen in the numerical solutions). Time-averaged numerical simulations has also shown similar results, albeit some issues were seen due to difficulties in resolving the wakes properly.

Thus, it can be stated that at the least partial self-similarity could be established in the wake of a complex geometric body, subject to conditions, both free-stream/initial and relative position to the body. Further analysis in this should aid in development of a description of the complex wake.

Recommendations

For future work, improving the data acquisition resolution along the height while mapping the wake would benefit in calculation of several parameters. Due to this, second order parameters such as Reynolds stresses could not be studied. Several studies have been done to use such second order parameters to calculate appropriate scaling factors which prove to be better at collapsing the profiles [4,7,9]. Use of higher frequency response instrumentation in the near wake would make it easier to distinguish between the eddy structures generated in the model wake and the ones due to wind tunnel environment. For the computational part, use of higher fidelity unsteady turbulence modelling will help in capturing the necessary fluctuations in the near wake. Considering the complexities in the near wake region, using a full vehicle model would be useful.

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Definitions/Abbreviations

CS	Car Scale
RANS	Reynolds-Averaged Navier Stokes
CL	Car Length
TI	Turbulence Intensity
TKE	Turbulent Kinetic Energy

Appendix

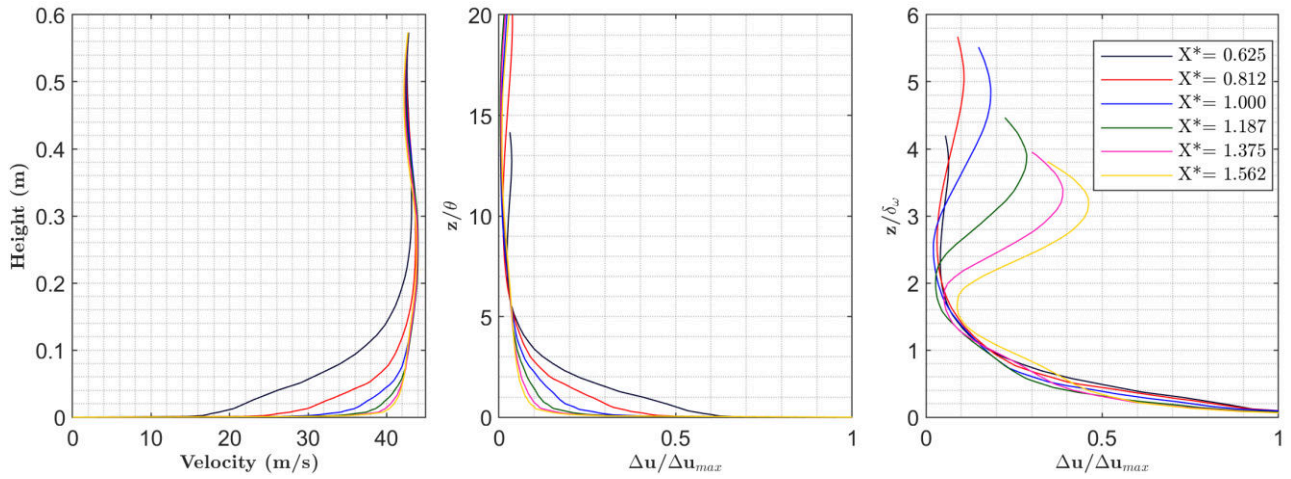


Figure A.1. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup CC; Obtained from numerical simulation data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (Profiles ranging from 0.625CL to ~1.5CL)

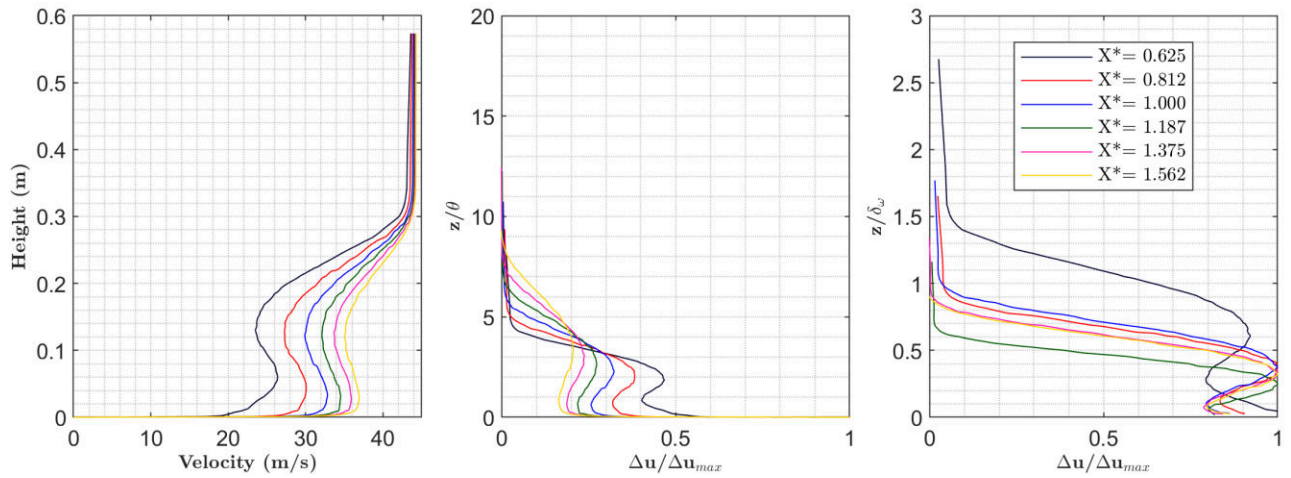


Figure A.2. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup SnC; Obtained from numerical simulation data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (Profiles ranging from 0.625CL to ~1.5CL)

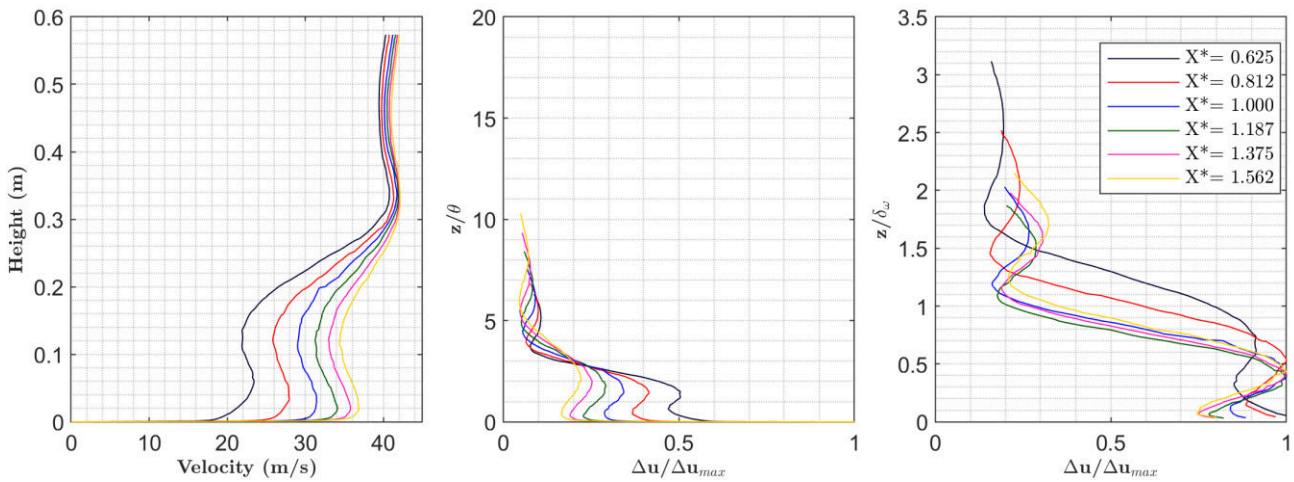


Figure A.3. Comparison of profiles with normalised profiles at locations P1, P3, P5 with setup SC; Obtained from numerical simulation data; left – velocity profiles, centre – normalised with momentum thickness, right – normalised using vorticity thickness; (Profiles ranging from 0.625CL to ~1.5CL)

The set of Figures A.1, A.2, A.3 show comparison of velocity profiles with normalised profiles obtained from the numerical solutions, The CC, SnC and SC setups are shown here (refer Table 6). The non-normalised profiles here show unexpected behaviour due to slower turbulent mixing of flow coming from under the underbody of the DrivAer model and the model wake. The use of scaling parameters is therefore affected significantly and does not produce results similar to the wind tunnel data. The interaction between the cylinder wake and model wake has also not been resolved properly, leading to unexpected nature of profiles.

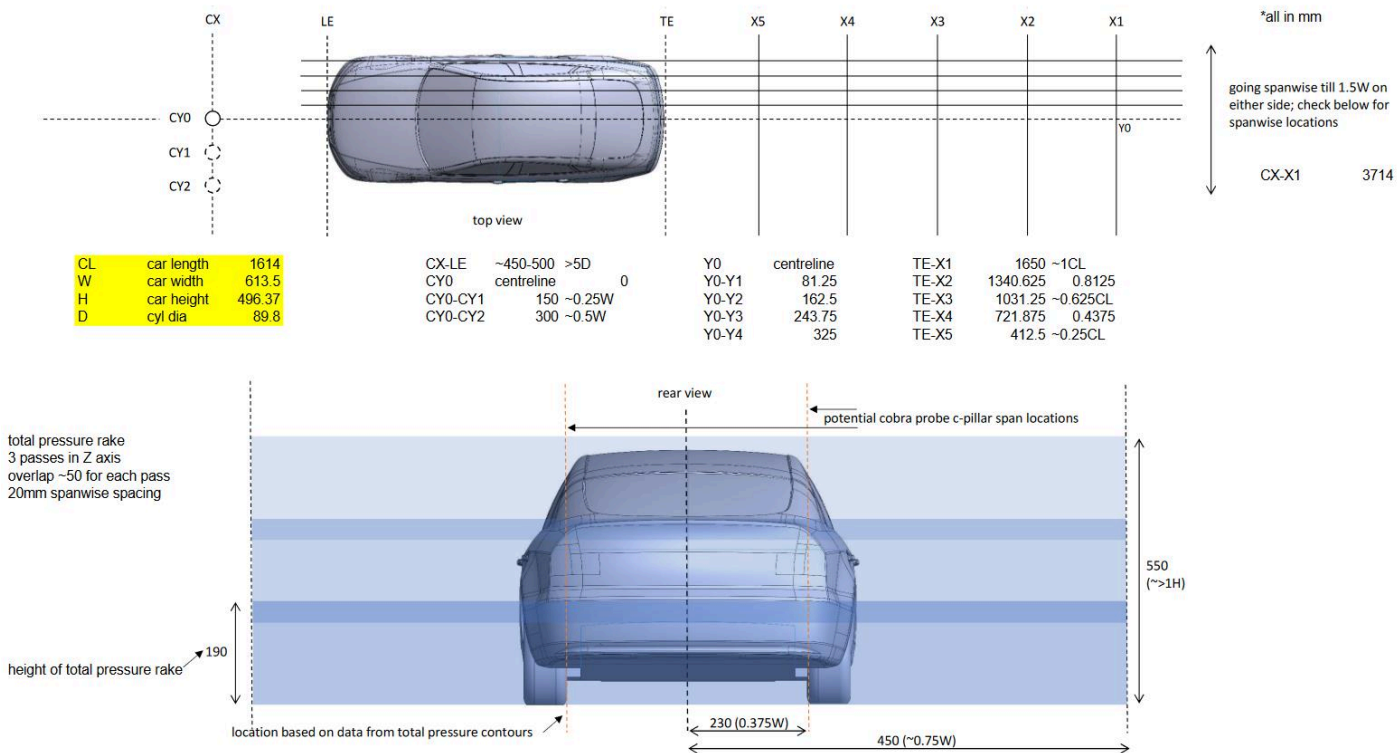


Figure A.4. Diagram describing the wind tunnel test plan for the Fastback DrivAer model at the Cranfield 8x6 Wind Tunnel

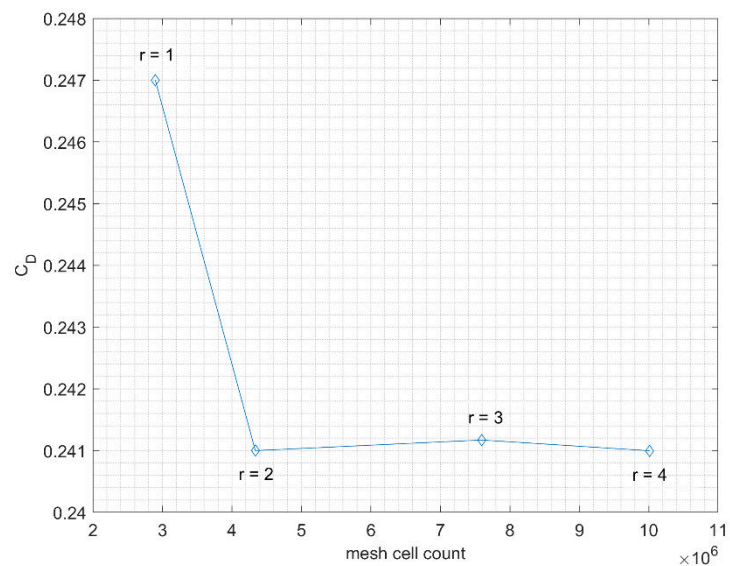


Figure A.5. Mesh grid independence study



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